# Bitcoin and Cryptocurrency Technologies

**Arvind Narayanan, Joseph Bonneau, Edward Felten,**
**Andrew Miller, Steven Goldfeder**

**with a preface by Jeremy Clark**

**Draft — Feb 9, 2016**

Feedback welcome! Email bitcoinbook@lists.cs.princeton.edu

For the latest draft and supplementary materials including programming assignments, see our Coursera course.

The official version of this book will be published by Princeton University Press in 2016. If you'd like to be notified when it's available, please sign up here.

# Introduction to the book

There's a lot of excitement about Bitcoin and cryptocurrencies. Optimists claim that Bitcoin will fundamentally alter payments, economics, and even politics around the world. Pessimists claim Bitcoin is inherently broken and will suffer an inevitable and spectacular collapse.

Underlying these differing views is significant confusion about what Bitcoin is and how it works. We wrote this book to help cut through the hype and get to the core of what makes Bitcoin unique.

To really understand what is special about Bitcoin, we need to understand how it works at a technical level. Bitcoin truly is a new technology and we can only get so far by explaining it through simple analogies to past technologies.

We'll assume that you have a basic understanding of computer science — how computers work, data structures and algorithms, and some programming experience. If you're an undergraduate or graduate student of computer science, a software developer, an entrepreneur, or a technology hobbyist, this textbook is for you.

In this book we'll address the important questions about Bitcoin. How does Bitcoin work? What makes it different? How secure are your bitcoins? How anonymous are Bitcoin users? What applications can we build using Bitcoin as a platform? Can cryptocurrencies be regulated? If we were designing a new cryptocurrency today, what would we change? What might the future hold?

Each chapter has a series of homework questions to help you understand these questions at a deeper level. In addition, there is a series of programming assignments in which you'll implement various components of Bitcoin in simplified models. If you're an auditory learner, most of the material of this book is also available as a series of video lectures. You can find all these on our Coursera course. You should also supplement your learning with information you can find online including the Bitcoin wiki, forums, and research papers, and by interacting with your peers and the Bitcoin community.

After reading this book, you'll know everything you need to be able to separate fact from fiction when reading claims about Bitcoin and other cryptocurrencies. You'll have the conceptual foundations you need to engineer secure software that interacts with the Bitcoin network. And you'll be able to integrate ideas from Bitcoin into your own projects.

# A note of thanks

We're immensely grateful to the students who helped develop programming assignments and to everyone who provided feedback on the drafts of this book. Princeton students Shivam Agarwal, Miles Carlsten, Paul Ellenbogen, Pranav Gokhale, Alex Iriza, Harry Kalodner, and Dillon Reisman, and Stanford students Allison Berke, Benedikt Bünz, and Alex Leishman deserve special praise. We're also thankful to Dan Boneh and Albert Szmigielski.

# Preface — The Long Road to Bitcoin

The path to Bitcoin is littered with the corpses of failed attempts. I've compiled a list of about a hundred cryptographic payment systems, both e-cash and credit card based technologies, that are notable in some way. Some are academic proposals that have been well cited while others are actual systems that were deployed and tested. Of all the names on this list, there's probably only one that you recognize — PayPal. And PayPal survived only because it quickly pivoted away from its original idea of cryptographic payments on hand-held devices!

There's a lot to learn from this history. Where do the ideas in Bitcoin come from? Why do some technologies survive while many others die? What does it take for complex technical innovations to be successfully commercialized? If nothing else, this story will give you an appreciation of how remarkable it is that we finally have a real, working payment mechanism that's native to the Internet.

| | | | | |
|---|---|---|---|---|
| ACC | CyberCents | iKP | MPTP | Proton |
| Agora | CyberCoin | IMB-MP | Net900 | Redi-Charge |
| AIMP | CyberGold | InterCoin | NetBill | S/PAY |
| Allopass | DigiGold | Ipin | NetCard | Sandia Lab E-Cash |
| b-money | Digital Silk Road | Javien | NetCash | Secure Courier |
| BankNet | e-Comm | Karma | NetCheque | Semopo |
| Bitbit | E-Gold | LotteryTickets | NetFare | SET |
| Bitgold | Ecash | Lucre | No3rd | SET2Go |
| Bitpass | eCharge | MagicMoney | One Click Charge | SubScrip |
| C-SET | eCoin | Mandate | PayMe | Trivnet |
| CAFÉ | Edd | MicroMint | PayNet | TUB |
| CheckFree | eVend | Micromoney | PayPal | Twitpay |
| ClickandBuy | First Virtual | MilliCent | PaySafeCard | VeriFone |
| ClickShare | FSTC Electronic Check | Mini-Pay | PayTrust | VisaCash |
| CommerceNet | Geldkarte | Minitix | PayWord | Wallie |
| CommercePOINT | Globe Left | MobileMoney | Peppercoin | Way2Pay |
| CommerceSTAGE | Hashcash | Mojo | PhoneTicks | WorldPay |
| Cybank | HINDE | Mollie | Playspan | X-Pay |
| CyberCash | iBill | Mondex | Polling | |

**Table 1: Notable electronic payment systems and proposals**

## Traditional financial arrangements

Back in time before there were governments, before there was currency, one system that worked for acquiring goods was barter. Let's say Alice wants a tool and Bob wants medicine. If each of them happen to have what the other person needs, then they can swap and both satisfy their needs.

On the other hand, let's say Alice has food that she's willing to trade for a tool, while Bob, who has a tool, doesn't have any need for food. He wants medicine instead. Alice and Bob can't trade with each other, but if there's a third person, Carol, who has medicine that she's willing to trade for food, then it becomes possible to arrange a three-way swap where everyone gets what they need.

The drawback, of course, is coordination — arranging a group of people, whose needs and wants align, in the same place at the same time. Two systems emerged to solve coordination: credit and cash. Historians, anthropologists, and economists debate which of the two developed first, but that's immaterial for our purposes.

In a credit-based system, in the example above, Alice and Bob would be able to trade with each other. Bob would give Alice the tool and Bob gets a favor that's owed to him. In other words, Alice has a debt that she needs to settle with Bob some time in the future. Alice's material needs are now satisfied, but she has a debt that she'd like to cancel, so that's her new "want". If Alice encounters Carol in the future, Alice can trade her food for Carol's medicine, then go back to Bob with the medicine and cancel the debt.

On the other hand, in a cash-based system, Alice would buy the tool from Bob. Later, she might sell her food to Carol, and Carol can sell her medicine to Bob, completing the cycle. These trades can happen in any order, provided that the buyer in each transaction has cash on hand. In the end, of course, it's as if no money ever changed hands.

Neither system is clearly superior. A cash-based system needs to be "bootstrapped" with some initial allocation of cash, without which no trades can occur. A credit-based system doesn't need bootstrapping, but the drawback is that anyone who's owed a debt is taking on some risk. There's a chance that the other person never comes back to settle the debt.

Cash also allows us to be precise about how much something is worth. If you're bartering, it's hard to say if a tool is worth more than medicine or medicine is worth more than food. Cash lets us use numbers to talk about value. That's why we use a blended system today — even when we're using credit, we measure debt in the amount of cash it would take to settle it.

These ideas come up in many contexts, especially online systems where users trade virtual goods of some kind. For example, peer-to-peer file-sharing networks must deal with the problem of "freeloaders," that is, users who download files without sharing in turn. While swapping files might work, there is also the issue of coordination: finding the perfect person who has exactly the file you want and wants exactly the file you have. In projects like MojoNation and academic proposals like Karma, users get some initial allocation of virtual cash that they must spend to receive a file and earn when they send a copy of a file to another user. In both cases, one or more central servers help keep track of users' balances and may offer exchange services between their internal currency and traditional currency. While MojoNation did not survive long enough to implement such an exchange, it became the intellectual ancestor of some protocols used today: BitTorrent and Tahoe-LAFS.

## The trouble with credit cards online

Credit and cash are fundamental ideas, to the point that we can sort the multitude of electronic payment methods into two piles. Bitcoin is obviously in the "cash" pile, but let's look at the other one first.

Credit card transactions are the dominant payment method that is used on the web today. If you've ever bought something from an online seller such as Amazon, you know how the arrangement goes. You type in your credit card details, you send it to Amazon, and then Amazon turns around with these credit card details and they talk to the "system"—a financial system involving processors, banks, credit card companies, and other intermediaries.

On the other hand, if you use something like PayPal, what you see is an intermediary architecture. There's a company that sits between you and the seller, so you send your credit card details to this intermediary, which approves the transaction and notifies the seller. The intermediary will settle its balance with the seller at the end of each day.

What you gain from this architecture is that you don't have to give the seller your credit card details, which can be a security risk. You might not even have to give the seller your identity, which would improve your privacy as well. The downside is that you lose the simplicity of interacting directly with the seller. Both you and the seller might have to have an account with the same intermediary.

Today most of us are comfortable with giving out our credit card information when shopping online, or at least we've grudgingly accepted it. We're also used to companies collecting data about our online shopping and browsing activity. But in the 1990s, the web was new, standards for protocol-level encryption were just emerging, and these concerns made consumers deeply uncertain and hesitant. In particular, it was considered crazy to hand over your credit card details to online vendors of unknown repute over an insecure channel. In such an environment, there was a lot of interest in the intermediary architecture.

A company called FirstVirtual was an early payment intermediary, founded in 1994. Incidentally, they were one of the first companies to set up a purely virtual office with employees spread across the country and communicating over the Internet — hence the name.

FirstVirtual's proposed system was a little like PayPal's current system but preceded it by many years. As a user you'd enroll with them and provide your credit card details. When you want to buy something from a seller, the seller contacts FirstVirtual with the details of the requested payment, FirstVirtual confirms these details with you, and if you approve your credit card gets billed. But two details are interesting. First, all of this communication happened over email; web browsers back in the day were just beginning to universally support encryption protocols like HTTPS, and the multi-party nature of payment protocol added other complexities. (Other intermediaries took the approach of encoding information into URLs or using a custom encryption protocol on top of HTTP.) Second, the customer would have ninety days to dispute the charge, and the merchant would receive the money only after three months! Today the merchant does get paid immediately, but, there still is the risk that the customer will file a chargeback or dispute the credit card statement. If that happens, the merchant will have to return the payment to the credit card company.

In the mid '90s there was a competing approach to the intermediary architecture which we'll call the SET architecture. SET also avoids the need for customers to send credit card information to merchants, but it additionally avoids the user having to enroll with the intermediary. In SET, when you are ready to make a purchase, your browser passes your view of the transaction details to a shopping application on your computer which, together with your credit card details, encrypts it in such a way that only the intermediary can decrypt it, and no one else can (including the seller). Having encrypted your data it this way, you can send it to the seller knowing that it's secure. The seller blindly forwards the encrypted data to the intermediary — along with their own view of the transaction details. The intermediary decrypts your data and approves the transaction only if your view matches the seller's view.

SET was a standard developed by VISA and MasterCard, together with many technology heavyweights of the day: Netscape, IBM, Microsoft, Verisign, and RSA. It was an umbrella specification that unified several existing proposals.

One company that implemented SET was called CyberCash. It was an interesting company in many ways. In addition to credit card payment processing, they had a digital cash product called CyberCoin. This was a micropayment system — intended for small payments such as paying a few cents to read an online newspaper article. That meant that you'd probably never have more than $10 in your CyberCoin account at any time. Yet, amusingly, they were able to get U.S. government (FDIC) insurance for each account for up to $100,000.

There's more. Back when CyberCash operated, there was a misguided — and now abandoned — U.S. government restriction on the export of cryptography, which was considered a weapon. That meant software that incorporated meaningful encryption couldn't be offered for download to users in other countries. However, CyberCash was able to get a special exemption for their software from the Department of State. The government's argument was that extracting the encryption technology out of CyberCash's software would be harder than writing the crypto from scratch.

Finally, CyberCash has the dubious distinction of being one of the few companies affected by the Y2K bug — it caused their payment processing software to double-bill some customers. They later went bankrupt in 2001. Their intellectual property was acquired by Verisign who then turned around and sold it to PayPal where it lives today.

Why didn't SET work? The fundamental problem has to do with certificates. A certificate is a way to securely associate a cryptographic identity, that is, a public key, with a real-life identity. It's what a website needs to obtain, from companies like Verisign that are called certification authorities, in order to show up as secure in your browser (typically indicated by a lock icon). Putting security before usability, CyberCash and SET decided that not only would processors and merchants in their system have to get certificates, all users would have to get one as well. Getting a certificate is about as pleasant as doing your taxes, so the system was a disaster. Over the decades, mainstream users have said a firm and collective 'no' to any system that requires end-user certificates, and such proposals have now been relegated to academic papers. Bitcoin deftly sidesteps this hairy problem by avoiding real-life identities altogether. In Bitcoin, public keys themselves are the identities by which users are known, as we'll see in Chapter 1.

In the mid 90s, when SET was being standardized, the World Wide Web Consortium was also looking at standardizing financial payments. They wanted to do it by extending the HTTP protocol instead so that users wouldn't need extra software for transactions—they could just use their browser. In fact, they had a very general proposal for how you might extend the protocol, and one of the use cases that they had was doing payments. This never happened -- the whole extension framework was never deployed in any browsers. In 2015, almost two decades later, the W3C has announced that it wants to take another crack at it, and that Bitcoin will be part of that standardization this time around. Given all the past failures, however, I won't be holding my breath.

## From Credit to (Crypto) Cash

Now let's turn to cash. We compared cash and credit earlier, and noted that a cash system needs to be "bootstrapped," but the benefit is that it avoids the possibility of a buyer defaulting on her debt. Cash offers two additional advantages. The first is better anonymity. Since your credit card is issued in your name, the bank can track all your spending. But when you pay in cash, the bank doesn't come into the picture, and the other party doesn't need to know who you are. Second, cash can enable offline transactions where there's no need to phone home to a third party in order to get the transaction approved. Maybe later, they go to a third party like a bank to deposit the cash, but that's much less of a hassle.

Bitcoin doesn't quite offer these two properties, but comes close enough to be useful. Bitcoin is not anonymous to the same level as cash is. You don't need to use your real identity to pay in Bitcoin, but it's possible that your transactions can be tied together based on the public ledger of transactions with clever algorithms, and then further linked to your identity if you're not careful. We'll get into the messy but fascinating details behind Bitcoin anonymity in Chapter 6.

Bitcoin doesn't work in a fully offline way either. The good news is it doesn't require a central server, instead relying on a peer-to-peer network which is resilient in the way that the Internet itself is. In Chapter 3 we'll look at tricks like "green addresses" and micropayments which allow us to do offline payments in certain situations or under certain assumptions.

The earliest ideas of applying cryptography to cash came from David Chaum in 1983. Let's understand this through a physical analogy. Let's say I start giving out pieces of paper that say: "The bearer of this note may redeem it for one dollar by presenting it to me" with my signature attached. If people trust that I'll keep my promise and consider my signature unforgeable, they can pass around these pieces of paper just like banknotes. In fact, banknotes themselves got their start as promissory notes issued by commercial banks. It's only in fairly recent history that governments stepped in to centralize the money supply and legally require banks to redeem notes.

I can do the same thing electronically with digital signatures, but that runs into the annoying "double spending" problem — if you receive a piece of data representing a unit of virtual cash, you can make two (or more) copies of it and pass it on to different people. To stick with our analogy, let's stretch it a little bit and assume that people can make perfect copies and we have no way to tell copies from the original. Can we solve double spending in this world?

Here's a possible solution: I put unique serial numbers into each note I give out. When you receive such a note from someone, you check my signature, but you also call me on the phone to ask if a note with that serial number has already been spent. Hopefully I'll say no, in which case you accept the note. I'll record the serial number as spent in my ledger, and if you try to spend that note, it won't work because the recipient will call me and I'll tell them the note has already been spent. What you'll need to do instead is to periodically bring me all the notes you've received, and I'll issue you the same number of *new* notes with fresh serial numbers.

This works. It's cumbersome in real life, but straightforward digitally provided I've set up a server to do the signing and record-keeping of serial numbers. The only problem is that this isn't really cash any more, because it's not anonymous — when I issue a note to you I can record the serial number along with your identity, and I can do the same when someone else later redeems it. That means I can keep track of all the places where you're spending your money.

This is where Chaum's innovation comes in. He figured out to both keep the system anonymous and prevent double-spending by inventing the digital equivalent of the following procedure: when I issue a new note to you, *you* pick the serial number. You write it down on the piece of paper, but cover it so that I can't see it. Then I'll sign it, still unable to see the serial number. This is called a "blind signature" in cryptography. It'll be in your interest to pick a long, random serial number to ensure that it will most likely be unique. I don't have to worry that you'll pick a serial number that's already been picked — you can only shoot yourself in the foot by doing so and end up with a note that can't be spent.

This was the first serious digital cash proposal. It works, but it still requires a server run by a central authority, such as a bank, and for everyone to trust that entity. Moreover, every transaction needs the participation of this server to go through. If the server goes down temporarily, payments grind to a halt. A few years later, in 1988, Chaum in collaboration with two other cryptographers Fiat and Naor proposed *offline* electronic cash. At first sight this might seem to be impossible: if you try to spend the same digital note or coin at two different shops, how can they possibly stop this unless they're both connected to the same payment network or central entity?

The clever idea is to stop worrying about preventing double-spending and focus on detecting it, after the fact, when the merchant re-connects to the bank server. After all, this is why you're able to use your credit card on an airplane even if there is no network connection up in the skies. The transaction processing happens later when the airline is able to re-connect to the network. If your card is denied, you'll owe the airline (or your bank) money. If you think about it, quite a bit of traditional finance is based on the idea of detecting an error or loss, followed by attempting to recover the money or punish the perpetrator. If you write someone a personal check, they have no guarantee that the money is actually in your account, but they can come after you if the check bounces. Conceivably, if an offline electronic cash system were widely adopted, the legal system would come to recognize double spending as a crime.

Chaum, Fiat, and Naor's idea for detecting double spending was an intricate cryptographic dance. At a high level, what it achieved was this: every digital coin issued to you encodes your identity, but in such a way that no one except you, not even the bank, can decode it. Every time you spend your coin, the recipient will require you to decode a random subset of the encoding, and they'll keep a record of this. This decoding isn't enough to allow them to determine your identity. But if you ever double spend a coin, eventually both recipients will go to the bank to redeem their notes, and when they do this, the bank can put the two pieces of information together to decode your identity completely, with an overwhelmingly high probability.

You might wonder if someone can frame you as a double spender in this system. Say you spend a coin with me, and then I turned around and tried to double-spend it (without redeeming it with the bank and getting a new coin with my identity encoded). This won't work — the new recipient will ask me to decode a random subset, and this will almost certainly not be the same as the subset you decoded for me, so I won't be able to comply with their decoding request.

Over the years, many cryptographers have looked at this construction and improved it in various ways. In the Chaum-Fiat-Naor scheme, if a coin is worth $100, and you wanted to buy something that cost only $75, say, there's no way to split that coin into $75 and a $25. All you could do is go back to the bank, cash in the $100 coin, and ask for a $75 coin and a $25 coin. But a paper by Okamoto and Ohta uses “Merkle trees” to create a system that does allow you to subdivide your coins. Merkle trees would show up in Bitcoin as well, and we'll meet them in Chapter 1. The Chaum-Fiat-Naor scheme also leaves a lot of room for improvements in efficiency. In particular, the application of something called zero-knowledge proofs to this scheme (most notably by Brands; and Camenisch, Hohenberger, and Lysyanskaya) was very fruitful—zero-knowledge proofs have also been applied to Bitcoin as we will see in Chapter 6.

But back to Chaum: he took his ideas and commercialized them. He formed a company in 1989 called DigiCash, probably the earliest company that tried to solve the problem of online payments. They had about a five-year head start on other companies like FirstVirtual and CyberCash that we just discussed. The actual cash in Digicash's system was called Ecash and they had another system called cyberbucks. There were banks that actually implemented it — a few in the US and at least one in Finland. This was in the 1990s, long before Bitcoin, which might come as surprise to some Bitcoin enthusiasts who view banks as tech-phobic, anti-innovative behemoths.

Ecash is based on Chaum's protocols. Clients are anonymous, so banks can't trace how they're spending their money. But merchants in ecash aren't anonymous. They have to return coins as soon as they receive them, so the bank knows how much they're making, at what times, and so on.

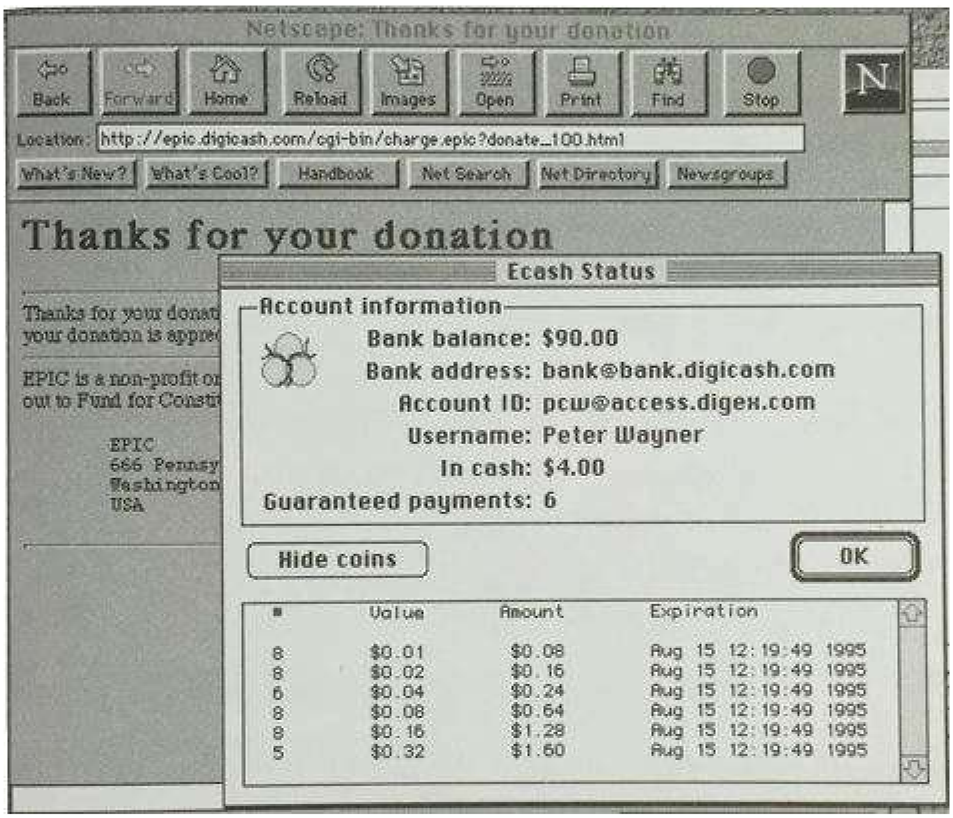


**Figure 2: Screenshot of DigiCash**

Figure 2 shows a screenshot from the software. As you can see, it shows you your balance as well as all the coins that you have that have been issued to you from the bank. Since there's no way to split your coins, the bank issues you a whole set of coins in denominations of a cent, two cents, four cents, and so on — powers of two. That way, you (or your software, on your behalf) can always select a set of coins to pay for the exact amount of a transaction.

When you want to make a transaction, say, as in this example, you want to make a donation to the non-profit privacy group EPIC, you'd click on a donation link that takes you to the Digicash website. That would then open a reverse web connection back to your computer. That means your computer had to have the ability to accept incoming connections and act as a server. You'd have to have your own IP address and your ISP would have to allow incoming connections. If the connection was successful, then the ecash software would launch on your computer and you'd be able to approve the transaction and send the money.

Chaum had several patents on Digicash technology, in particular, the blind-signature scheme that it used. This was controversial, and it stopped other people from developing ecash systems that used the same protocol. But a bunch of cryptographers who hung out on what was called the cypherpunks mailing list wanted an alternative. Cyperpunks was the predecessor to the mailing list where Satoshi Nakamoto would later announce Bitcoin to the world, and this is no coincidence. We'll talk about the cypherpunk movement and the roots of Bitcoin in Chapter 7.

The cypherpunk cryptographers implemented a version of of ecash called MagicMoney. It did violate the patents, but was billed as being only for experimental use. It was a fun piece of software to play with. The interface was all text-based. You could send transactions by email. You would just copy and paste the transactions into your email and send it to another user. Hopefully, you'd use end-to-end email encryption software such as PGP to protect the transaction in transit.

Then there's a proposal called Lucre by Ben Laurie with contributions from many other people. Lucre tries to replace the blind-signature scheme in ecash with a non-patent-encumbered alternative, with the rest of the system largely the same.

Yet another proposal, by Ian Goldberg, tries to fix the problem of not being able to split your coins to make change. His idea was that the merchant could send you coins back if they had some coins, so that you might overpay for the item if you didn't have exact change, and then you'd get some coins back. But notice that this introduces an anonymity problem. As we saw earlier, in ecash, senders are anonymous but merchants aren't. When the merchant sends cash back, technically, they're the sender, so they're anonymous. But you, as someone who has to return this cash to the bank, aren't anonymous. There's no way to design this system without breaking the anonymity of users trying to buy goods. So Goldberg came up with a  proposal where there were different types of coins that would allow these transactions to occur, allow you to get change back, and still preserve your anonymity.

Now, why did DigiCash fail? The main problem with DigiCash was that it was hard to persuade the banks and the merchants to adopt it. Since there weren't many merchants that accepted ecash, users didn't want it either. Worse, it didn't support user-to-user transactions, or at least not very well. It was really centered on the user-to-merchant transaction. So if merchants weren't on board, there was no other way to bootstrap interest in the system. So at the end of the day, DigiCash lost and the credit card companies won.

As a side note, Bitcoin allows user-to-merchant and user-to-user transactions. In fact, the protocol doesn't have a notion of merchant that's separate from the notion of user. The support for user-to-user transactions probably contributed to Bitcoin's success. There was something to do with your bitcoins right from the beginning: send it to other users, while the community tried to drum up support for Bitcoin and get merchants to accept it.

In the later years of the company, DigiCash also experimented with tamper-resistant hardware to try to *prevent* double-spending rather than just detecting it. In this system, you'd get a small hardware device that was usually called a wallet, or some sort of card. The device would keep track of your balance, which would decrease when you spent money and increase if you loaded the card with more money. The point of the device is that there should be no way to physically or digitally go in and tamper with its counter. So if the counter hits zero, then the card stops being able to spend money until it's re-loaded.

There were many other companies that had electronic cash systems based on tamper-resistant hardware. DigiCash later worked with a company called CAFE which was based in Europe. Another company formed around this idea was called Mondex and it was later acquired by Mastercard. Visa also had their own variant called VisaCash.


**Figure 3: Mondex system, showing user card and wallet.**

Figure 3 shows the user side of the Mondex system. There's a smart card and there's a wallet unit, and you can load either of them with cash. And if you wanted to do user-to-user swap of money, the giver user would first put their card into the wallet and move money off of the card onto the wallet. Then the receiver would stick their card in the wallet then you'd move the money onto the second card. This was a way to exchange digital cash, and it was anonymous.

Mondex trialled their technology in a bunch of communities. One community happened to be a city very close to where I grew up: Guelph, Ontario. You've probably already guessed that it didn't really catch on. A major problem with Mondex cards is that they're like cash — if you lose them or they get stolen, the money's gone. Worse, if there's some sort of malfunction with the card, if the card reader wouldn't read it, there's no way to figure out if that card had balance on it or not. In these scenarios, Mondex would typically eat the cost. They'd assume that the card was loaded and reimburse the user for that lost money. Of course, that can cost a company a lot of money.

Further, the wallet was slow and clunky. It was much faster to pay with a credit card or with cash. And retailers hated having several payment terminals; they wanted just one for credit cards. All these factors together did Mondex in.

However, these cards were smart cards, which means that they have small microcontrollers on them, and that technology has proved successful. In many countries today, including Canada, where I live, every single credit card and every single debit card now has smart card technology in it. It's used for a different purpose, though. It's not used to prevent double-spending — the problem doesn't arise since it's not a cash-based technology. The bank, rather than your card, keeps track of your balance or available credit. Instead the chip is used for authentication, that is, to prove that you know the PIN that's associated with your account. But Mondex was using it long before this technology was adopted widely by the banking industry.

## Minting Money out of Thin Air

In the DigiCash system, if you have a digital cash object that's worth $100, what makes it actually worth $100? The answer is simple: in order to obtain ecash worth $100, you'd have to take $100 out of your bank account and give it to the bank that was issuing you the ecash. But there were a bunch of different proposals for how to do this and different companies did it differently. One far-fetched possibility: what if the government of a particular country actually authorized services to mint digital money, creating new cash out of thin air? That was the idea behind NetCash, although it never got beyond the proposal stage. A different system, used by e-Gold, was to put a pile of gold in a vault and to issue digital cash only up to the value of the gold. Another company called Digigold wasn't fully backed by gold, but had partial reserves.

All of these ideas ultimately peg the value of digital cash to the dollar or a commodity. If the dollar's value goes up or down, the value of your digital money holdings will change along with it. A radically different possibility is to allow digital money to be it own currency, issued and valued independently of any other currency.

To create a free-floating digital currency that is likely to acquire real value, you need to have something that's scarce by design. In fact, scarcity is also the reason why gold or diamonds have been used as a backing for money. In the digital realm, one way to achieve scarcity is to design the system so that minting money requires solving a computational problem (or "puzzle") that takes a while to crack. This is what happens in Bitcoin "mining", which we'll look at in Chapter 5.

The basic idea — that solutions to computational puzzles could be digital objects that have some value — is pretty old. It was first proposed by cryptographers Dwork and Naor as a potential solution to email spam back in 1992. What if, every time you sent an email, your computer would have to solve one of these puzzles that would take a few seconds to solve? To enforce this requirement, the recipient's email program would simply ignore your email you didn't attach the solution to the computational puzzle. For the average user, it wouldn't be that much of a barrier to sending emails because you're not sending emails very frequently. But if you're a spammer, you're trying to send out thousands or millions of emails all at once, and solving those computational puzzles could become prohibitive. A similar idea was later discovered independently by Adam Back in 1997 in a proposal called Hashcash.

These computational puzzles need to have some specific properties to be a useful spam deterrent. First, it should be impossible for a spammer to solve one puzzle and attach the solution to every email he sends. To ensure this, the puzzle should be specific to the email: it should depend on the sender and receiver, the contents of the email, and the approximate time at which it's sent. Second, the receiver should be able to easily check the puzzle solution without having to repeat the process of solving the puzzle. Third, each puzzle should be totally independent of the others, in the sense that solving one puzzle does not decrease the amount of time it takes to solve any other puzzle. Finally, since hardware improves with time and solving any given computational puzzle gets faster and cheaper, recipients should be able to adjust the difficulty of the puzzle solutions that they will accept. These properties can be achieved by using cryptographic hash functions to design the puzzles, and we'll study this in Chapter 1.

Bitcoin uses essentially the same computational puzzle as Hashcash, but with some minor improvements. Bitcoin does a lot more than Hashcash does, though — after all, it takes a whole book to explain Bitcoin! I only mention this because Hashcash inventor Adam Back has said, "Bitcoin is Hashcash extended with inflation control." I think that's overreaching a bit. It's sort of like saying, "a Tesla is just a battery on wheels."

As with any good idea in cryptography, there are many variants of computational puzzles that aim to achieve slightly different properties. One proposal comes from Rivest and Shamir, the R and the S in the RSA cryptosystem. Observe that in Hashcash, your cost to solve a number of puzzles is simply the sum of the individual costs, by design. But this is different from the cost structure for a government to mint money. If you think about how anti-counterfeiting technology in a paper currency, there's a huge initial cost to acquire all the equipment, create the security features, and so on. But once they've done all that, their costs go down, and it doesn't matter much if they print one bill or a hundred bills. In other words, minting paper money has a huge fixed cost but low marginal cost. Rivest and Shamir wanted to design computational puzzles that would mimic these properties, so that minting the first coin is massively computationally challenging, but minting subsequent coins is a lot cheaper. Their proposal also utilized hash functions, but in a different way. We won't get into the details of their solution, but the problem they were trying to solve is interesting at a high level.

Why did Hashcash never catch on for its intended purpose of preventing spam? Perhaps spam just wasn't a big enough problem to solve. For most people spam as a nuisance, but not something that they want to spend their computing cycles on combatting. We have spam filters today that work pretty well at keeping spam out of our inboxes. It's also possible Hashcash wouldn't have actually stopped spammers. In particular, most spammers today send their spam using 'botnets', large groups of of other people's computers that they take control of using malware. They might just as well use those computers to harvest Hashcash. That said, the idea of using computational puzzles to limit access to resources is still an idea that's kicking around. You can see it in some proposals for replacing network protocols, such as MinimaLT.

## Recording Everything in a Ledger

Another key component of Bitcoin is the block chain: a ledger in which all Bitcoin transactions are securely recorded. The ideas behind the block chain are again quite old, and trace back to a paper by Haber and Stornetta in 1991. Their proposal was a method for secure timestamping of digital documents, rather than an digital money scheme. The goal of timestamping is to give an approximate idea of when a document came into existence. More importantly, timestamping accurately conveys the order of creation of these documents: if one came into existence before the other, the timestamps will reflect that. The security property requires that a document's timestamp can't be changed after the fact.

In Haber and Stornetta's scheme, there's a timestamping service to which clients send documents to timestamp. When the server receives a document, it signs the document together with the current time and as well as a link or a pointer to the previous document, and issues a "certificate" with this information. The pointer in question a special type pointer which links to a piece of data instead of a location. That means that if the data in question changes, the pointer automatically become invalid. In Chapter 1 we'll study how we can create such pointers using hash functions.

What this achieves is that each document's certificate ensures the integrity of the contents of the previous document. In fact, you can apply this argument recursively: each certificate essentially fixes the entire history of documents and certificates up until that point. If we assume that each client in the system keeps track of at least a few certificates — their own documents' certificates, and those of the previous and following documents — then collectively the participants can ensure that the history cannot be changed after the fact. In particular, the relative ordering of documents is preserved.

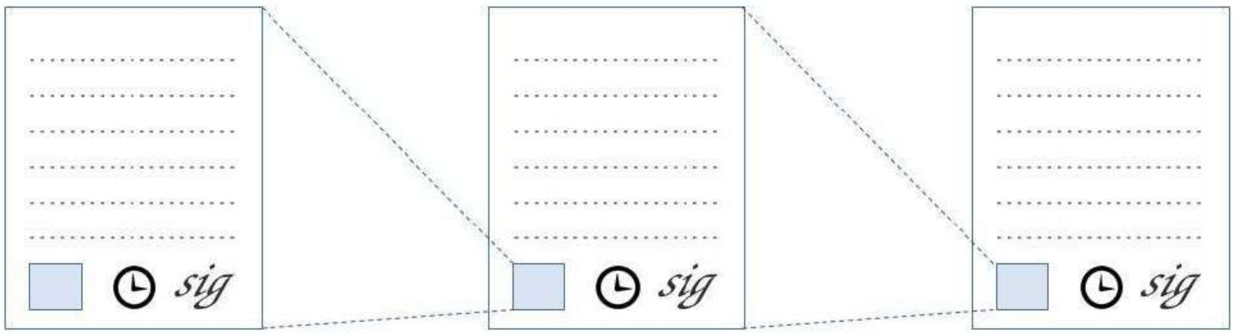



**Figure 4: linked timestamping**. To create a certificate for a document, the timestamp server includes a hash pointer to the previous document's certificate, the current time, and signs these three data elements together.

A later paper proposed an efficiency improvement: instead of linking documents individually, we can collect them into blocks and link blocks together in a chain. Within each block, the documents would again be linked together, but in a tree structure instead of linearly. This decreases the amount of checking needed to verify that a particular document appears at a particular point in the history of the system. Visually, this hybrid scheme looks like Figure 5.

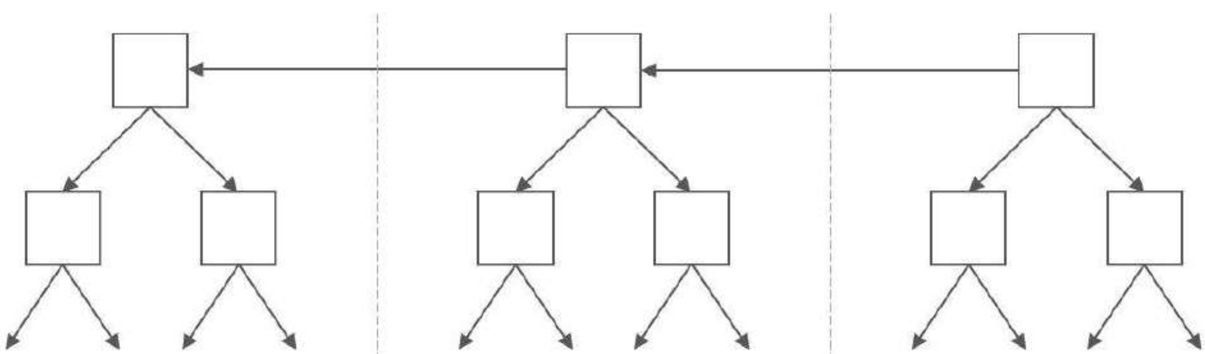


**Figure 5: efficient linked timestamping**. Arrows represent hash pointers and dotted vertical lines indicate time intervals.

This data structure forms the skeleton of Bitcoin's block chain, as we'll see in Chapter 3. Bitcoin refines it a subtle but important way: a Hashcash-esque protocol is used to delay how fast new blocks are added to the chain. This modification has profound and favorable consequences for Bitcoin's security model. There is no longer the need for trusted servers; instead, events are recorded by a collection of untrusted nodes called "miners". Every miner keeps track of blocks, rather than having to rely on regular users to do it. Anyone can become a miner by solving computational puzzles to create blocks. Bitcoin also gets rid of signatures, relying only on hash pointers to ensure the integrity of the data structure. Finally, the actual timestamps aren't of much importance in Bitcoin, and the point of the system is to record the relative ordering of transactions in a tamper-resistant way. In fact, Bitcoin blocks aren't created in a fixed schedule. The system ensures that a new one is created every 10 minutes on average, but there's considerable variation in the time between successive blocks.

In essence, Bitcoin combines the idea of using computational puzzles to regulate the creation of new currency units with the idea of secure timestamping to record a ledger of transactions and prevent double spending. There were earlier, less sophisticated proposals that combined these two ideas. The first is called b-money, and it was by Wei Dai in 1998. In b-money, anyone can create money using a hashcash-like system. There's a peer-to-peer network, sort of like in Bitcoin. Each node maintains a ledger, but it's not a global ledger like in the Bitcoin block chain. Each node has its own ledger of what it thinks everyone's balance is.

Another similar proposal, by Nick Szabo, is called Bitgold. Szabo says he had the idea for Bitgold as early as 1998, but didn't get around to blogging about it until 2005. The reason I mention this is that there's a minor conspiracy theory popularized by Nathaniel Popper, a New York Times reporter who wrote a very good book on the history of Bitcoin. Popper notes that the blog post timestamps were changed after Satoshi posted the Bitcoin whitepaper so that the Bitgold proposal looks like it was written up about two months after Bitcoin was released. Popper believes, like many other observers, that Szabo could be Satoshi, and he cites the timestamp change as evidence of Szabo/Satoshi trying to cover up the fact that he invented Bitgold before he knew about Bitcoin.

The problem with this explanation is that if you actually read the contents of the blog posts, Szabo is very clear about having had this idea in 1998, and he doesn't try to change those dates. So a more reasonable explanation is that he just bumped the post to the top of his blog after Bitcoin popularized similar ideas, to make sure that people were aware of his prior proposal.

Bitcoin has several important differences from b-money and Bitgold. In those proposals, computational puzzles are used directly to mint currency. Anyone can solve a puzzle and the solution is a unit of money itself. In Bitcoin, puzzle solutions themselves don't constitute money. They are used to secure the block chain, and only indirectly lead to minting money for a limited time. Second, b-money and Bitgold rely on timestamping services that sign off on the creation or transfer of money. Bitcoin, as we've seen, doesn't require trusted timestamping, and merely tries to preserve the relative order of blocks and transactions.

Finally, in b-money and Bitgold, if there is disagreement about the ledger among the servers or nodes, there isn't a clear way to resolve it. Letting the majority decide seems to be implicit in both authors' writings. But since anyone can set up a node — or a hundred, hiding behind different identities — these mechanisms aren't very secure, unless there is a centralized gatekeeper who controls entry into the network. In Bitcoin, by contrast, for an attacker to change history, they must solve computational puzzles at a faster rate than the rest of the participants combined. This is not only more secure, it allows us to quantify the security of the system.

B-money and Bitgold were informal proposals — b-money was a post on a mailing list and Bitgold was a series of blog posts. Neither took off, or was even implemented directly. Unlike the Bitcoin white paper, there wasn't a full specification or any code. The proposals gloss over issues that may or may not be solvable. The first, as we've already mentioned, is how to resolve disagreements about the ledger. Another problem is determining how hard the computational puzzle should be in order to mint a unit of currency. Since hardware tends to get dramatically cheaper over time for a fixed amount of computing power, Bitcoin incorporates a mechanism to automatically adjust the difficulty of the puzzles periodically. B-money and Bitgold don't include such a mechanism, which can result in problems since coins may lose their value if it become trivially easy to create new ones.

## Hints about Satoshi

You may know that Satoshi Nakamoto is the pseudonym adopted by the creator of Bitcoin. While his identity remains a mystery, he communicated extensively in Bitcoin's early days. Let's use this to dig a little bit into questions like when he started working on Bitcoin, to what extent he was influenced by the prior ideas we've looked at, and what motivated him.

Satoshi says he started coding Bitcoin around May 2007. I'll take him at his word; the fact that he's anonymous is not a reason to think he'd lie about things like that. He registered the domain bitcoin.org in August 2008. And at that time, he started sending private emails to a few people who he thought might be interested in the proposal. Then a little later in October 2008, he publicly released a white paper that described the protocol, and then soon after, he released the initial code for Bitcoin as well. Then he stuck around for about two years, during which he posted lots of messages on forums, emailed with lots of people, and responded to people's concerns. On the programming side, he submitted patches to the code. He maintained the source code in conjunction with other developers, fixing issues as they arose. By December 2010, others had slowly taken over the maintenance of the project, and he stopped communicating with them.

I've been referring to Satoshi Nakamoto as a "he," but I have no particular reason to believe Satoshi is a man and not a woman. I'm just using the male pronoun since Satoshi is a male name. I've also been referring to him as a single individual. There is a theory that Satoshi Nakamoto might be a collection of individuals. I don't buy this theory — I think Satoshi is probably just one person. The reason is that if we look at the entirety of the online interactions undertaken under the Satoshi pseudonym, if we think about the two years that Satoshi spent replying to emails and patching code, it's hard to imagine that this could be multiple people sharing user accounts and passwords, responding in a similar style and a similar voice, and making sure they didn't contradict each other. It just seems a much simpler explanation that at least this portion of Satoshi's activity was done by a single individual.

Furthermore, it's clear from his writings and patches that this individual understood the full code base of Bitcoin and all its design aspects. So it's very reasonable to assume that the same individual wrote the original code base and the white paper as well. Finally, it's possible that Satoshi had help with the original design. However, after Bitcoin's release, we can see for ourselves that Satoshi was quick to attribute any help he received from other contributors. It would be out of character for him to mislead us about inventing something by himself if he had had help from other people.

Next, we might ask ourselves, "What did Satoshi know about the history of ecash?" To understand this better, we can start by looking at what he cites in his white paper as well as the references that existed on early versions of the Bitcoin website. In the white paper he cites some papers on basic cryptography and probability theory. He also cites the time-stamping work that we saw earlier, and it's very natural to think that he based the design of the block chain on these references since the similarities are so apparent. He also cites the Hashcash proposal whose computational puzzle is very similar to the one that's used in Bitcoin. He also has a reference to b-money. Later, on the website, he added references to Bitgold and as well to a scheme by Hal Finney for reusing computational puzzle solutions.

But, if we look at the email exchanges that were made public by people who corresponded with Satoshi Nakamoto in the early days, we find that the b-money proposal was actually added after-the-fact, at the suggestion of Adam Back. Satoshi then emailed Wei Dai who created b-money and apparently, Dai was the one that told him about Bitgold. So these proposals weren't probably inspirations for the original design. He later corresponded a lot with Hal Finney, and that's quite a reasonable explanation for why he cites Finney's work, at least on the website.

Based on this, it seems plausible that when creating Bitcoin, Hashcash and time-stamping were the only things from the history of ecash that Satoshi knew about or thought were relevant. After he came to know of b-money and Bitgold, however, he seems to have appreciated their relevance. In mid-2010, the Wikipedia article on Bitcoin was flagged for deletion Wikipedia's editors because they thought it wasn't noteworthy. So there was some discussion between Satoshi and others about how to word the article so that Wikipedia would accept it. To that end, Satoshi suggested this description of Bitcoin: "Bitcoin is an implementation of Wei Dai's b-money proposal on Cypherpunks in 1998 and Nick Szabo's Bitgold proposal." So Satoshi, by this point, did see positioning Bitcoin as an extension of these two ideas or an implementation of these two prior systems as a good explanation of how it worked.

But, what about everything else — the Chaumian ecash schemes and the credit card proposals that we looked at? Did Satoshi know any of that history when designing Bitcoin? It's hard to tell. He didn't give any indication of knowing that history, but it's just as likely that he didn't reference this because it wasn't relevant to Bitcoin. Bitcoin uses a completely different decentralized model and so there's no compelling reason to dwell on old centralized systems that failed.

Satoshi himself makes this point, by mentioning Chaumian ecash in passing, in one of his posts to the Bitcoin forums. Writing about another proposal called opencoin.org, he notes that they seem to be "talking about the old Chaumian central mint stuff, but maybe only because that was the only thing available. Maybe they would be interested in a new direction. A lot of people automatically dismiss e-currency as a lost cause because of all the companies that failed since the 1990's. I hope it's obvious it was only the centrally controlled nature of those systems that doomed them. I think this is the first time we're trying a decentralized, non-trust-based system." That gives us a pretty good idea what Satoshi thought of the earlier proposals, and specifically how he felt Bitcoin was different. Bitcoin's decentralization is indeed a defining feature that sets it apart from almost everything we've look at.

Another interesting quote from Satoshi suggests that he might not be an academic. Most academic researchers think about ideas and write them down immediately, before they build the system. Satoshi says that he took an opposite approach: "I actually did Bitcoin kind of backwards. I had to write all the code before I could convince myself that I could solve every problem, then I wrote the paper. I think I will be able to release the code sooner than I could write a detailed specification."

Since there's bit of myth around Satoshi, it's worth mentioning that he made mistakes like everyone else and that wasn't a perfect oracle of the future. There are bugs and questionable design choices in the original Bitcoin code as well as in its design. For example, there was a feature to send bitcoins to IP addresses that never caught on and, in retrospect, was a bad idea. When he described what Bitcoin was useful for, his scenarios were centered on the idea of using it across the internet. That use case is central to Bitcoin, of course, but it's not the only one. He didn't indicate a vision of going into a coffee shop and being able to pay for your coffee with Bitcoin, for example.

A final question we may ask ourselves, colored by what we understand from the history of digital cash, is, "Why does Satoshi maintain his anonymity?" There are many possible reasons. To begin with, it might be just for fun. Many people write novels anonymously, and there are graffiti artists like Banksy who maintain their anonymity. In fact, in the community that Satoshi was involved in at that time, the Cypherpunk community and the cryptography mailing list, it was common practice for people to post anonymously.

On the other hand, there could have been legal worries behind Satoshi's choice. Two U.S. companies, Liberty Reserve and e-Gold, ran into legal trouble for money laundering. In 2006, one of the founders of Liberty Reserve fled the United States, fearing that he would be indicted on money laundering charges. E-Gold's founders, on the other hand, stayed in the United States, and one was actually indicted and eventually pled guilty to the charges. This guilty plea was registered just right before Satoshi set up the Bitcoin website and started emailing people about his proposal. That said, numerous people have invented ecash systems, and nobody else was scared of the legal implications or has chosen to remain anonymous. So this may have been the reason, it may not have been the reason.

It's also worth recalling that certain aspects of ecash were patented, and that members of the Cypherpunk movement were concerned about implementing ecash systems due to these patents. In fact, one post to the cypherpunks mailing list proposed that a group of anonymous coders implement ecash so that if someone were to sue, they wouldn't be able to find the coders. While it is difficult to think that Bitcoin would violate the ecash patents given how different its design is, perhaps Satoshi was being extra cautious. Or maybe he was just inspired by the idea of an anonymous coder from the cypherpunk community.

A final reason that's often cited is personal security. We know that Satoshi has a lot of bitcoins from his mining early on, and due to Bitcoin's success these are now worth a lot of money. I think this is a plausible reason. After all, choosing to be anonymous isn't a decision you make once, it's something that you do on a continual basis. That said, it probably wasn't Satoshi's original reason. The first time Satoshi used the name Satoshi Nakamoto, he hadn't even released the whitepaper or the codebase for Bitcoin, and it's hard to imagine that he had any idea that it would be as successful as it was. In fact, at many points in its early history, Satoshi was optimistic but cautious about Bitcoin's prospects. He seems to have understood that many previous efforts had failed and that Bitcoin might fail as well.

## Concluding remarks

The success of Bitcoin is quite remarkable if you consider all the ventures that failed trying to do what it does. Bitcoin has several notable innovations including the block chain and a decentralized model that supports user-to-user transactions. It provides a practically useful but less-than-perfect level of anonymity for users. In Chapter 6 we'll take a detailed look at anonymity in Bitcoin. In one sense it's weaker than the strong anonymity in DigiCash, but in another sense it's stronger. That's because in DigiCash, it was only the senders of the money that maintained their anonymity, and not the merchants. Bitcoin gives both senders and merchants (whether users or merchants) the same level of anonymity.

Let me conclude with some lessons that we can learn from Bitcoin through the lens of the previous systems that we've looked at. The first is to not give up on a problem. Just because people failed for 20 years in developing digital cash doesn't mean there isn't a system out there that will work. The second is to be willing to compromise. If you want perfect anonymity or perfect decentralization you'll probably need to worsen other areas of your design. Bitcoin, in retrospect, seems to have made the right compromises. It scales back anonymity a little bit and requires participants to be online and connected to the peer-to-peer network, but this turned out to be acceptable to users.

A final lesson is success through numbers. Bitcoin was able to build up a community of passionate users as well as developers willing to contribute to the open-source technology. This is a markedly different approach than previous attempts at digital cash, which were typically developed by a company, with the only advocates for the technology being the employees of the company itself. Bitcoin's current success is due in large part to the vibrant supporting community who pushed the technology, got people using it, and got merchants to adopt it.

## Further Reading

An accessible overview of digital cash schemes focused on practical issues:

**P. Wayner. Digital Cash: commerce on the net (2nd ed). Morgan Kaufmann, 1997.**

A cryptographically-oriented overview of e-cash systems (Chapter 1) and micropayments (Chapter 7):

**B. Rosenberg (ed.) Handbook of Financial Cryptography and Security. CRC Press, 2011.**

Although not Chaum's earliest paper on e-cash, this is arguably the most innovative, and it formed a template replicated by many other papers:

**D. Chaum, A. Fiat, M. Naor. Untraceable electronic cash. CRYPTO 1998.**

Many papers improved the efficiency of Chaum-Fiat-Naor using modern cryptographic techniques, but arguably the most significant is:

**J. Camenisch, S. Hohenberger, A. Lysyanskaya, Compact e-cash. Theory and Applications of Cryptographic Techniques, 2005**

Some practical security observations on the financial industry and proposals, including Mondex:

**R. Anderson. Security Engineering (2nd ed). Wiley, 2008.**

An overview of the implementation of Chaum's ecash proposal:

**B. Schoenmakers. Basic security of the ecash payment system. State of the Art in Applied Cryptography, 1997.**

Two papers cited by Satoshi Nakamoto in the Bitcoin whitepaper that are integral to Bitcon's design:

**A. Back. Hashcash - A Denial of Service Counter-Measure, Online, 2002.**

**S. Haber, W. S. Stornetta. Secure names for bitstrings. CCS, 1997.**

# Chapter 1: Introduction to Cryptography & Cryptocurrencies

All currencies need some way to control supply and enforce various security properties to prevent cheating. In fiat currencies, organizations like central banks control the money supply and add anti-counterfeiting features to physical currency. These security features raise the bar for an attacker, but they don't make money impossible to counterfeit. Ultimately, law enforcement is necessary for stopping people from breaking the rules of the system.

Cryptocurrencies too must have security measures that prevent people from tampering with the state of the system, and from equivocating, that is, making mutually inconsistent statements to different people. If Alice convinces Bob that she paid him a digital coin, for example, she should not be able to convince Carol that she paid her that same coin. But unlike fiat currencies, the security rules of cryptocurrencies need to be enforced purely technologically and without relying on a central authority.

As the word suggests, cryptocurrencies make heavy use of cryptography. Cryptography provides a mechanism for securely encoding the rules of a cryptocurrency system in the system itself. We can use it to prevent tampering and equivocation, as well as to encode the rules for creation of new units of the currency into a mathematical protocol. Before we can properly understand cryptocurrencies then, we'll need to delve into the cryptographic foundations that they rely upon.

Cryptography is a deep academic research field utilizing many advanced mathematical techniques that are notoriously subtle and complicated to understand. Fortunately, Bitcoin only relies on a handful of relatively simple and well-known cryptographic constructions. In this chapter, we'll specifically study cryptographic hashes and digital signatures, two primitives that prove to be very useful for building cryptocurrencies. Future chapters will introduce more complicated cryptographic schemes, such as zero-knowledge proofs, that are used in proposed extensions and modifications to Bitcoin.

Once we've learnt the necessary cryptographic primitives, we'll discuss some of the ways in which those are used to build cryptocurrencies. We'll complete this chapter with some examples of simple cryptocurrencies that illustrate some of the design challenges that we need to deal with.

## 1.1 Cryptographic Hash Functions

The first cryptographic primitive that we'll need to understand is a ***cryptographic hash function*.** A ***hash function*** is a mathematical function with the following three properties:

- Its input can be any string of any size.
- It produces a fixed size output. For the purpose of making the discussion in this chapter concrete, we will assume a 256-bit output size. However, our discussion holds true for any output size as long as it is sufficiently large.
- It is efficiently computable. Intuitively this means that for a given input string, you can figure

out what the output of the hash function is in a reasonable amount of time. More technically, computing the hash of an $n$-bit string should have a running time that is $O(n)$.

Those properties define a general hash function, one that could be used to build a data structure such as a hash table. We're going to focus exclusively on *cryptographic* hash functions. For a hash function to be cryptographically secure, we're going to require that it has the following three additional properties: (1) collision-resistance, (2) hiding, (3) puzzle-friendliness.

We'll look more closely at each of these properties to gain an understanding of why it's useful to have a function that behaves that way. The reader who has studied cryptography should be aware that the treatment of hash functions in this book is a bit different from a standard cryptography textbook. The puzzle-friendliness property, in particular, is not a general requirement for cryptographic hash functions, but one that will be useful for cryptocurrencies specifically.

***Property 1: Collision-resistance.*** The first property that we need from a cryptographic hash function is that it's collision-resistant. A collision occurs when two distinct inputs produce the same output. A hash function *H(.)* is collision-resistant if nobody can find a collision. Formally:

| |
|---|
| **Collision-resistance:** A hash function $H$ is said to be collision resistant if it is infeasible to find two values, $x$ and $y$, such that $x \neq y$, yet $H(x)=H(y)$. |

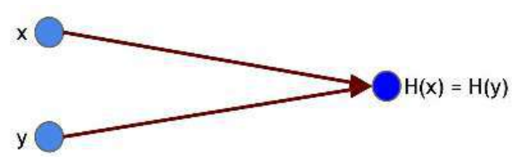



***Figure 1.1 A hash collision.*** $x$ and $y$ are distinct values, yet when input into hash function $H$, they produce the same output.

Notice that we said *nobody can find* a collision, but we did not say that no collisions exist. Actually, we know for a fact that collisions do exist, and we can prove this by a simple counting argument. The input space to the hash function contains all strings of all lengths, yet the output space contains only strings of a specific fixed length. Because the input space is larger than the output space (indeed, the input space is infinite, while the output space is finite), there must be input strings that map to the same output string. In fact, by the Pigeonhole Principle there will necessarily be a very large number of possible inputs that map to any particular output.

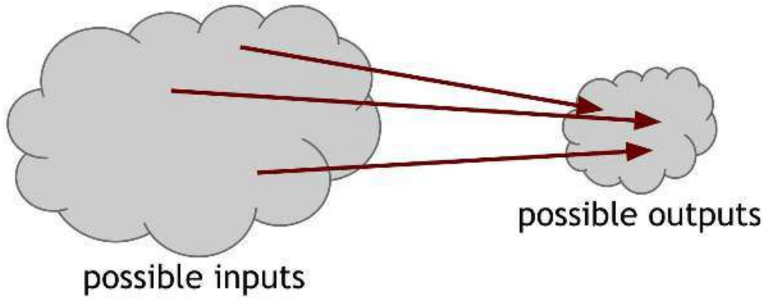



***Figure 1.2*** Because the number of inputs exceeds the number of outputs, we are guaranteed that there must be at least one output to which the hash function maps more than one input.

Now, to make things even worse, we said that it has to be impossible to find a collision. Yet, there are methods that are guaranteed to find a collision. Consider the following simple method for finding a collision for a hash function with a 256-bit output size: pick $2^{256} + 1$ distinct values, compute the hashes of each of them, and check if there are any two outputs are equal. Since we picked more inputs than possible outputs, some pair of them must collide when you apply the hash function.

The method above is guaranteed to find a collision. But if we pick random inputs and compute the hash values, we'll find a collision with high probability long before examining $2^{256} + 1$ inputs. In fact, if we randomly choose just $2^{130} + 1$ inputs, it turns out there's a 99.8% chance that at least two of them are going to collide. The fact that we can find a collision by only examining roughly the square root of the number of possible outputs results from a phenomenon in probability known as the ***birthday paradox***. In the homework questions at the end of this chapter, we will examine this in more detail.

This collision-detection algorithm works for every hash function. But, of course, the problem with it is that this takes a very, very long time to do. For a hash function with a 256-bit output, you would have to compute the hash function $2^{256} + 1$ times in the worst case, and about $2^{128}$ times on average. That's of course an astronomically large number — if a computer calculates 10,000 hashes per second, it would take more than one octillion ($10^{27}$) years to calculate $2^{128}$ hashes! For another way of thinking about this, we can say that, if every computer ever made by humanity was computing since the beginning of the entire universe, up to now, the odds that they would have found a collision is still infinitesimally small. So small that it's way less than the odds that the Earth will be destroyed by a giant meteor in the next two seconds.

We have thus seen a general but impractical algorithm to find a collision for *any* hash function. A more difficult question is: is there some other method that could be used on a particular hash function in order to find a collision? In other words, although the generic collision detection algorithm is not feasible to use, there still may be some other algorithm that can efficiently find a collision for a specific hash function.

Consider, for example, the following hash function:

$$H(x) = x \bmod 2^{256}$$

This function meets our requirements of a hash function as it accepts inputs of any length, returns a fixed sized output (256 bits), and is efficiently computable. But this function also has an efficient method for finding a collision. Notice that this function just returns the last 256 bits of the input. One collision then would be the values 3 and $3 + 2^{256}$. This simple example illustrates that even though our generic collision detection method is not usable in practice, there are at least some hash functions for which an efficient collision detection method does exist.

Yet for other hash functions, we don't know if such methods exist. We suspect that they are collision resistant. However, there are no hash functions *proven* to be collision-resistant. The cryptographic hash functions that we rely on in practice are just functions for which people have tried really, really hard to find collisions and haven't yet succeeded. In some cases, such as the old MD5 hash function, collisions were eventually found after years of work, leading the function to be deprecated and phased out of practical use. And so we choose to believe that those are collision resistant.

***Application: Message digests*** Now that we know what collision-resistance is, the logical question is: What is collision-resistance useful for? Here's one application: If we know that two inputs *x* and *y* to a collision-resistant hash function ***H*** are different, then it's safe to assume that their hashes ***H***(*x)* and ***H****(y)* are different — if someone knew an *x* and *y* that were different but had the same hash, that would violate our assumption that ***H*** is collision resistant.

This argument allows us to use hash outputs as a ***message digest***. Consider SecureBox, an authenticated online file storage system that allows users to upload files and ensure their integrity when they download them. Suppose that Alice uploads really large file, and wants to be able to verify later that the file she downloads is the same as the one she uploads. One way to do that would be to save the whole big file locally, and directly compare it to the file she downloads. While this works, it largely defeats the purpose of uploading it in the first place; if Alice needs to have access to a local copy of the file to ensure its integrity, she can just use the local copy directly.

Collision-free hashes provide an elegant and efficient solution to this problem. Alice just needs to remember the hash of the original file. When she later downloads the file from SecureBox, she computes the hash of the downloaded file and compares it to the one she stored. If the hashes are the same, then she can conclude that the file is indeed the one she uploaded, but if they are different, then Alice can conclude that the file has been tampered with. Remembering the hash thus allows her to detect *accidental* corruption of the file during transmission or on SecureBox's servers, but also *intentional* modification of the file by the server. Such guarantees in the face of potentially malicious behavior by other entities are at the core of what cryptography gives us.

The hash serves as a fixed length digest, or unambiguous summary, of a message. This gives us a very efficient way to remember things we've seen before and recognize them again. Whereas the entire file might have been gigabytes long, the hash is of fixed length, 256-bits for the hash function in our example. This greatly reduces our storage requirement. Later in this chapter and throughout the book, we'll see applications for which it's useful to use a hash as a message digest.

***Property 2: Hiding*** The second property that we want from our hash functions is that it's ***hiding***. The hiding property asserts that if we're given the output of the hash function $y = H(x)$, there's no feasible way to figure out what the input, $x$, was. The problem is that this property can't be true in the stated form. Consider the following simple example: we're going to do an experiment where we flip a coin. If the result of the coin flip was heads, we're going to announce the hash of the string "heads". If the result was tails, we're going to announce the hash of the string "tails".

We then ask someone, an adversary, who didn't see the coin flip, but only saw this hash output, to figure out what the string was that was hashed (we'll soon see why we might want to play games like this). In response, they would simply compute both the hash of the string "heads" and the hash of the string "tails", and they could see which one they were given. And so, in just a couple steps, they can figure out what the input was.

The adversary was able to guess what the string was because there were only two possible values of x, and it was easy for the adversary to just try both of them. In order to be able to achieve the hiding property, it needs to be the case that there's no value of $x$ which is particularly likely. That is, $x$ has to be chosen from a set that's, in some sense, very spread out. If $x$ is chosen from such a set, this method of trying a few values of x that are especially likely will not work.

The big question is: can we achieve the hiding property when the values that we want do not come from a spread-out set as in our "heads" and "tails" experiment? Fortunately, the answer is yes! So perhaps we can hide even an input that's not spread out by concatenating it with another input that *is* spread out. We can now be slightly more precise about what we mean by hiding (the double vertical bar $\|$ denotes concatenation).

> ***Hiding.*** A hash function H is hiding if: when a secret value $r$ is chosen from a probability distribution that has *high min-entropy*, then given $H(r \| x)$ it is infeasible to find $x$.

In information-theory, ***min-entropy*** is a measure of how predictable an outcome is, and high min-entropy captures the intuitive idea that the distribution (i.e., random variable) is very spread out. What that means specifically is that when we sample from the distribution, there's no particular value that's likely to occur. So, for a concrete example, if $r$ is chosen uniformly from among all of the strings that are 256 bits long, then any particular string was chosen with probability $1/2^{256}$, which is an infinitesimally small value.

***Application: Commitments.*** Now let's look at an application of the hiding property. In particular, what we want to do is something called a ***commitment***. A commitment is the digital analog of taking a value, sealing it in an envelope, and putting that envelope out on the table where everyone can see it. When you do that, you've committed yourself to what's inside the envelope. But you haven't opened it, so even though you've committed to a value, the value remains a secret from everyone else. Later, you can open the envelope and reveal the value that you committed to earlier.

***Commitment scheme.*** A commitment scheme consists of two algorithms:

- **com := commit(*msg, nonce*)** The commit function takes a message and secret random value, called a nonce, as input and returns a commitment.
- **verify(*com, msg, nonce*)** The verify function takes a commitment, nonce, and message as input. It returns true if *com* == commit(*msg*, *nonce*) and false otherwise.

We require that the following two security properties hold:

- ***Hiding***: Given *com*, it is infeasible to find *msg*
- ***Binding***: It is infeasible to find two pairs *(msg, nonce)* and *(msg', nonce')* such that *msg* ≠ *msg'* and commit(*msg, nonce*) == commit(*msg', nonce'*)

To use a commitment scheme, we first need to generate a random *nonce.* We then apply the *commit* function to this nonce together with *msg*, the value being committed to, and we publish the commitment *com*. This stage is analogous to putting the sealed envelope on the table. At a later point, if we want to reveal the value that they committed to earlier, we publish the random nonce that we used to create this commitment, and the message*, msg*. Now, anybody can verify that *msg* was indeed the message committed to earlier. This stage is analogous to opening up the envelope.

Every time you commit to a value, it is important that you choose a new random value *nonce*. In cryptography, the term *nonce* is used to refer to a value that can only be used once.

The two security properties dictate that the algorithms actually behave like sealing and opening an envelope. First, given *com*, the commitment, someone looking at the envelope can't figure out what the message is. The second property is that it's binding. This ensures that when you commit to what's in the envelope, you can't change your mind later. That is, it's infeasible to find two different messages, such that you can commit to one message, and then later claim that you committed to another.

So how do we know that these two properties hold? Before we can answer this, we need to discuss how we're going to actually implement a commitment scheme. We can do so using a cryptographic hash function. Consider the following commitment scheme:

commit(*msg, nonce)* := H(*nonce* ‖ *msg*) where *nonce* is a random 256-bit value

To commit to a message, we generate a random 256-bit nonce. Then we concatenate the nonce and the message and return the hash of this concatenated value as the commitment. To verify, someone will compute this same hash of the nonce they were given concatenated with the message. And they will check whether that's equal to the commitment that they saw.

Take another look at the two properties that we require of our commitment schemes. If we substitute the instantiation of *commit* and *verify* as well as *H(nonce* ‖ *msg)* for *com*, then these properties become:

- ***Hiding***: Given H(*nonce* ‖ *msg)*, it is infeasible to find *msg*
- ***Binding***: It is infeasible to find two pairs *(msg, nonce)* and *(msg', nonce')* such that *msg ≠ msg'* and H(*nonce* ‖ *msg*) == H(*nonce'* ‖ *msg'*)

The *hiding* property of commitments is exactly the hiding property that we required for our hash functions. If *key* was chosen as a random 256-bit value then the hiding property says that if we hash the concatenation of *key* and the message, then it's infeasible to recover the message from the hash output. And it turns out that the *binding property* is implied by[1] the collision-resistant property of the underlying hash function. If the hash function is collision-resistant, then it will be infeasible to find distinct values msg and msg' such that H(*nonce* ‖ *msg) =* H(*nonce'* ‖ *msg')* since such values would indeed be a collision.

Therefore, if *H* is a hash function that is collision-resistant and hiding, this commitment scheme will work, in the sense that it will have the necessary security properties.

***Property 3: Puzzle friendliness.*** The third security property we're going to need from hash functions is that they are puzzle-friendly. This property is a bit complicated. We will first explain what the technical requirements of this property are and then give an application that illustrates why this property is useful.

> ***Puzzle friendliness.*** A hash function *H* is said to be puzzle-friendly if for every possible n-bit output value *y*, if k is chosen from a distribution with high min-entropy, then it is infeasible to find *x* such that H(k ‖ x) = y in time significantly less than $2^n$.

Intuitively, what this means is that if someone wants to target the hash function to come out to some particular output value *y*, that if there's part of the input that is chosen in a suitably randomized way, it's very difficult to find another value that hits exactly that target.

***Application: Search puzzle.*** Now, let's consider an application that illustrates the usefulness of this property. In this application, we're going to build a ***search puzzle***, a mathematical problem which requires searching a very large space in order to find the solution. In particular, a search puzzle has no shortcuts. That is, there's no way to find a valid solution other than searching that large space.

[1] The reverse implications do not hold. That is, it's possible that you can find collisions, but none of them are of the form H(*nonce* ‖ *msg) ==* H(*nonce'* ‖ *msg')*. For example, if you can only find a collision in which two distinct nonces generate the same commitment for the same message, then the commitment scheme is still binding, but the underlying hash function is not collision-resistant.

***Search puzzle.*** A search puzzle consists of

- a hash function, *H*,
- a value, *id* (which we call the ***puzzle-ID***), chosen from a high min-entropy distribution
- and a target set *Y*

A solution to this puzzle is a value, *x*, such that

$$H(id \parallel x) \in \boldsymbol{Y}.$$

The intuition is this: if H has an n-bit output, then it can take any of $2^n$ values. Solving the puzzle requires finding an input so that the output falls within the set Y, which is typically much smaller than the set of all outputs. The size of Y determines how hard the puzzle is. If Y is the set of all n-bit strings the puzzle is trivial, whereas if Y has only 1 element the puzzle is maximally hard. The fact that the puzzle id has high min-entropy ensures that there are no shortcuts. On the contrary, if a particular value of the ID were likely, then someone could cheat, say by pre-computing a solution to the puzzle with that ID.

If a search puzzle is puzzle-friendly, this implies that there's no solving strategy for this puzzle which is much better than just trying random values of *x*. And so, if we want to pose a puzzle that's difficult to solve, we can do it this way as long as we can generate puzzle-IDs in a suitably random way. We're going to use this idea later when we talk about Bitcoin mining, which is a sort of computational puzzle.

***SHA-256.*** We've discussed three properties of hash functions, and one application of each of those. Now let's discuss a particular hash function that we're going to use a lot in this book. There are lots of hash functions in existence, but this is the one Bitcoin uses primarily, and it's a pretty good one to use. It's called ***SHA-256***.

Recall that we require that our hash functions work on inputs of arbitrary length. Luckily, as long as we can build a hash function that works on fixed-length inputs, there's a generic method to convert it into a hash function that works on arbitrary-length inputs. It's called the ***Merkle-Damgard transform***. SHA-256 is one of a number of commonly used hash functions that make use of this method. In common terminology, the underlying fixed-length collision-resistant hash function is called the ***compression function***. It has been proven that if the underlying compression function is collision resistant, then the overall hash function is collision resistant as well.

The Merkle-Damgard transform is quite simple. Say the compression function takes inputs of length *m* and produces an output of a smaller length *n*. The input to the hash function, which can be of any size, is divided into ***blocks*** of length *m-n*. The construction works as follows: pass each block together with the output of the previous block into the compression function. Notice that input length will then be (*m-n*) + *n* = *m*, which is the input length to the compression function. For the first block, to which there is no previous block output, we instead use an ***Initialization Vector (IV)***. This number is reused for every call to the hash function, and in practice you can just look it up in a standards document. The last block's output is the result that you return.

SHA-256 uses a compression function that takes 768-bit input and produces 256-bit outputs. The block size is 512 bits. See Figure 1.3 for a graphical depiction of how SHA-256 works.

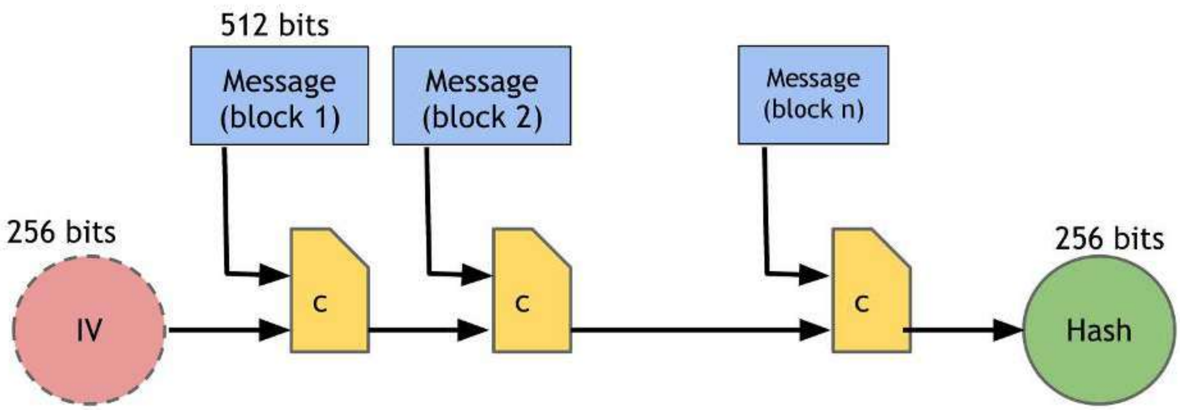



***Figure 1.3: SHA-256 Hash Function (simplified).*** SHA-256 uses the Merkle-Damgard transform to turn a fixed-length collision-resistant compression function into a hash function that accepts arbitrary-length inputs. The input is “padded” so that its length is a multiple of 512 bits.

We’ve talked about hash functions, cryptographic hash functions with special properties, applications of those properties, and a specific hash function that we use in Bitcoin. In the next section, we’ll discuss ways of using hash functions to build more complicated data structures that are used in distributed systems like Bitcoin.

**Sidebar: modeling hash functions.** Hash functions are the Swiss Army knife of cryptography: they find a place in a spectacular variety of applications. The flip side to this versatility is that different applications require slightly different properties of hash functions to ensure security. It’s proven notoriously hard to pin down a list of hash function properties that would result in provable security across the board.

In this text, we’ve selected three properties that are crucial to the way that hash functions are used in Bitcoin and other cryptocurrencies. Even within this space, not all of these properties are necessary for every use of hash functions. For example, puzzle-friendliness is only important in Bitcoin mining, as we’ll see.

Designers of secure systems often throw in the towel and model hash functions as functions that output an independent random value for every possible input. The use of this “random oracle model” for proving security remains controversial in cryptography. Regardless of one’s position on this debate, reasoning about how to reduce the security properties that we want in our applications to fundamental properties of the underlying primitives is a valuable intellectual exercise for building secure systems. Our presentation in this chapter is designed to help you learn this skill.

## 1.2 Hash Pointers and Data Structures

In this section, we're going to discuss ***hash pointers*** and their applications. A hash pointer is a data structure that turns out to be useful in many of the systems that we will talk about. A hash pointer is simply a pointer to where some information is stored together with a cryptographic hash of the information. Whereas a regular pointer gives you a way to retrieve the information, a hash pointer also gives you a way to verify that the information hasn't changed.

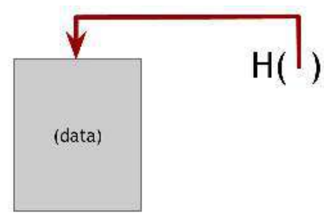



***Figure 1.4 Hash pointer.*** A hash pointer is a pointer to where data is stored together with a cryptographic hash of the value of that data at some fixed point in time.

We can use hash pointers to build all kinds of data structures. Intuitively, we can take a familiar data structure that uses pointers such as a linked list or a binary search tree and implement it with hash pointers, instead of pointers as we normally would.

***Block chain.*** In Figure 1.5, we built a linked list using hash pointers. We're going to call this data structure a ***block chain***. Whereas as in a regular linked list where you have a series of blocks, each block has data as well as a pointer to the previous block in the list, in a block chain the previous block pointer will be replaced with a hash pointer. So each block not only tells us where the value of the previous block was, but it also contains a digest of that value that allows us to verify that the value hasn't changed. We store the head of the list, which is just a regular hash-pointer that points to the most recent data block.

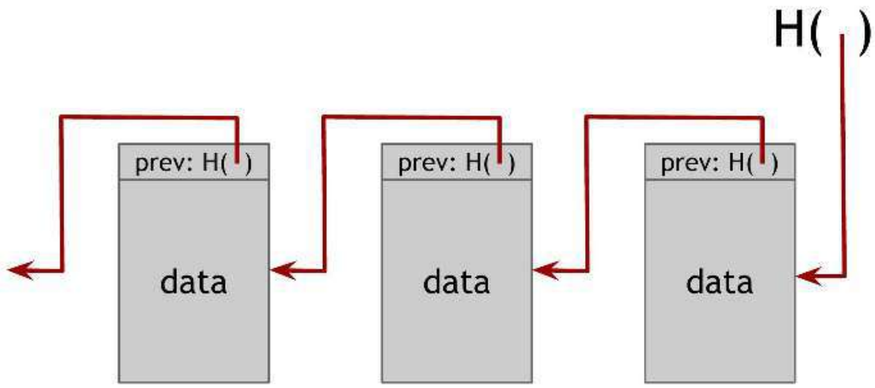



***Figure 1.5 Block chain.*** A block chain is a linked list that is built with hash pointers instead of pointers.

A use case for a block chain is a ***tamper-evident log***. That is, we want to build a log data structure that stores a bunch of data, and allows us to append data onto the end of the log. But if somebody alters data that is earlier in the log, we're going to detect it.

To understand why a block chain achieves this tamper-evident property, let's ask what happens if an adversary wants to tamper with data that's in the middle of the chain. Specifically, the adversary's goal is to do it in such a way that someone who remembers only the hash pointer at the head of the block chain won't be able to detect the tampering. To achieve this goal, the adversary changes the data of some block $k$. Since the data has been changed, the hash in block $k + 1$, which is a hash of the entire block $k$, is not going to match up. Remember that we are statistically guaranteed that the new hash will not match the altered content since the hash function is collision resistant. And so we will detect the inconsistency between the new data in block $k$ and the hash pointer in block $k + 1$. Of course the adversary can continue to try and cover up this change by changing the next block's hash as well. The adversary can continue doing this, but this strategy will fail when he reaches the head of the list. Specifically, as long as we store the hash pointer at the head of the list in a place where the adversary cannot change it, the adversary will be unable to change any block without being detected.

The upshot of this is that if the adversary wants to tamper with data anywhere in this entire chain, in order to keep the story consistent, he's going to have to tamper with the hash pointers all the way back to the beginning. And he's ultimately going to run into a roadblock because he won't be able to tamper with the head of the list. Thus it emerges, that by just remembering this single hash pointer, we've essentially remembered a tamper-evident hash of the entire list. So we can build a block chain like this containing as many blocks as we want, going back to some special block at the beginning of the list, which we will call the ***genesis block***.

You may have noticed that the block chain construction is similar to the Merkle-Damgard construction that we saw in the previous section. Indeed, they are quite similar, and the same security argument applies to both of them.

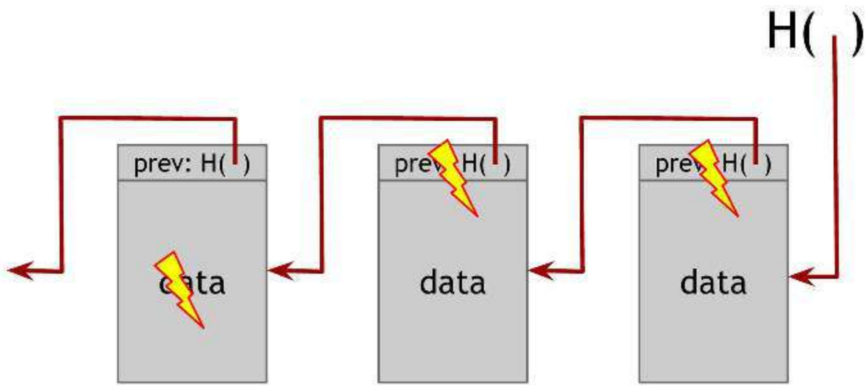



***Figure 1.6 Tamper-evident log.*** If an adversary modifies data anywhere in the block chain, it will result in the hash pointer in the following block being incorrect. If we store the head of the list, then even if the adversary modifies all of the pointers to be consistent with the modified data, the head pointer will be incorrect, and we will detect the tampering.

***Merkle trees.*** Another useful data structure that we can build using hash pointers is a binary tree. A binary tree with hash pointers is known as a ***Merkle tree***, after its inventor Ralph Merkle. Suppose we have a number of blocks containing data. These blocks comprise the leaves of our tree. We group these data blocks into pairs of two, and then for each pair, we build a data structure that has two hash pointers, one to each of these blocks. These data structures make the next level up of the tree. We in turn group these into groups of two, and for each pair, create a new data structure that contains the hash of each. We continue doing this until we reach a single block, the root of the tree.

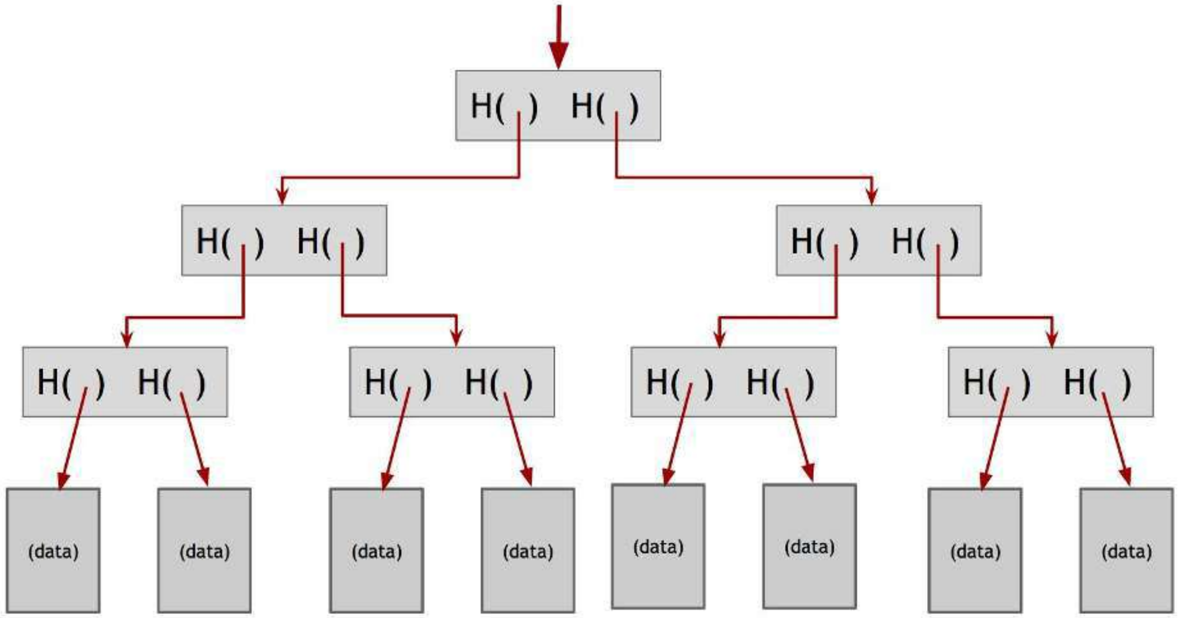



***Figure 1.7 Merkle tree.*** In a Merkle tree, data blocks are grouped in pairs and the hash of each of these blocks is stored in a parent node. The parent nodes are in turn grouped in pairs and their hashes stored one level up the tree. This continues all the way up the tree until we reach the root node.

As before, we remember just the hash pointer at the head of the tree. We now have the ability traverse down through the hash pointers to any point in the list. This allows us make sure that the data hasn't been tampered with because, just like we saw with the block chain, if an adversary tampers with some data block at the bottom of the tree, that will cause the hash pointer that's one level up to not match, and even if he continues to tamper with this block, the change will eventually propagate to the top of the tree where he won't be able to tamper with the hash pointer that we've stored. So again, any attempt to tamper with any piece of data will be detected by just remembering the hash pointer at the top.

***Proof of membership.*** Another nice feature of Merkle trees is that, unlike the block chain that we built before, it allows a concise proof of membership. Say that someone wants to prove that a certain data block is a member of the Merkle Tree. As usual, we remember just the root. Then they need to show us this data block, and the blocks on the path from the data block to the root. We can ignore the rest of the tree, as the blocks on this path are enough to allow us to verify the hashes all the way up to the root of the tree. See Figure 1.8 for a graphical depiction of how this works.

If there are *n* nodes in the tree, only about *log(n)* items need to be shown. And since each step just requires computing the hash of the child block, it takes about *log(n)* time for us to verify it. And so even if the Merkle tree contains a very large number of blocks, we can still prove membership in a relatively short time. Verification thus runs in time and space that's logarithmic in the number of nodes in the tree.

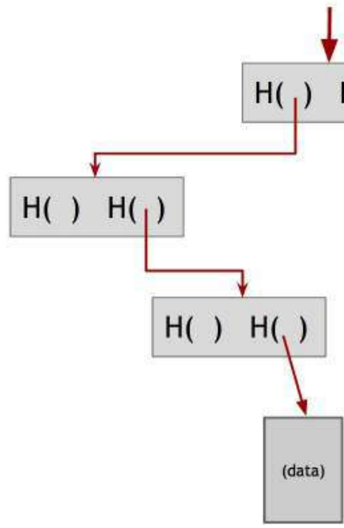



***Figure 1.8 Proof of membership.*** To prove that a data block is included in the tree, one only needs to show the blocks in the path from that data block to the root.

A ***sorted Merkle tree*** is just a Merkle tree where we take the blocks at the bottom, and we sort them using some ordering function. This can be  alphabetical, lexicographical order, numerical order, or some other agreed upon ordering.

***Proof of non-membership.*** With a sorted Merkle tree, it becomes possible to verify non-membership in a logarithmic time and space. That is, we can prove that a particular block is not in the Merkle tree. And the way we do that is simply by showing a path to the item that's just before where the item in question would be and showing the path to the item that is just after where it would be. If these two items are consecutive in the tree, then this serves as a proof that the item in question is not included. For if it was included, it would need to be between the two items shown, but there is no space between them as they are consecutive.

We've discussed using hash pointers in linked lists and binary trees, but more generally, it turns out that we can use hash pointers in any pointer-based data structure as long as the data structure doesn't have cycles. If there are cycles in the data structure, then we won't be able to make all the hashes match up. If you think about it, in an acyclic data structure, we can start near the leaves, or near the things that don't have any pointers coming out of them, compute the hashes of those, and then work our way back toward the beginning. But in a structure with cycles, there's no end we can start with and compute back from.

So, to consider another example, we can build a directed acyclic graph out of hash pointers. And we'll be able to verify membership in that graph very efficiently. And it will be easy to compute. Using hash pointers in this manner is a general trick that you'll see time and again in the context of the distributed data structures and throughout the algorithms that we discuss later in this chapter and throughout this book.

## 1.3 Digital Signatures

In this section, we'll look at ***digital signatures***. This is the second cryptographic primitive, along with hash functions, that we need as building blocks for the cryptocurrency discussion later on. A digital signature is supposed to be the digital analog to a handwritten signature on paper. We desire two properties from digital signatures that correspond well to the handwritten signature analogy. Firstly, only you can make your signature, but anyone who sees it can verify that it's valid. Secondly, we want the signature to be tied to a particular document so that the signature cannot be used to indicate your agreement or endorsement of a different document. For handwritten signatures, this latter property is analogous to assuring that somebody can't take your signature and snip it off one document and glue it onto the bottom of another one.

How can we build this in a digital form using cryptography? First, let's make the previous intuitive discussion slightly more concrete. This will allow us to reason better about digital signature schemes and discuss their security properties.

> ***Digital signature scheme.*** A digital signature scheme consists of the following three algorithms:
>
> - **(sk, pk) := generateKeys(*keysize*)** The generateKeys method takes a key size and generates a key pair. The secret key *sk* is kept privately and used to sign messages. *pk* is the public verification key that you give to everybody. Anyone with this key can verify your signature.
> - **sig := sign(*sk*, *message*)** The sign method takes a message and a secret key, *sk*, as input and outputs a signature for *message* under *sk*
> - **isValid := verify(*pk*, *message*, *sig*)** The verify method takes a message, a signature, and a public key as input. It returns a boolean value, *isValid*, that will be ***true*** if *sig* is a valid signature for *message* under public key *pk*, and ***false*** otherwise.
>
> We require that the following two properties hold:
>
> - *Valid signatures must verify*
>
>   **verify**(*pk*, *message*, **sign**(*sk*, *message*)) == **true**
> - Signatures are ***existentially unforgeable***

We note that **generateKeys** and **sign** can be randomized algorithms. Indeed, generateKeys had better be randomized because it ought to be generating different keys for different people. **verify**, on the other hand, will always be deterministic.

Let us now examine the two properties that we require of a digital signature scheme in more detail. The first property is straightforward — that valid signatures must verify. If I sign a message with *sk*, my secret key, and someone later tries to validate that signature over that same message using my public key, *pk*, the signature must validate correctly. This property is a basic requirement for signatures to be useful at all.

***Unforgeability.*** The second requirement is that it's computationally infeasible to forge signatures. That is, an adversary who knows your public key and gets to see your signatures on some other messages can't forge your signature on some message for which he has not seen your signature. This unforgeability property is generally formalized in terms of a game that we play with an adversary. The use of games is quite common in cryptographic security proofs.

In the unforgeability game, there is an adversary who claims that he can forge signatures and a challenger that will test this claim. The first thing we do is we use **generateKeys** to generate a secret signing key and a corresponding public verification key. We give the secret key to the challenger, and we give the public key to both the challenger and to the adversary. So the adversary only knows information that's public, and his mission is to try to forge a message. The challenger knows the secret key. So he can make signatures.

Intuitively, the setup of this game matches real world conditions. A real-life attacker would likely be able to see valid signatures from their would-be victim on a number of different documents. And maybe the attacker could even manipulate the victim into signing innocuous-looking documents if that's useful to the attacker.

To model this in our game, we're going to allow the attacker to get signatures on some documents of his choice, for as long as he wants, as long as the number of guesses is plausible. To give an intuitive idea of what we mean by a plausible number of guesses, we would allow the attacker to try 1 million guesses, but not $2^{80}$ guesses[2].

Once the attacker is satisfied that he's seen enough signatures, then the attacker picks some message, *M*, that they will attempt to forge a signature on. The only restriction on *M* is that it must be a message for which the attacker has not previously seen a signature (because the attacker can obviously send back a signature that he was given!). The challenger runs the **verify** algorithm to determine if the signature produced by the attacker is a valid signature on *M* under the public verification key. If it successfully verifies, the attacker wins the game.

[2] In asymptotic terms, we allow the attacker to try a number of guesses that is a polynomial function of the key size, but no more (e.g. the attacker cannot try exponentially many guesses).

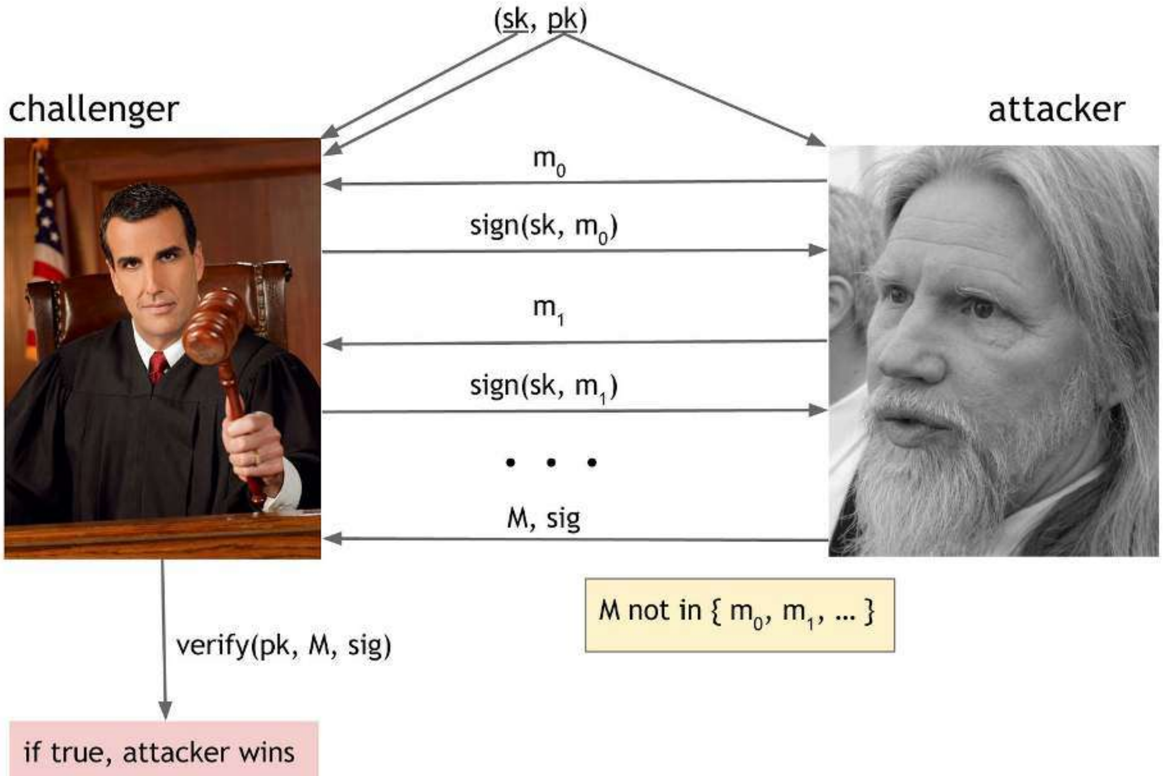



***Figure 1.9 Unforgeability game.*** The adversary and the challenger play the unforgeability game. If the attacker is able to successfully output a signature on a message that he has not previously seen, he wins. If he is unable, the challenger wins and the digital signature scheme is unforgeable.

We say that the signature scheme is unforgeable if and only if, no matter what algorithm the adversary is using, his chance of successfully forging a message is extremely small — so small that we can assume it will never happen in practice.

***Practical Concerns.*** There are a number of practical things that we need to do to turn the algorithmic idea into a digital signature mechanism that can be implemented in practice. For example, many signature algorithms are randomized (in particular the one used in Bitcoin) and we therefore need a good source of randomness. The importance of this really can't be underestimated as bad randomness will make your otherwise-secure algorithm insecure.

Another practical concern is the message size. In practice, there's a limit on the message size that you're able to sign because real schemes are going to operate on bit strings of limited length. There's an easy way around this limitation: sign the hash of the message, rather than the message itself. If we use a cryptographic hash function with a 256-bit output, then we can effectively sign a message of any length as long as our signature scheme can sign 256-bit messages. As we discussed before, it's safe to use the hash of the message as a message digest in this manner since the hash function is collision resistant.

Another trick that we will use later is that you can sign a hash pointer. If you sign a hash pointer, then the signature covers, or protects, the whole structure — not just the hash pointer itself, but everything the chain of hash pointers points to. For example, if you were to sign the hash pointer that was at the end of a block chain, the result is that you would effectively be digitally signing the that entire block chain.

***ECDSA.*** Now let's get into the nuts and bolts. Bitcoin uses a particular digital signature scheme that's called the Elliptic Curve Digital Signature Algorithm (ECDSA). ECDSA is a U.S. government standard, an update of the earlier DSA algorithm adapted to use elliptic curves. These algorithms have received considerable cryptographic analysis over the years and are generally believed to be secure.

More specifically, Bitcoin uses ECDSA over the standard elliptic curve "secp256k1" which is estimated to provide 128 bits of security (that is, it is as difficult to break this algorithm as performing $2^{128}$ symmetric-key cryptographic operations such as invoking a hash function). While this curve is a published standard, it is rarely used outside of Bitcoin, with other applications using ECDSA (such as key exchange in TLS for secure web browsing) typically using the more common "secp256r1" curve. This is just a quirk of Bitcoin, as this was chosen by Satoshi in the early specification of the system and is now difficult to change.

We won't go into all the details of how ECDSA works as there's some complicated math involved, and understanding it is not necessary for any other content in this book. If you're interested in the details, refer to our further reading section at the end of this chapter. It might be useful to have an idea of the sizes of various quantities, however:

| | |
|---|---|
| Private key: | 256 bits |
| Public key, uncompressed: | 512 bits |
| Public key, compressed: | 257 bits |
| Message to be signed: | 256 bits |
| Signature: | 512 bits |

Note that while ECDSA can technically only sign messages 256 bits long, this is not a problem: messages are always hashed before being signed, so effectively any size message can be efficiently signed.

With ECDSA, a good source of randomness is essential because a bad source of randomness will likely leak your key. It makes intuitive sense that if you use bad randomness in generating a key, then the key you generate will likely not be secure. But it's a quirk of ECDSA[3] that, even if you use bad

[3] For those familiar with DSA, this is a general quirk in DSA and not specific to the elliptic-curve variant.

randomness just in making a signature, using your perfectly good key, that also will leak your private key. And then it's game over; if you leak your private key, an adversary can forge your signature. We thus need to be especially careful about using good randomness in practice, and using a bad source of randomness is a common pitfall of otherwise secure systems.

This completes our discussion of digital signatures as a cryptographic primitive. In the next section, we'll discuss some applications of digital signatures that will turn out to be useful for building cryptocurrencies.

**Sidebar: cryptocurrencies and encryption.** If you've been waiting to find out which encryption algorithm is used in Bitcoin, we're sorry to disappoint you. There is no encryption in Bitcoin, because nothing needs to be encrypted, as we'll see. Encryption is only one of a rich suite of techniques made possible by modern cryptography. Many of them, such as commitment schemes, involve hiding information in some way, but they are distinct from encryption.

## 1.4 Public Keys as Identities

Let's look at a nice trick that goes along with digital signatures. The idea is to take a public key, one of those public verification keys from a digital signature scheme, and equate that to an identity of a person or an actor in a system. If you see a message with a signature that verifies correctly under a public key, *pk*, then you can think of this as *pk* is saying the message. You can literally think of a public key as kind of like an actor, or a party in a system who can make statements by signing those statements. From this viewpoint, the public key is an identity. In order for someone to speak for the identity *pk*, they must know the corresponding secret key, *sk*.

A consequence of treating public keys as identities is that you can make a new identity whenever you want — you simply create a new fresh key pair, *sk* and *pk*, via the **generateKeys** operation in our digital signature scheme. *pk* is the new public identity that you can use, and *sk* is the corresponding secret key that only you know and lets you speak for on behalf of the identity *pk*. In practice, you may use the hash of *pk* as your identity since public keys are large. If you do that, then in order to verify that a message comes from your identity, one will have to check (1) that *pk* indeed hashes to your identity, and (2) the message verifies under public key *pk*.

Moreover, by default, your public key *pk* will basically look random, and nobody will be able to uncover your real world identity by examining *pk*.[4] You can generate a fresh identity that looks random, that looks like a face in the crowd, and that only you can control.

***Decentralized identity management.*** This brings us to the idea of decentralized identity management. Rather than having a central authority that you have to go to in order to register as a user in a system, you can register as a user all by yourself. You don't need to be issued a username nor do you need to

[4] Of course, once you start making statements using this identity, these statements may leak information that allows one to connect *pk* to your real world identity. We will discuss this in more detail shortly.

inform someone that you're going to be using a particular name. If you want a new identity, you can just generate one at any time, and you can make as many as you want. If you prefer to be known by five different names, no problem! Just make five identities. If you want to be somewhat anonymous for a while, you can make a new identity, use it just for a little while, and then throw it away. All of these things are possible with decentralized identity management, and this is the way Bitcoin, in fact, does identity. These identities are called ***addresses***, in Bitcoin jargon. You'll frequently hear the term address used in the context of Bitcoin and cryptocurrencies, and that's really just a hash of a public key. It's an identity that someone made up out of thin air, as part of this decentralized identity management scheme.

**Sidebar.** The idea that you can generate an identity without a centralized authority may seem counterintuitive. After all, if someone else gets lucky and generates the same key as you can't they steal your bitcoins?

The answer is that the probability of someone else generating the same 256-bit key as you is so small that we don't have to worry about it in practice. We are for all intents and purposes guaranteed that it will never happen.

More generally, in contrast to beginners' intuition that probabilistic systems are unpredictable and hard to reason about, often the opposite is true — the theory of statistics allows us to precisely quantify the chances of events we're interested in and make confident assertions about the behavior of such systems.

But there's a subtlety: the probabilistic guarantee is true only when keys are generated at random. The generation of randomness is often a weak point in real systems. If two users' computers use the same source of randomness or use predictable randomness, then the theoretical guarantees no longer apply. So it is crucial to use a good source of randomness when generating keys to ensure that practical guarantees match the theoretical ones.

On first glance, it may seems that decentralized identity management leads to great anonymity and privacy. After all, you can create a random-looking identity all by yourself without telling anyone your real-world identity. But it's not that simple. Over time, the identity that you create makes a series of statements.  People see these statements and thus know that whoever owns this identity has done a certain series of actions. They can start to connect the dots, using this series of actions to infer things about your real-world identity. An observer can link together these things over time, and make inferences that lead them to conclusions such as, "Gee, this person is acting a lot like Joe. Maybe this person is Joe."

In other words, in Bitcoin you don't need to explicitly register or reveal your real-world identity, but the pattern of your behavior might itself be identifying. This is the fundamental privacy question in a cryptocurrency like Bitcoin, and indeed we'll devote the entirety of Chapter 6 to it.

## 1.5 A Simple Cryptocurrency

Now let's move from cryptography to cryptocurrencies. Eating our cryptographic vegetables will start to pay off here, and we'll gradually see how the pieces fit together and why cryptographic operations like hash functions and digital signatures are actually useful. In this section we'll discuss two very simple cryptocurrencies. Of course, it's going to require much of the rest of the book to spell out all the implications of how Bitcoin itself works.

***GoofyCoin***

The first of the two is GoofyCoin, which is about the simplest cryptocurrency we can imagine. There are just two rules of GoofyCoin. The first rule is that a designated entity, Goofy, can create new coins whenever he wants and these newly created coins belong to him.

To create a coin, Goofy generates a unique coin ID `uniqueCoinID` that he's never generated before and constructs the string "CreateCoin [`uniqueCoinID`]". He then computes the digital signature of this string with his secret signing key. The string, together with Goofy's signature, is a coin. Anyone can verify that the coin contains Goofy's valid signature of a CreateCoin statement, and is therefore a valid coin.

The second rule of GoofyCoin is that whoever owns a coin can transfer it on to someone else. Transferring a coin is not simply a matter of sending the coin data structure to the recipient — it's done using cryptographic operations.

Let's say Goofy wants to transfer a coin that he created to Alice. To do this he creates a new statement that says "Pay this to Alice" where "this" is a hash pointer that references the coin in question. And as we saw earlier, identities are really just public keys, so "Alice" refers to Alice's public key. Finally, Goofy signs the string representing the statement. Since Goofy is the one who originally owned that coin, he has to sign any transaction that spends the coin. Once this data structure representing Goofy's transaction signed by him exists, Alice owns the coin. She can prove to anyone that she owns the coin, because she can present the data structure with Goofy's valid signature. Furthermore, it points to a valid coin that was owned by Goofy. So the validity and ownership of coins are self-evident in the system.

Once Alice owns the coin, she can spend it in turn. To do this she creates a statement that says, "Pay this coin to Bob's public key" where "this" is a hash pointer to the coin that was owned by her. And of course, Alice signs this statement. Anyone, when presented with this coin, can verify that Bob is the owner. They would follow the chain of hash pointers back to the coin's creation and verify that at each step, the rightful owner signed a statement that says "pay this coin to [new owner]".

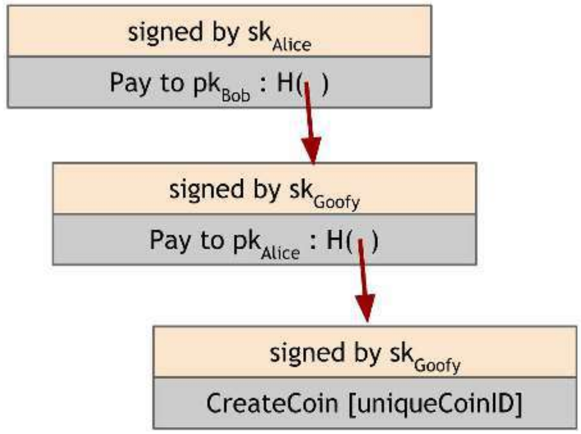



***Figure 1.10 GoofyCoin coin.*** Shown here is a coin that's been created (bottom) and spent twice (middle and top).

To summarize, the rules of GoofyCoin are:

- Goofy can create new coins by simply signing a statement that he's making a new coin with a unique coin ID.
- Whoever owns a coin can pass it on to someone else by signing a statement that saying, "Pass on this coin to X" (where X is specified as a public key)
- Anyone can verify the validity of a coin by following the chain of hash pointers back to its creation by Goofy, verifying all of the signatures along the way.

Of course, there's a fundamental security problem with GoofyCoin. Let's say Alice passed her coin on to Bob by sending her signed statement to Bob but didn't tell anyone else. She could create another signed statement that pays the very same coin to Chuck. To Chuck, it would appear that it is perfectly valid transaction, and now he's the owner of the coin. Bob and Chuck would both have valid-looking claims to be the owner of this coin. This is called a double-spending attack — Alice is spending the same coin twice. Intuitively, we know coins are not supposed to work that way.

In fact, double-spending attacks are one of the key problems that any cryptocurrency has to solve. GoofyCoin does not solve the double-spending attack and therefore it's not secure. GoofyCoin is simple, and its mechanism for transferring coins is actually very similar to Bitcoin, but because it is insecure it won't cut it as a cryptocurrency.

***ScroogeCoin***

To solve the double-spending problem, we'll design another cryptocurrency, which we'll call ScroogeCoin. ScroogeCoin is built off of GoofyCoin, but it's a bit more complicated in terms of data structures.

The first key idea is that a designated entity called Scrooge publishes an *append-only ledger* containing the history of all the transactions that have happened. The append-only property ensures that any data written to this ledger will remain forever. If the ledger is truly append-only, we can use it to defend against double-spending by requiring all transactions to be written the ledger before they are accepted. That way, it will be publicly visible if coins were previously sent to a different owner.

To implement this append-only functionality, Scrooge can build a block chain (the data structure we discussed before) which he will digitally sign. It's a series of data blocks, each with one transaction in it (in practice, as an optimization, we'd really put multiple transactions into the same block, as Bitcoin does.) Each block has the ID of a transaction, the transaction's contents, and a hash pointer to the previous block. Scrooge digitally signs the final hash pointer, which binds all of the data in this entire structure, and publishes the signature along with the block chain.

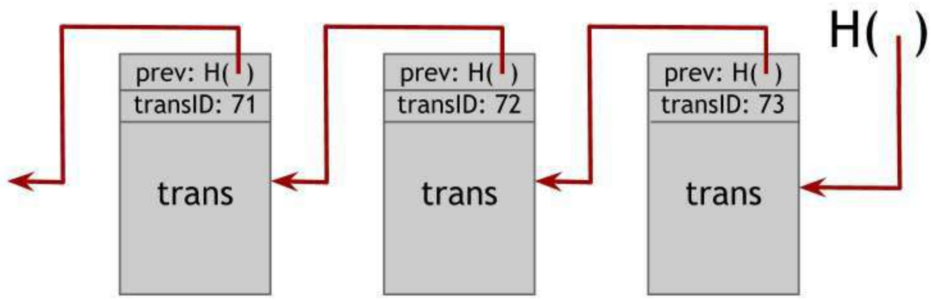



**Figure 1.11 ScroogeCoin block chain.**

In ScroogeCoin a transaction only counts if it is in the block chain signed by Scrooge. Anybody can verify that a transaction was endorsed by Scrooge by checking Scrooge's signature on the block that it appears in. Scrooge makes sure that he doesn't endorse a transaction that attempts to double-spend an already spent coin.

Why do we need a block chain with hash pointers in addition to having Scrooge sign each block? This ensures the append-only property. If Scrooge tries to add or remove a transaction to the history, or change an existing transaction, it will affect all of the following blocks because of the hash pointers. As long as someone is monitoring the latest hash pointer published by Scrooge, the change will be obvious and easy to catch. In a system where Scrooge signed blocks individually, you'd have to keep track of every single signature Scrooge ever issued. A block chain makes it very easy for any two individuals to verify that they have observed the exact same history of transactions signed by Scrooge.

In ScroogeCoin, there are two kinds of transactions. The first kind is CreateCoins, which is just like the operation Goofy could do in GoofyCoin that makes a new coin. With ScroogeCoin, we'll extend the semantics a bit to allow multiple coins to be created in one transaction.

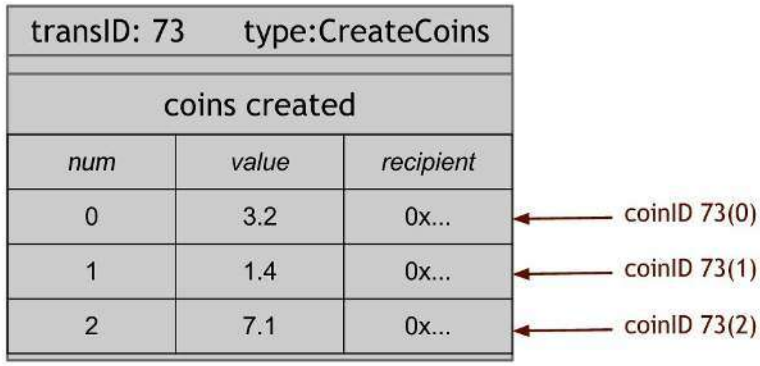



***Figure 1.12 CreateCoins transaction.*** This CreateCoins transaction creates multiple coins. Each coin has a serial number within the transaction. Each coin also has a value; it's worth a certain number of scroogecoins. Finally, each coin has a recipient, which is a public key that gets the coin when it's created. So CreateCoins creates a bunch of new coins with different values and assigns them to people as initial owners. We refer to coins by CoinIDs. A CoinID is a combination of a transaction ID and the coin's serial number within that transaction.

A CreateCoins transaction is always valid by definition if it is signed by Scrooge. We won't worry about when Scrooge is entitled to create coins or how many, just like we didn't worry in GoofyCoin about how Goofy is chosen as the entity allowed to create coins.

The second kind of transaction is PayCoins. It consumes some coins, that is, destroys them, and creates new coins of the same total value. The new coins might belong to different people (public keys). This transaction has to be signed by everyone who's paying in a coin. So if you're the owner of one of the coins that's going to be consumed in this transaction, then you need to digitally sign the transaction to say that you're really okay with spending this coin.

The rules of ScroogeCoin say that PayCoins transaction is valid if four things are true:

- The consumed coins are valid, that is, they really were created in previous transactions.
- The consumed coins were not already consumed in some previous transaction. That is, that this is not a double-spend.
- The total value of the coins that come out of this transaction is equal to the total value of the coins that went in. That is, only Scrooge can create new value.
- The transaction is validly signed by the owners of all of the consumed coins.

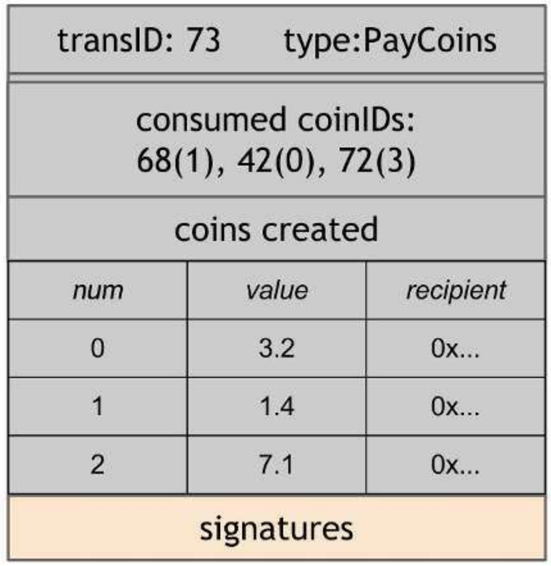



***Figure 1.13*** **A PayCoins Transaction.**

If all of those conditions are met, then this PayCoins transaction is valid and Scrooge will accept it. He'll write it into the history by appending it to the block chain, after which everyone can see that this transaction has happened. It is only at this point that the participants can accept that the transaction has actually occurred. Until it is published, it might be preempted by a douple-spending transaction even if it is otherwise valid by the first three conditions.

Coins in this system are immutable — they are never changed, subdivided, or combined. Each coin is created, once, in one transaction and later consumed in some other transaction. But we can get the same effect as being able to subdivide or combine coins by using transactions. For example, to subdivide a coin, Alice create a new transaction that consumes that one coin, and then produces two new coins of the same total value. Those two new coins could be assigned back to her. So although coins are immutable in this system, it has all the flexibility of a system that didn't have immutable coins.

Now, we come to the core problem with ScroogeCoin. ScroogeCoin will work in the sense that people can see which coins are valid. It prevents double-spending, because everyone can look into the block chain and see that all of the transactions are valid and that every coin is consumed only once. But the problem is Scrooge — he has too much influence. He can't create fake transactions, because he can't forge other people's signatures. But he could stop endorsing transactions from some users, denying them service and making their coins unspendable. If Scrooge is greedy (as his cartoon namesake suggests) he could refuse to publish transactions unless they transfer some mandated transaction fee to him. Scrooge can also of course create as many new coins for himself as he wants. Or Scrooge could get bored of the whole system and stop updating the block chain completely.

The problem here is centralization. Although Scrooge is happy with this system, we, as users of it, might not be. While ScroogeCoin may seem like an unrealistic proposal, much of the early research on cryptosystems assumed there would indeed be some central trusted authority, typically referred to as a *bank*. After all, most real-world currencies do have a trusted issuer (typically a government mint) responsible for creating currency and determining which notes are valid. However, cryptocurrencies with a central authority largely failed to take off in practice. There are many reasons for this, but in hindsight it appears that it's difficult to get people to accept a cryptocurrency with a centralized authority.

Therefore, the central technical challenge that we need to solve in order to improve on ScroogeCoin and create a workable system is: can we descroogify the system? That is, can we get rid of that centralized Scrooge figure? Can we have a cryptocurrency that operates like ScroogeCoin in many ways, but doesn't have any central trusted authority?

To do that, we need to figure out how all users can agree upon a single published block chain as the history of which transactions have happened. They must all agree on which transactions are valid, and which transactions have actually occurred. They also need to be able to assign IDs to things in a decentralized way. Finally, the minting of new coins needs to be controlled in a decentralized way. If we can solve all of those problems, then we can build a currency that would be like ScroogeCoin but without a centralized party. In fact, this would be a system very much like Bitcoin.

# Further Reading

Steven Levy's *Crypto* is an enjoyable, non-technical look at the development of modern cryptography and the people behind it:

**Levy, Steven. *Crypto: How the Code Rebels Beat the Government--Saving Privacy in the Digital Age.* Penguin, 2001.**

Modern cryptography is a rather theoretical field. Cryptographers use mathematics to define primitives, protocols, and their desired security properties in a formal way, and to prove them secure based on widely accepted assumptions about the computational hardness of specific mathematical tasks. In this chapter we've used intuitive language to discuss hash functions and digital signatures. For the reader interested in exploring these and other cryptographic concepts in a more mathematical way and in greater detail, we refer you to:

**Katz, Jonathan, and Yehuda Lindell. *Introduction to Modern Cryptography, Second Edition.* CRC Press, 2014.**

For an introduction to applied cryptography, see:

**Ferguson, Niels, Bruce Schneier, and Tadayoshi Kohno. *Cryptography engineering: design principles and practical applications*. John Wiley & Sons, 2012.**

Perusing the NIST standard that defines SHA-2 is a good way to get an intuition for what cryptographic standards look like:

**FIPS PUB 180-4, Secure Hash Standards, Federal Information Processing Standards Publication. Information Technology Laboratory, National Institute of Standards and Technology, Gaithersburg, MD, 2008.**

Finally, here's the paper describing the standardized version of the ECDSA signature algorithm.

**Johnson, Don, Alfred Menezes, and Scott Vanstone. The elliptic curve digital signature algorithm (ECDSA). International Journal of Information Security 1.1 (2001): 36-63.**

# Exercises

1. **Authenticated Data Structures.** You are designing SecureBox, an authenticated online file storage system. For simplicity, there is only a single folder. Users must be able to add, edit, delete, and retrieve files, and to list the folder contents. When a user retrieves a file, SecureBox must provide a proof that the file hasn't been tampered with since its last update. If a file with the given name doesn't exist, the server must report that — again with a proof.

We want to minimize the size of these proofs, the time complexity of verifying them, and the size of the digest that the user must store between operations. (Naturally, to be able to verify proofs, users must at all times store some nonzero amount of state derived from the folder contents. Other than this digest the user has no memory of the contents of the files she added.)

Here's a naive approach. The user's digest is a hash of the entire folder contents, and proofs are copies of the entire folder contents. This results in a small digest but large proofs and long verification times. Besides, before executing add/delete/edit operations, the user must retrieve the entire folder so that she can recompute the digest.

Alternatively, the digest could consist of a separate hash for each file, and each file would be its own proof. The downside of this approach is that it requires digest space that is linear in the number of files in the system.

Can you devise a protocol where proof size, verification time, and digest size are all sublinear? You might need a sub-protocol that involves some amount of two-way communication for the user to be able to update her digest when she executes and add, delete, or edit.

Hint: use the Merkle tree idea from Section 1.2.

2. **Birthday Attack.** Let H be an ideal hash function that produces an n-bit output. By ideal, we mean that as far as we can tell, each hash value is independent and uniformly distributed in $\{0,1\}^n$. Trivially,

we can go through $2^n + 1$ different values and we are guaranteed to find a collision. If we're constrained for space, we can just store 1 input-output pair and keep trying new inputs until we hit the same output again. This has time complexity $O(2^n)$, but has $O(1)$ space complexity. Alternatively, we could compute the hashes of about $O(2^{n/2})$ different inputs and store all the input-output pairs. As we saw in the text, there's a good chance that some two of those outputs would collide (the "birthday paradox"). This shows that we can achieve a time-space trade-off: $O(2^{n/2})$ time and $O(2^{n/2})$ space.

1. (Easy) Show that the time-space trade-off is parameterizable: we can achieve any space complexity between $O(1)$ and $O(2^{n/2})$ with a corresponding decrease in time complexity.
2. (Very hard) Is there an attack for which the product of time and space complexity is $o(2^n)$? [Recall the little oh notation.]

3. **Hash function properties** (again). Let H be a hash function that is both hiding and puzzle-friendly. Consider $G(z) = H(z) \| z_{last}$ where $z_{last}$ represents the last bit of z. Show that G is puzzle-friendly but not hiding.

4. **Randomness**. In ScroogeCoin, suppose Mallory tries generating (sk, pk) pairs until her secret key matches someone else's. What will she be able to do? How long will it take before she succeeds, on average? What if Alice's random number generator has a bug and her key generation procedure produces only 1,000 distinct pairs?

# Chapter 2: How Bitcoin Achieves Decentralization

In this chapter, we will discuss decentralization in Bitcoin. In the first chapter we looked at the crypto basics that underlie Bitcoin and we ended with a simple currency that we called ScroogeCoin. ScroogeCoin achieves a lot of what we want in a ledger-based cryptocurrency, but it has one glaring problem — it relies upon the centralized authority called Scrooge. We ended with the question of how to decentralize, or de-Scrooge-ify, this currency, and answering that question will be the focus of this chapter.

As you read through this chapter, take note that the mechanism through which Bitcoin achieves decentralization is not purely technical, but it's a combination of technical methods and clever incentive engineering. At the end of this chapter you should have a really good appreciation for how this decentralization happens, and more generally how Bitcoin works and why it is secure.

## 2.1 Centralization vs. Decentralization

Decentralization is an important concept that is not unique to Bitcoin. The notion of competing paradigms of centralization versus decentralization arises in a variety of different digital technologies. In order to best understand how it plays out in Bitcoin, it is useful to understand the central conflict — the tension between these two paradigms — in a variety of other contexts.

On the one hand we have the Internet, a famously decentralized system that has historically competed with and prevailed against "walled-garden" alternatives like AOL's and CompuServe's information services. Then there's email, which at its core is a decentralized system based on the Simple Mail Transfer Protocol (SMTP), an open standard. While it does have competition from proprietary messaging systems like Facebook or LinkedIn mail, email has managed to remain the default for person-to-person communication online. In the case of instant messaging and text messaging, we have a hybrid model that can't be categorically described as centralized or decentralized. Finally there's social networking: despite numerous concerted efforts by hobbyists, developers and entrepreneurs to create alternatives to the dominant centralized model, centralized systems like Facebook and LinkedIn still dominate this space. In fact, this conflict long predates the digital era and we see a similar struggle between the two models in the history of telephony, radio, television, and film.

Decentralization is not all or nothing; almost no system is purely decentralized or purely centralized. For example, email is fundamentally a decentralized system based on a standardized protocol, SMTP, and anyone who wishes can operate an email server of their own. Yet, what has happened in the market is that a small number of centralized webmail providers have become dominant. Similarly, while the Bitcoin protocol is decentralized, services like Bitcoin exchanges, where you can convert

Bitcoin into other currencies, and wallet software, or software that allows people to manage their bitcoins may be centralized or decentralized to varying degrees.

With this in mind, let's break down the question of how the Bitcoin protocol achieves decentralization into five more specific questions:

1. Who maintains the ledger of transactions?
2. Who has authority over which transactions are valid?
3. Who creates new bitcoins?
4. Who determines how the rules of the system change?
5. How do bitcoins acquire exchange value?

The first three questions reflect the technical details of the Bitcoin protocol, and it is these questions that will be the focus of this chapter.

Different aspects of Bitcoin fall on different points on the centralization/decentralization spectrum. The peer-to-peer network is close to purely decentralized since anybody can run a Bitcoin node and there's a fairly low barrier to entry. You can go online and easily download a Bitcoin client and run a node on your laptop or your PC. Currently there are several thousand such nodes. Bitcoin *mining*, which we'll study later in this chapter, is technically also open to anyone, but it requires a very high capital cost. Because of this there has been a high degree of centralization, or a concentration of power, in the Bitcoin mining ecosystem. Many in the Bitcoin community see this as quite undesirable. A third aspect is updates to the software that Bitcoin nodes run, and this has a bearing on how and when the rules of the system change. One can imagine that there are numerous interoperable implementations of the protocol, as with email. But in practice, most nodes run the reference implementation, and its developers are trusted by the community and have a lot of power.

## 2.2 Distributed consensus

We've discussed, in a generic manner, centralization and decentralization. Let's now examine decentralization in Bitcoin at a more technical level. A key term that will come up throughout this discussion is ***consensus***, and specifically, ***distributed consensus***. The key technical problem to solve in building a distributed e-cash system is achieving distributed consensus. Intuitively, you can think of our goal as decentralizing ScroogeCoin, the hypothetical currency that we saw in the first chapter.

Distributed consensus has various applications, and it has been studied for decades in computer science. The traditional motivating application is reliability in distributed systems. Imagine you're in charge of the backend for a large social networking company like Facebook. Systems of this sort typically have thousands or even millions of servers, which together form a massive distributed database that records all of the actions that happen in the system. Each piece of information must be recorded on several different nodes in this backend, and the nodes must be in sync about the overall state of the system.

The implications of having a distributed consensus protocol reach far beyond this traditional application. If we had such a protocol, we could use it to build a massive, distributed key-value store, that maps arbitrary keys, or names, to arbitrary values. A distributed key-value store, in turn, would enable many applications. For example, we could use it to build a distributive domain name system, which is simply a mapping between human understandable domain names to IP addresses. We could build a public key directory, which is a mapping between email addresses (or some other form of real-world identity) to public keys.

That's the intuition of what distributed consensus is, but it is useful to provide a technical definition as this will help us determine whether or not a given protocol meets the requirements.

***Distributed consensus protocol.*** There are *n* nodes that each have an input value. Some of these nodes are faulty or malicious. A distributed consensus protocol has the following two properties:

- It must terminate with all honest nodes in agreement on the value
- The value must have been generated by an honest node

What does this mean in the context of Bitcoin? To understand how distributed consensus could work in Bitcoin, remember that Bitcoin is a peer-to-peer system. When Alice wants to pay Bob, what she actually does is broadcast a transaction to all of the Bitcoin nodes that comprise the peer-to-peer network. See Figure 2.1.

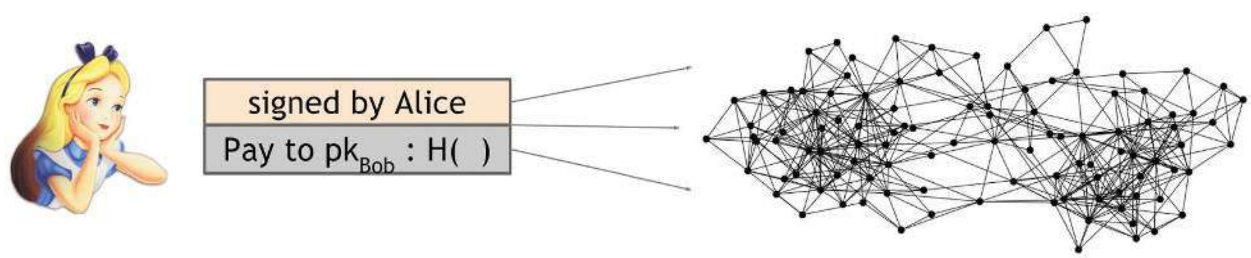



***Figure 2.1 Broadcasting a transaction*** In order to pay Bob, Alice broadcasts the transaction to the entire Bitcoin peer-to-peer network.

Incidentally, you may have noticed that Alice broadcasts the transaction to all the Bitcoin peer-to-peer nodes, but Bob's computer is nowhere in this picture. It's of course possible that Bob is running one of the nodes in the peer-to-peer network. In fact, if he wants to be notified that this transaction did in fact happen and that he got paid, running a node might be a good idea. Nevertheless, there is no requirement that Bob be listening on the network; running a node is not necessary for Bob to receive the funds. The bitcoins will be his whether or not he's operating a node on the network.

What exactly is it that the nodes might want to reach consensus on in the Bitcoin network? Given that a variety of users are broadcasting these transactions to the network, the nodes must agree on exactly which transactions were broadcast and the order in which these transactions happened. This will result in a single, global ledger for the system. Recall that in ScroogeCoin, for optimization, we put transactions into blocks. Similarly, in Bitcoin, we do consensus on a block-by-block basis.

So at any given point, all the nodes in the peer-to-peer network have a ledger consisting of a sequence of blocks, each containing a list of transactions, that they've reached consensus on. Additionally, each node has a pool of outstanding transactions that it has heard about but have not yet been included on the block chain. For these transactions, consensus has not yet happened, and so by definition, each node might have a slightly different version of the outstanding transaction pool. In practice, this occurs because the peer-to-peer network is not perfect, so some nodes may have heard about a transaction that other nodes have not heard about.

How exactly do nodes come to consensus on a block? One way to do this: at regular intervals, say every 10 minutes, every node in the system proposes its own outstanding transaction pool to be the next block. Then the nodes execute some consensus protocol, where each node's input is its own proposed block. Now, some nodes may be malicious and put invalid transactions into their blocks, but we might assume that other nodes will be honest. If the consensus protocol succeeds, a valid block will be selected as the output. Even if the selected block was proposed by only one node, it's a valid output as long as the block is valid. Now there may be some valid outstanding transaction that did not get included in the block, but this is not a problem. If some transaction somehow didn't make it into this particular block, it could just wait and get into the next block.

The approach in the previous paragraph has some similarities to how Bitcoin works, but it's not quite how it works. There are a number of technical problems with this approach. Firstly, consensus in general is a hard problem since nodes might crash or be outright malicious. Secondly, and specifically in the Bitcoin context, the network is highly imperfect. It's a peer-to-peer system, and not all pairs of nodes are connected to each other. There could be faults in the network because of poor Internet connectivity for example, and thus running a consensus protocol in which all nodes must participate is not really possible. Finally, there's a lot of latency in the system because it's distributed all over the Internet.

Sidebar: The Bitcoin protocol must reach consensus in the face of two types of obstacles: imperfections in the network, such as latency and nodes crashing, as well as deliberate attempts by some nodes to subvert the process.

One particular consequence of this high latency is that there is no notion of global time. What this means is that not all nodes can agree to a common ordering of events simply based on observing timestamps. So the consensus protocol cannot contain instructions of the form, "The node that sent the first message in step 1 must do X in step 2." This simply will not work because not all nodes will agree on which message was sent first in the step 1 of the protocol.

***Impossibility results.*** The lack of global time heavily constrains the set of algorithms that can be used in the consensus protocols. In fact, because of these constraints, much of the literature on distributed consensus is somewhat pessimistic, and many impossibility results have been proven. One very well known impossibility result concerns the ***Byzantine Generals Problem***. In this classic problem, the Byzantine army is separated into divisions, each commanded by a general. The generals communicate by messenger in order to devise a joint plan of action. Some generals may be traitors and may intentionally try to subvert the process so that the loyal generals cannot arrive at a unified plan. The goal of this problem is for all of the loyal generals to arrive at the same plan without the traitorous generals being able to cause them to adopt a bad plan. It has been proven that this is impossible to achieve if one-third or more of the generals are traitors.

A much more subtle impossibility result, known for the names of the authors who first proved it, is called the Fischer-Lynch-Paterson impossibility result. Under some conditions, which include the nodes acting in a deterministic manner, they proved that consensus is impossible with even a single faulty process.

Despite these impossibility results, there are some consensus protocols in the literature. One of the better known among these protocols is ***Paxos***. Paxos makes certain compromises. On the one hand, it never produces an inconsistent result. On the other hand, it accepts the trade-off that under certain conditions, albeit rare ones, the protocol can get stuck and fail to make any progress.

***Breaking traditional assumptions.*** But there's good news: these impossibility results were proven in a very specific model. They were intended to study distributed databases, and this model doesn't carry over very well to the Bitcoin setting because Bitcoin violates many of the assumptions built into the models. In a way, the results tell us more about the model than they do about the problem of distributed consensus.

Ironically, with the current state of research, consensus in Bitcoin works better in practice than in theory. That is, we observe consensus working, but have not developed the theory to fully explain why it works. But developing such a theory is important as it can help us predict unforeseen attacks and problems, and only when we have a strong theoretical understanding of how Bitcoin consensus works will we have strong guarantees Bitcoin's security and stability.

What are the assumptions in traditional models for consensus that Bitcoin violates? First, it introduces the idea of incentives, which is novel for a distributed consensus protocol. This is only possible in Bitcoin because it is a currency and therefore has a natural mechanism to incentivize participants to act honestly. So Bitcoin doesn't quite solve the distributed consensus problem in a general sense, but it solves it in the specific context of a currency system.

Second, Bitcoin embraces the notion of randomness. As we will see in the next two sections, Bitcoin's consensus algorithm relies heavily on randomization. Also, it does away with the notion of a specific starting point and ending point for consensus. Instead, consensus happens over a long period of time, about an hour in the practical system. But even at the end of that time, nodes can't be certain that any particular transaction or a block has made it into the ledger. Instead, as time goes on, the probability that your view of any block will match the eventual consensus view increases, and the probability that the views will diverge goes down exponentially. These differences in the model are key to how Bitcoin gets around the traditional impossibility results for distributed consensus protocols.

## 2.3 Consensus without identity using a block chain

In this section we'll study the technical details of Bitcoin's consensus algorithm. Recall that Bitcoin nodes do not have persistent, long-term identities. This is another difference from traditional distributed consensus algorithms. One reason for this lack of identities is that in a peer-to-peer system, there is no central authority to assign identities to participants and verify that they're not creating new nodes at will. The technical term for this is a ***Sybil attack***. Sybils are just copies of nodes that a malicious adversary can create to look like there are a lot of different participants, when in fact all those pseudo-participants are really controlled by the same adversary. The other reason is that pseudonymity is inherently a goal of Bitcoin. Even if it were possible or easy to establish identities for all nodes or all participants, we wouldn't necessarily want to do that. Although Bitcoin doesn't give strong anonymity guarantees in that the different transactions that one makes can often be linked together, it does have the property that nobody is forced to reveal their real-life identity, like their name or IP address, in order to participate. And that's an important property and a central feature of Bitcoin's design.

If nodes did have identities, the design would be easier. For starters, identities would allow us to put in the protocol instructions of the form, "Now the node with the lowest numerical ID should take some step." Without identities, the set of possible instructions is more constrained. But a much more serious reason for nodes to have identities is for security. If nodes were identified and it weren't trivial to create new node identities, then we could make assumptions on the number of nodes that are malicious, and we could derive security properties out of that. For both of these reasons, the lack of identities introduces difficulties for the consensus protocol in Bitcoin.

We can compensate for the lack of identities by making a weaker assumption. Suppose there is somehow an ability to pick a random node in the system. A good motivating analogy for this is a lottery or a raffle, or any number of real-life systems where it's hard to track people, give them identities and verify those identities. What we do in those contexts is to give out tokens or tickets or something similar. That enables us to later pick a random token ID, and call upon the owner of that ID. So for the moment, take a leap of faith and assume that it is possible to pick a random node from the Bitcoin network in this manner. Further assume, for the moment, that this token generation and distribution algorithm is sufficiently smart so that if the adversary is going to try to create a lot of Sybil nodes, all of those Sybils together will get only one token. This means the adversary is not able to multiply his power by creating new nodes. If you think this is a lot to assume, don't worry. Later in this chapter, we'll remove these assumptions and show in detail how properties equivalent to these are realized in Bitcoin.

***Implicit Consensus.*** This assumption of random node selection makes possible something called ***implicit consensus***. There are multiple rounds in our protocol, each corresponding to a different block in the block chain. In each round, a random node is somehow selected, and this node gets to propose the next block in the chain. There is no consensus algorithm for selecting the block, and no voting of any kind. The chosen node unilaterally proposes what the next block in the block chain will be. But what if that node is malicious? Well, there is a process for handling that, but it is an implicit one. Other nodes will implicitly accept or reject that block by choosing whether or not to build on top of it. If they accept that block, they will signal their acceptance by extending the block chain including the accepted block. By contrast, if they reject that block, they will extend the chain by ignoring that block, and building on top of whichever is the previous block that they accepted. Recall that each block contains a hash of the block that it extends. This is the technical mechanism that allows nodes to signal which block it is that they are extending.

**Bitcoin consensus algorithm (simplified)**

*This algorithm is simplified in that it assumes the ability to select a random node in a manner that is not vulnerable to Sybil attacks.*

1. New transactions are broadcast to all nodes
2. Each node collects new transactions into a block
3. In each round a random node gets to broadcast its block
4. Other nodes accept the block only if all transactions in it are valid (unspent, valid signatures)
5. Nodes express their acceptance of the block by including its hash in the next block they create

Let's now try to understand why this consensus algorithm works. To do this, let's consider how a malicious adversary — who we'll call Alice — may be able to subvert this process.

***Stealing Bitcoins.*** Can Alice simply steal bitcoins belonging to another user at an address she doesn't control? No. Even if it is Alice's turn to propose the next block in the chain, she cannot steal other users' bitcoins. Doing so would require Alice to create a valid transaction that spends that coin. This would require Alice to forge the owners' signatures which she cannot do if a secure digital signature scheme is used. So as long as the underlying cryptography is solid, she's not able to simply steal bitcoins.

***Denial of service attack.*** Let's consider another attack. Say Alice really dislikes some other user Bob. Alice can then decide that she will not include any transactions originating from Bob's address in any block that she proposes to get onto the block chain. In other words, she's denying service to Bob. While this is a valid attack that Alice can try to mount, luckily it's nothing more than a minor annoyance. If Bob's transaction doesn't make it into the next block that Alice proposes, he will just wait until an honest node gets the chance to propose a block and then his transaction will get into that block. So that's not really a good attack either.

***Double-spend attack.*** Alice may try to launch a double-spend attack. To understand how that works, let's assume that Alice is a customer of some online merchant or website run by Bob, who provides some online service in exchange for payment in bitcoins. Let's say Bob's service allows the download of some software. So here's how a double-spend attack might work. Alice adds an item to her shopping cart on Bob's website and the server requests payment. Then Alice creates a Bitcoin transaction from her address to Bob's and broadcasts it to the network. Let's say that some honest node creates the next block, and includes this transaction in that block. So there is now a block that was created by an honest node that contains a transaction that represents a payment from Alice to the merchant Bob.

Recall that a transaction is a data structure that contains Alice's signature, an instruction to pay to Bob's public key, and a hash. This hash represents a pointer to a previous transaction output that Alice received and is now spending. That pointer must reference a transaction that was included in some previous block in the consensus chain.

Note, by the way, that there are two different types of hash pointers here that can easily be confused. Blocks include a hash pointer to the previous block that they're extending. Transactions include one or more hash pointers to previous transaction outputs that are being redeemed.

Let's return to how Alice can launch a double spend attack. The latest block was generated by an honest node and includes a transaction in which Alice pays Bob for the software download. Upon seeing this transaction included in the block chain, Bob concludes that Alice has paid him and allows Alice to download the software. Suppose the next random node that is selected in the next round happens to be controlled by Alice. Now since Alice gets to propose the next block, she could propose a block that ignores the block that contains the payment to Bob and instead contains a pointer to the previous block. Furthermore, in the block that she proposes, Alice includes a transaction that transfers the very coins that she was sending to Bob to a different address that she herself controls. This is a classic double-spend pattern. Since the two transactions spend the same coins, only one of them can be included in the block chain. If Alice succeeds in including the payment to her own address in the block chain, then the transaction in which she pays Bob is useless as it can never be included later in the block chain.

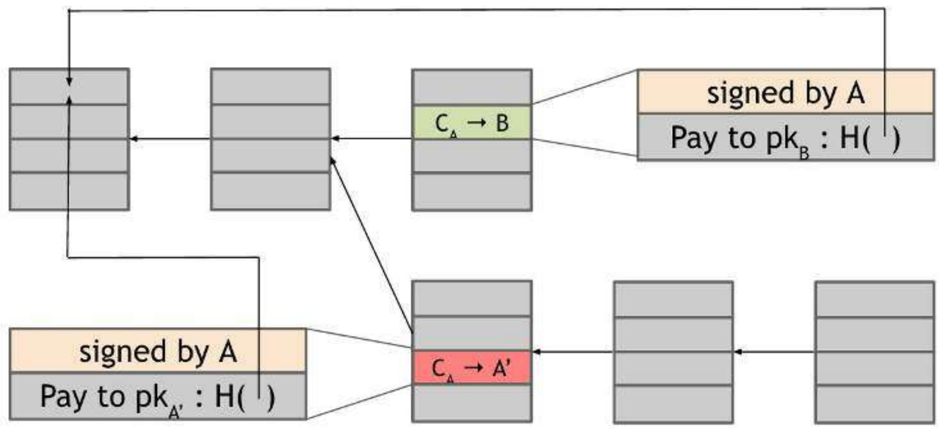



***Figure 2.2 A double spend attempt.*** Alice creates two transactions: one in which she sends Bob Bitcoins, and a second in which she double spends those Bitcoins by sending them to a different address that she controls. As they spend the same Bitcoins, only one of these transactions can be included in the block chain. The arrows are pointers from one block to the previous block that it extends including a hash of that previous block within its own contents. $C_A$ is used to denote a coin owned by Alice.

And how do we know if this double spend attempt is going to succeed or not? Well, that depends on which block will ultimately end up on the long-term consensus chain — the one with the Alice → Bob transaction or the one with the Alice → Alice transaction. What determines which block will be included? Honest nodes follow the policy of extending the longest valid branch, so which branch will they extend? There is no right answer! At this point, the two branches are the same length — they only differ in the last block and both of these blocks are valid. The node that chooses the next block then may decide to build upon either one of them, and this choice will largely determine whether or not the double-spend succeeds.

A subtle point: from a moral point of view, there is a clear difference between the block containing the transaction that pays Bob and the block containing the transaction in which Alice double spends those coins to her own address. But this distinction is only based on our knowledge of the story that Alice first paid Bob and then attempted to double spend. From a technological point of view, however, these two transactions are completely identical and both blocks are equally valid. The nodes that are looking at this really have no way to tell which is the morally legitimate transaction.

In practice, nodes often follow a heuristic of extending the block that they first heard about on the peer-to-peer network. But it's not a solid rule. And in any case, because of network latency, it could easily be that the block that a node first heard about is actually the one that was created second. So there is at least some chance that the next node that gets to propose a block will extend the block containing the double spend. Alice could further try to increase the likelihood of this happening by bribing the next node to do so. If the next node does build on the double-spend block for whatever reason, then this chain will now be longer than the one that includes the transaction to Bob. At this point, the next honest node is much more likely to continue to build on this chain since it is longer. This process will continue, and it will become increasingly likely that the block containing the double-spend will be part of the long-term consensus chain. The block containing the transaction to Bob, on the other hand, gets completely ignored by the network, and this is now called an ***orphan block***.

Let's now reconsider this whole situation from Bob-the-merchant's point of view. Understanding how Bob can protect himself from this double-spending attack is a key part of understanding Bitcoin security. When Alice broadcasts the transaction that represents her payment to Bob, Bob is listening on the network and hears about this transaction even before the next block is created. If Bob was even more foolhardy than we previously described, he can complete the checkout process on the website and allow Alice to download the software right at that moment. That's called a ***zero-confirmation transaction***. This leads to an even more basic double spend attack than the one described before. Previously, for the double-spend attack to occur, we had to assume that a malicious actor controls the node that proposes the next block. But if Bob allows Alice to download the software before the transaction receives even a single confirmation on the block chain, then Alice can immediately broadcast a double-spend transaction, and an honest node may include it in the next block instead of the transaction that pays Bob.

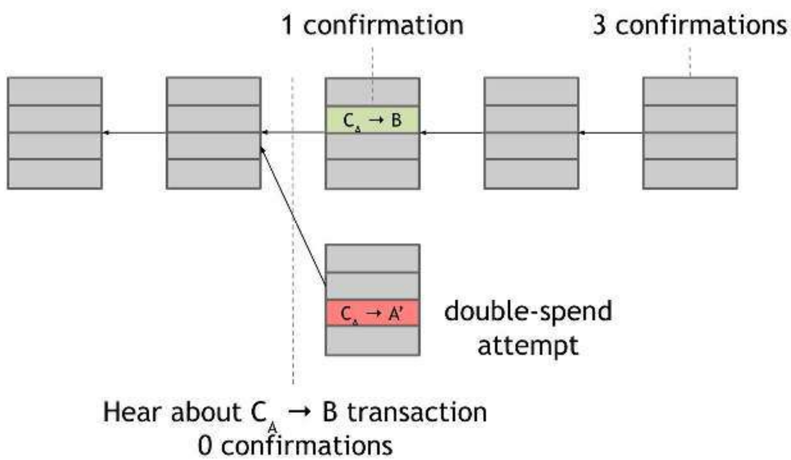



***Figure 2.3 Bob the Merchant's view.*** This is what Alice's double-spend attempt looks like from Bob the merchant's viewpoint. In order to protect himself from this attack, Bob should wait until the transaction with which Alice pays him is included in the block chain and has several confirmations.

On the other hand, a cautious merchant would not release the software to Alice even after the transaction was included in one block, and would continue to wait. If Bob sees that Alice successfully launches a double-spend attack, he realizes that the block containing Alice's payment to him has been orphaned. He should abandon the transaction and not let Alice download the software. Instead, if it happens that despite the double-spend attempt, the next several nodes build on the block with the Alice → Bob transaction, then Bob gains confidence that this transaction will be on the long-term consensus chain.

In general, the more confirmations a transaction gets, the higher the probability that it is going to end up on the long-term consensus chain. Recall that honest nodes' behavior is always to extend the longest valid branch that they see. The chance that the shorter branch with the double spend will catch up to the longer branch becomes increasingly tiny as it grows longer than any other branch. This is especially true if only a minority of the nodes are malicious — for a shorter branch to catch up, several malicious nodes would have to be picked in close succession.

In fact, the double-spend probability decreases exponentially with the number of confirmations. So, if the transaction that you're interested in has received *k* confirmations, then the probability that a double-spend transaction will end up on the long-term consensus chain goes down exponentially as a function of *k*. The most common heuristic that's used in the Bitcoin ecosystem is to wait for six confirmations. There is nothing really special about the number six. It's just a good tradeoff between the amount of time you have to wait and your guarantee that the transaction you're interested in ends up on the consensus block chain.

To recap, protection against invalid transactions is entirely cryptographic. But it is enforced by consensus, which means that if a node does attempt to include a cryptographically invalid transaction, then the only reason that transaction won't end up in the long-term consensus chain is because a majority of the nodes are honest and won't include an invalid transaction in the block chain. On the other hand, protection against double-spending is purely by consensus. Cryptography has nothing to say about this, and two transactions that represent a double-spend attempt are both valid from a cryptographic perspective. But it's the consensus that determines which one will end up on the long-term consensus chain. And finally, you're never 100 percent sure that a transaction you're interested in is on the consensus branch. But, this exponential probability guarantee is rather good. After about six transactions, there's virtually no chance that you're going to go wrong.

## 2.4 Incentives and proof of work

In the previous section, we got a basic look at Bitcoin's consensus algorithm and a good intuition for why we believe that it's secure. But recall from the beginning of the chapter that Bitcoin's decentralization is partly a technical mechanism and partly clever incentive engineering. So far we've mostly looked at the technical mechanism. Now let's talk about the incentive engineering that happens in Bitcoin.

We asked you to take a leap of faith earlier in assuming that we're able to pick a random node and, perhaps more problematically, that at least 50 percent of the time, this process will pick an honest node. This assumption of honesty is particularly problematic if there are financial incentives for participants to subvert the process, in which case we can't really assume that a node will be honest. The question then becomes: can we give nodes an incentive for behaving honestly?

Consider again the double-spend attempt after one confirmation (Figure 2.3). Can we penalize, somehow, the node that created the block with the double-spend transaction? Well, not really. As we mentioned earlier, it's hard to know which is the morally legitimate transaction. But even if we did, it's still hard to punish nodes since they don't have identities. So instead, let's flip the question around and ask, can we reward each of the nodes that created the blocks that did end up on the long-term consensus chain? Well, again, since those nodes don't reveal their real-world identities, we can't quite mail them cash to their home addresses. If only there were some sort of digital currency that we could use instead... you can probably see where this is going. We're going to use bitcoins to incentivize the nodes that created these blocks.

Let's pause for a moment. Everything that we've described so far is just an abstract algorithm for achieving distributed consensus and is not specific to the application. Now we're going to break out of that model, and we're going to use the fact that the application we're building through this distributed consensus process is in fact a currency. Specifically, we're going to incentivize nodes to behave honestly by paying them in units of this currency.

***Block Reward.*** How is this done? There are two separate incentive mechanisms in Bitcoin. The first is the ***block reward***. According to the rules of Bitcoin, the node that creates a block gets to include a special transaction in that block. This transaction is a coin-creation transaction, analogous to CreateCoins in Scroogecoin, and the node can also choose the recipient address of this transaction. Of course that node will typically choose an address belonging to itself. You can think of this as a payment to the node in exchange for the service of creating a block on the consensus chain.

At the time of this writing, the value of the block reward is fixed at 25 Bitcoins. But it actually halves every 210,000 blocks. Based on the rate of block creation that we will see shortly, this means that the rate drops roughly every four years. We're now in the second period. For the first four years of Bitcoin's existence, the block reward was 50 bitcoins; now it's 25. And it's going to keep halving. This has some interesting consequences, which we will see shortly.

You may be wondering why the block reward incentivizes honest behavior. It may appear, based on what what we've said so far, that this node gets the block reward regardless of whether it proposes a valid block or behaves maliciously. But this is not true! Think about it — how will this node "collect" its reward? That will only happen if the block in question ends up on the long-term consensus branch because just like every other transaction, the coin-creation transaction will only be accepted by other nodes if it ends up on the consensus chain. That's the key idea behind this incentive mechanism. It's a very subtle but very powerful trick. It incentivizes nodes to behave in whatever way they believe will get other nodes to extend their blocks. So if most of the network is following the longest valid branch rule, it incentivizes all nodes to continue to follow that rule. That's Bitcoin's first incentive mechanism.

We mentioned that every 210,000 blocks (or approximately four years), the block reward is cut in half. In Figure 2.4, the slope of this curve is going to keep halving. This is a geometric series, and you might know that it means that there is a finite sum. It works out to a total of 21 million bitcoins.

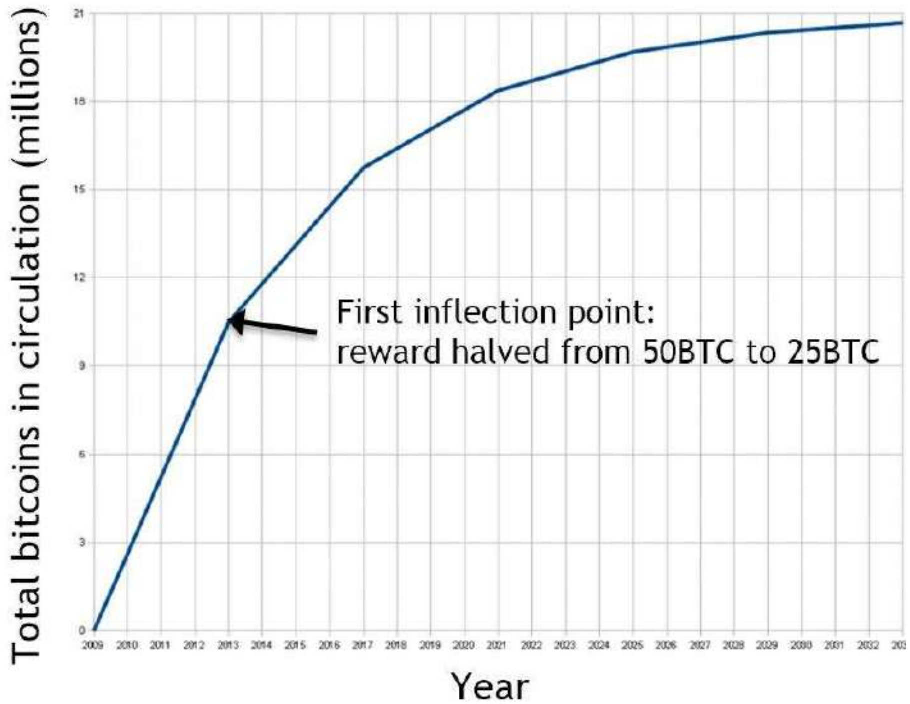



***Figure 2.4*** The block reward is cut in half every four years limiting the total supply of bitcoins to 21 million.

It is important to note that this is the only way in which new bitcoins are allowed to be created. There is no other coin generation mechanism, and that's why 21 million is a final and total number (as the rules stand now, at least) for how many bitcoins there can ever be. This new block creation reward is actually going to run out in 2140, as things stand now. Does that mean that the system will stop working in 2140 and become insecure because nodes no longer have the incentive to behave honestly? Not quite. The block reward is only the first of two incentive mechanisms in Bitcoin.

***Transaction fees*** The second incentive mechanism is called the ***transaction fee***. The creator of any transaction can choose to make the total value of the transaction outputs less than the total value of its inputs. Whoever creates the block that first puts that transaction into the block chain gets to collect the difference, which acts a transaction fee. So if you're a node that's creating a block that contains, say, 200 transactions, then the sum of all those 200 transaction fees is paid to the address that you put into that block. The transaction fee is purely voluntary, but we expect, based on our understanding of the system, that as the block reward starts to run out, it will become more and more important, almost mandatory, for users to include transaction fees in order to get a reasonable quality of service. To a certain degree, this is already starting to happen now. But it is yet unclear precisely how the system will evolve; it really depends on a lot of game theory which hasn't been fully worked out yet. That's an interesting area of open research in Bitcoin.

There are still a few problems remaining with the consensus mechanism as we described it. The first major one is the leap of faith that we asked you to take that somehow we can pick a random node. Second, we've created a new problem by giving nodes these incentives for participation. The system can become unstable as the incentives cause a free-for-all where everybody wants to run a Bitcoin node in the hope of capturing some of these rewards. And a third one is an even trickier version of this problem, which is that an adversary might create a large number of Sybil nodes to try and subvert the consensus process.

***Mining and proof-of-work.*** It turns out that all of these problems are related, and all of them have the same solution, which is called ***proof-of-work***. The key idea behind proof-of-work is that we approximate the selection of a random node by instead selecting nodes in proportion to a resource that we hope that nobody can monopolize. If, for example, that resource is computing power, then it's a proof-of-work system. Alternately, it could be in proportion to ownership of the currency, and that's called ***proof-of-stake***. Although it's not used in Bitcoin, proof-of-stake is a legitimate alternate model and it's used in other cryptocurrencies. We'll see more about proof-of-stake and other proof-of-work variants in Chapter 8.

But back to proof-of-work. Let's try to get a better idea of what it means to select nodes in proportion to their computing power. Another way of understanding this is that we're allowing nodes to compete with each other by using their computing power, and that will result in nodes automatically being picked in that proportion. Yet another view of proof-of-work is that we're making it moderately hard to create new identities. It's sort of a tax on identity creation and therefore on the Sybil attack. This might all appear a bit vague, so let's go ahead and look at the details of the proof-of-work system that's used in Bitcoin, which should make things a lot clearer.

Bitcoin achieves proof-of-work using ***hash puzzles***. In order to create a block, the node that proposes that block is required to find a number, or ***nonce***, such that when you concatenate the nonce, the previous hash, and the list of transactions that comprise that block and take the hash of this whole string, then that hash output should be a number that falls into a target space that is quite small in relation to the much larger output space of that hash function. We can define such a target space as any value falling below a certain target value. In this case, the nonce will have to satisfy the following inequality:

$$H(nonce \,\|\, prev\_hash \,\|\, tx \,\|\, tx \,\|\, \ldots \,\|\, tx) < target$$

As we saw earlier, normally a block contains a series of transactions that a node is proposing. In addition, a block also contains a hash pointer to the previous block[1]. In addition, we're now requiring that a block also contain a nonce. The idea is that we want to make it moderately difficult to find a nonce that satisfies this required property, which is that hashing the whole block together, including that nonce, is going to result in a particular type of output. If the hash function satisfies the

[1] We are using the term hash pointer loosely. The pointer is just a string in this context as it need not tell us where to find this block. We will find the block by asking other peers on the network for it. The important part is the hash that both acts as an ID when requesting other peers for the block and lets us validate the block once we have obtained it.

puzzle-friendliness property from Chapter 1, then the only way to succeed in solving this hash puzzle is to just try enough nonces one by one until you get lucky. So specifically, if this target space were just one percent of the overall output space, you would have to try about 100 nonces before you got lucky. In reality, the size of this target space is not nearly as high as one percent of the output space. It's much, much smaller than that as we will see shortly.

This notion of hash puzzles and proof of work completely does away with the requirement to magically pick a random node. Instead, nodes are simply independently competing to solve these hash puzzles all the time. Once in a while, one of them will get lucky and will find a random nonce that satisfies this property. That lucky node then gets to propose the next block. That's how the system is completely decentralized. There is nobody deciding which node it is that gets to propose the next block.

***Difficult to compute.*** There are three important properties of hash puzzles. The first is that they need to be quite difficult to compute. We said moderately difficult, but you'll see why this actually varies with time. As of the end of 2014, the difficulty level is about $10^{20}$ hashes per block. In other words the size of the target space is only $1/10^{20}$ of the size of the output space of the hash function. This is a lot of computation — it's out of the realm of possibility for a commodity laptop, for example. Because of this, only some nodes even bother to compete in this block creation process. This process of repeatedly trying and solving these hash puzzles is known as ***Bitcoin mining***, and we call the participating nodes ***miners***. Even though technically anybody can be a miner, there's been a lot of concentration of power in the mining ecosystem due to the high cost of mining.

***Parameterizable cost.*** The second property is that we want the cost to be parameterizable, not a fixed cost for all time. The way that's accomplished is that all the nodes in the Bitcoin peer-to-peer network will automatically recalculate the target, that is the size of the target space as a fraction of the output space, every 2016 blocks. They recalculate the target in such a way that the average time between successive blocks produced in the Bitcoin network is about 10 minutes. With a 10-minute average time between blocks, 2016 blocks works out to two weeks. In other words, the recalculation of the target happens roughly every two weeks.

Let's think about what this means. If you're a miner, and you've invested a certain fixed amount of hardware into Bitcoin mining, but the overall mining ecosystem is growing, more miners are coming in, or they're deploying faster and faster hardware, that means that over a two week period, slightly more blocks are going to be found than expected. So nodes will automatically readjust the target, and the amount of work that you have to do to be able to find a block is going to increase. So if you put in a fixed amount of hardware investment, the rate at which you find blocks is actually dependent upon what other miners are doing. There's a very nice formula to capture this, which is that the probability that any given miner, Alice, is going to win the next block is equivalent to the fraction of global hash power that she controls. This means that if Alice has mining hardware that's about 0.1 percent of total hash power, she will find roughly one in every 1,000 blocks.

What is the purpose of this readjustment? Why do we want to maintain this 10-minute invariant? The reason is quite simple. If blocks were to come very close together, then there would be a lot of inefficiency, and we would lose the optimization benefits of being able to put a lot of transactions in a single block. There is nothing magical about the number 10, and if you went down from 10 minutes to 5 minutes, it would probably be just fine. There's been a lot of discussion about the ideal block latency that altcoins, or alternative cryptocurrencies, should have. But despite some disagreements about the ideal latency, everybody agrees that it should be a fixed amount. It cannot be allowed to go down without limit. That's why we have the automatic target recalculation feature.

The way that this cost function and proof of work is set up allows us to reformulate our security assumption. Here's where we finally depart from the last leap of faith that we asked you to take earlier. Instead of saying that somehow the majority of nodes are honest in a context where nodes don't even have identities and not being clear about what that means, we can now state crisply, that a lot of attacks on Bitcoin are infeasible if the majority of miners, weighted by hash power, are following the protocol — or, are honest. This is true because if a majority of miners, weighted by hash power, are honest, the competition for proposing the next block will automatically ensure that there is at least a 50 percent chance that the next block to be proposed at any point is coming from an honest node.

***Sidebar.*** in the research fields of distributed systems and computer security, it is common to assume that some percentage of nodes are honest and to show that the system works as intended even if the other nodes behave arbitrarily. That's basically the approach we've taken here, except that we weight nodes by hash power in computing the majority. The original Bitcoin whitepaper contains this type of analysis as well.

But the field of game theory provides an entirely different, and arguably more sophisticated and realistic way to determine how a system will behave. In this view, we don't split nodes into honest and malicious. Instead, we assume that *every* node acts according to its incentives. Each node picks a (randomized) strategy to maximize its payoff, taking into account other nodes' potential strategies. If the protocol and incentives are designed well, then most nodes will follow the rules most of the time. "Honest" behavior is just one strategy of many, and we attach no particular moral salience to it.

In the game theoretic view, the big question is whether the default miner behavior is a "Nash equilibrium," that is, whether it represents a stable situation in which no miner can realize a higher payoff by deviating from honest behavior. This question is still contentious and an active area of research.

Solving hash puzzles is probabilistic because nobody can predict which nonce is going to result in solving the hash puzzle. The only way to do it is to try nonces one by one and hope that one succeeds. Mathematically, this process is called **Bernoulli trials**. A Bernoulli trial is an experiment with two possible outcomes, and the probability of each outcome occurring is fixed between successive trials. Here, the two outcomes are whether or not the hash falls in the target, and assuming the hash functions behaves like a random function, the probability of those outcomes is fixed. Typically, nodes try so many nonces that Bernoulli trials, a discrete probability process, can be well approximated by a continuous probability process called a **Poisson process**, a process in which events occur independently at a constant average rate. The end result of all of that is that the probability density function that shows the relative likelihood of the time until the next block is found looks like Figure 2.5.

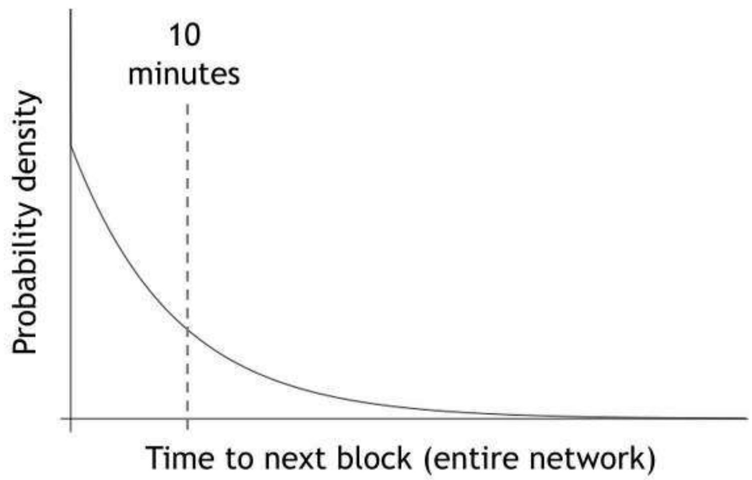



***Figure 2.5*** Probability density function of the time until the next block is found.

This is known as an exponential distribution. There is some small probability that if a block has been found now, the next block is going to be found very soon, say within a few seconds or a minute. And there is also some small probability that it will take a long time, say an hour, to find the next block. But overall, the network automatically adjusts the difficulty so that the inter-block time is maintained at an average, long term, of 10 minutes. Notice that Figure 2.5 shows how frequently blocks are going to be created by the entire network not caring about which miner actually finds the block.

If you're a miner, you're probably interested in how long it will take you to find a block. What does this probability density function look like? It's going to have the same shape, but it's just going to have a different scale on the x-axis. Again, it can be represented by a nice equation.
For a specific miner:

$$mean\ time\ to\ next\ block\ =\ \frac{10\ minutes}{fraction\ of\ hash\ power}$$

If you have 0.1 percent of the total network hash power, this equation tells us that you're going to find blocks once every 10,000 minutes, which is just about a week. Not only is your mean time between blocks going to be very high, but the variance of the time between blocks found by you is also going to be very high. This has some important consequences that we're going to look at in chapter 5.

***Trivial to verify.*** Let's now turn to the third important property of this proof of work function, which is that it is trivial to verify that a node has computed proof of work correctly. Even if it takes a node, on average, $10^{20}$ tries to find a nonce that makes the block hash fall below the target, that nonce must be published as part of the block. It is thus trivial for any other node to look at the block contents, hash them all together, and verify that the output is less than the target. This is quite an important property because, once again, it allows us to get rid of centralization. We don't need any centralized authority verifying that miners are doing their job correctly. Any node or any miner can instantly verify that a block found by another miner satisfies this proof-of-work property.

## 2.5 Putting it all together

***Cost of mining.*** Let's now look at mining economics. We mentioned it's quite expensive to operate as a miner. At the current difficulty level, finding a single block takes computing about $10^{20}$ hashes and the block reward is about 25 Bitcoins, which is a sizable amount of money at the current exchange rate. These numbers allow for an easy calculation of whether it's profitable for one to mine, and we can capture this decision with a simple statement:

> If
>     **mining reward** > **mining cost**
>     then miner profits
> where
>     **mining reward = block reward + tx fees**
>     **mining cost = hardware cost + operating costs (electricity, cooling, etc.)**

Fundamentally, the mining reward that the miner gets is in terms of the block reward and transaction fees. The miner asks himself how it compares to the total expenditure, which is the hardware and electricity cost.

But there are some complications to this simple equation. The first is that, as you may have noticed, the hardware cost is a fixed cost whereas the electricity cost is a variable cost that is incurred over time. Another complication is that the reward that miners get depends upon the rate at which they find blocks, which depends on not just the power of their hardware, but on the ratio of their hash rate to the total global hash rate. A third complication is that the costs that the miner incurs are typically denominated in dollars or some other traditional currency, but their reward is denominated in bitcoin. So this equation has a hidden dependence on Bitcoin's exchange rate at any given time. And finally, so far we've assumed that the miner is interested in honestly following the protocol. But the miner might choose to use some other mining strategy instead of always attempting to extend the longest valid branch. So this equation doesn't capture all the nuances of the different strategies that the miner can employ. Actually analyzing whether it makes sense to mine is a complicated game theory problem that’s not easily answered.

At this point, we’ve obtained a pretty good understanding of how a Bitcoin achieves decentralization. We will now recap the high level points and put it all together in order to get an even better understanding.

Let’s start from identities. As we’ve learned, there are no real-world identities required to participate in the Bitcoin protocol. Any user can create a pseudonymous key pair at any moment, any number of them. When Alice wants to pay Bob in bitcoins, the Bitcoin protocol does not specify how Alice learns Bob’s address. Given these pseudonymous key pairs as identities, transactions are basically messages that are broadcast to the Bitcoin peer-to-peer network that are instructions to transfer coins from one address to another. Bitcoins are just transaction outputs, and we will discuss this in much more detail in the next chapter.

**Sidebar.** Bitcoin doesn’t have fixed denominations like US dollars, and in particular, there is no special designation of “1 bitcoin.” Bitcoins are just transaction outputs, and in the current rules, they can have an arbitrary value with 8 decimal places of precision. The smallest possible value is 0.00000001 BTC (bitcoins), which is called 1 **Satoshi**.

The goal of the Bitcoin peer-to-peer network is to propagate all new transactions and new blocks to all the Bitcoin peer nodes. But the network is highly imperfect, and does a best-effort attempt to relay this information. The security of the system doesn’t come from the perfection of the peer-to-peer network. Instead, the security comes from the block chain and the consensus protocol that we devoted much of this chapter to studying.

When we say that a transaction is included in the block chain, what we really mean is that the transaction has achieved numerous confirmations. There’s no fixed number to how many confirmations are necessary before we are sufficiently convinced of its inclusion, but six is a commonly-used heuristic. The more confirmations a transaction has received, the more certain you can be that this transaction is part of the consensus chain. There will often be orphan blocks, or blocks that don’t make it into the consensus chain. There are a variety of reasons that could lead to a block being orphaned. The block may contain an invalid transaction, or a double-spend attempt. It could also just be a result of network latency. That is, two miners may simply end up finding new blocks within just a few seconds of each other. So both of these blocks were broadcast nearly simultaneously onto the network, and one of them will inevitably be orphaned.

Finally, we looked at hash puzzles and mining. Miners are special types of nodes that decide to compete in this game of creating new blocks. They’re rewarded for their effort in terms of both newly minted bitcoins (the new-block reward) and existing bitcoins (transaction fees), provided that other miners build upon their blocks. A subtle but crucial point: say that Alice and Bob are two different miners, and Alice has 100 times as much computing power as Bob. This does not mean that Alice will always win the race against Bob to find the next block. Instead, Alice and Bob have a probability ratio of finding the next block, in the proportion 100 to 1. In the long term, Bob will find, on average, one percent of the number of blocks that Alice finds.

We expect that miners will typically be somewhere close to the economic equilibrium in the sense that the expenditure that they incur in terms of hardware and electricity will be roughly equal to the rewards that they obtain. The reason is that if a miner is consistently making a loss, she will probably stop mining. On the other hand, and if mining is very profitable given typical hardware and electricity costs, then more mining hardware would enter the network. The increased hash rate would lead to an increase in the difficulty, and each miner's expected reward would drop.

This notion of distributed consensus permeates Bitcoin quite deeply. In a traditional currency, consensus does come into play to a certain limited extent. Specifically, there is a consensus process that determines the exchange rate of the currency. That is certainly true in Bitcoin as well; We need consensus around the value of Bitcoin. But in Bitcoin, additionally, we need consensus on the state of the ledger, which is what the block chain accomplishes. In other words, even the accounting of how many bitcoins you own is subject to consensus. When we say that Alice owns a certain amount or number of bitcoins, what we actually mean is that the Bitcoin peer-to-peer network, as recorded in the block chain, considers the sum total of all Alice's addresses to own that number of bitcoins. That is ultimate nature of truth in Bitcoin: ownership of bitcoins is nothing more than other nodes agreeing that a given party owns those bitcoins.

Finally, we need consensus about the rules of the system because occasionally, the rules of the system have to change. There are two types of changes to the rules of Bitcoin, known respectively as ***soft forks*** and ***hard forks***. We're going to defer this discussion of the differences to later chapters in which we will discuss them in detail.

***Getting a cryptocurrency off the ground.*** Another subtle concept is that of ***bootstrapping***. There is a tricky interplay between three different ideas in Bitcoin: the security of the block chain, the health of the mining ecosystem, and the value of the currency. We obviously want the block chain to be secure for Bitcoin to be a viable currency. For the block chain to be secure, an adversary must not be able to overwhelm the consensus process. This in turn means that an adversary cannot create a lot of mining nodes and take over 50 percent or more of the new block creation.

But when will that be true? A prerequisite is having a healthy mining ecosystem made up of largely honest, protocol-following nodes. But what's a prerequisite for that — when can we be sure that a lot of miners will put a lot of computing power into participating in this hash puzzle solving competition? Well, they're only going to do that if the exchange rate of Bitcoin is pretty high because the rewards that they receive are denominated in Bitcoins whereas their expenditure is in dollars. So the more the value of the currency goes up, the more incentivized these miners are going to be.

But what ensures a high and stable value of the currency? That can only happen if users in general have trust in the security of the block chain. If they believe that the network could be overwhelmed at any moment by an attacker, then Bitcoin is not going to have a lot of value as a currency. So you have this interlocking interdependence between the security of the block chain, a healthy mining ecosystem and the exchange rate.

Because of the cyclical nature of this three-way dependence, the existence of each of these is predicated on the existence of the others. When Bitcoin was first created, none of these three existed. There were no miners other than Nakamoto himself running the mining software. Bitcoin didn't have a lot of value as a currency. And the block chain was, in fact, insecure because there was not a lot of mining going on and anybody could have easily overwhelmed this process.

There's no simple explanation for how Bitcoin went from not having any of these properties to having all three of them. Media attention was part of the story — the more people hear about Bitcoin, the more they're going to get interested in mining. And the more they get interested in mining, the more confidence people will have in the security of the block chain because there's now more mining activity going on, and so forth. Incidentally, every new Altcoin that wants to succeed also has to somehow solve this problem of pulling itself up by its bootstraps.

***51-percent attack.*** Finally, let's consider what would happen if consensus failed and there was in fact a ***51-percent attacker*** who controls 51 percent or more of the mining power in the Bitcoin network. We'll consider a variety of possible attacks and see which ones can actually be carried out by such an attacker.

First of all, can this attacker steal coins from an existing address? As you may have guessed, the answer is no, because stealing from an existing address is not possible unless you subvert the cryptography. It's not enough to subvert the consensus process. This is not completely obvious. Let's say the 51 percent attacker creates an invalid block that contains an invalid transaction that represents stealing Bitcoins from an existing address that the attacker doesn't control and transferring them to his own address. The attacker can pretend that it's a valid transaction and keep building upon this block. The attacker can even succeed in making that the longest branch. But the other honest nodes are simply not going to accept this block with an invalid transaction and are going to keep mining based on the last valid block that they found in the network. So what will happen is that there will be what we call a fork in the chain.

Now imagine this from the point of view of the attacker trying to spend these invalid coins, and send them to some merchant Bob as payment for some goods or service. Bob is presumably running a Bitcoin node himself, and it will be an honest node. Bob's node will reject that branch as invalid because it contains an invalid transaction. It's invalid because the signatures didn't check out. So Bob's node will simply ignore the longest branch because it's an invalid branch. And because of that, subverting consensus is not enough. You have to subvert cryptography to steal bitcoins. So we conclude that this attack is not possible for a 51 percent attacker.

We should note that all this is only a thought experiment. If there were, in fact, actual signs of a 51 percent attack, what will probably happen is that the developers will notice this and react to it. They will update the Bitcoin software, and we might expect that the rules of the system, including the peer-to-peer network, might change in some form to make it more difficult for this attack to succeed. But we can't quite predict that. So we're working in a simplified model where a 51 percent attack happens, but other than that, there are no changes or tweaks to the rules of the system.

Let's consider another attack. Can the 51-percent attacker suppress some transactions? Let's say there is some user, Carol, whom the attacker really doesn't like. The attacker knows some of Carol's addresses, and wants to make sure that no coins belonging to any of those addresses can possibly be spent. Is that possible? Since he controls the consensus process of the block chain, the attacker can simply refuse to create any new blocks that contain transactions from one of Carol's addresses. The attacker can further refuse to build upon blocks that contain such transactions. However, he can't prevent these transactions from being broadcast to the peer-to-peer network because the network doesn't depend on the block chain, or on consensus, and we're assuming that the attacker doesn't fully control the network. The attacker cannot stop the transactions from reaching the majority of nodes, so even if the attack succeeds, it will at least be apparent that the attack is happening.

Can the attacker change the block reward? That is, can the attacker start pretending that the block reward is, instead of 25 Bitcoins, say 100 Bitcoins? This is a change to the rules of the system, and because the attacker doesn't control the copies of the Bitcoin software that all of the honest nodes are running, this is also not possible. This is similar to the reason why the attacker cannot include invalid transactions. Other nodes will simply not recognize the increase in the block reward, and the attacker will thus be unable to spend them.

Finally, can the attacker somehow destroy confidence in Bitcoin? Well, let's imagine what would happen. If there were a variety of double-spend attempts, situations in which nodes did not extend the longest valid branch, and other attempted attacks, then people are going to likely decide that Bitcoin is no longer acting as a decentralized ledger that they can trust. People will lose confidence in the currency, and we might expect that the exchange rate of Bitcoin will plummet. In fact, if it is known that there is a party that controls 51 percent of the hash power, then it's possible that people will lose confidence in Bitcoin even if the attacker is not necessarily trying to launch any attacks. So it is not only possible, but in fact likely, that a 51 percent attacker of any sort will destroy confidence in the currency. Indeed, this is the main practical threat if a 51 percent attack were ever to materialize. Considering the amount of expenditure that the adversary would have to put into attacking Bitcoin and achieving a 51 percent majority, none of the other attacks that we described really make sense from a financial point of view.

Hopefully, at this point you've obtained a really good understanding of how decentralization is achieved in Bitcoin. You should have a good command on how identities work in Bitcoin, how transactions are propagated and validated, the role of the peer-to-peer network in Bitcoin, how the block chain is used to achieve consensus, and how hash puzzles and mining work. These concepts provide a solid foundation and a good launching point for understanding a lot of the more subtle details and nuances of Bitcoin, which we're going to see in the coming chapters.

## Further reading

The Bitcoin whitepaper:

**Nakamoto, Satoshi. Bitcoin: A peer-to-peer electronic cash system. (2008)**

The original application of proof-of-work:

**Back, Adam. Hashcash-a denial of service counter-measure. (2002)**

The Paxos algorithm for consensus:

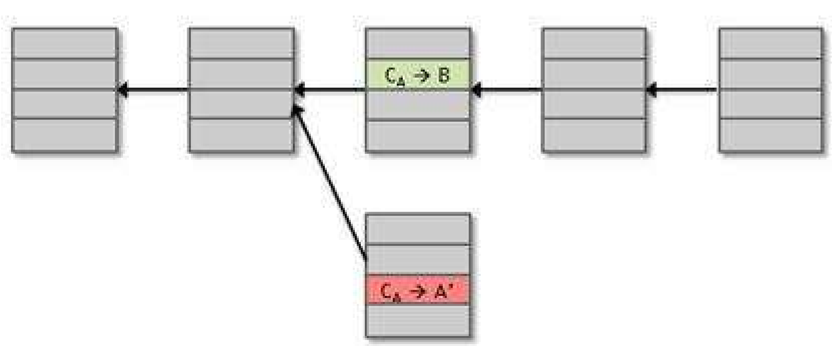
**Lamport, Leslie. Paxos made simple. ACM Sigact News 32.4 (2001): 18-25.**

## Exercises

1. Why do miners run "full nodes" that keep track of the entire block chain[2] whereas Bob the merchant can get away with a "lite node" that implements "simplified payment verification," needing to examine only the last few blocks?

2. If a malicious ISP completely controls a user's connections, can it launch a double-spend attack against the user? How much computational effort would this take?

3. Consider Bob the merchant deciding whether or not to accept the $C_A \rightarrow B$ transaction. What Bob is really interested in is whether or not the other chain will catch up. Why, then, does he simply check how many confirmations $C_A \rightarrow B$ has received, instead of computing the difference in length between the two chains?




[2] This only applies to "solo" miners who're not part of a mining pool, but we haven't discussed that yet.

4. Even when all nodes are honest, blocks will occasionally get orphaned: if two miners Minnie and Mynie discover blocks nearly simultaneously, neither will have time to hear about the other's block before broadcasting hers.

4a. What determines whose block will end up on the consensus branch?

4b. What factors affect the rate of orphan blocks? Can you derive a formula for the rate based on these parameters?

4c. Try to empirically measure this rate on the Bitcoin network.

4d. If Mynie hears about Minnie's block just before she's about to discover hers, does that mean she wasted her effort?

4e. Do all miners have their blocks orphaned at the same rate, or are some miners affected disproportionately?

5a. How can a miner establish an identity in a way that's hard to fake? (i.e., anyone can tell which blocks were mined by her.)

5b. If a miner misbehaves, can other miners "boycott" her by refusing to build on her blocks on an ongoing basis?

6a. Assuming that the total hash power of the network stays constant, what is the probability that a block will be found in the next 10 minutes?

6b. Suppose Bob the merchant wants to have a policy that orders will ship within *x* minutes after receipt of payment. What value of *x* should Bob choose so that with 99% confidence 6 blocks will be found within *x* minutes?

# Chapter 3: Mechanics of Bitcoin

This chapter is about the mechanics of Bitcoin. Whereas in the first two chapters, we've talked at a relatively high level, now we're going to delve into detail. We'll look at real data structures, real scripts, and try to learn the details and language of Bitcoin in a precise way to set up everything that we want to talk about in the rest of this book. This chapter will be challenging because a lot of details will be flying at you. You'll learn the specifics and the quirks that make Bitcoin what it is.

To recap where we left off last time, the Bitcoin consensus mechanism gives us an append-only ledger, a data structure that we can only write to. Once data is written to it, it's there forever. There's a decentralized protocol for establishing consensus about the value of that ledger, and there are miners who perform that protocol and validate transactions. Together they make sure that transactions are well formed, that they aren't already spent, and that the ledger and network can function as a currency. At the same time, we assumed that a currency existed to motivate these miners. In this chapter we'll look at the details of how we actually build that currency, to motivate the miners that make this whole process happen.

## 3.1 Bitcoin transactions

Let's start with transactions, Bitcoin's fundamental building block. We're going to use a simplified model of a ledger for the moment. Instead of blocks, let's suppose individual transactions are added to the ledger one at a time.

| |
|---|
| Create 25 coins and credit to Alice$_{\text{ASSERTED BY MINERS}}$ |
| Transfer 17 coins from Alice to Bob$_{\text{SIGNED(Alice)}}$ |
| Transfer 8 coins from Bob to Carol$_{\text{SIGNED(Bob)}}$ |
| Transfer 5 coins from Carol to Alice$_{\text{SIGNED(Carol)}}$ |
| Transfer 15 coins from Alice to David$_{\text{SIGNED(Alice)}}$ |

***Figure 3.1*** an account-based ledger

How can we build a currency on top of such a ledger? The first model you might think of, which is actually the mental model many people have for how Bitcoin works, is that you have an account-based system. You can add some transactions that create new coins and credit them to somebody. And then later you can transfer them. A transaction would say something like "we're moving 17 coins from Alice to Bob", and it will be signed by Alice. That's all the information about the transaction that's contained in the ledger. In Figure 3.1, after Alice receives 25 coins in the first transaction and then transfers 17 coins to Bob in the second, she'd have 8 Bitcoins left in her account.

The downside to this way of doing things is that anyone who wants to determine if a transaction is valid will have to keep track of these account balances. Take another look at Figure 3.1. Does Alice have the 15 coins that she's trying to transfer to David? To figure this out, you'd have to look backwards in time forever to see every transaction affecting Alice, and whether or not her net balance at the time that she tries to transfer 15 coins to David is greater than 15 coins. Of course we can make this a little bit more efficient with some data structures that track Alice's balance after each transaction. But that's going to require a lot of extra housekeeping besides the ledger itself.

Because of these downsides, Bitcoin doesn't use an account-based model. Instead, Bitcoin uses a ledger that just keeps track of transactions similar to ScroogeCoin in Chapter 1.

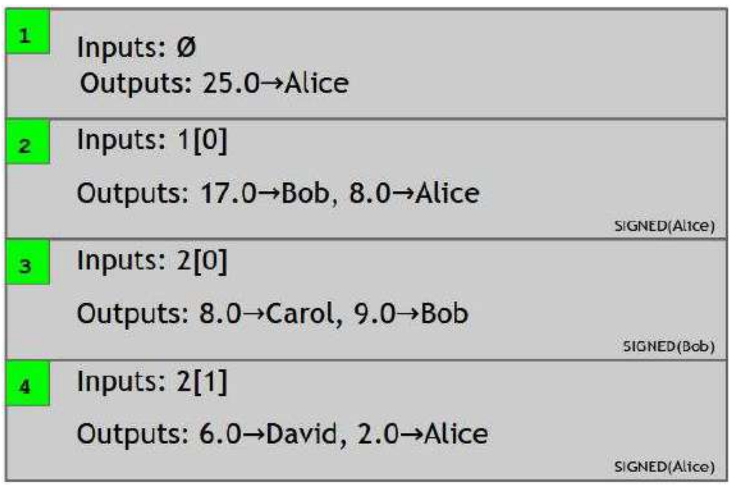



***Figure 3.2*** a transaction-based ledger, which is very close to Bitcoin

Transactions specify a number of inputs and a number of outputs (recall PayCoins in ScroogeCoin). You can think of the inputs as coins being consumed (created in a previous transaction) and the outputs as coins being created. For transactions in which new currency is being minted, there are no coins being consumed (recall CreateCoins in ScroogeCoin). Each transaction has a unique identifier. Outputs are indexed beginning with 0, so we will refer to the first output as "output 0".

Let's now work our way through Figure 3.2. Transaction 1 has no inputs because this transaction is creating new coins, and it has an output of 25 coins going to Alice. Also, since this is a transaction where new coins are being created, no signature is required. Now let's say that Alice wants to send some of those coins over to Bob. To do so, she creates a new transaction, transaction 2 in our example. In the transaction, she has to explicitly refer to the previous transaction where these coins are coming from. Here, she refers to output 0 of transaction 1 (indeed the only output of transaction 1), which assigned 25 bitcoins to Alice. She also must specify the output addresses in the transaction.

In this example, Alice specifies two outputs, 17 coins to Bob, and 8 coins to Alice. And, of course, this whole thing is signed by Alice, so that we know that Alice actually authorizes this transaction.

***Change addresses.*** Why does Alice have to send money to herself in this example? Just as coins in ScroogeCoin are immutable, in Bitcoin, the entirety of a transaction output must be consumed by another transaction, or none of it. Alice only wants to pay 17 bitcoins to Bob, but the output that she owns is worth 25 bitcoins. So she needs to create a new output where 8 bitcoins are sent back to herself. It could be a different address from the one that owned the 25 bitcoins, but it would have to be owned by her. This is called a ***change address***.

***Efficient verification.*** When a new transaction is added to the ledger, how easy is it to check if it is valid? In this example, we need to look up the transaction output that Alice referenced, make sure that it has a value of 25 bitcoins, and that it hasn't already been spent. Looking up the transaction output is easy since we're using hash pointers. To ensure it hasn't been spent, we need to scan the block chain between the referenced transaction and the latest block. We don't need to go all the way back to the beginning of the block chain, and it doesn't require keeping any additional data structures (although, as we'll see, additional data structures will speed things up).

***Consolidating funds.*** As in ScroogeCoin, since transactions can have many inputs and many outputs, splitting and merging value is easy. For example, say Bob received money in two different transactions — 17 bitcoins in one, and 2 in another. Bob might say, I'd like to have one transaction I can spend later where I have all 19 bitcoins. That's easy — he creates a transaction with the two inputs and one output, with the output address being one that he owns. That lets him consolidate those two transactions.

***Joint payments.*** Similarly, joint payments are also easy to do. Say Carol and Bob both want to pay David. They can create a transaction with two inputs and one output, but with the two inputs owned by two different people. And the only difference from the previous example is that since the two outputs from prior transactions that are being claimed here are from different addresses, the transaction will need two separate signatures — one by Carol and one by Bob.

***Transaction syntax.*** Conceptually that's really all there is to a Bitcoin transaction. Now let's see how it's represented at a low level in Bitcoin. Ultimately, every data structure that's sent on the network is a string of bits. What's shown in Figure 3.3 is very low-level, but this further gets compiled down to a compact binary format that's not human-readable.


***Figure 3.3*** **An actual Bitcoin transaction.**

As you can see in Figure 3.3, there are three parts to a transaction: some metadata, a series of inputs, and a series of outputs.

- ***Metadata***. There's some housekeeping information — the size of the transaction, the number of inputs, and the number of outputs. There's the hash of the entire transaction which serves as a unique ID for the transaction. That's what allows us to use hash pointers to reference transactions. Finally there's a "lock_time" field, which we'll come back to later.
- ***Inputs.*** The transaction inputs form an array, and each input has the same form. An input specifies a previous transaction, so it contains a hash of that transaction, which acts as a hash pointer to it. The input also contains the index of the previous transaction's outputs that's being claimed. And then there's a signature. Remember that we have to sign to show that we actually have the ability to claim those previous transaction outputs.
- ***Outputs.*** The outputs are again an array. Each output has just two fields. They each have a value, and the sum of all the output values has to be less than or equal to the sum of all the input values. If the sum of the output values is less than the sum of the input values, the difference is a transaction fee to the miner who publishes this transaction.

  And then there's a funny line that looks like what we want to be the recipient address. Each output is supposed to go to a specific public key, and indeed there is something in that field that looks like it's the hash of a public key. But there's also some other stuff that looks like a set of commands. Indeed, this field is a script, and we'll discuss this presently.

## 3.2 Bitcoin Scripts

Each transaction output doesn't just specify a public key. It actually specifies a script. What is a script, and why do we use scripts? In this section we'll study the Bitcoin scripting language and understand why a script is used instead of simply assigning a public key.

The most common type of transaction in Bitcoin is to redeem a previous transaction output by signing with the correct key. In this case, we want the transaction output to say, "this can be redeemed by a signature from the owner of address X." Recall that an address is a hash of a public key. So merely specifying the address X doesn't tell us what the public key is, and doesn't give us a way to check the signature! So instead the transaction output must say: "this can be redeemed by a public key that hashes to X, along with a signature from the owner of that public key." As we'll see, this is exactly what the most common type of script in Bitcoin says.

```
OP_DUP
OP_HASH160
69e02e18...
OP_EQUALVERIFY
OP_CHECKSIG
```

***Figure 3.4.*** an example Pay-to-PubkeyHash script, the most common type of output script in Bitcoin

But what happens to this script? Who runs it, and how exactly does this sequence of instructions enforce the above statement? The secret is that the inputs also contain scripts instead of signatures. To validate that a transaction redeems a previous transaction output correctly, we combine the new transaction's input script and the earlier transaction's output script. We simply concatenate them, and the resulting script must run successfully in order for the transaction to be valid. These two scripts are called ***scriptPubKey*** and ***scriptSig*** because in the simplest case, the output script just specifies a public key (or an address to which the public key hashes), and the input script specifies a signature with that public key. The combined script can be seen in Figure 3.5.

***Bitcoin scripting language.*** The scripting language was built specifically for Bitcoin, and is just called 'Script' or the Bitcoin scripting language. It has many similarities to a language called Forth, which is an old, simple, stack-based, programming language. But you don't need to understand Forth to understand Bitcoin scripting. The key design goals for Script were to have something simple and compact, yet with native support for cryptographic operations. So, for example, there are special-purpose instructions to compute hash functions and to compute and verify signatures.

The scripting language is stack-based. This means that every instruction is executed exactly once, in a linear manner. In particular, there are no loops in the Bitcoin scripting language. So the number of instructions in the script gives us an upper bound on how long it might take to run and how much memory it could use. The language is not Turing-complete, which means that it doesn't have the ability to compute arbitrarily powerful functions. And this is by design — miners have to run these scripts, which are submitted by arbitrary participants in the network. We don't want to give them the power to submit a script that might have an infinite loop.

```
<sig>
<pubKey>
-------------
OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG
```

***Figure 3.5.*** To check if a transaction correctly redeems an output, we create a combined script by appending the scriptPubKey of the referenced output transaction (bottom) to the scriptSig of the redeeming transaction (top). Notice that <pubKeyHash?> contains a '?'. We use this notation to indicate that we will later check to confirm that this is equal to the hash of the public key provided in the redeeming script.

There are only two possible outcomes when a Bitcoin script is executed. It either executes successfully with no errors, in which case the transaction is valid. Or, if there's any error while the script is executing, the whole transaction will be invalid and shouldn't be accepted into the block chain.

The Bitcoin scripting language is very small. There's only room for 256 instructions, because each one is represented by one byte. Of those 256, 15 are currently disabled, and 75 are reserved. The reserved instruction codes haven't been assigned any specific meaning yet, but might be instructions that are added later in time.

Many of the basic instructions are those you'd expect to be in any programming language. There's basic arithmetic, basic logic — like 'if' and 'then' — , throwing errors, not throwing errors, and returning early. Finally, there are crypto instructions which include hash functions, instructions for signature verification, as well as a special and important instruction called CHECKMULTISIG that lets you check multiple signatures with one instruction. Figure 3.6 lists some of the most common instructions in the Bitcoin scripting language.

The CHECKMULTISIG instruction requires specifying *n* public keys, and a parameter *t*, for a threshold. For this instruction to execute validly, there have to be at least *t* signatures from *t* out of *n* of those public keys that are valid. We'll show some examples of what you'd use multisignatures for in the next section, but it should be immediately clear this is quite a powerful primitive. We can express in a compact way the concept that *t* out of *n* specified entities must sign in order for the transaction to be valid.

Incidentally, there's a bug in the multisignature implementation, and it's been there all along. The CHECKMULTISIG instruction pops an extra data value off the stack and ignores it. This is just a quirk of the Bitcoin language and one has to deal with it by putting an extra dummy variable onto the stack. The bug was in the original implementation, and the costs of fixing it are much higher than the damage it causes, as we'll see later in Section 3.5. At this point, this bug is considered a feature in Bitcoin, in that it's not going away.

| | |
|---|---|
| **OP_DUP** | Duplicates the top item on the stack |
| **OP_HASH160** | Hashes twice: first using SHA-256 and then RIPEMD-160 |
| **OP_EQUALVERIFY** | Returns true if the inputs are equal. Returns false and marks the transaction as invalid if they are unequal |
| **OP_CHECKSIG** | Checks that the input signature is a valid signature using the input public key for the hash of the current transaction |
| **OP_CHECKMULTISIG** | Checks that the *k* signatures on the transaction are valid signatures from *k* of the specified public keys. |

***Figure 3.6*** a list of common Script instructions and their functionality.

***Executing a script.*** To execute a script in a stack-based programming language, all we'll need is a stack that we can push data to and pop data from. We won't need any other memory or variables. That's what makes it so computationally simple. There are two types of instructions: data instructions and opcodes. When a data instruction appears in a script, that data is simply pushed onto the top of the stack. Opcodes, on the other hand, perform some function, often taking as input data that is on top of the stack.

Now let's look at how the Bitcoin script in Figure 3.5 is executed. Refer to Figure 3.7, where we show the state of the stack after each instruction. The first two instructions in this script are data instructions — the signature and the public key used to verify that signature — specified in the scriptSig component of a transaction input in the redeeming transaction. As we mentioned, when we see a data instruction, we just push it onto the stack. The rest of the script was specified in the scriptPubKey component of a transaction output in the referenced transaction.

First we have the duplicate instruction, OP_DUP, so we just push a copy of the public key onto the top of the stack. The next instruction is OP_HASH160, which tells us to pop the top value, compute its cryptographic hash, and push the result onto the top of the stack. When this instruction finishes executing, we will have replaced the public key on the top of the stack with its hash.

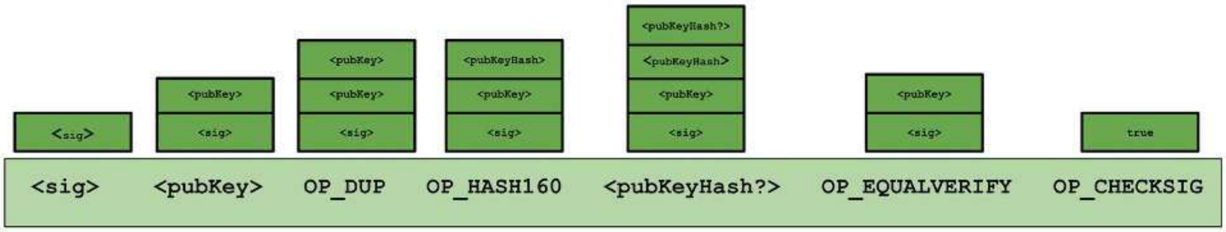



***Figure 3.7*** **Execution of a Bitcoin script.** On the bottom, we show the instruction in the script. Data instructions are denoted with surrounding angle brackets, whereas opcodes begin with "OP_". On the top, we show the stack just after that instruction has been executed.

Next, we're going to do one more push of data onto the stack. Recall that this data was specified by the sender of the referenced transaction. It is the hash of a public key that the sender specified; the corresponding private key must be used to generate the signature to redeem these coins. At this point, there are two values at the top of the stack. There is the hash of the public key, as specified by the sender, and the hash of the public key that was used by the recipient when trying to claim the coins.

At this point we'll run the EQUALVERIFY command, which checks that the two values at the top of the stack are equal. If they aren't, an error will be thrown, and the script will stop executing. But in our example, we'll assume that they're equal, that is, that the recipient of the coins used the correct public key. That instruction will consume those two data items that are at the top of the stack, And the stack now contains two items — a signature and the public key.

We've already checked that this public key is in fact the public key that the referenced transaction specified, and now we have to check if the signature is valid. This is a great example of where the Bitcoin scripting language is built with cryptography in mind. Even though it's a fairly simple language in terms of logic, there are some quite powerful instructions in there, like this "OP_CHECKSIG" instruction. This single instruction pops those two values off of the stack, and does the entire signature verification in one go.

But what is this a signature of? What is the input to the signature function? It turns out there's only one thing you can sign in Bitcoin — an entire transaction. So the "CHECKSIG" instruction pops the two values, the public key and signature, off the stack, and verifies that is a valid signature for the entire transaction using that public key. Now we've executed every instruction in the script, and there's nothing left on the stack. Provided there weren't any errors, the output of this script will simply be **true** indicating that the transaction is valid.

***What's used in practice.*** In theory, Script lets us specify, in some sense, arbitrary conditions that must be met in order to spend coins. But, as of today, this flexibility isn't used very heavily. If we look at the scripts that have actually been used in the history of Bitcoin so far, the vast majority, 99.9 percent, are exactly the same script, which is in fact the script that we used in our example. As we saw, this script just specifies one public key and requires a signature for that public key in order to spend the coins. There are a few other instructions that do get some use. MULTISIG gets used a little bit as does a special type of script called Pay-to-Script-Hash which we'll discuss shortly. But other than that, there hasn't been much diversity in terms of what scripts get used. This is because Bitcoin nodes, by default, have a whitelist of standard scripts, and they refuse to accept scripts that are not on the list. This doesn't mean that those scripts can't be used at all; it just makes them harder to use. In fact this distinction is a very subtle point which we'll return to in a bit when we talk about the Bitcoin peer-to-peer network.

***Proof of burn.*** A proof-of-burn is a script that can never be redeemed. Sending coins to a proof-of-burn script establishes that they have been destroyed since there's no possible way for them to be spent. One use of proof-of-burn is to bootstrap an alternative to Bitcoin by forcing people to destroy Bitcoin in order to gain coins in the new system. We'll discuss this in more detail in Chapter 10. Proof-of-burn is quite simple to implement: the OP_RETURN opcode throws an error if it's ever reached. No matter what values you put before OP_RETURN, that instruction will get executed eventually, in which case this script will return false.

Because the error is thrown, the data in the script that comes after OP_RETURN will not be processed. So this is an opportunity for people to put arbitrary data in a script, and hence into the block chain. If, for some reason, you want to write your name, or if you want to timestamp and prove that you knew some data at a specific time, you can create a very low value Bitcoin transaction. You can destroy a very small amount of currency, but you get to write whatever you want into the block chain, which should be kept around forever.

***Pay-to-script-hash.*** One consequence of the way that Bitcoin scripts works is that the sender of coins has to specify the script exactly. But this can sometimes be quite a strange way of doing things. Say, for example, you're a consumer shopping online, and you're about to order something. And you say, "Alright, I'm ready to pay. Tell me the address to which I should send my coins." Now, say that the company that you're ordering from is using MULTISIG addresses. Then, since the one spending the coins has to specify this, the retailer will have to come back and say, "Oh, well, we're doing something fancy now. We're using MULTISIG. We're going to ask you to send the coins to some complicated script." You might say, "I don't know how to do that. That's too complicated. As a consumer, I just want to send to a simple address."

Bitcoin has a clever solution to this problem, and it applies to not just multi-sig addresses but to any complicated condition governing when coins can be spent. Instead of telling the sender "send your coins to the hash of this public key", the receiver can instead tell the sender "send your coins to the hash of this *script*. Impose the condition that to redeem those coins, it is necessary to reveal the script that has the given hash, and further, provide data that will make the script evaluate to true." The sender achieves this by using the Pay-to-script-hash (P2SH) transaction type, which has the above semantics.

Specifically, the P2SH script simply hashes the top value on the stack, checks if it matches the provided hash value, then executes a special second step of validation: that top data value from the stack is reinterpreted as a sequence of instructions, and executed a second time as a script, with the rest of the stack as input.

Getting support for P2SH was quite complicated since it wasn't part of Bitcoin's initial design specification. It was added after the fact. This is probably the most notable feature that's been added to Bitcoin that wasn't there in the original specification. And it solves a couple of important problems. It removes complexity from the sender, so the recipient can just specify a hash that the sender sends money to. In our example above, Alice need not worry that Bob is using multisig; she just sends to Bob's P2SH address, and it is Bob's responsibility to specify the fancy script when he wants to redeem the coins.

P2SH also has a nice efficiency gain. Miners have to track the set of output scripts that haven't been redeemed yet, and with P2SH outputs, the output scripts are now much smaller as they only specify a hash. All of the complexity is pushed to the input scripts.

## 3.3 Applications of Bitcoin scripts

Now that we understand how Bitcoin scripts work, let's take a look at some of the powerful applications that can be realized with this scripting language. It turns out we can do many neat things that will justify the complexity of having the scripting language instead of just specifying public keys.

***Escrow transactions.*** Say Alice and Bob want to do business with each other — Alice wants to pay Bob in Bitcoin for Bob to send some physical goods to Alice. The problem though is that Alice doesn't want to pay until after she's received the goods, but Bob doesn't want to send the goods until after he has been paid. What can we do about that? A nice solution in Bitcoin that's been used in practice is to introduce a third party and do an escrow transaction.

Escrow transactions can be implemented quite simply using MULTISIG. Alice doesn't send the money directly to Bob, but instead creates a MULTISIG transaction that requires two of three people to sign in order to redeem the coins. And those three people are going to be Alice, Bob, and some third party arbitrator, Judy, who will come into play in case there's any dispute. So Alice creates a 2-of-3 MULTISIG transaction that sends some coins she owns and specifies that they can be spent if any two of Alice, Bob, and Judy sign. This transaction is included in the block chain, and at this point, these coins are held in escrow between Alice, Bob, and Judy, such that any two of them can specify where the coins should go. At this point, Bob is convinced that it's safe to send the goods over to Alice, so he'll mail them or deliver them physically. Now in the normal case, Alice and Bob are both honest. So, Bob will send over the goods that Alice is expecting, and when Alice receives the goods, Alice and Bob both sign a transaction redeeming the funds from escrow, and sending them to Bob. Notice that in this case where both Alice and Bob are honest, Judy never had to get involved at all. There was no dispute, and Alice's and Bob's signatures met the 2-of-3 requirement of the MULTISIG transaction. So in the normal case, this isn't that much less efficient than Alice just sending Bob the money. It requires just one extra transaction on the block chain.

But what would have happened if Bob didn't actually send the goods or they got lost in the mail? Or perhaps the goods were different than what Alice ordered? Alice now doesn't want to pay Bob because she thinks that she got cheated, and she wants to get her money back. So Alice is definitely not going to sign a transaction that releases the money to Bob. But Bob also may deny any wrongdoing and refuse to sign a transaction that releases the money back to Alice. This is where Judy needs to get involved. Judy's going to have to decide which of these two people deserves the money. If Judy decides that Bob cheated, Judy will be willing to sign a transaction along with Alice, sending the money from escrow back to Alice. Alice's and Judy's signatures meet the 2-of-3 requirement of the MULTISIG transaction, and Alice will get her money back. And, of course, if Judy thinks that Alice is at fault here, and Alice is simply refusing to pay when she should, Judy can sign a transaction along with Bob, sending the money to Bob. So Judy decides between the two possible outcomes. But the nice thing is that she won't have to be involved unless there's a dispute.

***Green addresses.*** Another cool application is what are called green addresses. Say Alice wants to pay Bob, and Bob's offline. Since he's offline, Bob can't go and look at the block chain to see if a transaction that Alice is sending is actually there. It's also possible that Bob is online, but doesn't have the time to go and look at the block chain and wait for the transactions to be confirmed. Remember that normally we want a transaction to be in the block chain and be confirmed by six blocks, which takes up to an hour, before we trust that it's really in the block chain. But for some merchandise such as food, Bob can't wait an hour before delivering. If Bob were a street vendor selling hot dogs, it's unlikely that Alice would wait around for an hour to receive her food. Or maybe Bob for some other reason doesn't have any connection to the internet at all, and is thus not going to be able to check the block chain.

To solve this problem of being able to send money using Bitcoin without the recipient being able to access the block chain, we have to introduce another third party, which we'll call the bank (in practice it could be an exchange or any other financial intermediary). Alice is going to talk to her bank, and say, "Hey, it's me, Alice. I'm your loyal customer. Here's my card or my identification. And I'd really like to pay Bob here, could you help me out?" And the bank will say, "Sure. I'm going to deduct some money out of your account. And draw up a transaction from one of my green addresses over to Bob."

So notice that this money is coming directly from the bank to Bob. Some of the money, of course, might be in a change address going back to the bank. But essentially, the bank is paying Bob here from a bank-controlled address, which we call a green address. Moreover, the bank guarantees that it will not double-spend this money. So as soon as Bob sees that this transaction is signed by the bank, if he trusts the bank's guarantee not to double-spend the money, he can accept that that money will eventually be his when it's confirmed in the block chain.

Notice that this is not a Bitcoin-enforced guarantee. This is a real-world guarantee, and in order for this system to work, Bob has to trust that the bank, in the real world, cares about their reputation, and won't double-spend for that reason. And the bank will be able to say, "You can look at my history. I've been using this green address for a long time, and I've never double spent. Therefore I'm very unlikely to do so in the future." Thus Bob no longer has to trust Alice, whom he may know nothing about. Instead, he places his trust in the bank that they will not double-spend the money that they sent him.

Of course, if the bank ever does double-spend, people will stop trusting its green address(es). In fact, the two most prominent online services that implemented green addresses were Instawallet and Mt. Gox, and both ended up collapsing. Today green addresses aren't used very much. When the idea was first proposed, it generated much excitement as a way to do payments more quickly and without accessing the block chain. Now, however, people have become quite nervous about the idea and are worried that it puts too much trust in the bank.

***Efficient micro-payments.*** A third example of Bitcoin scripts is a way to do efficient micro-payments. Say that Alice is a customer who wants to continually pay Bob small amounts of money for some service that Bob provides. For example, Bob may be Alice's wireless service provider, and requires her to pay a small fee for every minute that she talks on her phone.

Creating a Bitcoin transaction for every minute that Alice speaks on the phone won't work. That will create too many transactions, and the transaction fees add up. If the value of each one of these transactions is on the order of what the transaction fees are, Alice is going to be paying quite a high cost to do this.

What we'd like is to be able to combine all these small payments into one big payment at the end. It turns out that there's a neat way to do this. We start with a MULTISIG transaction that pays the maximum amount Alice would ever need to spend to an output requiring both Alice and Bob to sign to release the coins. Now, after the first minute that Alice has used the service, or the first time Alice needs to make a micropayment, she signs a transaction spending those coins that were sent to the MULTISIG address, sending one unit of payment to Bob and returning the rest to Alice. After the next minute of using the service, Alice signs another transaction, this time paying two units to Bob and sending the rest to herself. Notice these are signed only by Alice, and haven't been signed by Bob yet, nor are they being published to the block chain. Alice will keep sending these transactions to Bob every minute that she uses the service. Eventually, Alice will finish using the service, and tells Bob, "I'm done, please cut off my service." At this point Alice will stop signing additional transactions. Upon hearing this, Bob will say "Great. I'll disconnect your service, and I'll take that last transaction that you sent me, sign it, and publish that to the block chain."

Since each transaction was paying Bob a little bit more, and Alice a little bit less, the final transaction that Bob redeems pays him in full for the service that he provided and returns the rest of the money to Alice. All those transactions that Alice signed along the way won't make it to the block chain. Bob doesn't have to sign them. They'll just get discarded.

Technically all of these transactions are double-spends. So unlike the case with green addresses where we were specifically trying to avoid double-spends, with a strong guarantee, with this micro-payment protocol, we're actually generating a huge amount of potential double-spends. In practice, however, if both parties are operating normally, Bob will never sign any transaction but the last one, in which case the block chain won't actually see any attempt at a double-spend.

There's one other tricky detail: what if Bob never signs the last transaction? He may just say, "I'm happy to let the coins sit there in escrow forever," in which case, maybe the coins won't move, but Alice will lose the full value that she paid at the beginning. There's a very clever way to avoid this problem using a feature that we mentioned briefly earlier, and will explain now.

***Lock time.*** To avoid this problem, before the micro-payment protocol can even start, Alice and Bob will both sign a transaction which refunds all of Alice's money back to her, but the refund is "locked" until some time in the future. So after Alice signs, but before she broadcasts, the first MULTISIG transaction that puts her funds into escrow, she'll want to get this refund transaction from Bob and hold on to it. That guarantees that if she makes it to time *t* and Bob hasn't signed any of the small transactions that Alice has sent, Alice can publish this transaction which refunds all of the money directly to her.

What does it mean that it's locked until time *t*? Recall when we looked at the metadata in Bitcoin transactions, that there was this lock_time parameter, which we had left unexplained. The way it works is that if you specify any value other than zero for the lock time, it tells miners not to publish the transaction until the specified lock time. The transaction will be invalid before either a specific block number, or a specific point in time, based on the timestamps that are put into blocks. So this is a way of preparing a transaction that can only be spent in the future if it isn't already spent by then. It works quite nicely in the micro-payment protocol as a safety valve for Alice to know that if Bob never signs, eventually she'll be able to get her money back.

Hopefully, these examples have shown you that we can do some neat stuff with Bitcoin scripts. We discussed three simple and practical examples, but there are many others that have been researched. One of them is multi-player lotteries, a very complicated multi-step protocol with lots of transactions having different lock times and escrows in case people cheat. There are also some neat protocols that utilize the scripting language to allow different people to get their coins together and mix them, so that it's harder to trace who owns which coin. We'll see that in detail in Chapter 6.

***Smart contracts.*** The general term for contracts like the ones we saw in this section is smart contracts. These are contracts for which we have some degree of technical enforcement in Bitcoin, whereas traditionally they are enforced through laws or courts of arbitration. It's a really cool feature of Bitcoin that we can use scripts, miners, and transaction validation to realize the escrow protocol or the micro-payment protocol without needing a centralized authority.

Research into smart contracts goes far beyond the applications that we saw in this section. There are many types of smart contracts which people would like to be able to enforce but which aren't supported by the Bitcoin scripting language today. Or at least, nobody has come up with a creative way to implement them. As we saw, with a bit of creativity you can do quite a lot with the Bitcoin script as it currently stands.

## 3.4 Bitcoin blocks

So far in this chapter we've looked at how individual transactions are constructed and redeemed. But as we saw in chapter 2, transactions are grouped together into blocks. Why is this? Basically, it's an optimization. If miners had to come to consensus on each transaction individually, the rate at which new transactions could be accepted by the system would be much lower. Also, a hash chain of blocks is much shorter than a hash chain of transactions would be, since a large number of transactions can be put into each block. This will make it much more efficient to verify the block chain data structure.

The block chain is a clever combination of two different hash-based data structures. The first is a hash chain of blocks. Each block has a block header, a hash pointer to some transaction data, and a hash pointer to the previous block in the sequence. The second data structure is a per-block tree of all of the transactions that are included in that block. This is a Merkle tree and allows us to have a digest of all the transactions in the block in an efficient way. As we saw in Chapter 1, to prove that a transaction is included in a specific block, we can provide a path through the tree whose length is logarithmic in the number of transactions in the block. To recap, a block consists of header data followed by a list of transactions arranged in a tree structure.

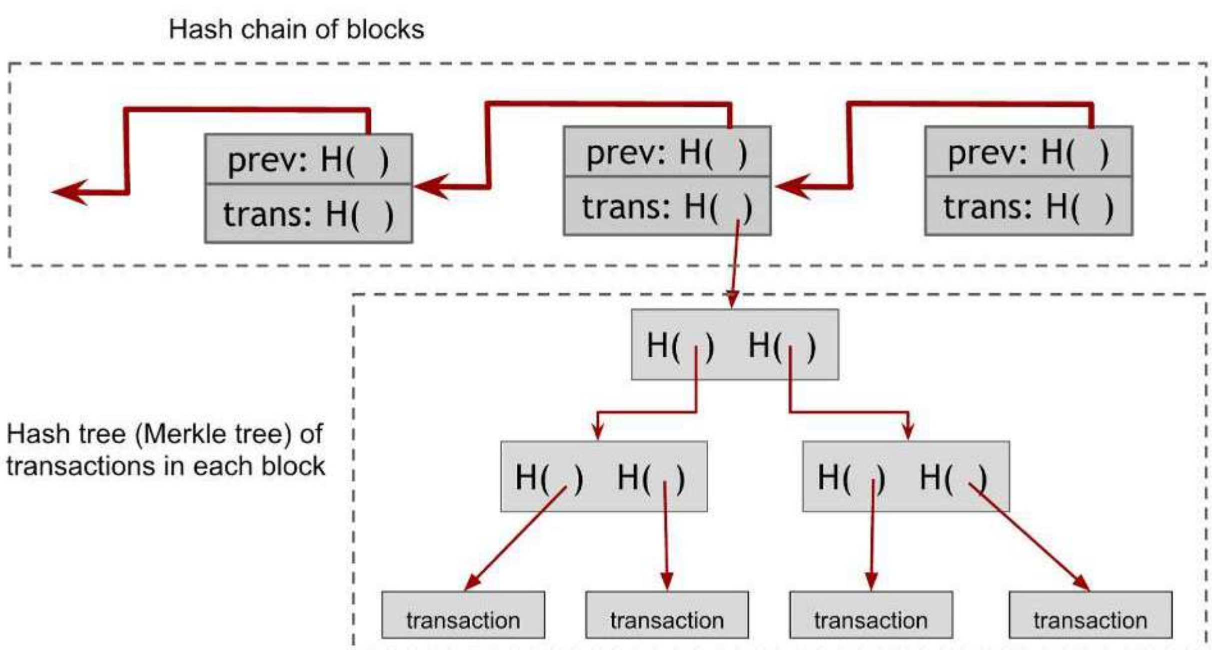



***Figure 3.8.*** The Bitcoin block chain contains two different hash structures. The first is a hash chain of blocks that links the different blocks to one another. The second is internal to each block and is a Merkle Tree of transactions within the blocks.

The header mostly contains information related to the mining puzzle which we briefly discussed in the previous chapter and will revisit in Chapter 5. Recall that the hash of the block header has to start with a large number of zeros for the block to be valid. The header also contains a “nonce” that miners can change, a time stamp, and “bits”, which is an indication of how difficult this block was to find. The header is the only thing that’s hashed during mining. So to verify a chain of blocks, all we need to do is look at the headers. The only transaction data that’s included in the header is the root of the transaction tree — the “mrkl_root” field.

```
"in":[
      {
        "prev_out":{
          "hash":"000000.....0000000",
          "n":4294967295
        },
        "coinbase":"..."
      },
    ]
"out":[
      {
        "value":"25.03371419",
        "scriptPubKey":"OPDUP OPHASH160 ... ”
      }
     ]
```

***Figure 3.9.*** **coinbase transaction.** A coinbase transaction creates new coins. It does not redeem a previous output, and it has a null hash pointer indicating this. It has a coinbase parameter which can contain arbitrary data. The value of the coinbase transaction is the block reward plus all of the transaction fees included in this block.

Another interesting thing about blocks is that they have a special transaction in the Merkle tree called the “coinbase” transaction. This is analogous to CreateCoins in Scroogecoin. So this is where the creation of new coins in Bitcoin happens. It mostly looks like a normal transaction but with several differences: (1) it always has a single input and a single output, (2) the input doesn’t redeem a previous output and thus contains a null hash pointer, since it is minting new bitcoins and not spending existing coins, (3) the value of the output is currently a little over 25 Bitcoins. The output value is the miner’s revenue from the block. It consists of two components: a flat mining reward, which is set by the system and which halves every 210,000 blocks (about 4 years), and the transaction fees collected from every transaction included in the block. (4) There is a special “coinbase” parameter, which is completely arbitrary — miners can put whatever they want in there.

Famously, in the very first block ever mined in Bitcoin, the coinbase parameter referenced a story in the Times of London newspaper involving the Chancellor bailing out banks. This has been interpreted as political commentary on the motivation for starting Bitcoin. It also serves as a sort of proof that the first block was mined after the story came out on January 3, 2009. One way in which the coinbase parameter has since been used is to signal support by miners for different new features.

To get a better feel for the block format and transaction format, the best way is to explore the block chain yourself. There are many websites that make this data accessible, such as [blockchain.info](blockchain.info). You can look at the graph of transactions, see which transactions redeem which other transactions, look for transactions with complicated scripts, and look at the block structure and see how blocks refer to other blocks. Since the block chain is a public data structure, developers have built pretty wrappers to explore it graphically.

## 3.5 The Bitcoin network

So far we've been talking about the ability for participants to publish a transaction and get it into the block chain as if this happens by magic. In fact this happens through the Bitcoin network. It's a peer-to-peer network, and it inherits many ideas from peer-to-peer networks that have been proposed for all sorts of other purposes. In the Bitcoin network, all nodes are equal. There is no hierarchy, and there are no special nodes or master nodes. It runs over TCP and has a random topology, where each node peers with other random nodes. New nodes can join at any time. In fact, you can download a Bitcoin client today, spin up your computer as a node, and it will have equal rights and capabilities as every other node on the Bitcoin network.

The network changes over time and is quite dynamic due to nodes entering and leaving. There isn't an explicit way to leave the network. Instead, if a node hasn't been heard from in a while — three hours is the duration that's hardcoded into the common clients — other nodes start to forget it. In this way, the network gracefully handles nodes going offline.

Recall that nodes connect to random peers and there is no geographic topology of any sort. Now say you launch a new node and want to join the network. You start with a simple message to one node that you know about. This is usually called your ***seed node***, and there are a few different ways you can look up lists of seed nodes to try connecting to. You send a special message, saying, "Tell me the addresses of all the other nodes in the network that you know about." You can repeat the process with the new nodes you learn about as many times as you want. Then you can choose which ones to peer with, and you'll be a fully functioning member of the Bitcoin network. There are several steps that involve randomness, and the ideal outcome is that you're peered with a random set of nodes. To join the network,  all you need to know is how to contact one node that's already on the network.

What is the network good for? To maintain the block chain, of course. So to publish a transaction, we want to get the entire network to hear about it. This happens through a simple ***flooding*** algorithm, sometimes called a ***gossip protocol***. If Alice wants to pay Bob some money, her client creates and her node sends this transaction to all the nodes it's peered with. Each of those nodes executes a series of checks to determine whether or not to accept and relay the transaction. If the checks pass, the node in turn sends it to all of its peer nodes. Nodes that hear about a transaction put it in a pool of transactions which they've heard about but that aren't on the block chain yet. If a node hears about a transaction that's already in its pool, it doesn't further broadcast it. This ensures that the flooding protocol terminates and transactions don't loop around the network forever. Remember that every transaction is identified uniquely by its hash, so it's easy to look up a transaction in the pool.

When nodes hear about a new transaction, how do they decide whether or not they should propagate it? There are four checks. The first and most important check is transaction validation — the transaction must be valid with the current block chain. Nodes run the script for each previous output being redeemed and ensure that the scripts return true. Second, they check that the outputs being redeemed here haven't already been spent. Third, they won't relay an already-seen transaction, as mentioned earlier. Fourth, by default, nodes will only accept and relay "standard" scripts based on a small whitelist of scripts.

All these checks are just sanity checks. Well-behaving nodes all implement these to try to keep the network healthy and running properly, but there's no rule that says that nodes have to follow these specific steps. Since it's a peer-to-peer network, and anybody can join, there's always the possibility that a node might forward double-spends, non-standard transactions, or outright invalid transactions. That's why every node must do the checking for itself.

Since there is latency in the network, it's possible that nodes will end up with a different view of the pending transaction pool. This becomes particularly interesting and important when there is an attempted double-spend. Let's say Alice attempts to pay the same bitcoin to both Bob and Charlie, and sends out two transactions at roughly the same time. Some nodes will hear about the Alice → Bob transaction first while others will hear about the Alice → Charlie transaction first. When a node hears either of these transactions, it will add it to its transaction pool, and if it hears about the other one later it will look like a double-spend. The node will drop the latter transaction and won't relay it or add it to its transaction pool. As a result, the nodes will temporarily disagree on which transactions should be put into the next block. This is called a race condition.

The good news is that this is perfectly okay. Whoever mines the next block will essentially break the tie and decide which of those two pending transactions should end up being put permanently into a block. Let's say the Alice → Charlie transaction makes it into the block. When nodes with the Alice → Bob transaction hear about this block, they'll drop the transaction from their memory pools because it is a double-spend. When nodes with the Alice → Charlie transaction hear about this block, they'll drop the transaction from their memory pools because it's already made it into the block chain. So there will be no more disagreement once this block propagates to the network.

Since the default behavior is for nodes to hang onto whatever they hear first, network position matters. If two conflicting transactions or blocks get announced at two different positions in the network, they'll both begin to flood throughout the network and which transaction a node sees first will depend on where it is in the network.

Of course this assumes that every node implements this logic where they keep whatever they hear first. But there's no central authority enforcing this, and nodes are free to implement any other logic they want for choosing which transactions to keep and whether or not to forward a transaction. We'll look more closely at miner incentives in Chapter 5.

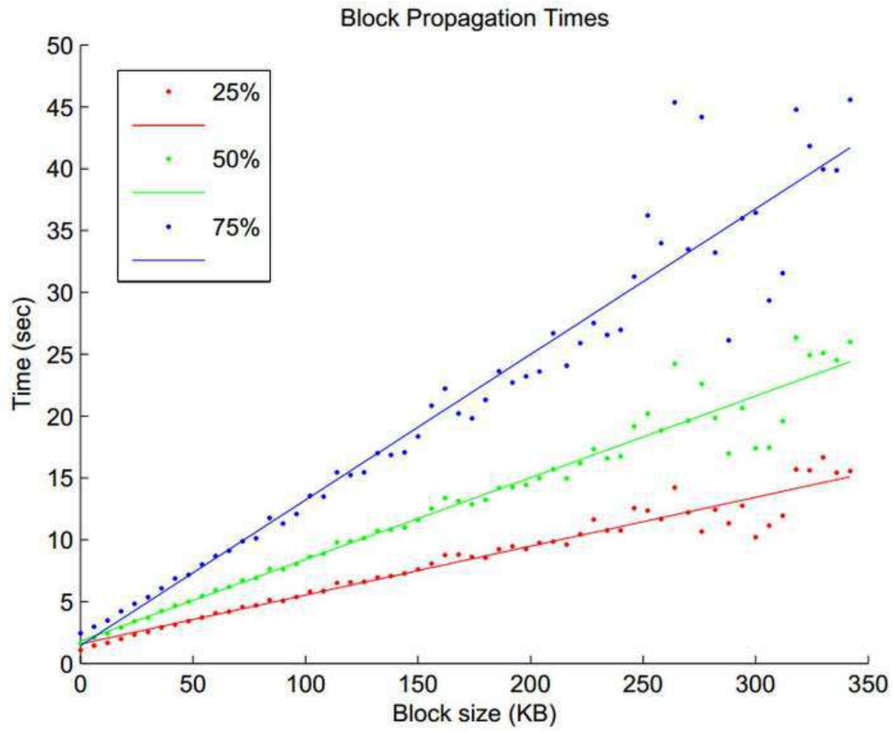
**Sidebar: Zero-confirmation transactions and replace-by-fee.** In Chapter 2 we looked at zero-confirmation transactions, where the recipient accepts the transaction as soon as it is broadcast on the network. This isn't designed to be secure against double spends. But as we saw, the default behavior for miners in the case of conflicting transactions is to include the transaction they received first, and this makes double-spending against zero-confirmation transactions moderately hard. As a result, and due to their convenience, zero-confirmation transactions have become common.

Since 2013, there has been interest in changing the default policy to *replace-by-fee* (RBF) whereby nodes will replace a pending transaction in their pool if they hear a conflicting transaction which includes a higher fee. This is the rational behavior for miners, at least in a short-term sense, as it gives them a better fee. However, replace-by-fee would make double-spending against zero-confirmation attacks far easier in practice.

Replace-by-fee has therefore attracted controversy, both in terms of the technical question of whether it is possible to prevent or deter double-spending in an RBF world, and the philosophical question of whether Bitcoin should try to support zero-confirmation as best it can, or abandon it. We won't dive into the long-running controversy here, but Bitcoin has recently adopted "opt-in" RBF whereby transactions can mark themselves (using the sequence-number field) as eligible for replacement by higher-fee transactions.

So far we've been mostly discussing propagation of transactions. The logic for announcing new blocks, whenever miners find a new block, is almost exactly the same as propagating a new transaction and it is all subject to the same race conditions. If two valid blocks are mined at the same time, only one of these can be included in the long term consensus chain. Ultimately, which of these blocks will be included will depend on which blocks the other nodes build on top of, and the one that does not get into the consensus chain will be orphaned.

Validating a block is more complex than validating transactions. In addition to validating the header and making sure that the hash value is in the acceptable range, nodes must validate every transaction included in the block. Finally, a node will forward a block only if it builds on the longest branch, based on its perspective of what the block chain (which is really a tree of blocks) looks like. This avoids forks building up. But just like with transactions, nodes can implement different logic if they want — they may relay blocks that aren't valid or blocks that build off of an earlier point in the block chain. This would build a fork, but that's okay. The protocol is designed to withstand that.




Source: Yonatan Sompolinsky and Aviv Zohar: "Accelerating Bitcoin's Transaction Processing" 2014

***Figure 3.10*** **Block propagation time.** This graph shows the average time that it takes a block to reach various percentages of the nodes in the network.

What is the latency of the flooding algorithm? The graph in Figure 3.10 shows the average time for new blocks to propagate to every node in the network. The three lines show the 25th, the 50th, and the 75th percentile block propagation time. As you can see, propagation time is basically proportional to the size of the block. This is because network bandwidth is the bottleneck. The larger blocks take over 30 seconds to propagate to most nodes in the network. So it isn't a particularly efficient protocol. On the Internet, 30 seconds is a pretty long time. In Bitcoin's design, having a simple network with little structure where nodes are equal and can come and go at any time took priority over efficiency. So a block may need to go through many nodes before it reaches the most distant nodes in the network. If the network were instead designed top-down for efficiency, we could make sure that the path between any two nodes is short.

***Size of the network.*** It is difficult to measure how big the network is since it is dynamic and there is no central authority. A number of researchers have come up with estimates. On the high end, some say that over a million IP addresses in a given month will, at some point, act, at least temporarily, as a Bitcoin node. On the other hand, there seem to be only about 5,000 to 10,000 nodes that are permanently connected and fully validate every transaction they hear. This may seem like a surprisingly low number, but as of this writing there is no evidence that the number of fully validating nodes is going up, and it may in fact be dropping.

***Storage requirements.*** Fully validating nodes must stay permanently connected so as to hear about all the data. The longer a node is offline, the more catching up it will have to do when it rejoins the network. Such nodes also have to store the entire block chain and need a good network connection to be able to hear every new transaction and forward it to peers. The storage requirement is currently in the low tens of gigabytes (see Figure 3.11), well within the abilities of a single commodity desktop machine.

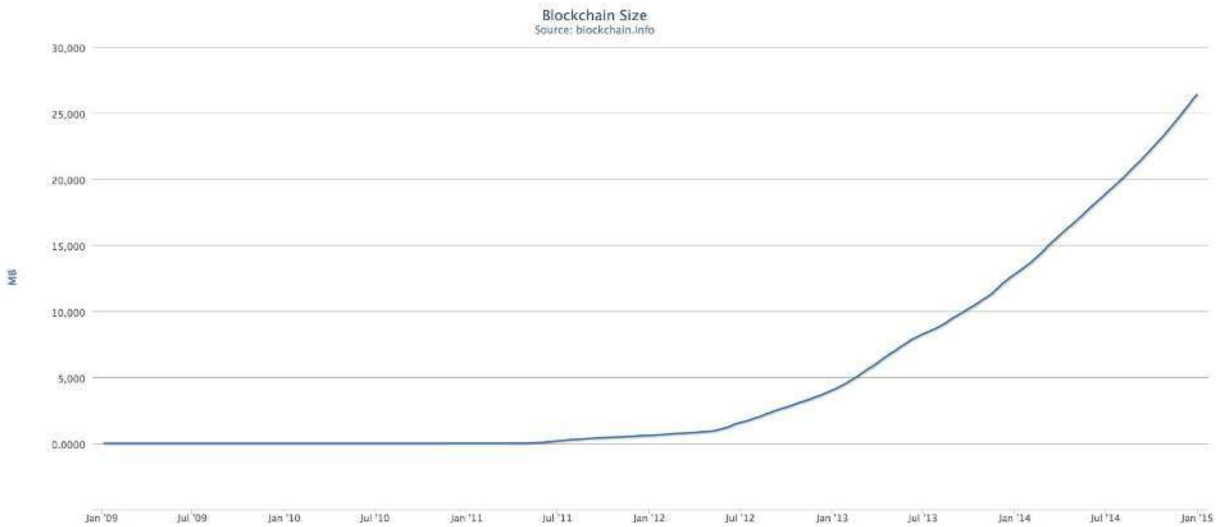



***Figure 3.11.*** **Size of the block chain.** Fully validating nodes must store the entire block chain, which as of the end of 2014 is over 26 gigabytes.

Finally, fully validating nodes must maintain the entire set of unspent transaction outputs, which are the coins available to be spent. Ideally this should be stored in RAM, so that upon hearing a new proposed transaction on the network, the node can quickly look up the transaction outputs that it's attempting to claim, run the scripts, see if the signatures are valid, and add the transaction to the transaction pool. As of mid-2014, there are over 44 million transactions on the block chain of which 12 million are unspent. Fortunately, that's still small enough to fit in less than a gigabyte of RAM in an efficient data structure.

***Lightweight nodes.*** In contrast to fully validating nodes, there are lightweight nodes, also called thin clients or Simple Payment Verification (SPV) clients. In fact, the vast majority of nodes on the Bitcoin network are lightweight nodes. These differ from fully validating nodes in that they don't store the entire block chain. They only store the pieces that they need to verify specific transactions that they care about. If you use a wallet program, it would typically incorporate an SPV node. The node downloads the block headers and transactions that represent payments to your addresses.

An SPV node doesn't have the security level of a fully validating node. Since the node has block headers, it can check that the blocks were difficult to mine, but it can't check to see that every transaction included in a block is actually valid because it doesn't have the transaction history and doesn't know the set of unspent transactions outputs. SPV nodes can only validate the transactions that actually affect them. So they're essentially trusting the fully validating nodes to have validated all the other transactions that are out there. This isn't a bad security trade off. They're assuming there are fully validating nodes out there that are doing the hard work, and that if miners went through the trouble to mine this block, which is a really expensive process, they probably also did some validation to make sure that this block wouldn't be rejected.

The cost savings of being an SPV node are huge. The block headers are only about 1/1,000 the size of the block chain. So instead of storing a few tens of gigabytes, it's only a few tens of megabytes. Even a smartphone can easily act as an SPV node in the Bitcoin network.

Since Bitcoin rests on an open protocol, ideally there would be many different implementations that interact with each other seamlessly. That way if there's a bad bug in one, it's not likely to bring down the entire network. The good news is that the protocol has been successfully re-implemented. There are implementations in C++ and Go, and people are working on quite a few others. The bad news is that most of the nodes on the network are running the bitcoind library, written in C++, maintained by the Bitcoin Core developers, and some of these nodes are running previous out-of-date versions that haven't been updated. In any event, most are running some variation of this one common client.

## 3.6 Limitations and improvements

Finally, we'll talk about some built-in limitations to the Bitcoin protocol, and why it's challenging to improve them. There are many constraints hard-coded into the Bitcoin protocol, which were chosen when Bitcoin was proposed in 2009, before anyone really had any idea that it might grow into a globally-important currency. Among them are the limits on the average time per block, the size of blocks, the number of signature operations in a block, and the divisibility of the currency, the total number of Bitcoins, and the block reward structure.

The limitations on the total number of Bitcoins in existence, as well as the structure of the mining rewards are very likely to never be changed because the economic implications of changing them are too great. Miners and investors have made big bets on the system assuming that the Bitcoin reward structure and the limited supply of Bitcoins will remain the way it was planned. If that changes, it will have large financial implications for people. So the community has basically agreed that those aspects, whether or not they were wisely chosen, will not change.

There are other changes that would seem to make everybody better off, because some initial design choices don't seem quite right with the benefit of hindsight. Chief among these are limits that affect the throughput of the system. How many transactions can the Bitcoin network process per second? This limitation comes from the hard coded limit on the size of blocks. Each block is limited to a megabyte, about a million bytes. Each transaction is at least 250 bytes. Dividing 1,000,000 by 250, we see that each block has a limit of 4,000 transactions, and given that blocks are found about every 10 minutes, we're left with about 7 transactions per second, which is all that the Bitcoin network can handle. It may seem that changing these limits would be a matter of tweaking a constant in a source code file somewhere. However, it's really hard to effect such a change in practice, for reasons that we will explain shortly.

So how does seven transactions per second compare? It's quite low compared to the throughput of any major credit card processor. Visa's network is said to handle about 2,000 transactions per second around the world on average, and capable of handling 10,000 transactions per second during busy periods. Even Paypal, which is newer and smaller than Visa, can handle 100 transactions per second at peak times. That's an order of magnitude more than Bitcoin.

Another limitation that people are worried about in the long term is that the choices of cryptographic algorithms in Bitcoin are fixed. There are only a couple of hash algorithms available, and only one signature algorithm, ECDSA, over a specific elliptic curve called secp256k1. There's some concern that over the lifetime of Bitcoin — which people hope will be very long — this algorithm might be broken. Cryptographers might come up with a clever new attack that we haven't foreseen which makes the algorithm insecure. The same is true of the hash functions; in fact, in the last decade hash functions have seen steady progress in cryptanalysis. SHA-1, which is included in Bitcoin, already has some known cryptographic weaknesses, albeit not fatal. To change this, we would have to extend the Bitcoin scripting language to support new cryptographic algorithms.

***Changing the protocol.*** How can we go about introducing new features into the Bitcoin protocol? You might think that this is simple — just release a new version of the software, and tell all nodes to upgrade. In reality, though, this is quite complicated. In practice, it's impossible to assume that every node would upgrade. Some nodes in the network would fail to get the new software or fail to get it in time. The implications of having most nodes upgrade while some nodes are running the old version depends very much on the nature of the changes in the software. We can differentiate between two types of changes: those that would cause a ***hard fork*** and those that would cause a ***soft fork***.

***Hard forks.*** One type of change that we can make introduces new features that were previously considered invalid. That is, the new version of the software would recognize blocks as valid that the old software would reject. Now consider what happens when most nodes have upgraded, but some have not. Soon the longest branch will contain blocks that are considered invalid by the old nodes. So the old nodes will go off and work on a branch of the block chain that excludes blocks with the new feature. Until they upgrade their software, they'll consider their (shorter) branch to be the longest valid branch.

This type of change is called a hard forking change because it makes the block chain split. Every node in the network will be on one or the other side of it based on which version of the protocol it's running. Of course, the branches will never join together again. This is considered unacceptable by the community since old nodes would effectively be cut out of the Bitcoin network if they don't upgrade their software.

***Soft forks.*** A second type of change that we can make to Bitcoin is adding features that make validation rules stricter. That is, they restrict the set of valid transactions or the set of valid blocks such that the old version would accept all of the blocks, whereas the new version would reject some. This type of change is called a soft fork, and it can avoid the permanent split that a hard fork introduces.

Consider what happens when we introduce a new version of the software with a soft forking change. The nodes running the new software will be enforcing some new, tighter, set of rules. Provided that the majority of nodes switch over to the new software, these nodes will be able to enforce the new rules. Introducing a soft fork relies on enough nodes switching to the new version of the protocol that they'll be able to enforce the new rules, knowing that the old nodes won't be able to enforce the new rules because they haven't heard of them yet.

There is a risk that old miners might mine invalid blocks because they include some transactions that are invalid under the new, stricter, rules. But the old nodes will at least figure out that some of their blocks are being rejected, even if they don't understand the reason. This might prompt their operators to upgrade their software. Furthermore, if their branch gets overtaken by the new miners, the old miners switch to it. That's because blocks considered valid by new miners are also considered valid by old miners. Thus, there won't be a hard fork; instead, there will be many small, temporary forks.

The classic example of a change that was made via soft fork is pay-to-script-hash, which we discussed earlier in this chapter. Pay-to-script-hash was not present in the first version of the Bitcoin protocol. This is a soft fork because from the view of the old nodes, a valid pay-to-script-hash transaction would still verify correctly. As interpreted by the old nodes, the script is simple — it hashes one data value and checks if the hash matches the value specified in the output script. Old nodes don't know to do the (now required) additional step of running that value itself to see if it is a valid script. We rely on new nodes to enforce the new rules, i.e. that the script actually redeems this transaction.

So what could we possibly add with a soft fork? Pay-to-script-hash was successful. It's also possible that new cryptographic schemes could be added by a soft fork. We could also add some extra metadata in the coinbase parameter that had some meaning. Today, any value is accepted in the coinbase parameter. But we could, in the future, say that the coinbase has to have some specific format. One idea that's been proposed is that, in each new block, the coinbase includes the Merkle root of a tree containing the entire set of unspent transactions. It would only result in a soft fork, because old nodes might mine a block that didn't have the required new coinbase parameter that got rejected by the network, but they would catch up and join the main chain that the network is mining.

Other changes might require a hard fork. Examples of this are adding new opcodes to Bitcoin, changing the limits on block or transactions size, or various bug fixes. Fixing the bug we discussed earlier, where the MULTISIG instruction pops an extra value off the stack, would also require a hard fork. That explains why, even though it's an annoying bug, it's much easier to leave it in the protocol and have people work around it rather than have a hard-fork change to Bitcoin. Hard forking changes, even though they would be nice, are very unlikely to happen within the current climate of Bitcoin. But many of these ideas have been tested out and proved to be successful in alternative cryptocurrencies, which start over from scratch. We'll be talking about those in a lot more detail in Chapter 10.

**Sidebar: Bitcoin's block size conundrum.** Due to Bitcoin's growing popularity, as of early 2016 it has become common for the 1-megabyte space in blocks to be filled up within the period between blocks (especially when, due to random chance, a block take longer than 10 minutes to find)first, resulting in some transactions having to wait one or more additional blocks to make their way into the block chain. Increasing the block size limit will require a hard fork.

The question of whether and how to address the block chain's limited bandwidth for transactions has gripped the Bitcoin community. The discussion started years ago, but with little progress toward a consensus, it has gradually gotten more acrimonious, escalating into a circus. We'll discuss Bitcoin's community, politics, and governance in Chapter 7.

Depending on the resolution of the block-size problem, some of the details in this chapter might become slightly out of date. The technical details of increasing Bitcoin's transaction-processing capacity are interesting, and we encourage you to read more online.

At this point, you should be familiar with the technical mechanics of Bitcoin and how a Bitcoin node operates. But, human beings aren't Bitcoin nodes, and you're never going to run a Bitcoin node in your head. So how do you, as a human, actually interact with this network to get it to be useable as a currency? How do you find a node to inform about your transaction? How do you get Bitcoins in exchange for cash? How do you store your Bitcoins? All of these questions are crucial for building a currency that will actually work for people, as opposed to just software, and we will answer these questions in the next chapter.

## Further Reading

***Online resources.*** In this chapter, we discussed a lot of technical details, and you may find it difficult to absorb them all at once. To supplement the material in this chapter, it's useful to go online and see some of the things we discussed in practice. There are numerous websites that allow you to examine blocks and transactions and see what they look like. One such "blockchain explorer" is the website blockchain.info.

A developer-focused book on Bitcoin that covers the technical details well (especially Chapters 5, 6, and 7):

**Antonopoulos, Andreas M. Mastering Bitcoin: unlocking digital cryptocurrencies. O'Reilly Media, 2014.**

## Exercises

1. **Transaction validation**: Consider the steps involved in processing Bitcoin transactions. Which of these steps are computationally expensive? If you're an entity validating many transactions (say, a miner) what data structure might you build to help speed up verification?
2. **Bitcoin script**: For the following questions, you're free to use non-standard transactions and op codes that are currently disabled. You can use <data> as a shorthand to represent data values pushed onto the stack. For a quick reference, see here: https://en.bitcoin.it/wiki/Script.
    a. Write the Bitcoin ScriptPubKey script for a transaction that can be redeemed by anybody who supplies a square root of 1764.
    b. Write a corresponding ScriptSig script to redeem your transaction.
    c. Suppose you wanted to issue a new RSA factoring challenge by publishing a transaction that can be redeemed by anybody who can factor a 1024-bit RSA number (RSA numbers are the product of two large, secret prime numbers). What difficulties might you run into?
3. **Bitcoin script II**: Alice is backpacking and is worried about her devices containing private keys getting stolen. So she would like to store her bitcoins in such a way that they can be redeemed via knowledge of only a password. Accordingly, she stores them in the following ScriptPubKey address:
   OP_SHA1
   <0x084a3501edef6845f2f1e4198ec3a2b81cf5c6bc>
   OP_EQUALVERIFY
    a. Write a ScriptSig script that will successfully redeem this transaction. [Hint: it should only be one line long.]
    b. Explain why this is not a secure way to protect Bitcoins using a password.
    c. Would implementing this using Pay-to-script-hash (P2SH) fix the security issue(s) you identified? Why or why not?
4. **Bitcoin script III.**
    a. Write a ScriptPubKey that requires demonstrating a SHA-256 collision to redeem.
    b. (Hard) write a corresponding ScriptSig that will successfully redeem this transaction.
5. **Burning and encoding**
    a. What are some ways to burn bitcoins, i.e., to make a transaction unredeemable? Which of these allow a proof of burn, i.e., convincing any observer that no one can redeem such a transaction?
    b. What are some ways to encode arbitrary data into the block chain? Which of these result in burnt bitcoins?
       [Hint: you have more control over the contents of the transaction "out" field than might at first appear.]
    c. One user encoded some JavaScript code into the block chain. What might have been a motivation for doing this?
6. **Green addresses:** One problem with green addresses is that there is no punishment against double-spending within the Bitcoin system itself. To solve this, you decide to design an altcoin

called “GreenCoin” that has built-in support for green addresses. Any attempt at double spending from addresses (or transaction outputs) that have been designated as “green” must incur a financial penalty in a way that can be enforced by miners. Propose a possible design for GreenCoin.

7. **SPV proofs**: Suppose Bob the merchant runs a lightweight client and receives the current head of the block chain from a trusted source.
    a. What information should Bob’s customers provide to prove that their payment to Bob has been included in the block chain? Assume Bob requires 6 confirmations.
    b. Estimate how many bytes this proof will require. Assume there are 1024 transactions in each block.
8. **Adding new features**: Assess whether the following new features could be added using a hard fork or a soft fork:
    a. Adding a new OP_SHA3 script instruction
    b. Disabling the OP_SHA1 instruction
    c. A requirement that each miner include a Merkle root of unspent transaction outputs (UTXOs) in each block
    d. A requirement that all transactions have their outputs sorted by value in ascending order
9. **More forking**
    a. The most prominent Bitcoin hard fork was a transient one caused by the version 0.8 bug. How many blocks were abandoned when the fork was resolved?
    b. The most prominent Bitcoin soft fork was the addition of pay-to-script-hash. How many blocks were orphaned because of it?
    c. Bitcoin clients go into “safe mode” when they detect that the chain has forked. What heuristic(s) could you use to detect this?

# Chapter 4: How to Store and Use Bitcoins

This chapter is about how we store and use bitcoins in practice.

## 4.1 Simple Local Storage

Let’s begin with the simplest way of storing bitcoins, and that is simply putting them on a local device. As a recap, to spend a bitcoin you need to know some public information and some secret information. The public information is what goes on the block chain — the identity of the coin, how much it's worth, and so on. The secret information is the secret key of the owner of the bitcoin, presumably, that’s you. You don’t need to worry too much about how to store the public information because you can always get it back when you need to. But the secret signing key is something you’d better keep track of. So in practice storing your bitcoins is all about storing and managing your keys.

Storing bitcoins is really all about storing and managing Bitcoin secret keys.

When figuring out how to store and manage keys, there are three goals to keep in mind. The first is availability: being able to actually spend your coins when you want to. The second is security: making sure that nobody else can spend your coins. If someone gets the power to spend your coins they could just send your coins to themselves, and then you don't have the coins anymore. The third goal is convenience, that is, key management should be relatively easy to do. As you can imagine, achieving all three simultaneously can be a challenge.

Different approaches to key management offer different trade-offs between availability, security, and convenience.

The simplest key management method is storing them on a file on your own local device: your computer, your phone, or some other kind of gadget that you carry, or own, or control. This is great for convenience: having a smartphone app that allows spending coins with the push of a few buttons is hard to beat. But this isn’t great for availability or security — if you lose the device, if the device crashes, and you have to wipe the disc, or if your file gets corrupted, your keys are lost, and so are your coins. Similarly for security: if someone steals or breaks into your device, or it gets infected with malware, they can copy your keys and then they can send all your coins to themselves.

In other words, storing your private keys on a local device, especially a mobile device, is a lot like carrying around money in your wallet or in your purse. It's useful to have some spending money, but you don't want to carry around your life savings because you might lose it, or somebody might steal it. So what you typically do is store a little bit of information/a little bit of money in your wallet, and keep most of your money somewhere else.

**Wallets**. If you're storing your bitcoins locally, you'd typically use wallet software, which is software that keeps track of all your coins, manages all the details of your keys, and makes things convenient with a nice user interface. If you want to send $4.25 worth of bitcoins to your local coffee shop the wallet software would give you some easy way to do that. Wallet software is especially useful because you typically want to use a whole bunch of different addresses with different keys associated with them. As you may remember, creating a new public/private key pair is easy, and you can utilize this to improve your anonymity or privacy. Wallet software gives you a simple interface that tells you how much is in your wallet. When you want to spend bitcoins, it handles the details of which keys to use and how to generate new addresses and so on.

**Encoding keys: base 58 and QR codes**. To spend or receive bitcoins, you also need a way to exchange an address with the other party — the address to which bitcoins are to be sent. There are two main ways in which addresses are encoded so that they can be communicated from receiver to spender: as a text string or as a QR code.

To encode an address as a text string, we take the bits of the key and convert it from a binary number to a base 58 number. Then we use a set of 58 characters to encode each digits as a character; this is called base58 notation. Why 58? Because that's the number we get when we include the upper case letters, lower case letters, as well as digits as characters, but leave out a few that might be confusing or might look like another character. For example, capital letter 'O' and zero are both taken out because they look too much alike. This allows encoded addresses to be read out over the phone or read from printed paper and typed in, should that be necessary. Ideally such manual methods of communicating addresses can be avoided through methods such as QR codes, which we now discuss.

`1A1zP1eP5QGefi2DMPTfTL5SLmv7DivfNa`

The address that received the very first Bitcoin block reward in the genesis block, base58 encoded.

**Figure 4.1**: **a QR code representing an actual Bitcoin address.** Feel free to send us some bitcoins.

The second method for encoding a Bitcoin address is as a QR code, a simple kind of 2-dimensional barcode. The advantage of a QR code is that you can take a picture of it with a smartphone and wallet software can automatically turn the barcode into the a sequence of bits that represents the corresponding Bitcoin address. This is useful in a store, for example: the check-out system might display a QR code and you can pay with your phone by scanning the code and sending coins to that address. It is also useful for phone-to-phone transfers.

**Vanity addresses**. Some individuals or merchants like to have an address that starts with some human-meaningful text. For example, the gambling website Satoshi Bones has users send money to addresses containing the string "bones" in positions 2--6, such as `1bonesEeTcABPjLzAb1VkFgySY6Zqu3sX` (all regular addresses begin with the character 1, indicating pay-to-pubkey-hash.)

We said that addresses are outputs of a hash function, which produces random-looking data, so how did the string "bones" get in there? If Satoshi Bones were simply making up these addresses, lacking the ability to invert hash function, they wouldn't know the corresponding private keys and hence wouldn't actually control those addresses. Instead, they repeatedly generated private keys until they got lucky and found one which hashed to this pattern. Such addresses are called *vanity addresses* and there are tools to generate them.

How much work does this take? Since there are 58 possibilities for every character, if you want to find an address which starts with a specific $k$-character string, you'll need to generate $58^k$ addresses on average until you get lucky. So finding an address starting with "bones" would have required generating over 600 million addresses! This can be done on a normal laptop nowadays. But it gets exponentially harder with each extra character. Finding a 15-character prefix would require an infeasible amount of computation and (without finding a break in the underlying hash function) should be impossible.

**Sidebar**: **Speeding up vanity address generation.** In Bitcoin, if we call the private key $x$, the public key is $g^x$. The exponentiation represents what's called scalar multiplication in an elliptic curve group. The address is $H(g^x)$, the hash of the public key. We won't get into the details here, but exponentiation is the slow step in address generation.

The naive way to generate vanity addresses would be to pick a pseudorandom $x$, compute $H(g^x)$, and repeat if that address doesn't work. A much faster approach is to try $x+1$ if the first $x$ fails, and continue incrementing instead of picking a fresh $x$ each time. That's because $g^{x+1} = x\ g^x$, and we've already computed $g^x$, so we only need a multiplication operation for each address instead of exponentiation, and that's much faster. In fact, it speeds up vanity address generation by over two orders of magnitude.

## 4.2 Hot and Cold Storage

As we just saw, storing bitcoins on your computer is like carrying money around in your wallet or your purse. This is called "hot storage". It's convenient but also somewhat risky. On the other hand, "cold storage" is offline. It's locked away somewhere. It's not connected to the internet, and it's archival. So it's safer and more secure, but of course, not as convenient. This is similar to how you carry some money around on your person, but put your life's savings somewhere safer.

To have separate hot and cold storage, obviously you need to have separate secret keys for each — otherwise the coins in cold storage would be vulnerable if the hot storage is compromised. You'll want to move coins back and forth between the hot side and the cold side, so each side will need to know the other's addresses, or public keys.

Cold storage is not online, and so the hot storage and the cold storage won't be able to connect to each other across any network. But the good news is that cold storage doesn't have to be online to receive coins — since the hot storage knows the cold storage addresses, it can send coins to cold storage at any time. At any time if the amount of money in your hot wallet becomes uncomfortably large, you can transfer a chunk of it over to cold storage, without putting your cold storage at risk by connecting to the network. Next time the cold storage connects it will be able to receive from the block chain information about those transfers to it and then the cold storage will be able to do what it wants with those coins.

But there's a little problem when it comes to managing cold storage addresses. On the one hand, as we saw earlier, for privacy and other reasons we want to be able to receive each coin at a separate address with different secret keys. So whenever we transfer a coin from the hot side to the cold side we'd like to use a fresh cold address for that purpose. But because the cold side is not online we have to have some way for the hot side to find out about those addresses.

The blunt solution is for the cold side to generate a big batch of addresses all at once and send those over for the hot side to use them up one by one. The drawback is that we have to periodically reconnect the cold side in order to transfer more addresses.

**Hierarchical wallets**. A more effective solution is to use a hierarchical wallet. It allows the cold side to use an essentially unbounded number of addresses and the hot side to know about these addresses, but with only a short, one-time communication between the two sides. But it requires a little bit of cryptographic trickery.

To review, previously when we talked about key generation and digital signatures back in chapter 1, we looked at a function called generateKeys that generates a public key (which acts as an address) and a secret key. In a hierarchical wallet, key generation works differently. Instead of generating a single address we generate what we'll call address generation info, and rather than a private key we generate what we'll call private key generation info. Given the address generation info, we can generate a sequence of addresses: we apply an address generation function that takes as input the address generation info and any integer *i* and generates the *i*'th address in the sequence. Similarly we can generate a sequence of private keys using the private key generation info.

The cryptographic magic that makes this useful is that for every *i*, the *i*'th address and *i*'th secret key "match up" — that is, the *i*'th secret key controls, and can be used to spend, bitcoins from the *i*'th address just as if the pair were generated the old fashioned way. So it's as if we have a sequence of regular key pairs.

The other important cryptographic property here is security: the address generation info doesn't leak any information about the private keys. That means that it's safe to give the address generation info to anybody, and so that anybody can be enabled to generate the 'i'th key.

Now, not all digital signature schemes that exist can be modified to support hierarchical key generation. Some can and some can't, but the good news is that the digital signature scheme used by Bitcoin, ECDSA, does support hierarchical key generation, allowing this trick. That is, the cold side generates arbitrarily many keys and the hot side generates the corresponding addresses.

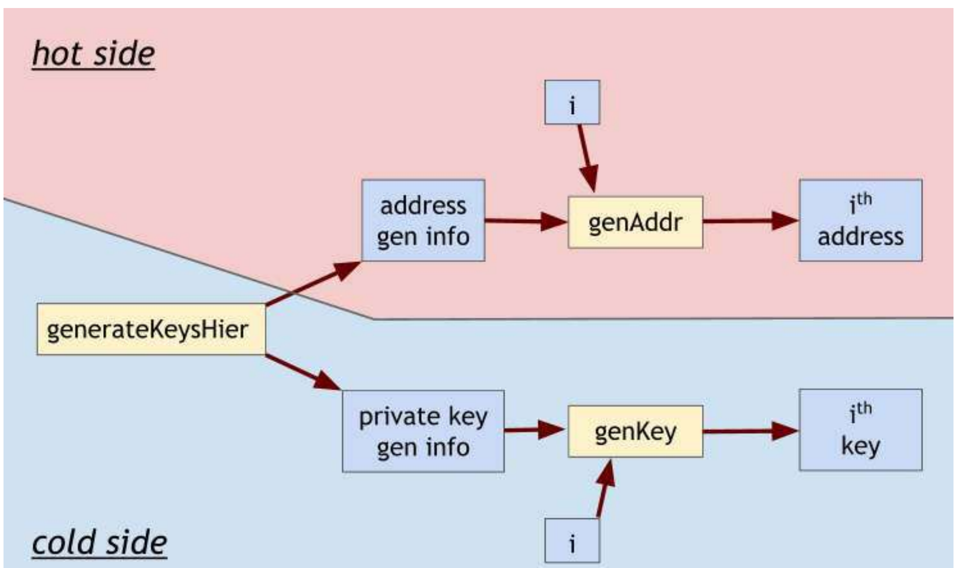



**Figure 4.2: Schema of a hierarchical wallet**. The cold side creates and saves private key generation info and address generation info. It does a one-time transfer of the latter to the hot side. The hot side generates a new address sequentially every time it wants to send coins to the cold side. When the cold side reconnects, it generates addresses sequentially and checks the block chain for transfers to those addresses until it reaches an address that hasn't received any coins. It can also generate private keys sequentially if it wants to send some coins back to the hot side or spend them some other way.

Here's how it works. Recall that normally an ECDSA private key is a random number $x$ and the corresponding public key is $g^x$. For hierarchical key generation, we'll need two other random values $k$ and $y$.

| | |
|---|---|
| Private key generation info: | $k, x, y$ |
| $i^{\text{th}}$ private key: | $x_i = y + H(k \,\|\, i)$ |
| Address generation info: | $k, g^y$ |
| $i^{\text{th}}$ public key: | $g^{x\_i} = g^{H(k \| i)} \cdot g^y$ |
| $i^{\text{th}}$ address: | $H(g^{x\_i})$ |

This has all the properties that we want: each side is able to generate its sequence of keys, and the corresponding keys match up because (because the public key corresponding to a private key $x$ is $g^x$). It has one other property that we haven't talked about: when you give out the public keys, those keys won't be linkable to each other, that is, it won't be possible to infer that they come from the same wallet. The straw-man solution of having the cold side generate a big batch of addresses does have this property, but we had to take care to preserve it when with the new technique considering that the keys aren't in fact independently generated. This property is important for privacy and anonymity, which will be the topic of Chapter 6.

Here we have two levels of security, with the hot side being at a lower level. If the hot side is compromised, the unlinkability property that we just discussed will be lost, but the private keys (and the bitcoins) are still safe. In general, this scheme supports arbitrarily many security levels --- hence "hierarchical" --- although we haven't seen the details. This can be useful, for instance, when there are multiple levels of delegation within a company.

Now let's talk about the different ways in which cold information — whether one or more keys, or key-generation info — can be stored. The first way is to store it in some kind of device and put that device in a safe. It might be a laptop computer, a mobile phone or tablet, or a thumb drive. The important thing is to turn the device off and lock it up, so that if somebody wants to steal it they have to break into the locked storage.

**Brain wallet**. The second method we can use is called a brain wallet. This is a way to control access to bitcoins using nothing but a secret passphrase. This avoids the need for hard drives, paper, or any other long-term storage mechanism. This property can be particularly useful in situations where you have poor physical security, perhaps when you're traveling internationally.

The key trick behind a brain wallet is to have a predictable algorithm for turning a passphrase into a public and private key. For example, you could hash the passphrase with a suitable hash function to derive the private key, and given the private key, the public key can be derived in a standard way. Further, combining this with the hierarchical wallet technique we saw earlier, we can generate an entire sequence of addresses and private keys from a passphrase, thus enabling a complete wallet.

However, an adversary can also obtain all private keys in a brain wallet if they can guess the passphrase. As always in computer security, we must assume that the adversary knows the procedure you used to generate keys, and only your passphrase provides security. So the adversary can try various passphrases and generate addresses using them; if he finds any unspent transactions on the block chain at any of those addresses, he can immediately transfer them to himself. The adversary may never know (or care) who the coins belonged to and the attack doesn't require breaking into any machines. Guessing brain wallet passphrases is not directed toward specific users, and further, leaves no trace.

Furthermore, unlike the task of guessing your email password which can be *rate-limited* by your email server (called *online guessing*), with brain wallets the attacker can download the list of addresses with unredeemed coins and try as many potential passphrases as they have the computational capacity to check. Note that the attacker doesn't need to know which addresses correspond to brain wallets. This is called *offline guessing* or *password cracking*. It is much more challenging to come up with passphrases that are easy to memorize and yet won't be vulnerable to guessing in this manner. One secure way to generate a passphrase is to have an automatic procedure for picking a random 80-bit number and turning that number into a passphrase in such a way that different numbers result in different passphrases.

**Sidebar: generating memorable passphrases.** One passphrase-generation procedure that gives about 80 bits of entropy is to pick a random sequence of 6 words from among the 10,000 most common English words ($6 \times \log_2(10000)$ is roughly 80). Many people find these easier to memorize than a random string of characters. Here are a couple of passphrases generated this way.

```
worn till alloy focusing okay reducing
earth dutch fake tired dot occasions
```

In practice, it is also wise to use a deliberately slow function to derive the private key from the passphrase to ensure it takes as long as possible for the attacker to try all possibilities. This is known as *key streching*. To create a deliberately slow key-derivation function, we can take a fast cryptographic hash function like SHA-256 and compute say $2^{20}$ iterations of it, multiplying the attacker's workload by a factor of $2^{20}$. Of course, if we make it too slow it will start to become annoying to the user as their device must re-compute this function any time they want to spend coins from their brain wallet.

If a brain wallet passphrase is inaccessible — say it's been forgotten, hasn't been written down, and can't be guessed — then the coins are lost forever.

**Paper wallet**. The third option is what's called a paper wallet. We can print the key material to paper and then put that paper into a safe or secure place. Obviously, the security of this method is just as good or bad as the physical security of the paper that we're using. Typical paper wallets encode both the public and private key in two ways: as a 2D barcode and in base 58 notation. Just like with a brain wallet, storing a small amount of key material is sufficient to re-create a wallet.


**Figure 4.3: A Bitcoin paper wallet** with the public key encoded both as a 2D barcode and in base 58 notation. Observe that the private key is behind a tamper-evident seal.

**Tamper-resistant device.** The fourth way that we can store offline information is to put it in some kind of tamper-resistant device. Either we put the key into the device or the device generates the key; either way, the device is designed so that there's no way it will output or divulge the key. The device instead signs statements with the key, and does so when we, say, press a button or give it some kind of password. One advantage is that if the device is lost or stolen we'll know it, and the only way the key can be stolen is if the device is stolen. This is different from storing your key on a laptop.

In general, people might use a combination of four of these methods in order to secure their keys. For hot storage, and especially for hot storage holding large amounts of bitcoins, people are willing to work pretty hard and come up with novel security schemes in order to protect them, and we'll talk a little bit about one of those more advanced schemes in the next section.

## 4.3 Splitting and Sharing Keys

Up to now we've looked at different ways of storing and managing the secret keys that control bitcoins, but we've always put a key in a single place — whether locked in a safe, or in software, or on paper. This leaves us with a single point of failure. If something goes wrong with that single storage place then we're in trouble. We could create and store backups of the key material, but while this decreases the risk of the key getting lost or corrupted (availability), it *increases* the risk of theft (security). This trade-off seems fundamental. Can we take a piece of data and store it in such a way that availability and security increase at the same time? Remarkably, the answer is yes, and it is once again a trick that uses cryptography, called *secret sharing*.

Here's the idea: we want to divide our secret key into some number N of pieces. We want to do it in such a way that if we're given any K of those pieces then we'll be able to reconstruct the original secret, but if we're given fewer than K pieces then we won't be able to learn anything about the original secret.

Given this stringent requirement, simply "cutting up" the secret into pieces won't work because even a single piece gives some information about the secret. We need something cleverer. And since we're not cutting up the secret, we'll call the individual components "shares" instead of pieces.

Let's say we have N=2 and K=2. That means we're generating 2 shares based on the secret, and we need both shares to be able to reconstruct the secret. Let's call our secret S, which is just a big (say 128-bit) number. We could generate a 128-bit random number R and make the two shares be R and S ⊕ R. (⊕ represents bitwise XOR). Essentially, we've "encrypted" S with a one-time pad, and we store the key (R) and the ciphertext (S ⊕ R) in separate places. Neither the key nor the ciphertext by itself tells us anything about the secret. But given the two shares, we simply XOR them together to reconstruct the secret.

This trick works as long as N and K are the same — we'd just need to generate N-1 different random numbers for the first N-1 shares, and the final share would be the secret XOR'd with all other N-1 shares. But if N is more than K, this doesn't work any more, and we need some algebra.

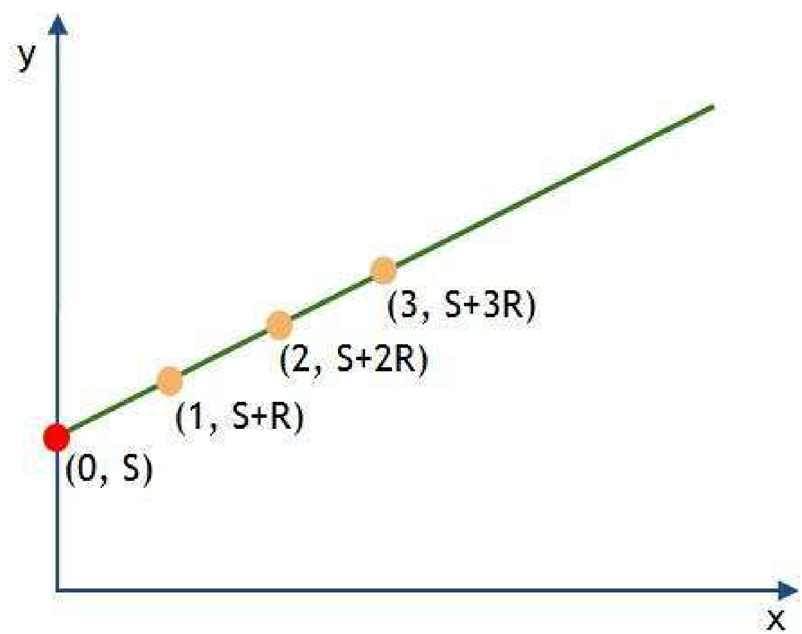



**Figure 4.4: Geometric illustration of 2-out-of-N secret sharing.** S represents the secret, encoded as a (large) integer. The green line has a slope chosen at random. The orange points (specifically, their Y-coordinates S+R, S+2R, ...) correspond to shares. Any two orange points are sufficient to reconstruct the red point, and hence the secret. All arithmetic is done modulo a large prime number.

Take a look at Figure 4.4. What we've done here is to first generate the point (0, S) on the Y-axis, and then drawn a line with a random slope through that point. Next we generate a bunch points on that line, as many as we want. It turns out that this is a secret sharing of S with N being the number of points we generated and K=2.

Why does this work? First, if you're given two of the points generated, you can draw a line through them and see where it meets the Y-axis. That would give you S. On the other hand, if you're given only a single point, it tells you nothing about S, because the slope of the line is random. Every line through your point is equally likely, and they would all intersect the Y-axis at different points.

There's only one other subtlety: to make the math work out, we have to do all our arithmetic modulo a large prime number P. It doesn't need to be secret or anything, just really big. And the secret S has to be between 0 and P-1, inclusive. So when we say we generate points on the line, what we mean is that we generate a random value R, also between 0 and P-1, and the points we generate are

x=1, y=(S+R) mod P
x=2, y=(S+2R) mod P
x=3, y=(S+3R) mod P

and so on. The secret corresponds to the point x=0, y=(S+0*R) mod P, which is just x=0, y=S.

What we've seen is a way to do secret sharing with K=2 and any value of N. This is already pretty good — if N=4, say, you can divide your secret key into 4 shares and put them on 4 different devices so that if someone steals any one of those devices, they learn nothing about your key. On the other hand, even if two of those devices are destroyed in a fire, you can reconstruct the key using the other two. So as promised, we've increased both availability and security.

But we can do better: we can do secret sharing with any N and K as long as K is no more than N. To see how, let's go back to the figure. The reason we used a line instead of some other shape is that a line, algebraically speaking, is a polynomial of degree 1. That means that to reconstruct a line we need two points and no fewer than two. If we wanted K=3, we would have used a parabola, which is a quadratic polynomial, or a polynomial of degree 2. Exactly three points are needed to construct a quadratic function. We can use the table below to understand what's going on.

| Equation | Degree | Shape | Random parameters | Number of points (K) needed to recover S |
|---|---|---|---|---|
| (S + RX) mod P | 1 | Line | R | 2 |
| $(S + R_1X + R_2X^2)$ mod P | 2 | Parabola | $R_1$, $R_2$ | 3 |
| $(S + R_1X + R_2X^2 + R_3X^3)$ mod P | 3 | Cubic | $R_1$, $R_2$, $R_3$ | 4 |

**Table 4.1: The math behind secret sharing.** Representing a secret via a series of points on a random polynomial curve of degree K-1 allows the secret to be reconstructed if, and only if, at least K of the points ("shares") are available.

There is a formula called Lagrange interpolation that allows you to reconstruct a polynomial of degree K-1 from any K points on its curve. It's an algebraic version (and a generalization) of the geometric intuition of drawing a straight line through two points with a ruler. As a result of all this, we have a way to store any secret as N shares such that we're safe even if an adversary learns up to K-1 of them, and at the same time we can tolerate the loss of up to N-K of them.

None of this is specific to Bitcoin, by the way. You can secret-share your passwords right now and give shares to your friends or put them on different devices. But no one really does this with secrets like passwords. Convenience is one reason; another is that there are other security mechanisms available for important online accounts, such as two-factor security using SMS verification. But with Bitcoin, if you're storing your keys locally, you don't have those other security options. There's no way to make the control of a Bitcoin address dependent on receipt of an SMS message. The situation is different with online wallets, which we'll look at in the next section. But not too different — it just shifts the problem to a different place. After all, the online wallet provider will need some way to avoid a single point of failure when storing *their* keys.

**Threshold cryptography**. But there's still a problem with secret sharing: if we take a key and we split it up in this way and we then want to go back and use the key to sign something, we still need to bring the shares together and recalculate the initial secret in order to be able to sign with that key. The point where we bring all the shares together is still a single point of vulnerability where an adversary might be able to steal the key.

Cryptography can solve this problem as well: if the shares are stored in different devices, there's a way to produce Bitcoin signatures in a decentralized fashion without ever reconstructing the private key on any single device. This is called a "threshold signature." The best use-case is a wallet with two-factor security, which corresponds to the case N=2 and K=2. Say you've configured your wallet to split its key material between your desktop and your phone. Then you might initiate a payment on your desktop, which would create a partial signature and send it to your phone. Your phone would then alert you with the payment details — recipient, amount, etc. — and request your confirmation. If the details check out, you'd confirm, and your phone would complete the signature using its share of the private key and broadcast the transaction to the block chain. If there were malware on your desktop that tried to steal your bitcoins, it might initiate a transaction that sent the funds to the hacker's address, but then you'd get an alert on your phone for a transaction you didn't authorize, and you'd know something was up. The mathematical details behind threshold signatures are complex and we won't discuss them here.

**Multi-signatures**. There's an entirely different option for avoiding a single point of failure: multi-signatures, which we saw earlier in Chapter 3. Instead of taking a single key and splitting it, Bitcoin script directly allows you to stipulate that control over an address be split between different keys. These keys can then be stored in different locations and the signatures produced separately. Of course, the completed, signed transaction will be constructed on some device, but even if the adversary controls this device, all that he can do is to prevent it from being broadcast to the network.

He can’t produce valid multi-signatures of some other transaction without the involvement of the other devices.

As an example, suppose that Andrew, Arvind, Ed, Joseph, and Steven, the authors of this book, are co-founders of a company — perhaps we started it with the copious royalties from the sale of this free book — and the company has a lot of bitcoins. We might use multi-sig to protect our large store of bitcoins. Each of the five of us will generate a key pair, and we’ll protect our cold storage using 3-out-of-5 multi-sig, which means that three of us must sign to create a valid transaction.

As a result, we know that we're relatively secure if the five of us keep our keys separately and secure them differently. An adversary would have to compromise three out of the five keys. If one or even two of us go rogue, they can't steal the company’s coins because you need at least three keys to do that. At the same time, if one of us loses our key or gets run over by a bus and our brain wallet is lost, the others can still get the coins back and transfer them over to a new address and re-secure the keys. In other words, multi-sig helps you to manage large amounts of cold-stored coins in a way that's relatively secure and requires action by multiple people before anything drastic happens.

**Sidebar**. Threshold signatures are a cryptographic technique to take a single key, split it into shares, store them separately, and sign transactions without reconstructing the key. Multi-signatures are a feature of Bitcoin script by which you can specify that control of an address is split between multiple independent keys. While there are some differences between them, they both increase security by avoiding single points of failure.

In our presentation above, we motivated threshold signatures by explaining how it can help achieve two-factor (or multi-factor) security, and multi-signatures by explaining how it can help a set of individuals share control over jointly held funds. But either technology is applicable to either situation.

## 4.4 Online Wallets and Exchanges

So far we've talked about ways in which you can store and manage your bitcoins itself. Now we'll talk about ways you can use other people’s services to help you do that. The first thing you could do is use an online wallet.

**Online wallets**. An online wallet is kind of like a local wallet that you might manage yourself, except the information is stored in the cloud, and you access it using a web interface on your computer or using an app on your smartphone. Some online wallet services that are popular in early 2015 are Coinbase and blockchain.info.

What’s crucial from the point of view of security is that the site delivers the code that runs on your browser or the app, and it also stores your keys. At least it will have the ability to access your keys.

Ideally, the site will encrypt those keys under a password that only you know, but of course you have to trust them to do that. You have to trust their code to not leak your keys or your password.

An online wallet has certain trade offs to doing things yourself. A big advantage is that it's convenient. You don't have to install anything on your computer in order to be able to use an online wallet in your browser. On your phone you maybe just have to install an app once, and it won't need to download the block chain. It will work across multiple devices — you can have a single wallet that you access on your desktop and on your phone and it will just work because the real wallet lives in the cloud.

On the other hand, there are security worries. If the site or the people who operate the site turn out to be malicious or are compromised somehow, your bitcoins are in trouble. The site supplies the code that has its grubby fingers on your bitcoins, and things can go wrong if there's a compromise or malice at the service provider.

Ideally, the site or the service is run by security professionals who are better trained, or perhaps more diligent than you in maintaining security. So you might hope that they do a better job and that your coins are actually more secure than if you stored them yourself. But at the end of day, you have to trust them and you have to rely on them not being compromised.

**Bitcoin exchanges**. To understand Bitcoin exchanges, let's first talk about how banks or bank like services operate in the traditional economy. You give the bank some money — a deposit — and the bank promises to give you back that money later. Of course, crucially, the bank doesn't actually just take your money and put it in a box in the back room. All the bank does is promise that if you show up for the money they'll give it back. The bank will typically take the money and put it somewhere else, that is, invest it. The bank will probably keep some money around in reserve in order to make sure that they can pay out the demand for withdrawals that they'll face on a typical day, or maybe even an unusual day. Many banks typically use something called ***fractional reserve*** where they keep a certain fraction of all the demand deposits on reserve just in case.

Now, Bitcoin exchanges are businesses that at least from the user interface standpoint function in a similar way to banks. They accept deposits of bitcoins and will, just like a bank, promise to give them back on demand later. You can also transfer fiat currency — traditional currency like dollars and euros — into an exchange by doing a transfer from your bank account. The exchange promises to pay back either or both types of currency on demand. The exchange lets you do various banking-like things. You can make and receive Bitcoin payments. That is, you can direct the exchange to pay out some bitcoins to a particular party, or you can ask someone else to deposit funds into the particular exchange on your behalf — put into your account. They also let you exchange bitcoins for fiat currency or vice versa. Typically they do this by finding some customer who wants to buy bitcoins with dollars and some other customer who wants to sell bitcoins for dollars, and match them up. In other words, they try to find customers willing to take opposite positions in a transaction. If there's a mutually acceptable price, they will consummate that transaction.

Suppose my account at some exchange holds 5000 dollars and three bitcoins and I use the exchange, I put in an order to buy 2 bitcoins for 580 dollars each, and the exchange finds someone who is willing to take the other side of that transaction and the transaction happens. Now I have five bitcoins in my account instead of three, and 3840 dollars instead of 5000.

The important thing to note here is that when this transaction happened involving me and another customer of the same exchange, no transaction actually happened on the Bitcoin block chain. The exchange doesn't need to go to the block chain in order to transfer bitcoins or dollars from one account to another. All that happens in this transaction is that the exchange is now making a different promise to me than they were making before. Before they said, “we'll give you 5000 USD and 3 BTC” and now they're saying “we'll give you 3840 USD and 5 BTC.” It's just a change in their promise — no actual movement of money through the dollar economy or through the block chain. Of course, the other person has had their promises to them change in the opposite way.

There are pros and cons to using exchanges. One of the big pros is that exchanges help to connect the Bitcoin economy and the flows of bitcoins with the fiat currency economy so that it's easy to transfer value back and forth. If I have dollars and bitcoins in my account I can trade back and forth between them pretty easily, and that's really helpful.

The con is risk. You have the same kind of risk that you face with banks, and those risks fall into three categories.

**Three types of risks**. The first risk is the risk of a ***bank run***. A run is what happens when a bunch of people show up all at once and want their money back. Since the bank maintains only fractional reserves, it might be unable to cope with the simultaneous withdrawals. The danger is a kind of panic behavior where once the rumor starts to get around that a bank or exchange might be in trouble and they might be getting close to not honoring withdrawals, then people stampede in to try to withdraw their money ahead of the crowd, and you get a kind of avalanche.

The second risk is that the owners of the banks might just be crooks running a Ponzi scheme. This is a scheme where someone gets people to give them money in exchange for profits in the future, but then actually takes their money and uses it to pay out the profits to people who bought previously. Such a scheme is doomed to eventually fail and lose a lot of people a lot of money. Bernie Madoff most famously pulled this off in recent memory.

The third risk is that of a hack, the risk that someone — perhaps even an employee of the exchange — will manage to penetrate the security of the exchange. Since exchanges store key information that controls large amounts of bitcoins, they need to be really careful about their software security and their procedures — how they manage their cold and hot storage and all of that. If something goes wrong, your money could get stolen from the exchange.

All of these things have happened. We have seen exchanges that failed due to the equivalent of a bank run. We've seen exchanges fail due to the operators of the exchange being crooks, and we've seen exchanges that fail due to break-ins. In fact, the statistics are not encouraging. A study in 2013 found that 18 of 40 Bitcoin exchanges had ended up closing due to some failure or some inability to pay out the money that the exchange had promised to pay out.

The most famous example of this of course is Mt. Gox. Mt. Gox was at one time the largest Bitcoin exchange, and it eventually found itself insolvent, unable to pay out the money that it owed. Mt. Gox was a Japanese company and it ended up declaring bankruptcy and leaving a lot of people wondering where their money had gone. Right now the bankruptcy of Mt. Gox is tangled up in the Japanese and American courts, and it's going to be a while before we know exactly where the money went. The one thing we know is that there's a lot of it and Mt. Gox doesn't have it anymore. So this is a cautionary tale about the use of exchanges.

Connecting this back to banks, we don't see a 45% failure rate for banks in most developed countries, and that’s partly due to regulation. Governments regulate traditional banks in various ways.

**Bank regulation**. The first thing that governments do is they often impose a minimum reserve requirement. In the U.S., the fraction of demand deposits that banks are required to have in liquid form is typically 3-10%, so that they can deal with a surge of withdrawals if that happens. Second, governments often regulate the types of investments and money management methods that banks can use. The goal is to ensure that the banks’ assets are invested in places that are relatively low risk, because those are really the assets of the depositors in some sense.

Now, in exchange for these forms of regulation governments typically do things to help banks or help their depositors. First, governments will issue deposit insurance. That is, the government promises depositors that if a bank that follows these rules goes under, the government will make good on at least part of those deposits. Governments also sometimes act as a “lender of last resort.” If a bank gets itself into a tough spot, but it's basically solvent, the government may step in and loan the bank money to tide it over until it can move money around as necessary to get itself out of the woods.

So, traditional banks are regulated in this way. Bitcoin exchanges are not. The question of whether or how Bitcoin exchanges or other Bitcoin business should be regulated is a topic that we will come back to in chapter 7.

**Proof of reserve**. A Bitcoin exchange or someone else who holds bitcoins can use a cryptographic trick called a proof of reserve to give customers some comfort about the money that they deposited. The goal is for the exchange or business holding bitcoins to prove that it has a fractional reserve — that they retain control of perhaps 25% or maybe even 100% of the deposits that people have made.

We can break the proof-of-reserve problem into two pieces. The first is to prove how much reserve you’re holding — that's the relatively easy part. The company simply publishes a valid payment-to-self transaction of the claimed reserve amount. That is, if they claim to have 100,000 bitcoins, they create a transaction in which they pay 100,000 bitcoins to themselves and show that that transaction is valid. Then they sign a challenge string — a random string of bits generated by some impartial party — with the same private key that was used to sign the payment-to-self transaction. This proves that someone who knew that private key participated in the proof of reserve.

We should note two caveats. Strictly speaking, that's not a proof that the party that's claiming to own the reserve owns it, but only that whoever does own those 100,000 bitcoins is willing to cooperate in this process. Nonetheless, this looks like a proof that somebody controls or knows someone who controls the given amount of money. Also, note that you could always under-claim: the organization might have 150,000 bitcoins but choose to make a payment-to-self of only 100,000. So this proof of reserve doesn't prove that this is all you have, but it proves that you have at least that much.

**Proof of liabilities.** The second piece is to prove how many demand deposits you hold, which is the hard part. If you can prove your reserves and your demand deposits then anyone can simply divide those two numbers and that's what your fractional reserve is. We'll present a scheme that allows you to *over-claim* but not under-claim your demand deposits. So if you can prove that your reserves are at least a certain amount and your liabilities are at most a certain amount, taken together, you've proved a lower bound on your fractional reserve.

If you didn't care at all about the privacy of your users, you could simply publish your records — specifically, the username and amount of every customer with a demand deposit. Now anyone can calculate your total liabilities, and if you omitted any customer or lied about the value of their deposit, you run the risk that that customer will expose you. You could make up fake users, but you can only increase the value of your claimed total liabilities this way. So as long as there aren't customer complaints, this lets you prove a lower bound on your deposits. The trick, of course, is to do all this while respecting the privacy of your users.

To do this we'll use Merkle trees, which we saw in chapter 1. Recall that a merkle tree is a binary tree that's built with hash pointers so that each of the pointers not only says where we can get a piece of information, but also what the cryptographic hash of that information is. The exchange executes the proof by constructing a Merkle tree in which each leaf corresponds to a user, and publishing its root hash. Similar to the naive protocol above, it's each user's responsibility to ensure that they are included in the tree. In addition, there's a way for users to collectively check the claimed total of deposits. Let's delve into detail now.

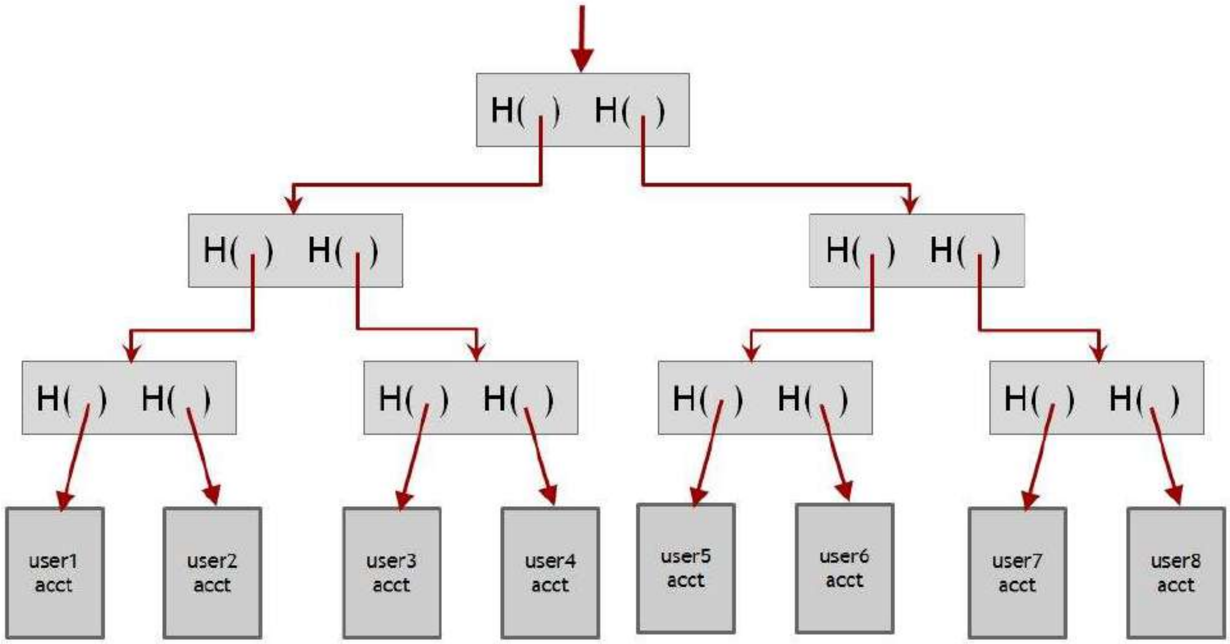



**Figure 4.5: Proof of liabilities.** The exchange publishes the root of a Merkle tree that contains all users at the leaves, including deposit amounts. Any user can request a proof of inclusion in the tree, and verify that the deposit sums are propagated correctly to the root of the tree.

Now, we're going to add to each one of these hash pointers another field, or attribute. This attribute is a number that represents the total monetary value in bitcoins of all deposits that are in the sub-tree underneath that hash pointer in the tree. For this to be true, the value corresponding to each hash pointer should be the sum of the values of the two hash pointers beneath it.

The exchange constructs this tree, cryptographically signs the root pointer along with the root attribute value, and publishes it. The root value is of course the total liabilities, the number we're interested in. The exchange is making the claim that all users are represented in the leaves of the tree, their deposit values are represented correctly, and that the values are propagated correctly up the tree so that the root value is the sum of all users' deposit amounts.

Now each customer can go to the organization and ask for a proof of correct inclusion. The exchange must then show the customer the partial tree from that user's leaf up to the root, as shown in Figure 4.6. The customer then verifies that:

1. The root hash pointer and root value are the same as what the exchange signed and published.
2. The hash pointers are consistent all the way down, that is, each hash value is indeed the cryptographic hash of the node it points to.
3. The leaf contains the correct user account info (say, username/user ID, and deposit amount).
4. Each value is the sum of the values of the two values beneath it.

5. Neither of the values is a negative number.

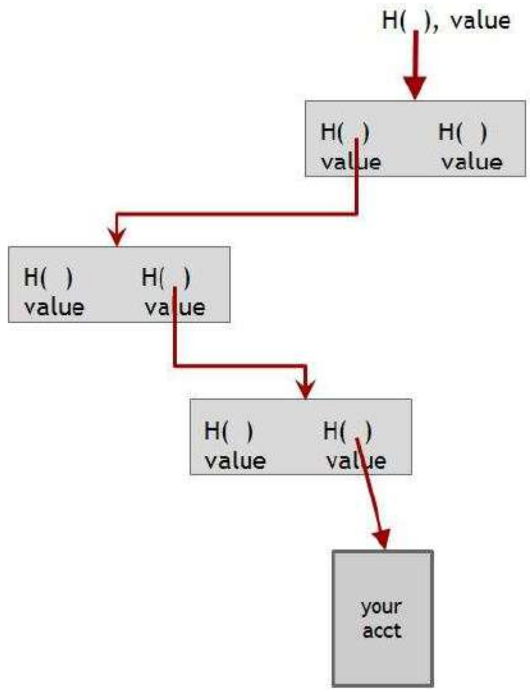



**Figure 4.6: Proof of inclusion in a Merkle tree.** The leaf node is revealed, as well as the siblings of the nodes on the path from the leaf to the root.

The good news is that if every customer does this, then every branch of this tree will get explored, and someone will verify that for every hash pointer, its associated value equals the sum of the values of its two children. Crucially, the exchange cannot present different values in any part of the tree to different customers. That's because doing so would either imply the ability find a hash collision, or presenting different root values to different customers, which we assume is impossible.

Let's recap. First the exchange proves that they have at least X amount of reserve currency by doing a self transaction of X amount. Then they prove that their customers have at most an amount Y deposited. This shows that their reserve fraction is at least X/Y. What that means is that if a Bitcoin exchange wants to prove that they hold 25% reserves on all deposits — or 100% — they can do that in a way that's independently verifiable by anybody, and no central regulator is required.

You might notice that the two proofs presented here (the proof of reserves by signing a challenge string and the proof of liabilities via a Merkle tree) reveal a lot of private information. Specifically, they reveal all of the addresses being used by the exchange, the total value of the reserves and liabilities, and even some information about the individual customers balances. Real exchanges are hesitant to publish this, and as a result cryptographic proofs of reserve have been rare.

A recently proposed protocol called Provisions enables the same proof-of-solvency, but without revealing the total liabilities or reserves or the addresses in use. This protocol uses more advanced crypto and we won't cover it here, but it's another example showing how cryptography can be used to ensure privacy.

Solvency is one aspect of regulation that Bitcoin exchanges can prove voluntarily, but other aspects of regulation are harder to guarantee, as we'll see in Chapter 7.

## 4.5 Payment Services

So far we've talked about how you can store and manage your bitcoins. Now let's consider how a merchant — whether an online merchant or a local retail merchant — can accept payments in bitcoins in a practical way. Merchants generally support Bitcoin payments because their customers want to be able to pay with bitcoins. The merchant may not want to hold on to bitcoins, but simply receive dollars or whatever is the local fiat currency at the end of the day. They want an easy way to do this without worrying too much about technology, changing their website or building some type of point of sale technology.

The merchant also wants low risk. There are various possible risks: using new technology may cause their website to go down, costing them money. There's the security risk of handling bitcoins — someone might break into their hot wallet or some employee will make off with their bitcoins. Finally there's the exchange rate risk: the value of bitcoins in dollars might fluctuate from time to time. The merchant who might want to sell a pizza for twelve dollars wants to know that they're going to get twelve dollars or something close to it, and that the value of the bitcoins that they receive in exchange for that pizza won't drop drastically before they can exchange those bitcoins for dollars.

Payment services exist to allow both the customer and the merchant to get what they want, bridging the gap between these different desires.

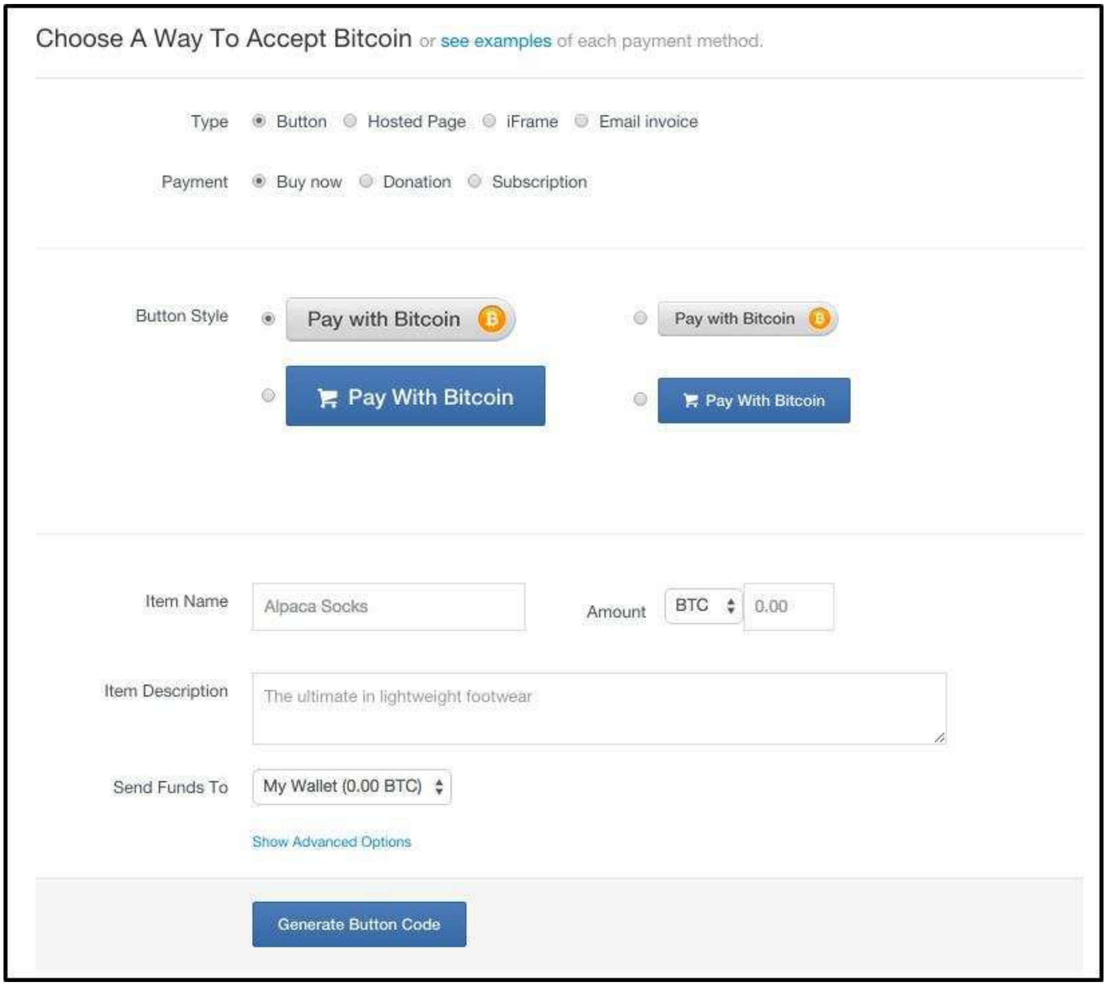



**Figure 4.7: Example payment service interface for generating a pay-with-Bitcoin button.** A merchant can use this interface to generate a HTML snippet to embed on their website.

The process of receiving Bitcoin payments through a payment service might look like this to the merchant:

1. The merchant goes to payment service website and fills out a form describing the item, price, and presentation of the payment widget, and so on. Figure 4.7 shows an illustrative example of a form from Coinbase.
2. The payment service generates HTML code that the merchant can drop into their website.
3. When the customer clicks the payment button, various things happen in the background and eventually the merchant gets a confirmation saying, “a payment was made by customer ID [customer-id] for item [item-id] in amount [value].”

While this manual process makes sense for a small site selling one or two items, or a site wishing to receive donations, copy-pasting HTML code for thousands of items is of course infeasible. So payment services also provide programmatic interfaces for adding a payment button to dynamically generated web pages.

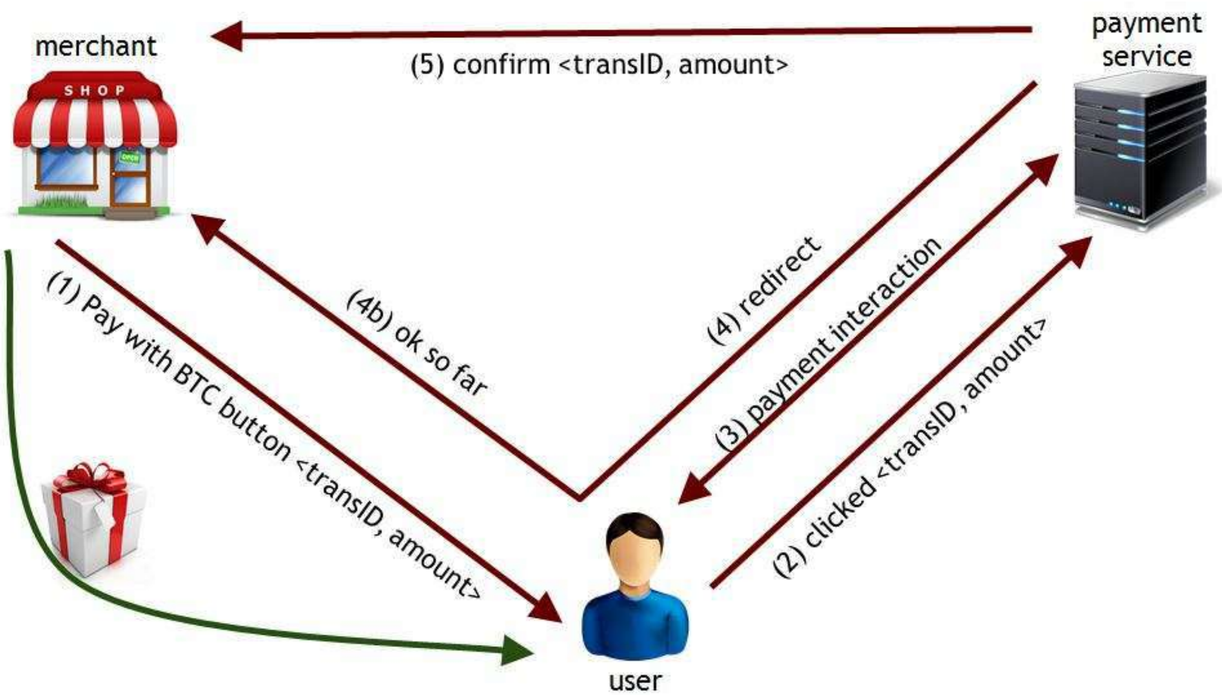



**Figure 4.8: Payment process involving a user, merchant, and payment service.**

Now let's look at the payment process in more detail to see what happens when the customer makes a purchase with Bitcoin. The steps below are illustrated in Figure 4.8.

1. The user picks out an item to buy on the merchant website, and when it comes time to pay, the merchant will deliver a webpage which will contain the Pay with Bitcoin button, which is the HTML snippet provided by the payment service. The page will also contain a transaction ID — which is an identifier that's meaningful to the merchant and allows them to locate a record in their own accounting system — along with an amount the merchant wants to be paid.
2. If the user wants to pay with bitcoins, they will click that button. That will trigger an HTTPS request to the payment service saying that the button was clicked, and passing on the identity of the merchant, the merchant's transaction ID, and the amount.
3. Now the payment service knows that this customer — whoever they are — wants to pay a certain amount of bitcoins, and so the payment service will pop up some kind of a box, or initiate some kind of an interaction with the user. This gives the user information about how to pay, and the user will then initiate a bitcoin transfer to the payment service through their preferred wallet.
4. Once the user has created the payment, the payment service will redirect the browser to the merchant, passing on the message from the payment service that it looks okay so far. This might mean, for example, that the payment service has observed the transaction broadcast to the peer-to-peer network, but the transaction hasn't received enough (or any) confirmations so far. This completes the payment as far as the user is concerned, with the merchant's shipment of goods pending a final confirmation from the payment service.

5. The payment service later directly sends a confirmation to the merchant containing the transaction ID and amount. By doing this the payment service tells the merchant that the service owes the merchant money at the end of the day. The merchant then ships the goods to the user.

The final step is the one where the payment service actually sends money to the merchant, in dollars or some fiat currency, via a deposit to the merchant's bank account. This happens at the end of fixed settlement periods, perhaps once a day, rather than once for each purchase. The payment service keeps a small percentage as a fee; that's how they make their revenue. Some of these details might vary depending on the payment service, but this is the general scheme of things.

To recap, at the end of this process the customer pays bitcoins and the merchant gets dollars, minus a small percentage, and everyone is happy. Recall that the merchant wants to sell items for a particular number of dollars or whatever is the local fiat currency. The payment service handles everything else — receiving bitcoins from customers and making deposits at the end of the day.

Crucially, the payment service absorbs all of the risk. It absorbs the security risk, so it needs to have good security procedures to manage its bitcoins. It absorbs the exchange rate risk because it's receiving bitcoins and paying out dollars. If the price of dollars against bitcoins fluctuates wildly, the payment service might lose money. But then if it fluctuates wildly in the other direction the service might earn money, but it's a risk. Absorbing it is part of the payment service's business.

Note that the payment service probably operates at a large scale, so it receives large numbers of bitcoins and pays out large numbers of dollars. it will have a constant need to exchange the bitcoins it's receiving for more dollars so that it can keep the cycle going. Therefore a payment service has to be an active participant in the exchange markets that link together fiat currencies and the Bitcoin economy. So the service needs to worry about not just what the exchange rate is, but also how to exchange currency in large volumes.

That said, if it can solve these problems the fee that the service receives on every transaction makes it a potentially lucrative business because it solves the mismatch between customers' desire to pay bitcoins and merchants' desire to just get dollars and concentrate on selling goods.

## 4.6 Transaction Fees

The topic of transaction fees has come up in previous chapters and it will come up again in later chapters. Here we'll discuss the practical details of how transaction fees are set in Bitcoin today.

Whenever a transaction is put into the Bitcoin block chain, that transaction might include a transaction fee. Recall from a previous chapter that a transaction fee is just defined to be the difference between the total value of coins that go into a transaction minus the total value of coins that come out. The inputs always have to be at least as big as the outputs because a regular transaction can't create coins, but if the inputs are bigger than the outputs then the difference is deemed to be a transaction fee, and that fee goes to the miner who makes the block that includes this transaction.

The economics of transaction fees are interesting and complex, but we'll limit ourselves to how transaction fees are actually set in Bitcoin as it operates as of early 2015. These details do change from time to time, but we'll give you a snapshot of the current state.

Why do transaction fees exist at all? The reason is that there is some cost that someone has to incur in order to relay your transaction. The Bitcoin nodes need to relay your transaction and ultimately a miner needs to build your transaction into a block, and it costs them a little bit to do that. For example, if a miner's block is slightly larger because it contains your transaction, it will take slightly longer to propagate to the rest of the network and there's a slightly higher chance that the block will be orphaned if another block was found near-simultaneously by another miner.

So, there is a cost — both to the peer to peer network and to the miners — of incorporating your transaction. The idea of a transaction fee is to compensate miners for those costs they incur to process your transaction. Nodes don't receive monetary compensation in the current system, although running a node is of course far less expensive than being a miner. Generally you're free to set the transaction fee to whatever you want it to be. You can pay no fee, or if you like you can set the fee quite high. As a general matter, if you pay a higher transaction fee it's natural that your transaction will be relayed and recorded more quickly and more reliably.

**Current default transaction fees.** The current transaction fees that most miners expect are as follows: first of all, no fee is charged if a transaction meets all of these three conditions:

1. the transaction is less than 1000 bytes in size,
2. all outputs are 0.01 BTC or larger
3. priority is large enough

Priority is defined as: (sum of input age * input value) / (transaction size). In other words, look at all of the inputs to the transaction, and for each one compute the product of that input's age and its value in bitcoins, and add up all those products. Note that the longer a transaction output sits unspent, the more it ages, and the more it will contribute to priority when it is finally spent.

If you meet these three requirements then your transaction will be relayed and it will be recorded in the block chain without a fee. Otherwise a fee is charged and that fee is about .0001 BTC per 1000 bytes, and as of 2015 that's a fraction of a U.S. penny per 1000 bytes. The approximate size of a transaction is 148 bytes for each input plus, 34 bytes for each output and ten bytes for other information. So a transaction with two inputs and two outputs would be about 400 bytes.

The current status quo is that most miners enforce the above fee structure, which means that they will either not service or will service last transactions that don't provide the necessary transaction fees. But there are other miners who don't enforce these rules, and who will record and operate on a transaction even if it pays a smaller fee or no fee at all.

If you make a transaction that doesn't meet the fee requirements it will probably find its way into the block chain anyway, but the way to get your transaction recorded more quickly and more reliably is to pay the standard fee, and that's why most wallet software and most payment services include the standard fee structure in the payments that go on, and so you'll see a little bit of money raked off for transaction fees when you engage in everyday Bitcoin business.

## 4.7 Currency Exchange Markets

By currency exchange we mean trading bitcoins against fiat currency like dollars and euros. We've talked earlier about services that let you do this, but now we want to look at this as a market — its size, extent, how it operates, and a little bit about the economics of this market.

The first thing to understand is that it operates in many ways like the market between two fiat currencies such as dollars and euros. The price will fluctuate back and forth depending on how badly people want to buy euros versus how badly people want to buy dollars on a particular day. In the Bitcoin world there are sites like bitcoincharts.com that show the exchange rate with various fiat currencies on a number of different exchanges.

As you'll see if you explore the site, there's a lot of trading going on, and the prices move in real time as trades are made. It's a liquid market and there are plenty of places that you can go to to buy or sell bitcoins. In March 2015 the volume on Bitfinex, the largest Bitcoin — USD exchange, was about 70,000 bitcoins or about 21 million dollars over a 24 hour period.

Another option is to meet people to trade bitcoins in real life. There are sites that help you do this. On localbitcoins.com, for example, you can specify your location and that you wish to buy bitcoins with cash. You'll get a bunch of results of people who at the time of your search are willing to sell bitcoins at that location, and in each case it tells you what price and how many bitcoins they're offering. You can then contact any of them and arrange to meet at a coffee shop or in a park or wherever, give them dollars and receive bitcoins in exchange. For small transactions, it may be sufficient to wait for one or two confirmations on the block chain.

Finally, in some places there are regular meet-ups where people go to trade bitcoins, and so you can go to a certain park or street corner or cafe at a scheduled day and time and there will be a bunch of people wanting to buy or sell bitcoins and you can do business with them. One reason someone might prefer obtaining bitcoins in person over doing so online is that it's anonymous, to the extent that a transaction in a public place can be considered anonymous. On the other hand, opening an account with an exchange generally requires providing government-issued ID due to banking regulation. We'll discuss this in more detail in Chapter 7.

**Supply and demand.** Like any market, the Bitcoin exchange market matches buyers who want to do one thing with sellers that are willing to do the opposite thing. It's a relatively large market — millions of U.S. dollars per day pass through it. It's not at the scale of the New York Stock Exchange or the dollar–euro market, which are vastly larger, but it's large enough that there is a notion of a consensus price. A person who wants to come into this market can buy or sell at least a modest amount and will always be able to find a counterparty.

The price of this market, this consensus price, like the price of anything in a liquid market will be set by supply and demand. By that we mean the supply of bitcoins that might potentially be sold and the demand for bitcoins by people who have dollars. The price through this market mechanism will be set to the level that matches supply and demand. Let's dig into this in a little more detail.

What is the supply of bitcoins? This is the number of bitcoins that you might possibly buy in one of these markets, and it is equal to the supply of bitcoins that are in circulation currently. There's a fixed number of bitcoins in circulation. As of October 2015 it's about 13.9 million, and the rules of Bitcoin as they currently stand say that this number will slowly go up and eventually hit a limit of 21 million.

You might also include demand deposits of bitcoins. That is, if someone has put money into their account in a Bitcoin exchange, and the exchange doesn't maintain a full reserve to meet every single deposit, then there will be demand deposits at that exchange that are larger than the number of coins that the exchange is holding.

Depending on what question you're asking about the market it might or might not be correct to include demand deposits in the supply. Basically, you should include demand deposits in a market analysis when demand-deposited money can be sold in that market. For example, if you've traded dollars for a demand deposit of bitcoins, and the exchange allows demand-deposited bitcoins to be redeemed for dollars, then they count.

It's worth noting, as well, that when economists conventionally talk about the supply of fiat currency they typically include in the money supply not only the currency that's in circulation — that is, paper and metal money — but also the total amount of demand deposits, and that's for the logical reason that people can actually spend their demand-deposited money to buy stuff. So although it's tempting to say that the supply of bitcoins is fixed at 13.9 million currently or 21 million eventually, for some purposes we have to include demand deposits where those demand deposits function like money, and so the supply might not be fixed the way some Bitcoin advocates might claim. We need to look at the circumstances of the particular market we're talking about in order to understand what the proper money supply is. But let's assume we've agreed on what supply we're using based on what market we're analyzing.

Let's now look at demand. There are really two main sources of demand for bitcoins. There's a demand for bitcoins as a way of mediating fiat currency transactions and there's demand for bitcoins as an investment.

First let's look at mediating fiat currency transactions. Imagine that Alice wants to buy something from Bob and wants to pay some money to Bob, and Alice and Bob want to transfer let's say a certain amount of dollars, but they find it convenient to use Bitcoin to do this transfer. Let's assume here that neither Alice nor Bob is interested in holding bitcoins long-term. We'll return to that possibility in a moment. So Alice would buy bitcoins for dollars and transfer them, and once they receive enough confirmations to Bob's satisfaction, he'll sell those bitcoins for dollars. The key thing here from the point of view of demand for bitcoins is that the bitcoins mediating this transaction have to be taken out of circulation during the time that the transaction is going on. This creates a demand for bitcoins.

The second source of demand is that Bitcoin is sometimes demanded as an investment. That is if somebody wants to buy bitcoins and hold them in the hope that the price of bitcoins will go up in the future and that they'll be able to sell them. When people buy and hold, those bitcoins are out of circulation. When the price of Bitcoin is low, you might expect a lot of people to want to buy bitcoins as an investment, but if the price goes up very high then the demand for bitcoins as an investment won't be as high.

**A simple model of market behavior.** Now, we can do some simple economic modeling to understand how these markets will behave. We won't do a full model here although that's an interesting exercise. Let's look specifically at the the transaction-mediation demand and what effect that might have on the price of bitcoins.

We'll start by assuming some parameters. T is the total transaction value mediated via Bitcoin by everyone participating in the market. This value is measured in dollars per second. That's because we assume for simplicity that the people who want to mediate these transactions have in mind a certain dollar value of the transactions, or some other fiat currency that we'll translate into dollars. So there's a certain amount of dollars per second of transactions that need to be mediated. D is the duration of time that bitcoins need to be held out of circulation in order to mediate a transaction. That's the time from when the payer buys the bitcoins to when the receiver is able to sell them back into the market, and we'll measure that in seconds. S is the total supply of bitcoins that are available for this purchase, and so that's going to be all of the hard-currency bitcoins that exist — currently about 14 million or eventually up to 21 million — minus those that are held out by people as long term investments. In other words, we're talking about the bitcoins sloshing around and available for the purpose of mediating transactions. Finally, P is the price of Bitcoin, measured in dollars per bitcoin.

Now we can do some calculations. First we'll calculate how many bitcoins become available in order to service transactions every second. There are S bitcoins available in total and because they're taken out of circulation for a time of D seconds, every second on average an S/D fraction of those bitcoins will become newly available because they'll emerge from the out-of-circulation state and become available for mediating transactions every second. That's the supply side.

On the demand side — the number of bitcoins per second that are needed to mediate transactions — we have T dollars worth of transactions to mediate and in order to mediate one dollar worth of transactions we need 1/P bitcoins. So T/P is the number of bitcoins per second that are needed in order to serve all of the transactions that people want to serve.

Now if you look at a particular second of time, for that second there's a supply of S/D and a demand of T/P. In this market, like most markets, the price will fluctuate in order to bring supply into line with demand. If the supply is higher than the demand then there are bitcoins going unsold, so people selling bitcoins will be willing to lower their asking price in order to sell them. And according to our formula T/P for demand, when the price drops the demand increases, and supply and demand will reach equilibrium.

On the other hand, if supply is smaller than demand it means that there are people who want to get bitcoins in order to mediate a transaction but can't get them because there aren't enough bitcoins around. Those people will then have to bid more in order to get their bitcoins because there will be a lot of competition for a limited supply of bitcoins. This drives the price up, and referring to our formula again, it means that demand will come down until there is equilibrium. In equilibrium, the supply must equal the demand, so we have

$$\frac{S}{D} = \frac{T}{P}$$

which gives us a formula for the price:

$$P = \frac{TD}{S}$$

What does this equation tell us? We can simplify it a bit further: we can assume that D, the duration for which you need to hold a bitcoin to mediate a transaction, doesn't change. The total supply S also doesn't change, or at least changes slowly over time. That means the price is proportional to the demand for mediation as measured in dollars. So if the demand for mediation in dollars doubles then the price of bitcoins should double. We could in fact graph the price against some estimate of the demand for transaction mediation and see whether or not they match up. When economists do this, the two do tend to match up pretty well.

Notice that the total supply S includes only the bitcoins that aren't being held as investments. So if more people are buying bitcoins as an investment, S will go down, and our formula tells us that P will go up. This makes sense — if there's more demand on the investment side then the price that you need to pay to mediate a transaction will go up.

Now this is not a full model of the market. To have a full model we need to take into account the activity of investors. That is, investors will demand bitcoins when they believe the price will be higher in the future, and so we need to think about investors' expectations. These expectations, of course, have something to do with the expected demand in the future. We could build a model that is more complex and takes that into account, but we won't do that here.

The bottom line here is that there is a market between bitcoins and dollars, and between bitcoins and other fiat currencies. That market has enough liquidity that you can buy or sell in modest quantities in a reliable way, although the price does go up and down. Finally, it's possible to do economic modeling and have some idea about how supply and demand interact in this market and predict what the market might do, as long as you have a way to estimate unknowable things like how much are people going to want to use Bitcoin to mediate transactions in the future. That kind of economic modeling is important to do and very informative, and surely there are people who are doing it in some detail today, but a detailed economic model of this market is beyond the scope of this text.

## Further reading

Securing bitcoins has some similarities, as well as important differences, to the way banks secure money. Chapter 10 of Ross Anderson's security textbook, titled "Banking and bookkeeping", is a great read. The entire book is freely available online.

**Anderson, Ross. *Security engineering*. John Wiley & Sons, 2008.**

The study analyzing closures of Bitcoin exchanges that we referenced:

**Moore, Tyler, and Nicolas Christin. *Beware the middleman: Empirical analysis of bitcoin-exchange risk.* Financial Cryptography and Data Security 2013.**

Adi Shamir's paper on secret sharing:

**Shamir, Adi. *How to share a secret*. Communications of the ACM 22.11 (1979).**

Paper describing Provisions, a protocol for privacy-preserving solvency proofs:

**Dagher, Gaby and Benedikt Bünz and Joseph Bonneau and Jeremy Clark and Dan Boneh. Provisions: Privacy-preserving proofs of solvency for Bitcoin exchanges. In ACM CCS, 2015.**

It's difficult for users to pick memorable yet hard-to-guess passwords because modern password-cracking techniques are quite clever and effective. This paper presents one such technique:

**Weir, Matt, Sudhir Aggarwal, Breno De Medeiros, and Bill Glodek. Password cracking using probabilistic context-free grammars. In Security and Privacy, 2009.**

A survey of transaction fees in practice through 2014:

**Möser, Malte and Böhme, Rainer. Trends, Tips, Tolls: A Longitudinal Study of Bitcoin Transaction Fees. 2nd Workshop on Bitcoin Research, 2015.**

## Exercises

1. **Proof of reserve.** TransparentExchange claims that it controls at least 500,000 BTC and wants to prove this to its customers. To do this it publishes a list of addresses that have a total

balance of 500,000 BTC. It then signs the statement "TransparentExchange controls at least 500,000 BTC" with each of the corresponding private keys, and presents these signatures as proof.

What are some ways in which TransparentExchange might be able to produce such a proof even if it doesn't actually currently control 500,000 BTC? How would you modify the proof to make it harder for the exchange to cheat?

2. **Proof of liabilities.**

   TransparentExchange implements a Merkle Tree based protocol to prove an upper bound on its total deposits. (Combined with a proof of reserve, this proves that the exchange is solvent.) Every customer is assigned a leaf node containing an ID which is the hash of her username and a value which is her BTC balance. The protocol specifies that TransparentExchange should propagate IDs and values up the tree by the following recursive definition — for any internal node:

   node.value = node.left_child.value + node.right_child.value

   node.id = Hash(node.left_child.id ‖ node.right_child.id ‖ node.value)

   The exchange publishes the root ID and value, and promises to prove to any customer that her node is included in the tree (by the standard Merkle tree proof of inclusion). The idea is that if the exchange tries to claim a lower total than the actual sum of deposits by leaving some customers out of the tree or by making their node value less than their balance, it will get caught when any of those customers demand a proof of inclusion.

   **2.1.** Why can't the exchange include fake customers with negative values to lower the total?

   **2.2.** Show an attack on this scheme that would allow the exchange to claim a total less than the actual sum of deposits.

   **2.3.** Fix this scheme so that it is not vulnerable to the attack you identified.

   **2.4.** Ideally, the proof that the exchange provides to a customer shouldn't leak information about other customers. Does this scheme have this property? If not, how can you fix it?

3. **Transaction fees.**

   **3.1.** Alice has a large number of coins each of small value *v*, which she would like to combine into one coin. She constructs a transaction to do this, but finds that the transaction fee she'd have to spend equals the sum of her coin values. Based on this information (and the default transaction fee policy specified in slide 50), estimate *v*.

   **3.2.** Can Alice somehow consolidate her coins without incurring any transaction fee under the default policy?

   **3.3.** Compared to a fee structure that doesn't factor the age of the inputs into the transaction fee, what effect might the current default fee structure have on the behavior of users and services?

4. **Multi-signature wallet**

   **4.1.** BitCorp has just noticed that Mallory has compromised one of their servers holding their Bitcoin private keys. Luckily, they are using a 2-of-3 multi-signature wallet, so Mallory has learnt only one of the three sets of keys. The other two sets of keys are on different servers that Mallory cannot access. How do they re-secure their wallet and effectively revoke the information that Mallory has learned?

**4.2.** If BitCorp uses a 2-out-of-2 instead of a 2-out-3 wallet, what steps can they take in advance so that they can recover even in the event of one of their servers getting broken into (and Mallory not just learning but also potentially deleting the key material on that server)?

**5. Exchange rate**

**5.1.** Speculate about why buying bitcoins in person is generally more expensive than buying from an online exchange.

**5.2.** Moore and Christin observe that security breaches and other failures of exchanges have little impact on the Bitcoin exchange rate. Speculate on why this might be.

**6. Payments.** A Bitcoin payment service might receive thousands of payments from various users near-simultaneously. How can it tell whether a particular user Alice who logged into the payment service website and initiated the payment protocol actually made a payment or not?

**7. BitcoinLotto:** Suppose the nation of Bitcoinia has decided to convert its national lottery to use Bitcoin. A trusted scratch-off ticket printing factory exists and will not keep records of any values printed. Bitcoinia proposes a simple design: a weekly run of tickets is printed with an address holding the jackpot on each ticket. This allows everybody to verify the jackpot exists. The winning ticket contains the correct private key under the scratch material.

**7.1.** What might happen if the winner finds the ticket on Monday and immediately claims the jackpot? Can you modify your design to ensure this won't be an issue?

**7.2.** Some tickets inevitably get lost or destroyed. So you'd like to modify the design to roll forward any unclaimed jackpot from Week *n* to the winner in Week *n+1*. Can you propose a design that works, without letting the lottery administrators embezzle funds? Also make sure that the Week *n* winner can't simply wait until the beginning of Week *n+1* to attempt to double their winnings.

# Chapter 5: Bitcoin Mining

This chapter is all about mining. We've already seen quite a bit about miners and how Bitcoin relies on them — they validate every transaction, they build and store all the blocks, and they reach a consensus on which blocks to include in the block chain. We also have already seen that miners earn some reward for doing this, but we still have left many questions unanswered. Who are the miners? How did they get into this? How do they operate? What's the business model like for miners? What impact do they have on the environment? In this chapter, we will answer all of these questions.

## 5.1 The task of Bitcoin miners

Do you want to get into Bitcoin mining? If you do, we're not going to completely discourage you, but beware that Bitcoin mining bears many similarities to gold rushes. Historical gold rushes are full of stories of young people rushing off to find fortune and inevitably many of them lose everything they have. A few strike it rich, but even those that do generally endure lots of hardship along the way. We'll see in this section why Bitcoin mining shares many of the same challenges and risks as traditional gold rushes and other get-rich-quick schemes.

But first, let's look at the technical details. To be a Bitcoin miner, you have to join the Bitcoin network and connect to other nodes. Once you're connected, there are six tasks to perform:

1. *Listen for transactions.* First, you listen for transactions on the network and validate them by checking that signatures are correct and that the outputs being spent haven't been spent before.
2. *Maintain block chain and listen for new blocks.* You must maintain the block chain. You start by asking other nodes to give you all of the historical blocks that are already part of the block chain before you joined the network. You then listen for new blocks that are being broadcast to the network. You must validate each block that you receive — by validating each transaction in the block and checking that the block contains a valid nonce. We'll return to the details of nonce checking later in this section.
3. *Assemble a candidate block.* Once you have an up-to-date copy of the block chain, you can begin building your own blocks. To do this, you group transactions that you heard about into a new block that extends the latest block you know about. You must make sure that each transaction included in your block is valid.
4. *Find a nonce that makes your block valid.* This step requires the most work and it's where all the real difficulty happens for miners. We will see this in detail shortly.
5. *Hope your block is accepted.* Even if you find a block, there's no guarantee that your block will become part of the consensus chain. There's bit of luck here; you have to hope that other miners accept your block and start mining on top of it, instead of some competitor's block.
6. *Profit.* If all other miners do accept your block, then you profit! At the time of this writing in early 2015, the block reward is 25 bitcoins which is currently worth over $6,000. In addition, if

any of the transactions in the block contained transaction fees, the miner collects those too. So far transaction fees have been a modest source of additional income, only about 1% of block rewards.

We can classify the steps that a miner must take into two categories. Some tasks — validating transactions and blocks — help the Bitcoin network and are fundamental to its existence. These tasks are the reason that the Bitcoin protocol requires miners in the first place. Other tasks — the race to find blocks and profit —- aren't necessary for the Bitcoin network itself but are intended to incentivize miners to perform the essential steps. Of course, both of these are necessary for Bitcoin to function as a currency, since miners need an incentive to perform the critical steps.

***Finding a valid block.*** Let's return to the question of finding a nonce that makes your block valid. In Chapter 3 we saw that there are two main hash-based structures. There's the block chain where each block header points to the previous block header in the chain, and then within each block there's a Merkle tree of all of the transactions included in that block.

The first thing that you do as a miner is to compile a set of valid transactions that you have from your pending transaction pool into a Merkle tree. Of course, you may choose how many transactions to include up to the limit on the total size of the block. You then create a block with a header that points to the previous block. In the block header, there's a 32 bit nonce field, and you keep trying different nonces looking for one that causes the block's hash to be under the target — roughly, to begin with the required number of zeros. A miner may begin with a nonce of 0 and successively increment it by one in search of a nonce that makes the block valid. See Figure 5.1.

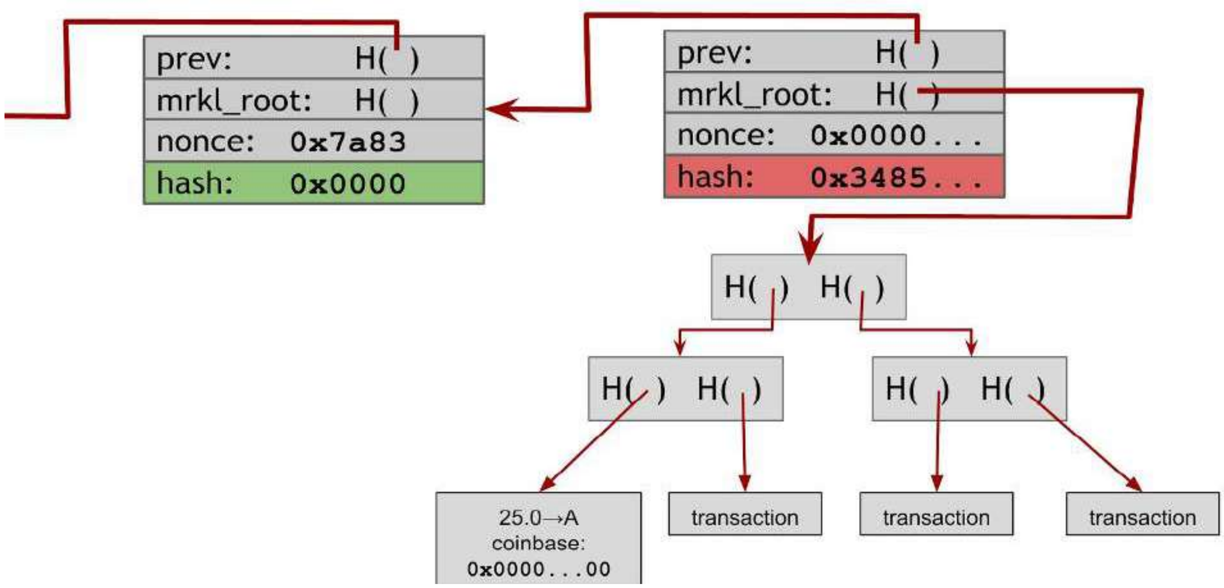



**Figure 5.1: Finding a valid block.** In this example, the miner tries a nonce of all 0s. It does not produce a valid hash output, so the miner would then proceed to try a different nonce.

In most cases you'll try every single possible 32-bit value for the nonce and none of them will produce a valid hash. At this point you're going to have to make further changes. Notice in Figure 5.1 that there's an additional nonce in the coinbase transaction that you can change as well. After you've exhausted all possible nonces for the block header, you'll change the extra nonce in the coinbase transaction — say by incrementing it by one — and then you'll start searching nonces in the block header once again.

When you change the nonce parameter in the coinbase transaction, the entire Merkle tree of transactions has to change (See Figure 5.2). Since the change of the coinbase nonce will propagate all the way up the tree, changing the extra nonce in the coinbase transaction is much more expensive operation than changing the nonce in the block header. For this reason, miners spend most of their time changing the nonce in the block header and only change the coinbase nonce when they have exhausted all of the $2^{32}$ possible nonces in the block header without finding a valid block.

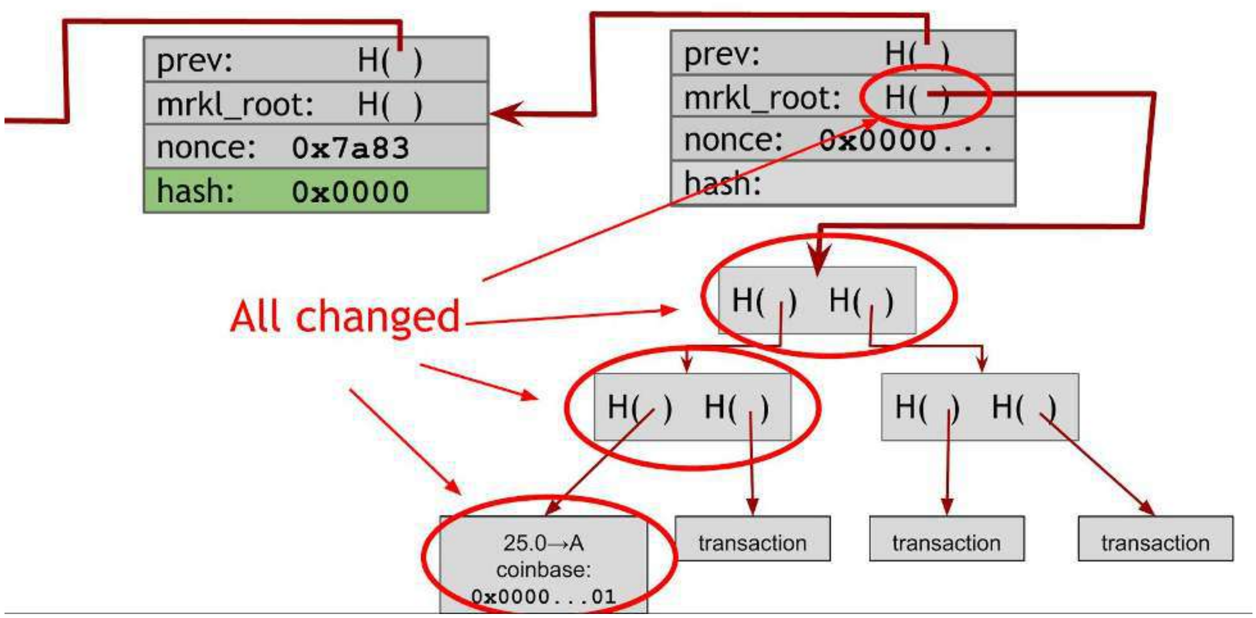



**Figure 5.2:** Changing a nonce in the coinbase transaction propagates all the way up the Merkle tree.

The vast, vast majority of nonces that you try aren't going to work, but if you stay at it long enough you'll eventually find the right combination of the extra nonce in the coinbase transaction and the nonce in the block header that produce a block with a hash under the target. When you find this, you want to announce it as quickly as you can and hope that you can profit from it.

**Is everyone solving the same puzzle?** You may be wondering: if every miner just increments the nonces as we described, aren't all miners solving the exact same puzzle? Won't the fastest miner always win? The answer is no! Firstly, it's unlikely that miners will be working on the exact same block as each miner will likely include a somewhat different set of transactions and in a different order. But more importantly, even if two different miners were working on a block with identical transactions, the blocks would still differ. Recall that in the coinbase transaction, miners specify their own address as the owner of the newly minted coins. This address by itself will cause changes which propagate up to the root of the Merkle tree, ensuring that no two miners are working on exactly the same puzzle unless they share a public key. This would only happen if the two miners are part of the same mining pool (which we'll discuss shortly), in which case they'll communicate to ensure they include a distinct nonce in the coinbase transaction to avoid duplicating work.

***Difficulty.*** Exactly how difficult is it to find a valid block? As of March 2015, the mining difficulty target (in hexadecimal) is:

0000000000000000172EC0000000000000000000000000000000000000000000

so the hash of any valid block has to be below this value. In other words only one in about $2^{67}$ nonces that you try will work, which is a really huge number. One approximation is that it's greater than the human population of Earth squared. So, if every person on Earth was themselves their own planet Earth with seven billion people on it, the total number of people would be close to $2^{67}$.

***Determining the difficulty.*** The mining difficulty changes every 2016 blocks, which are found about once every 2 weeks. It is adjusted based on how efficient the miners were over the period of the previous 2016 blocks according to this formula:

**next_difficulty = (previous_difficulty * 2016 * 10 minutes) / (time to mine last 2016 blocks)**

Note that 2016*10 minutes is exactly two weeks, so 2016 blocks would take two weeks to mine 2016 blocks if a block were created exactly every 10 minutes. So the effect of this formula is to scale the difficulty to maintain the property that blocks should be found by the network on average about once every ten minutes. There's nothing special about 2 weeks, but it's a good trade-off. If the period were much shorter, the difficulty might fluctuate due to random variations in the number of blocks found in each period. If the period were much higher, the network's hash power might get too far out of balance with the difficulty.

Each Bitcoin miner independently computes the difficulty and will only accept blocks that meet the difficulty that they computed. Miners who are on different branches might not compute the same difficulty value, but any two miners mining on top of the same block will agree on what the difficulty should be. This allows consensus to be reached.

You can see in Figure 5.3 that over time the mining difficulty keeps increasing. It's not necessarily a steady linear increase or an exponential increase, but it depends on activity in the market. Mining difficulty is affected by factors like how many new miners are joining, which in turn may be affected by the current exchange rate of Bitcoin. Generally, as more miners come online and mining hardware gets more efficient, blocks are found faster and the difficulty is increased so that it always takes about ten minutes to find a block.

In Figure 5.3 you can see that in the red line on the graph there's a step function of difficulty even though the overall network hash rate is growing smoothly. The discrete step results from the fact that the difficulty is only adjusted every 2016 blocks.

Another way to view the network's growth rate is to consider how long it takes to find a block on average. Figure 5.4 (a) shows how many seconds elapse between consecutive blocks in the block chain. You can see that this gradually goes down, jumps up and then gradually goes down again. Of course what's happening is that every 2016 blocks the difficulty resets and the average block time goes back up to about ten minutes. Over the next period the difficulty stays unchanged, but more and more miners come online. Since the hash power has increased but the difficulty has not, blocks are found more quickly until the difficulty is again adjusted after 2016 blocks, or about two weeks.

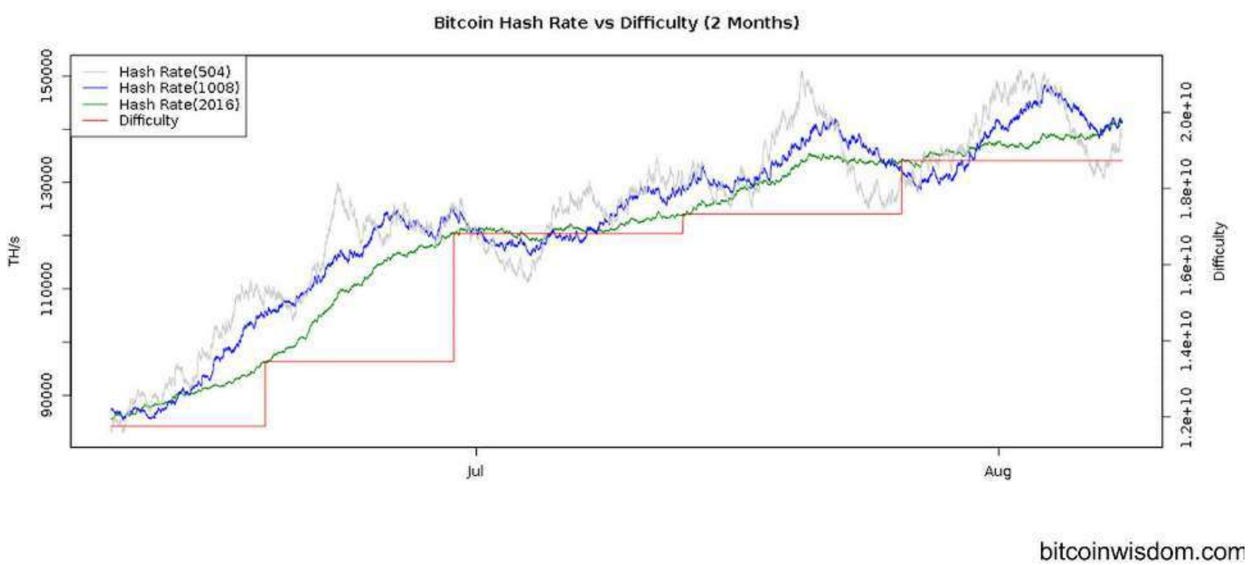



**Figure 5.3: Mining difficulty over time (mid-2014).** Note that the y-axis begins at 80,000 TH/s.

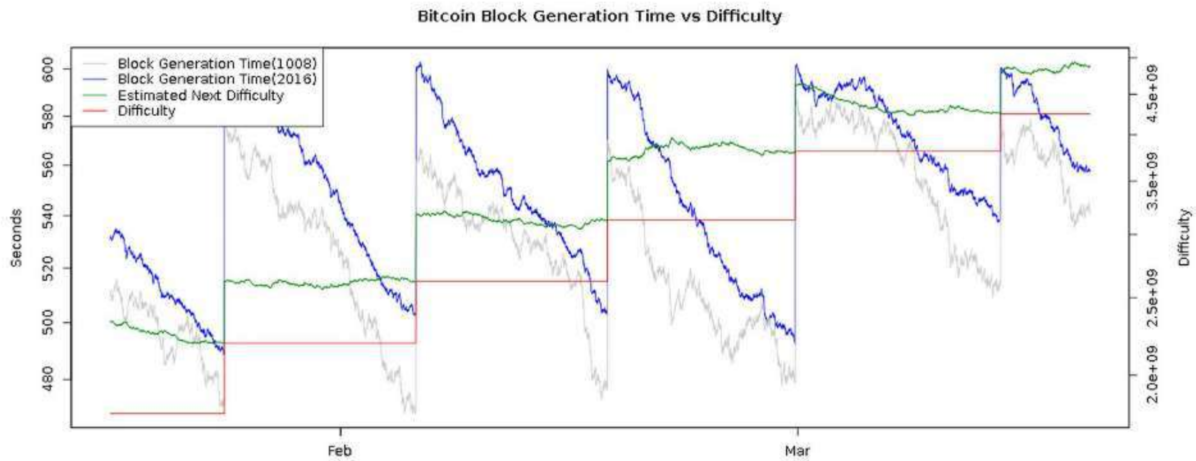



**Figure 5.4 (a) : Time to find a block (early 2014).** Note that the y-axis begins at 460 seconds. Due to continued rapid growth in mining power during this time, the time to find a block decreased steadily within each two-week window. Source: bitcoinwisdom.com

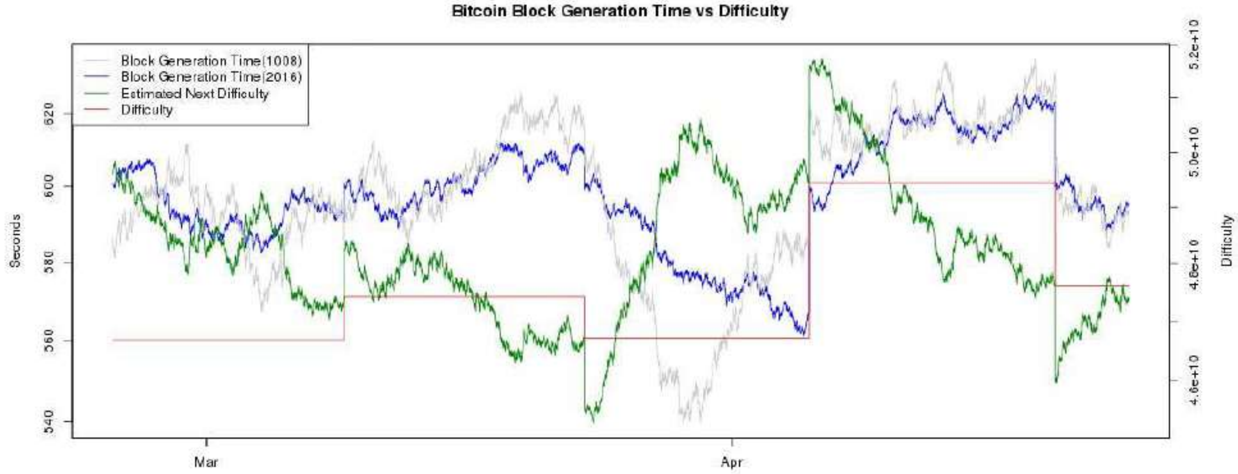



**Figure 5.4 (b) : Time to find a block (early 2015).** Note that the y-axis begins at 540 seconds. As the growth of the network has slowed, the time to find each block is much closer to 10 minutes and is occasionally over during periods where the network's hash power actually shrinks. Source: bitcoinwisdom.com

Even though the goal was for a block to be found every ten minutes on average, for most of 2013 and 2014 it was closer to about nine minutes on average and would approach 8 minutes at the end of each two week cycle. Quick calculations show that this requires an astonishing 25% growth rate every two weeks, or several hundred fold per year.

Unsurprisingly, this was not sustainable forever and in 2015 the growth rate has been much slower (and occasionally negative). In Figure 5.4(b), we can see that as the mining power is closer to a steady-state, the period to find each block stays much closer to 10 minutes. It can even take longer than 10 minutes, in which case there will be a difficulty *decrease*. Once considered unthinkable, this has happened fairly regularly in 2015.

While there have been no catastrophic declines of the network's mining power so far, there's no inherent reason why that cannot happen. One proposed scenario for Bitcoin's collapse is a "death spiral" in which a dropping exchange rate makes mining unprofitable for some miners, causing an exodus, in turn causing the price to drop further.

## 5.2 Mining Hardware

We've mentioned that the computation that miners have to do is very difficult. In this section, we'll discuss why it is so computationally difficult and take a look at the hardware that miners use to perform this computation.

The core of the difficult computation miners are working on is the SHA-256 hash function. We discussed hash functions abstractly in Chapter 1. SHA-256 is a general purpose cryptographic hash function that's part of a bigger family of functions that was standardized in 2001 (SHA stands for Secure Hash Algorithm). SHA-256 was a reasonable choice as this was strongest cryptographic hash function available at the time when Bitcoin was designed. It is possible that it will become less secure over the lifetime of Bitcoin, but for now it remains secure. Its design did come from the NSA (US National Security Agency), which has led to some conspiracy theories, but it's generally believed to be a very strong hash function.

***A closer look at SHA-256.*** Figure 5.5 shows more detail about what actually goes on in a SHA-256 computation. While we don't need to know all of the details to understand how Bitcoin works, it's good to have a general idea of the task that miners are solving.

SHA-256 maintains 256 bits of state. The state is split into eight 32-bit words which makes it highly optimized for 32-bit hardware. In each round a number of words in the state are taken — some with small bitwise tweaks applied — and added together mod 32. The entire state is then shifted over with the result of the addition becoming the new left-most word of the state. The design is loosely inspired by simpler bitwise Linear Feedback Shift Registers (LFSRs).

**Sidebar: the SHA family.** The "256" in SHA-256 comes from its 256-bit state and output. Technically SHA-256 is one of several closely-related functions in the SHA-2 family, including SHA-512 (which has a larger state and is therefore more secure). There is also SHA-1, an earlier generation with 160-bit output which is now considered insecure but is still implemented in Bitcoin script.

Although the SHA-2 family, including SHA-256, are still considered to be cryptographically secure, the next generation SHA-3 family has now been picked by a contest. SHA-3 is in the final stages of standardization today, but it wasn't available at the time Bitcoin was designed.

Figure 5.5 shows just one round of the SHA-256 compression function. A complete computation of SHA-256 does this for 64 iterations. During each round, there are slightly different constants applied so that no iteration is exactly the same.

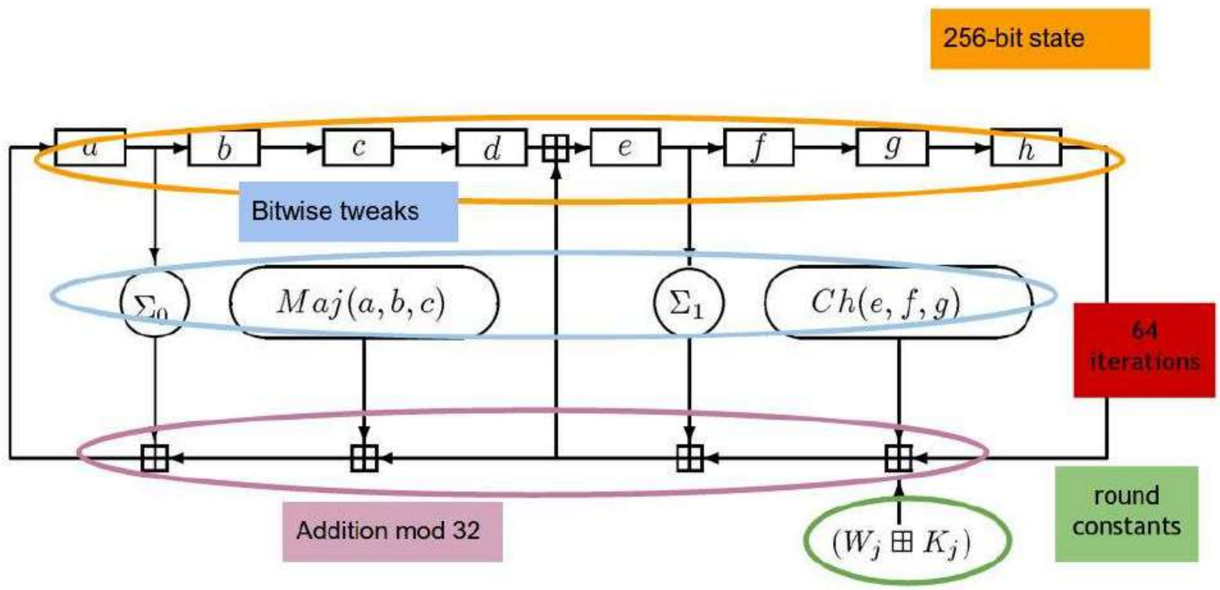



**Figure 5.5 : The structure of SHA-256.** This is one round of the compression function.

The task for miners is to compute this function as quickly as possible. Remember that miners are racing each other so the faster they do this, the more they earn. To do this, they need to be able to manipulate 32-bit words, do 32-bit modular addition and also do some bitwise logic.

As we will see shortly, Bitcoin actually requires SHA-256 to be applied twice to a block in order to get the hash that is used by the nodes. This is a quirk of Bitcoin. The reasons for the double computation are not fully specified, but at this point, it's just something that miners have to deal with.

***CPU mining.*** The first generation of mining was all done on general purpose computers — that is general purpose central processing units (CPUs). In fact, CPU mining was as simple as running the code shown in Figure 5.6. That is, miners simply searched over nonces in a linear fashion, computed SHA 256 in software and checked if the result was a valid block. Also, notice in the code that as we mentioned, SHA-256 is applied twice.

```
TARGET = (65535 << 208) / DIFFICULTY;
coinbase_nonce = 0;
while (1) {
	header = makeBlockHeader(transactions, coinbase_nonce);
	for (header_nonce = 0; header_nonce < (1 << 32); header_nonce++){
		if (SHA256(SHA256(makeBlock(header, header_nonce))) <
	TARGET)
			break; //block found!
	}
	coinbase_nonce++;
}
```
**Figure 5.6 : CPU mining pseudocode.**

How fast will this run on a general purpose computer? On a high-end desktop PC you might expect to compute about 20 million hashes per second (MH/s). At that speed, it would take you several hundred thousand years on average at the early-2015 difficulty level ($2^{67}$) to find a valid block. We weren't kidding when we said mining was going to be a difficult slog!

If you're mining on a general purpose PC today, CPU mining is no longer profitable with the current difficulty. For the last few years, anyone trying to mine on a CPU probably doesn't understand how Bitcoin works and was probably pretty disappointed that they never made any money doing it.

***GPU mining.*** The second generation began when people started to get frustrated with how slow their CPUs were and instead used their graphics card, or graphics processing unit (GPU).

Almost every modern PC has a GPU built-in to support high performance graphics. They're designed to have high throughput and also high parallelism, both of which are very useful for Bitcoin mining. Bitcoin mining can be parallelized easily because you can try computing multiple hashes at the same time with different nonces. In 2010, a language called OpenCL was released. OpenCL is a general purpose language to do things other than graphics on a GPU. It's a high level-language and over time people have used it to run many types of computation more quickly on graphics cards. This paved the way for Bitcoin mining on GPUs.

Mining with graphics cards had several attractive properties at the time. For one thing, they're easily available and easy for amateurs to set up. You can order graphics cards online or buy them at most big consumer electronics stores. They're the most accessible high-end hardware that's available to the general public. They also have some properties that make them specifically good for Bitcoin mining. They're designed for parallelism so they have many Arithmetic Logic Units (ALUs) that can be used for simultaneous SHA-256 computations. Some GPUs also have specific instructions to do bitwise operations that are quite useful for SHA-256.

Most graphics cards can also be ***overclocked***, meaning you can run them faster than they're actually designed for if you want to take on the risk that they might overheat or malfunction. This is a property gamers have demanded for years. With Bitcoin mining, it might be profitable to run the chip much faster than it was designed for even if you induce a few errors by doing so.

For example, say you can run your graphics card 50 percent faster but doing so will cause errors in the SHA-256 computation to 30 percent of the time. If an invalid solution is erroneously declared valid by the graphics card — something that would happen rarely — you can always double-check it on your CPU. On the other hand, if a valid solution is erroneously missed, you'd never know. But if your speed increase from overclocking can overcome the decrease in output due to errors, you'd still come out ahead. In the above example, the throughput is 1.5x compared to not overclocking, whereas the success rate is 0.7x. The product is 1.05, which means overclocking increases your expected profits by 5%. People have spent considerable time optimizing exactly how much they should overclock a given chip to maximize profits.

Finally, you can drive many graphics cards from one motherboard and CPU. So you can take your computer, which will be running your actual Bitcoin node which gathers transactions from the network and assembles blocks, and attach multiple graphics cards to it to try to find the right nonces to make the SHA-256 of the block valid. Many people created some really interesting home-brewed setups like this one shown in Figure 5.7 to drive many, many GPUs from a single CPU. This was still in the early days of Bitcoin when miners were still mostly hobbyists without much experience running servers, but they came up with some quite ingenious designs for how to pack many graphics cards into a small place and keep them cool enough to operate.

**Figure 5.7: A home-built rack of GPUs used for Bitcoin mining.** You can also see the fans that they used to build a primitive cooling system. Source: LeonardH, cryptocurrenciestalk.com.

***Disadvantages of GPU mining.*** GPU mining has some disadvantages. GPUs have a lot of hardware built into them for doing video processing that can't be utilized for mining. Specifically, they have a large number of floating point units that aren't used at all in SHA-256. GPUs also don't have the greatest cooling characteristics when you put a lot of them next to one another. They're not designed to run side by side as they are in the picture; they're designed to be in a single box doing graphics for one computer.

**Miners vs. Gamers.** According to folklore, by 2011 Bitcoin miners were purchasing enough GPUs to upset the normal market. This caused friction with the gaming community who found it increasingly difficult to find certain popular GPUs in local electronics stores. Interestingly, however, it may have increased interest in Bitcoin mining as many of these frustrated gamers learned about the currency to understand where all the GPUs were going, with some of gamers becoming miners themselves!

GPUs can also draw a fairly large amount of power, so a lot of electricity is used relative to a computer. Another disadvantage initially was that you had to either build your own board or buy expensive boards to house multiple graphics cards.

On a really high-end graphics card with aggressive tuning you might get as high as 200 MH/s, or 200 million hashes per second, an order of magnitude better than you would be doing with a CPU. But even with that improved performance, and even if you're really enterprising and used one hundred GPUs together, it would still take you over 300 years on average to find a block at the early-2015 difficulty level. As a result, GPU mining is basically dead for Bitcoin today, though it still shows up sometimes in early-stage altcoins.

***FPGA mining.*** Around 2011 some miners started switching from GPUs to FPGAs, or Field Programmable Gate Arrays, after the first implementation of Bitcoin mining came out in Verilog, a hardware design language that's used to program FPGAs. The general rationale behind FPGAs is to try to get close as possible to the performance of custom hardware while also allowing the owner of the card to customize it or reconfigure it "in the field." By contrast, custom hardware chips are designed in a factory and do the same thing forever.

FPGAs offer better performance than graphics cards, particularly on "bit fiddling" operations which are trivial to specify on an FPGA. Cooling is also easier with FPGAs and, unlike GPUs, you can theoretically use nearly all of the transistors on the card for mining. Like with GPUs, you can pack many FPGAs together and drive them from one central unit, which is exactly what people began to do (see Figure 5.8). Overall, it was possible to build a big array of FPGAs more neatly and cleanly than you could with graphics cards.

Using an FPGA with a careful implementation, you might get up to a GH/s, or one billion hashes per second. This is certainly a large performance gain over CPUs and GPUs, but even if you had a hundred boards together, each with a 1 GH/s throughput, it would still take you about 50 years on average to find a Bitcoin block at the early-2015 difficulty level.

**Figure 5.8: A home-built rack of FPGAs.** Although you don't see the cooling setup pictured here, a rack like this would need a cooling system.

Despite the performance gain, the days of FPGA mining were quite limited. Firstly, they were being driven harder for Bitcoin mining — by being on all the time and overclocked — than consumer grade FPGAs were really designed for. Because of this, many people saw errors and malfunctions in their FPGAs as they were mining. It also turned out to be difficult to optimize the 32-bit addition step which is critical in doing SHA-256. FPGAs are also less accessible-you can't buy them at most stores and there are fewer people who know how to program and set up an FPGA than a GPU.

Most importantly though, even though FPGAs improved performance the cost-per-performance was only marginally improved over GPUs. This made FPGA mining was a rather short-lived phenomenon. Whereas GPU mining dominated for about a year or so, the days of FPGA mining were far more limited — lasting only a few months before custom ASICs arrived.

***ASIC mining.*** Mining today is dominated by Bitcoin *ASICs*, or ***application-specific integrated circuits***. These are chips that were designed, built, and optimized for the sole purpose of mining Bitcoins. There are a few big vendors that sell these to consumers with a good deal of variety: you can choose between slightly bigger and more expensive models, more compact models, as well as models with varying performance and energy consumption claims.

Designing ASICs requires considerable expertise and their lead-time is also quite long. Nevertheless, Bitcoin ASICs were designed and produced surprisingly quickly. In fact, analysts have said that this may be the fastest turnaround time in the history of integrated circuits from specifying a problem and to have a working chip in people's hands. Partially as a result of this, the first few generations of Bitcoin ASICs were quite buggy and most of them didn't quite deliver the promised performance numbers. Bitcoin ASICs have since matured and there are now fairly reliable ASICs available.

Up until 2014, the lifetime of ASICs was quite short due to the rapidly increasing network hash rate, with most boards in the early ASIC era growing obsolete in about six months. Within this time, the bulk of the profits are made up front. Often, miners will make half of the expected profits for the lifetime of the ASIC during just the first six weeks. This meant shipping speed can become a crucial factor in making a profit. Due to the immaturity of the industry though, consumers often experienced shipping delays with boards often nearly obsolete by the time they arrived. As the growth rate of Bitcoin’s hash power has stabilized, mining equipment has a longer life time, but the early era saw many frustrated customers and accusations of fraud by vendors.

For much of Bitcoin’s history, the economics of mining haven’t been favorable to the small miner who wants to go online, order mining equipment, and start making money. In fact, in most cases people who have placed orders for mining hardware would have lost money based on the calculation that they made at the time. Until 2013 though, the exchange rate of Bitcoin rose enough to bail most customers out from losing money outright. In effect, mining has been an expensive way to simply bet that the price of Bitcoin would rise, and many miners — even though they've made money mining Bitcoins — would have been better off if they had just taken the money that they were going to spend on mining equipment, invested it in bitcoins, and eventually sold them at a profit.

You can still order Bitcoin mining equipment today and we wouldn’t want to discourage that as a way to learn about Bitcoin and cryptocurrencies. However, we’ll note again that this is not an advisable way to make money. Most ASICs sold commercially today are unlikely to pay for themselves in mining rewards once you factor in the price of electricity and cooling.

***Today : Professional mining.*** Today mining has mostly moved away from individuals and toward professional mining centers. Exact details about how these centers operate are not very well known because companies want to protect their setups to maintain a competitive advantage. Presumably, these operations maintain profitability by buying slightly newer and more efficient ASICs than are available for general sale at a bulk discount. In Figure 5.9, we see a picture of a professional mining center in the Republic of Georgia.

**Figure 5.9: BitFury mining center,** a professional mining center in the republic of Georgia.

When determining where to set up a mining center, the three biggest considerations are: climate, cost of electricity, and network speed. In particular, you want a cold climate to keep cooling costs low. Cooling is particularly challenging with Bitcoin mining, which is estimated to use an order of magnitude more electricity per square foot than traditional data centers (and hence give off an order of magnitude more heat). You obviously want cheap electricity. You also want a fast network connection to be well connected to other nodes in the Bitcoin peer-to-peer network so that you can hear about new blocks as quickly as possible after they've been announced. Georgia and Iceland have reportedly been popular destinations for Bitcoin mining data centers.

***Similarities to gold mining.*** While 'mining' may seem to be just a cute name, if we step back and think about the evolution of mining, we can see interesting parallels between Bitcoin mining and gold mining. For starters, both saw a similar gold rush mentality with many young, amateur individuals eager to get into the business as soon as possible.

Whereas with Bitcoin mining we've seen a slow evolution from CPUs to GPUs to FPGAs, to now ASICs, gold mining saw an evolution from individuals with gold pans to small groups of people with sluice boxes, to placer mining — consisting of large mining groups blasting away hillsides with water — to modern gold mining which often utilizes gigantic open pit mines to extract tons of raw material from the earth (See Figure 5.10). Both with Bitcoin and with gold, the friendliness and accessibility to individuals has gone down over time and large companies have eventually consolidated most of the operations (and profits). Another pattern that has emerged in both places is that most of the profits have been earned by those selling equipment, whether gold pans or mining ASICs, at the expense of individuals hoping to strike it rich.

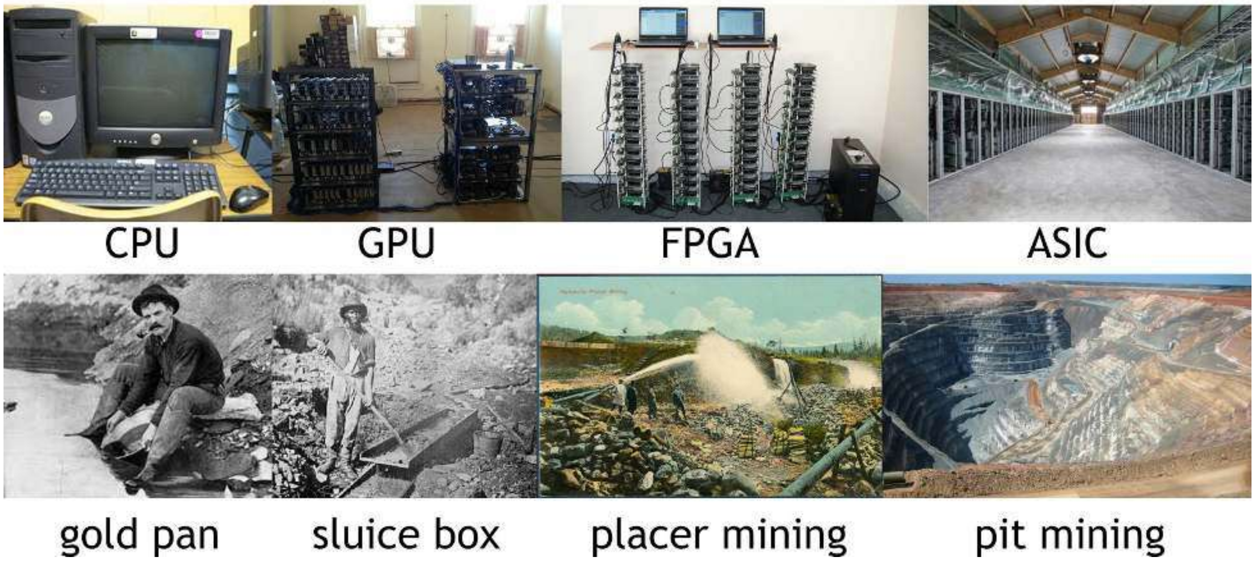



**Figure 5.10: Evolution of mining.** We can see a clear parallel between the evolution of Bitcoin mining and the evolution of gold mining. Both were initially friendly to individuals and over time became massive operations controlled by large companies.

***The future.*** Currently ASIC mining is the only realistic means to be profitable in Bitcoin and it's not very friendly to small miners. This raises a few questions about what will happen going forward. Are small miners out of Bitcoin mining forever, or is there a way to re-incorporate them? Moreover, does ASIC mining and the development of professional mining centers violate the original vision of Bitcoin which was to have a completely decentralized system in which every individual in the network mined on his or her own computer?

Furthermore, if this is indeed a violation of Satoshi Nakamoto's original vision for Bitcoin, would we be better off with a system in which the only way to mine was with CPUs? In Chapter 8, we'll consider these questions and look at ideas for alternative forms that might be less friendly to ASICs.

***The cycle repeats itself.*** It's also worth noting here that several smaller altcoins have indeed used a different puzzle than SHA-256, but have seen a similar trajectory in mining as Bitcoin. We'll discuss these altcoins more in Chapter 9 but recall that for ASICs there is still a long lead time between designing a chip and shipping it, so if a new altcoin uses an new puzzle (even just a modified version of SHA-256), this will buy some time in which ASICs are not yet available. Typically, mining will proceed just at Bitcoin did from CPUs to GPUs and/or FPGAs to ASICs (if the altcoin is very successful, like LiteCoin).

Thus, one strategy for smaller miners may be to try to pioneer new altcoins which aren't yet valuable enough for large mining groups to invest in-just like small gold miners who have been driven out of proven goldfields might try prospecting unproven new areas. Of course, this means the pioneers are facing a significant risk that the altcoin will never succeed.

## 5.3 Energy consumption and ecology

We saw how large professional mining data centers have taken over the business of Bitcoin mining, and how this parallels the movement to pit mining in gold mining. You may be aware that pit mines have been a major source of concern over the years due to the damage they cause to the environment. Bitcoin is not quite at that level yet, but it is starting to use a significant amount of energy which has become a topic of discussion. In this section we'll see how much energy Bitcoin mining is using and what the implications are for both the currency and for our planet.

***Thermodynamic limits.*** There's a physical law known as ***Landauer's principle*** developed by Ralph Landauer in the 1960s that states that any non-reversible computation must use a minimum amount of energy. Logically irreversible computations can be thought of as those which lose information. Specifically, the principle states that erasing any bit must consume a minimum of ($kT \ln 2$) joules, where $k$ is the Boltzmann constant (approximately $1.38 \times 10^{-23}$ J/K), $T$ is the temperature of the circuit in kelvins, and ln 2 is the natural logarithm of 2, roughly 0.69. This a tiny amount of energy per bit, but this does provide a hard lower bound on energy usage from basic physics.

We're not going to go through the derivation here, but the high-level idea is that every time you flip one bit in a non-reversible way there's a minimum number of joules that you have to use. Energy is never destroyed; it's converted from one form into another. In the case of computation the energy is mostly transformed from electricity, which is useful, high-grade energy, into heat which is dissipated into the environment.

As a cryptographic hash function, SHA-256 is not a reversible computation. We can recall from Chapter 1 that this is a basic requirement of cryptographic hash functions. So, since non-reversible computation has to use some energy and SHA-256 — the basis of Bitcoin mining — is not reversible, energy consumption is an inevitable result of Bitcoin mining. That said, the limits placed by Landauer's principle are far, far below the amount of electricity that is being used today. We're nowhere close to the theoretical optimal consumption of computing, but even if we did get to the theoretical optimum we would still be using energy to perform Bitcoin mining.

How does Bitcoin mining use energy? There are three steps in the process that requires energy, some of which may not be so obvious:

***1. Embodied energy.*** First, Bitcoin mining equipment needs to be manufactured. This requires physical mining of raw materials as well as turning these raw materials into a Bitcoin mining ASIC, both of which require energy. This is the embodied energy. As soon as you receive a Bitcoin mining ASIC in the mail, you've already consumed a lot of energy — including the shipping energy, of course — before you've even powered it on!

Hopefully, over time the embodied energy will go down as less and less new capacity comes online. As fewer people are going out to buy new mining ASICs, they're going to be obsoleted less quickly, and the embodied energy will be amortized over years and years of mining.

***2. Electricity.*** When your ASIC is powered on and mining, it consumes electricity. This is the step that we know has to consume energy due to Landauer's principle. As mining rigs get more efficient, the electrical energy cost will go down. But because of Landauer's principle, we know that it will never disappear; electrical energy consumption will be a fact of life for Bitcoin miners forever.

***3. Cooling.*** A third important component of mining that consumes energy is cooling off your equipment to make sure that it doesn't malfunction. If you're operating at a small scale in a very cold climate your cooling cost might be trivial, but even in cold climates once you get enough ASICs in a small space you're going to have to pay extra to cool off your equipment from all of the waste heat that it is generating. Generally, the energy used to cool off mining equipment will also be in the form of electricity.

***Mining at scale.*** Both embodied energy and electricity decrease (per unit of mining work completed) when operating at a large scale. It's cheaper to build chips that are designed to run in a large data center, and you can deliver the power more efficiently as you don't need as many power supplies.

When it comes to cooling, however, the opposite is usually true: cooling costs tend to increase the larger your scale is. If you want to run a very large operation and have a lot of Bitcoin mining equipment all in one place, there's less air for the heat to dissipate into in the area surrounding your equipment. Your cooling budget will therefore increase at scale (per unit of mining work completed) unless you scale your physical area along with the number of chips you have in use.

***Estimating energy usage.*** How much energy is the entire Bitcoin system using? Of course, we can't compute this precisely because it's a decentralized network with miners operating all over the place without documenting exactly what they're doing. But there are two basics approaches to estimating how much energy Bitcoin miners are using collectively. We'll do some back-of-the-envelope calculations here based on early 2015 values. We must emphasize that these figures are very rough, both because some of the parameters are hard to estimate and because they change quickly. At best they should be treated as order-of-magnitude estimates.

***Top-down approach.*** The first approach is a top-down approach. We start with the simple fact that every time a block is found today 25 bitcoins, worth about 6,500 US dollars, are given to the miners. That's about 11 dollars every second, being created out of thin air in the Bitcoin economy and given to the miners.

Now let's ask this question: if the miners are turning all of those 11 dollar per second into electricity, how much can they buy? Of course miners aren't actually spending all of the revenue on electricity, but this will provide an upper bound on the electricity being used. Electricity prices vary greatly, but we can use as an estimate that electricity costs around 10 cents per kilowatt-hour (kWh) at an industrial rate in the US, or equivalently 3 cents per megajoule (MJ). If Bitcoin miners were spending all 11 dollars per second of earnings buying electricity, they could purchase 367 megajoules per second, consuming a steady 367 megawatts (MW).

| |
|---|
| **Units of energy and power.** In the International System of Units (SI), energy is measured in ***joules***. A ***watt*** is a unit of power, where one ***watt*** is defined as one joule per second. |

***Bottom-up approach.*** A second way to estimate the cost is to use a bottom-up approach. In this approach, we look at the number of hashes the miners are actually computing, which we know by observing the difficulty of each block. If we then assume that all miners are using the most efficient hardware, we can derive a lower bound on the electricity consumption.

Currently,  the best claimed efficiency figure amongst commercially available mining rigs is about 3 GH/s/W. That is, the most cutting-edge ASICs claim to perform three billion hashes per second while consuming 1 watt of power. The total network hashrate is about 350,000,000 GH/s, or equivalently 350 petahashes per second (PH/s). Multiplying these two together, we see that it takes about 117 MW to produce that many hashes per second at that efficiency. Of course this figure excludes all of the cooling energy and all of the embodied energy that's in those chips, but we're doing an optimal calculation and deriving a lower bound so that's okay.

Combining the top down and bottom up approaches, we can derive a ballpark estimate of the amount of power being used for Bitcoin miners is probably on the order of a few hundred MW.

How much is a megawatt? To build up intuition, we can see how much large power plants produce. One of the largest power plants in the world, the Three Gorges Dam in China is a 10,000 MW power plant. A typical large hydroelectric power plant produces around 1,000 MW. The largest nuclear power plant in the world, Kashiwazaki-Kariwa in Japan, is a 7,000 MW plant, whereas the average nuclear power plant is about 4,000 MW. A major coal-fired plant produces about 2,000 MW.

According to our estimates then, the whole Bitcoin network is consuming perhaps 10% of a large power plant's worth of electricity. Although this is a significant amount of power, it's still small compared to all the other things that people are using electricity for on the planet.

***Is Bitcoin mining wasteful?*** It's often said Bitcoin "wastes" energy because the energy expended on SHA-256 computations which don't serve any other useful purpose. It's important to recognize, however that any payment system requires energy and electricity. With traditional currency, considerable energy is consumed printing currency and running ATM machines, coin sorting machines, cash registers, and payment processing services, as well as transporting money and gold bullion in armored cars. You could equally argue that all of this energy is "wasted" in that it doesn't serve any purpose besides maintaining the currency system. So, if we value Bitcoin as a useful currency system, then the energy required to support it is not really being wasted.

Still, if we could replace Bitcoin mining with a less energy-intensive puzzle and still have a secure currency, this would be a positive change. We'll see in Chapter 8, however, that we don't know if that's actually possible

***Repurposing energy.*** Another idea to make Bitcoin more eco-friendly is to capture the heat generated from Bitcoin mining do something useful with it instead of just heating up the atmosphere. This model of capturing waste heat from computation is called the approach is called the *data furnace* approach. The concept is that instead of buying a traditional electric heater to heat your home, or to heat water in your home, you could buy a heater which doubled as a Bitcoin mining rig, mining bitcoins and heating up your home as a byproduct of that computation. It turns out that the efficiency of doing this isn't much worse than buying an electric heater, and perhaps this would be no more complicated for a home consumer than plugging their heater into their Internet connection as well as their electricity outlet.

There are a few drawbacks to this approach. Although it's about as efficient as using an electric heater, electric heaters are themselves much less efficient than gas heaters. Besides, what happens when everybody turns off their Bitcoin mining rig during the summer (or at least everybody in the Northern Hemisphere)? Mining hash power might go down seasonally based on how much heat people need. It might even go down on days that happen to be warmer than average! This would caused many interesting effects for Bitcoin consensus if the data furnace model actually caught on.

The question of ownership is also not clear. If you buy a Bitcoin data furnace, do you own the Bitcoin mining rewards that you get, or does the company that sold them to you? Most people don't have any interest in Bitcoin mining — and probably never will — so it might make more sense to buy it as an appliance and have the company that sold it to you keep the rewards. This might mean the heater is sold at a slight loss then, in which case some enterprising users might want to buy them and modify them to keep the mining rewards for themselves, leading to a potentially ugly DRM (Digital Rights Management) battle.

***Turning electricity in cash.*** Another long-term question posed by Bitcoin is that it might provide the most efficient means of turning electricity into cash. Imagine a world in which Bitcoin mining ASICs are a readily-available commodity and the dominant cost of mining is electricity. In effect, this would mean providing free or low-cost electricity is open to new forms of abuse.

In many countries around the world, governments subsidize electricity, particularly industrial electricity. Among other reasons, they often do so to encourage industry to be located in their country. But Bitcoin provides a good way to turn electricity into cash, which might cause governments to rethink that model if their subsidized electricity is converted en masse to bitcoins. Electricity subsidies are intended to attract businesses that will contribute to the country's economy and labor market and subsidizing Bitcoin mining may not have the intended effect.

An even bigger problem is the billions of freely available electrical outlets around the world in people's homes, universities, hotels, airports, office buildings and so on. People might try to plug in mining equipment so that they can profit while someone else is paying the electricity bill. In fact, they might use outdated hardware and not bother to upgrade, considering that they will not be paying the electricity bill. It is quite daunting to consider the possibility of monitoring every power outlet in the world of for potential unauthorised used a source of electricity for Bitcoin mining.

## 5.4 Mining pools

Consider the economics of being a small miner. Suppose you're an individual who spent $6,000 of your hard-earned money to buy a nice, shiny, new Bitcoin mining rig. Say that the performance is such that you expect to find a block every 14 months (and remember that a block is worth about 6,500 dollars as of early 2015).

Amortized, the expected revenue of your miner is perhaps $400 per month once you factor in electricity and other operating costs. If you actually got a check in the mail every month for $400, it would make a lot of sense to buy the mining rig. But remember that mining is a random process. You don't know when you're going to find the next block, and until that happens you won't earn anything.

***High variance.*** If we look at the distribution of how many blocks you're likely to find in the first year, the variance is pretty high and the expected number is quite low. Because you find blocks at a fixed, low rate which is independent of the time since the last block you found, your expected number of blocks is very well approximated by a ***Poisson distribution***. A Poisson distribution arises if you have $N$ independent trials each with a chance $\lambda/N$ of success as $N$ approaches infinity. With Bitcoin mining, each individual nonce attempted is in fact a random trial with a small chance of success, so $N$ is indeed very large even for small miners and the approximation is very good.

If you expect to find about 1 block per 14 months (a Poisson distribution with $\lambda=6/7$ blocks/year), there's a greater than 40% chance that you won't find any blocks within the first year. For an individual miner, this could be devastating. You spent thousands of dollars on the miner, paid lots in electricity to run it, and received nothing in return. There's a roughly 36% chance that you'll find one block within the first year which means maybe you're barely scraping by, provided your electricity costs weren't too high. Finally, there's a smaller chance that you'll find two or more blocks, in which case you might make out with a nice profit.

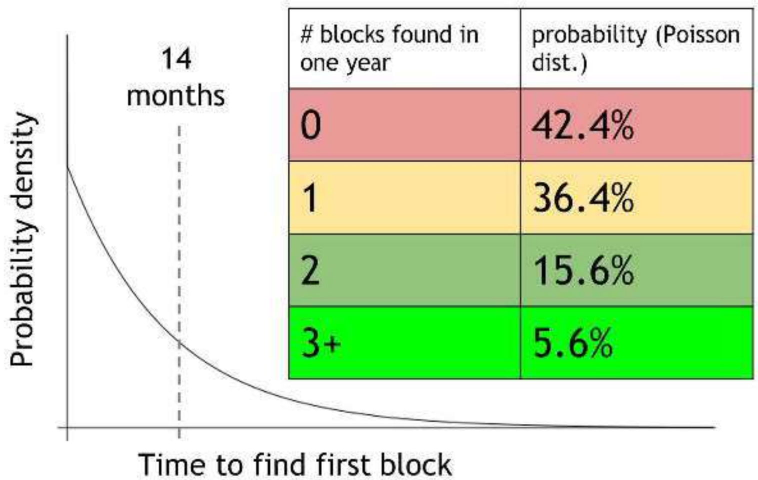



**Figure 5.11: Illustration of uncertainty in mining.** Assuming that the global hash rate is constant and the mean time to find a block is 14 months, the variance for a small miner is quite high.

These numbers are only approximate, but the main point here is that even though on expectation you might be doing okay — that is, earning enough to make a return on your investment — the variance is sufficiently high that there's a big chance that you'll make nothing at all. For a small miner, this means mining is a major gamble.

***Mining pools.*** Historically, when small business people faced a lot of risk, they formed mutual insurance companies to lower that risk. Farmers, for example, would get together and agree that if any individual farmer's barn burned down the others would share their profits with that farmer. Could we have a mutual insurance model that works for small Bitcoin miners?

A mining pool is exactly that — mutual insurance for Bitcoin miners. A group of miners will form a pool and all attempt to mine a block with a designated coinbase recipient. That recipient is called the pool manager. So, no matter who actually finds the block, the pool manager will receive the rewards. The pool manager will take that revenue and distribute it to all the participants in the pool based on how much work each participant actually performed. Of course, the pool manager will also probably take some kind of cut for their service of managing the pool.

Assuming everybody trusts the pool manager, this works great for lowering miners' variance. But how does a pool manager know how much work each member of the pool is actually performing? How can the pool manager divide the revenue commensurate with the amount of work each miner is doing? Obviously the pool manager doesn't want to just take everyone's word for it because people might claim that they've done more than they actually did.

***Mining shares.*** There's an elegant solution to this problem. Miners can prove probabilistically how much work they're doing by outputting *shares*, or near-valid blocks. Say the target is a number beginning with 67 zeros. A block's hash must be lower than the target for the block to be valid. In the process of searching for such a block, miners will find some blocks with hashes beginning with a lot of zeros, but not quite 67. Miners can show these nearly valid blocks to prove that they are indeed working. A share might require say 40 or 50 zeros, depending on the type of miners the pool is geared for.

```
4AA087F0A52ED2093FA816E53B9B6317F9B8C1227A61F9481AFED67301F2E3FB
D3E51477DCAB108750A5BC9093F6510759CC880BB171A5B77FB4A34ACA27DEDD
0000000008534FF68B98935D090DF5669E3403BD16F1CDFD41CF17D6B474255
BB34ECA3DBB52EFF4B104EBBC0974841EF2F3A59EBBC4474A12F9F595EB81F4B
00000000002F891C1E232F687E41515637F7699EA0F462C2564233FE082BB0AF
0090488133779E7E98177AF1C765CF02D01AB4848DF555533B6C4CFCA201CBA1
460BEFA43B7083E502D36D9D08D64AFB99A100B3B80D4EA4F7B38E18174A0BFB
000000000000000078FB7E1F7E2E4854B8BC71412197EB1448911FA77BAE808A
652F374601D149AC47E01E7776138456181FA4F9D0EEDD8C4FDE3BEF6B1B7ECE
785526402143A291CFD60DA09CC80DD066BC723FD5FD20F9B50D614313529AF3
000000000041EE593434686000AF77F54CDE839A6CE30957B14EDEC10B15C9E5
9C20B06B01A0136F192BD48E0F372A4B9E6BA6ABC36F02FCED22FD9780026A8F
```

**Figure 5.12: Mining Shares.** Miners continually try to find blocks with a hash below the target. In the process, they'll find other blocks whose hashes contain fewer zeros — but are still rare enough to prove that they have been working hard. In this figure, the dull green hashes are shares, while the bright green hash is from a valid block (which is also a valid share).

The pool manager will also run a Bitcoin node on behalf of participants, collecting transactions and assemble them into a block. The manager will include their own address in the coinbase transaction and send the block to all of the participants in the pool. All pool participants work on this block, and they prove that they've been working on it by sending in shares.

When a member of the pool finds a valid block, they sends it to the pool manager who distributes the reward in proportion to the amount of work done. The miner who actually finds the block is not awarded a special bonus, so if another miner did more work than, that other miner will be paid more even though they weren't the one who ended up finding a valid block. See Figure 5.13.

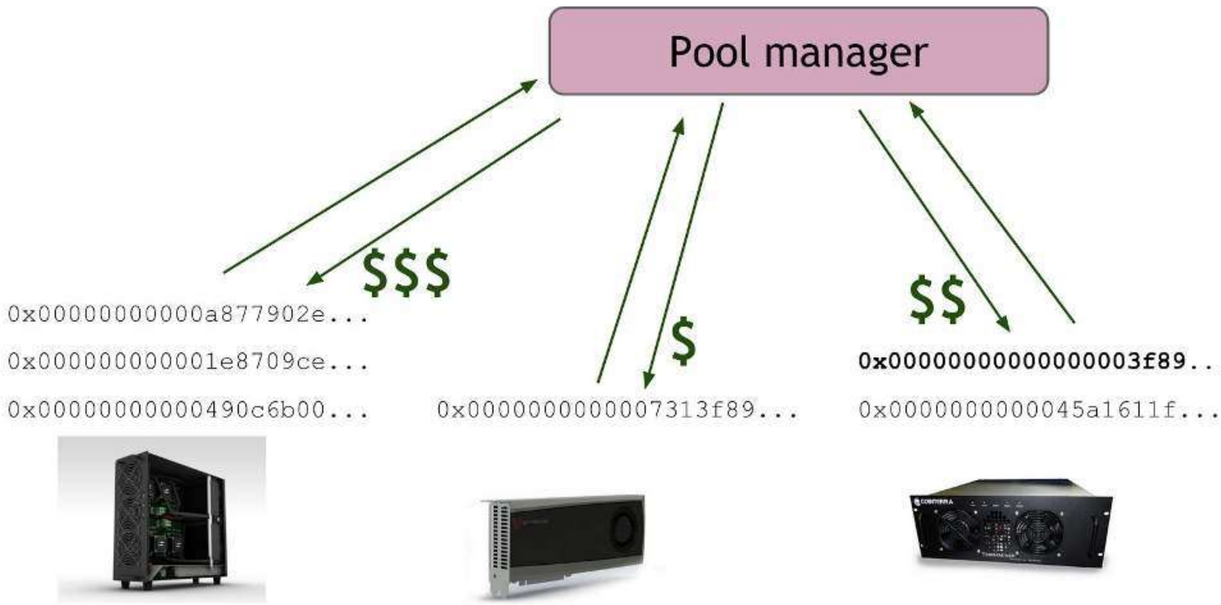



**Figure 5.13: Mining rewards.** Three participants pictured here are all working on the same block. They are awarded commensurate with the amount of work done. Even though the miner on the right was the one to find the valid block, the miner on the left is paid more since this miner did more work. There is (typically) no bonus paid to the miner who actually finds the block.

There are a few options for exactly how exactly the pool manager calculates how much to pay each miner based on the shares they submit. We'll look at two of the common, simpler ones. There are many other schemes that are also used, but these will illustrate the trade-offs between reward schemes.

***Pay-per-share.*** In the pay per share model, the pool manager pays a flat fee for every share above a certain difficulty for the block that the pool is working on. In this model, miners can send their shares to the pool manager right away and get paid without waiting for the pool to find a block.

In some ways, the pay-per-share model is the best for miners. They are guaranteed a certain amount of money every time they find a share. The pool manager essentially absorbs all of the risk since they pay rewards even if a block is not found. Of course, as a result of the increased risk, in the pay-per-share model, the pool manager will probably charge higher fees as compared with other models.

One problem with the pay-per-share model is that miners don't actually have any incentive to send valid blocks to the pool manager. That is, they can discard valid blocks but still be paid the same rewards, which will cause a big loss to the pool. A malicious pool manager might attack a competing pool in this fashion to try to drive them out of business.

***Proportional.*** In the proportional model, instead of paying a flat fee per share, the amount of payment depends on whether or not the pool actually found a valid block. Every time a valid block is found the rewards from that block are distributed to the members proportional to how much work they actually did.

In the proportional model, the miners still bear some risk proportional to the risk of the pool in general. But if the pool is large enough, the variance of how often the pool finds blocks will be fairly low. Proportional payouts provide lower risk for the pool manager because they only pay out when valid blocks are found. This also gets around the problem that we mentioned with the pay-per-share model, as miners are incentivized to send in the valid blocks that they find because that triggers revenue coming back to them.

The proportional model requires a little more work on behalf of the pool managers to verify, calculate, and distribute rewards as compared to the flat pay-per-share model.

***Pool hopping.*** Even with just these two types of pools, we can see that miners might be incentivized to switch between the pools at different times. To see this, consider that a purely proportional pool will effectively pay out a larger amount per share if a block is found quickly, as it always pays one block reward no matter how long it has been since the last block was found.

A clever miner might try mining in a proportional pool early in the cycle (just after the previous block was found) while the rewards per share are relatively high, only to switch ("hop") to a pay-per-share pool later in the cycle, when the expected rewards from mining in the proportional pool are relatively low. As a result of this, proportional pools aren't really practical. More complicated schemes, such as "pay per last *N* shares submitted" are more common, but even these are subject to subtle pool hopping behavior. It remains open how to design a mining pool reward scheme that is not vulnerable to this kind of manipulation.

***History and standardization.*** Mining pools first started around 2010 in the GPU era of Bitcoin mining. They instantly became very popular for the obvious reason that they lowered the variance for the participating miners. They've become quite advanced now. There are many protocols for how to run mining pools and it has even been suggested that these mining pool protocols should be standardized as part of Bitcoin itself. Just like there's a Bitcoin protocol for running the peer-to-peer network, mining pool protocols provide a communication API for the pool manager to send all of the members the details of the block to work on and for the miners to send back to the pool manager the shares that they're finding. getblocktemplate (GBT) is officially standardised as a Bitcoin Improvement Proposal (BIP). A competing protocol, Stratum, is currently more popular in practice and is a proposed BIP. Unlike the Bitcoin protocol itself, it is only a minor inconvenience to have multiple incompatible mining pool protocols. Each pool can simply pick whichever protocol they like and the market can decide.

Some mining hardware even supports these protocols at the hardware level, which will ultimately limit their development flexibility somewhat. However, this makes it very simple to buy a piece of mining hardware and join a pool. You just plug it into the wall — both the electricity and your network connection — choose a pool, and then it will start immediately getting instructions from the pool, mining and converting your electricity into money.

***51% mining pools.*** As of early 2015, the vast majority of all miners are mining through pools with very few miners mining “solo” anymore. In June 2014, Ghash.io, the largest mining pool, got so big that it actually had over 50% of the entire capacity over the Bitcoin network. Essentially Ghash offered such a good deal to participating miners that the majority wanted to join.

This is something that people had feared for a long time and this led to a backlash against Ghash. By August, Ghash’s market share had gone down by design as they stopped accepting new participants. Still, two mining pools controlled about half of the power in the network.

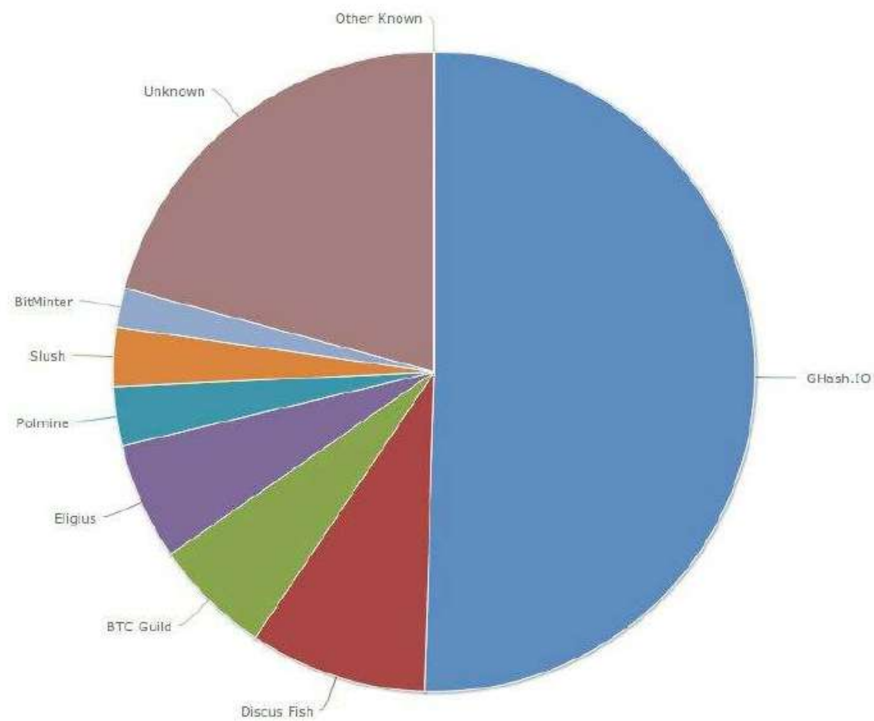



**Figure 5.14 (a) Hash power by mining pool, via blockchain.info (June 2014)**

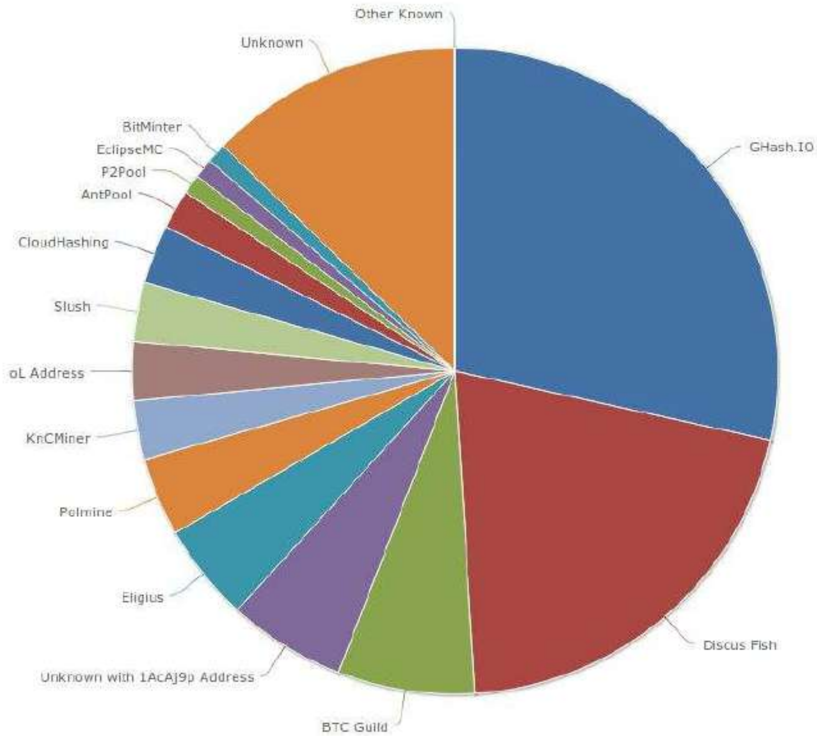



**Figure 5.14 (b) Hash power by mining pool, via blockchain.info (August 2014)**

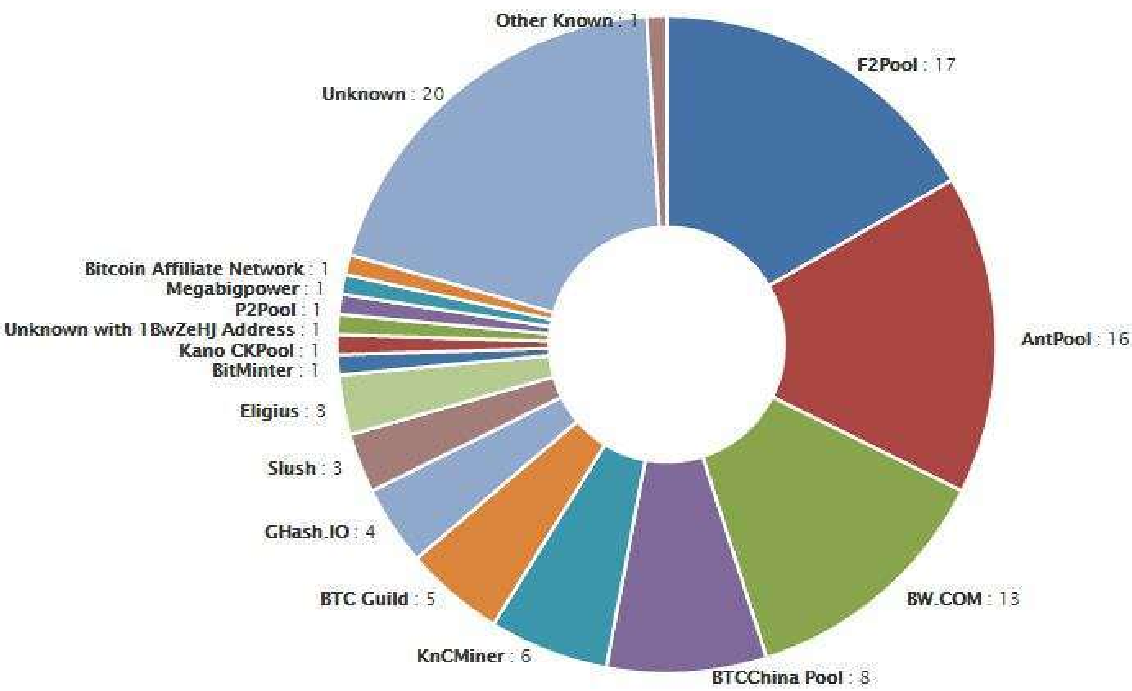



**Figure 5.14 (c) Hash power by mining pool, via blockchain.info (April 2015)**

By April 2015, the situation looks very different and less concentrated, at least on the surface. The possibility of a pool acquiring 51% is still a concern in the community, but the negative publicity GHash received has led pools to avoid becoming too large since then. As new miners and pools have entered the market and standardized protocols have increased the ease of switching between pools for miners, the market share of different pools has remained quite fluid. It remains to be seen how things will evolve in the long run.

However, it is worth noting that mining pools might be hiding actual concentration of mining power in the hands of a few large mining organizations which can participate in multiple mining pools simultaneously to hide their true size. This practice is called *laundering hashes.* It remains unknown how concentrated physical control of mining hardware actually is and mining pools make this quite difficult to determine from the outside.

***Are mining pools a good thing?*** The advantages of mining pools are that they make mining much more predictable for the participants and they make it easier for smaller miners to get involved in the game. Without mining pools, the variance would make mining infeasible for many small miners.

Another advantage of mining pools is that since there's one central pool manager who is sitting on the network and assembling blocks it makes it easier to upgrade the network. Upgrading the software that the mining pool manager is running that effectively updates the software that all of the pool members are running.

The main disadvantage of mining pools, of course, is that they are a form of centralization. It's an open question how much power the operators of a large mining pool actually have. In theory miners are free to leave a pool if it is perceived as too powerful, but it’s unclear how often miners do so in practice.

Another disadvantage of mining pools is that it lowers the population of people actually running a fully validating Bitcoin node. Previously all miners, no matter how small, had to run their own fully validating node. They all had to store the entire block chain and validate every transaction. Now, most miners offload that task to their pool manager. This is the main reason why, as we mentioned in Chapter 3, the number of fully validated nodes may actually be going down in the Bitcoin network.

If you're concerned about the level of centralization introduced by mining pools, you might ask: could we redesign the mining process so that we don't have any pools and everybody has to mine for themselves? We'll consider this question in Chapter 8.

## 5.5 Mining incentives and strategies

We've spent most of this chapter describing how the main challenge of being a miner is getting good hardware, finding cheap electricity, getting up and running as fast as you can and hoping for some good luck. There are also some interesting strategic considerations that every miner has to make before they pick which blocks to work on.

1. *Which transactions to include.* Miners get to choose which transactions they include in a block. The default strategy is to include any transaction which includes a transaction fee higher than some minimum.
2. *Which block to mine on.* Miners also get to decide on top of which block they want to mine. The default behavior for this decision is to extend the longest known valid chain.
3. *Choosing between blocks at the same height.* If two different blocks are mined and announced at around the same time, it results in a 1-block fork, with either block admissible under the longest valid chain policy. Miners then have to decide which block to extend. The default behavior is to build on top of the block that they heard about first.
4. *When to announce new blocks.* When they find a block, miners have to decide when to announce this to the Bitcoin network. The default behavior is to announce it immediately, but they can choose to wait some time before announcing it.

Thus miners are faced with many decisions. For each decision there is a default strategy employed by the Bitcoin reference client, which is run by the vast majority of miners at the time of this writing. It may be possible though that a non-default strategy is more profitable. Finding such scenarios and strategies is an active area of research. Let's look at several such potentially profitable deviations from default behavior. In the following discussion, we'll assume there's a non-default miner who controls some fraction of mining power which we'll denote by $\alpha$.

***Forking attack.*** The simplest attack is a forking attack and the obvious way to profit to perform a double spend. The miner sends some money to a victim, Bob, in payment for some good or service. Bob waits and sees that the transaction paying him has indeed been included in the block chain. Perhaps he follows the common heuristic and even waits for six confirmations to be sure. Convinced that he has been paid, Bob ships the good or performs the service.

The miner now goes ahead and begins working on an earlier block — before the block that contains the transaction to Bob. In this forked chain, the miner inserts an alternate transaction — or a double spend — which sends the coins paid to Bob on the main chain back to one of the miner's own addresses.

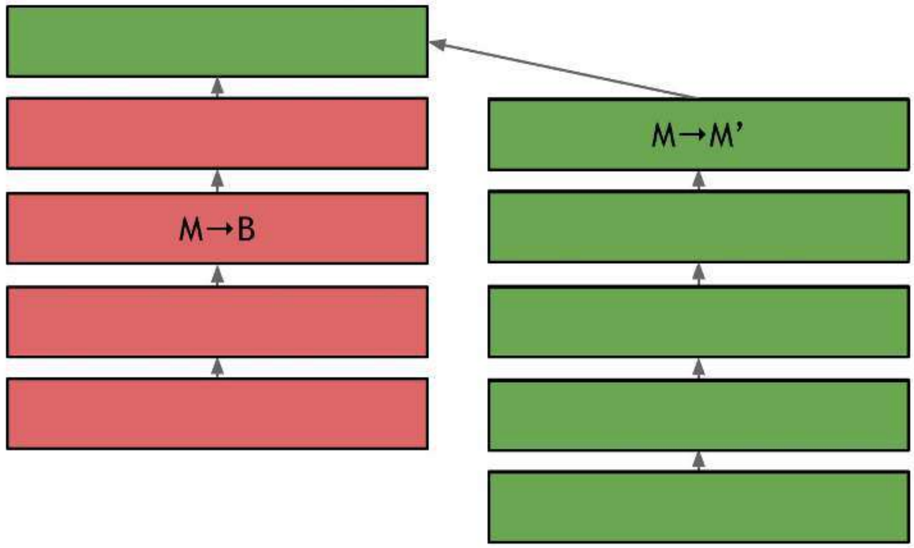



**Figure 5.15 Forking attack.** A malicious miner sends a transaction to Bob and receives some good or service in exchange for it. The miner then forks the block chain to create a longer branch containing a conflicting transaction. The payment to Bob will be invalid in this new consensus chain.

For the attack to succeed, the forked chain must overtake the current longest chain. Once this occurs, the transaction paying Bob no longer exists on the consensus block chain. This will surely happen eventually if the attacking miner has a majority of the hash power — that is, if $\alpha > 0.5$. That is, even though there is a lot of random variation in when blocks are found, the chain that is growing faster on average will eventually become longer. Moreover, since the miner's coins have already been spent (on the new consensus chain), the transaction paying Bob can no longer make its way onto the block chain.

***Is 51% necessary?*** Launching a forking attack is certainly possible if $\alpha > 0.5$. In practice, it might be possible to perform this attack with a bit less than that because of other factors like network overhead. Default miners working on the main chain will generate some stale blocks for the usual reason: there is a latency for miners to hear about each others' blocks. But a centralized attacker can communicate much more quickly and produce fewer stale blocks, which might amount to savings of 1% or more.

Still, at close to 50% the attack may take a long time to succeed due to random chance. The attack gets much easier and more efficient the further you go over 50%. People often talk about a 51% attacker as if 51% is a magical threshold that suddenly enables a forking attack. In reality, it's more of a gradient.

***Practical countermeasures.*** It's not clear whether a forking attack would actually succeed in practice. The attack is detectable, and it's possible that the community would decide to block the attack by refusing to accept the alternate chain even though it is longer.

***Attacks and the exchange rate.*** More importantly, it's likely that such an attack would completely crash the Bitcoin exchange rate. If a miner carried out such an attack, confidence in the system would decline and the exchange rate would fall as people seek to move their wealth out of the system. Thus, while an attacker with 51% of the hashing power might profit in the short term from double-spending, they might seriously undermine their long-term earning potential to just mine honestly and cash in their mining rewards.

For these reasons, perhaps a more plausible motivation for a forking attack is to specifically destroy the currency by a dramatic loss of confidence.  This has been referred to as a G*oldfinger attack* after the Bond villain that tried to irradiate all the gold in Fort Knox to make it valueless. A Goldfinger attacker's goal might be to destroy the currency, possibly to profit either by having shorted Bitcoin or by having significant holdings in some competing currency.

***Forking attack via bribery.*** Buying enough hardware to control the majority of the hash power appears to be an expensive and difficult task. But it's possible that there is an easier way to launch a forking attack. Whereas it would be really expensive to directly buy enough mining capacity to have more than everybody else in the world, it might be possible to bribe the people who do control all that capacity to work on your behalf.

There are a few ways that you could bribe miners. One way is to do this "out of band" — perhaps locate some large miners and hand them an envelope of cash for working on your fork. A more clever technique is to create a new mining pool and run it at a loss, offering greater incentives than other pools. Even though the incentives might not be sustainable, an attacker could keep them going for long enough to successfully launch a forking attack and perhaps profit. A third technique is to leave big "tips" in blocks on the forking chain— big enough to cause miners to leave the longest chain and work on the forking chain in hopes that it will become the longest chain and they can collect the tips.

Whatever the mechanics of the bribing are, the idea is the same: instead of actually acquiring all the mining capacity directly, the attacker just pays those who already have it to help their fork overcome the longest chain.

Perhaps miners won't want to help because to do so would hurt the currency in which they have invested so much money and mining equipment. On the other hand, while miners as a group might want to keep the currency solvent, they don't act collectively. Individual miners might defect and accept a bribe if they thought they could make more money in the short term. This would be a classic tragedy of the commons from an economic perspective.

None of this has actually happened and it's an open question if a bribery attack like this could actually be viable.

***Temporary block-withholding attacks.*** Say that you just found a block. The default behavior is to immediately announce it to the network, but if you're carrying out a temporary block-withholding attack, you don't announce it right away. Instead you try to get ahead by doing some more mining on top of this block in hopes of finding two blocks in a row before the rest of network finds even one, keeping your blocks secret the whole time.

If you're ahead of the public block chain by two secret blocks, all of the mining effort of the rest of the network will be wasted. Other miners will mine on top of what they think is the longest chain, but as soon as they find a valid block, you can announce the two blocks that you were withholding. That would instantly be the new longest valid chain and the block that the rest of the network worked so hard to find would immediately be orphaned and cut off from the longest chain. This has been called ***selfish mining.*** By causing the rest of the network to waste hash power trying to find a block you can immediately cause to be stale, you hope to increase your effective share of mining rewards.

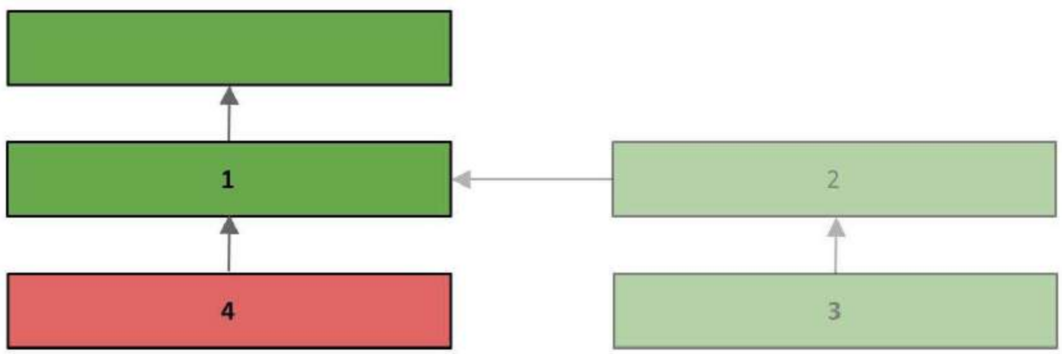



**Figure 5.16: Illustration of selfish mining.** This shows one of several possible ways in which the attack could play out. (1) Block chain before attack. (2) Attacker mines a block, withholds it, starts mining on top of it. (3) Attacker gets lucky, finds a second block before the rest of the network, continues to withhold blocks. (4) Non-attacker finds a block and broadcasts it. In response, the attacker broadcasts both his blocks, orphaning the red block and wasting the mining power that went into finding it.

The catch is that you need to get lucky to find two blocks in a row. Chances are that someone else in the network announces a valid block when you're only one block ahead. If this happens, you'll want to immediately announce your secret block yourself. This creates a 1-block fork and every miner will need to make a decision about which of those blocks to mine on. Your hope is that a large fraction of other miners will hear about your block first and decide to work on it. The viability of this attack depends heavily on your ability to win these races, so network position is critical. You could try to peer with every node so that your block will reach most nodes first.

As it turns out, if you assume that you only have a 50 percent chance of winning these races, selfish mining is an improvement over the default strategy if $\alpha$ > .25. Even if you lose every race, selfish mining is still more profitable if $\alpha$ > .333. The existence of this attack is quite surprising and it's contrary to the original widely-held belief that without a majority of the network — that is with $\alpha \leq .5$, there was no better mining strategy then the default. So it's not safe to assume that a miner who doesn't control 50 percent of the network doesn't have anything to gain by switching to an alternate strategy.

At this point temporary block withholding is just a theoretical attack and hasn't been observed in practice. Selfish mining would pretty easy to detect because it would increase the rate of near-simultaneous block announcements.

***Blacklisting and punitive forking.*** Say a miner wants to blacklist transactions from address *X*. In other words, they want to freeze the money held by that address, making it unspendable. Perhaps you intend to profit off of this by some sort of ransom or extortion scheme demanding that the person you're blacklisting pay you in order to be taken off of your blacklist. Blacklisting also might be something that you are compelled to do for legal reasons. Maybe certain addresses are designated as evil by the government. Law enforcement may demand that all miners operating in their jurisdiction try to blacklist those addresses.

Conventional wisdom is that there's no effective way to blacklist addresses in Bitcoin. Even if some miners refuse to include some transactions in blocks, other miners will. If you're a miner trying to blacklist, however, you could try something stronger, namely, punitive forking. You could announce that you'll refuse to work on a chain containing a transaction originating from this address. If you have a majority of the hash power, this should be enough to guarantee the blacklisted transactions will never get published. Indeed, other miners would probably stop trying, as doing so would simply cause their blocks to be elided in forks.

***Feather-forking.*** Punitive forking doesn't appear to work without a majority of the network hash power. By announcing that you'll refuse to mine on any chain that has certain transactions, if such a chain does come into existence and is accepted by the rest of the network as the longest chain, you will have cut yourself off from the consensus chain forever (effectively introducing a hard fork) and all of the mining that you're doing will go to waste. Worse still, the blacklisted transactions will still make it into the longest chain.

In other words, a threat to blacklist certain transactions via punitive forking in the above manner is not credible as far as the other miners are concerned. But there's a much more clever way to do it. Instead of announcing that you're going to fork forever as soon as you see a transaction originating from address *X*, you announce that you'll attempt to fork if you see a block that has a transaction from address *X*, but you will give up after a while. For example, you might announced that after *k* blocks confirm the transaction from address *X,* you'll go back to the longest chain.

If you give up after one confirmation, your chance of orphaning the block with the transaction from *X* is $\alpha^2$. The reason for this is that you'll have to find two consecutive blocks to get rid of the block with the transaction from address *X* before the rest of the network finds a block and $\alpha^2$ is the chance that you will get lucky twice.

A chance of $\alpha^2$ might not seem very good. If you control 20% of the hash power, there's only a 4% chance of actually getting rid of that transaction that you don't want to see in the block chain. But it's better than it might seem as you might motivate other miners to join you. As long as you've been very public about your plans, other miners know that if they include a transaction from address *X*, they have an $\alpha^2$ chance that the block that they find will end up being eliminated because of your feather-forking attack. If they don't have any strong motivation to include that transaction from address X and it doesn't have a high transaction fee, the $\alpha^2$ chance of losing their mining reward might be a much bigger incentive than collecting the transaction fee.

It emerges then that other miners may rationally decide to join you in enforcing the blacklist, and you can therefore enforce a blacklist even if $\alpha < .5$. The success of this attack is going to depend entirely on how convincing you are to the other miners that you're definitely going to fork.

***Transitioning to mining rewards dominated by transaction fees.*** As of 2015, transaction fees don't matter that much since block rewards provide the vast majority — over 99% — of all the revenue that miners are making. But every four years the block reward is scheduled to be halved, and eventually the block reward will be low enough that transaction fees will be the main source of revenue for miners. It's an open question exactly how miners will operate when transaction fees become their main source of income. Are miners going to be more aggressive in enforcing minimum transaction fees. Are they going to cooperate to enforce that?

***Open problems.*** In summary, miners are free to implement any strategy that they want although in practice we've seen very little behavior of anything other than the default strategy. There's no complete model for miner behavior that says the default strategy is optimal. In this chapter we've seen specific examples of deviations that may be profitable for miners with sufficient hash power. Mining strategy may be an area in which the practice is ahead of the theory. Empirically, we've seen that in a world where most miners do choose the default strategy, Bitcoin seems to work well. But we're not sure if it works in theory yet.

We also can't be sure that it will always continue to work well in practice. The facts on the ground are going to change for Bitcoin. Miners are becoming more centralized and more professional, and the network capacity is increasing. Besides, in the long run Bitcoin must contend with the transition from fixed mining rewards to transaction fees. We don't really know how this will play out and using game-theoretic models to try to predict it is a very interesting current area of research.

## Further reading

An excellent paper on the evolution of mining hardware:

**Taylor, Michael Bedford. Bitcoin and the age of bespoke Silicon. Proceedings of the 2013 International Conference on Compilers, Architectures and Synthesis for Embedded Systems. IEEE Press, 2013.**

A paper discussing some aspects of running a Bitcoin mining center including cooling costs:

**Kampl, Alex. Analysis of Large-Scale Bitcoin Mining Operations. White paper, Allied Control, 2014.**

The “systematization of knowledge” paper on Bitcoin and cryptocurrencies, especially Section III on Stability:

**Bonneau, Joseph, Andrew Miller, Jeremy Clark, Arvind Narayanan, Joshua A. Kroll, and Edward W. Felten. Research Perspectives and Challenges for Bitcoin and Cryptocurrencies. Proceedings of 2015 IEEE Security and Privacy Conference, 2015.**

A comprehensive 2011 paper analyzing different reward systems for pooled mining (some of the information is a bit out of date, but overall it’s still a good resource):

**Rosenfeld, Meni. Analysis of bitcoin pooled mining reward systems. arXiv preprint arXiv:1112.4980 (2011).**

Several papers that analyze mining strategy:

**Eyal, Ittay, and Emin Gün Sirer. Majority is not enough: Bitcoin mining is vulnerable. Financial Cryptography and Data Security. Springer Berlin Heidelberg, 2014.**

**Kroll, Joshua A., Ian C. Davey, and Edward W. Felten. The economics of Bitcoin mining, or Bitcoin in the presence of adversaries. Proceedings of WEIS. Vol. 2013.**

**Eyal, Ittay. The Miner's Dilemma. Proceedings of 2015 IEEE Security and Privacy Conference, 2015.**

# Chapter 6: Bitcoin and Anonymity

**"Bitcoin is a secure and anonymous digital currency"**

— WikiLeaks donations page

**"Bitcoin won't hide you from the NSA's prying eyes"**

— Wired UK

One of the most controversial things about Bitcoin is its supposed anonymity. First, is Bitcoin anonymous? As you can see from the mutually contradictory quotes above, there's some confusion about this. Second, do we *want* a cryptocurrency that is truly anonymous? There are pros and cons of anonymity, which leads to some basic questions: is having an anonymous cryptocurrency beneficial for the stakeholders? Is it good for society? Is there a way to isolate the positive aspects of anonymity while doing away with the negative parts?

These questions are hard because they depend in part on one's ethical values. We won't answer them in this chapter, though we will examine arguments for and against anonymity. Mostly we'll stick to studying various technologies — some already present in Bitcoin and others that have been proposed to be added to it — that aim to increase Bitcoin's anonymity. We'll also look at proposals for alternative cryptocurrencies that have different anonymity properties from Bitcoin. These technologies raise new questions: How well do they work? How difficult would they be to adopt? What are the tradeoffs to be made in adopting them?

## 6.1 Anonymity Basics

***Defining anonymity.*** Before we can properly discuss whether (or to what extent) Bitcoin is anonymous, we need to define anonymity. We must understand what exactly we mean by anonymity, and the relationship between anonymity and similar terms, such as privacy.

At a literal level, anonymous means "without a name." When we try to apply this definition to Bitcoin, there are two possible interpretations: interacting without using your real name, or interacting without using any name at all. These two interpretations lead to very different conclusions as to whether Bitcoin is anonymous. Bitcoin addresses are hashes of public keys. You don't need to use your real name in order to interact with the system, but you do use your public key hash as your identity. Thus, by the first interpretation, Bitcoin is anonymous as you do not use your real name. However, by the second interpretation, it is not; the address that you use is a pseudo-identity. In the language of computer science, this middle ground of using an identity that is not your real name is called ***pseudonymity.***

Recall that you are free to create as many Bitcoin addresses as you like. With this in mind, you might be wondering whether Bitcoin addresses really are pseudo-identities considering that you can create as many of these pseudonyms as you like. As we'll see, this still does not make Bitcoin anonymous.

In computer science, anonymity refers to pseudonymity together with ***unlinkability***. Unlinkability is a property that's defined with respect to the capabilities of a specific adversary. Intuitively, unlinkability means that if a user interacts with the system repeatedly, these different interactions should not be able to be tied to each other from the point of view of the adversary in consideration.

**Sidebar.** The distinction between anonymity and mere pseudonymity is something that you might be familiar with from a variety of other contexts. One good example is online forums. On a forum like Reddit, you pick a long-term pseudonym and interact over a period of time with that pseudonym. You could create multiple pseudonyms, or even a new one for every comment, but that would be tedious and annoying and most people don't do it. So interacting on Reddit is usually pseudonymous but not quite anonymous. 4Chan, by contrast, is an online forum in which users generally post anonymously — with no attribution at all.

Bitcoin is pseudonymous, but pseudonymity is not enough if your goal is to achieve privacy. Recall that the block chain is public and anyone can look up all Bitcoin transactions that involved a given address. If anyone is ever able to link your Bitcoin address to your real world identity, then all of your transactions — past, present, and future — will have been linked back to your identity.

To make things worse, linking a Bitcoin address to a real-world identity is often easy. If you interact with a Bitcoin business — be it an online wallet servics, exchange, or other merchant — they are usually going to want your real life identity in order to let you transact with them. For example, an exchange might require your credit card details, while a merchant will need your shipping address.

Or you might go to a coffee shop and pay for your coffee with bitcoins. Since you're physically present in the store, the barista knows a lot about your identity even if they don't ask for your real name. Your physical identity thus gets tied to one of your Bitcoin transactions, making all the other transactions that involved that address linkable to you. This is clearly not anonymous.

***Side channels.*** Even if a direct linkage doesn't happen, your pseudonymous profile can be ***deanonymized*** due to side channels, or indirect leakages of information. For example, someone may look at a profile of pseudonymous Bitcoin transactions and note at what times of day that user is active. They can correlate this information with other publicly available information. Perhaps they'll notice that some Twitter user is active during roughly same time intervals, creating a link between the pseudonymous Bitcoin profile and a real-world identity (or at least a Twitter identity). Clearly pseudonymity does not guarantee privacy or anonymity. To achieve those, we require the stronger property of unlinkability as well.

***Unlinkability.*** To understand unlinkability in the Bitcoin context more concretely, let’s enumerate some key properties that are required for Bitcoin activity to be unlinkable:

1. It should be hard to link together different addresses of the same user.
2. It should be hard to link together different transactions made by the same user.
3. It should be hard to link the sender of a payment to its recipient.

The first two properties are intuitive, but the third one is a bit tricky. If you interpret “a payment” as a Bitcoin transaction, then the third property is clearly false. Every transaction has inputs and outputs, and these inputs and outputs are inevitably going to be in the block chain and publicly linked together. However, what we mean by a payment is not a single Bitcoin transaction, but rather anything that has the effect of transferring bitcoins from the sender to the recipient. It might involve a roundabout series of transactions. What we want to ensure is that it’s not feasible to link the sender and the ultimate recipient of the payment by looking at the block chain.

***Anonymity set.*** Even under our broader definition of a payment, the third property seems hard to achieve. Say you pay for a product that costs a certain number of bitcoins and you send that payment through a circuitous route of transactions. Somebody looking at the block chain will still be able to infer something from the fact that a certain number of bitcoins left one address and roughly the same number of bitcoins (minus transaction fees, perhaps) ended up at some other address. Moreover, despite the circuitous route, the initial sending and the ultimate receiving will happen in roughly the same time period because the merchant will want to receive payment without too much of a delay.

Because of this difficulty, we usually don't try to achieve complete unlinkability among all possible transactions or addresses in the system, but rather something more limited. Given a particular adversary, the *anonymity set* of your transaction is the set of transactions which the adversary cannot distinguish from your transaction. Even if the adversary knows you made a transaction, they can only tell that it’s one of the transactions in the set, but not which one it is. We try to maximize the size of the anonymity set — the set of other addresses or transactions amongst which we can hide.

Calculating the anonymity set is tricky. Since the anonymity set is defined with respect to a certain adversary or set of adversaries, you must first concretely define what your adversary model is. You have to reason carefully about what that adversary knows, what they don't know, and what is it that we are trying to hide from the adversary — that is, what the adversary *cannot* know for the transaction to be considered anonymous. There's no general formula for doing this. It requires carefully analyzing each protocol and system on a case-by-case basis.

***Taint analysis.*** In the Bitcoin community, people often carry out intuitive analyses of anonymity services without rigorous definitions. *Taint analysis* is particularly popular: it’s a way of calculating how “related” two addresses are. If bitcoins sent by an address S always end up at another address R, whether directly or after passing through some intermediate addresses, then S and R will have a high taint score. The formula accounts for transactions with multiple inputs and/or outputs and specifies how to allocate taint.

Unfortunately, taint analysis is not a good measure of Bitcoin anonymity. It implicitly assumes that the adversary is using the same mechanical calculation to link pairs of addresses. A slightly cleverer adversary may use other techniques such as looking at the timing of transactions or even exploit idiosyncrasies of wallet software as we'll see later in this chapter. So taint analysis might suggest that you have a high degree of anonymity in a certain situation, but in fact you might not.

***Why we need anonymity.*** Having seen what anonymity means, let's answer some meta-questions about anonymity before we go further: Why do people want anonymity? What are the ethical implications of having an anonymous currency?

In block chain-based currencies, all transactions are recorded on the ledger, which means that they are publicly and permanently traceable to the associated addresses. So the privacy of your Bitcoin transactions can potentially be far worse than with traditional banking. If your real-world identity ever gets linked to a Bitcoin address, then you have totally lost privacy for all transactions — past, present, and future — associated with that address. Since the block chain is publicly available, literally anyone might be able to carry out this type of deanonymization without you even realizing that you've been identified.

With this in mind, we can identify two different motivations for having anonymous cryptocurrencies. The first is simply to achieve the level of privacy that we are already used to from traditional banking, and mitigate the deanonymization risk that the public block chain brings. The second is to go above and beyond the privacy level of traditional banking and develop currencies that make it technologically infeasible for anyone to track the participants.

***Ethics of anonymity.*** There are many important (though often overlooked) reasons for anonymity that we take for granted with traditional currencies. Most people are uncomfortable sharing their salaries with their friends and coworkers. If individual's addresses in the blockchain are easily identifiable though and they receive their salary in Bitcoin, it would be quite easy to infer their salary by looking for a large, regular monthly payment. Organizations also have important financial privacy concerns. For example, if a video game console manufacturer were to be observed in the blockchain paying a subcontractor which manufactures virtual reality glasses, this might tip off the public (and their competitors) about a new product they are preparing to launch.

However, there is legitimate concern that truly anonymous cryptocurrencies can be used for money laundering or other illegal activities. The good news is that while cryptocurrency transactions themselves may be pseudonymous or anonymous, the interface between digital cash and fiat currencies is not. In fact, these flows are highly regulated, as we'll see in the next chapter. So cryptocurrencies are no panacea for money laundering or other financial crimes.

Nevertheless one may ask: can't we design the technology in such a way that only the good uses of anonymity are allowed and the bad uses are somehow prohibited? This is in fact a recurring plea to computer security and privacy researchers. Unfortunately, it never turns out to be possible. The reason is that use cases that we classify as good or bad from a moral viewpoint turn out to be technologically identical. In Bitcoin, it’s not clear how we could task miners with making moral decisions about which transactions to include.

Our view is that the potential good that’s enabled by having anonymous cryptocurrencies warrant their existence, and that we should separate the technical anonymity properties of the system from the legal principles we apply when it comes to using the currency. It's not a completely satisfactory solution, but it's perhaps the best way to achieve a favorable trade-off.

***Sidebar: Tor.*** The moral dilemma of how to deal with a technology that has both good and bad uses is by no means unique to Bitcoin. Another system whose anonymity is controversial is Tor, an anonymous communication network.

On the one hand, Tor is used by normal people who want to protect themselves from being tracked online. It's used by journalists, activists, and dissidents to speak freely online without fear of repercussion from oppressive regimes. It's also used by law enforcement agents who want to monitor suspects online without revealing their IP address (after all, ranges or blocks of IP addresses assigned to different organizations, including law enforcement agencies, tend to be well known). Clearly, Tor has many applications that we might morally approve of. However, it also has clearly bad uses: it’s used by operators of botnets to issue commands to the infected machines under their control and it’s used to distribute child sexual abuse images.

Distinguishing between these uses at a technical level is essentially impossible. The Tor developers and the Tor community have grappled extensively with this conundrum. Society at large has grappled with it to some degree as well. We seem to have concluded that overall, it's better for the world that the technology exists. In fact one of the main funding sources of the Tor project is the U.S. State Department. They're interested in Tor because it enables free speech online for dissidents in oppressive regimes. Meanwhile, law enforcement agencies seem to have grudgingly accepted Tor’s existence, and have developed ways to work around it. The FBI has regularly managed to bust websites on the “dark net” that distributed child sexual abuse images, even though these sites hid behind Tor. Often this is because the operators tripped up. We must remember that technology is only a tool and that perpetrators of crimes live in the real world, where they may leave physical evidence or commit all-too-human errors when interacting with the technology.

***Anonymization vs. decentralization.*** We’ll see a recurring theme throughout this chapter that the design criteria of anonymization and decentralization are often in conflict with one another. If you recall Chaum’s ecash from the preface, it achieved perfect anonymity in a sense, but through an interactive blind-signature protocol with a central authority, a bank. As you can imagine, such protocols are very difficult to decentralize. Secondly, if we decentralize, then we must keep some sort of mechanism to trace transactions and prevent double spending. This public traceability of transactions is a threat to anonymity.

Later in this chapter, we'll see Zerocoin and Zerocash, anonymous decentralized cryptocurrencies that have some similarities to Chaum's ecash, but they have to tackle thorny cryptographic challenges because of these two limitations.

## 6.2 How to De-anonymize Bitcoin

We've said several times that Bitcoin is only pseudonymous, so all of your transactions or addresses could potentially be linked together. Let's take a closer look at how that might actually happen.

Figure 6.1 shows a snippet of the Wikileaks donation page (including the quote at the beginning of the chapter). Notice the refresh button next to the donation address. As you might expect, clicking the button will replace the donation address with an entirely new, freshly generated address. Similarly, if you refresh the page or close it and visit it later, it will have another address, never previously seen. That's because Wikileaks wants to make sure that each donation they receive goes to a new public key that they create just for that purpose. Wikileaks is taking maximal advantage of the ability to create new pseudonyms. This is in fact the best practice for anonymity used by Bitcoin wallets.


***Figure 6.1: Snippet from Wikileaks donation page.*** Notice the refresh icon next to the Bitcoin address. Wikileaks follows the Bitcoin best practice of generating a new receiving address for every donation.

At first you might think that these different addresses must be unlinkable. Wikileaks receives each donation separately, and presumably they can also spend each of those donations separately. But things quickly break down.

***Linking.*** Suppose Alice wants to buy a teapot that costs 8 bitcoins (more likely 8 centi-bitcoins, at 2015 exchange rates). Suppose, further, that her bitcoins are in three separate unspent outputs at different addresses whose amounts are 3, 5, and 6 bitcoins respectively. Alice doesn't actually have an address with 8 bitcoins sitting in it, so she must combine two of her outputs as inputs into a single transaction that she pays to the store.

But this reveals something. The transaction gets recorded permanently in the block chain, and anyone who sees it can infer that the two inputs to the transaction are most likely under the control of the same user. In other words, **shared spending is evidence of joint control** of the different input addresses. There could be exceptions, of course. Perhaps Alice and Bob are roommates and agree to jointly purchase the teapot by each supplying one transaction input. But by and large, joint inputs imply joint control.

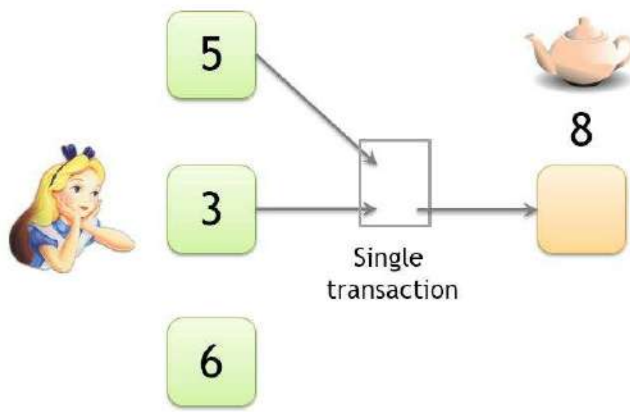



***Figure 6.2 :*** To pay for the teapot, Alice has to create a single transaction having inputs that are at two different address. In doing so, Alice reveals that these two addresses are controlled by a single entity.

But it doesn't stop there. The adversary can repeat this process and **transitively** link an entire cluster of transactions as belonging to a single entity. If another address is linked to **either** one of Alice's addresses in this manner, then we know that all three addresses belong to the same entity, and we can use this observation to cluster addresses. In general, if an output at a new address is spent together with one from any of the addresses in the cluster, then this new address can also be added to the cluster.

Later in this chapter we'll study an anonymity technique called CoinJoin that works by violating this assumption. But for now, if you assume that people are using regular Bitcoin wallet software without any special anonymity techniques, then this clustering tends to be pretty robust. We haven't yet seen how to link these clusters to real-world identities, but we'll get to that shortly.

***Sidebar: Change address randomization.*** An early version of the bitcoin-qt library had a bug which always put the change address as the first output in a transaction with two outputs. This meant that it was trivial to identify the change address in many transactions. This bug was fixed in 2012 but highlights an important point: wallet software has an important role to play in protecting anonymity. If you're developing wallet software, there are many pitfalls you should be aware of; in particular, you should always choose the position of the change address at random to avoid giving too much away to the adversary!

Going back to our example, suppose the price of the teapot has gone up from 8 bitcoins to 8.5 bitcoins. Alice can no longer find a set of unspent outputs that she can combine to produce the exact change needed for the teapot. Instead, Alice exploits the fact that transactions can have multiple outputs, as shown in Figure 6.3. One of the outputs is the store's payment address and the other is a "change" address owned by herself.

Now consider this transaction from the viewpoint of an adversary. They can deduce that the two input addresses belong to the same user. They might further suspect that one of the output addresses also belongs to that same user, but has no way to know for sure which one that is. The fact that the 0.5 output is smaller doesn't mean that it's the change address. Alice might have 10,000 bitcoins sitting in a transaction, and she might spend 8.5 bitcoins on the teapot and send the remaining 9,991.5 bitcoins back to herself. In that scenario the bigger output is in fact the change address.

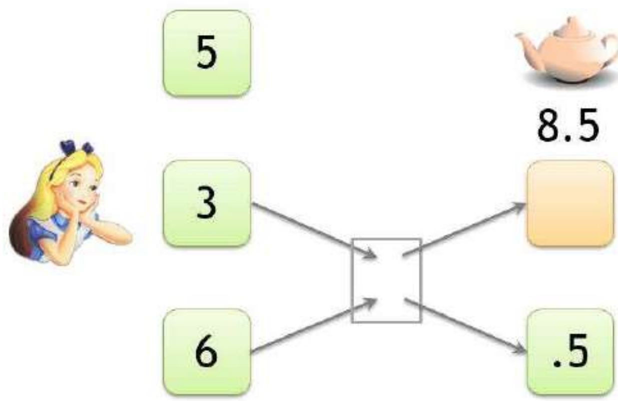



***Figure 6.3: Change address.*** To pay for the teapot, Alice has to create a transaction with one output that goes to the merchant and another output that sends change back to herself.

A somewhat better guess is that if the teapot had cost only 0.5 bitcoins, then Alice wouldn't have had to create a transaction with two different inputs, since either the 3 bitcoin input or the 6 bitcoin input would have been sufficient by itself. But the effectiveness of this type of heuristic depends entirely on the implementation details of commonly used wallet software. There's nothing preventing wallets (or users) from combining transactions even when not strictly necessary.

***Idioms of use.*** Implementation details of this sort are called "idioms of use". In 2013, a group of researchers found an idiom of use that was true of most wallet software, and led to a powerful heuristic for identifying change addresses. Specifically, they found that wallets typically generate a fresh address whenever a change address is required. Because of this idiom of use, change addresses are generally addresses that have never before appeared in the block chain. Non-change outputs, on the other hand, are often not new addresses and may have appeared previously in the block chain. An adversary can use this knowledge to distinguish change addresses and link them with the input addresses.

Exploiting idioms of use can be error prone. The fact that change addresses are fresh addresses just happens to be a feature of wallet software. It was true in 2013 when the researchers tested it. Maybe it's still true, but maybe it's not. Users may choose to override this default behavior. Most importantly, an adversary who is aware of this technique can easily evade it. Even in 2013, the researchers found that it produced a lot of false positives, in which they ended up clustering together addresses that didn't actually belong to the same entity. They reported that they needed significant manual oversight and intervention to prune the false positives.

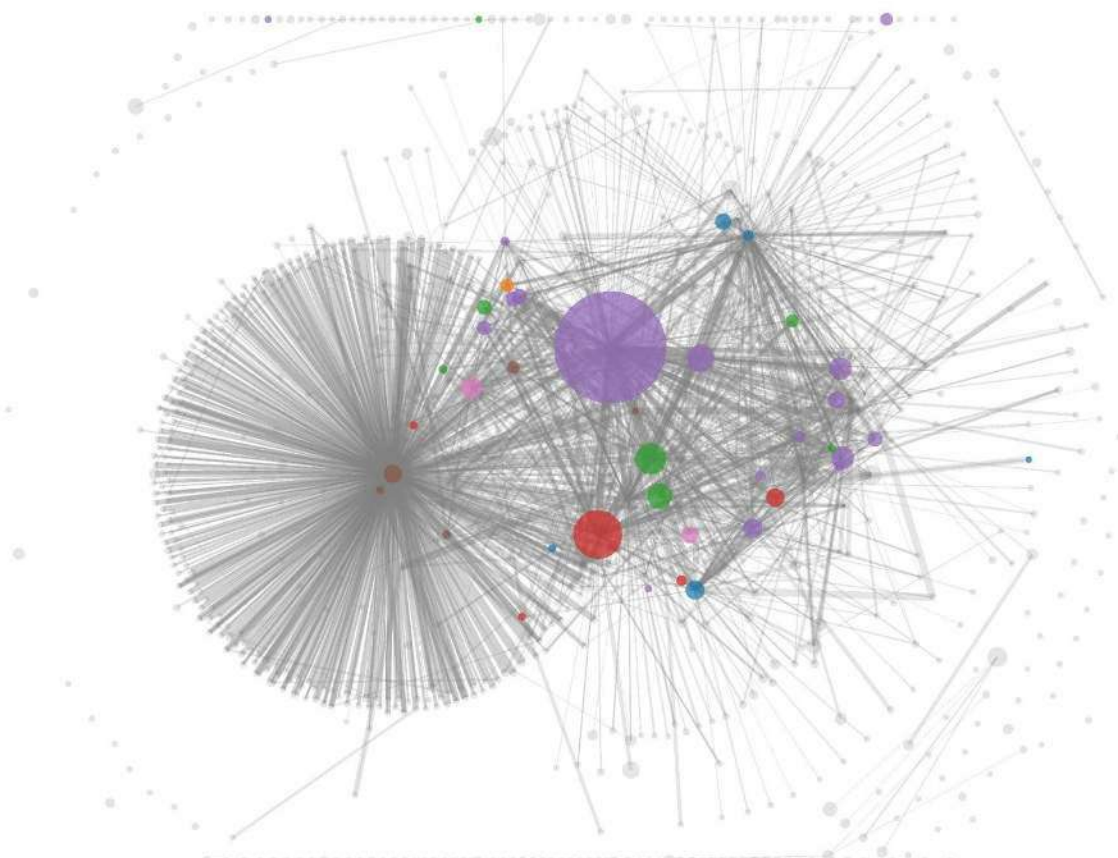


***Figure 6.4: Clustering of addresses.*** In the 2013 paper *A Fistful of Bitcoins: Characterizing Payments Among Men with No Names,* researchers combined the shared-spending heuristic and the fresh-change-address heuristic to cluster Bitcoin addresses. The sizes of these circles represent the quantity of money flowing into those clusters, and each edge represents a transaction.

***Attaching real-world identities to clusters.*** In Figure 6.4. we see how Meiklejohn et al. clustered Bitcoin addresses using basic idioms of use as heuristics. But the graph is not labeled — we haven't yet attached identities to the clusters.

We might be able to make some educated guesses based on what we know about the Bitcoin economy. Back in 2013, Mt. Gox was the largest Bitcoin exchange, so we might guess that the big purple circle represents addresses controlled by them. We might also notice that the brown cluster on the left has a tiny volume in Bitcoins despite having the largest number of transactions. This fits the pattern of the gambling service Satoshi Dice, which is a popular game in whic you send a tiny amount of bitcoins as a wager. Overall though, this isn't a great way to identify clusters. It requires knowledge and guesswork and will only work for the most prominent services.

***Tagging by transacting.*** What about just visiting the website for each exchange or merchant and looking up the address they advertise for receiving bitcoins? That doesn't quite work, however, because most services will advertise a new address for every transaction and the address shown to you is not yet in the block chain. There's no point in waiting, either, because that address will never be shown to anyone else.

The only way to reliably infer addresses is to actually transact with that service provider — depositing bitcoins, purchasing an item, and so on. When you send bitcoins to or receive bitcoins from the service provider, you will now know one of their addresses, which will soon end up in the block chain (and in one of the clusters). You can then tag that entire cluster with the service provider's identity.

This is is exactly what the *Fistful of Bitcoins* researchers (and others since) have done. They bought a variety of things, joined mining pools, used Bitcoin exchanges, wallet services, and gambling sites, and interacted in a variety of other ways with service providers, compromising 344 transactions in all.

In Figure 6.5, we again show the clusters of Figure 6.4, but this times with the labels attached. While our guesses about Mt. gox and Satoshi Dice were correct, the researchers were able to identify numerous other service providers that would have been hard to identify without transacting with them.

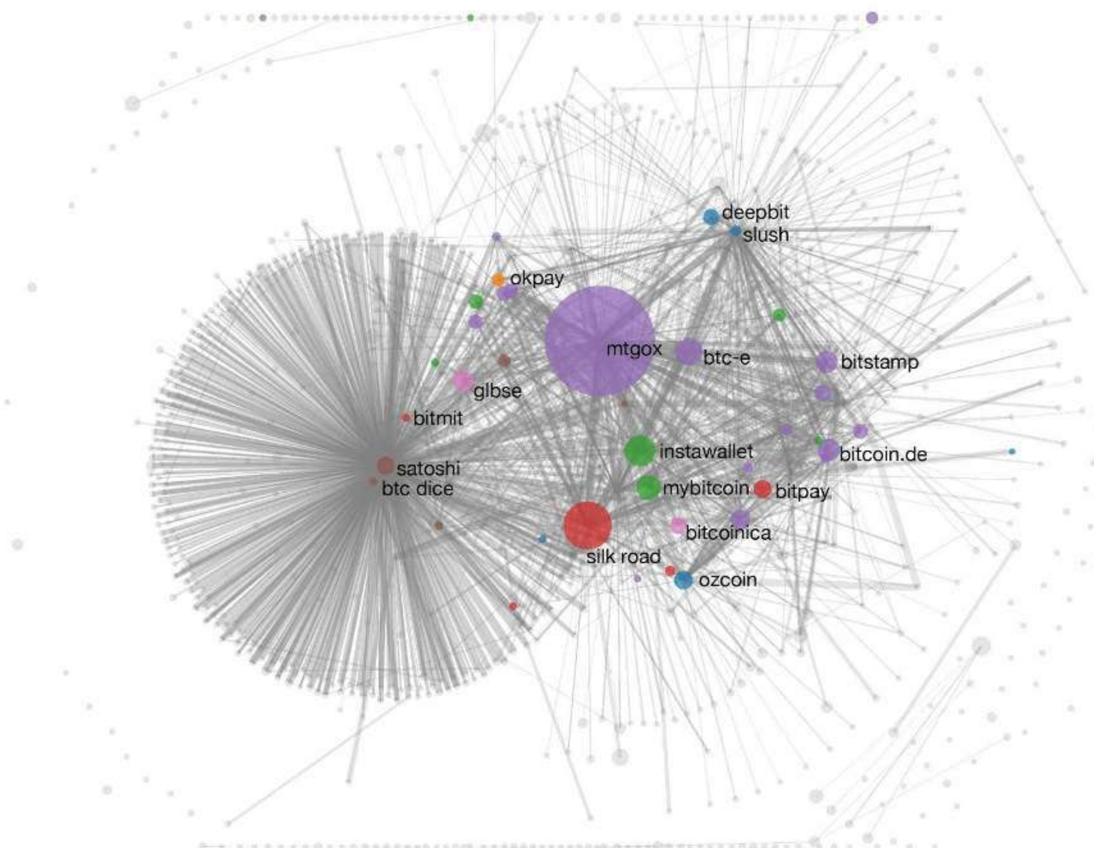



***Figure 6.5**. **Labeled clusters.*** By transacting with various Bitcoin service providers, Meiklejohn et al. were able to attach real world identities to their clusters.

***Identifying individuals.*** The next question is: can we do the same thing for individuals? That is, can we connect little clusters corresponding to individuals to their real-life identities?

*Directly transacting.* Anyone who transacts with an individual — an online or offline merchant, an exchange, or a friend who splits a dinner bill using Bitcoin — knows at least one address belonging to them.

*Via service providers.* In the course of using Bitcoin over a few months or years, most users will end up interacting with an exchange or another centralized service provider. These service typically providers ask users for their identities — often they're legally required to, as we'll see in the next chapter. If law enforcement wants to identify a user, they can turn to these service providers.

*Carelessness.* People often post their Bitcoin addresses in public forums. A common reason is to request donations. When someone does this it creates a link between their identity and one of their addresses. If they don't use the anonymity services that we'll look at in the following sections, they risk having all their transactions de-anonymized.

*Things get worse over time.* History shows that deanonymization algorithms usually improve over time when the data is publicly available as more researchers study the problem and identify new attack techniques. Besides, more auxiliary information becomes available that attackers can use to attach identities to clusters. This is something to worry about if you care about privacy.

The deanonymization techniques we've examined so far are all based on analyzing the graphs of transactions in the block chain. They are collectively known as ***transaction graph analysis.***

***Network-layer deanonymization.*** There's a completely different way in which users can get deanonymized that does not rely on the transaction graph. Recall that in order to post a transaction to the block chain, one typically broadcasts it to Bitcoin's peer-to-peer network where messages are sent around that don't necessarily get permanently recorded in the block chain.

In networking terminology, the block chain is called the ***application layer*** and the peer-to-peer network is the ***network layer***. Network-layer deanonymization was first pointed out by Dan Kaminsky at the 2011 Black Hat conference. He noticed that when a node creates a transaction, it connects to many nodes at once and broadcasts the transaction. If sufficiently many nodes on the network collude with each other (or are run by the same adversary), they could figure out the first node to broadcast any transaction. Presumably, that would be a node that's run by the user who created the transaction. The adversary could then link the transaction to the node's IP address. An IP address is close to a real-world identity; there are many ways to try to unmask the person behind an IP address. Thus, network-layer de-anonymization is a serious problem for privacy.

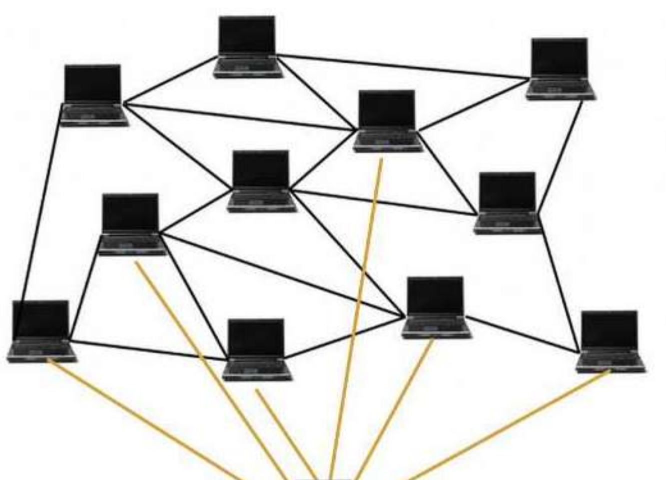


***Figure 6.6**. **Network level deanonymization.*** As Dan Kaminsky pointed out in his 2011 Black Hat talk, "the first node to inform you of a transaction is probably the source of it." This heuristic is amplified when multiple nodes cooperate and identify the same source.

Luckily, this is a problem of communications anonymity, which has already been the subject of considerable research. As we saw earlier in Section 6.1, there's a widely deployed system called Tor that you can use for communicating anonymously.

There are a couple of caveats to using Tor as a network-layer anonymity solution for Bitcoin. First, there can be subtle interactions between the Tor protocol and any protocol that's overlaid on top of it, resulting in new ways to breach anonymity. Indeed, researchers have found potential security problems with using Bitcoin-over-Tor, so this must be done with extreme caution. Second, there might be other anonymous communication technologies better suited to use in Bitcoin. Tor is intended for "low-latency" activities such as web browsing where you don't want to sit around waiting for too long. It makes some compromises to achieve anonymity with low latency. Bitcoin, by comparison, is a high-latency system because it takes a while for transactions to get confirmed in the block chain. In theory, at least, you might want to use an alternative anonymity technique such as a **mix net**, but for the moment, Tor has the advantage of being an actual system that has a large user base and whose security has been intensely studied.

So far, we've seen that different addresses might be linked together by transaction graph analysis and that they might also be linkable to a real-world identity. We've also seen that a transaction or address could get linked to an IP address based on the peer-to-peer network. The latter problem is relatively easy to solve, even if it can't be considered completely solved yet. The former problem is much trickier, and we're going to spend the rest of this chapter talking about ways to solve it.

## 6.3 Mixing

There are several mechanisms that can make transaction graph analysis less effective. One such technique is *mixing*, and the intuition behind it is very simple: if you want anonymity, use an intermediary. This principle is not specific to Bitcoin and is useful in many situations where anonymity is a goal. Mixing is illustrated in Figure 6.7.

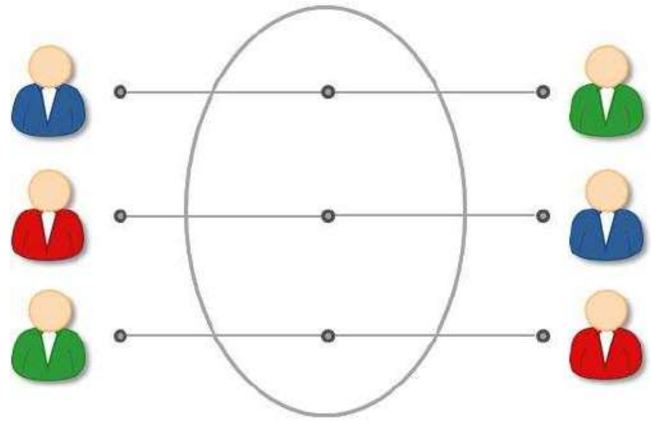


***Figure 6.7 : Mixing.*** Users send coins to an intermediary and get back coins that were deposited by other users. This makes it harder to trace a user's coins on the block chain.

***Online wallets as mixes.*** If you recall our discussion of online wallets, they may seem to be suitable as intermediaries. Online wallets are services where you can store your bitcoins online and withdraw them at some later date. Typically the coins that you withdraw won't be the same as the coins you deposited. Do online wallets provide effective mixing, then?

Online wallets do provide a measure of unlinkability which can foil attempts at transaction graph analysis — in one case, prominent researchers had to retract a claim that had received a lot of publicity because the link they thought they'd found was a spurious one caused by an online wallet.

On the other hand, there are several important limits to using online wallets for mixing. First, most online wallets don't actually promise to mix users' funds; instead, they do it because it simplifies the engineering. You have no guarantee that they won't change their behavior. Second, even if they do mix funds, they will almost certainly maintain records internally that will allow them to link your deposit to your withdrawal. This is a prudent choice for wallet services for reasons of both security and legal compliance. So if your threat model includes the possibility of the service provider itself tracking you, or getting hacked, or being compelled to hand over their records, you're back to square one. Third, in addition to keeping logs internally, reputable and regulated services will also require and record your identity (we'll discuss regulation in more detail in the next chapter). You won't be able to simply create an account with a username and password. So in one sense it leaves you worse off than not using the wallet service. That's why we called out the tension between centralization and anonymity in the previous section.

The anonymity provided by online wallets is similar to that provided by the traditional banking system. There are centralized intermediaries that know a lot about our transactions, but from the point of view of a stranger with no privileged information we have a reasonable degree of privacy. But as we discussed, the public nature of the block chain means that if something goes wrong (say, a wallet or exchange service gets hacked and records are exposed), the privacy risk is worse than with the traditional system. Besides, most people who turn to Bitcoin for anonymity tend to do so because they are unhappy with anonymity properties of the traditional system and want a better (or a different kind of) anonymity guarantee. These are the motivations behind dedicated mixing services.

***Dedicated mixing services.*** In contrast to online wallets, dedicated mixes promise not to keep records, nor do they require your identity. You don't even need a username or other pseudonym to interact with the mix. You send your bitcoins to an address provided by the mix, and you tell the mix a destination address to send bitcoins to. Hopefully the mix will soon send you (other) bitcoins at address you specified. It's essentially a swap.

While it's good that dedicated mixes promise not to keep records, you still have to trust them to keep that promise. And you have to trust that they'll send you back your coins at all. Since mixes aren't a place where you store your bitcoins, unlike wallets, you'll want your coins back relatively quickly, which means that the pool of other coins that your deposit will be mixed with is much smaller — those that were deposited at roughly the same time.

***Sidebar: Terminology.*** In this book, we'll use the term ***mix*** to refer to a dedicated mixing service. An equivalent term that some people prefer is ***mixer***.

You might also encounter the term ***laundry***. We don't like this term, because it needlessly attaches a moral judgement to something that's a purely technical concept. As we've seen, there are very good reasons why you might want to protect your privacy in Bitcoin and use mixes for everyday privacy. Of course, we must also acknowledge the bad uses, but using the term laundry promotes the negative connotation, as it implies that your coins are 'dirty' and you need to clean them.

There is also the term ***tumbler***. It isn't clear if this refers to the mixing action of tumbling drums or their cleaning effect (on gemstones and such). Regardless, we'll stick to the term 'mix'.

A group of researchers, including four of the five authors of this textbook, studied mixes and proposed a set of principles for improving the way that mixes operate, both in terms of increasing anonymity and in terms of the security of entrusting your coins to the mix. We will go through each of these guidelines.

***Use a series of mixes.*** The first principle is to use a series of mixes, one after the other, instead of just a single mix. This is a well-known and well-established principle — for example, Tor, as we'll see in a bit, uses a series of 3 routers for anonymous communication. This reduces your reliance on the trustworthiness of any single mix. As long as any one of the mixes in the series keeps its promise and deletes its records, you have reason to expect that no one will be able to link your first input to the ultimate output that you receive.

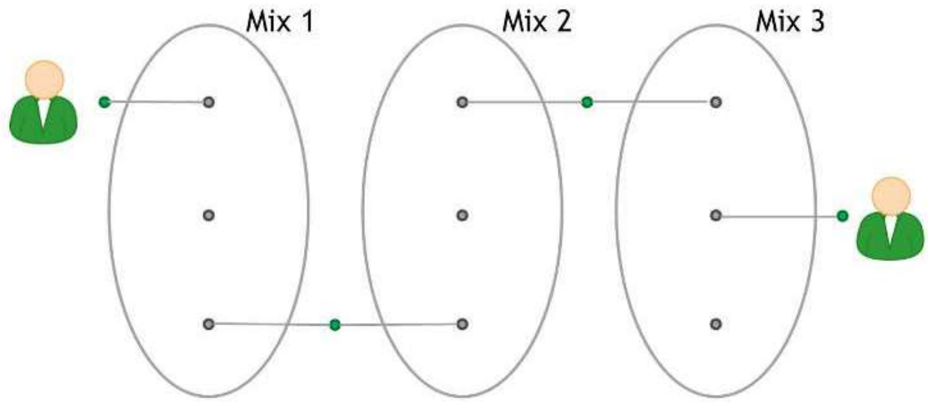



***Figure 6.8. Series of mixes*.** We begin with a user who has a coin or input address that we assume the adversary has managed to link to them. The user sends the coin through various mixes, each time providing a freshly generated output address to the mix. Provided that at least one of these mixes destroys its records of the input to output address mapping, and there are no side-channel leaks of information, an adversary won't be able to link the user's original coin to their final one.

***Uniform transactions.*** If mix transactions by different users had different quantities of bitcoins, then mixing wouldn't be very effective. Since the value going into the mix and coming out of a mix would have to be preserved, it will enable linking a user's coins as they flow through the mix, or at least greatly diminish the size of the anonymity set.

Instead, we want mix transactions to be uniform in value so that linkability is minimized. All mixes should agree on a standard ***chunk size***, a fixed value that incoming mix transactions must have. This would increase the anonymity set as all transactions going through *any* mix would look the same and would not be distinguishable based on their value. Moreover, having a uniform size across all mixes would make it easy to use a series of mixes without having to split or merge transactions.

In practice, it might be difficult to agree on a single chunk size that works for all users. If we pick it to be too large, users wanting to mix a small amount of money won't be able to. But if we pick it to be too small, users wanting to mix a large amount of money will need to divide it into a huge number of chunks which might be inefficient and costly. Multiple standard chunk sizes would improe performance, but also split the anonymity sets by chunk size. Perhaps a series of two or three increasing chunk sizes will provide a reasonable tradeoff between efficiency and privacy.

***Client side should be automated.*** In addition to trying to link coins based on transaction values, a clever adversary can attempt various other ways to de-anonymize, for example, by observing the timing of transactions. These attacks can be avoided, but the precautions necessary are too complex and cumbersome for human users. Instead, the client-side functionality for interacting with mixes should be automated and built into privacy-friendly wallet software.

***Fees should be all-or-nothing.*** Mixes are businesses and expect to get paid. One way for a mix to charge fees is to take a cut of each transaction that users send in. But this is problematic for anonymity, because mix transactions can no longer be in standard chunk sizes. (If users try to split and merge their slightly-smaller chunks back to the original chunk size, it introduces serious and hard-to-analyze anonymity risks because of the new linkages between coins that are introduced.)

Don't confuse mixing fees with transaction fees, which are collected by miners. Mixing fees are separate from and in addition to such fees.

To avoid this problem, mixing fees should be all-or-nothing, and applied probabilistically. In other words, the mix should swallow the whole chunk with a small probability or return it in its entirety. For example, if the mix wants to charge a 0.1% mixing fee, then one out every 1,000 times the mix should swallow the entire chunk, whereas 999 times out of 1,000 the mix should return the entire chunk without taking any mixing fee.

This is a tricky to accomplish. The mix must make a probabilistic decision and convince the user that it didn't cheat: that it didn't bias its random number generator so that it has (say) a 1% probability of retaining a chunk as a fee, instead of 0.1%. Cryptography provides a way to do this, and we'll refer you to the *Mixcoin* paper in the Further Reading section for the details. The paper also talks about various ways in which mixes can improve their trustworthiness.

***Mixing in practice.*** As of 2015, there isn't a functioning mix ecosystem. There are many mix services out there, but they have low volumes and therefore small anonymity sets. Worse, many mixes have been reported to steal bitcoins. Perhaps the difficulty of "bootstrapping" such an ecosystem is one reason why it has never gotten going. Given the dodgy reputation of mixes, not many people will want to use them, resulting in low transaction volumes and hence poor anonymity. There's an old saying that *anonymity loves company*. That is, the more people using an anonymity service, the better anonymity it can provide. Furthermore, in the absence of much money to be made from providing the advertised services, mix operators might be tempted to steal funds instead, perpetuating the cycle of untrustworthy mixes.

Today's mixes don't follow any of the principles we laid out. Each mix operates independently and typically provides a web interface,with which the user interacts manually to specify the receiving address and any other necessary parameters. The user gets to choose the amount that they would like to mix. The mix will take a cut of every transaction as a mixing fee and send the rest to the destination address.

We think it's necessary for mixes (and wallet software) to move to the model we presented in order to achieve strong anonymity, resist clever attacks, provide a usable interface, and attract high volumes. But it remains to be seen if a robust mix ecosystem will ever evolve.

## 6.4 Decentralized Mixing

Decentralized mixing is the idea of getting rid of mixing services and replacing them with a peer-to-peer protocol by which a group of users can mix their coins. As you can imagine, this approach is better philosophically aligned with Bitcoin.

Decentralization also has more practical advantages. First, it doesn't have the bootstrapping problem: users don't have to wait for reputable centralized mixes to come into existence. Second, theft is impossible in decentralized mixing; the protocol ensures that when you put in bitcoins to be mixed, you'll get bitcoins back of equal value. Because of this, even though some central coordination turns out to be helpful in decentralized mixing, it's easier for someone to set up such a service because they don't have to convince users that they're trustworthy. Finally, in some ways decentralized mixing can provide better anonymity.

***Coinjoin.*** The main proposal for decentralized mixing is called Coinjoin. In this protocol, different users jointly create a single Bitcoin transaction that combines all of their inputs. The key technical principle that enables Coinjoin to work is this: when a transaction has multiple inputs coming from different addresses, the signatures corresponding to each input are separate from and independent of each other. So these different addresses could be controlled by different people. You don't need one party to collect all of the private keys.

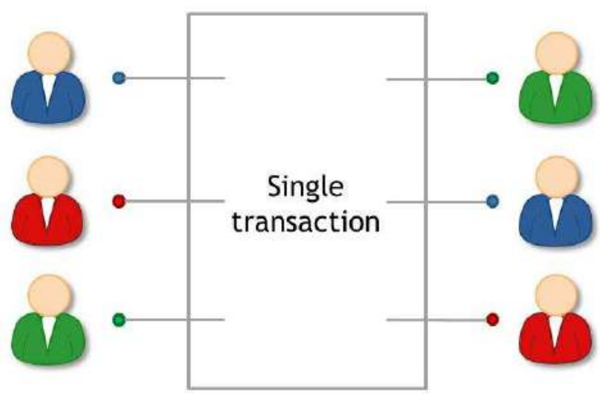



***Figure 6.9. A Coinjoin transaction.***

This allows a group of users to mix their coins with a single transaction. Each user supplies an input and output address and together they form a transaction with these addresses. The order of the input and output addresses is randomized so an outsider will be unable to determine the mapping between inputs and outputs. Participants check that their output address is included in the transaction and that it receives the same amount of Bitcoin that they are inputting (minus any transaction fees). Once they have confirmed this, they sign the transaction.

Somebody looking at this transaction on the block chain — even if they know that it is a Coinjoin transaction — will be unable to determine the mapping between the inputs and outputs. From an outsider's perspective the coins have been mixed, which is the essence of Coinjoin.

What we've described so far is just one round of mixing. But the principles that we discussed before still apply. You'd want to repeat this process with (presumably) different groups of users. You'd also want to make sure that the chunk sizes are standardized so that you don't introduce any side channels.

Let's now delve into the details of Coinjoin, which can be broken into 5 steps:

1. Find peers who want to mix
2. Exchange input/output addresses
3. Construct transaction
4. Send the transaction around. Each peer signs after verifying their output is present.
5. Broadcast the transaction

***Finding peers.*** First, a group of peers who all want to mix need to find each other. This can be facilitated by servers acting as "watering-holes," allowing users to connect and grouping together. Unlike centralized mixes, these servers are not in a position to steal users' funds or compromise anonymity.

***Exchanging addresses.*** Once a peer group has formed, the peers must exchange their input and output addresses with each other. It's important for participants to exchange these addresses in such a way that even the other members of the peer group do not know the mapping between input and output addresses. Otherwise, even if you execute a coinjoin transaction with a supposedly random set of peers, an adversary might be able to weasel their way into the group and note the mapping of inputs to outputs. To swap addresses in an unlinkable way, we need an anonymous communication protocol. We could use the Tor network, which we looked at earlier, or a special-purpose anonymous routing protocol called a decryption mix-net.

***Collecting signatures and denial of service.*** Once the inputs and outputs have been communicated, one of these users — it doesn't matter who — will then construct the transaction corresponding to these inputs and outputs. The unsigned transaction will then be passed around; each peer will verify that its input and output address are included correctly, and sign.

If all peers follow the protocol, this system works well. Any peer can assemble the transaction and any peer can broadcast the transaction to the network. Two of them could even broadcast it independently; it will be published only once to the block chain, of course. But if one or more of the peers wants to be disruptive, it's easy for them to launch a denial-of-service attack, preventing the protocol from completing.

In particular, a peer could participate in the first phase of the protocol, providing its input and output addresses, but then refuse to sign in the second phase. Alternately, after signing the transaction, a disruptive peer can try to take the input that it provided to its peers and spend it in some other transaction instead. If the alternate transaction wins the race on the network, it will be confirmed first and the Coinjoin transaction will be rejected as a double spend.

There have been several proposals to prevent denial of service in Coinjoin. One is to impose a cost to participate in the protocol, either via a proof of work (analogous to mining), or by a proof of burn, a technique to provably destroy a small quantity of bitcoins that you own, which we studied in Chapter 3. Alternatively, there are cryptographic ways to identify a non-compliant participant and kick them out of the group. For details, see the Further Reading section.

***High-level flows.*** We mentioned side channels earlier. We'll now take a closer look at how tricky side channels can be. Let's say Alice receives a very specific amount of bitcoins, say 43.12312 BTC, at a particular address on a weekly basis, perhaps as her salary. Suppose further that she has a habit of automatically and immediately transferring 5% of that amount to her retirement account, which is another Bitcoin address. We call this transfer pattern a high-level flow. No mixing strategy can effectively hide the fact that there's a relationship between the two addresses in this scenario. Think about the patterns that will be visible on the block chain: the specific amounts and timing are extraordinarily unlikely to occur by chance.

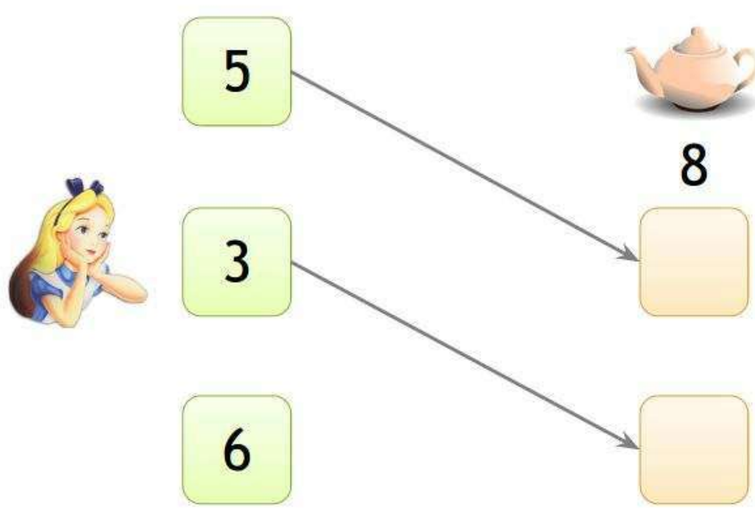



***Figure 6.10: Merge avoidance*.** Alice wishes to buy a teapot for 8 BTC. The store gives her two addresses and she pays 5 to one and 3 to the other, matching her available input funds. This prevents revealing that these two addresses were both belong to Alice.

One technique that can help regain unlinkability in the presence of high-level flows is called **merge avoidance**, proposed by Bitcoin developer Mike Hearn. Generally, to make a payment, a user creates a single transaction that combines as many coins as necessary in order to pay the entire amount to a single address. What if they could avoid the need to merge and consequently link all of their inputs? The merge avoidance protocol enables this by allowing the receiver of a payment to provide multiple output addresses — as many as necessary. The sender and receiver agree upon a set of denominations to break up the payment into, and carry it out using multiple transactions, as shown in Figure 6.10.

Assuming the store eventually combines these two payments with many other inputs from other payments it has received, it will no longer be obvious that these two addresses were associated with each other. The store should avoid re-combining these two inputs as soon as it receives them or else it will still be clear they were made by the same entity. Also, Alice might want to avoid sending the two payments at the exact same time, which might similarly reveal this information.

Generally though, merge avoidance can help mitigate the problem of high-level flows: an adversary might not be able to discern a flow if it is broken up into many smaller flows that aren't linked to each other. It also defeats address clustering techniques that rely on coins being spent jointly in a single transaction.

## 6.5 Zerocoin and Zerocash

No cryptocurrency anonymity solutions have caused as much excitement as Zerocoin and its successor Zerocash. That's both because of the ingenious cryptography that they employ and because of the powerful anonymity that they promise. Whereas all of the anonymity-enhancing technologies that we have seen so far add anonymity on top of the core protocol, ***Zerocoin*** and ***Zerocash*** incorporate anonymity at the protocol level. We'll present a high-level view of the protocol here and necessarily simplify some details, but you can find references to the original papers in the Further Reading section.

***Compatibility.*** As we'll see, the strong anonymity guarantees of Zerocoin and Zerocash come at a cost: unlike centralized mixing and Coinjoin, these protocols are not compatible with Bitcoin as it stands today. It is technically possible to deploy Zerocoin with a soft fork to Bitcoin, but the practical difficulties are serious enough to make this infeasible. With Zerocash, a fork is not even possible, and an altcoin is the only option.

***Cryptographic guarantees.*** Zerocoin and Zerocash incorporate protocol-level mixing, and the anonymity properties come with cryptographic guarantees. These guarantees are qualitatively better than those of the other mixing technologies that we have discussed. You don't need to trust anybody — mixes, peers, or intermediaries of any kind, or even miners and the consensus protocol — to ensure your privacy. The promise of anonymity relies only on the adversary's computational limits, as with most cryptographic guarantees.

***Zerocoin.*** To explain Zerocoin, we'll first introduce the concept of Basecoin. Basecoin is a Bitcoin-like altcoin, and Zerocoin is an extension of this altcoin. The key feature that provides anonymity is that you can convert basecoins into zerocoins and back again, and when you do that, it breaks the link between the original basecoin and the new basecoin. In this system, Basecoin is the currency that you transact in, and Zerocoin just provides a mechanism to trade your basecoins in for new ones that are unlinkable to the old ones.

You can view each zerocoin you own as a token which you can use to prove that you owned a basecoin and made it unspendable. The proof does not reveal which basecoin you owned, merely that you did own a basecoin. You can later redeem this proof for a new basecoin by presenting this proof to the miners. An analogy is entering a casino and exchanging your cash for poker chips. These serve as proof that you deposited some cash, which you can later exchange for different cash of the same value on exiting the casino. Of course, unlike poker chips, you can't actually do anything with a zerocoin except hold on to it and later redeem it for a basecoin.

To make this work in a cryptocurrency, we implement these proofs cryptographically. We need to make sure that each proof can be used only once to redeem a basecoin. Otherwise you'd be able to earn basecoins for free by turning a basecoin into a zerocoin and then redeeming it more than once.

***Zero-knowledge proofs.*** The key cryptographic tool we'll use is a zero-knowledge proof, which is a way for somebody to prove a (mathematical) statement without revealing any other information that leads to that statement being true. For example, suppose you've done a lot of work to solve a hash puzzle, and you want to convince someone of this. In other words, you want to prove the statement

I know x such that `H(x || ⟨other known inputs⟩ ) < ⟨target⟩` .

You could, of course, do this by revealing x. But a zero-knowledge proof allows you to do this in such a way that the other person is no wiser about the value of x after seeing the proof than they were before.

You can also prove a statement such as "I know x such that H(x) belongs to the following set: {...}". The proof would reveal nothing about x, nor about which element of the set equals H(x). Zerocoin crucially relies on zero-knowledge proofs and in fact the statements proved in Zerocoin are very similar to this latter example. In this book, we'll treat zero-knowledge proofs as black-boxes. We'll present the properties achieved by zero-knowledge proofs and show where they are necessary in the protocol, but we will not delve into the technical details of how these proofs are implemented. Zero-knowledge proofs are a cornerstone of modern cryptography and form the basis of many protocols. Once again, we refer the motivated reader to the Further Reading section for more detailed treatment.

***Minting Zerocoins.*** Zerocoins come into existence by minting, and anybody can mint a zerocoin. They come in standard denominations. For simplicity, we'll assume that there is only one denomination worth 1.0 zerocoins, and that each zerocoin is worth one basecoin. While anyone can mint a Zerocoin, just minting one doesn't automatically give it any value — you can't get free money. It acquires value only when you put it onto the block chain, and doing that will require giving up one basecoin.

To mint a Zerocoin, you use a cryptographic ***commitment***. Recall from Chapter 1 that a commitment scheme is the cryptographic analog of sealing a value in an envelope and putting it on a table in everyone's view.


***Figure 6.11: Committing to a serial number.*** The real world analog of a cryptographic commitment is sealing a value inside an envelope.

Minting a zerocoin is done in three steps:

1. Generate serial number *S* and a random secret *r*
2. Compute *Commit(S, r)*, the commitment to the serial number
3. Publish the commitment onto the block chain as shown in Figure 6.12. This burns a basecoin, making it unspendable, and creates a Zerocoin. Keep S and r secret for now.

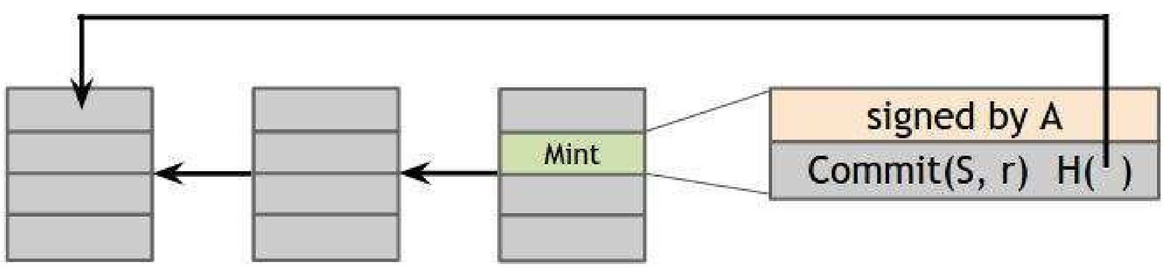



***Figure 6.12: Putting a zerocoin on the block chain*.** To put a zerocoin on the blockchain, you create a special 'mint' transaction whose output 'address' is the cryptographic commitment of the zerocoin's serial number. The input of the mint transaction is a basecoin, which has now been spent in creating the zerocoin. The transaction does *not* reveal the serial number.

To spend a zerocoin and redeem a new basecoin, you need to prove that you previously minted a zerocoin. You could do this by opening your previous commitment, that is, revealing *S* and *r*. But this makes the link between your old basecoin and your new basecoin apparent. How can we break the link?

This is where the zero-knowledge proof comes in. At any point, there will be many commitments on the block chain — let's call them $c_1, c_2, \ldots, c_n$.

Here are the steps that go into spending a zerocoin with serial number S to redeem a new basecoin:

- Create a special "spend" transaction that contains S, along with a zero-knowledge proof of the statement:

  "I know $r$ such that $Commit(S, r)$ is in the set $\{c_1, c_2, \ldots, c_n\}$".
- Miners will verify your zero-knowledge proof which establishes your *ability* to open one of the zerocoin commitments on the block chain, without actually opening it.
- Miners will also check that the serial number S has never been used in any previous spend transaction (since that would be a double-spend).
- The output of your spend transaction will now act as a new basecoin. For the output address, you should use an address that you own.

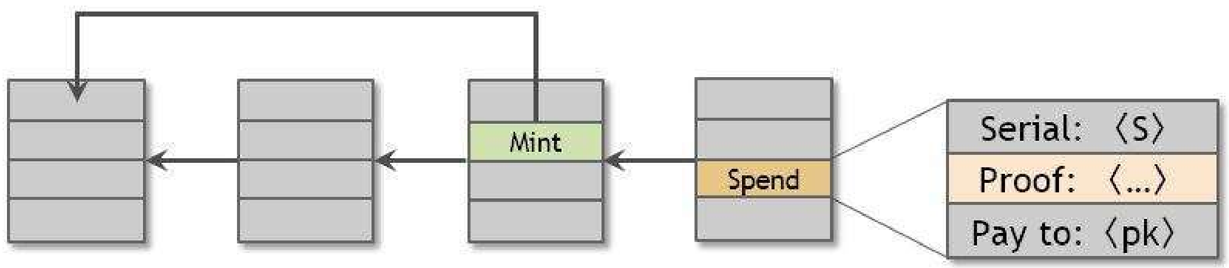



***Figure 6.13: Spending a zerocoin***. The spend transaction reveals the serial number S committed by the earlier mint transaction, along with a zero-knowledge proof that S corresponds to *some* earlier mint transaction. Unlike a mint transaction (or a normal Bitcoin/basecoin transaction), the spend transaction has no inputs, and hence no signature. Instead the zero-knowledge proof serves to establish its validity.

Once you spend a zerocoin, the serial number becomes public, and you will never be able to redeem this serial number again. And since there is only one serial number for each zerocoin, it means that each zerocoin can only be spent once, exactly as we required for security.

***Anonymity.*** Observe that $r$ is kept secret throughout; neither the mint nor the spend transaction reveals it. That means nobody knows which serial number corresponds to which zerocoin. This is the key concept behind Zerocoin's anonymity. There is no link on the block chain between the mint transaction that committed a serial number S and the spend transaction that later revealed S to redeem a basecoin. This is a magical-sounding property that is possible through cryptography but we wouldn't get in a physical, envelope-based system. It's as if there are a bunch of sealed envelopes on a table with different serial numbers, and you can prove that a particular serial number is one of them, without having to reveal which one and without having to open any envelopes.

***Efficiency.*** Recall the statement that's proved in a spend transaction:

"I know $r$ such that *Commit(S, r)* is in the set $\{c_1,c_2,\ldots,c_n\}$".

This sounds like it would be horribly inefficient to implement, because the size of the zero-knowledge proofs would grow linearly as $n$ increases, which is the number of zerocoins that have *ever* been minted. Remarkably, Zerocoin manages to make the size of these proofs only logarithmic in $n$. Note that even though the *statement* to be proved has a linear length, it doesn't need to be included along with the proof. The statement is implicit; it can be inferred by the miners since they know the set of all zerocoins on the block chain. The proof itself can be much shorter. Nevertheless, compared to Bitcoin, Zerocoin still adds quite a sizable overhead, with proofs about 50 kB in size.

***Trusted setup.*** One of the cryptographic tools used in building Zerocoin (RSA accumulators) which require a one-time *trusted setup*. Specifically, a trusted party needs to choose two large primes $p$ and $q$ and publish $N=p\cdot q$ which is a parameter that everybody will use for the lifetime of the system. Think of $N$ like a public key, except for all of Zerocoin as opposed to one particular entity. As long as the trusted party destroys any record of $p$ and $q$, the system is believed to be secure. In particular, this rests on the widely-believed assumption that it's infeasible to factoring a number that's a product of two large primes. But if *anyone* knows the secret factors $p$ and $q$ (called the "trapdoor"), then they'd be able to create new zerocoins for themselves without being detected. So these secret inputs must be used once in generating the public parameters and then securely destroyed.

There's an interesting sociological problem here. It's not clear how an entity could choose $N$ and convince everybody that they have securely destroyed the factors $p$ and $q$ that were used during the setup. There have been been various proposals for how to achieve this, including "threshold cryptography" techniques that allow a set of delegates to jointly compute $N$ in such a way that as long as any one of them deletes their secret inputs, the system will remain secure.

It's also possible to use a slightly different cryptographic construction to avoid the trusted setup. Specifically, it has been shown that simply generating a very large random value for $N$ is secure with high probability, because the number probably cannot be completely factored. Unfortunately this carries a huge efficiency hit and is thus not considered practical.

***Zerocash.*** Zerocash is a different anonymous cryptocurrency that builds on the concept of Zerocoin but takes the cryptography to the next level. It uses a cryptographic technique called zero-knowledge SNARKs (zk-SNARKS) which are a way of making zero-knowledge proofs much more compact and efficient to verify. The upshot is that the efficiency of the system overall gets to a point where it becomes possible to run the whole network without needing a basecoin. All transactions can be done in a zero-knowledge manner. As we saw, Zerocoin supports regular transactions for when you don't need unlinkability, augmented with computationally expensive transactions that are used only for mixing. The mix transactions are of fixed denominations and splitting and merging of values can happen only in Basecoin. In Zerocash, that distinction is gone. The transaction amounts are now inside the commitments and no longer visible on the block chain. The cryptographic proofs ensure that the splitting and merging happens correctly and that users can't create zerocash out of thin air.

The only thing that the ledger records publicly is the existence of these transactions, along with proofs that allow the miners to verify all the properties needed for the correct functioning of the system. Neither addresses nor values are revealed on the block chain at any point. The only users who need to know the amount of a transaction are the sender and the receiver of that particular transaction. The miners don't need to know transaction amounts. Of course, if there is a transaction fee, the miners need to know that fee, but that doesn't really compromise your anonymity.

The ability to run as an entirely untraceable system of transactions puts zerocash in its own category when it comes to anonymity and privacy. Zerocash is immune to the side-channel attacks against mixing because the public ledger no longer contains transaction amounts.

***Setting up Zerocash.*** In terms of its technical properties, Zerocash might sound too good to be true. There is indeed a catch. Just like Zerocoin, Zerocash requires "public parameters" to set up the zero-knowledge proof system. But unlike Zerocoin, which requires just one number *N* which is only a few hundred bytes, Zerocash requires an enormous set of public parameters — over a gigabyte long. Once again, to generate these public parameters, Zerocash requires *random and secret inputs*, and if *anyone* knows these secret inputs, it compromises the security of the system by enabling undetectable double-spends.

We won't delve any deeper into the challenge of setting up a zk-SNARK system here. It remains an active area of research, but as of 2015 we don't know exactly how to set up the system in practice in a sufficiently trustworthy way. To date, zk-SNARKs have not been used in practice.

***Putting it all together.*** Let's now compare the solutions that we have seen, both in terms of the anonymity properties that they provide and in terms of how deployable they are in practice.

| System | Type | Anonymity attacks | Deployability |
|---|---|---|---|
| **Bitcoin** | pseudonymous | transaction graph analysis | default |
| **Manual mixing** | mix | transaction graph analysis, bad mixes/peers | usable today |
| **Chain of mixes or coinjoins** | mix | side channels, bad mixes/peers | bitcoin-compatible |
| **Zerocoin** | cryptographic mix | side channels (possibly) | altcoin, trusted setup |
| **Zerocash** | untraceable | none known | altcoin, trusted setup |

***Table 6.14: A comparison of the anonymity technologies presented in this chapter***

We start with Bitcoin itself, which is already deployed and is the ‘default’ system. But it's only pseudonymous and we've seen that powerful transaction graph analysis is possible. We looked at ways to cluster large groups of addresses, and how to sometimes attach real-world identities to those clusters.

The next level of anonymity is using a single mix in a manual way, or doing a Coinjoin by finding peers manually. This obscures the link between input and output but leaves too many potential clues in the transaction graph. Besides, mixes and peers could be malicious, hacked, or coerced into revealing their records. While far from perfect in terms of anonymity, mixing services exist and so this option is usable today.

The third level we looked at is a chain of mixes or Coinjoins. The anonymity improvement comes from the fact that there’s less reliance on any single mix or group of peers. Features like standardized chunk sizes and client-side automation can minimize information leaks, but some side channels are still present. There’s also the danger of an adversary who controls or colludes with multiple mixes or peers. Wallets and services that implement a chain of mixes could be deployed and adopted today, but to our knowledge a secure mix-chain solution isn’t yet readily available.

Next, we saw that Zerocoin bakes cryptography directly into the protocol and brings a mathematical guarantee of anonymity. We think some side channels are still possible, but it's certainly superior to the other mixing-based solutions. However, Zerocoin would have to be launched as an altcoin.

Finally, we looked at Zerocash. Due to its improved efficiency, Zerocash can be run as a fully untraceable — and not just anonymous — cryptocurrency. However, like Zerocoin, Zerocash is not Bitcoin compatible. Worse, it requires a complex setup process which the community is still figuring out how best to accomplish.

We've covered a lot of technology in this chapter. Now let's take a step back. Bitcoin’s anonymity (and potential for anonymity) is powerful, and gains power when combined with other technologies, particularly anonymous communication. As we’ll see in the next chapter, this is the potent combination behind the Silk Road and other anonymous online marketplaces.

Despite its power, anonymity is fragile. One mistake can create an unwanted, irreversible link. But anonymity is worth protecting, since it has many good uses in addition to the obvious bad ones. While these moral distinctions are important, we find ourselves unable to express them at a technical level. Anonymity technologies seem to be deeply and inherently morally ambiguous, and as a society we must learn to live with this fact.

Bitcoin anonymity is an active area of technical innovation as well as ethical debate. We still do not know which anonymity system for Bitcoin, if any, is going to become prominent or mainstream. That’s a great opportunity for you — whether a developer, a policy maker, or a user — to get involved and make a contribution. Hopefully what you've learned in this chapter has given you the right background to do that.

## Further reading

Even more than the topics discussed in previous chapters, anonymity technologies are constantly developing and are an active area of cryptocurrency research. The best way to keep up with the latest in this field is to begin with the papers listed here, and to look for papers that cite them.

The “Fistful of bitcoins” paper on transaction graph analysis:

**Meiklejohn, Sarah, Marjori Pomarole, Grant Jordan, Kirill Levchenko, Damon McCoy, Geoffrey M. Voelker, and Stefan Savage. A fistful of bitcoins: characterizing payments among men with no names. In Proceedings of the 2013 conference on Internet measurement conference, 2013.**

A study of mixing technologies and the source of the principles for effective mixing that we discussed:

**Bonneau, Joseph, Arvind Narayanan,  Andrew Miller, Jeremy Clark, Joshua A. Kroll, and Edward W. Felten. Mixcoin: Anonymity for Bitcoin with accountable mixes. Financial Cryptography 2014.**

A study of mixing services in practice, showing that many are not reputable:

**Malte Möser, Rainer Böhme and Dominic Breuker. An Inquiry into Money Laundering Tools in the Bitcoin Ecosystem. 2013 eCrime Researchers Summit.**

Coinjoin was presented on the Bitcoin forums by Bitcoin Core developer Greg Maxwell:

**Maxwell, Gregory. CoinJoin: Bitcoin privacy for the real world. Bitcoin Forum, 2013.**

Zerocoin was developed by cryptographers from Johns Hopkins University. Keep in mind Zerocoin and Zerocash have the most complex cryptography of any scheme we’ve discussed in this book.

**Miers, Ian, Christina Garman, Matthew Green, and Aviel D. Rubin. Zerocoin: Anonymous distributed E-Cash from Bitcoin. Proceedings of 2013 IEEE Symposium on Security and Privacy, 2013.**

The Zerocoin authors teamed up with other researchers who had developed the SNARK technique. This collaboration resulted in Zerocash:

**Ben Sasson, Eli, Alessandro Chiesa, Christina Garman, Matthew Green, Ian Miers, Eran Tromer, and Madars Virza. Zerocash: Decentralized anonymous payments from Bitcoin. Proceedings of 2013 IEEE Symposium on Security and Privacy, 2014.**

An alternative design to Zerocoin is CryptoNote, which uses different cryptography and offers different anonymity properties. We didn't discuss in this chapter for lack of space, but it is an interesting design approach:

**Nicolas van Saberhagen. CryptoNote v. 2.0.**

This classic book on cryptography includes a chapter on zero-knowledge proofs:

**Goldreich, Oded. Foundations of Cryptography: Volume 1. Cambridge university press, 2007.**

The paper that describes the technical design of the anonymous communication network Tor:

**Dingledine, Roger, Nick Mathewson, and Paul Syverson. Tor: The second-generation onion router. Naval Research Lab Washington DC, 2004.**

The "systematization of knowledge" paper on Bitcoin and cryptocurrencies, especially Section VII on Anonymity and Privacy:

**Bonneau, Joseph, Andrew Miller, Jeremy Clark, Arvind Narayanan, Joshua A. Kroll, and Edward W. Felten. Research Perspectives and Challenges for Bitcoin and Cryptocurrencies. Proceedings of 2015 IEEE Security and Privacy Conference, 2015.**

# Chapter 7: Community, Politics, and Regulation

In this chapter we'll look at all the ways that the world of Bitcoin and cryptocurrency technology touches the world of people. We'll discuss the Bitcoin community's internal politics as well as the ways that Bitcoin interacts with traditional politics, namely law enforcement and regulation issues.

## 7.1: Consensus in Bitcoin

First let's look at consensus in Bitcoin, that is, the way that the operation of Bitcoin relies on the formation of consensus amongst people. There are three kinds of consensus that have to operate for Bitcoin to be successful.

**1. Consensus about rules.** By rules we mean things like what makes a transaction or a block valid, the core protocols and data formats involved in making Bitcoin work.

You need to have a consensus about these things so that all the different participants in the system can talk to each other and agree on what's happening.

**2. Consensus about history.** That is, consensus about what is and isn't in the block chain, and therefore a consensus about which transactions have occurred. Once you have that, what follows is a consensus about which coins — which unspent outputs — exist and who owns them.

This consensus results from the processes we've looked at in Chapter 2 and other earlier chapters from which the block chain is built and by which nodes come to consensus about the contents of the block chain. This is the most familiar and most technically intricate kind of consensus in Bitcoin.

**3. Consensus that coins are valuable.** The third form of consensus is the general agreement that bitcoins are valuable and in particular the consensus that if someone gives you a bitcoin today, then tomorrow you will be able to redeem or trade that for something of value.

Any currency, whether it's a fiat currency like the dollar or cryptocurrency like Bitcoin, relies on consensus that it has value. That is, you need people to generally accept that it's exchangeable for something else of value, now and in the future.

In a fiat currency, this is the *only* kind of consensus. The rules don't emerge by consensus --- what is and isn't a dollar bill is declared by fiat. History isn't salient, but state is --- who owns what. State is either determined by physical possession, as with cash, or delegated to professional record keepers, i.e., banks. In cryptocurrencies, on the other hand, rules and history are also subject to consensus.

In Bitcoin, this form of consensus, unlike the others, is a bit circular. In other words, my belief that the bitcoins I'm receiving today are of value depends on my expectation that tomorrow other people will believe the same thing. So consensus on value relies on believing that consensus on value will continue. This is sometimes called the Tinkerbell effect by analogy to Peter Pan where it's said that Tinkerbell exists because you believe in her.

Whether it's circular or not, it seems to exist and it's important for Bitcoin to operate. Now, what's important about all three forms of consensus is that they're intertwined with each other, as Figure 7.1 shows.

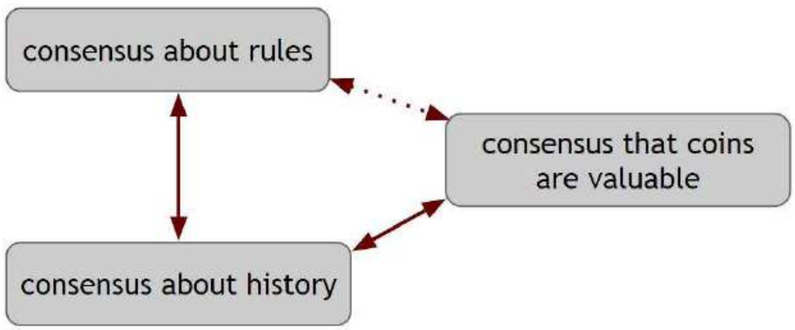



**Figure 7.1: Relationships between the three forms of consensus in Bitcoin**

First of all, consensus about rules and consensus about history go together. Without knowing which blocks are valid you can't have consensus about the block chain. And without consensus about which blocks are in the block chain, you can't know if a transaction is valid or if it's trying to spend an already-spent output.

Consensus about history and consensus that coins are valuable are also tied together. Consensus about history means that we agree on who owns which coins, and that's a prerequisite for believing that the coins have value — without a consensus that I own a particular coin I can't have any expectation that people will accept that coin from me as payment in the future. It's true in reverse as well — as we saw in Chapter 2, consensus about value is what incentivizes miners to maintain the security of the block chain, which gets us consensus about history.

The genius in Bitcoin's original design was in recognizing that it would be very difficult to get any one of these types of consensus by itself. Consensus about the rules in a worldwide decentralized environment where there's no notion of identity isn't the kind of thing that's likely to happen.

Consensus about history, similarly, is a very difficult distributed data structure problem that is not likely to be solvable on its own. And a consensus that some kind of cryptocurrency has value is also very difficult to achieve. What the design of Bitcoin and the continued operation of Bitcoin show is that even if you can't build any one of these forms of consensus by itself you can somehow stand up all three of them together and get them to operate in an interdependent way. So when we talk about how things operate in the Bitcoin community we have to bear in mind that Bitcoin relies on agreement by the participants and that consensus is a fragile and interdependent thing.

## 7.2: Bitcoin Core Software

Bitcoin Core is a piece of open-source software which is a focal point for discussion and debate about Bitcoin's rules.

Bitcoin Core is licensed under the MIT license which is a very permissive open-source license. It allows the software to be used for almost any purpose as long as the source is attributed and the MIT license is not stripped out. Bitcoin Core is the most widely used Bitcoin software and even those who don't use it tend to look to it to define what the rules are. That is, people building alternative Bitcoin software typically try to mimic the rule-defining parts of the Bitcoin Core software, the parts that check validity of transactions and blocks.

| |
|---|
| Bitcoin Core is the de-facto rulebook of Bitcoin. If you want to know what's valid in Bitcoin, the Bitcoin Core software — or explanations of it — is where to look. |

**Bitcoin Improvement Proposals.** Anyone can contribute technical improvements via "pull requests" to Bitcoin Core, a familiar process in the world of open-source software. For more substantial changes, especially protocol modifications, there is a process called Bitcoin Improvement Proposals or BIPs. These are formal proposals for changes to Bitcoin. Typically a BIP will include a technical specification for a proposed change as well as a rationale for it. So if you have an idea for how to improve Bitcoin by making some technical change, you're encouraged to write up one of these documents and to publish it as part of the Bitcoin Improvement Proposal series, and that will then kick off a discussion in the community about what to do. While the formal process is open to anyone, there's a learning curve for participation like any open-source project.

BIPs are published in a numbered series. Each one has a champion, that is, an author who evangelizes in favor of it, coordinates discussion and tries to build a consensus within the community in favor of going forward with or implementing a particular proposal.

What we said above applies to proposals to change the technology. There are also some BIPs that are purely informational and exist just to tell people things that they might not otherwise know, to standardize some part of the protocol previously only specified in source code, or that are process oriented, that talk about how things should be decided in the Bitcoin community.

In summary, Bitcoin has a rulebook as well as a process for proposing, specifying, and discussing rule changes, namely BIPs.

**Bitcoin Core developers.** To understand the role of the Bitcoin Core software we also have to understand the role of Bitcoin Core developers. The original code was written by Satoshi Nakamoto, who we'll return to later in the chapter. Nakamoto is no longer active, but instead there are a group of developers who maintain Bitcoin Core. As of early 2015 there are five with “commit” access to the Core repository: Gavin Andresen, Jeff Garzik, Gregory Maxwell, Wladimir J. van der Laan, and Pieter Wuille. The Core developers lead the effort to continue development of the software and are in charge of which code gets pushed into new versions of Bitcoin Core.

How powerful are these people? In one sense they’re very powerful, because you could argue that any of the rule changes to the code that they make will get shipped in Bitcoin Core and will be followed by default. These are the people who hold the pen that can write things into the de-facto rulebook of Bitcoin. In another sense, they’re not powerful at all. Because it's open-source software, anyone can copy it and modify it, in other words, fork the software at any time, and so if the lead developers start behaving in a way that the community doesn't like, the community can go in a different direction.

One way of thinking about this is to say that the lead developers are leading the parade. They’re out in front of the parade marching and the parade will generally follow them when they turn a corner, but if they try to lead the parade into an action that is disastrous, then the parade members marching behind them might decide to go in a different direction. They can urge people on, and as long as they seem to be behaving reasonably, the group will probably follow them, but they don't have formal power to force people to follow them if they take the system in a technical direction that the community doesn't like.

Let’s think about what you as a user of a system can do if you don't like the way the rules are going or the way it's being run, and compare it to a centralized currency like a fiat currency. In a centralized currency if you don't like what's going on you have a right to exit, that is, you can stop using it. You’d have to try and sell any currency you hold, and you might have to move to someplace with a different fiat currency. Whether or not it’s easy, with a centralized currency that's really your only option.

With Bitcoin, you certainly have the right to exit, but because it operates in an open-source way, you additionally have the right to fork the rules. That means you, and some of your friends and colleagues can decide that you would rather live under a different rule set, and you can fork the rules and go a different direction from the lead developers. The right to fork is more empowering for users than the right to exit, and therefore the community has more power in a system like Bitcoin which is open source than it would in a purely centralized system. So although the lead developers might look like a centralized entity controlling things, in fact they don't have the power that a purely centralized manager or software owner would have.

**Forks in the rules.** One way to fork the software and the rules is to start a new block chain with a new genesis block. This is a popular option for creating altcoins, which we’ll discuss in Chapter 10. But for now let’s consider a different type of fork in the rules, one in which those who fork decide to fork the block chain as well.

If you recall the distinction between a hard fork and a soft fork from Chapter 3, we’re talking about a hard fork here. At the point when there’s a disagreement about the rules, there will be a fork in the block chain, resulting in two branches. One branch is valid under rule set A but invalid under rule set B, and vice versa. Once the miners operating under the two rule sets separate they can't come back together because each branch will contain transactions or blocks that are invalid according to the other rule set.

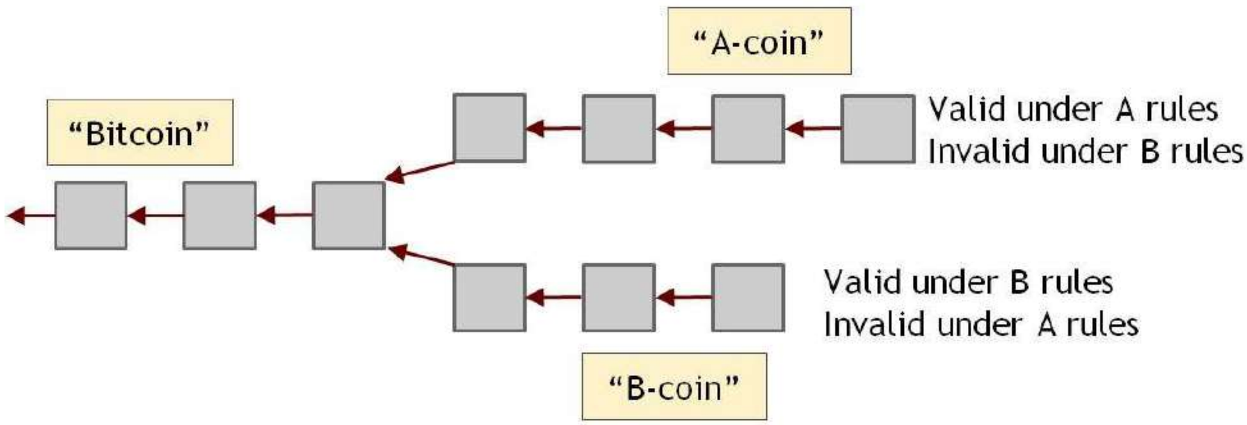



**Figure 7.2: A fork in the currency.** If a fork in the rules leads to a hard fork in the block chain, the currency itself forks and two new currencies result.

We can think of the currency we had up until the fork as being Bitcoin — the big happy Bitcoin that everyone agreed on. After the fork it's as if there are two new currencies, A-coin corresponding rule set A and B-coin corresponding to rule set B. At the moment of the fork, it's as if everyone who owned one bitcoin receives one A-coin and one B-coin. From that point on, A-coin and B-coin will operate separately as if they were separate currencies, and they might operate independently. The two groups might continue to evolve their rules in different ways.

We should emphasize that it's not just the software, or the rules, or the software implementing the rules that forked — it's the currency itself that forked. This is an interesting thing that can happen in a cryptocurrency that couldn't happen in a traditional currency where the option of forking is not available to users. To our knowledge, neither Bitcoin nor any altcoin has ever forked in this way, but it's a fascinating possibility.

How might people respond to a fork like this? It depends on why the fork happened. The first case is where the fork was not intended as a disagreement about the rules, but instead as a way of starting an altcoin. Someone might start an altcoin by forking Bitcoin's block chain if they want to start with a ruleset that's very close to Bitcoin's. This doesn't really pose a problem for the community — the altcoin goes its separate way, the branches coexist peacefully, and some people will prefer to use bitcoins while others will prefer the altcoin. But as we said earlier, as far as we know, no one's ever started an altcoin by forking Bitcoin's or another existing altcoin's block chain. They've always started with a new genesis block.

The interesting case is if the fork reflected a fight between two groups about what the future of Bitcoin should be — in other words, a rebellion within the Bitcoin community where a sub-group decides to break off and decides they have a better idea about how the system should be run. In that case, the two branches are rivals and will fight for market share. A-coin and B-coin will each try to get more merchants to accept it and more people to buy it. Each will want to be perceived as the "real Bitcoin." There may be a public-relations fight where each claims legitimacy and portrays the other as a weird splinter group.

The probable outcome is that one branch will eventually win and the other will melt away. These sorts of competitions tend to tip in one direction. Once one of the two gets seen as more legitimate and obtains a bigger market share, the network effect will prevail and the other becomes a niche currency and will eventually fall away. The rule set and the governance structure of the winner will become the de-facto rule set and governance structure of Bitcoin.

## 7.3: Stakeholders: Who's in Charge?

Who are the stakeholders in Bitcoin, and who's really in charge? We've seen how Bitcoin relies on consensus and how its rulebook is written in practice. We've analyzed the possibility of a fork or a fight about what the rules should be. Now let's take up the question of who has the power to determine who might win a fight like that.

In other words, if there's a discussion and negotiation in the community about rule-setting, and that negotiation fails, we want to know what will determine the outcome. Generally speaking, in any negotiation, the party that has the best alternative to a negotiated agreement has the advantage in a negotiation. So figuring out who might win a fight will tell us who has the upper hand in community discussions and negotiations about the future of Bitcoin.

We can claims on behalf of many different stakeholders:

1. Core developers have the power — they write the rulebook and almost everybody uses their code.
2. Miners have the power — they write history and decide which transactions are valid. If miners decide to follow a certain set of rules, arguably everyone else has to follow it. The fork with more mining power behind it will build a stronger, more secure block chain and so has some ability to push the rules in a particular direction. Just how much power they have depends on whether it's a hard fork or a soft fork, but either way they have some power.
3. Investors have the power — they buy and hold bitcoins, so it's the investors who decide whether Bitcoin has any value. You could argue that if the developers control consensus about the rules and the miners control consensus about history, it's the investors who control consensus that Bitcoin has value. In the case of a hard fork, if investors mostly decide to put their money in either A-coin or B-coin, that branch will be perceived as legitimate.
4. Merchants and their customers have the power — they generate the primary demand for Bitcoin. While investors provide some of the demand that supports the price of the currency,

the primary demand that drives the price of the currency, as we saw in Chapter 4, arises from a desire to mediate transactions using Bitcoin as a payment technology. Investors, according to this argument, are just guessing where the primary demand will be in the future.

5. Payment services have the power — they're the ones that handle transactions. A lot of merchants don't care which currency they follow and simply want to use a payment service that will give them dollars at the end of the day, allow their customers to pay using a cryptocurrency, and handle all the risk. So maybe payment services drive primary demand and merchants, customers, and investors will follow them.

As you may have guessed, there's some merit to all these arguments, and all of those entities have some power. In order to succeed, a coin needs all these forms of consensus — a stable rulebook written by developers, mining power, investment, participation by merchants and customers, and the payment services that support them. So all of these parties have some power in controlling the outcome about a fight over the future of Bitcoin, and there's no one that we can point to as being the definite winner. It's a big, ugly, messy consensus-building exercise.

**Sidebar: governance of open protocols.** We've described a system where numerous stakeholders with imperfectly aligned interests collaborate on open protocols and software and try to reach technical and social consensus. This might remind you of the architecture of the Internet itself. There are indeed many similarities between the development process of Bitcoin Core and that of the Internet. For example, the BIP process is reminiscent of the RFC, or Request For Comments, which is a type of standards-setting document for the Internet.

**Bitcoin advocacy groups.** Another player that's relevant to the governance of Bitcoin is the Bitcoin Foundation. It was founded in 2012 as a nonprofit. It's played two main roles. The first is funding some of the Core developers out of the foundation's assets so that they can work full time on continuing to develop the software. The second is talking to government, especially the US government, as the "voice of Bitcoin."

Now, some members of the Bitcoin community believe that Bitcoin should operate outside of and apart from traditional national governments. They believe Bitcoin should operate across borders and shouldn't explain or justify itself to governments or negotiate with them. Others take a different view. They view regulation as inevitable, desirable, or both. They would like the interests of the Bitcoin community to be represented in government and for the community's arguments to be heard. The Foundation arose partly to fill this need, and it's fair to say that its dealings with government have done a lot to smooth the road for an understanding and acceptance of Bitcoin.

The Foundation has had quite a bit of controversy. Some board members have gotten into criminal or financial trouble, and there have been questions about the extent to which some of them represent the community. The Foundation has had to struggle with members of the board that become liabilities and have to be replaced on short notice. It's been accused of lacking transparency and of being effectively bankrupt. As of early 2015, it's at best unclear if the Bitcoin Foundation will have much of a role in Bitcoin's future.

A different non-profit group, Coin Center, launched in September 2014 based in Washington, D.C., has taken on one of the roles the Bitcoin Foundation played, namely advocacy and talking to government. Coin Center acts as a "think tank." It has operated without much controversy as of early 2015. Neither the Bitcoin Foundation nor Coin Center is in charge of Bitcoin anymore than any of the other stakeholders. The success and perceived legitimacy of any such representative entity will be driven by how much support — and funding — it can obtain from the community over time, like everything else in this kind of open source based ecosystem.

To summarize, there's no one entity or group that is definitively in control of Bitcoin's evolution. In another sense, everybody is in charge because it's the existence of consensus about how the system will operate — the three interlocking forms of consensus, on rules, on history, and on value — that governs Bitcoin. Any ruleset, group, or governance structure that can maintain that consensus over time will, in a very real sense, be in charge of Bitcoin.

## 7.4: Roots of Bitcoin

Let's look at the roots of Bitcoin — how it got started, what its precursors were, and what we know about its mysterious founder.

**Cypherpunk and digital cash.** There are two precursors to Bitcoin worth discussing. One of these was *cypherpunk*, a movement that brought together two viewpoints. First was libertarianism and in particular the idea that society would be better off with either no government or very minimal government. Together with that strong libertarian (or perhaps even anarchist) notion, we had the idea of strong cryptography and in particular public-key cryptography which started in the late 1970s. The cypherpunk movement was a group of people who believed that with strong online privacy and strong cryptography you could re-architect the way that people interact with each other. In this world, cypherpunks believed, people could protect themselves and their interests more effectively and with much less activity (or, as they would say, interference) from government.

One of the challenges in the cypherpunk movement was how to deal with money in a future cypherpunk world where people were interacting online via strong technical and cryptographic measures. This inspired much research, led especially by early digital cash work by David Chaum and others, that aimed to create new forms of digital value that functioned like money, specifically cash, in the sense of being anonymous and easily exchangeable. There's a whole interesting story about how these technical ideas were developed and why early digital cash *didn't* sweep the world, but we won't go into it here. In any event, early work in that area came together with cypherpunk beliefs and in particular the desire to have a strong currency that would be decentralized, online, and relatively private to sow the seeds from which Bitcoin would be born. It's also the basis for the philosophy that many of Bitcoin's supporters follow.

**Satoshi Nakamoto.** Bitcoin began in 2008 with the release of a white paper titled *Bitcoin: A Peer to Peer Electronic Cash System* that was authored by Satoshi Nakamoto. This paper, which was made freely available online, is the initial description of what Bitcoin is, how it works, and the philosophy behind its design. It's still a good resource to get a quick idea of how Bitcoin's technical design and philosophy were specified. Open-source software implementing that specification was released soon after by the same Satoshi Nakamoto, and that's where everything started. To this day, Satoshi is one of the central mysteries of Bitcoin.

We know that the name Satoshi Nakamoto is almost certainly a pseudonym that some person or group of people adopted for Bitcoin-related purposes. There is no prior record of the same Satoshi Nakamoto existing and Satoshi Nakamoto essentially only spoke about Bitcoin. Satoshi's identity is associated with certain public keys and certain accounts in some websites. Digital signatures with these keys offer the only convincing proof that something was said or done by the real Satoshi. So Satoshi, while being a pseudonym, is also an identity which can speak, and who spoke especially extensively in the early history of Bitcoin. Satoshi was fairly active in working on and writing about Bitcoin, and participating in online forums from 2008 until mid-2010 at which point Satoshi handed over control of the Bitcoin Core source code to other developers and has since said nothing. Most in the community feel Satoshi is not going to return.

Satoshi claimed to be a 37-year old male living in Japan (as of 2009). However, there is no evidence that Satoshi spoke or understood Japanese but we do know that Satoshi writes fairly fluently in English, although sometimes with American spelling sometimes with British spelling. There have been numerous attempts to look at Satoshi's text, code, post times, machine identifiers, and so on to try to answer questions like: what is Satoshi's native language? Where is Satoshi from? There have even been attempts to use *stylometry* (the algorithmic analysis of text for writer-specific patterns) to uncover Satoshi's identity. The real identity of Satoshi is still unknown, despite occasional confident pronouncements by individuals and, at least once, a news organization.

We also know that Satoshi acquired a huge number of bitcoins from early mining. In the very beginning Satoshi was the only miner and one of a limited number for much of Bitcoin's early history. Until Bitcoin mining took off and the network's hash rate started to increase due to the influx of other miners, Satoshi was accumulating a significant portion of block rewards, which was then 50 bitcoins every 10 minutes. As Bitcoin's price appreciated, this turned into a small fortune, at one point worth several billion dollars. We know that these bitcoins haven't been cashed out. Indeed, they've never been moved since being mined. Everybody can see which Bitcoin addresses probably belong to Satoshi, and so if those coins were to be sold and the proceeds transferred into any particular bank account, it would be a very notable event and an important clue to Satoshi's identity. So, interestingly, even though Satoshi has on paper made a considerable profit from Bitcoin mining, Satoshi is unable to cash in that profit without identifying himself or herself, and that's something that, for whatever reason, Satoshi doesn't want to do.

In an important sense it doesn't matter that we don't know Satoshi's identity because of the notable feature of Bitcoin that it is decentralized and with no single entity in charge. Satoshi's not in charge, and to some extent it doesn't really matter what Satoshi thinks anymore. Any special influence that Satoshi has is only because of respect that Satoshi would have in the Bitcoin community should Satoshi become active again.

**Growth.** Bitcoin has grown considerably since the system became operational in January 2009. We can see it in the graph of transaction volume (Figure 7.3) and in the graph of the exchange rate (7.4), although the all-time peak price, as of April 2015, was back in late 2013. Sometimes the growth has been gradual, but sometimes there have been jumps or spurts, often corresponding to newsworthy events. Generally speaking, the growth has accelerated over time.

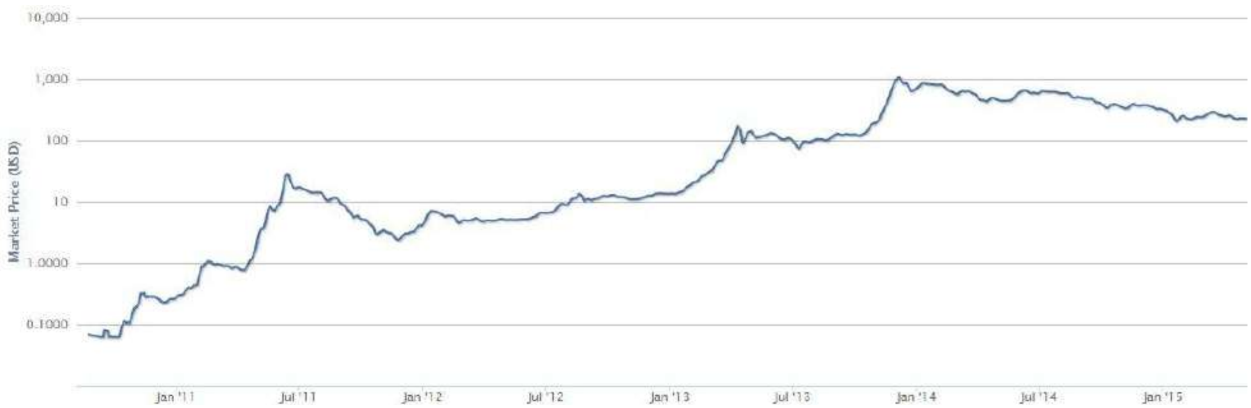



**Figure 7.3: Market Price of Bitcoin** (7-day average). Note the logarithmic scale.
Source: bitcoincharts.com.

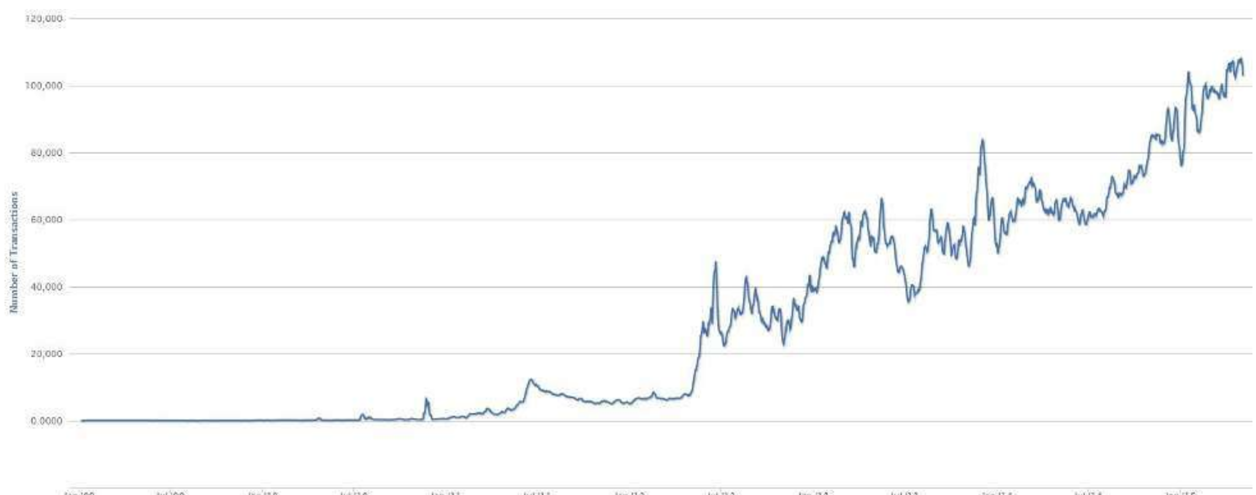



**Figure 7.4: Daily transaction volume** (7-day average). Source: bitcoincharts.com.

## 7.5: Governments Notice Bitcoin

The rest of this chapter is about governments — government interaction with Bitcoin and attempts to regulate Bitcoin. Let's start with the moment when governments noticed Bitcoin, that is, when Bitcoin became a big enough phenomenon that government started to worry about the impact it might have and how to react to it. In this section and the next we'll discuss why governments might worry about Bitcoin specifically. Then in Section 7.7 we'll turn to areas where Bitcoin businesses may be regulated for similar reasons as other types of businesses. Finally in Section 7.8 we'll look at a case study of a proposed regulation that combines elements of regular consumer financial protection with Bitcoin-specific aspects.

**Capital controls.** One reason why governments would notice a digital currency like Bitcoin is that untraceable digital cash, if it exists, defeats capital controls. Capital controls are rules or laws that a country has in place that are designed to limit the flow of capital (money and other assets) into or out of the country. By putting controls on banks, investments, and so on, the country can try to regulate these flows.

Bitcoin is a very easy way, under some circumstances, to defeat capital controls. Someone can simply buy bitcoins with capital inside the country, transmit those bitcoins outside the country electronically, and then trade them for capital or wealth outside the country. That would let them move capital or wealth from inside to outside and similarly they can move capital from outside to inside. Because wealth in this electronic form can move so easily across borders and can't really be controlled, a government that wants to enforce capital controls in a world with Bitcoin has to try to disconnect the Bitcoin world from the local fiat currency banking system. That would make it infeasible for someone to turn large amounts of local currency into Bitcoin, or large amounts of Bitcoin into local currency. We have indeed seen countries trying protect their capital controls do exactly that, with China being a notable example. China has engaged in increasingly strong measures to try to disconnect bitcoins from the Chinese fiat currency banking system by preventing business from exchanging bitcoins for yuan.

**Crime.** Another reason governments might worry about untraceable digital cash is that it makes certain kinds of crimes easier — in particular, crimes like kidnapping and extortion that involve the payment of a ransom. Those crimes become easier when payment can be done at a distance and anonymously.

Law enforcement against kidnappers, for example, often has relied upon exploiting the hand-off of money from the victim or the victim's family to the criminals. When that can be done at a distance in an anonymous way, it becomes much harder for law enforcement to follow the money. Another example: the "CryptoLocker" malware encrypts victims' files and demands ransom in Bitcoin (or other types of electronic money) to decrypt them. So the crime and the payment are both carried out at a distance. Similarly, tax evasion becomes easier when it's easier for people to move money around and to engage in transactions that are not easily tied to a particular individual or identity. Finally, the sale of illegal items becomes potentially easier when the transfer of funds can happen at a distance and without needing to go through a regulated institution.

**Silk Road.** A good example of that is Silk Road, a self-styled “anonymous marketplace” which has also been called “the eBay for illegal drugs.” Figure 7.5 shows a screenshot of Silk Road’s website when it was operating. Illegal drugs were the primary items for sale, with a smattering of other categories that you can see on the left.

Silk Road allowed sellers to advertise goods for sale and buyers to buy them. The goods were delivered typically through the mail or through shipment services and payment was made in bitcoins. The website operated as a Tor hidden service, a concept we discussed in Chapter 6. As you can see in the screenshot, its address was `http://silkroadvb5piz3r.onion`. This way the server’s location was hidden from law enforcement. Due to the use of bitcoins for payment it was also difficult for law enforcement to follow the money and figure out who the people participating in the market were.

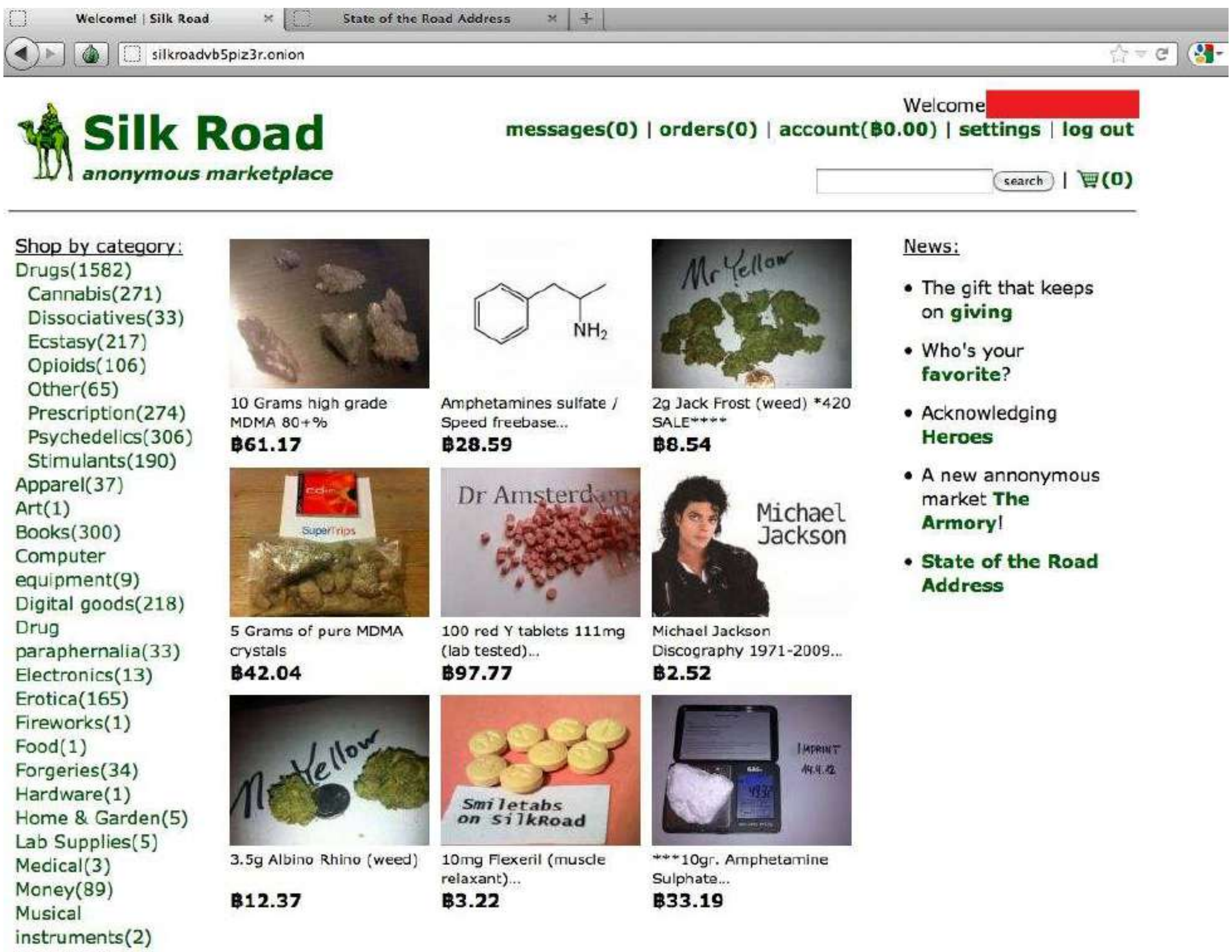



**Figure 7.5: Screenshot of Silk Road website (April 2012).**

Silk Road held the bitcoins in escrow while the goods were shipped. There was an innovative escrow system which helped protect the buyers and sellers against cheating by other parties. The bitcoins would be released once the buyer certified that the goods had arrived. There was also an eBay-like reputation system that allowed buyers and sellers to get reputations for following through on their deals, and by using that reputation system Silk Road was able to give the market participants an incentive to play by the rules. So, Silk Road was innovative among criminal markets in finding ways of enforcing the rules of the criminal market at a distance, which is something that criminal markets in the past have had difficulty doing.

Silk Road was run by a person who called himself Dread Pirate Roberts — obviously a pseudonym, which you might recognize as reference to hero of the novel/film *The Princess Bride*. It operated from February 2011 until October 2013. Silk road was shut down after the arrest of its operator Ross Ulbricht, who was later identified as Dread Pirate Roberts. Ulbricht had tried to cover his tracks by operating pseudonymous accounts and by using Tor, anonymous remailers, and so on. The government was nevertheless able to connect the dots and connect him to Silk Road activity — to the servers and the bitcoins he controlled as the operator of Silk Road. He was convicted of various crimes relating to operating Silk Road. He was also charged with attempted murder for hire, although fortunately he was incompetent enough at it that nobody actually got killed.

In the course of taking down Silk Road, the FBI seized about 174,000 bitcoins, worth over $30 million at the time. As with the proceeds of any crime under US law, they could be seized by the government. Later the government auctioned off a portion of the seized bitcoins.

**Lessons from Silk Road.** There are several lessons from Silk Road and from the encounter between law enforcement and Ulbricht. First it's pretty hard to keep the real world and the virtual world separate. Ulbricht believed that he could live his real life in society and at the same time have a secret identity in which he operated a sizeable business and technology infrastructure. It's difficult to keep these separate worlds completely apart, and not accidentally create some linkage between them. It's hard to stay anonymous for a long time while being active and engaging in a course of coordinated conduct working with other people over time. If there's ever a connection between those two identities — say, if you slip up and use the name of one while wearing the mask of another — that link can never be destroyed and over time the different anonymous identities or mask that someone is trying to use tend to get connected. That's exactly what happened to Ulbricht-he made a few mistakes early on in using the same computers to access his personal accounts and Dread Pirate Roberts accounts and this was eventually enough for investigators to discover his offline identity.

Another lesson is that law enforcement can follow the money. Even before Ulbricht's arrest, the government knew that certain Bitcoin addresses were controlled by the operator of Silk Road, and they were watching those addresses. The result is that Ulbricht, while wealthy according to the block chain, was not actually able to benefit from that wealth because any attempt to transfer those assets into dollars would have resulted in a traceable event, and probably would have resulted in rapid arrest. So although Ulbricht was the owner of something like 174,000 bitcoins, in the real world he was not living like a king. He lived in a one-bedroom apartment in San Francisco while apparently unable to get to the wealth that he controlled.

In short, if you intend to operate an underground criminal enterprise — and obviously we wouldn't recommend this path — then it's a lot harder to do than you might think. Technologies like Bitcoin and Tor are not bullet-proof and law enforcement still has significant tools at their disposal. Although there's been some panic in the world of law enforcement over the rise of Bitcoin, they are starting to realize that they can still follow the money up to a point and they still do have a substantial ability to investigate crimes and to make life difficult for people who want to engage in coordinated criminal action.

At the same time, we don't mean to suggest that by taking down Silk Road, law enforcement has shut down Bitcoin-based hidden markets for illegal drugs for good. In fact, after the demise of Silk Road there has been a mushrooming of such markets. Some of the more prominent ones are Sheep Marketplace, Silk Road 2, Black Market Reloaded, Evolution, and Agora. Most of these are now defunct, either due to law-enforcement actions or due to theft, often by insiders. However, research has found that the total volume of sales has only gone up, with law enforcement actions against individual sites not significantly slowing the growth of this underground market. To address the security risk of the site operator disappearing with buyers' escrowed funds, the newer marketplaces use multi-signature escrow (which we saw in Chapter 3) rather than Silk Road's model of depositing the funds with the market operator.

## 7.6: Anti Money-Laundering

In this section we'll look at money laundering and the Anti Money Laundering (AML) rules that governments have imposed, especially in the US, that affect some Bitcoin-related businesses.

The goal of anti-money-laundering policy is to prevent large flows of money from crossing borders or moving between the underground and legitimate economy without being detected. Earlier we looked at capital controls that exist to prevent money from crossing borders. In some cases, countries are just fine with money crossing borders, but they want to know who's transferring what to whom and where that money came from.

Anti-money laundering is aimed at trying to make certain kinds of crime more difficult, especially organized crime. Organized crime groups often find themselves getting a lot of money coming in in one place and wanting to move it somewhere else, but not wanting to explain where that money came from — hence the desire to get money across borders. Or they might find themselves making a lot of money in an underground economy and wanting to get that money into the legitimate economy so that they can spend it on sports cars and big houses or whatever it is that the leaders of the group want to do. Anti-money laundering, then, has the goals of making it harder to move money around this way and making it easier to catch people trying to do it.

**Know Your Customer.** One of the essential countermeasures against money laundering is something called Know Your Customer laws, sometimes called KYC. The details can be a bit complicated and will depend on your locale, but the basic idea is this: Know Your Customer rules require certain kinds of businesses that handle money to do three things:

1. *Identify and authenticate clients* — get some kind of authentication that clients really are who they claim they are and that those claimed identities correspond to some kind of real-world identity. So a person can't just walk in and they're John Smith from 123 Main Street in AnyTown, USA — they have to provide reliable identification documents.
2. *Evaluate risk of client* — determine the risk of a certain client engaging in underground activities. This will be based on how the client behaves — how longstanding their business relationship is with the company, how well known they are in the community, and various other factors. KYC rules generally require covered companies to treat clients whose activities seem riskier with more attention.
3. *Watch for anomalous behavior* — that is, behavior that seems to be indicative of money laundering or criminal activity. KYC will often require a company to cut off business with a client who looks dodgy, or who is unable to authenticate themselves or their activities sufficiently for the rule.

**Mandatory reporting.** There are mandatory reporting requirements in the United States that are worth talking about. Companies in a broad range of sectors have to report currency transactions that are over $10,000. They must file what's called a currency transaction report to say what the transaction is and who the other party to the transaction is. There is also some requirement to authenticate who that party is. Once reported, the information goes into government databases and then might be analyzed to look for patterns of behavior that are indicative of money laundering.

Companies are also required to watch for clients who might be "structuring" transactions to avoid reporting, like engaging in a series of $9,999 transactions to get around the $10,000 reporting rule. Companies that see evidence of structuring must report it by filing a Suspicious Activity Report. Again, the information goes into a government database and might lead to investigation of the client.

The requirements here differ significantly by country. We're not by any means trying to give you legal advice about whether you need this or what you have to do. This discussion is meant to give you an idea about what kind of requirements are imposed by anti money-laundering rules. That said, take note that governments — in the U.S. and other countries— tend to take anti money-laundering rules very, very seriously with large criminal sentences for violations. These aren't the kind of rules that you can just blow off and deal with if you get a complaint from the government later.

Bitcoin businesses have been shut down — sometimes temporarily, sometimes permanently. Business people have been arrested, and people have gone to jail for not following these rules. This is an area where government will enforce the law vigorously, regardless of whether fiat currency or Bitcoin is used. Government has enforced these laws against Bitcoin-based businesses ever since they noticed that Bitcoin was large enough to pose a risk of money laundering. If you're interested in starting any kind of business that will handle large volumes of currency, you'll need to talk to a lawyer who understands these rules.

## 7.7: Regulation

Now let's directly address the 'R' word — regulation. Regulation often gets a bad name, especially among the kind of people who tend to like Bitcoin. As the argument goes, regulation is some bureaucrat who doesn't know my business or what I'm trying to do, coming in and messing things up. It's a burden. It's stupid and pointless. This argument is common and well understood, and while it's often at least partially correct, we won't repeat it here.

Instead, in this section we'll look in some detail at reasons why regulations might sometimes be justified, because that argument is not as well understood. To be clear, the fact that we're spending most of this section talking about why regulation might be good shouldn't be read as an endorsement of widespread regulation. It's simply that we want to bring a bit more balance to the discussion in a community where regulation is often considered to be inherently bad.

The bottom line argument in favor or regulation is this: when markets fail and produce outcomes that are bad — and agreed to be bad by pretty much everyone in the market — then regulation can step in and try to address the failure. So the argument for regulation, when there is an argument, starts with the idea that markets don't always give you the result that you'd like.

Let's make this a bit more precise, using terms from economics. What worries us is a market failure, and by that we don't simply mean that something bad is happening or somebody feels they are getting ripped off or treated unfairly. We mean that there is an alternate allocation of goods to the market participants that would result in *everybody* being better off, or at least not worse off. Such an alternate allocation is called a *Pareto improvement*.

**Lemons market.** Let's discuss one way in which the market can fail, a classic example called the lemons market. The name originated in the context of selling cars. Let's say that all cars are either of low quality or high quality (with nothing in between). A high-quality car costs a little bit more to manufacture than a low-quality car, but it's much, much better for the consumer who buys it.

If the market is operating well (if it's *efficient* as economists call it) it will deliver mostly high-quality car to consumers. That's because even though the high-quality car is a bit costlier, most consumers prefer it and are willing to pay more for it. So under certain assumptions a market will provide this happy outcome.

On the other hand, let's suppose customers can't tell low-quality cars apart from high-quality cars. A low-quality car (a *lemon*) sitting on the lot may look pretty good, but you can't really tell if it's going to break down tomorrow or if it's going to run for a long time. The dealer probably knows if it's a lemon, but you as the customer can't tell the difference.

Let’s think about the incentives that drive people in this kind of lemons market. As a consumer, you're not willing to pay extra for a high-quality car, because you just can't tell the difference. Even if the used car dealer says that a car is perfect and is only an extra hundred dollars, you don’t have a good reason to trust the dealer.

As a consequence, producers can't make any extra money by selling a high-quality car. In fact, they lose money by selling a high-quality car because it costs a bit more to produce and they don't get any price premium. So the market gets stuck at an equilibrium where only low-quality cars are produced, and consumers are relatively unhappy with them.

This outcome is worse for everybody than a properly functioning market would be. It's worse for buyers because they have to make do with low-quality cars. In a more efficient market they could have bought a car that was much, much better for a slightly higher price. It's also worse for producers — since the cars that are on the market are all lousy, consumers don't buy as many cars as they might otherwise, so there's less money to be made selling cars than there would be in a healthy market.

That's a market failure. This particular example has is not inherently dependent on cars. Any good (r “widget”) for sale which suffers from “asymmetric information” in which either sellers or buyers are have much better information about the quality of the good may result in a market failure. This type of market failure is called a lemons market, though the economics literature provides many more examples.

**Fixing a lemons market.** There are some market-based approaches that try to fix a lemons market. The first relies on seller reputation. The idea is that if a seller consistently tells the truth to consumers about which widgets are high vs. low quality, then the seller might acquire a reputation for telling the truth. Once they have that reputation, they may be able to sell high-quality widgets for a higher price because consumers will believe them and therefore the market can operate more efficiently.

This sometimes works and sometimes doesn't depending on the precise assumptions you make about the market. Of course, it will never work as well as a market where consumers can actually tell the difference in quality. For one thing, it takes a while for a producer to build up a good reputation. That means they have to sell high-quality widgets at low prices for a while until consumers learn that they’re telling the truth. That makes it harder for an honest seller to get into the market.

The other potential problem is that a seller, even if they've been honest up to now, no longer has the incentive to be honest if they want to get out of the market (say, if their sales are shrinking). In that case their incentive is to massively cheat people all at once and then exit the market. So reputation doesn’t work well at either the beginning or end of a seller’s presence in the market.

A reputation-based approach also tends not to work in businesses where consumers don't do repeat business with the same entity, or where the product category is very new, and therefore there hasn’t been enough time for sellers to build up a reputation. A high-tech market like Bitcoin exchanges suffers just those problems.

The other market-based approach is warranties. The idea is that a seller could provide a warranty to a buyer that says if the widget turns out to be low quality, the seller will provide an exchange or a refund. That can work well up to a point, but there's also a problem: a warranty is just another kind of product that can also come in high-quality or low-quality versions! A low-quality warranty is one where the seller doesn't really come through when you come back with the broken product. They renege on their promise or they make you jump through all kinds of hoops.

**Regulatory fixes.** So if a lemons market has developed, and if these market-based approaches don't work for the particular market, then regulation might be able to help. Specifically, there are three ways in which regulation might be able to address the problem.

First, regulation could require disclosure. It could require, say, that all widgets be labeled as high quality or low quality, combined with penalties on the firms for lying. That gives consumers the information that they were missing. A second approach to regulation is to have quality standards so that no widget can be sold unless it meets some standard of quality testing, with that standard set so that only high-quality widgets can pass the test. That would result in a market that again has only one kind of widget, but at least it's high-quality widgets, assuming that the regulation works as intended. The third approach is to require all sellers to issue warranties and then enforce the operation of those warranties so that sellers are held to the promises that they make.

Any of these forms of regulation could obviously fail — it might not work as intended, might be mis-written or misapplied, or might be burdensome on sellers. But there’s at least the possibility that regulation of this type might help to address the market failure due to a lemons market. People who argue for regulation of Bitcoin exchanges, for example, sometimes point to them as an example of a lemons market.

**Collusion and antitrust law.** Another example of markets not operating the way we would like them to is price fixing. Price fixing is when different sellers collude with each other and agree to raise prices or to not lower them. A related situation is where companies that would otherwise go into competition with each other agree not to compete. For example, if there were two bakeries in town they might agree that one of them will only sell muffins and the other will only sell bagels, and that way there's less competition between them than there would be if they both sold muffins and bagels. As a result of the reduced competition presumably prices go up, and the merchants are able to foil the operation of the market.

After all, the reason that the market protects consumers well in its normal operation is through the vehicle of competition. Sellers have to compete in order to offer the best goods at the best price to consumers, and if they don't compete in that way then they won't get business. An agreement to fix prices or to not compete circumvents that competition. When people take steps that prevent competition, that’s another kind of market failure.

These kinds of agreements — to raise prices or to not compete — are illegal in most jurisdictions. This is part of antitrust law or competition law. The goal of this body of law is to prevent deliberate actions that prevent or harm competition. More generally, it limits actions other than simply offering good products at good prices, such as attempts to reduce competition through mergers. Antitrust law is very complicated and we've given you only a sketch of it, but it's another instance of how the market can fail and how the law can and will step in to prevent it.

## 7.8: New York's BitLicense Proposal

So far we've discussed regulation in general: different forms of regulation, why regulation might be justified in some cases and might make good economic sense. Now let's turn to a specific effort by a specific state to introduce specific regulation of Bitcoin, namely New York State's BitLicense proposal. The information here is current as of early 2015, but the landscape of Bitcoin regulation changes quickly. That doesn't matter much for our purposes, because our goal isn't so much to help you understand a specific piece of actual or proposed regulation. Rather, we want to help you understand the kinds of things regulators are doing and give you a sense of how they think about the problem.

The BitLicense proposal was issued in July 2014 and has since been revised in response to comments from the Bitcoin community, industry, the public, and other stakeholders. It was issued by the New York State Department of Financial Services, the part of the state of New York that regulates the financial industry. Of course, the state of New York has the world's largest financial center, and so it's a part of the state government that is used to dealing with relatively large institutions.

**Who's covered.** BitLicense is a proposed set of codes, rules, and regulations that has to do with virtual currencies. Fundamentally, it says that you'd need to get something called a BitLicense from the New York Department of Financial Services if you wanted to do any of the things listed in the box below:

Virtual Currency Business Activity means the conduct of any one of the following types of activities involving New York or a New York Resident:

1. receiving Virtual Currency for Transmission or Transmitting Virtual Currency, except where the transaction is undertaken for non-financial purposes and does not involve the transfer of more than a nominal amount of Virtual Currency;
2. storing, holding, or maintaining custody or control of Virtual Currency on behalf of others;
3. buying and selling Virtual Currency as a customer business;
4. performing Exchange Services as a customer business; or
5. controlling, administering, or issuing a Virtual Currency.

The development and dissemination of software in and of itself does not constitute Virtual Currency Business Activity.

The text refers to “activities involving New York or a New York Resident,” reflecting the regulatory authority of NYDFS. Yet the impacts of regulations like these extend well beyond the borders of the state, for two reasons. First, for states with significant populations such as New York or California, faced with the choice between complying with state laws and not doing business with consumers in those states, most companies will choose to comply. Second, some states are generally perceived as leaders in regulating certain economic sectors — finance in the case of New York, technology in the case of California. That means that other U.S. states often follow the direction that they set.

Notice the exception for non-financial uses in the first category — this was added in the second revision, and it is a good one. It’s a carve-out for just the kind of Bitcoin-as-a-platform applications that we’ll look at starting in Chapter 9. The second category might cover things like wallet services. As for the third category, it appears that you can buy and sell bitcoins for yourself, but doing it as a customer business requires a BitLicense. The fourth category is self-explanatory. The final one might apply more to altcoins, many of which are somewhat centralized, than to Bitcoin. We’ll look at altcoins in Chapter 10.

The software-development exception at the end is again an important one. The language wasn’t in the original version, and there was an outcry from the community. NYDFS superintendent Benjamin Lawsky clarified soon after that the intent was not to regulate developers, miners, or individuals using Bitcoin. The second version contains the explicit language above.

**Requirements.** If the regulation goes into effect and you’re one of the covered entities, you’ll have to apply for a license. To apply for a license there's detailed language in the proposal which you can read, but roughly speaking you have to provide information on the ownership of your enterprise, on your finances, and insurance, on your business plan — generally to allow the NYDFS to know who you are, how well-backed you are, where your money comes from, and what you're planning to do. And you have to pay an application fee.

If you get a license, you’d then have to provide updated information to NYDFS about the things we listed: ownership, finances, insurance, and so on. You'd have to provide periodic financial statements so they could keep track of how you're doing financially. You'd be required to maintain a financial reserve, the amount of which will be set by NYDFS based on various factors about your business.

There are detailed rules about things like how you would keep custody of consumer assets. There are anti-money laundering rules which might or might not go beyond what’s already required by existing laws. There are rules about having a security plan and penetration testing and so on. There are rules about disaster recovery — you have to have a disaster-recovery plan that meets various criteria. There are rules about record keeping — you have to keep records, and make them available to the NYDFS under certain circumstances. You have to have written policies about compliance and you have to designate a compliance officer —someone within your organization who's in charge of compliance and has the necessary responsibility and authority. There's a requirement that you disclose risk to consumers, so that consumers understand the risks of doing business with you.

As you can see, the requirements are substantial, and they're analogous to the sort of requirements for a mutual fund or a publicly traded stock. The NYDFS must still decide what to do with the proposal — whether to withdraw it, issue it in its current form, or make further modifications. Along with that decision they'll issue some kind of a document that gives the rationale for what they decided to do.

If something like the BitLicense goes into effect, it would be a major step in the history of Bitcoin. You would have a situation where not only NYDFS, but perhaps other jurisdictions would start to step in and regulate, and you'd start to see Bitcoin businesses start to get closer to the traditional model of regulated financial institutions.

This would be a step that's in some ways contrary to the cypherpunk or cypher-libertarian ideas about what Bitcoin should be, but on the other hand there's a certain inevitability that as soon as Bitcoin became really valuable, Bitcoin businesses became big businesses, and government got interested, regulation would ensue. Bitcoin businesses touch real people and the fiat currency economy. If Bitcoin is big enough to matter, then it is big enough to get regulated. It represents a retreat from what the original advocates of Bitcoin had in mind, but in another way it represents the Bitcoin ecosystem growing up and integrating into the regular economy which is much more regulated. Regardless of your stance on it, regulation is starting to happen, and if you're interested in starting a Bitcoin business you need to be paying attention to this trend.

Will this be a success? There are different ways to look at it, but here's one way to evaluate the effectiveness of regulation like BitLicense with respect to the public policy goal of improving the quality of Bitcoin businesses: if something like BitLicense goes into effect, and if companies start advertising to customers outside New York that they can be trusted because they have a BitLicense, and if that argument is convincing to consumers when they're picking a company to do business with, then regulation will be working in the way that its advocates wanted it to. Whether that will happen and how it will affect the future of Bitcoin is something that we'll have to wait and see.

## Further reading

Two papers which contain many interesting details of how Silk Road and it successors have operated:

**Christin, Nicolas. Traveling the Silk Road: A measurement analysis of a large anonymous online marketplace. Proceedings of the 22nd International Conference on World Wide Web, 2013.**

**Soska, Kyle and Christin, Nicolas. Measuring the Longitudinal Evolution of the Online Anonymous Marketplace Ecosystem. Proceedings of the 24th USENIX Security Symposium, 2015.**

A guide to the regulatory issues that Bitcoin raises:

**Brito, Jerry, and Andrea Castillo. Bitcoin: A primer for policymakers. Mercatus Center at George Mason University, 2013.**

A book that looks at the history of modern cryptography and the cypherpunk movement, which gives some intuition for the early political roots of Bitcoin:

**Levy, Steven. *Crypto: How the Code Rebels Beat the Government—Saving Privacy in the Digital Age*. Penguin, 2001.**

A popular exposition of early work on digital cash, combined with a vision for a world with digital privacy:

**Chaum, David. Security without identification: Transaction systems to make big brother obsolete. Communications of the ACM, 1985.**

A survey of the economics of information security which discusses several reasons for market failure:

**Anderson, Ross, and Tyler Moore. The economics of information security. Science 314, no. 5799, 2006.**

A discussion of Bitcoin-specific economic issues and regulatory options:

**Böhme, Rainer, Nicolas Christin, Benjamin Edelman, and Tyler Moore. Bitcoin: Economics, Technology, and Governance. The Journal of Economic Perspectives 29, no. 2, 2015.**

The text of the BitLicense proposal:

**New York State Department of Financial Services Regulations of the Superintendent of Financial Services. Part 200: Virtual Currencies (revised), 2015.**

# Chapter 8: Alternative Mining Puzzles

Mining puzzles are at the very core of Bitcoin because their difficulty limits the ability of any one party to control the consensus process. Because Bitcoin miners earn rewards for the puzzles that they solve, we expect that they'll spend considerable effort trying to find any available shortcuts to solve these puzzles faster or more efficiently, in the hope of increasing their profits. On the other hand, if there's work that helps the network but doesn't directly help them solve puzzles any faster, miners might be incentivized to skip it to minimize their costs. So the design of the puzzle plays an important role in steering and guiding participation in the network.

In this chapter, we're going to discuss a variety of possible alternative puzzle designs, assuming we could modify Bitcoin's puzzle or even design a new puzzle from scratch. A classic design challenge has been to make a puzzle which is ASIC-resistant, leveling the playing field between users with ordinary computing equipment and users with optimized custom hardware. What else could we design the puzzle to achieve? What other kinds of behaviors would we like to encourage or discourage? We'll talk about a few examples with various interesting properties, from decreasing energy consumption to having some socially-useful side effects to discouraging the formation of mining pools. Some of these are already used by altcoins, while others are research ideas that might turn out to be used in the future.

## 8.1 Essential Puzzle Requirements

We'll start by looking at some essential security requirements for mining puzzles. It doesn't do us any good to introduce fancy new features if the puzzle doesn't still satisfy the basic requirements that it needs to keep Bitcoin secure.

There are many possible requirements, some of which we've talked about in Chapters 2 and 5. Mining puzzles need to be quick to verify because every node on the network validates every puzzle solution — even nodes that aren't involved in mining directly, including SPV clients. We would also like to have adjustable difficulty so that the difficulty of the puzzle can be changed over time as new users enter the network with increasing amounts of hash power contributed. This enables the puzzle to be difficult enough that attacks on the block chain are costly, but puzzle solutions are still found at a fairly steady rate (about once every ten minutes in Bitcoin).

> **What exactly is Bitcoin's mining puzzle?** So far we've just called it "Bitcoin's puzzle." More precisely, we can call it a *partial hash-preimage puzzle*, since the goal is to find preimages for a partially specified hash output — namely, an output below a certain target value. Some other rare property could also work, such as finding a block whose hash has at least k bits set to zero, but comparing the output to a target is probably the simplest.

It’s easy to see how Bitcoin’s SHA-256 hash-based mining puzzle already satisfies these two requirements. It can be made arbitrarily more difficult by tweaking a single parameter (the *target*). Checking solutions is trivial, requiring just a single SHA-256 computation and a comparison, no matter how difficult the puzzle was to solve.

***Progress-freeness.*** Another central requirement is more subtle: the chance of winning a puzzle solution in any unit of time should be roughly proportional to the hash power used. This means that really large miners with very powerful hardware should only have proportional advantage in being the next miner to find a puzzle solution. Even small miners should have some proportional chance of being successful and receiving compensation.

To illustrate this point, let’s think about a bad puzzle that doesn't satisfy this requirement. Consider a mining puzzle that takes exactly *n* steps to find a solution. For example, instead of finding a block whose SHA-256 hash is below a certain target, we could require computing *n* consecutive SHA-256 hashes. This wouldn’t be efficient to check, but nevermind that for now. The bigger problem here is that since it takes exactly *n* steps to find a solution, then the fastest miner in the network will always be the one who wins the next reward. It would soon become clear which miner was solving every puzzle, and other miners would have no incentive to participate at all.

Again, a good puzzle gives every miner the chance of winning the next puzzle solution in proportion to the amount of hash power they contribute. Imagine throwing a dart at a board randomly, with different size targets which correspond to the mining power held by different miners. If you think about it, this requirement means the odds of solving the puzzle must be independent of how much work you have already spent trying to solve it (because big miners will have always spent more work). This is why a good mining puzzle is called *progress-free*.

From a mathematical perspective, this means that a good mining puzzle must be a *memoryless process* — anything else would inevitably reward miners for past progress in some way. Therefore any feasible puzzle will inherently involve some sort of trial-and-error. The time to find a solution will therefore inevitably form an exponential distribution as we saw in Chapter 2.

Adjustable difficulty, fast verification, and progress-freeness are three crucial properties of Bitcoin mining puzzles. SHA-256-based partial pre-image finding certainly satisfies all three. Some people argue that other properties which Bitcoin’s mining puzzle satisfies are also essential, but we’ll discuss other potential requirements as they come up while we explore other potential functions.

## 8.2 ASIC-resistant puzzles

We’ll start with the challenge of designing an *ASIC-resistant* puzzle, which has been by far the most widely discussed and sought after type of alternative mining puzzle. As we discussed in Chapter 5, Bitcoin mining was initially done primarily with ordinary computers, eventually extended to GPUs and customized FPGA devices, and now is almost exclusively done by very powerful optimized ASIC chips.

These ASICs are so much more efficient than general purpose computing equipment that mining with an ordinary computer (or even some early generation ASICs) is no longer worth the price of electricity, even if the hardware is free.

This transition has meant that most individuals participating in the Bitcoin ecosystem (for example customers or merchants transacting using Bitcoin) no longer have any role in the mining process. Some people feel this is a dangerous development, with a smaller group of professional miners controlling the mining process. In Satoshi Nakamoto's original papers on Bitcoin, the phrase "one-CPU-one-vote" was used, which has sometimes been taken to mean Bitcoin should be a democratic system owned by all of its users.

Others feel the rise of ASICs is inevitable and not to the detriment of Bitcoin, and that the desire for ASIC-resistance is simply people wanting to go back to "the good old days." Without taking a side on whether ASIC-resistance is desirable, we can dive into the technical challenges and some of the proposed approaches for achieving this goal.

***What does ASIC-resistance mean?*** Generally speaking, we want to disincentivize the use of custom-built hardware for mining. Interpreting this strictly would mean designing a puzzle for which existing general-purpose computers are already the cheapest and most efficient devices. But this would be impossible. After all, general purpose computers already have special-purpose optimizations. Not all products have the same optimizations and they change with time. For example, in the past decade Intel and AMD have both added support for special instructions (often called "adding hardware support") to compute the AES block cipher more efficiently. So some computers will always be less efficient than others at mining. Besides, it's hard to imagine designing a mining puzzle that would rely on features like the speakers and screen that most individual's personal computers contain. So special-purpose machines stripped of these features would still probably be cheaper and more efficient.

So in reality our goal is a more modest one: coming up with a puzzle that reduces the gap between the most cost-effective customized hardware and what most general-purpose computers can do. ASICs will inevitably be somewhat more efficient, but if we could limit this to an order of magnitude or less it might still be economical for individual users to mine with the computers they already have.

***Memory-hard puzzles.*** The most widely used puzzles which are designed to be ASIC-resistant are called *memory-hard* puzzles — puzzles that require a large amount of memory to compute, instead of, or in addition to, a lot of CPU time. A similar but different concept is *memory-bound* puzzles in which the time to access memory dominates the total computation time. A puzzle can be just memory-hard without being memory-bound, or memory-bound without being memory-hard, or both. It's a subtle but important distinction arising from the fact that even if CPU speed is the bottleneck for computation *time*, the *cost* of solving a large number of such puzzles in parallel might still be dominated by the cost of memory, or vice versa. Typically for a computational puzzle we want something that is memory-hard *and* memory-bound, ensuring that a large amount of memory is required and this is the limiting factor.

Why might memory-hard and memory-bound puzzles help ASIC resistance? The logical operations required to compute modern hash functions are only a small part of what goes on in a CPU, meaning that for Bitcoin's puzzle, ASICs get a lot of mileage by not implementing any of the unnecessary functionality. A related factor is that the variation in memory performance (and cost per unit of performance) is much lower than the variation in computing speeds across different types of processors. So if we could design a puzzle that was memory-hard, requiring relatively simple computation but lots of memory to compute, this means that the cost of solving a puzzle would improve at the slower rate of memory cost improvements.

SHA-256 is decidedly not memory-hard, as we've seen, requiring only a tiny 256-bit state which easily fits into CPU registers. But it isn't too difficult to design a memory-hard proof-of-work puzzle.

***Scrypt***. The most popular memory-hard puzzle is called scrypt. This puzzle is already widely used in Litecoin, the second most popular cryptocurrency, and a variety of other Bitcoin alternatives.

Scrypt is a memory-hard hash function, originally designed for hashing passwords in a way that is difficult to brute-force, so the mining puzzle is the same Bitcoin's partial hash-preimage puzzle except with scrypt replacing SHA-256.

The fact that scrypt existed prior to Bitcoin and has been used for password hashing gives some confidence in its security. Password hashing has a similar goal of ASIC-resistance, because for security we want an attacker with customized hardware to not be able to compute password hashes much faster than the legitimate user or server, who presumably have only general-purpose computers.

Scrypt basically works in two steps. The first step involves filling a large buffer of random access memory (RAM) with random data. The second step involves reading from (and updating) this memory in a pseudorandom order, requiring that the entire buffer is stored in RAM.

**Figure 8.1: Scrypt pseudocode**

```
def scrypt(N, seed):
    V = [0] * N  // initialize memory buffer of length N

  // Fill up memory buffer with pseudorandom data
  V[0] = seed
  for i = 1 to N:
     V[i] = SHA-256(V[i-1])

  // Access memory buffer in a pseudorandom order
  X = SHA-256(V[N-1])
  for i = 1 to N:
     j = X % N  // Choose a random index based on X
     X = SHA-256(X ^ V[j]) // Update X based on this index

  return X
```

Figure 8.1 shows Scrypt pseudocode. It demonstrates the core principles but we've omitted a few details: in reality scrypt works on slightly larger blocks of data and the algorithm for filling up the buffer is slightly more complex.

To see why scrypt is memory-hard, let's imagine trying to compute the same value without using the buffer V. This would certainly be possible — however, in line 9, we would need to recompute the value V[j] on the fly, which would require computing j iterations of SHA-256. Because the value of j during each iteration of the loop will be pseudorandomly chosen between 0 and N-1, this will require about N/2 SHA-256 computations. This means computing the entire function will now take N * N/2 = $N^2/2$ SHA-256 computations, instead of just 2N if a buffer is used! Thus, the use of memory converts scrypt from an O(N) function to an $O(N^2)$. It should be simple to choose N large enough that the $O(N^2)$ is slow enough that using memory is faster.

***Time-memory tradeoffs***. While it would be much slower to compute scrypt without the help of a large memory buffer, it is still possible to use less memory at the cost of slightly more computation. Suppose that we use a buffer of size N/2 (instead of size N). Now, we could store only the values V[j] if j is even, discarding the values for which j is odd. In the second loop, about half of the time an odd value of j will be chosen, but this is now fairly easy to compute on the fly — we simply compute SHA-256(V[j-1]) since V[j-1] will be in our buffer. Since this happens about half the time, it adds N/2 extra SHA-256 computations.

Thus, halving our memory requirement increases the number of SHA-256 computations by only a quarter (from 2N to 5N/2). In general, we could store only every kth row of the buffer V, using N/k memory and computing (k+3)N/2 iterations of SHA-256. In the limit, if we set k = N, we're back up to our earlier calculation where the running time becomes $O(N^2)$. These numbers don't apply precisely for scrypt itself, but the asymptotic estimates do.

There are alternate designs that mitigate the ability to trade off memory with time. For example, if the buffer is continually updated in the second loop, it makes the time-memory tradeoff less effective as the updates will have to be stored.

***Verification cost***. Another limitation of scrypt is that it takes as much memory to verify as it does to compute. In order to make the memory hardness meaningful, N will need to be fairly large. This means that a single computation of scrypt is orders of magnitude more expensive than a single iteration of SHA-256, which is all that is needed to check Bitcoin's simpler mining puzzle.

This has some negative consequences, as every client in the network must repeat this computation in order to check that a claimed new block is valid. This could slow down propagation and acceptance of new blocks and increase the risk of forks. It also means every client (even lightweight SPV clients) must have enough memory to compute the function efficiently. As a result, the amount of memory N which can be used for scrypt in a cryptocurrency is somewhat limited by practical concerns.

Until recently, it wasn't known if it was possible to design a mining puzzle that was memory-hard to compute but fast (and memory-easy) to verify. This property is not useful for password hashing, which had been the primary use case for memory-hard functions before their use in cryptocurrencies.

In 2014, a new puzzle called Cuckoo Cycle was proposed by John Tromp. Cuckoo Cycle is based on the difficulty of finding cycles in a graph generated from a cuckoo hash table, a data structure which itself was only proposed in 2001. There isn't any known way to compute it without building up a large hash table, but it can be checked simply by checking that a (relatively small) cycle has been found.

This might make memory-hard or memory-bound proof of work much more practical for use in Bitcoin consensus. Unfortunately, there is no mathematical proof that this function can't be computed efficiently without using memory. Often, new cryptographic algorithms appear secure, but the community is not convinced until they have been around for many years without an attack being found. For this reason, and due to its recent discovery, Cuckoo Cycle has not been used by any cryptocurrency as of 2015.

***Scrypt in practice***. Scrypt has been used in many cryptocurrencies, including several popular ones such as Litecoin. The results have been somewhat mixed. Scrypt ASICs are already available for the parameters chosen by Litecoin (and copied by many other altcoins). Surprisingly, the performance improvement of these ASICs compared to general purpose computers has been equal to or larger than that for SHA-256! Thus, scrypt was decidedly not ASIC-resistant in the end, as least as used by Litecoin. The developers of Litecoin initially claimed ASIC-resistance was a key advantage over Bitcoin, but have since admitted this is no longer the case.

This may be a result of the relatively low value of N (the memory usage parameter) used by Litecoin, requiring only 128kB to compute (or less if a time-memory tradeoff is used, which was commonly done on GPUs to get the entire buffer to fit into a faster cache). This has made it relatively easy to design lightweight mining ASICs without a complicated memory access bus needed to access gigabytes of RAM, as general purpose computers have. Litecoin developers didn't choose a value that was much higher (which would make ASICs more difficult to design) because they considered the verification cost impractical.

***Other approaches to ASIC-resistance.*** Recall that our original goal was simply to make it hard to build ASICs with dramatic performance speedups. Memory-hardness is only one approach to this goal, and there are others.

The other approaches, unfortunately, are not very scientific and have not been as rigorously designed or attacked as memory-hard functions. The most well known is called X11, which is simply a combination of eleven different hash functions introduced by an altcoin called Darkcoin (later renamed DASH) and since used by several others. The goal of X11 is to make it considerably more complicated to design an efficient ASIC as all 11 functions must be implemented in hardware. But this is nothing more than an inconvenience for hardware designers. If an ASIC were built for X11, it would surely make CPU and GPU mining obsolete.

**Sidebar: where did X11's hash functions come from?** From 2007 to 2012, the US National Institute of Standards ran a competition to choose a new hash function family to be the SHA-3 standard. This produced a large number of hash functions which were submitted as candidates, complete with design documents and source code. While many of these candidates were shown not to be cryptographically secure during the competition, 24 survived without any known cryptographic attacks. X11 chose eleven of these, including Keccak, the ultimate competition winner.

Another approach which has been proposed, but not actually implemented, is to have a mining puzzle that's a moving target. That is, the mining puzzle itself would change, just as the difficulty periodically changes in Bitcoin. Ideally, the puzzle would change in such a way that optimized mining hardware for the previous puzzle would no longer be useful for the new puzzle. It's unclear exactly how we would actually change the puzzle once every so often in order to obtain the security requirements we need. If the decision were to be made by the developers of an altcoin, it might be an unacceptable source of centralization. For example, the developers might choose a new puzzle for which they have already developed hardware (or just an optimized FPGA implementation), giving them an early advantage.

Perhaps the sequence of puzzles could be generated automatically, but this seems difficult as well. One idea might be to take a large set of hash functions (say, the 24 SHA-3 candidates which were not broken) and use each for six months to one year, too short of a time for hardware to be developed. Of course, if the schedule were known in advance, then the hardware could simply be designed just in time to ship for the time each function was being used.

***The ASIC honeymoon.*** The lack of ASICs for X11 so far, even though they are clearly possible to build, demonstrates a potentially useful pattern. Because no altcoins using X11 have a particularly high market share, there simply hasn't been a large enough market for anybody to build ASICs for X11 yet. In general, designing ASICs has very high upfront costs (in both time and money) and relatively low marginal costs per unit of hardware produced. Thus, for new and unproven cryptocurrencies, it is not worth making an investment to build hardware if the currency might fail before the new hardware is available for mining. Even when there is a clear market, there is a time delay before hardware units will be ready. It took over a year for the first Bitcoin ASICs to be shipped from when they were first designed, and this was considered to be lightning fast for the hardware industry.

Thus, any new altcoin with a new mining puzzle is likely to experience an *ASIC honeymoon* during which time GPU and FGPA mining (and potentially CPU mining) will be profitable. It may not be possible to stem the tide of ASICs forever, but there is perhaps some value in making it appealing for individuals to participate in mining (and earn some units of the new currency) while it is bootstrapping.

***Arguments against ASIC-resistance.*** We've seen that it may be impossible to achieve ASIC-resistance in the long run. There are also arguments that it is risky to move away from the relatively proven SHA-256 mining puzzle towards a new puzzle that might be weaker cryptographically. Furthermore, SHA-256 mining ASICs are already being designed at close to modern limits on hardware efficiency, meaning the exponential growth period is probably over and SHA-256 mining will therefore offer the most stability to the network.

Finally, there is an argument that even in the short run ASIC-resistance is a bad feature to have. Recall from Chapter 3 that even if there is a 51% miner, many types of attack aren't rational for them to attempt because it could crash the exchange rate and decimate the value of the miner's investment in hardware since the bitcoins they earn from mining will be worth much less.

With a highly ASIC-resistant puzzle, this security argument might fall apart. For example, an attacker might be able to rent a huge amount of generic computing power temporarily (from a service such as Amazon's EC2), use it to attack, and then suffer no monetary consequences as they no longer need to rent the capacity after the attack. By contrast, with an "ASIC-friendly" puzzle, such an attacker would inherently need to control a large number of ASICs which are useful only for mining the cryptocurrency. Such an attacker would be maximally invested in the future success of the currency. Following this argument to its logical conclusion, to maximize security, perhaps mining puzzles should not only enable efficient mining ASICs to be be built, but be designed such that those ASICs are completely useless outside of the cryptocurrency!

## 8.3 Proof-Of-Useful-Work

In Chapter 5 we discussed how the energy consumed (some would say wasted) by Bitcoin mining, referred to as *negative externalities* by economists, is a potential concern. We estimated that Bitcoin mining consumes several hundred megawatts of power. The obvious question is whether there is some puzzle for which the work done to solve it provides some other benefit to society. This would amount to a form of recycling and could help increase political support for cryptocurrencies. Of course, this puzzle would still need to satisfy several basic requirements to make it suitable for use in a consensus protocol.

***Previous distributed computing projects.*** The idea of using idle computers (or "spare cycles") for good is much older than Bitcoin. Table 8.3 lists a few of the most popular volunteer computing projects. All these projects have a property that might make them suitable for use as a computational puzzle: specifically, they involve some sort of a "needle in a haystack" problem where there is a large space of potential solutions and small portions of the search space can be checked relatively quickly and in parallel. For example, in SETI@home volunteers are given small portions of observed radio signals to scan for potential patterns, while in distributed.net volunteers are given a small range of potential secret keys to test.

Volunteer computing projects have succeeded by assigning small portions of the solution space to individuals for checking. In fact, this paradigm is so common that a specific library called BOINC (Berkeley Open Infrastructure for Network Computing) was developed to make it easy to parcel out small pieces of work for individuals to finish.

In these applications, volunteers were motivated mainly by interest in the underlying problem, though these projects also often use leaderboards for volunteers to show off how much computation they have contributed. This has led to some attempts to game the leaderboards by reporting work that wasn't actually finished, requiring some projects to resort to sending a small amount of redundant work to detect cheating. For use in a cryptocurrency, of course, the motivation is primarily monetary and we can expect participants to attempt to cheat as much as technically possible.

| Project | Founded | Goal | Impact |
|---|---|---|---|
| Great Internet Mersenne Prime Search | 1996 | Finding large Mersenne primes | Found the new "largest prime number" twelve straight times, including $2^{57885161} - 1$ |
| distributed.net | 1997 | Cryptographic brute-force demos | First successful public brute-force of a 64-bit cryptographic key |
| SETI@home | 1999 | Identifying signs of extraterrestrial life | Largest project to date with over 5 million participants |
| Folding@home | 2000 | Atomic-level simulations of protein folding | Greatest computing capacity of any volunteer computing project. More than 118 scientific papers. |

**Table 8.3: Popular "Volunteer computing" projects**

***Challenges in adapting useful-proof-of-work.*** Given the success of these projects, we might attempt to simply use these problems directly. For example, in the case of SETI@Home, where volunteers are given segments of radio observations which they test for statistical anomalies, we might decide that statistical anomalies which are rarer than some threshold are considered "winning" solutions to the puzzle and allow any miner who finds one to create a block.

There are a few problems with this idea. First, note that potential solutions are not all equally likely to be a winning solution. Participants might realize that certain segments are more likely to produce anomalies than others. With a centralized project, participants are assigned work so all segments can be analyzed eventually (perhaps with more promising segments given priority). For mining, however, any miner can attempt any segment, meaning miners might flock to try the most likely segments first. This could mean the puzzle is not entirely progress-free, if faster miners know they can test the most promising segments first. Compare this to Bitcoin's puzzle, in which any nonce is equally likely to any other to produce a valid block, so all miners are incentivized to choose random nonces to try. The problem here demonstrates a key property of Bitcoin's puzzle that we previously took for granted, that of an *equiprobable solution space.*

Next, consider the problem that SETI@home has a fixed amount of data to analyze based on observations taken by radio telescopes. It's possible that as mining power increased, there would be no more raw data to analyze. Compare this again to Bitcoin, in which an effectively infinite number of SHA-256 puzzles can be created. This reveals another important requirement: an *inexhaustible puzzle space* is needed.

Finally, consider that SETI@home uses a trusted, centralized set of administrators to curate the new radio data and determine what participants should be looking for. Again, since we are using our puzzle to build a consensus algorithm we can't assume a centralized party to manage the puzzle. Thus, we need a puzzle that can be *algorithmically generated*.

***Which volunteer computing projects might be suitable as puzzles?.*** Returning to Figure 8.3, we can see that SETI@home and Folding@home clearly won't work for a decentralized consensus protocol. Both probably lack all three properties we've now added to our list. The cryptographic brute-force problems taken on by distributed.net could work, although they are typically chosen in response to specific decryption challenges that have been set by companies looking to evaluate the security of certain algorithms. These can't be algorithmically generated. We can algorithmically generate decryption challenges to be broken by brute forcing, but in a sense this is exactly what SHA-256 partial pre-image finding already does and it serves no beneficial function.

This leaves the Great Internet Mersenne Prime Search, which turns out to be close to workable. The challenges can be algorithmically generated (find a prime larger than the previous one) and the puzzle space is inexhaustible. In fact, it's infinite, since it has been proven that there are an infinite number of prime numbers (and an infinite number of Mersenne Primes in particular).

The only real drawback is that large Mersenne Primes take a long time to find and are very rare. In fact, the Great Internet Mersenne Prime Search has found only 14 Mersenne primes in over 18 years! It clearly wouldn't work to add less than one block per year to a block chain. This specific problem appears to lack the adjustable difficulty property that we stated was essential in Section 8.1. It turns out, however, that a similar problem involving finding prime numbers appears workable as a computational puzzle.

***Primecoin.*** As of this writing, the only proof-of-useful-work system deployed in practice is called Primecoin. The challenge in Primecoin is to find a *Cunningham chain* of prime numbers. A Cunningham chain is a sequence of *k* prime numbers $p_1$, $p_2$, ... $p_k$ such that $p_i = 2p_{i-1} + 1$ for each number in the chain. That is, you take a prime number, double it and add one to get another prime number, and continue until you get a composite number. The sequence 2, 5, 11, 23, 47 is a Cunningham chain of length 5. The potential sixth number in the chain, 95, is not prime ($95 = 5 \cdot 19$). The longest known Cunningham chain is of length 19 (starting at 79910197721667870187016101). It is conjectured and widely believed, but not proven, that there exist Cunningham chains of length *k* for any *k*.

Now, to turn this into a computational puzzle, we need three parameters *m*, *n*, and *k* which we will explain momentarily. For a given challenge *x* (the hash of the previous block), we take the first *m* bits of *x* and consider any chain of length *k* or greater in which the first prime in the chain is an *n*-bit prime and has the same *m* leading bits as *x* to be a valid solution. Note that we can adjust *n* and *k* to make the puzzle harder. Increasing *k* (the required chain length) makes the problem exponentially harder, while increasing *n* (the size of the starting prime) makes it linearly harder. This provides fine-tuning of the difficulty. The value of *m* just needs to be large enough that trying to pre-compute solutions before seeing the value of the previous block is infeasible.

All of the other properties we have discussed appear to be provided: solutions are relatively quick to verify, the problem is progress-free, the problem space is infinite (assuming some well-studied mathematical conjectures about the distribution of prime numbers are true), and puzzles can be algorithmically generated. Indeed, this puzzle has been in use for Primecoin for almost two years and this has produced the largest-known primes in Cunningham chains for many values of *k*. Primecoin has since expanded to include additional, similar types of prime chains in its proof of work, including "second kind" Cunningham chains in which $p_i = 2p_{i-1} - 1$.

This provides strong evidence that it is possible to make proof-of-useful-work practical in some limited circumstances. Of course, it's debatable the extent to which finding large Cunningham chains is useful. It's possible that they may have some applied purpose in the future and they certainly stand as a small contribution to our collective mathematical knowledge. Currently, however, they have no known practical applications.

***Permacoin and proof-of-storage.*** A different approach to proof-of-useful work is *proof-of-storage* (also sometimes called *proof-of-retrievability*). Rather than requiring a solely computational puzzle, what if we could design a puzzle that required storing a large amount of data to compute? If this data were useful, then miners' investment in mining hardware would effectively be contributing to a widely distributed and replicated archival storage system.

We'll take a look at *Permacoin*, the first proposal for proof-of-storage for use in consensus. We begin with a large file which we'll call *F*. For now, let's assume everybody agrees on the value of *F* and the file will not change. For example, *F* might be chosen by a trusted dealer when a cryptocurrency is launched, much as any new currency needs to agree on a genesis block to get going. This would ideally be a file of public value. For example, experimental data collected from the Large Hadron Collider already consists of several hundred petabytes (PB). Providing a free backup to this data would be quite useful.

Of course, since *F* is a huge file most participants will not be able to store the entire file. But we already know how to use cryptographic hash functions to ensure everybody agrees on *F* without knowing the entire thing. The simplest approach would be for everybody to agree on *H(F)*, but a better approach is to represent *F* using a large Merkle tree and have all participants agree on the value of the root. Now, everybody can agree on the value of *F* and it is efficient to prove that any portion of *F* is correct.

In Permacoin, each miner $M$ stores a random subset $F_M \subseteq F$. To achieve this, when the miner generates a public key $K_M$ which they will use to receive funds, they hash their public key to generate a pseudorandom set of blocks $F_M$ which they must store to be able to mine. This subset will be of some fixed number of blocks $k_1$. We have to assume here that there is some way for them to fetch those blocks when they start mining — perhaps downloading them from a canonical source.

Once the miner has stored $F_M$ locally, the puzzle is fairly similar to conventional SHA-256 mining. Given a previous block hash $x$, the miner chooses a random nonce value $n$ and hashes this to generate a pseudorandom subset $F_{M,n} \subseteq F_M$ consisting of $k_2 < k_1$ blocks. Note that this subset depends both on the nonce they have chosen and their public key. Finally, the miner computes a SHA-256 hash of $n$ and the blocks in $F_k$. If the value of this hash is below a target difficulty, they have found a valid solution.

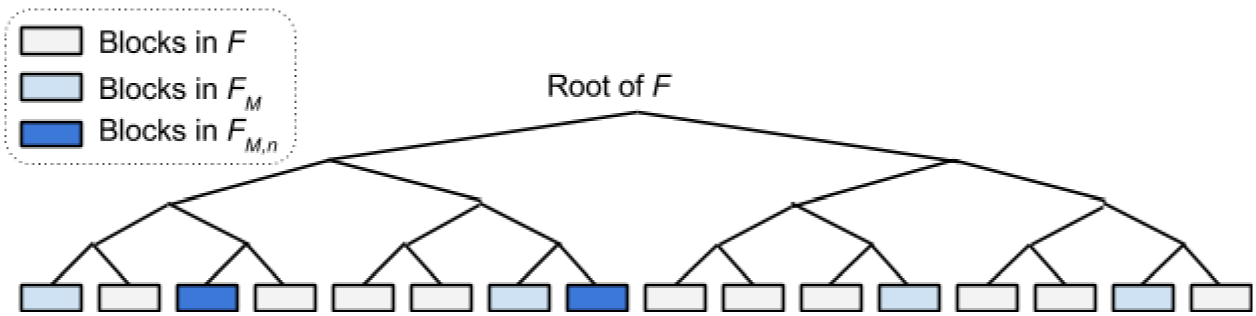



**Figure 8.4: Choosing random blocks in a file in Permacoin.**
**In this example $k_1$=6 and $k_2$=2. In a real implementation these parameters would be much larger.**

Verifying a solution requires the following steps:

- Verify that $F_{M,n}$ was correctly generated from the miner's public key $K_M$ and nonce $n$
- Verify that each block of of $F_{M,n}$ is correct by verifying their path in the Merkle tree to the globally-agreed upon root of $F$.
- Verify that H($F_{M,n}$ // $n$) is less than the target difficulty.

It should be easy to see why solving the puzzle requires the miner to store all of $F_{M,n}$ locally. For each nonce, the miner needs to test the hash of a random subset of blocks of $F_{M,n}$, which would be prohibitively slow to fetch over the network from remote storage.

Unlike the case with scrypt, there are no reasonable time/memory trade-offs provided that $k_2$ is big enough. If a miner stored only half of $F_M$ locally, and $k_2$=20, they'd have to try a million nonces before they found one that didn't require any blocks to be fetched over the network. So decreasing their storage burden by a constant factor increases their computational burden exponentially. Of course, setting $k_2$ to be too large will not be very efficient, since $k_2$ Merkle tree paths must be transmitted and verified in any valid solution.

There is also a trade-off in setting $k_1$. The smaller $k_1$ is, the less storage is needed to function as a miner and hence mining is more democratic. However, this also means larger miners have no incentive to store more than $k_1$ blocks of *F*, even if they have the ability to store more.

As usual, this is a slight simplification of the full Permacoin proposal, but this is enough to understand the key design components. The biggest practical challenge, of course, is finding a suitably large file that is important, public and in need of additional replication. There are also significant complexities if the file *F* changes over time, as well as with adjusting the mining difficulty over time.

***Long-term challenges and economics.*** To summarize this section, proof-of-useful-work is a very natural goal, but it is quite challenging to achieve it given the other requirements of a good computational puzzle for a consensus protocol. Although at least two examples are known which are technically feasible, Primecoin and Permacoin, both carry some technical drawbacks (primarily longer verification time of purported solutions). Furthermore, both provide fairly minor public benefits compared to the scale of effort we've seen levied at Bitcoin mining with millions of dollars worth of capital and megawatts of electricity consumed.

There is an interesting economic argument that the benefit of any proof-of-useful-work should be a pure *public good*. In economics, a public good is one that is non-excludable, meaning nobody can be prevented from using it, and non-rivalrous, meaning the good's use by others does not affect its value. The classic example is a lighthouse.

Some of the examples we discussed here, such as protein folding, might not be a pure public good because some firms (such as large pharmaceutical corporations) may benefit more from increased knowledge about protein folding than others. Essentially, mining would be cheaper for these parties since they are gaining more benefit from the public benefits than others would be.

## 8.4 Nonoutsourceable Puzzles

Let's turn to another potential design goal for alternative mining puzzles: preventing the formation of mining pools. As we discussed in Chapter 5 and elsewhere, most Bitcoin miners mine as part of a pool rather than independently. This has resulted in a few large pools which together represent most of the mining power. Since each pool is operated by a central pool administrator, some feel this is a dangerous trend away from Bitcoin's core design principle of decentralization and can compromise its security.

While a mining pool with a majority share is an obvious problem, any large centrally managed pool might implement a non-default mining strategy and attack the network. Such pools are also a juicy target for hackers to try and compromise to immediately control a large amount of mining power. The pool operators might collude to censor transactions or enforce high transaction fees. At the very least, having most miners in pools also means that most miners aren't running a fully validating node.

Interestingly, these concerns have an analogy in the realm of voting. It's illegal in the United States and many other nations for individuals to sell their vote. Arguably participating in a pool controlled by someone else is akin to selling your vote in the Bitcoin consensus protocol.

**Technical requirements for pools.** Recall that mining pools appear to be an emergent phenomenon. There's no evidence that Satoshi was thinking of mining pools at the time of Bitcoin's original design. It wasn't apparent for a few years that efficient pools could be run between many individuals who don't know or trust each other.

As we saw in Chapter 5, mining pools typically work by designating a pool operator with a well-known public key. Each of the participating miners mines as usual but sends in shares to the pool operator. These shares are "near misses" or "partial solutions" which would be valid solutions at a lower difficulty level. This shows the pool operator how much work the miner is performing. Whenever one of the pool participants finds a valid block, the pool operator then distributes the rewards amongst the pool participants based on the number of shares they have submitted. As we discussed in Chapter 5, there are many formulas for dividing the revenue up, but all mining pools follow this basic structure.

The existence of pools thus relies on at least two technical properties of Bitcoin. The first is that it's easy for a miner to prove (probabilistically) how much work they are doing by submitting shares. By choosing a low enough threshold for shares, miners can easily prove how much work they are performing with arbitrary precision regardless of the actual difficulty of finding an valid block. This facet of mining puzzles appears difficult to change, given that we need a puzzle that can be created with arbitrary difficulty.

Second, pool members can easily prove to the pool operator that they're following the rules and working to find valid blocks which would reward the pool as a whole. This works because the pool's public key is committed to in the coinbase transaction included in the block's Merkle tree of transactions. Once a miner finds a block or even a share, they can't change which public key is the recipient of the newly minted coins.

**Block discarding attacks.** There is one weakness in this scheme for implementing mining pools: there is nothing to to enforce that participating miners actually submit valid blocks to the pool manager in the event that they find them. Suppose that there's a pool member that's upset with a large mining pool. They can participate in the pool by mining and submitting shares just like normal, but in the event that they actually find a valid block that would reward the pool they simply discard it and don't tell the pool operator about it.

This attack reduces the pool's overall mining power as none of the attacker's work is contributing towards finding valid blocks. However the attacker will still be rewarded as they appear to be submitting valid shares and simply getting unlucky to not find any valid blocks. If the mining pool is designed to be revenue-neutral (that is, all mining rewards are redistributed back to participants) then this attack can cause the pool to run at a loss.

This attack is sometimes called a *vigilante* or *sabotage* attack and is considered a form of vandalism because the attack appears to be costly for both the attacker and the pool. The attacker loses money because every block they discard would have led to some proportion of the block rewards being returned to them. Of course, the attacker still gets rewards for other puzzle solutions that are found.

It appears that a rational attacker wouldn't employ this strategy, since they would lose money without gaining anything tangible. It turns out (quite surprisingly) that there are cases where this strategy can be profitable, as discussed in the box below. But in any case, we want to design an entirely new mining puzzle formulation that ensures this strategy is always profitable.

**Sidebar: block discarding attacks between pools.** People assumed for years that it can't be profitable for a participant to discard valid blocks found on behalf of the pool. It turns out this strategy can be profitable if one mining pool uses it to attack another. This was proposed apocryphally many times and first thoroughly analyzed in a paper by Ittay Eyal in 2015.

Let's consider a simple case: suppose two mining pools, A and B, each have 50% of the total mining capacity. Now suppose B uses half of its mining power (25% of the total capacity) to mine as a member in pool A, but discards all blocks found. We can show, in a simplified model, that B will now earns 5/9 of the total rewards, greater than the 50% it would earn by mining normally. In this simple case, dedicating half of its mining power to attacking can be shown to be the optimal strategy for pool B.

The situation grows more complicated with multiple pools. Block discarding has not been observed in practice on a large scale as of this writing. But it remains possible that in the long run, attacks like this one will throw the viability of large mining pools into question.

**Rewarding sabotage.** Our design goal is to make it so that miners are incentivized to mine in a pool but not submit valid blocks to the pool manager. Currently, only the pool manager can collect the mining rewards because the manager requires all participants to include a specific public key in the coinbase transaction of blocks they are mining. Proper inclusion can be easily checked in submitted partial solutions. The pool manager is the only party that knows the private key and hence can determine where the newly minted coins go.

But what if we required that all participants also knew the private key (and hence could redirect the funds after mining a block?). To do this, we need a puzzle in which each solution attempt requires knowledge of the private key in the coinbase transaction. We can change the puzzle from "find a block whose hash is below a certain target" to "find a block for which the hash of *a signature* on the block is below a certain target." This signature must be computed using the same public key in the coinbase transaction.

Such a puzzle leaves would-be pool operators with two untenable choices. They might distribute the private key to all pool participants, in which case any of them can steal all of the funds. Alternately, they can perform the signatures on behalf of pool participants. Computing a signature is orders of magnitude more expensive than computing a hash, however, so in this case the pool manager would be doing the majority of the heavy lifting. It would be better for the pool manager to simply be a solo miner.

**The pros and cons of non-outsourceable mining.** Since this puzzle can't effectively be outsourced to an untrusted participant, it makes it much more challenging, if not outright impossible, to form a mining pool with untrusted participants. It effectively prevents *all* pools, even efforts like P2Pool to make a decentralized pool without a pool manager.

There's an argument that deploying such a puzzle might perversely lead to *more* centralization, not less, because it would discourage small miners from participating due to the high variance they would face. This would leave only large mining operations. Currently, while pools may nominally control a large amount of mining power, it isn't clear that they can use this to launch an attack without seeing many of their members defect. It remains an open question which risk is worse — that of large mining pools, or of limiting mining to operators large enough to live with a high variance.

The holy grail would be to design a consensus protocol which is "naturally" low-variance by rewarding miners a small amount for lower-difficulty puzzles. This would mean miners don't need to form pools and yet small miners may still participate. Simply decreasing the average time between blocks won't work — it would need to be decreased by a factor of 1,000 or more for the resulting variance to be equivalent to today's large mining pools. But then the delay between blocks would be less than a second and the number of stale blocks would be chaotically high. It remains an open question if there is an alternate version of the consensus protocol which would enable easier mining puzzles without requiring near-instantaneous broadcast of all solutions.

## 8.5 Proof-of-Stake and Virtual Mining

To wrap up this chapter, let's look at the idea of replacing computational puzzles with *virtual mining*. This term refers to a disparate set of approaches but they all have in common that they require only a small expenditure of computational resources by participating miners.

**Closing the loop on mining.** As a thought experiment, suppose Bitcoin or another cryptocurrency becomes the dominant form of payment globally. Miners would start with some initial holding of cryptocurrency, use it to purchase mining equipment and electricity, consume these resources, and in the process, acquire new cryptocurrency in the form of mining rewards. This process continually burns energy and raw materials.


**Figure 8.5: The cycle of Bitcoin mining**

Once mining hardware becomes a commodity and electricity is a commodity (as it generally already is), no miner would have a significant advantage over any other miner in terms of how efficiently they could convert their initial cryptocurrency holdings into mining rewards. Barring minor variations in efficiency, whoever invests the most into mining will receive the most rewards.

The basic question motivating virtual mining is: what would happen if we removed the step of spending money on power and equipment? After all, this process is primarily used to prove who has invested the most in mining. Why not simply allocate mining "power" directly to all currency holders in proportion to how much currency they actually hold?

Recall that the original goal of Bitcoin mining was to enable a form of voting on the state of the block chain, with miners with more computing power gaining more votes. We could instead design our "voting" system so that votes are determined by how much currency one currently holds.

**Advantages of virtual mining.** The primary advantage of this approach is obvious: it removes the wasteful right half of the mining cycle from Figure 8.5, leaving us with a "closed" system as shown in Figure 8.6.


**Figure 8.6: The virtual mining cycle**

In addition to simplicity, this approach would dramatically reduce Bitcoin's environmental footprint. It wouldn't reduce energy consumption to zero, because miners will always have to expend some computational resources to communicate with the network and validate. Some virtual mining schemes also require a small amount of computational mining as well. But in either case, the vast majority of the mining work performed in Bitcoin can potentially be eliminated.

Virtual mining may also reduce the trend towards centralization. Because there is no mining hardware involved there is no concern about an ASIC advantage; all miners are able to mine as “efficiently” as all others. Any virtual mining puzzle achieves all of the goals of ASIC-resistant puzzles.

Perhaps most importantly, virtual mining might solve the problem which we discussed in the context of ASIC-resistant puzzles, namely that miners may not be invested in the long-term health of the currency. Anybody who holds any bitcoins is effectively a stakeholder in the currency, and a powerful virtual miner (such as one who holds 51% or more of all currency) is a very large stakeholder. They have an incentive to do things that would benefit the system as a whole because it increases the value of the coins that they hold. This argument is even stronger than the argument that a miner sitting on a large stock of mining equipment whose value depends on the future of the currency will not behave maliciously.

This is where the term *proof-of-stake* comes from. Even more than eliminating mining and saving energy, perhaps the most fundamental motivation for virtual mining is to ensure that mining is done by stakeholders in the currency who have the strongest incentives to be good stewards of the system.

**Implementing virtual mining: Peercoin.** There are many variations of virtual mining of which we’ll describe a few of the most common ideas. We should emphasize that these ideas have not yet been studied in a scientific and rigorous way, nor have they undergone the level of practical testing that proof-of-work has due to Bitcoin’s popularity.

To start with, we’ll consider the approach taken by Peercoin, which was launched in 2012 as the first altcoin using proof-of-stake. Peercoin is a hybrid proof-of-work/proof-of-stake algorithm in which “stake” is denominated by “coin-age.” The coin-age of a specific unspent transaction output is the product of the amount held by that output and the number of blocks that output has remained unspent. Now, to mine a block in Peercoin a miner must solve a SHA-256 based computational puzzle just like in Bitcoin. However, the difficulty of this puzzle is adjusted down based on how much coin-age they are willing to consume. To do this, the block includes a special “coinstake” transaction in which some transactions are spent simply to reset their coin-age to zero. The sum of the coin-ages consumed in the coinstake transaction decides how difficult the proof-of-work puzzle is to make a given block valid.

It is possible for miners to mine with very little stake and a large amount of computational power, but the difficulty formula is chosen to make it dramatically easier to find a block if some coin-age is consumed. The effect of the computational puzzle is mainly to ensure that the process is randomized if two miners attempt to consume a similar quantity of coin-age.

Many virtual mining altcoins have adopted slightly different designs, including Nxt, BitShares, BlackCoin and Reddcoin. In each of these, some amount of stake is used to make a computational puzzle vastly easier, purportedly to the point that the computational puzzle is no longer the main challenge in mining.

**Alternate forms of stake.** A couple of alternatives to this hybrid model that are worth discussing:

- **Proof-of-stake.** The purest form of proof-of-stake is simply to make mining easier for those who can show they control a large amount of currency. This is similar to Peercoin's proof-of-coin-age, only with age not taken into account. The downside of this approach is that unlike coin-age which resets after successful mining, the richest participants are always given the easiest mining puzzle.
- **Proof-of-deposit**. In this formulation, when coins are used by a miner to mint a block, they become frozen for a set number of blocks. This can be thought of as a mirror of coin-age: instead of rewarding a miner for holding coins which have been unspent for a long time in the past, this system rewards miners who are willing to have coins go unmoved for a long time into the future. In both approaches, miners' stake effectively comes from the opportunity cost of not being able to use the coins to perform other actions.

**The nothing-at-stake problem.** Virtual mining is an active area of ongoing research and there are large open problems. While a few cryptocurrencies have launched and survived using virtual mining, they have faced the same pressure as Bitcoin to withstand motivated attackers.

The generic vulnerability of virtual mining schemes is what's often called the *nothing-at-stake* problem or *stake-grinding attacks.* Suppose an attacker with a proportion $\alpha < 50\%$ of the stake is attempting to create a fork of *k* blocks. As we've discussed previously, this attack will fail with high probability that is exponentially increasing in *k*. In traditional mining, a failed attack has a significant opportunity cost, because that miner could have been earning mining rewards during the mining process instead of wasting mining resources on its failed attack.

With virtual mining, this opportunity cost doesn't exist. A miner can use their stake to mine in the current longest chain while simultaneously attempting to create a fork. If their fork succeeds, it will have consumed a large amount of their stake. If it fails, the record of it failing will not be reflected on the eventual longest chain.

Thus, rational miners might be constantly attempting to fork the chain. Various attempts have been made to address this issue. Most virtual mining schemes have been much more aggressive about using checkpointing to prevent long forks, but as discussed previously, this is a bit of an end-run around a decentralized consensus protocol.

For Ethereum (an altcoin launched in mid 2015 that we will discuss in Chapter 10), a proposal called Slasher allows punishment for miners who attempt to fork the chain. In Slasher, using stake to mine requires signing the current block with the private key corresponding to the transactions making up the miner's stake. If a miner ever uses the same stake to sign two inconsistent chains (neither of which is a prefix of the other), Slasher allows miners to enter these two signatures later on in the block chain as proof of misbehavior and collect a portion of this stake as a bounty. While this appears to provide an effective solution, the details of the protocol are quite complicated and it has yet to be deployed successfully.

A final countermeasure that may exist is that, as we've seen for traditional mining schemes, miners may simply not have a strong incentive to attack because this would damage the system and undermine their stake, even if the attack is successful.

**Other drawbacks of virtual mining.** Two other drawbacks are worth quickly mentioning. The first is that some forms of virtual mining, even in the absence of stake-grinding, might make some types of attacks easier because it is possible to "save up" for a burst of mining power. For example, a large amount of coin-stake can be pooled to enable a dramatic surge of mining to, perhaps, introduce a fork. This is possible even if a system like Slasher is used to discourage mining on two chains at once. To discourage this type of attack, Peercoin limits the age parameter to 90 days when computing coin-age.

A second issue is that if a miner in a virtual mining system obtains 51% of the available stake, they can maintain it forever by only mining on top of their own blocks, essentially taking control of the block chain. Even if new stake emerges from mining rewards and transaction fees, the 51% miner will obtain this new stake and their share of the total stake will slowly approach 100%. In traditional mining, even if a 51% miner exists it is always possible that some new miner will emerge with more mining equipment and energy and reduce the majority miner. With virtual mining, it is much more difficult to avoid this problem.

**Can virtual mining actually work?** Virtual mining remains somewhat controversial in the mainstream Bitcoin community. There is an argument that security fundamentally requires burning real resources, requiring real computational hardware and expending real electrical power in order to find puzzle solutions. If this argument is believed, then the apparent waste of the proof of work system can be interpreted as the cost of the security that you get. But this argument hasn't been proven, just as the security of virtual mining hasn't been proven.

In summary, there are numerous things one might want to change about Bitcoin's mining puzzle, and this has been an area of furious research and innovation. So far, however, none of the alternatives seems to have both demonstrated theoretical soundness and found practical adoption. For example, even though scrypt has been a popular choice in altcoins, it hasn't actually achieved ASIC resistance, and its usefulness is unclear. It is entirely possible that alternative mining puzzles will find more success in the future. After all, Bitcoin itself came after decades of failed attempts to create a cryptocurrency and managed to hit the sweet spot between principled design and practical trade-offs.

## Further Reading

The paper that defines memory-hard functions and proposes scrypt:

**Percival, Colin. Stronger key derivation via sequential memory-hard functions. Self-published, 2009.**

Earlier papers on memory-bound functions:

**Abadi, Martin, Mike Burrows, Mark Manasse, and Ted Wobber. Moderately hard, memory-bound functions. ACM Transactions on Internet Technology, 2005.**

**Dwork, Cynthia, Andrew Goldberg, and Moni Naor. On memory-bound functions for fighting spam. In Advances in Cryptology—Crypto, 2003.**

The Cuckoo Cycle proposal:

**Tromp, John. Cuckoo Cycle: a memory-hard proof-of-work system. IACR Cryptology ePrint Archive 2014.**

The Permacoin proposal:

**Miller, Andrew, Ari Juels, Elaine Shi, Bryan Parno, and Justin Katz. Permacoin: Repurposing bitcoin work for data preservation. In IEEE Security and Privacy, 2014.**

This paper discusses different hash function designs and the SHA-3 contest:

**Preneel, Bart. The first 30 years of cryptographic hash functions and the NIST SHA-3 competition. In Topics in Cryptology — CT-RSA, 2010.**

The proposal for non-outsourceable puzzles:

**Miller, Andrew, Elaine Shi, Ahmed Kosba, and Jonathan Katz. Nonoutsourceable Scratch-Off Puzzles to Discourage Bitcoin Mining Coalitions. Pre-print 2015.**

# Chapter 9: Bitcoin as a Platform

In earlier chapters we developed the technical underpinnings of Bitcoin and saw how it can be used as a currency. Now we'll look at applications *other than currency* that we can build using Bitcoin as a central component. Some of these rely on Bitcoin as it is today, without any modifications, and many others would require only small modifications.

We've chosen these applications for a combination of practical usefulness and intellectual interest. This list is not in any way exhaustive, but seeing how these applications work (or could work, since many are only ideas or proposals) will give you insight into the many ways in which Bitcoin's functionality can be repurposed.

## 9.1. Bitcoin as an Append-Only Log

It's helpful to think about Bitcoin as an *append-only log* — a data structure to which we can write new data, and that which once we've written data, is tamper-proof and available forever. We also have a secure notion of ordering: we can tell if one piece of data was written to the log before or after another piece. This ordering arises from the block hash pointers, not the block timestamps — a block's timestamp can in fact be a lower (earlier) value than its predecessor. That's because miners can lie about timestamps, miners' clocks may not be synchronized, and there is latency on the network. That said, if a block timestamp appears to be off by more than a few hours, then other miners will reject it, so we can rely on the timestamps being approximately correct. As we'll see, these properties turn out to be quite useful.

***Secure timestamping.*** The append-only log can be used to build a secure timestamping system from Bitcoin. We want to be able to prove that we know some value $x$ at some specific time $T$. We might not want to actually *reveal* $x$ at time $T$. Instead we only want to reveal $x$ when we actually make the proof, which may be much later than $T$ (and of course if we knew it at $T$, we still know it after $T$ too). However, once we have made the proof, we want the evidence to be permanent.

Recall from Chapter 1 that we can use hash functions to commit to data. Instead of publishing the data $x$ that we want to prove that we know, we can publish just the hash $H(x)$ to the block chain. The properties of the hash function guarantee that we can't later find some different value $y$ with the same value, $y \neq x$ such that $H(x) = H(y)$. We also rely on the convenient property that the hash of $x$ doesn't reveal any information about $x$, as long as $x$ is chosen from a distribution with high min-entropy, that is, it is sufficiently unpredictable. If $x$ doesn't have this property, then we can pick a random number $r$ with high min-entropy and use $H(r \mid x)$ as the commitment, as we saw in Chapter 1.

The main idea is that we can publish just the hash $H(r \mid x)$ at time T, and then at some point later on we can reveal $r$ and $x$. Anybody can look at the append-only log and be convinced that we must have known $x$ at the time we published $H(r \mid x)$, because there is no other feasible way to have generated that data.

***Applications of timestamping.*** What could we do with this kind of secure timestamping? One possible use is to prove prior knowledge of some idea. Suppose we wanted to prove that some invention we filed a patent on was actually in our heads much earlier. We could do this by publishing the hash of a design document or schematic when we first thought of the invention — without revealing to anybody what the idea is. Later on, when we file our patent or when we publicize the idea, we can publish the original documents and information and anybody can look backwards in time and confirm we must have known it earlier when we published the commitment to it.

We can also prove that someone has else has received a message we sent them. Suppose Alice hires Bob to perform a programming job; their contract requires Bob to submit his work to Alice by a specific time. Both parties want to make sure that if there is a dispute later about whether Bob submitted the work or whether the code performed to specification, they have proof of what was submitted and when. To ensure this, they can mutually agree to publish a hash of Bob's submitted work signed by both parties. If either party later lies about what was submitted or when, the other party can prove them wrong (say, in a court of arbitration) by revealing the input to the hash.

Many other interesting things can be built just from secure timestamping. There's even an entire public-key signature scheme (called the Guy Fawkes signature scheme) that just uses hash functions and an append-only log. It doesn't require any of the heavy-weight cryptography that's usually used for public-key signatures.

***Attacks on Proofs-of-"Clairvoyance".*** One thing that we *can't* do with secure timestamping alone — although it would be very nice if we could — is to prove *clairvoyance*, the ability to predict the future. This might seem possible. The idea would be to publish a commitment to a description of an event that's about to occur (such as the outcome of a sporting event or of an election) and then later reveal that information to prove we predicted the event ahead of time. But does this work?

In late 2014, during the final match of the World Cup, someone used this method to "prove" that FIFA, the organization running the World Cup, was corrupt. After the match was over, a Twitter account received significant attention for having tweeted about several events that occurred during the game, timestamped *before the match even began*. For example, it correctly tweeted that Germany would win in extra time and that Mario Götze would score. Seemingly this proves that either the owner of this Twitter account could tell the future or that the match was rigged. But in fact the account had tweeted *every possible outcome* before the match started. For every player involved in the match, there was a tweet predicting that he would score; there was a tweet for every conceivable final score of the game; and so on (see Figure 9.1). Before the match ended, all of the false predictions were deleted, leaving the Twitter account with only true "predictions."

This same basic attack can be performed against any secure timestamping system. You simply commit to a variety of possible outcomes, and then only reveal the commitments that turn out to be true. This means that if you actually *do* have the ability to predict the future and want to prove it, you must prove that you are timestamping *one specific prediction* rather than that multiple predictions. If you are publishing hash-based commitments, this is difficult to do. This is especially true in Bitcoin, since our secure timestamping system does not tie commitments to any individual's public identity. If you don't reveal them, it is easy to publish a large number of commitments and the ones you never reveal cannot easily be traced back to you.


**Figure 9.1:** A Twitter account which attempted to "prove" that the 2014 FIFA Men's World Cup Final was rigged by "predicting" the outcome of the match. The first, third and fourth tweets ended up being true, the rest were deleted after the match.

***Secure timestamping the old-fashioned way.*** Here's a simple low-tech way to do secure timestamping: publish the hash of your data in a newspaper, or some other media which is widely seen by the public, by purchasing an advertisement. Archives of old newspaper issues are maintained at libraries and online. This method provides a high degree of assurance that you knew that data on the day the newspaper was published. Later, when you want to reveal the data you committed, you can even take out a second advertisement to publish the data in the same newspaper.


**Figure 9.2**: **A timestamping service (GuardTime) that publishes hashes in a daily newspaper rather than the Bitcoin block chain.** Customers of the company can pay to have their data included in the timestamp. Recall from Chapter 1 that we can use Merkle trees to encapsulate many pieces of data in a single hash and still efficiently prove that any one of those pieces of data is included in the hash.

***Secure timestamping in Bitcoin.*** If we want to use Bitcoin instead of newspapers for timestamping, where should we place the hash commitment? Somewhere in a transaction? Or directly in a block?

The simplest solution (and the one people came up with first) is instead of sending money to the hash of a public key, just send it to the hash of your data. This “burns” those coins, that is, makes them unspendable and hence lost forever, since you don’t know the private key corresponding to that address. To keep your cost down, you’d want to send a very small amount, such as one satoshi (the minimum possible transaction value in Bitcoin).

Although this approach is very simple, the need to burn coins is a disadvantage (although the amount burned is probably negligible compared to the transaction fees incurred). A bigger problem is that Bitcoin miners have no way to know that the transaction output is unspendable, so they must track it forever. The community frowns on this method for this reason.

A more sophisticated approach called CommitCoin allows you to encode your data into the *private* key. Recall that in Chapter 1, we said: “With ECDSA, a good source of randomness is essential because a bad source of randomness will likely leak your key. It makes intuitive sense that if you use bad randomness in generating a key, the key that you generate will likely not be secure. But it’s a quirk of ECDSA that, even if you use bad randomness just in making a signature, using your perfectly good key, that also will leak your private key.”

CommitCoin exploits this property. We generate a new private key that encodes our commitment and we derive its corresponding public key. Then we send a tiny transaction (of, say, 2000 satoshi) to that address, and then send it back in two chunks of 1000 satoshi each. Crucially, when sending it back we use the same randomness both times for signing the transaction. This allows anyone looking at the block chain to compute the private key, which contains the commitment, using the two signatures.

Compared to encoding your commitment in the public key, this CommitCoin avoids the need to burn coins and for miners to track an unspendable output forever. However, it is quite complex.

***Unspendable outputs.*** As of 2014, the preferred way to do Bitcoin timestamping is with an OP_RETURN transaction which results in a provably unspendable output. The OP_RETURN instruction returns immediately with an error so that this script can never be run successfully, and the data you include is ignored. As we saw in Chapter 3, this can be used both as a proof of burn as well as to encode arbitrary data. As of 2015, OP_RETURN allows 80 bytes of data to be pushed, which is more than enough for a hash function output (32 bytes for SHA-256).

OP_RETURN <H(data)>

**Figure 9.3:** A provably “unspendable” transaction output script that embeds a data commitment

This method avoids bloat in the unspent transaction output set since miners will prune OP_RETURN outputs. The cost of such a commitment is essentially the cost of one transaction fee. Throughout 2014, a typical transaction fee is less than a penny. The cost can be reduced even further by using a single commitment for multiple values. As of late 2014 there are already several website services that help with this. They collect a bunch of commitments from different users and combine them into a large Merkle tree, publishing one unspendable output containing the Merkle tree root. This acts like a commitment for all the data that users wanted to timestamp that day.

***Illicit Content.*** One downside of being able to write arbitrary data into the block chain is that people might abuse the feature. In most countries, it is illegal to possess and/or distribute some kinds of content, notably child pornography, and penalties can be severe. Copyright laws also restrict the distribution of some content.

Sure enough, several people have tried doing things like this to “grief” (i.e., to harass or annoy) the Bitcoin community. For example, there have been reports of links to pornography published in the Bitcoin block chain. The goal of these griefers is to make it dangerous to download the block chain onto your hard drive and to run a full node, since to do so might mean storing and transmitting material whose possession or dissemination is illegal.

There's no good way to prevent people from writing arbitrary data into the bitcoin block chain. One possible countermeasure is to only accept *Pay-to-Script-Hash* transactions. This would make it a little bit more expensive to write in arbitrary data, but it still wouldn’t prevent it outright.

Fortunately, the law is not an algorithm. It is tempting to try to "hack" the law by technical means to produce unexpected or unintended outcomes, but this not easy. Laws are intended to be interpreted by humans and incorporate factors such as intent. For example, U.S. Code 2252, the section of U.S. federal law that pertains to possession, distribution and receipt of child pornography, uses the wording "*knowingly* possesses, or *knowingly* accesses with intent to view" when describing prohibited activities (emphasis ours).

It is also worth noting that due to the size limitations we discussed above, data such as images (except, perhaps, tiny ones) cannot be directly written into the Bitcoin block chain. They will either have to be hosted externally, with only links written into the block chain, or be encoded in a cumbersome way across multiple transactions. Finally, most Bitcoin clients do not ship with the ability to decode and view data written into transactions, let alone data that's encoded across multiple transactions.

***Overlay Currencies.*** On the positive side, since we *can* write whatever data we want into Bitcoin, we can also build an entirely new currency system *on top of Bitcoin* without needing to develop a new consensus mechanism. We can simply use Bitcoin as it exists today as an append-only log, and write all of the data that we need for our new currency system directly into the Bitcoin block chain. We call this approach an "overlay currency". Bitcoin serves as the underlying substrate, and the data of the overlay currency is written into the Bitcoin block chain using unspendable transaction outputs.

Of course, Bitcoin miners will not actually *validate* what you're writing into the block chain, since they don't know (and don't care!) whether the data you write is valid under the rules of your new currency. Anyone can write anything in there who's willing to pay the Bitcoin transaction fees. Instead, you must develop more complicated logic for validating transactions in the new currency, and this logic must reside in each end-user client that participates in sending or receiving this currency.

For example, in an overlay currency miners are no longer able to reject double spends. Instead, every user of the overlay currency has to look at the history of what's been written in the block chain. If an overlay transaction attempts to spend an overlay coin that has already been spent, then that second transaction should simply be ignored. For this reason, there's no such thing as a lightweight SPV client for overlay currencies.

Counterparty is a prominent overlay currency. All Counterparty transactions are written into the Bitcoin block chain. During 2014, between 0.5% and 1% of all Bitcoin transactions carried Counterparty data. It also supports a much larger and richer feature set than Bitcoin. The idea is that since Counterparty doesn't have to develop a new consensus algorithm, and since Bitcoin miners don't need to know about the Counterparty rules, they can instead focus on developing interesting features such as smart contracts, user defined currencies, and more. The Counterparty API can be much larger than the Bitcoin API since Bitcoin miners don't need to understand it or approve of it.

The potential to develop a new currency without having to create a new consensus system is very appealing. You don't even need to encourage new miners to join your system, and you can add new features without needing to change Bitcoin. However, such systems are still reliant on Bitcoin — for example, they are subject to the same fee requirements as other Bitcoin transactions. This approach can also be inefficient, since nodes on the overlay currency may need to process a lot of data, since Bitcoin nodes don't filter these transactions for you.

## 9.2 Bitcoins as "Smart Property"

Now we'll talk about using bitcoins to represent something other than a unit of currency in the Bitcoin system.

Recall from Chapter 6 that you can trace ownership of value in the Bitcoin system over time, simply by following the transaction graph. Keep in mind the caveat: there's no such thing as a "bitcoin" per se — just unspent transaction outputs, which we refer to as coins. Every bitcoin has a history that anybody can view in the block chain. A coin's history traces all the way back to one or more coinbase transactions in which coins were originally minted. As we said discussed earlier, this is bad for anonymity, since you can often track ownership of coins this way.

***Fungibility*.** This also leads to an interesting observation: bitcoins aren't *fungible*. In economics, a fungible good is one where all individual units are equivalent and can be substituted for one another. For example, gold is fungible since one ounce of (pure) gold can be substituted for any other ounce of gold. But this isn't always true of Bitcoin because every bitcoin is unique and has a different history.

In many contexts this history may not matter, but if the history is meaningful to someone you want to trade with, it may mean be that your 1.0 bitcoin is not the same as their 1.0 bitcoin. Maybe they wouldn't be willing to exchange theirs with yours because they prefer the history of their coin to that of your coin. For example, just as coin collectors value old coins, some day bitcoin collectors might place special value on coins originating in the genesis block or some other early block in Bitcoin's history.

***Smart Property.*** Could this non-fungibility property be *useful*? We've already seen why it can be bad for privacy because of the potential for deanonymizing users. In this section we'll look at why it can also be useful to give *meaning* to the history of a bitcoin.

Let's think about what it would mean to give meaning to the history of ordinary offline physical currency. Suppose we wanted to add metadata to offline currency. In fact, some people already do this. For example, they like to write various messages on banknotes, often as a joke or a political protest. This generally doesn't affect the value of the banknote, and is just a novelty.

But what if we could have *authenticated* metadata attached to our currency — metadata that cannot easily be duplicated? One way to achieve this is to include a cryptographic signature in the metadata we write, and tie this metadata to the *serial number* of the banknote.


**Figure 9.4:** An example of adding useful metadata to ordinary bank notes

What could this be used for? Say a baseball team wants to use dollar bills as tickets. This way they no longer have to go through the hassle of printing their own tickets and making sure that no one can print counterfeit tickets. The New York Yankees could simply assert that the dollar bill with a specific serial number now represents a ticket to a specific game, and in a specific seat. These dollar bills would be distributed in the same ways that paper tickets are normally distributed, such as by being mailed to fans when they buy tickets online. Whoever is holding that note has the right to enter the stadium, sit in the assigned seat, and watch the game, with no other questions asked. The banknote itself is the ticket!

To add authenticity, the Yankees could use digital signatures. They’d sign a message that includes the specific game date, the seat number, and the serial number of the bill — and stamp the message and the signature right on the bill. A 2D barcode would be a convenient form for that data (See Figure 9.4). Alternatively, the stadium could maintain a database that lists the serial numbers and corresponding seat numbers for each game. They could check the database for this information when you tried to enter the gate. This avoids the need to stamp the banknotes.

What does this buy us? Now currency can represent many things. Besides the example of a sports ticket, there are many other applications. We inherit the anti-counterfeiting property that banknotes already have. Governments work very hard to make sure it's difficult to duplicate a banknote! Also, the underlying currency value of the banknote is maintained. After the fan redeems their ticket, the banknote is perfectly usable as regular currency. It may be a problem if everybody wants to physically stamp metadata on currency, but this problem goes away if we use the database approach.

Of course, all of the useful meaning of this new metadata is only as good as our trust in the *issuer* who signed it. Someone must know that there's a specific key used to sign valid Yankees tickets — or download the Yankees’ database — in order to recognize its value as a ticket. To anyone else, it would just look like a dollar bill. But that's okay. It's actually a desirable property, since once the ticket has fulfilled its purpose,  it can go back into circulation as an ordinary dollar bill.

***Colored coins***. Can we do this digitally on top of Bitcoin? We'd like to keep Bitcoin's nice features such as the ability to transact online, fast transaction settlement, and non-reliance on a bank.

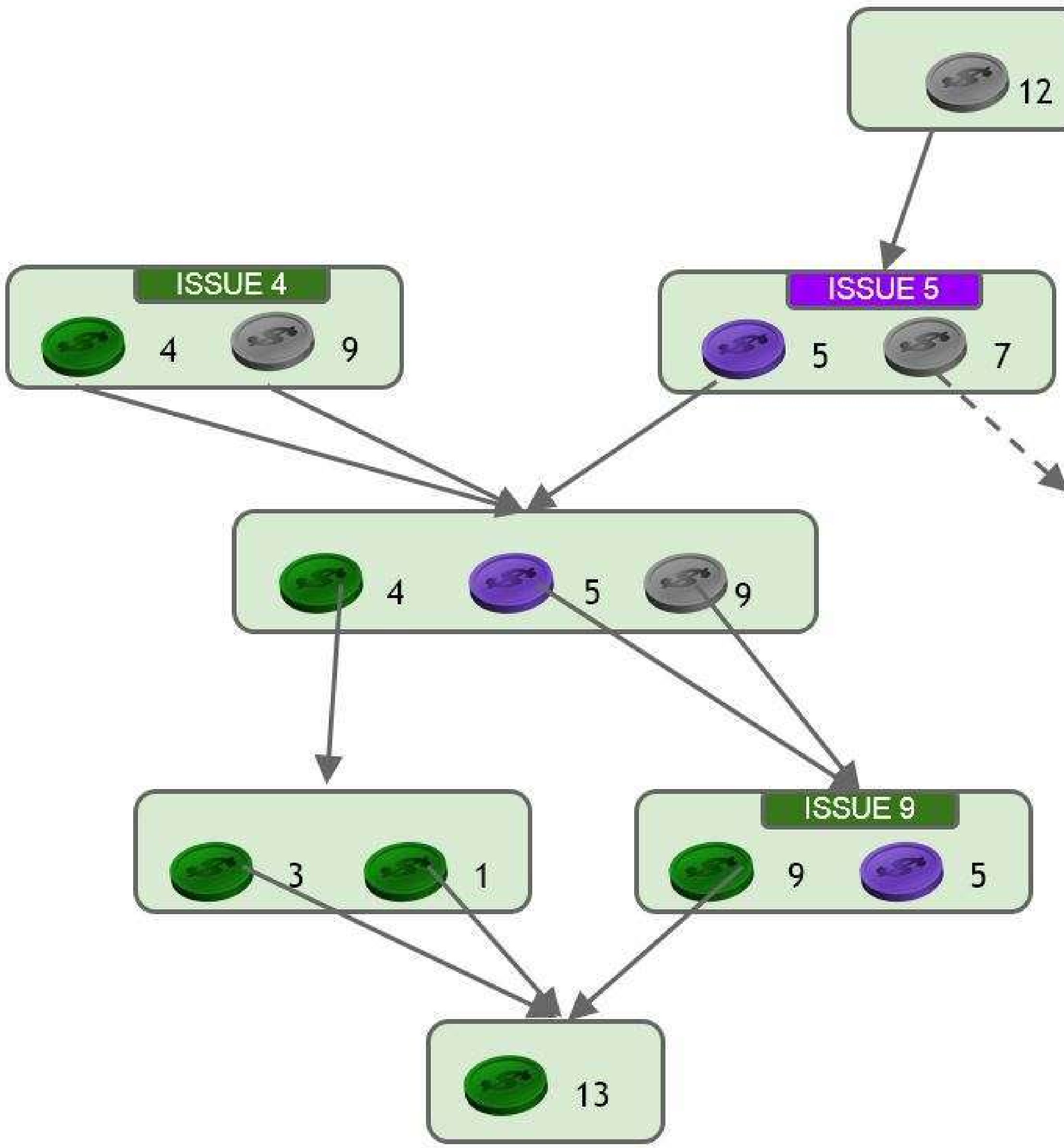



**Figure 9.5: Colored coins.** The transaction graph shown illustrates issuance and propagation of color

The main idea is to stamp some Bitcoins with a "color", and track that color stamp even as the coin changes hands, just like we are able to stamp metadata onto a physical currency.  A bitcoin stamped with a color still functions as a valid bitcoin, but additionally carries this metadata.

To achieve this, in one transaction, called the “issuing” transaction, we’ll insert some extra metadata that declares some of the outputs to have a specific color. An example is illustrated in Figure 9.5. In one transaction, we issue five “purple” bitcoins in one transaction output, while the other output continues to be normal uncolored bitcoins. Someone else, perhaps with a different signing key, issues “green” bitcoins in a different transaction. We call these colors for intuitiveness, but in practice colors are just bit strings. The only property that matters is that coins of the same color and same value are equivalent.

Now we have bitcoins with different colors associated with them. We can still do all the normal things we do with bitcoin transactions. We could have another bitcoin transaction that takes several inputs: some green coins, some purple coins, some uncolored coins, and shuffles them around. It can have some outputs that maintain the color. There may need to be some metadata included in the transaction to determine which color goes to which transaction output. We can split a transaction output of four green coins into two smaller green coins. Later on we could combine multiple green coins into one big green coin.

***OpenAssets*.** As of 2015, the most popular proposal for implementing this in Bitcoin is called OpenAssets. Assets are issued using a special Pay-to-Script-Hash address. If you want to issue colored coins, you first choose a P2SH address to use. Any coin that transfers through that address and comes in without a color will leave with the color designated by that address. For this to be meaningful, you’d have to publicize that address somewhere. There are various exchanges that track which addresses confer which colors onto coins. Since coins can sequentially pass through more than one color-issuing address, they can have more than one color, and that’s fine.

Every time you have a transaction that involves colored coins, you have to insert a special marker output. This is a provably unspendable output, similar to what we used for timestamping data commitments. The metadata embedded in the marker output encodes details about how the incoming color value should be divided among the different outputs.

As we noted earlier, this is compatible with Bitcoin. Since it doesn’t require changing Bitcoin, the community of miners tends not to discourage or interfere with these schemes. It allows anybody to declare any color they want without having to ask a central authority for the right to issue colored coins. If there are others who understand and abide by the meaning you ascribe to the color you issue, your colored coins may attain additional value beyond their nominal bitcoin value. For example, if the Yankees issue colored coins, these coins will be able to function as tickets to a game provided the stadium operators understand their meaning and let you in based on colored-coin tickets.

One disadvantage of this scheme is that we have to put in the unspendable marker output into every transaction. This adds a bit of overhead, since we must forfeit some money every time we want to trade a colored coin. A second disadvantage is that miners don’t check the validity of colored coins, only the underlying bitcoins. To verify that a colored coin you receive is valid, you have to check the *entire transaction history* that the coin was involved in, or trust a third party to do the checking for you. In particular, you can't use a thin SPV client like you can for regular Bitcoin. That makes it harder to use colored coins on computationally limited devices like mobile phones.

***Uses of colored coins and smart property.*** *Stock in a Company.* A frequently cited motivation for smart property is stock in a company. A company wishing to issue colored coins as stock would publicize its issuing address, and bitcoins that are colored with this address function as shares. One satoshi might represent one share in the company. Shareholders can then trade the stock on the block chain without needing a centralized intermediary like a stock exchange. Of course, shareholders will have to trust that the company will honor the shares. For example, the company may promise to disburse dividends proportionally to each stock or to give shareholders voting power in the company's decisions. With traditional shares these promises are enforced legally. As of 2015, colored coins or other block chain-based assets don't have legal recognition in any jurisdiction.

*Physical property.* Another potential use is that colored coins might represent a claim to some real-world property. For example, a colored coin could be associated with a house or a car. Maybe you have a sophisticated car that actually tracks a specific colored coin on the block chain, and automatically starts and drives for anybody who owns that colored coin. Then you could sell your car, or at least transfer control of it, simply by making a single transaction in the block chain. We'll see in Chapter 11 how this can potentially be implemented technologically as well as the social and legal obstacles to making it happen. But the dream of colored coins and smart property is that any real-world property could be represented in the world of Bitcoin and transferred or traded as easily as bitcoins themselves.

*Domain Names*. As a final example, consider using colored coins to perform some of the functions of the existing Domain Name System: tracking the ownership and transfer of internet domain names as well as the mapping of domain names to IP addresses. The domain name market has a variety of interesting properties: there are a potentially infinite number of names, these names have widely different values based on their memorability and other factors, and the same name might have very different utility to different people. It is possible to use colored coins to handle domain name registration and the functions we listed. However, supporting this application has also been the focus of a prominent altcoin called Namecoin, which we'll look at in detail in the next chapter. Each approach has benefits: with colored coins you get the security of Bitcoin's block chain whereas with an altcoin it's easier to implement the complex logic needed for domain name ownership, transfer, and IP address mapping.

## 9.3: Secure Multi-Party Lotteries in Bitcoin

Now we're going to talk about hosting a "coin flip" game in Bitcoin. Again, we'll start off by describing the offline version of what we're trying to build.

Alice and Bob want to bet five dollars. They both agree to the bet ahead of time and the method for determining the winner. Bob will flip a coin in the air, and while it's rotating Alice calls out "Heads" or

“Tails”. When the coin lands, they both immediately have a clear understanding of who won the bet, and they both have assurance that the outcome was random and that neither of them was able to influence the outcome.

The sequence of steps in this ceremony as well as the physics of coin flipping play a crucial role in convincing both parties that the game is fair. One shortcoming of this scheme is that both parties have to be present at the same place at the same time. Also, both parties still have to trust that whoever loses will pay up. In the online world, we’d like to be able to have a lottery that is just as “fair”, but also solves the problem of making sure the loser pays.

At first this might seem like a rather peculiar and limited application to be studying in detail. Amusingly, Bitcoin-based betting services such as Satoshi Dice — which rely on a trusted party, unlike the system we’d like to design — have proven very popular, at times representing a large fraction of all Bitcoin transactions on the network.

The real reason we want to study cryptographic coin flipping, however, is that it turns out that if we can design a secure protocol for it, we can use those techniques to build many other interesting and useful protocols. Cryptographers study “secure multiparty computation” where two or more mutually untrusting parties each have some data and want to compute a result that depends on all of their data, but without revealing the data to each other. Think of a sealed-bid auction, but without a trusted auctioneer. Often, these computations need to be randomized, say, to break ties. Finally, we might want the result of the *computation* to determine a *monetary* outcome in an irrevocable way. Maybe we want to ensure that the winning bidder in the auction pays the seller; perhaps we even want to ensure that the seller’s (smart) property being auctioned is automatically transferred to the winning bidder. Alternatively, maybe we want to penalize parties if they deviate from the protocol.

In other words, a secure multi-party lottery is a simple setting in which to study an extraordinarily powerful paradigm: mutually untrusting participants with sensitive inputs jointly executing a program that has the power to manipulate not only bits, but also money.

***Coin Flipping Online.*** The first challenge is replacing the “coin flip” mechanism with some online equivalent. Let’s say we now have three parties, Alice, Bob, and Carol, who all want to select a number 1, 2, or 3 with equal probability. Here’s one attempt at such a protocol. Each of them picks a large random number — Alice chooses x, Bob y, and Carol Z. They tell each other their numbers, and they compute the output as (x + y + z) % 3.

If all of them chose their random numbers independently, this would indeed work. But remember that we’re doing this over the internet, and there’s no way to insist that they all send their numbers “simultaneously”. Alice might wait until she hears Bob’s and Carol’s numbers before broadcasting hers. If she does this, you can see how it’s trivial for her to make the final output whatever she wants. We can’t design the protocol to convince every party that none of the other parties cheated.

To solve this problem we can once again use hash commitments. First, each of them picks a large random number and publishes a hash of this number. Once this is done, each of them reveals the number they picked. The others then check that the revealed numbers hash to the values published in the first step, and compute the final outcome from the three random numbers as shown in Figure 9.6.

**Round 1:**

Each party picks a large random string — Alice picks x, Bob picks y, and Carol picks z.
The parties publish H(x), H(y), H(z) respectively.
Each party checks that H(x), H(y), H(z) are all distinct values (otherwise aborts the protocol).

**Round 2:**

The three parties reveal their values, x, y, and z.
Each party checks that the revealed values agree with the hashes published in Round 1.
The outcome is (x + y + z) % 3.

**Figure 9.6:** Using hash commitments to implement a fair random number generator. This protocol can be easily extended to support any number of parties.

The reason this protocol works is twofold. First, since the hash inputs x, y, and z are large random numbers, no party can predict the others' inputs after the first round. Second, if (say) Alice chooses her input randomly as specified by the protocol, she can be sure that the final output will be random *regardless* of whether or not Bob and Carol choose their inputs randomly.

***Fairness*.** What happens if somebody fails to reveal their commitment? In round 2 of the protocol, suppose Carol waits until Alice and Bob have revealed their secrets. Carol, before revealing hers, realizes that she's going to lose if she does. So she might refuse to publish her random number — she can claim to have forgotten it or pretend to go offline. Alice and Bob would likely be suspicious, but they would have no good recourse.

What we'd like is a scheme where whoever makes a commitment is forced to reveal it within some time limit. In cryptography, this property is called fairness. Bitcoin provides us with an excellent mechanism for this.

Let's say that Alice wants to make a timed commitment, and Bob is the only other person who is concerned with it. First, Alice puts up a bond, in the form of a Bitcoin transaction output script that specifies that it can be spent in one of two ways. One way is with a signed transaction from both Alice and Bob. The other way to spend it is with a signature from just Alice, but only if she also reveals her random number. If Alice's random string is **x**, then the scriptPubkey actually contains the value **`H(x)`**.

Next, Alice and Bob both sign a transaction that pays the bond to Bob (which is one of the two ways it can be spent). Why would Alice agree to this? The transaction carries an ***nLockTime*** value that guarantees Bob can't claim the bond before some time **t**. Since Alice plans to reveal her committed value before then and recover the bond, it is safe for her sign this transaction.

Now if Alice leaves without revealing her value, Bob can claim the bond at time **t**. This doesn't *force* Alice to reveal her commitment but she *will* lose the entire bond that she put up. So the guarantee that she'll reveal her secret value depends on the amount of money she's willing to put in the bond.

scriptPubKey:

```
OP_IF
    <AlicePubKey> OP_CHECKSIGVERIFY <BobPubKey> OP_CHECKSIG
OP_ELSE
    <AlicePubKey> OP_CHECKSIGVERIFY OP_HASH <H(x)> OP_EQUAL
OP_ENDIF
```

scriptSig for Case 1:

```
<BobSignature> <AliceSignature> 0
```

scriptSig for Case 2:

```
x <AliceSignature> 1
```

**Figure 9.7:** The transaction output scriptPubkey and scriptSigs used in a timed hash commitment.

How can we use this timed hash commitment to implement our secure lottery? We'll have almost the exact same structure as before, except instead of using the simple hash commitments, we'll use these timed commitments. Whoever does not reveal their random value before the deadline will forfeit a security deposit that's used to compensate the other two players. Revealing the random value is now simply a matter of recovering the bond by providing the correct secret input **x**.

This lottery scheme can be implemented on top of Bitcoin. But it's a bit complicated and the timed hash commitments require multiple non-standard transactions. When there are **n** parties in the lottery, $\mathbf{n^2}$ commitments are needed since each party needs to put up a bond for each other party. The players have to escrow more money in total than they are even betting. But it is reasonable for a small number of participants, and there are variants with better efficiency. Most importantly, it serves as an existence proof that seemingly impossible protocols such as flipping a virtual coin over the internet and penalizing a party for aborting the protocol are possible in the Bitcoin world.

## 9.4: Bitcoin as Public Randomness Source

In the last section, we showed how a group of people can jointly choose a fair random value. In this section we'll talk about using Bitcoin to generate random values that are fair to *anyone* in the public.

Why would we want this? Let's discuss a few examples of applications that already rely on public sources of random values.

***NBA draft lottery.*** One example that occurs every spring in the U.S. is the NBA draft lottery. All 30 teams in the NBA get together and randomly choose — with some weighting based on how each team performed in the previous season — the order in which teams get to select the top amateur players in the country who are ready to turn professional. This was first done in 1985. The lottery was conducted over live television, and involved picking envelopes after they're shuffled in a transparent spinning drum. This lottery generated a bit of controversy then, because the New York Knicks won in the first year and were able to draft the highly sought-after center Patrick Ewing (an eventual member of the Basketball Hall of Fame). Since the lottery was filmed in New York City, some fans of other teams alleged that the process was rigged in favor of the Knicks.

There are numerous conspiracy theories for how the NBA might have rigged this process, such as the famous "bent corner" theory suggesting that the Knicks' envelope had its corner bent so the commissioner could distinguish it from the others by touch. Another theory suggests the Knicks' envelope was kept in a freezer and the commissioner simply grabbed the one cold envelope. These theories show why it is very hard to hold a drawing like this and prove that it was fair — there are many plausible avenues to cheat. Just think of what professional sleight-of-hand magicians can appear to do! Even today, this lottery occurs every year and each time it leads to a variety of conspiracy theories and rumors that the lottery isn't a fair random drawing.

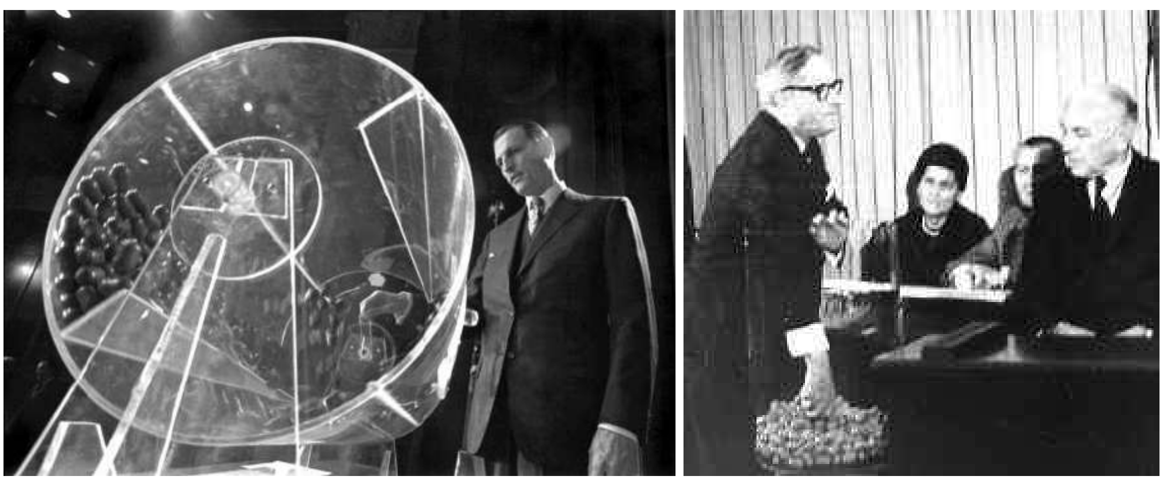


**Figure 9.8:** Images from the 1969 (Vietnam war) military draft lottery.

***U.S. military draft lottery.*** A more serious example comes from 1969, when there was a conscription lottery in the United States to determine which young men would be required to join the armed services. Most of them were sent to fight in the Vietnam War. A procedure similar to the NBA lottery was used, carried out by several representatives from the US Congress and broadcast on live television (Figure 9.8). They dumped small capsules labeled with each day of the year into a large plastic drum, and then took turns reaching in with their hands to pull the numbers out. Men eligible to be drafted were given a priority number based on the day of the year their birthday fell on. The priority number determined the order in which they would be drafted.

This 1969 draft was the first time this lottery procedure was used on a national scale. The goal was to make the process more fair (by taking it out of the hands of thousands of local draft boards) and to demonstrate to the public that it was a random process. Unfortunately, the lottery was botched. Within a week, statisticians looking at the data noticed an anomalous pattern (illustrated in Figure 9.9). Days late in the year received low draft numbers. Though the deviation is very subtle, it is statistically significant and very unlikely to have happened due to chance. When they went back to review the tapes, it turned out that they rotated the drum exactly an even number of times, such that the capsules that started out on top tended to still be on the top. There wasn't sufficient mixing to make it a statistically random draw.

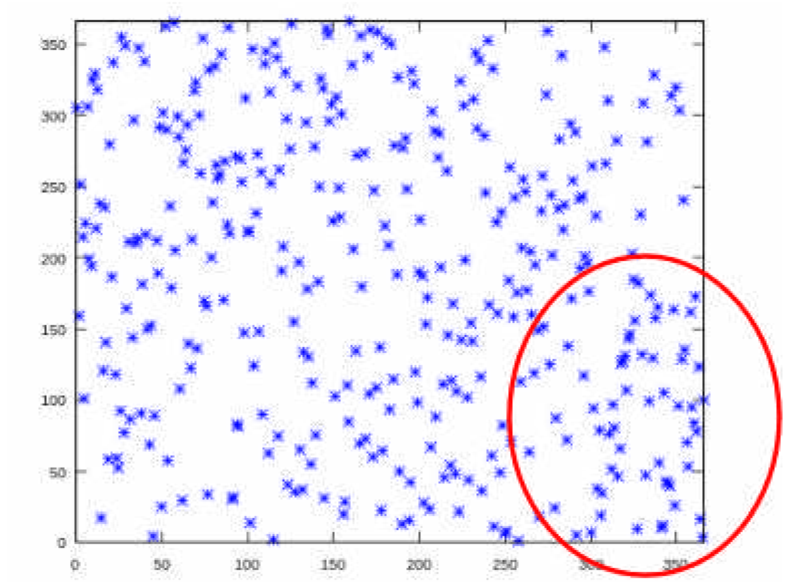



**Figure 9.9:** Statistical bias of the 1969 draft lottery. Day of the year (x-axis) versus lottery number (y-axis).

What both of those examples show is that it's very hard to generate public randomness and convince the public that you've actually done a good job. There's a risk that the process might not be truly random and free of influence. There's also a risk that even if the process *is* random, the public won't believe you.

***Cryptographic "Beacons".*** Public displays of randomness using a wheel, flipping coins, rolling a dice, and so on have been so popular throughout history because they're cheap and easy to understand. But they don't cope so well with large-scale scenarios because they're very hard for people to audit. Even if the video of the procedure appears legitimate, people may reasonably be suspicious that the lottery conductor has performed some sleight of hand to rig the process.

Could we do better cryptographically? Let's use the term "cryptographic beacon" to refer to a service that provides a public source of randomness. The idea is that the beacon will continuously publish new random data at a regular rate that nobody can predict in advance. Hopefully everybody agrees that there’s no way for anyone to predict what the beacon will output next, so everybody can rely on it as a fair random value.

If a perfect cryptographic beacon existed, then it could be used for any of the public lotteries we looked at. Even if you just wanted to play bingo at your local social club, you wouldn’t need to use a large drum of numbers. If everybody trusted the beacon, you would save a lot of effort compared to using physical displays of randomness.

Cryptographers have proposed many other applications of public randomness, including voting systems, zero-knowledge proofs, and cut-and-choose protocols. Many of these can be done much more simply and efficiently if you have a perfect cryptographic beacon. Unfortunately, we haven't found a perfect way to implement such a beacon yet.

***The NIST beacon*.** The National Institute of Standards and Technology (NIST) has, since 2011, run its own beacon service. They claim to generate their random numbers through a complicated laboratory setup involving two entangled photons. The idea is to provide strong guarantees that the numbers are random because they are generated from a quantum mechanical phenomenon. If you accept the Heisenberg Uncertainty Principle and other widely-believed laws of physics, then this should be truly random and unpredictable. The service is set up so that it produces new random data every sixty seconds along with a digital signature over the data. The NIST beacon provides a convenient interface for programmatic applications: the numbers can simply be read out from a web feed.

This quantum mechanical procedure is in some sense the “limit” for physical displays of randomness. But it does nothing to alleviate the essential problem of trust — you have to trust that NIST is in fact carrying out the procedure as they claim. You have to trust that somewhere in a building in Maryland NIST has their actual laboratory that produces these numbers and that they aren’t simply staging the procedure. You also have to believe that they aren’t reserving the ability to deliberately overwrite some of the random values before they publish them.

***Other potential ways to build a beacon: natural phenomena.*** What about an alternate approach where we use some natural phenomenon that everybody can observe? Perhaps we could use details about the weather, such as what temperature it's going to be tomorrow at a specific place, or how strong the wind will be, or whether or not it will rain. Of course, we have some ability to predict the weather ahead of time, but not precisely, so perhaps we can use the “least significant bits” of the measured values. The limitation here is that all participants need to be at the same place to get the same measurements.

To avoid this we could turn to sunspots, which are bursts of activity on the surface of the sun. Another example is cosmic background radiation, which is noise that you can listen to with a radio antenna from any point on the planet; everybody should be able to read the same value. These are phenomena that happen at such a large scale that it's easy to convince yourself that nobody will succeed in rigging the process. It's far fetched to imagine that somebody would fly a spacecraft towards the surface of the Sun in order to somehow tamper with it just to rig some lottery back on

Earth. So these approaches have several good properties: public observability, security against manipulation, and, in most cases, an acceptable level of unpredictability.

One problem with these approaches is that they're fairly slow. For example, if your random signal is the daily high temperature, then you only get one reading per day. The surface of the sun doesn't change too often. In many cryptographic applications, random bits are used as input to a *pseudorandom generator* (PRG). For the PRG to be secure, the input needs to be 80 bits (or more) in length. It might take a while for 80 bits of randomness to accumulate with sources based on weather and astronomy.

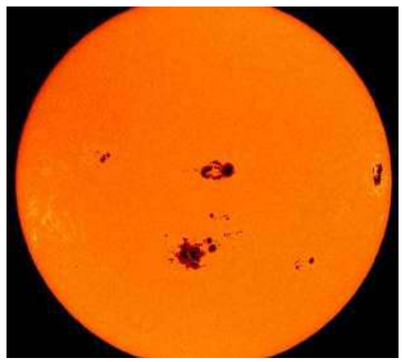


**Figure 9.10: NASA image of sunspots.**

Besides, it requires expertise to measure sunspots, so you'd effectively need to rely on some trusted observer to publish the measurements. However, there could be many trusted observers, and we can hope that they'd "keep each other honest". Applications that consume beacons, or users of such applications, could choose which of the observers they'd like to rely on. They can also easily switch observers at any time. This property is called "trust agility" and is arguably superior to having a single entity such as NIST that produces the beacon.

There's a deeper problem, one that at first sight might seem trivial. How do we turn a real-world observation — a temperature, a photograph of sunspots — into a string of bits in such a way that every observer will end up with the same bit string? We could try quantizing the measurement: for example, we could express the temperature in Fahrenheit and use the first decimal digit as the beacon output. But unless every observer's thermometer is unrealistically precise, there will be times when some observers will read the temperature as (say) 62.7 and others will read it as 62.8. It seems that no matter which natural phenomenon we pick and what protocol we use, there will always be "corner cases". For a cryptographic beacon, even a small probability of inconsistent measurements may be unacceptable because it will cause the random bits output by a PRG to be completely different.

***Financial data.*** A similar idea is to use feeds of financial data such as stock market prices. Again, these are publicly observable values. Unlike natural phenomena, they are reported as digital values, so the problem of inconsistent observations goes away. There's a strong reason to believe that it's very hard to predict the low-level fluctuation of stock prices: if you could predict within a penny what the final price of a specific stock will be on the New York stock exchange tomorrow, you could make a lot of profit as a day trader. Someone could try to influence the price by buying or selling the stock to drive it to a specific value, but that has a real cost that you can't avoid.

However, this approach also has the problem of relying on a trusted party, namely the stock exchange. Even though the stock exchange has a strong incentive to establish that it's honest and acting in good faith, there could still be the suspicion that they might try to change the price of a stock by a penny (for example, by inserting their own order into the order book) if it would let them rig a valuable lottery.

With all the approaches we've looked at, it seems hard to avoid having some trusted party who has influence over some crucial part of the process.

***Using Bitcoin as a Beacon*.** Fortunately, a theme so far of this entire book has been that Bitcoin is a promising technology for removing centralized trust from protocols in ways we didn't previously think were possible. Can we use Bitcoin as a random beacon? We'd like to extract random data from the Bitcoin block chain while keeping all of the decentralized properties that make Bitcoin itself so attractive.

Recall that miners must compute lots of random hash values while they're attempting to find a winning block. Perhaps this means that no one can predict or influence what the next block hash will be without actually doing the work of mining. Of course the first several bits of any block hash will be zero, but it turns out that under suitable assumptions, the only way to predict the remaining bits would be to influence them by finding a winning block and selectively discarding it.

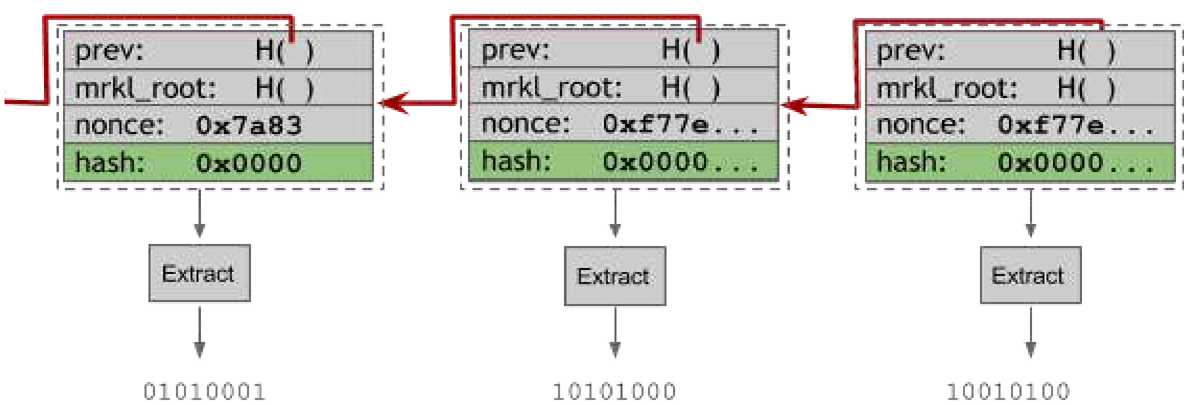



**Figure 9.11:** Extracting public randomness from the hashes of blocks in the block chain.

That makes it simple to turn the block chain into a randomness beacon. For every block in the chain, we apply a "randomness extractor" to the value of the block header. A randomness extractor, roughly speaking, is like a hash function that is designed to squeeze all of the random entropy of the input into the one uniformly random string. Every time a block is published, we have new beacon output.

***Evaluating the security of a Bitcoin beacon.*** Let's say you're participating in a lottery whose outcome is determined by the output of the Bitcoin beacon for some pre-specified future block at height H in the block chain. There are N players in this lottery, and each of them is betting B bitcoins. If you're also a miner, you might get lucky and find a hash puzzle solution for block H. Then you have the choice of whether or not to publish the block. If you don't like the lottery outcome that would result from your publishing the block you found, you can simply discard it and let the lottery be determined by whoever else publishes block B. However, you'd forfeit the revenue that you could earn from that block.

Let's calculate how big the bet B needs to be for you to find the selective discarding strategy worthwhile. You successfully find a block at block height H and realize that if you publish it, you will definitely lose the lottery, whereas if you discard the block you'll still have a 1/N chance of winning B * N bitcoins. That means it will be rational to discard the block if your expected payout of 1/N * B * N bitcoins (i.e., B bitcoins) is greater than the reward for mining a block (roughly 25 bitcoins in 2015, ignoring transaction fees). So the attack is profitable if B > 25. In mid 2015, 25 bitcoins is worth over 5,000 U.S. dollars. So if the bet per player is under $5,000, the lottery will be secure against this attack if the players are rational.

One of the advantages of this scheme is that it's a fully decentralized beacon, with no central point of trust. Compared to some other beacon proposals, it is fairly fast. It can create an output roughly every ten minutes. It's also useful to be able to estimate the cost to an attacker to manipulate the beacon outputs using our simple model above.

A downside of using Bitcoin as a beacon is that its timing is somewhat imprecise. Say we want to read the value of the beacon tomorrow at noon. We don't know exactly which block will be the latest block at that time. Although on average a block will be published within 10 minutes before or after noon, there is some variance. We also have to plan to tolerate a bit more delay if we want to reduce the likelihood of the block we look at being lost in a short fork. As is usual in Bitcoin, we'd want to wait for roughly six blocks to arrive before we believe that the beacon value has truly settled.

Another downside is that the cost of manipulating the beacon value may be too low for some applications we care about. If we were actually running the NBA draft, where there are tens of millions of dollars at stake, it may suddenly look worthwhile for one of the teams to start bribing Bitcoin miners to manipulate this process. It remains an open question if we can extend this construction to make it secure when millions of dollars are on the line.

Finally, our security evaluation ignores some real-life factors. For example, a miner who is part of a mining pool doesn't lose much by discarding a block, since they're rewarded on the basis of shares rather than blocks. For now, Bitcoin beacons are an interesting but unproven idea.

***Scripting support for beacons.*** What if we extended Bitcoin's scripting language with a special opcode to read beacon values? Currently there's no way to have any randomness in Bitcoin scripts. That's by design, because miners have to verify scripts and they all want to agree on whether a script is valid or not. But if we use the beacon value, it's a public source of verifiable randomness. We could use the beacon to add randomness into transaction scripts that every miner could agree on.

Suppose we had one opcode that would make a random decision based on the beacon output of the previous block. We could replace the entire complicated lottery protocol with just one script that reads the beacon value and assigns the output to one of **n** keys. It wouldn't require a multi-round protocol, security deposits, or timed hash commitments.

One drawback of this idea is that it would now be possible for miners to manipulate the lottery simply by delaying the lottery transaction until a later block if they find that including the transaction in the block they're mining would cause them to lose the lottery. It no longer requires forfeiting block rewards. It's possible to make a variation of the beacon opcode that avoids this attack. Instead of referring to the previous block, you specify to use the beacon value at a particular block height.

## 9.5: Prediction Markets and Real World Data Feeds

For the final topic of this chapter, we'll look at how to implement a prediction market in a decentralized way using cryptocurrencies and the related topic bringing real-world data into Bitcoin.

A prediction market allows people to come together and make bets on future events such as a sports game or an election. Participants in a prediction market buy, sell, and trade "shares" in specific outcomes of such events.

| Team | Germany | Argentina | Brazil | United States | England | Netherlands |
|---:|---|---|---|---|---|---|
| Pre-tournament | 0.12 | 0.09 | 0.22 | 0.01 | 0.05 | 0.03 |
| After group stage | 0.18 | 0.15 | 0.31 | 0.06 | 0.00 | 0.05 |
| Before semifinals | 0.26 | 0.21 | 0.45 | 0.00 | 0.00 | 0.08 |
| Before finals | 0.64 | 0.36 | 0.00 | 0.00 | 0.00 | 0.00 |
| Final | 1 | 0 | 0 | 0 | 0 | 0 |

**Table 9.12:** Prices in dollars in a hypothetical prediction market for a selection of teams during the 2014 World Cup. The price of a share betting on the U.S. team to win the cup rose from 1 cent to 6 cents after U.S. performed well in the group stage. A share in Brazil rose progressively to 45 cents as Brazil advanced into the semifinals and then lost its entire value after Brazil lost its semifinal match. After the tournament only shares in Germany (who won the tournament) had any value.

Let's walk through an example that should make the concepts behind prediction markets more clear. The 2014 World Cup was held in Brazil. Suppose there was a market where you could buy and sell shares associated with each team, and the shares for the team that wins will ultimately be worth 1 dollar and all the other shares are worth 0. Going into the tournament, every team would start out with some nonzero price, based on what the market believes their chances of winning are. Examples are shown in Table 9.12 for five different teams.

In the pre-tournament phase, Germany shares are trading for about 12 cents, which means that the market roughly believes Germany has a 12% chance of winning. As the tournament progresses, these prices will fluctuate, reflecting how the market participants adjust their beliefs of how likely each team is to win.

In our example, England was initially trading at five cents but went to zero after the group stage. That's because England was knocked out in the group stage. There's no longer any way for them to win, and the price reflects that; their shares are now worthless. On the other hand, the U.S. team that was initially thought to have a very poor chance of surviving the group stage turned out to do very well. If you had thought to buy U.S. shares in the beginning when they were very cheap (one cent), you could sell them immediately after the group stage for six cents. You'd get back six times the money you bet. You wouldn't have to wait until after the end of the tournament to make a profit. Even though the U.S. team didn't end up winning the tournament, you'd be able to profit from the fact that you anticipated a change in beliefs about their chances of winning after their strong performance in the group stage.

When we get to the semifinals, there are only four teams left. U.S. and England were knocked out so their share prices have already gone to zero. Now every remaining team has a relatively high price, and their share prices should add up to 1.0. Brazil in particular was favored to win, and thus had the highest price. In fact, Brazil lost in the semifinals and their share price went to zero. Within the span of a couple of hours, the market's beliefs changed dramatically. You would have been able to profit in a very short time frame if you were confident going in to the match that Brazil was overrated; you could take a "short position" on Brazil and/or bet on the other teams.

Going into the finals there are only two teams left and their shares again add up to 1.0. At the very end of the tournament, of course, the only shares that finally have any value are those of the German team since they ended up winning.

Obviously, one way you could have made a profit would have been to buy shares in Germany at the beginning for 12 cents and hold them all the way to to the end. This is basically how traditional sports betting works — you place a bet before the tournament starts and collect the payout after the end of the tournament. However, in a prediction market, there are many other ways to play and to profit. You can invest in any team at any time, and you can profit solely on the ability to predict that people's beliefs will change, regardless of the final outcome.

Here's another example, this time from a real prediction market. Before the 2008 US Presidential election, the Iowa Electronic Markets allowed people to buy shares for whether Barack Obama or or John McCain would win. In Figure 9.13, the price of Barack Obama shares is shown in blue and McCain shown in red. You can see that as the months of the campaigning unfolded, people's beliefs about who would win fluctuated. But by the day before the election, Obama was given a 90% chance to win. The market was well aware that the outcome was basically settled before votes were cast.

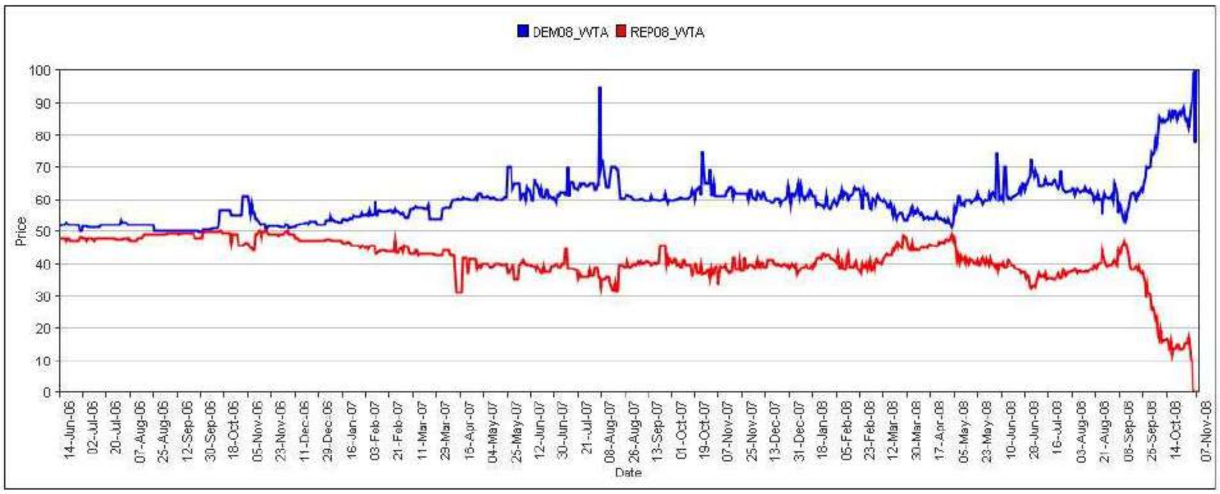



**Figure 9.13**: The price of prediction market shares about the 2008 US Presidential election, from Iowa Electronic Markets.

**Sidebar: The Power of Prediction Markets.** Economists tend to be enthusiastic about prediction markets. Information that's relevant to forecasting future events is often widely dispersed, and prediction markets are an excellent mechanism to aggregate that information by giving participants a way to profit from their knowledge. Under suitable economics models, the market price of shares can be interpreted as the probability of the outcome, although there are concerns that real prediction markets suffer from biases. Empirically, prediction markets have held up very well against other forecasting methods such as polling and expert panels.

However, prediction markets face many regulatory uncertainties and hurdles. Intrade was the most popular prediction market on the internet before it ran into regulatory compliance issues in the U.S. and shut down in 2013. Many economists were disappointed by this because they felt we lost a valuable social tool that revealed useful information about the future.

***Decentralized prediction markets*.** What would it take to build a *decentralized* prediction market? There are a few tasks that we'll have to decentralize. We need a way of accepting money and disbursing payouts, and we need a way of enforcing that the correct amounts are paid out according to the outcome. We'll especially need decentralized arbitration. Arbitration is the process of asserting which outcomes actually happened. Most of the time, in the case of a national election or a sports match, it’s pretty obvious who won and who lost. But there are also many gray areas. We’ll also need to decentralize the order book, which is a way for people to find counterparties to trade shares with. We'll go through each of these challenges in order.

Let’s design a hypothetical altcoin called “Futurecoin” that has explicit support for prediction markets. We’d need a few new transaction types that perform functions specific to prediction markets. It might look something like Figure 9.14.

CreateMarket allows any user to create a prediction market for any event by specifying an arbitrator (in terms of a public key) who is authorized to declare the outcome of that event, and the number of possible outcomes. The event_id is an arbitrary string that ties together the different transactions that refer to the same market. Futurecoin doesn’t care about what real-world event the event_id refers to, nor what the outcomes are, and there is no way to specify these within the system. Users will have to obtain this information from the market creator (who will typically be the same as the arbitrator). We’ll discuss different options for arbitration shortly.

***Payment and settlement*.** BuyPortfolio lets you purchase a portfolio of shares of some event. For the price of one futurecoin, you can buy one share in *every* possible outcome of the event. Suppose we’re betting on the 2014 World Cup. There are 32 teams that could win. For one coin, you could buy 32 shares, one for each team — this is clearly “worth” exactly one coin since exactly one of the teams will ultimately win. Any user can unilaterally create a BuyPortfolio without needing a counterparty. The transaction essentially destroys one futurecoin provided as input by the user and creates one new share in every outcome. There is also a transaction type to sell a portfolio, which lets you sell (or burn) a share in every outcome to get one futurecoin back. For one futurecoin, you can buy a share in every outcome and then you can turn a share in every outcome back into a futurecoin.

**`CreateMarket(event_id, arbitrator_key, num_outcomes)`**
    create a new prediction market, specifying the arbitrator and parameters
**`BuyPortfolio(event_id)`**
    purchase one share in every outcome for 1 futurecoin
**`TradeShares(...)`**
    transfer shares in exchange for futurecoins
**`SellPortfolio(event_id)`**
    redeem one share in every outcome for 1 futurecoin
**`CloseMarket(event_id, outcome_id)`**
    close the market for the specified event by converting all shares of the specified outcome into 1 newly minted futurecoin and destroying all shares of all other outcomes in the event (`outcome_id` is an integer between 1 and `num_outcomes` for the event)

**Figure 9.14:** New transaction types in Futurecoin, a hypothetical altcoin that implements a decentralized prediction market

You can also trade shares for futurecoins, or one kind of share for another kind of share, as long as you can find someone to trade with. This case is much more interesting. You could spend a futurecoin to buy a share in every outcome, and then sell off the shares in outcomes you don't think are likely to occur. For the teams you don't want to bet on, you could sell those shares to someone else who does want to bet on that team. Once you do this, you no longer have a balanced portfolio on every team, and you can no longer automatically redeem your portfolio for one futurecoin. Instead you have to wait until the bet ends in order to redeem your shares — and if the team(s) you bet on didn't win, you might not be able to redeem them for anything at all. On the other hand, you can also profit directly by trading. You could buy a balanced portfolio, wait for prices to change, and then sell all of the shares directly for futurecoins, which you could then trade for Bitcoin or any other currency of your choice.

***Prediction market arbitration*.** How can we do arbitration in a decentralized way? How can we make assertions about who actually won so we can let people redeem their winning shares at the end? The simplest system is to have a trusted arbitrator, which is what CreateMarket above does. Any user can launch a market where they are the arbitrator (or designate someone else as the arbitrator). They can create a transaction and announce that they are opening a market on the World Cup outcomes. They will decide who won in the end, and if you trust them then you should be willing to accept their signature on a CloseMarket transaction as evidence of the outcome.

Like in many other markets, we imagine that over time some entities will build reputations as reliable arbitrators. Then they would have some incentive to arbitrate correctly in order to maintain their valuable reputations. But there's always the risk that they could steal a lot of money — more than their reputation is worth — by rigging a bet. This would be very dangerous in a prediction market. For example, in the World Cup market, the arbitrator could assert that Argentina won, even though they actually lost. If the arbitrator had bet heavily on Argentina themselves, then they might be able to profit enough from it to justify ruining their reputation.

Could we have a more decentralized arbitration system? One option is to designate multiple arbitrators, with the outcome being decided based on the majority. There are also ideas based on voting — either by all users who hold shares in the market, or by miners of the cryptocurrency. Proposals along these lines often propose penalizing voters for voting against the majority. But there are many potential problems with these approaches and we simply don't know how well they will work in practice.

A further wrinkle is that sometimes reality is complicated. In addition to the problem of arbitrators lying, there might be a legitimate dispute over the outcome of the event. Our favorite example is from the 2014 Super Bowl. There's a tradition at the Super Bowl of the winning team dumping a bucket of Gatorade on their head coach. People like to bet on the color of the Gatorade that the winning team uses for this celebration, and this betting has happened for two or three decades. In 2014, there were bets taken on Yellow, Orange, and all the other colors of Gatorade. But that year, an unprecedented outcome made it hard to settle the bet. When the Seahawks won, they dumped orange Gatorade on their head coach, Pete Carroll. Then a little bit later, a few other players decided to do it again and dump *another* bucket of Gatorade on him. The first bucket contained orange Gatorade, and the second bucket contained yellow Gatorade.

If you were running a prediction market where people had bet on the color of the Gatorade, how would you handle this scenario? It's not clear if orange, yellow, or both should win. What happened in practice with several sports betting services is that they decided it was better to lose some money in order to maintain their reputations. As a show of good faith to their customers, they paid out winnings to anyone who bet on *either* orange or yellow.

Of course, in a decentralized prediction market this isn't so easy, because you can't just create money out of thin air to pay both sets of parties. Instead the arbitrator could split the winnings equally among both orange and yellow. Instead of closing at a value of 1.0, both shares would close at a value of 0.5. You could define the contract carefully to avoid this confusion, but you can't be sure you've anticipated every possibility. The lesson here is that arbitration is partly a social problem and no technical solution is going to be perfect.

***Data feeds*.** The idea of arbitration leads to a more general concept: extending cryptocurrencies with a mechanism to assert facts about the real world. We call such a mechanism a data feed. A fact might be about typical prediction-market events like who won an election, or the price of a stock or commodity on a certain day, or any other real world data of importance. If we had such facts available in Bitcoin, the scripting language would be able to use them as inputs. For example, a script might be able to load the current price of copper onto the stack and make decisions based on the value.

If trusted data feeds existed, we could place — and automatically settle — bets on sports matches or the future price of commodities. A prediction market is only one application that this would enable. You could hedge risks in your investment portfolio by making bets against the price of stocks you own. And you could derive a variety of financial instruments like forwards and futures that are ordinarily traded in financial markets. Wouldn't it be great if we could do all of this within Bitcoin?

We can separate the technical question of how to *represent* real-world facts in Bitcoin (or an altcoin) from the socio-technical question of how to improve our confidence in the correctness of the feed. We've already looked at the former question when discussing options for arbitration.

A clever way to encode data feeds into ordinary Bitcoin is called Reality Keys. In this system, the arbitrator creates a pair of signing keys for every outcome of every event they are interested in — one key pair for "Yes", and one key pair for "No". They publish the public keys when the event is first registered, and later publish exactly one of the two *private* keys when the outcome is settled. If Alice were betting against Bob that the outcome would occur, they could send their wagers to a Bitcoin output that can either be claimed by Alice using a signature from Alice and from the "Yes" key, or claimed by Bob using a signature from Bob and from the "No" key. This falls well short of the ideal goal of being able to use data feed values as script inputs in arbitrary ways, but it allows simple applications like the wager described above. Note that the arbitrator doesn't need to know about or get involved in the specific wager between Alice and Bob.

***Order books*.** The final piece of a prediction market is a decentralized order book. Once again this is a pretty general concept, and realizing it would allow many other applications. What's an order book? In real prediction markets, or most financial markets, there isn't a single market price. Instead there are *bids* and *asks* which are listed in the *order book*. A bid is the highest price that anyone is willing to buy a share for, and the *ask* is the lowest price that anyone is willing to sell the share for. Typically the ask is greater than the bid (otherwise there would be two participants who would be matched up, a trade would occur, and at least one of the orders would no longer remain in the order book). A participant who wants to buy a share right away can do so at the ask price and a participant who wants to sell right away can do so at the bid price. These are called "market orders" since they execute at market price, as opposed to the "limit orders" that are recorded in the order book that execute at the specified limit price (or better).

Traditionally this has been done in a centralized way with a single order book service (typically an exchange) that collects all the orders. The problem, as is typical of centralized services, is that a dishonest exchange might profit at the expense of the participants. If the exchange receives a market buy order, they might themselves buy from the best ask before placing the order they received, then turn around and sell the shares they just bought at a higher price, pocketing the difference. This practice is called frontrunning. It shows up in a variety of financial settings, and it's considered a crime. Centralized order books require legal enforcement in order to discourage frontrunning and ensure confidence in the integrity of the system.

In a decentralized order book, we can't rely on strong legal enforcement. But there's a clever solution, which is to simply forget about frontrunning. Instead of declaring it a crime and defending against it, we'll call it a feature. The idea is that anybody can submit limit orders to miners by broadcasting transactions, and miners can match any two orders as long as the bid is *greater* than or equal to the ask. The miner simply gets to keep the difference as a form of transaction fee. Now miners have no incentive to frontrun because frontrunning an order will never be more profitable than simply fulfilling it and capturing the surplus.

This is an elegant way to build a decentralized order book. The main downside is the miner fees that traders must pay. To avoid paying that fee, people might submit much more conservative orders and may not be willing to reveal up front the best price at which they are willing to trade. This might make the market less efficient. We don't yet know how this kind of order book with miners matching orders will function in practice, but it seems to be a promising idea.

In conclusion, Bitcoin as it is today can act as a platform for a variety of applications. But for some applications Bitcoin only takes us so far. It doesn't have all the features we need for a secure decentralized prediction market or a decentralized order book.

But what if we could start from scratch and forget about soft forks, hard forks, and other challenges in bolting new features on to Bitcoin? We've learned a lot since 2008 when Bitcoin first came out. Why not design a new cryptocurrency from scratch and make everything better?

In the next chapter, we'll look at altcoins, which are attempts to do just that. We'll talk about all the promising ideas and the challenges to face in starting a new cryptocurrency.

## Further Reading

Project pages / specifications of two of the overlay protocols we looked at:

**The Counterparty protocol specification**

**The OpenAssets protocol**

The secure multiparty lottery protocol we described is from the following paper, which is not for the faint of heart!

**Andrychowicz, Marcin, Stefan Dziembowski, Daniel Malinowski, and Lukasz Mazurek. Secure multiparty computations on Bitcoin. In IEEE Security and Privacy 2014.**

Papers by economists on the power of prediction markets:

**Wolfers, Justin, and Eric Zitzewitz. Prediction markets. No. w10504. National Bureau of Economic Research, 2004.**

**Arrow, Kenneth J. et al. The promise of prediction markets. 2008.**

The prediction market design we described is from this paper, co-authored by several of the present authors:

**Clark, Jeremy, Joseph Bonneau, Edward W. Felten, Joshua A. Kroll, Andrew Miller, and Arvind Narayanan. On Decentralizing Prediction Markets and Order Books. In Workshop on the Economics of Information Security, 2014.**

# Chapter 10: Altcoins and the Cryptocurrency Ecosystem

Bitcoin is just one component (albeit an important one) of a broader ecosystem of alternative, but often quite similar, currencies called *altcoins*. In this chapter, we'll look at altcoins and the ecosystem of cryptocurrencies.

## 10.1 Altcoins: History and Motivation

Bitcoin was launched in January 2009. It wasn't for another two years, until the middle of 2011, that the first Bitcoin-like derived system, Namecoin, was launched. The rate of altcoin launches exploded in 2013, and hundreds have since followed. How many are there in all? It's impossible to provide an exact number because it's not clear which altcoins are worth counting. For example, if someone announces an altcoin and perhaps release some source code, but no one has started mining or using it yet, does that count? Other altcoins have been launched and seen some initial use, but then died very quickly after their launch.

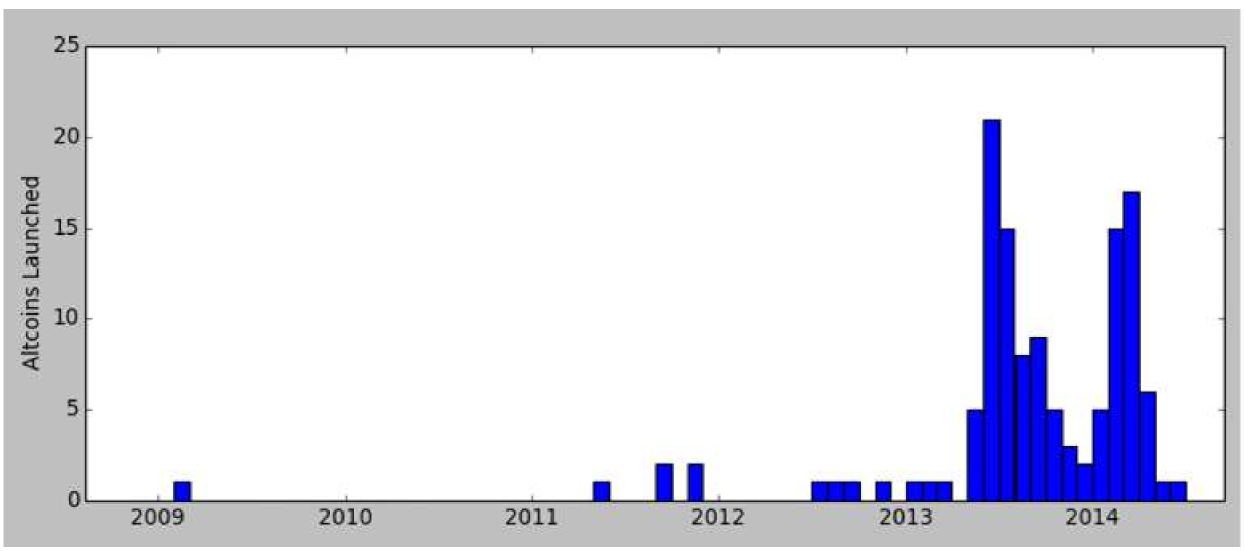



**Figure 10.1: Altcoins launched per month (measured by genesis block creation).**

It's also not quite clear what is an altcoin as opposed to simply another cryptographic currency. There were, after all, various cryptocurrency proposals and systems which predate Bitcoin and these are usually not called altcoins. Many altcoins borrow concepts from Bitcoin, often directly forking its code base or otherwise adopting some of Bitcoin's code. Some make only very minor modifications to Bitcoin, such as changing the value of some parameters of the system, and continue to incorporate changes made by Bitcoin's developers. To date, all altcoins that we know of begin with a new genesis block and their own alternate view of transaction history, rather than forking Bitcoin's block chain after a certain point in history. For our purposes, we don't need a precise definition of an altcoin. Instead we'll loosely refer to any cryptocurrency launched since Bitcoin as an altcoin.

We’ll briefly mention non-altcoin systems like Ripple and Stellar: these are distributed consensus protocols in the tradition that we looked at in Chapter 2. These systems achieve consensus in a model where nodes have identifiers and need to be aware of each other. Bitcoin, of course, radically departs from this model. In both Ripple and Stellar, the consensus protocol supports a payment/settlement network, and each system has a native currency. Despite these similarities with altcoins, we don’t consider them to be in scope for this book.

**Reasons for launching altcoins.** Every altcoin needs some kind of story to tell. If an altcoin can’t claim some characteristic that distinguishes it from all of the others, there is no reason for it to exist. In the simplest case, an altcoin simply changes some of the built-in parameters to Bitcoin. This includes things like the average time between blocks, the block size limit, the schedule of rewards being created, or the inflation rate of the altcoin.

There can also be more complex technical differences, which is a more interesting case. For example there can be additions to the scripting language to express different kinds of transactions or security properties. Mining could work differently and the consensus algorithm could be significantly different from Bitcoin’s.

Sometimes altcoins are also launched with a theme or a sense of a community that the altcoin is intended to support or be associated with, often giving members of this community a special role or abilities in the altcoin. We’ll look at examples of all of these later in this section.

**How to launch an altcoin.** Let's consider what’s involved in the process of launching an altcoin and what happens after an altcoin is launched. As we mentioned, creating an altcoin involves creating a new reference client, typically by forking the existing code base of some existing, more well-established altcoin, or of Bitcoin itself. The easy part is to add in a bunch of technical features or modified parameters you think will work out well. In fact, there was once a website called Coingen that would automate this process for a small fee. It allowed you to specify various parameters like the average block time and the proof-of-work algorithm you wanted, in addition to a name for your altcoin, a 3-letter currency code, and a logo. Then at the click of a button you’d download a fork of Bitcoin with the parameters you chose, and you (and others) could immediately start running it.

The hard part is bootstrapping adoption of your altcoin. You can fork the source code and you can announce it publicly, but at this point nobody is using your altcoin so it has no market value (since nobody wants the coins) and no security (since there aren’t miners yet). In Chapter 7 we saw that there a number of stakeholders in Bitcoin: developers, miners, investors, merchants, customers, and payment services. Eventually you’ll have to attract all these types of participants to your altcoin economy to get it off the ground.

All of these are important and interrelated, and analogous to the challenge involved in launching any other platform and getting it adopted. If you wanted to launch a new smartphone operating system, say, you’d need to attract users, device manufacturers, app developers and various other stakeholders, and each of these groups needs the others.

Attracting miners has special importance for cryptocurrencies because without adequate hash power behind an altcoin, security may fail badly if double-spending and forks are possible. In fact, your altcoin might be run over entirely; we'll look at "altcoin infanticide" later in this chapter. There isn't a simple recipe for bootstrapping adoption, but in general miners will come once they believe the coinbase rewards they receive will be worth the effort. To encourage this, many altcoins give early miners greater rewards. Bitcoin, of course, pioneered this approach but some altcoins have taken a more aggressive approach to rewarding early miners.

Getting a community of people to believe the altcoin is valuable is the most difficult trick. As we discussed in Chapter 7, even for Bitcoin it's not clear exactly how this process was bootstrapped as it relies on the Tinkerbell effect. This ties back to why altcoins need a good narrative: to get off the ground community of people need to believe that the new altcoin is really going to be valuable in the future (and believe that others will believe it is valuable, and so on).

Given a community of people interested in obtaining an altcoin, miners will typically come (although it might be risky if the value increases more quickly than miners can switch to begin mining the currency). Other important elements will usually follow in turn once value is perceived-like getting your altcoin listed on exchanges and developing various types of supporting infrastructure are useful, ranging from an advocacy foundation to tools for exploring the block chain

**Pump-and-dump scams.** When the creators of an altcoin have succeed in bootstrapping a community and a real exchange market, they have often found themselves very wealthy. That's because they almost certainly own a large quantity of coins — for example by being early miners before the hash rate increases, or even "pre-mining," which we discuss below. Once the altcoin's exchange rate rises, the founders will be in a position to sell off their coins if they choose to.

The possibility of getting rich has attracted entrepreneurial individuals and venture capital to altcoins, and unsurprisingly, it has also attracted scammers. Indeed, the line between the two is sometimes a bit blurry. A scammer might use a variety of methods to exaggerate an altcoin's potential and drum up interest. They may hype up its supposed technical merits, fake the appearance of grassroots support, purchase the altcoin on the market at inflated prices, and so on.

In fact, this scam can be pulled off even by someone who is not the founder of an altcoin. They would first need to buy up shares of some obscure altcoin, then convince the public of this coin's supposed undiscovered potential (i.e., "pump" the altcoin). If they succeed in inflating the price this way, they can unload their shares and reap a profit (i.e., "dump" their coins). At this point investors will probably become wise to the fraud and the price will plummet, with many people left holding worthless coins. This kind of pump-and-dump fraud has long been perpetrated in mainstream finance, using obscure, low-priced stocks, and it was common in the early days of altcoins as enthusiasm was high and investors struggled to differentiate truly innovative altcoins from "me-too" systems with slick marketing but no real innovation. As a result, users and investors are somewhat weary of altcoins today.

**Initial allocation.** In Bitcoin, currency is allocated to users solely through mining. But for various reasons, altcoin developers have sought other ways of initial currency allocation in addition to mining.

Developers may "pre-mine" the currency, that is, reserve some portion of the money supply for themselves or some other designated entity (such as a non-profit foundation with a charter to develop the currency). The idea is that the possibility of a windfall gives developers more of an incentive to spend time creating and bootstrapping a new cryptocurrency. Sometimes they go further and do a "pre-sale," where they sell these pre-mined units to other speculators for bitcoins or fiat currency. This somewhat analogous to investing in a startup: the speculators can strike it rich if the altcoin makes it big.

Another motivation for seeking additional methods of initial allocation is to ensure that there's a diverse community of early adopters who own the currency and have a stake in its success, given that mining today is rather centralized and might lead to concentrated ownership of assets. A clever way to enable diverse ownership is to allocate altcoin units to existing Bitcoin owners.

How can we technically design the system so that anyone who owns bitcoins can claim their share of the altcoin, with this claim being automatically adjudicated? One option is a proof-of-burn, which we discussed in Chapter 3: users can claim units of a new altcoin in proportion to a quantity of bitcoins they provably destroy. The owner will commit to some data in the proof of burn, such as a special string identifying the specific altcoin, to show that they are burning bitcoins solely to earn new units of this specific altcoin.

Allocating altcoins via a proof-of-burn is also called a "one-way peg" or "price ceiling". Associating one altcoin unit to (say) one bitcoin doesn't actually make it *worth* one bitcoin. It ensures instead that the altcoin will be worth *at most* one bitcoin, since one bitcoin can always be cashed in for an altcoin, but not vice versa.

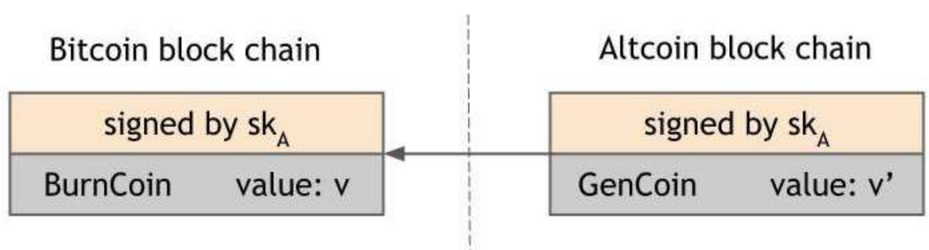



**Figure 10.2: Allocating altcoins via proof-of-burn.** The altcoin supports a GenCoin transaction that takes a *Bitcoin* transaction as input. GenCoin is signed by the same private key that signed the proof-of-burn (and using the same signature scheme). This ensures that the same user who burned bitcoins also created the GenCoin. If the peg ratio is 1:1, then $v'$ must be no greater than $v$.

There's a less heavy-handed alternative: require proving ownership of bitcoins, but not burning them, to claim altcoins. Specifically, the altcoin would designate a Bitcoin block height (perhaps coinciding with the launch date of the altcoin) during which anyone who owned an unspent Bitcoin transaction output as of that block would be able to claim a proportional amount of altcoins. In this system, there isn't necessarily a fixed relationship between the price of a bitcoin and the price of an altcoin, because bitcoins aren't being "converted" to altcoins via the proof-of-burn.

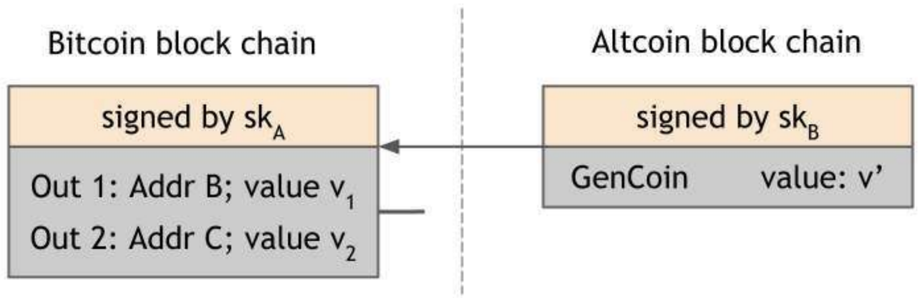



**Figure 10.3: Allocating altcoins by proving ownership of bitcoins.** The input to GenCoin is one or more *unspent Bitcoin transaction outputs* at the designated block height. It is be signed by the private keys that control those unspent outputs, as in any normal Bitcoin transaction. Here the Bitcoin transaction shown has two unspent transaction outputs, to addresses B and C, at the designated block height. The owner of address B has claimed their altcoins, but the owner of address C hasn't yet done so. If the peg ratio is 1:1, then $v'$ must be no greater than $v_1$.

Of course, to make all this happen, altcoin miners need to stay on top of the Bitcoin block chain as well. The altcoin must specify what counts as a confirmed Bitcoin transaction. One option is to require some fixed number of confirmations, say 6. Another option is to specify the most recent Bitcoin block in each altcoin Block. This way, Bitcoin transactions become immediately available to spend in the altcoin. This is analogous to the fact that within Bitcoin itself, transaction outputs can be spent in the very next block or even in the same block. Merge mining, which we'll discuss in the next section, is one way to tie altcoin blocks to Bitcoin blocks.

Finally, donating already-allocated coins is another way of increasing the diversity of the currency owners. One method is tipping: various services allow sending tips to an email address or a social media account, which is partly a way to incentivize the recipient to learn about and have a stake in the currency. The tipping service keeps the coins in escrow and the recipient gets a message telling them that they have coins they can collect. The recipient can claim the coins by authenticating themselves to the service via their email address or social media account. They'll also need to install wallet software or enable another way to receive coins. Another donation method is a faucet: these are services that give out a small quantity of coins to anyone who visits a site and perhaps enters an email address.

## 10.2 A Few Altcoins in Detail

Now we're going to focus on a few of the oldest altcoins and study their features in more detail.

**Namecoin.** We've seen how Bitcoin's block chain is a secure, global database. Once data has been written to it, it is tamper-proof and its inclusion can be proved forever. Could we modify Bitcoin's design to support other applications of secure global databases, such as a naming system?

We'll need a few ground rules to make this database more useful for non-currency applications. First, we agree to view data entries as name/value pairs, with names being globally unique. This allows everyone to look up the value mapped to a name, just like a hash table or a database with a primary-key field. To enforce the global uniqueness of names, if a name/value pair has the same name as a previous database entry, then we view it as an update to the value rather than a new entry.

Second, we agree that only the user who initially created the entry for a particular name is allowed to make updates to that name. We can easily enforce this by associating each name with a Bitcoin address and requiring the update transactions to be signed by the private key for that address.

We could do all this on top of Bitcoin, just as we said in Chapter 9 that we could build any overlay currency using Bitcoin as an append-only log. But it's simpler to do it in an altcoin because we can take this gentleman's agreement and write it into the rules of the altcoin. These rules would then be inviolable and enforced by the miners, rather than requiring each user (i.e., full node) to check the rules for itself and independently decide what to do if they are violated. Done right, it would even allow SPV-style proofs: a lightweight client would be able to submit a query (i.e, a name) to a server running a full node, and the server would return a value for that name, along with a proof that the returned value in fact the latest update for that name in the database.

That's Namecoin in a nutshell. It's a global name/value store where each user can register one or more names (for a nominal fee) and then issue updates to the values of any of their names. Users can also transfer control of their names to others. In fact, you can make a transaction that transfers your domain to someone, and at the same time, transfers units of the Namecoin currency from them to you. Since this is a single atomic transaction, it's a secure way to sell your domain to someone you've never met and don't trust. As of 2015 Namecoin doesn't support secure lightweight clients, but an extension that supports this has been proposed.

Namecoin's goal is to provide a decentralized version of the Domain Name System (DNS), the names in the database being domain names and the values being IP addresses. You can't use this by default with an unmodified browser, but you can download a browser plugin for say Firefox or Chrome that would allow you to type in an address like example.bit — any domain name that ends in .bit — and it will look up the location in the Namecoin registry instead of the traditional DNS.

Namecoin is technically interesting, and it's also historically interesting — it was in fact the first altcoin to be launched, in April 2011, a little over two years after Bitcoin was launched. It features "merge mining" which we'll discuss later in this chapter.

Namecoin isn't used very much as of 2015. The vast majority of registered domains are taken by "squatters," hoping (but failing so far) to sell their names for a profit. Namecoin supporters tend to argue that the existing DNS puts too much control over a critical component of the Internet into the hands of a single entity. This view is popular in the Bitcoin community, as you can imagine, but it doesn't look like mainstream users are clamoring for an alternative to DNS, robbing Namecoin of the killer app it needs to see significant adoption.

**Litecoin.** Litecoin was also launched in 2011, some time after Namecoin. For the past several years, Litecoin has been the number one altcoin in terms of overall popularity and user base. It is also the most widely forked codebase. In fact, it has been forked more times than Bitcoin itself.

The main technical distinction between Litecoin and Bitcoin is that Litecoin features a memory-hard mining puzzle (based on scrypt), which we talked about in Chapter 8. When Litecoin was launched, Bitcoin mining was in the GPU era, and so the goal of Litecoin's use of a memory-hard mining puzzle was GPU-resistance. When it was launched, you could still mine on Litecoin with a CPU, long after this had become futile for Bitcoin. But since then, Litecoin hasn't succeeded in resisting the transition to GPU mining and then to ASICs. Each of those mining transitions took a bit longer in Litecoin than Bitcoin, but it's not clear if this is because Litecoin's puzzle was actually harder to implement in hardware or simply because Litecoin's lower exchange rate provided less incentive to do so.

In any case, the performance improvements of ASICs compared to CPU mining are roughly similar for Litecoin as they are for Bitcoin. In this sense, Litecoin failed in its original goal of creating a more decentralized system by maintaining a community of CPU miners. But, importantly, this narrative still worked for bootstrapping Litecoin — it attracted many adopters who ended up staying even after the original premise failed. Litecoin has since explicitly changed its narrative, stating that its initial allocation was more fair than Bitcoin's because it resisted ASICs for longer.

Litecoin also makes a few minor parameter changes: for example blocks in Litecoin arrive four times faster than in Bitcoin, every 2.5 minutes. Litecoin otherwise borrows as much from Bitcoin as possible. In fact, its development has followed Bitcoin, so that as patches and improvements have been made to Bitcoin, Litecoin has also adopted these.

**Peercoin.** Peercoin, sometimes called PPCoin, was launched in late 2012 and was the first altcoin to use proof-of-stake mining. We discussed proof-of-stake mining (and Peercoin's implementation of it) in Chapter 8, but Peercoin is interesting to discuss for an additional, entirely different reason: its administrators have a trusted public key which they use to assign checkpoints of "blessed" blocks every so often. This is intended to act as a safeguard against forking attacks, but it is controversial because the ability of the administrators to control the system means that Peercoin isn't truly decentralized. The checkpoint system isn't inherent to Peercoin and could be removed in the future;

nevertheless its existence means that we can’t infer that proof-of-stake has led to a secure system in practice. We don’t know what would happen if this safeguard were removed.


**Figure 10.4: One of several Dogecoin logos. The selling point is humor more than technical innovation.**

**Dogecoin.** Dogecoin has perhaps been the most colorful of all altcoins to date. It was released in late 2013, and what distinguishes it is not primarily technical (it is a close fork of Litecoin) but rather a set of community values: tipping, generosity, and not taking cryptocurrency so seriously. Indeed, it is named after Doge, an amusing Internet meme featuring a grammatically-challenged Shiba Inu dog. The community has had several interesting and successful marketing campaigns such as sponsoring a NASCAR driver and putting Dogecoin logos all over his car. They also raised over $30,000 to support the Jamaica National Bobsled Team so that they could travel and compete in the 2014 Winter Olympics. Amusingly, this closely mirrors the plot to the ‘90s movie *Cool Runnings*.

The combination of the community’s generosity, PR activities, and the inherent meme value of Doge meant that Dogecoin became very popular in 2014. It appears many of the early adopters were unfamiliar with cryptocurrencies prior to Dogecoin, providing a new community to bootstrap the currency’s value without having to offer a compelling story in terms of advantage over other currencies. Dogecoin showed that bootstrapping could be successful with a non-technical narrative. Unfortunately, like many Internet phenomena, the popularity has not lasted and Dogecoin’s exchange rate has since tanked.

## 10.3 Relationship Between Bitcoin and Altcoins

To get a sense of the relative size or impact of different altcoins, there are a variety of metrics we can use.

**Comparing altcoins: market capitalization.** Traditionally, market capitalization or market cap is a simple method of estimating the value of a public corporation by multiplying the price of a share by the total number of shares outstanding. In the context of altcoins, this market cap is often similarly used to estimate the total value of the altcoin by multiplying the price of an individual unit of the altcoin (measured, perhaps, at the most popular third party exchanges) by the total number of units of currency of the altcoin thought to be in circulation. By this metric, Bitcoin is by far the largest — as of 2015, it accounts for over 90% of the overall market cap of all of the cryptocurrencies combined. The relative ranking of the other altcoins tends to vary quite a lot, but the point is that most altcoins are comparatively tiny in terms of monetary value.

It's important not to read too much into the market cap. First, it isn't necessarily how much it would cost for someone to buy up all the coins in circulation. That number might be higher or lower, because large orders will move the price of the currency. Second, even though the calculation considers only the coins currently in circulation, we should expect that market participants factor into the exchange rate the fact that new coins will come into circulation in the future, which further complicates the interpretation of the number. Finally, we cannot even accurately estimate the true number of coins currently in circulation because the owners of some coins may have lost their private keys, and we'd have no way to know.

**Comparing altcoins: mining power.** If two altcoins use the same mining puzzle, we can directly compare them by how much mining power all of the the altcoin's miners have. This is often just called the hash rate due to the prominence of hash-based puzzles. For example, Zetacoin is an altcoin that uses SHA-256 mining puzzles, just as Bitcoin does, and has a network hash rate of about 5 Terahashes/second ($5*10^{12}$ hashes/second) as of December 2015. This number is about a hundred-thousandth of Bitcoin's mining power. It's trickier to compare the mining power between coins that use different mining puzzles because the puzzles may take different amounts of time to compute. Besides, mining hardware specialized for one of the coins won't necessarily usable for mining (including attacking) the other coin.

Even for an altcoin using a completely unique mining puzzle, we can still learn something from the relative change in mining power over time. Growth in mining power indicates either that more participants have joined or that they have upgraded to more powerful mining equipment. Loss of mining power usually means some miners have abandoned the altcoin and is typically an ominous sign.

**Comparing altcoins: other indicators.** There are several other indicators we can look at. Changes in an altcoin's exchange rate over time gives us clues about its health, and tends to correlate with changes in its hash rate over long time periods. Exchange volume on various third-party exchanges is a measure of activity and interest in the altcoin. On the other hand, the volume of transactions that have been made on the altcoin's block chain doesn't tell us much, since it could simply be users shuffling their own coins around in their wallet, perhaps even automatically. Finally, we can also look at how many merchants and payment processors support the altcoin — only the most prominent ones tend to be supported by payment processors.

**The economic view of Bitcoin-altcoin interactions.** The relationship between Bitcoin and altcoins is complicated. In one sense, cryptocurrencies compete with each other, because they all offer a way to do online payments. If there are two standards, protocols, or formats in competition that are roughly equivalent in terms of what they offer, then one of them will usually come to dominate, because of what economists call "network effects."

For example, Blu-ray and HD-DVD were in fierce competition in the mid-to-late 2000s to be the successor to the DVD format. Gradually, Blu-ray started to become more popular, in large part because the popular PlayStation 3 console functioned as a Blu-ray player. This made Blu-ray a more attractive format for movie studios and this popularity fed on itself: as more movies were released for Blu-ray, more consumers bought stand-alone Blu-ray players, leading to more movie releases and so on. Similarly, if your friends all have Blu-ray players, you'd want to buy one yourself rather than a HD DVD player because you'd be able to easily swap movies with them. Within about two years, HD DVD was a historical footnote.

**Sidebar: who wins the race?** Long before HD DVD, there have been countless examples of technological standards which rapidly lost out to a competitor and slid into obscurity, from Betamax analog video tapes to Russian gauge railroad tracks. If you've never heard of these, network effects are the reason why. Sometimes, like in the case of Thomas Edison's direct-current power grid vs. Nikola Tesla's alternating-current power grid, the winner (AC) was determined by overwhelming technical superiority. In many other cases though, such as Betamax tapes losing to VHS tapes, the loser may have actually been technically superior, with network effects being strong enough to overcome a slight technological disadvantage.

This line of reasoning suggests that one cryptocurrency will dominate — presumably Bitcoin, which is far and away the most popular one today — even if some successor systems could be argued to be technically superior. But that would be an oversimplification. There are at least two reasons why competition between cryptocurrencies is not as hostile as the competition between disc formats.

First, it's relatively easy for users to convert one cryptocurrency into another, and for vendors to accept more than one cryptocurrency, which means that multiple cryptocurrencies can more easily coexist and thrive. In economics terms, cryptocurrencies exhibit relatively low *switching costs*. Compare to DVD players, where most people really don't want two bulky machines in their home and can't convert their existing library of discs if they change to a machine which plays the other format.

Switching costs are certainly not zero for cryptocurrencies. For example, users might buy hardware wallets which can't be upgraded. But by and large it's easy to switch cryptocurrencies or to use more than one at the same time.

Second, as we said earlier, many altcoins have unique features which provide a distinct reason for existing. These altcoins shouldn't be seen as mere substitutes for Bitcoin; they may be orthogonal, or perhaps even complementary. Viewed this way, complementary altcoins actually increase the usefulness of Bitcoin rather than compete with it. If Namecoin succeeds, for example, Bitcoin users have one more useful thing they can do with their bitcoins.

But this picture of happy cooperation is also an oversimplification. Some altcoins, like Litecoin, simply try to achieve the same functionality as Bitcoin but in a different, perhaps more efficient manner. Even when new functionality is being offered, often those use-cases can in fact be achieved within Bitcoin itself, albeit in a less elegant way (we'll have more to say about this in Chapter 11). Supporters of the do-it-on-top-of-Bitcoin model argue that having numerous altcoins divides the hash power available and makes each currency less secure.

Supporters of altcoins argue, by contrast, that altcoins allow market forces to determine which features are worth having, which systems are technically superior, and so on. They further argue that having numerous altcoins limits the damage of a potential catastrophic failure of any one system. They also point out that Bitcoin developers are highly risk averse and that adding new features to Bitcoin via a soft or a hard fork is slow and difficult. On the other hand, it is easy to try out a new idea via an altcoin; altcoins can be seen as a research-and-development test bed for potential Bitcoin features.

The practical upshot is that there is some tension between supporters of Bitcoin and those of altcoins, but also a sense of collaboration.

## 10.4 Merge Mining

In this section and the next, we'll set aside issues of culture, politics, and economics. Instead we'll focus on the technical interactions between Bitcoin and altcoins.

**Altcoin infanticide.** As of 2015, Bitcoin's hash power dwarfs that of any other altcoin. Indeed, there are powerful miners and mining pools that control more mining power than entire altcoins. Such a miner or entity could easily carry out an attack against a small altcoin (if it uses the same SHA-256 mining puzzle as Bitcoin), causing forks and general havoc which are often enough to kill the altcoin. We call this phenomenon *altcoin infanticide*.

Why would anyone do this, given that they must use their valuable mining power to do so and won't gain a significant monetary reward? Take the case of the 2012 attack on a small altcoin called CoiledCoin: the operator of the Bitcoin mining pool Eligius decided that CoiledCoin was a scam and an affront to the cryptocurrency ecosystem. So Eligius pointed its mining resources at CoiledCoin, mining blocks that reversed days' worth of CoiledCoin transaction history as well as mining a long chain with empty blocks, effectively causing a denial-of service attack which prevented CoiledCoin users from making any transactions. After a fairly short siege, users abandoned CoiledCoin, and it doesn't exist any more. In this example and in other altcoin infanticide attacks, the attacker is motivated by something other than direct profit.

**Merge mining.** By default — say if an altcoin forks the Bitcoin source code but makes no other changes — mining on the altcoin is exclusive. That is, you can try to solve the mining puzzle solution to find a valid block for the altcoin or for Bitcoin, but you can't try to solve both puzzles at once. Of course, you can divide your mining resources to dedicate some to mining on the altcoin and some to mining on Bitcoin. You can even divide between multiple different altcoins and you can adjust your allocation over time, but there's no way to get your mining power to do double duty.

With exclusive mining, network effects can make it difficult for an altcoin to bootstrap. If you wanted to launch an altcoin and convince today's Bitcoin miners to participate in your network, they would have to stop mining Bitcoin (with at least some of their resources) which will mean an immediate loss of Bitcoin mining rewards. This means your altcoin is likely to remain small in terms of hashing power and more vulnerable to infanticide-style attacks by Bitcoin miners.

Can we design an altcoin so that it's possible to mine blocks both on the altcoin and on Bitcoin at the same time? To do that we need to create blocks that include transactions from both Bitcoin and the altcoin, making them valid in both block chains. It's easy to design the altcoin so that it allows Bitcoin transactions in its blocks, because we can write the rules of the altcoin however we want. The reverse is harder. Where can we put altcoin transactions in Bitcoin blocks? In Chapter 3 and later in Chapter 9 we've seen how to put arbitrary data into Bitcoin blocks, but the bandwidth of these methods is very limited.

There's a trick, though: even if we can't put the *contents* of the altcoin's transactions into Bitcoin blocks, we can put a *summary* of the altcoin transactions into Bitcoin blocks in the form of a hash pointer to the altcoin block. Finding a way to put a single hash pointer into each Bitcoin block is easy. Specifically, recall that each Bitcoin block has a special transaction called the coinbase transaction which is where the miner creates new coins as a block reward. The scriptSig field of this transaction has no significance and can therefore be used to store arbitrary data (there's no need to sign the Coinbase transaction since it's not spending any previous transaction outputs). So in a merge-mined altcoin, the mining task is to compute *Bitcoin* blocks whose Coinbase scriptsig contains a hash pointer to an altcoin block.

This block can now do double-duty: to Bitcoin clients, it looks just like any other Bitcoin block, with a hash in the coinbase transaction that can be ignored. Altcoin clients know how to interpret the block by ignoring the Bitcoin transactions and looking at the altcoin transactions committed to by the hash in the coinbase transaction. Note that while this doesn't require any changes to Bitcoin, it does require the altcoin to specifically understand Bitcoin and accept merge-mined blocks.

If our altcoin is merge-mined, we hope that many Bitcoin miners will mine it, because doing so doesn't require any additional hash power. It requires a modicum of additional computational resources for processing blocks and transactions, and miners need to know and care enough about our altcoin to even bother to mine it. Let's say 25% of Bitcoin miners by hash power are mining our altcoin. This means that on average 25% of Bitcoin blocks contain pointers to altcoin blocks. It seems, then, that in our altcoin a new block would be mined on average every 40 minutes. Worse, while the altcoin is still being bootstrapped and the fraction of Bitcoin miners mining it is very small, the time between blocks will be hours or days, which is unacceptable.

Can we ensure that blocks of a merge-mined altcoin are created at a steady rate, as high or low as we want, irrespective of the fraction of Bitcoin miners mining it? The answer is yes. The trick is that even though the mining task for the altcoin is the same as that of Bitcoin, the mining *target* need not be. The altcoin network computes the target and difficulty for its blocks independently of the Bitcoin network. Just as Bitcoin adjusts its mining target so that blocks are found every 10 minutes on average, the altcoin would adjust its own target so that blocks in the altcoin are found every 10 minutes, or any other fixed value.

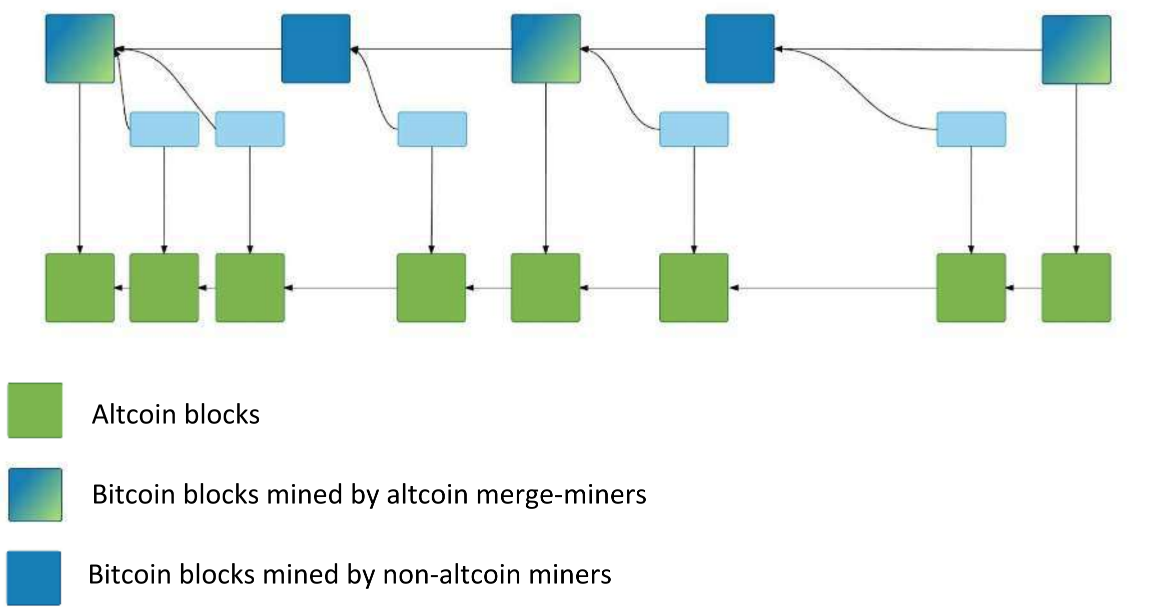



**Figure 10.5: merge mining.**

This means that the altcoin's target will typically be much less than Bitcoin's target, and some (or even most) altcoin blocks will not be pointed to by valid Bitcoin blocks. But that's okay! You should think of the Bitcoin block chain and the altcoin block chain as two parallel chains, with occasional pointers from a Bitcoin block to an altcoin block. This is illustrated in Figure 10.5. In this example, 60% of Bitcoin miners mine the altcoin, and the altcoin's time-between-blocks is 5 minutes. This means that the altcoin's difficulty is 60% * 5 / 10 = 30% that of Bitcoin. Note that 40% of Bitcoin blocks do not contain hash pointers to altcoin blocks.

Conversely, every valid altcoin block results from an attempt at mining a Bitcoin block, but only 30% of them actually meet Bitcoin's difficulty target. For the other 70% of altcoin blocks, the altcoin network needs to be able to verify the mining puzzle solution. The simple way to do this is to broadcast the Bitcoin near-block in addition to the altcoin block. But a cleverer way is to broadcast just the header of the Bitcoin near-block and the Merkle proof of inclusion of the Coinbase transaction in the Bitcoin block.

It's also possible (although rarely seen) for the altcoin to actually have a *more difficult* puzzle than Bitcoin. This is unusual because most altcoins want to have blocks found more often than once per 10 minutes, but if for some reason you wanted a slower rate this would be easy to achieve as well. In this case, you would see some Bitcoin blocks which the miner hoped would also be an altcoin block, but will be rejected on the altcoin network because they didn't meet the harder difficulty target.

Finally, note that any number of altcoins can be simultaneously merge-mined with Bitcoin, and every miner is free to pick an arbitrary subset of altcoins to merge mine. In this case, the Coinbase scriptSig would itself be a Merkle tree of hash pointers to various altcoin blocks. Note the levels of complexity: verifying the inclusion of an altcoin transaction requires verifying, among other things: (1) a Merkle proof of inclusion of the altcoin transaction in the altcoin block (2) a Merkle proof of inclusion of the altcoin block hash in the Coinbase scriptSig and (3) a Merkle proof of inclusion of the Coinbase scriptSig in the Bitcoin block or near-block!

**Merge mining and security.** Merge mining is a mixed blessing. It makes bootstrapping easier, as we've discussed, and the resulting boost to your altcoin's total hash power increases its resilience to attack. An adversary who is looking to buy computing power to destroy your altcoin will need to make an enormous up-front investment.

On the other hand, one could argue that this is a false sense of security, because such an adversary would presumably recoup the cost of his investment by mining Bitcoin, and the marginal cost to attack your altcoin is trivial. This is easier to appreciate if we think about an adversary who is already a large Bitcoin miner. Indeed, CoiledCoin, the altcoin described earlier that suffered infanticide, was merge-mined. The Eligius mining pool and its participants did not need to stop Bitcoin mining in order to attack it. In fact, the pool participants were not even aware that their computing resources were being used in the attack!

**Sidebar: trends in altcoin mining puzzles.** As of 2015 few altcoins launch with the same SHA-256 mining puzzle as Bitcoin, with or without merge mining, which suggests that it is perhaps considered a security risk. Scrypt is a much more popular choice, which makes Bitcoin ASICs useless for mining or attacking such altcoins. Of course, scrypt ASICs being manufactured for Litecoin mining could be used to attack them.

When we think about a rational miner deciding whether or not to merge mine, we find more problems with the security of merge mining. Recall that roughly speaking, mining makes sense if the expected reward equals or exceeds the expected costs. For Bitcoin mining, the cost is primarily that of hash computation. But for someone who's already a Bitcoin miner deciding whether or not to merge mine an altcoin, there is no additional cost from hashing. Instead, the additional costs arise from two factors: the computation, bandwidth, and storage needed to validate the altcoin transactions, and need to keep software up to date and perhaps make informed decisions if the altcoin is undergoing hard or soft forks.

This reasoning yields two insights. First, merge mining has strong economies of scale, because all miners incur roughly the same costs regardless of their hash power. This is in stark contrast to Bitcoin where cost is proportional to hash power, to a first approximation. So for a low-value altcoin, a small solo miner will find it unprofitable to merge mine it because the cost exceeds the meager reward they will make due to their low hash power. Keep in mind that as of 2015, the potential revenue from mining altcoins remains a small fraction of Bitcoin mining revenue. This predicts that compared to Bitcoin, merge-mined altcoins will have a greater centralization or concentration of mining power.

A related prediction is that most miners will choose to outsource their transaction validation. The smaller the altcoin, the greater the incentive to outsource. The natural way to do this is to join a Bitcoin mining pool. That's because pools typically take those computations out of miners' hands. The pool operator assembles a Bitcoin block that incorporates blocks from (zero or more) altcoins, after validating the transactions in the Bitcoin block as well as all those altcoin blocks. The miner merely tries to solve for the nonce. These predictions are borne out in practice. For example, GHash.IO, at one time the largest Bitcoin mining pool, allows merge mining Namecoin, IXCoin and DevCoin. So those became the most popular merge-mined altcoins.

The second insight from the economic reasoning is perhaps even more worrying for security than the concentration of mining power. When miners' primary cost is proof of work, by design there is no way for miners to "cheat". There is no shortcut to mining given the security of hash functions, and additionally, other miners easily can and will verify the proof of work. Both assumptions fail when the cost is that of transaction validation. A miner could assume that transactions they heard about are valid and hope to get away with it. Besides, for other miners to validate a block and its transactions is just as much work as it was for the miner who found it. For these reasons, we should expect that at least for small merge miners, there's an incentive to skimp on validation. The existence of improperly validating miners makes attacks easier because a malicious miner can create a block that will cause the rest of the miners to disagree on what the longest valid branch is.

To summarize, merge mining solves one security problem but creates many others, in part because the economics of merge mining differ in important ways from the economics of exclusive mining. Overall, it's far from clear that merge mining is a good idea for a new altcoin concerned about mining attacks.

## 10.5 Atomic Cross-chain Swaps

In Bitcoin it's straightforward to create a single transaction that swaps currency or assets controlled by different people or entities. This is the intuition behind Coinjoin, which we studied in Chapter 6. It is also useful for trading smart property, which we looked at briefly in Chapter 9 and will return to in Chapter 11. The same idea enables selling domain names in Namecoin, as mentioned earlier in this chapter.

But in all these cases, the swap transactions are confined to a single block chain, even if they involve different types of assets within that block chain. In general, a transaction on one altcoin is entirely independent of and has no way of referring to a transaction that happens on some other altcoin's transaction history. But is this a fundamental limitation, or is there some way to swap one type of coin for another? That is, if Alice wants to sell a quantity *a* of altcoin to Bob in exchange for a quantity *b* of his bitcoin, can they do so in an atomic fashion, without having to trust each other or relying on an intermediary, such as an exchange service? At first sight this seems impossible, because there is no way to force transactions on two different block chains to happen simultaneously. If one of them, say Alice, carries out her transfer before the other, what prevents him from reneging on his side of the bargain?

The solution is clever, and involves cryptographic commitments and time-locked deposits, both of which are techniques we've seen before. Figure 10.6 describes the protocol. For the moment, assume that blocks in the two block chains are generated in lockstep: one block is generated every time unit. Let $T$ represent the time at the start of the protocol.

1. Alice generates a refundable deposit of *a* altcoins as follows:
   - 1.1 Alice generates a random string *x* and computes the hash $h=H(x)$
   - 1.2 Alice generates **DepositA** as shown below, but doesn't publish it yet
   - 1.3 Alice generates **RefundA**, and gets Bob's signature on it
   - 1.4 Once Bob signs **RefundA**, she publishes DepositA (but doesn't publish **RefundA**)
2. Bob generates a refundable deposit of *b* bitcoins as follows:
   - 2.1 Bob generates **DepositB** as shown below, but doesn't publish it yet
   - 2.2 Bob generates **RefundB**, and gets Alice's signature on it
   - 2.2 Once Alice signs **RefundB**, he publishes **DepositB** (but doesn't publish **RefundB**)
3. Case 1: Alice goes through with the swap
   - 3.1 Alice claims the bitcoins by time $T_1$, revealing *x* to Bob (and everyone) in the process
   - 3.2 Bob claims the altcoins by time $T_2$

   Case 2: Alice changes her mind, does not claim the altcoins, does not reveal *x* to Bob
   - 3.1 Bob claims his altcoin refund at time $T_1$
   - 3.2 Alice claims her Bitcoin refund at time $T_2$

| **DepositA [Altcoin block chain]** | |
|---|---|
| Input: | Alice’s coins of value *a* |
| ScriptPubkey: | Redeemable by providing either (*sigA* and *sigB*) or *sigB* and *x* s.t. *H(x) = <h>* |

→

| **RefundA [Altcoin block chain]** | |
|---|---|
| Input: | DepositA |
| Output: | AddrA |
| Timelock: | $T_2$ |
| ScriptSig: | *sigA, sigB* |

| **DepositB [Bitcoin block chain]** | |
|---|---|
| Input: | Bob’s coins of value *b* |
| ScriptPubkey: | Redeemable by providing either (*sigA* and *sigB*) or *sigA* and *x* s.t. *H(x) = <h>* |

→

| **RefundB [Bitcoin block chain]** | |
|---|---|
| Input: | DepositB |
| Output: | AddrB |
| Timelock: | $T_1$ |
| ScriptSig: | *sigA, sigB* |

**Figure 10.6: Atomic cross-chain swap protocol**

In step 1, Alice deposits altcoins of value *a* so that can be redeemed in one of two ways (a “deposit” simply means sending those coins to a ScriptPubkey that specifies two possible conditions for spending it). First, if Alice and Bob mutually agree, they can redeem it. Indeed, Alice publishes the deposit only after making sure to get a refund transaction signed by Bob — this allows her to redeem her deposit if 2 time units elapse and it hasn’t already been claimed.

The other way to claim Alice’s deposit, at any time, is by providing Bob’s signature as well as the value *x* which opens the hash commitment *h.* Note that we write *<h>* in *DepositA* to indicate that Alice literally writes the value of *h* into the ScriptPubkey. Since *x* is known only to Alice, at the end of stage 1 neither party is able to claim the deposit this way. The idea is that Bob will learn the value *x*, enabling him to claim the altcoins, if and only if Alice claims his bitcoins, as we’ll see.

Step 2 is roughly the reverse of step 1: Bob deposits bitcoins of value *b* so that it can be redeemed in one of two ways. The key difference is that he doesn’t pick a new secret; instead, he uses the same hash value *h* (he would just copy the value from the *DepositA* transaction to the *DepositB* transaction). This is the key to tying together transactions on the two block chains.

At this point the ball is in Alice’s court. She could change her mind about the swap — if at time $T_1$ Alice hasn’t done anything to reveal *x* to Bob, he will simply claim his deposit and quit the protocol. Alice’s other option is to claim Bob’s bitcoins before time $T_1$. But she can only do this by creating and broadcasting a ScriptSig which contains the value *x*; Bob can listen to this broadcast and use the value same *x* to claim Alice’s altcoins, completing the swap.

Note that if Alice tries to claim Bob’s bitcoins a tad too late (after time $T_1$ but before time $T_2$), Bob might be able to claim *both* deposits. Similarly if Alice claims Bob’s bitcoins on time but Bob waits too long, Alice might be able to go home with both deposits. But this is not a problem: we are happy as long as there is no way for a player deviating from the protocol to cheat the other player.

Finally, blocks in Bitcoin or any altcoin don't arrive in fixed time steps, which introduces some messiness, particularly as the two chains may not be synchronized. Let's say both block chains have an average time of 10 minutes between blocks. Then we'd want to pick a "time unit" of say 1 hour. In other words, we'd want to have $T_1$ be at least `current_altcoin_block + 12` and $T_2$ be at least `current_bitcoin_block + 6`, possibly with a greater safety margin.

Unfortunately, there's a small but nonzero chance that the next 12 altcoin block blocks will be found before the next 6 Bitcoin blocks. In this case Alice might be able to claim both deposits. This probability can be made arbitrarily small by increasing the time unit, but at the expense of speed.

This is a neat protocol, but as of 2015 no one uses it. Instead, cryptocurrencies are traded on traditional, centralized exchanges. There are many reasons for this. The first is the complexity, inconvenience, and slowness of the protocol. Second, while the protocol prevents theft, it cannot prevent a denial of service. Someone might advertise offers at amazing exchange rates, only to quit after step 1 or step 2, wasting everyone else's time. To mitigate this and to aggregate and match people's offers, you probably need a centralized exchange anyway -- albeit one you don't need to trust not to steal your coins -- further diminishing the usefulness of the protocol.

## 10.6 Bitcoin-Backed Altcoins, "Side Chains"

Earlier in this chapter we talked about two ways in which we can allocate units of a new altcoin to existing owners of bitcoins: either requiring provably burning bitcoins to acquire altcoins, or simply allocating altcoins to existing holders of bitcoins based on bitcoin addresses that own unspent transaction outputs. As we saw, neither of these allows bilaterally pegging the price of the altcoin to that of Bitcoin. Without such pegging, the price of an altcoin is likely to be volatile during its bootstrapping phase. The motivation for sidechains is the view that this price volatility is problematic: it is a distraction and makes it difficult for altcoins to compete on their technical merits.

Here's what we need in terms of technical features to be able to actually peg the altcoin's price to Bitcoin's at a fixed exchange rate. First, you should be able to put a bitcoin that you own into some sort of escrow and mint one altcoin (or a fixed quantity of altcoins). You should be able to spend this altcoin normally on the altcoin block chain. Finally, you should be able to burn an altcoin that you own and redeem a previously escrowed bitcoin. This is similar to Zerocoin, where we escrow basecoins to create zerocoins, but the difference is that here we need to do it across two different block chains.

The bad news is that as far as we know, there is no way to achieve this without modifying Bitcoin, because Bitcoin transactions can't be dependent on events happening in another block chain. Bitcoin script simply isn't powerful enough to verify an entire separate block chain. The good news is that it can be enabled with a relatively practical soft-fork modification to Bitcoin, and that's the idea behind

Sidechains. The sidechains vision is that of numerous flourishing altcoins that rapidly innovate and experiment, using Bitcoin as a sort of reserve currency. As of 2015 it is only a proposal, but one that is being actively worked on and has serious traction in the Bitcoin community. The proposal is still in flux, and we'll take the liberty to simplify some details for pedagogical purposes.

The obvious but impractical way to extend Bitcoin to allow converting coins from a sidechain back to bitcoins is this: encode all of the sidechain's rules into Bitcoin, including validating all of the sidechain's transactions and checking the sidechain's proof-of-work. The reason this is impractical is that the resulting extensions to Bitcoin's script would be too complex, and the verification effort needed for Bitcoin nodes would be prohibitive. Besides, the complexity and effort would grow with the number of pegged sidechains.

**The SPV trick.** The trick to avoiding this complexity is to use "SPV proofs." Recall from Chapter 3 that Simplified Payment Verification is used by lightweight clients such as mobile apps for Bitcoin. SPV nodes don't validate transactions they're not interested in; they merely verify block headers. Instead of worrying about the longest *valid* branch, SPV clients merely look for evidence that the transaction they care about is in the longest branch, valid or not, and that it has received some number of confirmations. They assume that the miners who created these blocks wouldn't have put in the effort to mine them without validating the transactions in those blocks.

Perhaps, then, we could extend Bitcoin's script with an instruction to verify a proof that a particular transaction (say, one that destroyed a coin) happened in the sidechain. The Bitcoin nodes doing this verification would still be fully validating as far as Bitcoin's block chain is concerned, but they would do relatively lightweight SPV verification of events in the sidechain.

**Contesting a transfer.** This is better, but still not ideal. To do even simplified verification, Bitcoin nodes would still have to connect to the sidechain's peer-to-peer network (for each pegged sidechain!) and track all of the sidechain block headers so that they can determine the longest sidechain branch. What we want instead is this: when a transaction tries to convert a coin in a sidechain back into a bitcoin, it contains all the information that Bitcoin nodes need in order to verify its legitimacy, that is, to verify that a particular sidechain transaction happened. This is the notion of an "SPV proof."

Here we present one way in which it could work, with the caveat that this component of Sidechains is still an area of research. To reference a sidechain transaction in Bitcoin, the user must provide proof of (1) inclusion of the sidechain transaction in a sidechain block and (2) sidechain block headers showing that this block has received a certain number of confirmations which cumulatively represent a certain amount of proof of work. Bitcoin nodes will verify these claims, but will make no attempt to verify that the chain of block headers presented is the longest. Instead, they will wait for a certain defined period, say a day or two, to allow other users to present evidence that the block headers presented in step 2 above are *not* on the longest branch. If such evidence is presented within the defined period, the acceptance of the sidechain transaction in Bitcoin will be invalidated.

The rationale is that if an SPV proof has been presented that shouldn't be accepted because the transaction is not on the longest branch, there must be *some* sidechain user who will be harmed by the acceptance of this proof. This user will have the incentive to present evidence to invalidate the proof. If there is no user who will be harmed (perhaps there was a fork or reorganization of the side chain, but the transaction in question was also present in the other branch) then there is no harm in accepting the proof.

More generally, the system doesn't try to be bulletproof against problems in sidechains, and it won't prevent you from shooting yourself in the foot. If you transfer your bitcoin into a sidechain that has broken crypto, for example, someone else might be able to steal your coin on the sidechain and convert it back into a bitcoin. Or all mining on the sidechain might collapse due to bugs, with the locked bitcoins lost forever. But what the proposal does make sure of is that problems on sidechains can't damage Bitcoin. In particular, there is no way to redeem the same coin twice from a sidechain regardless of how buggy it may be — that is, sidechains won't allow you to mint bitcoins.

**Compact SPV proofs via proof-of-work samples.** There is one final difficulty. Some of the sidechains might have a high block rate, perhaps one block every few seconds. In this case, even verifying SPV proofs might be too onerous for Bitcoin nodes. It turns out that we can use a clever statistical technique to decrease the amount of computation needed to verify $N$ block confirmations from $O(N)$ to a number that grows much slower than linear.

The intuition is this: when we're verifying that a block is buried deep in the block chain, we're verifying that each block that builds on it meets the target difficulty, i.e., it satisfies $hash < target$. Now the hash values of these blocks will uniformly distributed in the interval $(0, target)$, which means that statistically, about 25% of those blocks will in fact satisfy $hash < target / 4$. In fact, the amount of work needed to find $N/4$ blocks that each satisfy $hash < target / 4$ is the same as the amount of work needed to compute $N$ blocks each satisfying $hash < target.$ There is of course nothing special about the number 4; we could replace it by any factor.

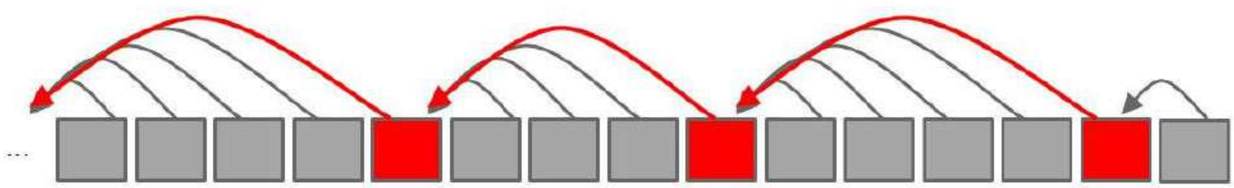


**Figure 10.7: a proof-of-work skiplist.** Blocks contain pointers both to the previous block and to the nearest block that satisfies $hash < target / 4$. The concept could be applied recursively, with a third level of pointers to blocks satisfying $hash < target / 16$, and so on.

What this means is that if we had some way of knowing which blocks in the chain satisfied $hash < target / 4$, and verified only those blocks (or block headers), we'd be done, having put in only one-fourth of the verification work! How would we know which blocks satisfy $hash < target / 4$? The block themselves could tell us. This is shown in Figure 10.7, each block would contain a pointer both to its predecessor as well as to the most recent block that satisfied *hash < target / 4*.

How far can we push this? Can we pick arbitrarily large multiples? Not really. The logic here is similar to pooled mining, but in reverse. In pooled mining, the pool operator verifies shares, which are blocks with a lowered difficulty (that is, a higher target value). Miners find many more shares than blocks, so the operator must do extra work to verify them. The benefit of doing so is the ability to estimate the miner's hash power much more accurately — the variance of the estimate is lower.

Here we see the opposite tradeoff. As we do less and less work to estimate the total amount of work that has gone into building the chain, our estimate will have a greater and greater variance. Here's an example. Suppose *N=4*, so that without the skiplist solution, we'd check that there are 4 blocks that satisfy *hash < target*. The expected amount of work that an adversary must do to fool us is 4 times the average amount of work needed to find a block.

Suppose the adversary only does half this amount of work. If we do the math, it turns out that this adversary has a 14% chance of finding 4 blocks that satisfy *hash < target*. On the other hand, with a skiplist solution with a factor of 4, the adversary's task would be to find a single block that satisfies *hash < target/4*. In this scenario, the lazy adversary who only does half the expected amount of work will be able to fool us with a probability of 40% instead of 14%.

## 10.7 Ethereum and Smart Contracts

We have seen several ways to use Bitcoin's scripting language to support interesting applications, such as an escrowed payment transaction. We've also seen how Bitcoin script is somewhat limited, with a small instruction set that isn't Turing-complete. As a result, some new altcoins propose adding application-specific functionality. Namecoin was the first example but many others have proposed cryptocurrencies much like Bitcoin but supporting gambling, stock issuance, prediction markets, and so on.

What if, instead of needing to launch a new system to support every application, we built a cryptocurrency that could support *any* application we might dream up in the future? This what Turing-completeness is all about: to the best of our knowledge, a Turing-complete programming language lets you specify any functionality that is possible to be specified by any other computer. To some extent, the situation today harkens back to the early days of computers themselves in the 1940s: increasingly complicated machines were being built for various specific applications during World War II (such as brute-forcing keys used by mechanical cipher machines or determining firing trajectories for naval artillery), motivating researchers to build the first reprogrammable general-purpose computers that could be used for any conceivable applications.

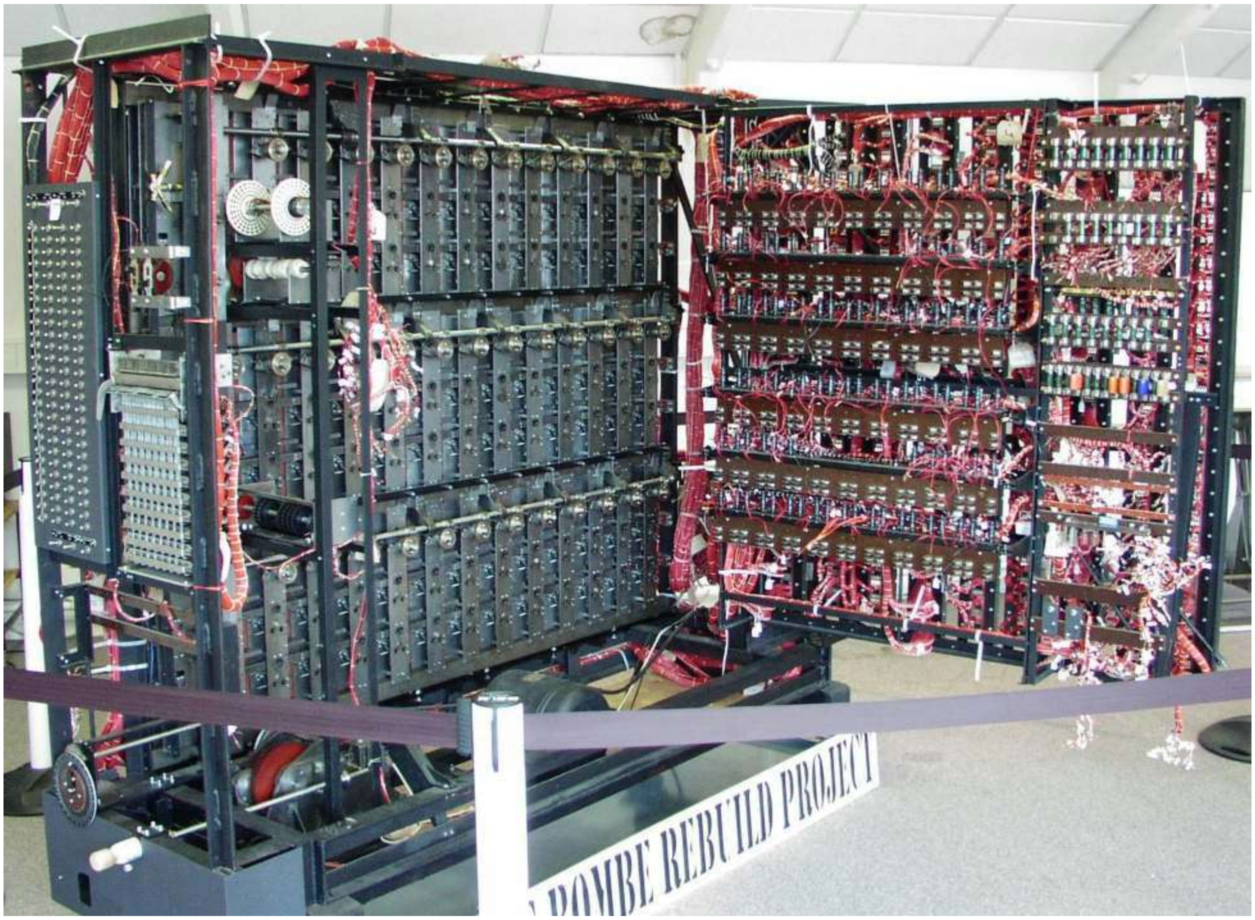



**Figure 10.8: A rebuilt Bombe machine located at the Bletchley Park museum.** The Bombe was a special-purpose computer designed by Alan Turing to crack German Enigma ciphers. Will Ethereum do to application-specific altcoins what the general-purpose computer did to Bombe-like contraptions?

Ethereum is an ambitious altcoin that aims to provide a Turing-complete programming language for writing scripts or “contracts”. While there are other proposals to do this, Ethereum is the most notable: it introduced several novel technical ideas, held a successful crowd-funding campaign, raising $20 million over several months, and adopted aggressive choices for parameters such as block time. In this section we’ll provide a brief overview of Ethereum — though the system is complex enough that we could easily devote an entire second textbook to it!

**Smart Contract Programming Model.** The term *smart contract* was first used to describe the use of computer systems (or other automated means) to enforce contracts. As an example, you could think of a vending machine as a mechanical smart contract that enforces an agreement between you and the machine’s owner involving the purchase of a candy bar.

In Ethereum, a contract is a program that lives on the blockchain. Anybody can create an Ethereum contract, for a small fee, by uploading its program code in a special transaction. This contract is written in bytecode and executed by a special Ethereum-specific virtual machine, usually just called EVM. Once uploaded, the contract will live on the blockchain. It has its own balance of funds, other users can make procedure calls through whatever API the program exposes, and the contract can send and receive money.

**A simple example: Namecoin in Ethereum.** We claimed that Ethereum can be used to implement any application-specific altcoin's functionality. As a simple example, we can show how to implement Namecoin-style functionality in a very simple Ethereum contract.

One example implementation is shown in Figure 10.8. It is coded in Solidity, Ethereum's high-level programming language for defining contracts. This contract implements a crude name/value store or name registry, in which names are assigned values once and for all. The contract defines a data variable, registryTable, which is a mapping from 32-byte strings to public keys. initially, it maps every string to the null address 0x0000000000...000. This contract also defines a single entry point, called "claimName". This entry point accepts a single argument, name. First, the contract makes sure that the caller has sent a value of at least 10 wei, wei being the smallest currency unit in Ethereum. If insufficient funds have been sent, the contract terminates with an error (the "throw" statement does this) and no action is taken. If sufficient funds are sent and the name is not yet taken, then it is permanently assigned the value of whichever address invoked this function.

```
contract NameRegistry {
      mapping(bytes32 => address) public registryTable;
      function claimName(bytes32 name) {
            if (msg.value < 10) {
                  throw;
            }
            if (registryTable[name] == 0) {
                  registryTable[name] = msg.sender;
            }
      }
}
```

**Figure 10.8: A simple Ethereum smart contract implementing a name registry.**

That's all this contract can do in 8 lines of code. But we could add all of the other features of Namecoin with a little more work. For example, we could store more data with each mapping than just the address of the entity that claimed it. We could require name owners to re-register periodically by storing a "last updated" time and allowing other users to claim names that haven't been updated in a long time.

We might also want to add a second function to allow the money be withdrawn. As currently programmed, the money will just accumulate at the contract forever, essentially being removed from circulation. Of course, in the function allowing money to be withdrawn, we'd better make sure to check that the caller is the owner of the contract. Anybody can call any function on an Ethereum contract, but the calls are signed so we can securely identify who the caller is.

**Gas, incentives, and security.** Unlike Bitcoin, Ethereum supports loops, although we didn't need them in our first example. That should immediately raise alarm bells. If there are loops, there can be infinite loops. In general, Ethereum contracts might run forever for a variety of reasons. A famous result in computer science (the undecidability of the Halting Problem) states that there's no algorithm that can look at a program's source code and always correctly determine if it will run forever or not. So how can we prevent contracts from running forever?

More generally, we need some way to limit contracts that take a long time to run, even if it's finite. Ethereum uses a mechanism called *gas* to achieve this. Essentially, executing each virtual-machine instruction costs a small amount of money, called gas. Different operations cost different amounts. Basic operations like addition or comparison cost 1 gas, whereas computing a SHA-3 hash (available as a built-in instruction) costs 20 gas and writing a 256-bit word to persistent storage costs 100 gas. Every transaction also costs 21,000 gas right off the bat. You can think of Ethereum like flying on an ultra-discount airline: you pay to get on board and you pay extra for everything you do from there. The complete list of instructions available in Ethereum and the gas cost of each is fixed; changing these would require a hard fork just like changing the semantics of Bitcoin's scripting language.

Gas is paid for using Ethereum's built-in currency, called ether. It's just called gas when being used to pay for contract execution. Every transaction can specify the "gas price", that is, how much ether it will pay per unit of gas consumed. The gas price offered is like the transaction fee in Bitcoin: miners are free to publish transactions with any gas price, and each miner can independently decide their fee structure. This should result in a market price for gas reflecting supply and demand. As of early 2016, however, the network remains experimental, and has coalesced around a default of 50 gigawei per unit of gas. 50 gigawei is $5\times10^{-8}$ ether, or about $3\times10^{-10}$ BTC given the ether-BTC exchange rate in January 2016.

Every call must specify up front how much gas it is willing to spend (the "gas limit"). If this value is hit (running out of gas), execution halts, all changes to the program's state are undone, and the miner pockets the gas anyway. So it's very important not to run out of gas.

The gas requirement means that very expensive computations are not suitable for Ethereum. The system is not designed to be a cloud-computing service where you to pay others to do a difficult computation that you're unable to do yourself. Services like Amazon's Elastic Compute Cloud or Microsoft's Azure provide millions of times more bang for your buck. On the other hand, Ethereum is suitable for implementing security protocol logic. Essentially, it provides a service that two (or more) anonymous parties can count on to behave as specified.

The security of Ethereum's block chain is not nearly as well-established as Bitcoin's. Theoretically, the system is much more complex and therefore harder to reason about mathematically. Practically, Ethereum hasn't been around for very long and hasn't been subject to the same kind of scrutiny as

Bitcoin. In particular, there are concerns that the cost of transaction processing throws Bitcoin-style incentive arguments out of whack, similar to our discussion about merge mining. When transaction processing is a nontrivial fraction of a miner's total cost, the system favors larger miners since this cost is independent of hash power. More importantly, the gas payment goes only to the miner who initially includes the transaction in a block. But all miners building on that block must also validate the transaction, and they don't get paid for doing so. This means they have an incentive to skip validation. As we saw earlier, this can be dangerous for the health of the block chain.

**A second example: chess in Ethereum.** We still haven't said much about what you can do with Ethereum that's new, so let's look at a second example. Suppose Alice wants to challenge Bob to a game of chess with money on the line. The only problem is that Alice and Bob live in different countries and neither trusts each other to pay if they lose. This is a problem Ethereum can solve!

Alice will write an Ethereum program that implements the rules of chess and upload it to Ethereum. She'll send the contract a quantity of ether equal to the amount she wants to bet. Bob can see this contract, and if he decides to accept the challenge, he can start the game by sending his own betting stake to the contract. Before doing this, Bob should make sure the contract is correctly written in that it implements chess and will ultimately send all of its value to the winning player.

Once both players have sent their stake in, the contract should check that the stakes are equal, assuming they're making an even wager. At this point the game is afoot, and there should be no way for either player to extract the money from the contract without actually winning the game, or for anyone else to extract the money under any circumstance.

Alice and Bob will take turns sending transactions to the contract which indicate the next move they'd like to play. The contract, of course, must ensure that each move is sent in only by the player whose turn it is to move, and not by the other player or by someone else entirely. Remember that every transaction (which causes the contract to execute a function) is signed by the caller, so the contract can ensure this. The contract will also have to check all of the rules of chess. If a player tries to move a pawn three spaces, that will have to be rejected.

Eventually, the game will end. After each move, the contract must check if either player is mated, or if the game is a draw by stalemate or one of the other drawing conditions in chess. Players should also be able to send in a move indicating their resignation. When the game ends, the contract can terminate itself and send all of the money to the winning player. or split the money in case of a draw.

Conceptually, this is a simple application of Ethereum, but there are subtleties. What if a player in a losing position simply walks away? The contract will need a mechanism that awards the money to the opponent if a player hasn't submitted a valid move in a specified period of time.

Which player gets to move first? "Playing white" confers a slight advantage in chess, so both players want this advantage. This points to a difficulty faced by many Ethereum contracts: there is no built-in source of randomness. This is a hard problem, as the random number generator needs to be verifiable by all miners (so they can check that the contract was executed correctly) but shouldn't be predictable to either player (or else they might refuse to join if they know they will have to play second).

This is the problem of randomness beacons. As we discussed in Section 9.4, the contract might hash the value of the next block in the blockchain after both players have joined. For our specific application, the problem is a bit easier, since only Alice and Bob need to be convinced that the coin flip is random, not the whole world. So they might use the approach from Section 9.3: they both submit the hash of a random value, then both reveal the inputs, and derive the random bit from the inputs. Both approaches have been seen in practice.

**Other applications.** Playing chess might be fun, but the real excitement for Ethereum is about financial applications. Many of the applications we've discussed in the text so far, including prediction markets, smart property, escrowed payments, micropayment channels, and mixing services, can all be implemented in Ethereum. There are subtleties to all of these applications, but they are all possible and in most cases are much simpler to implement than the types of bolt-on protocols we've seen with Bitcoin. There are also a host of other applications, like auctions and order books, that we haven't talked about but which people are enthusiastic about using Ethereum to implement.

**State and account balances in Ethereum.** In Chapter 3, we discussed two ways to design a ledger: account-based and transaction-based. In a transaction-based ledger like Bitcoin, the blockchain stores only transactions (plus a small amount of metadata in the block headers). To make it easier to validate transactions, Bitcoin treats coins as immutable, and transaction outputs must be spent in their entirety, with change addresses used if necessary. Effectively, transactions operate on a global state which is a list of UTXOs, but this state is never made explicit in the Bitcoin protocol and is simply something miners create on their own to speed up verification.

Ethereum, on the other hand, uses an account-based model. Since Ethereum already stores a data structure mapping contract addresses to state, it is natural to also store the account balance of every regular address (also called an owned address) in the system. This means that instead of representing payments using an acyclic transaction graph where each transaction spends some inputs and creates some outputs, Ethereum just stores a balance for each address like a traditional bank might store the balance of each account number.

**Data structures in Ethereum.** In Chapter 3, we said that an account-based ledger would necessitate fancy data structures for record-keeping. Ethereum has just such data structures. Specifically, every block contains a digest of the current state (balance and transaction count) of every address as well as the state (balance and storage) of every contract. Each contract's storage tree maps arbitrary 256-bit addresses to 256-bit words, making for a whopping $2^{256} \times 256 = 2^{264}$ bytes of storage! Of course, you could never fill up all of this storage, but that's the theoretical space. The digest makes it easy to prove that a given address has a given balance or storage state. For example, Alice can prove to Bob what her balance is without Bob having to scan the entire block chain to verify the proof.

The simple binary Merkle tree used in Bitcoin would work for this purpose as it allows efficient proofs of inclusion (provided miners ensure that no tree will include two different states for the same address). But we also want fast lookups and the ability to efficiently update an address's value. To do this Ethereum uses a slightly more complicated tree structure called a *Patricia tree*, also known as a prefix tree, trie, or radix tree. Each Ethereum block includes the root of a Merkle Patricia tree committing to the state of every address, including contract addresses. Each contract's state, in turn, includes a tree committing to the entire state of its storage.

Another tricky issue with an account-based ledger is preventing replay attacks. In Bitcoin, since every transaction consumes its input UTXOs, the same signed transaction can never be valid twice. With Ethereum's design, we need to make sure that if Alice signs a transaction saying "pay 1 ether to Bob", Bob can't broadcast the transaction over and over again until Alice's account is drained. To avoid this, every account in Ethereum has a transaction counter tracking how many transactions it has sent. The statement Alice really signs is "I authorize my *n*th transaction to be a payment of 1 ether to Bob." This transaction can't be replayed because after it is processed, Alice's transaction counter will increment and is part of the global state.

To summarize, Ethereum uses more powerful data structures than Bitcoin as part of its ledger. Although we haven't looked at the details, it allows efficient proofs of a variety of types of statements about accounts, contracts, and transactions.

**Ethereum project.** Ethereum was initially described in late 2013 and launched its first release, dubbed Frontier, in 2015. Ethereum utilized a pre-sale, making units of the ether currency publicly available for a fixed price in Bitcoin, with all of the proceeds going to the Ethereum Foundation.

This is a slower pace of development compared to many altcoins, but it reflects that fact that Ethereum is much more complex. In addition to EVM, a new programming model, and new data structures, Ethereum made significant changes to Bitcoin's consensus protocol as well. The block time is targeted at 12 seconds instead of 10 minutes. To lessen the impact of stale blocks, which comprise a larger fraction of blocks in Ethereum than in Bitcoin, Ethereum uses an alternative protocol called GHOST to compute the consensus branch. It also uses a different proof-of-work. Currently, it's a mix of hash functions designed to be memory hard, though in the future Ethereum plans to switch to a proof-of-stake system.

This represents another major departure in philosophy from Bitcoin. The Ethereum project is stewarded by a non-profit foundation and is relatively centralized in planning and decision making. There is an announced schedule of future versions of the protocol that will introduce changes based on early Ethereum experience. These will be hard forks by design, and furthermore, every Ethereum contract will be destroyed in between versions. So Ethereum is still very much an experimental system with major changes planned. As of 2015, it's premature to invest too much in building real applications on top of Ethereum. But it's a very promising system. Perhaps future versions of this textbook might even be called "Ethereum and Cryptocurrency Technologies."

To wrap up this chapter, we've talked about how a Bitcoin is an important part of a much larger ecosystem of cryptocurrencies and altcoins. They compete, cooperate, and interact in various ways, some cooperative, some harmful. It's also possible that in the future, there will be technical ways for transactions in one block chain to explicitly refer to transactions in another block chain.

There remain several open questions. Will the altcoin ecosystem consolidate so that a small number dominate, or will it stay diversified? Will application-specific altcoins proliferate or will the Ethereum model of a general-purpose platform come to dominate? Is Bitcoin itself eventually going to be overtaken by some other altcoin? Is it a good idea to encourage interaction between Bitcoin and altcoins? Or should each cryptocurrency be a separate system, for example by using incompatible mining puzzles rather than merge mining? We can't answer these questions right now, but we've talked about all of the concepts you need to understand and appreciate their importance.

## Further Reading

The sidechains white paper:

**Back, Adam, Matt Corallo, Luke Dashjr, Mark Friedenbach, Gregory Maxwell, Andrew Miller, Andrew Poelstra, Jorge Timón, and Pieter Wuille. Enabling blockchain innovations with pegged sidechains. 2014.**

A paper about Namecoin and alternate ways to design name/value stores using cryptocurrencies:

**Kalodner, Harry, Miles Carlsten, Paul Ellenbogen, Joseph Bonneau, and Arvind Narayanan. An empirical study of Namecoin and lessons for decentralized namespace design. In Workshop on the Economics of Information Security, 2015.**

The Ethereum white paper:

**Various authors. A Next-Generation Smart Contract and Decentralized Application Platform.**

A paper that analyzes the incentive misalignment in Ethereum:

**Luu, Loi, Jason Teutsch, Raghav Kulkarni, and Prateek Saxena. Demystifying incentives in the consensus computer. ACM SIGSAC Conference on Computer and Communications Security, 2015.**

# Chapter 11: Decentralized Institutions: The Future of Bitcoin?

So far in this book we've explored the state of Bitcoin and block chain technologies as of 2015. In this chapter, we'll consider what future possibilities may be realized by Bitcoin. We won't claim to know what might unfold, following the adage "never make predictions, especially about the future." Hence the question mark in the title.

Instead, we'll stick to the academic approach we've taken so far in this book, even when studying potential future technologies. Bitcoin's future is a subject that seems to muster enthusiastic and breathless visions of a true technological revolution. This chapter could be a manifesto. It is not. We identify notable proposals and take a clinical approach to categorizing them and critically evaluating their relative pros and cons.

Bitcoin is a broad subject that encompasses the protocol itself as well as its potential as a platform for new applications. The focus of this chapter is not the future of the Bitcoin protocol, although we recognize that there are many issues that will shape the future of the protocol that are important to study, including Bitcoin's governance, efficiency, scalability, and feature set.

Instead we will focus on how Bitcoin's apparent success at decentralizing currency may cause us to rethink other centralized institutions — ones dealing with stocks, bonds, property titles, and more. We'll ask if block chain technology could be applied to decentralizing them as well. Not only should we ask if decentralization is technically possible, but also if it is financially sensible and beneficial to society.

## 11.1 The Block Chain as a Vehicle for Decentralization

There were numerous failed attempts at digital or electronic cash before Bitcoin (the preface to this book touched upon many of them). Bitcoin's key difference compared to most of these attempts is decentralization. The core innovation of Bitcoin that enables decentralization is the block chain.

In this section, we will consider how block chain technology may enable decentralization in areas other than currency. Throughout this chapter, we'll use a running example of a car whose ownership is controlled through a block chain. This is a specific example of a more general idea of smart property which we introduced in Chapter 9. Smart property, and digital contracts that govern them, were pioneered by Nick Szabo and others in the early 1990s, well before Bitcoin was proposed. However with a block chain, the idea can be made concrete.

**Motivating Example.** Modern automobiles use two primary locking mechanisms: physical locks on the doors and a vehicle immobilizer which electronically prevents the engine from starting. The owner is provided with a key fob that communicates wirelessly with the car to authorize the doors to unlock and the engine to start based on the proximity of the fob to the car and potentially a user action such as pushing a button.

To prevent an adversary from spoofing the car key, such unlocking mechanisms should use cryptography. While security researchers have found problems with many recently deployed locking protocols, it's possible to get it right. Typically these algorithms employ symmetric key cryptography, but for the purposes of our example, consider one that uses a digital signature scheme, such as ECDSA, based on asymmetric cryptography.

In this example, the car might store a copy of the public key(s) of the fob(s) authorized to open the doors and start the engine. When a fob requests access, the car sends a random challenge and asks the fob to sign it with the private key that it stores. If and only if the fob can respond with a proper signature on this challenge, the car authorizes access. So far this is not much of a departure from how locking mechanisms actually work, except that it uses heavier-weight crypto that would be slightly more costly to deploy.

**Get Smart.** The next iteration of designing a smart car is to assume that the public key that verifies the key fob is not hardcoded by the manufacturer directly. Instead, the car has the technical capability to constantly, wirelessly receive new blocks from a block chain such as Bitcoin's. When the car is manufactured, the public key in the key fob of its first user (say a manager on the assembly plant) is added to the block chain in a special transaction, and the car is programmed with its transaction ID.

The core idea is that as the car changes possession — it might go from an assembly line to quality control to a delivery person to a car dealership to its first owner — updates to the block chain will authorize each transfer. It is important to note that in this model, the authorized key fob does not travel with the car. Each person or entity has a pre-existing key fob (or carries/wears technology suitable for implementing the functions of a key fob) with a unique signing key which is activated or deactivated based on transactions that occur on the block chain. Such a transaction would take the car's most recent transaction ID as an input and designate a new public key as the output. It would be signed with the private key corresponding to the current owner.

This is similar to the idea of smart property that we discussed in Chapter 9, but with a key difference. The block chain transaction doesn't merely *represent* a change in *ownership* of the car: it additionally transfers actual physical control or *possession* of the car. When a car is transferred this way the earlier owner's key fob stops working and the new owner's key fob gains the ability to open the locks and start the engine. Equating ownership with possession in this way has profound implications. It enables a powerful kind of decentralization, but it is not obvious if this is a good idea. We'll return to this question in the final section of this chapter.

**Secure exchange.** Let's consider the situation where Alice owns a smart car and wants to sell it to Bob. The ability to transfer control digitally opens up interesting possibilities. For example, Alice might be traveling overseas and to fund further travel expenses might want to sell her car, which is physically parked in her driveway back home. With an internet connection, Bob could pay Alice for the car with

Bitcoin, Alice can remotely transfer ownership to Bob with the block chain used by the car, and Bob can drive away with his new car.

However, such transactions carry a certain risk. If Bob sends payment first, Alice might keep the money and not transfer ownership. If Alice transfers ownership first, Bob might drive away without paying for the car. Even if Alice is physically present, one party might abort and it could be difficult for a third party who was not present to mediate the dispute.

We've encountered this problem several times before, including in Coinjoin (Chapter 6), and in Namecoin (Chapter 10). The solution in all these cases uses the same principle. As long as the currency used for payment and the car ownership co-exist on the same block chain, Alice and Bob can form a single atomic transaction that simultaneously transfers ownership of the car and the payment for the car. Specifically, the transaction would specify two inputs: Alice's ownership and Bob's payment; and specify two outputs: the ownership to Bob and the payment to Alice. The transaction requires both parties to sign because both are providing inputs. If one signs and the other does not, the transaction is not valid. Once one party signs, the transaction details cannot be changed without invalidating the signature. Once the signed transaction is broadcast to the block chain, the car will wait for a preset number of confirmations (say, 6) and then allow Bob access. Simultaneously, Bob's payment to Alice will be confirmed. One cannot happen without the other.

The diligent reader might notice a subtle problem. Bob could accept a transaction signed by Alice, sign it, but not actually broadcast it (yet). If the price of what Alice is selling changes, Bob can then broadcast the old transaction at the original price. More complicated atomic transactions have been proposed that include a time-out. Alice can also simply spend the input to a new address she controls to invalidate the signed transaction she gave to Bob as a means of revoking it.

This is the first of many examples that we'll see in this lecture that allows us to use block chain technologies to decentralize a variety of different types of real-world protocols, and we'll achieve different types of decentralization. But this idea of **atomicity** is common to most of them, that is, coupling together the deliverables of each side of a transaction so they all happen simultaneously (or not at all). Atomicity is an important security concept with applications outside of block chain technology.

## 11.2 Routes to Block Chain Integration

Because Bitcoin's block chain has been tailored for currency, it can be challenging to repurpose it to represent the semantics of other applications. In the Bitcoin community, you will find many people who are quite partial to either Bitcoin or alternative block chains as a platform for decentralization. We will try to neutrally examine the two alternatives in this section.

## Route 1: Directly on Bitcoin

The natural starting point for block chain integration is Bitcoin's block chain. This is the approach we used in the previous example of a smart car. The main advantage to using Bitcoin directly is deployability: the code runs, the network has acquired significant mining power, and the consensus process appears sound. However we were only able to use Bitcoin in the example application with some hacks, such as an equivalence between the crypto that's used to authorize Bitcoin transactions and the crypto that's used to open car doors. It will not always be the case that such hacks are possible. More fundamentally, if you have some arbitrarily complex contract between different parties, it is not necessarily the case that it can be represented adequately on Bitcoin's block chain and executed atomically. To illustrate the perils of using Bitcoin's block chain, let us consider how we might implement a few natural applications of disintermediation.

First consider **crowd funding services**. As of 2015, the largest example is Kickstarter which matches entrepreneurs with funders through a central website. If we liked the idea of Kickstarter but wanted to build a completely decentralized alternative, we would need to realize a system where entrepreneurs can request contributions, but cannot spend the money until they collect a pre-specified amount, all without the existence of an intermediary.

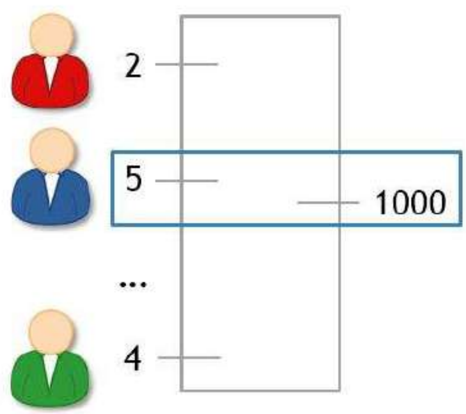



**Figure 11.1: crowd-funding via Bitcoin.** Each contributor signs their own input and the output. The transaction will be invalid until the cumulative sum of inputs matches or exceeds the output.

An approach to technically achieving this, with Bitcoin, is to instruct entrepreneurs to create a single transaction with an arbitrary number of inputs (that can vary as the process in underway) and a single output to themselves for a specified amount, say 1000. Such transactions will circulate amongst potential sponsors, where anyone can contribute by adding an input to the transaction for the amount of their contribution and digitally signing their own input, as well as the overall output. Such a transaction cannot be spent by the entrepreneur until the inputs are greater than or equal to the output. This uses some little-known features of Bitcoin in order to spend the final transaction given only these signatures of limited form. While this is achievable on Bitcoin today, we already have to delve into some little known-corners of Bitcoin. It is not an everyday standard Bitcoin transaction.

Now consider a second example: **paying for a proof**. This example may initially seem strange but has some important applications. To illustrate it, say there is a hash function H and a publicly known value *y* that is ostensibly an output value of *H* on some input value, or pre-image, *x*. Alice claims she knows this value *x* and Bob would like to pay Alice to learn it as well. In general, *H* could instead be any computable program, and Bob would like to learn input values that produce certain outputs he is interested in. In a variant of this problem, Bob might pay for the input values to be published publicly on the block chain.

To securely realize this transaction, we must ensure atomicity: Alice should only get paid if she produces a correct input and Bob must be committed to paying upon production of such an input. Recall that in the protocol for atomic cross-chain swaps in Chapter 10, we showed how to tie a payment with the revelation of the input value to a given hash output. A similar approach can be used here.

These examples illustrate an important limitation of the direct approach of using Bitcoin's block chain. In each case, we had to encode a complex transaction from the real world into Bitcoin's abstractions. This may not always be possible. In the example of the smart car, we conveniently assumed that the car uses ECDSA signatures for authenticating the car owner. That allowed us to use the same public/private key pair on the block chain and in a key fob to unlock and start the car. In the crowd-funding example, the way we have described it, the entrepreneur is able to collect only the exact amount they requested, no more. If the contributions exceed that amount, that excess becomes a transaction fee. Finally, in the paying for proof example, linking the payment to the revelation of a value becomes tricky if the function *H* isn't one of the hash functions that Bitcoin's script supports.

If you can't — or don't want to — shoehorn your application into Bitcoin's transaction semantics, there is always the option of using an overlay currency, which we saw in Chapter 9. This treats Bitcoin as a mere data store, so the expressiveness of Bitcoin's script becomes irrelevant. In addition to the ability to implement many more types of applications, this approach can also enable transparency. Consider the car sale example again. If the color of real world objects (in the sense of colored coins) is known, anyone can examine the block chain to see when a car sale has happened and how much was paid for it without necessarily knowing the identities of the buyer and seller. This may be useful in some circumstances, and the color can be kept private in situations where it is detrimental.

On the other hand, there are important drawbacks. Users of an overlay currency can't rely on Bitcoin miners to validate their transactions (since miners don't understand the transaction semantics of the overlay). This means all users of the overlay must run their own full nodes, and SPV is not possible. Overlay currencies are also brittle if there are bugs in implementations that cause consensus protocol to fail. If two implementations of an overlay currency mutually disagree on whether a particular transaction is valid, it may fork the currency into two, with potentially disastrous consequences. By contrast, when miners are validating transactions, this is much less likely to happen, and if it does, it will be noticed quickly and is likely to get resolved without resulting in a fork.

An additional consideration, whether or not we're using an overlay, is the issue of burdening or "polluting" the Bitcoin block chain with transactions that are outside its original scope. This is a divisive issue in the Bitcoin community. We won't pick a side, but we'll point out that there is a way to mitigate this problem: using Bitcoin as a mere timestamping service, as we saw in Chapter 9.1, and not even as a data store. As of 2015 there are nascent services that offer a separate block chain or data store, but one that is timestamped via the Bitcoin block chain. This is just like the GuardTime service from Chapter 9, but with hashes committed every 10 minutes to the Bitcoin block chain instead of every week in the newspaper. Using Bitcoin for timestamping requires only one transaction per block (for each such service or protocol). One drawback is that such external data stores are unlikely to be as widely replicated and available as Bitcoin's block chain. Additionally, it introduces a degree of centralization.

To summarize, whether using an embedding technique or not, Bitcoin's block chain does enable many novel applications. It comes with the benefit of wide-scale adoption, from both users and miners, which makes it a secure and readily deployable option.

## Route 2: Alternative block chains

The other route to decentralization is to utilize an alternative block chain. Here again there are a few options. The most obvious one is to have a separate block chain with its own rules, functionality, and currency, i.e., an altcoin. Another option is sidechains, which we looked at in Chapter 10. The main difference is that the currency represented by the sidechain would be pegged in a 1:1 fashion to Bitcoin. Sidechains with enhanced scripting capabilities could allow us to achieve complex contracts and enable disintermediation. However, supporting sidechains requires modifications to Bitcoin, and as of 2015 it hasn't yet happened.

The third option is to utilize an already-existing alternative block chain that supports the ability to create new applications on top of it. As of 2015, the most prominent project that seeks to be a platform for decentralized cryptocurrency-based applications is Ethereum, which we discussed in Chapter 10. Conceptually, it is a dream platform for decentralizing arbitrary complex contracts. However it also has some practical challenges: at least as of 2015, it does not have the maturity, adoption, or mining power of Bitcoin, nor has it received a comparable level of scrutiny. Nevertheless, it is a fascinating thought experiment for decentralizing powerful contracts, and either Ethereum or a similar system might become practically viable in the future.

## 11.3 Template for Decentralization

We have reviewed a number of avenues for achieving decentralization on a block chain. Next, it would be useful to establish a template for what decentralization looks like in terms of what is being decentralized, which type of block chain is appropriate, and what exactly decentralization means in terms of entities and security.

### Levels of Decentralization

**Decentralization through disintermediation.** Let's return to the example of the smart car. To understand it better, let us ask, what is the real-world process that this digital type of ownership transfer seeks to replace?

Sticking with cars as the example of property, in the United States, ownership is determined by the title document. This is a centralized form of ownership. The title document only has meaning to the extent that the Department of Motor Vehicles (DMV) recognizes it. When a car is sold, it is not enough to physically transfer this document from the seller to the buyer. The transfer has to be registered in person with the DMV, who will update their central database. With block chain transfers, we move from a state-controlled centralized process to one without any intermediaries. It achieves decentralization through **disintermediation**.

**Dispute mediation: decentralization through competition.** Now assume that there is a dispute about the sale of a car. Perhaps the seller sold a lemon car to the buyer, and the buyer is unhappy and wants to reverse the transaction. In Chapter 3, we discussed 2-out-of-3 multisignature transactions which can allow escrow if, in addition to the buyer and the seller, there is a judge or a mediator. In this scenario, the buyer can transfer bitcoins in a separate transaction from the car, not directly to the seller, but instead to a two-out-of-three address which is controlled jointly by the buyer, the seller and the mediator. The mediator can either approve the transfer or revert it with the help of one or the other party, but cannot steal the money.

This is a good start to building a dispute-resolution mechanism, but there are still many details to sort out. First, we lose the atomicity of the car sale that we relied on earlier. Second, it is not clear if the car's ownership can be reverted with the money. Third, if the car is transacted to a 2-out-of-3 address as well, whose key fob should be authorized to unlock it while in this state? Our purpose here is not to iron out these issues but to use the example to carefully consider the role of the mediator. Specifically, let us compare this model of mediation to a more traditional model.

How would dispute mediation happen in the physical world? It would likely go through the court system, a centralized, state-controlled mediation process that is best navigated with the help of hired lawyers. On the other hand, with a digital contract, the parties are free to choose any mediator they want. No longer mandated to work with the legal system, a private market for mediation could emerge where potential intermediaries can compete on perceived fairness, efficiency, and cost. There are also a number of challenges. The first is incentives: mediators might be bribed by either of the parties to a transaction. The second is that funds are locked up during the dispute-filing period. Finally, participants may be anonymous, which makes it difficult to ultimately involve the courts if internal dispute resolution fails. Even if the parties are identified, digital contracts are currently not recognized by courts.

Our point here, however, is that this is not decentralization through disintermediation — we are not completely removing the intermediary. Rather, it enables entities to choose who they trust. In other words, it is decentralization through **competition**. Thus there is a spectrum where on one side you have a single mandatory intermediary and on the other side, you remove the need for any intermediary at all — complete disintermediation. In the middle, you could have multiple competing intermediaries as we just saw. In fact, we saw this earlier in Chapter 9 when we discussed decentralized prediction markets. Instead of a single entity, like InTrade, running the market, participants are free to choose who they trust from multiple competing arbitrators that perform the sensitive operations within the market.

## How Security is Achieved

There is another observation we can make about this example. The security of the dispute-mediation process does not rely on atomicity. Instead, it requires trusting the mediator. How do mediators become trustworthy? There could be a variety of ways, but an obvious one is reputation. Unlike atomicity, which is a technological security-enhancing mechanism, reputations are built up over time through inherently social mechanisms.

Reputation has a role to play in the absence of technological solutions or as a complement to them. However, it is not without drawbacks. Reputations are tied to identities, and if identities are not static or binding, reputation doesn't work well. For example, if a restaurant receives terrible reviews online and decides to close and reopen under the same management but a new name, its bad reputation is reset. In an anonymous environment, reputations cannot work at all, and in a pseudonymous environment where identities can be switched effortlessly, reputation-based systems face significant challenges. Reputation systems also struggle to validate the "he said / she said" assertions that impact one's reputation. In traditional systems like Yelp, business operate under their real names, and so do users to some extent. However, in a pseudonymous environment, it could be infeasible to sensibly sort out spurious accusations from facts.

There are other security mechanisms including secure hardware that we won't elaborate on. Regardless of the mechanism used, ultimately there is a big security challenge because there is no real-world enforcement. There are no punitive measures for misbehavior and disputes cannot end up in court, especially if no one is using real-world identities. Offering debts is infeasible, as there is no enforcement to ensure that they will be repaid, and so transactions often require deposits, which lock up funds for the dispute period.

**Sidebar: trust.** Some people in the Bitcoin community use terms such as “trust minimization” or “trustlessness” as a goal. This might sound backwards --- don’t we want systems that we can trust to operate correctly?

The word trust has different meanings which might cause this confusion. When Alice lends Bob ten dollars and says she trusts him, she means that she thinks he’s a trustworthy person, and that she has confidence that he’ll pay her back. In the security context, a trusted component is one that you’re forced to be reliant on. When people use the word trusted to describe Certification Authorities, they mean that online security guarantees would be void if such authorities misbehaved.

“Trust minimization” is a worthwhile goal in the sense that other things being equal, we want to build systems with fewer components that we’re reliant on for security. But when you have a hammer, everything looks like a nail, and Bitcoin enthusiasts often get carried away with removing trusted components from systems. A trusted component is not always bad, and the existence of a real-world trust relationship is certainly not a problem by itself. Removing trusted components might also have other non-obvious drawbacks.

We’ll elaborate on these points in the final section, but for now, having noted the complexity of the word trust, we’ll seek to avoid it and instead talk about security, a less ambiguous word.

## The Framework

To summarize this chapter up this point, we can characterize proposals for decentralizing a wide variety of things by asking four questions:

1. What is being decentralized?
2. What is the level of decentralization?
3. What block chain is deployed?
4. What security mechanism does it use?

With answers to these four questions, we can succinctly represent almost any of the proposals that we see in the Bitcoin community for block-chain-based decentralization. Let’s consider a few examples.

## Example: Smart Property

1. What is being decentralized? Property ownership and trading
2. What is the level of decentralization? Disintermediation
3. What block chain is deployed? Bitcoin’s block chain
4. What security mechanism does it use? Atomicity

Smart property, as we've seen, decentralizes the notion of property ownership and transfers of ownership. It achieves complete disintermediation — it eliminates the need for entities like the DMV or the state. We saw how to realize it using Bitcoin's block chain, but you could certainly use an alternative block chain. And finally, the key security principle that we used was atomicity in tying together the payment with the transfer of the car ownership.

## Example: Decentralized Prediction Markets

1. What is being decentralized? Prediction market
2. What is the level of decentralization? Competition, disintermediation
3. What block chain is deployed? Altcoin
4. What security mechanism does it use? Reputation, atomicity

In a centralized prediction market, the centralized platform or exchange performs at least two crucial services: arbitrating the outcome of each event being wagered on, and selling shares to participants (or facilitating participants to securely trade with each other). The decentralized prediction market that we saw in Chapter 9 does away with the need for a central authority for both of these features. It allows anyone to create a market for an event and be its arbiter by sending a simple transaction, lowering the barrier to entry for performing this function. Thus, intermediaries still exist, but users a free to choose from a set of competing intermediaries, and if the user is still unhappy, they can always perform this function themselves. On the other hand, users directly trade shares with each other atomically, so this function of the central authority has been disintermediated. Decentralized prediction markets require new functionality not present in Bitcoin itself, and are thus naturally implemented through a customized altcoin with its own block chain.

## Example: StorJ

1. What is being decentralized? File storage and retrieval
2. What is the level of decentralization? Competition
3. What block chain is deployed? Bitcoin
4. What security mechanism does it use? Reputation

StorJ is a proposal by Greg Maxwell for file storage and retrieval. It has evolved over time, but we'll discuss a simple version of it. At a high level, StorJ deploys an "agent" that lives in the cloud and is programmed to make certain decisions on its own. For example, it can rent cloud computation and storage to give itself computational resources. Another feature it provides to users is the ability to store a file for a certain period of time, say 24 hours, in exchange for payment in Bitcoin. It will keep hosting the file as long it keeps receiving payment. Beyond simple storage, it can do a number of interesting things we will not consider here. Within our framework, StorJ decentralizes file storage and retrieval, which are the core features of centralized services like Dropbox. The agent is an intermediary; it doesn't matter for our purposes that it is automated. However, there can be competition among intermediaries. Payment is done with Bitcoin, but there is no atomic link between the agent performing its services and the payments it receives, so security is a matter of the agent's reputation.

## Example: Zerocoin

1. What is being decentralized? Mixing of coins
2. What is the level of decentralization? Disintermediation
3. What block chain is deployed? Altcoin
4. What security mechanism does it use? Atomicity

Zerocoin, which we discussed in Chapter 6, is effectively a method for decentralizing the mixing coins to achieve anonymity. Instead of using a centralized mixing service, Zerocoin realizes a cryptographic protocol that is functionally equivalent to using a mix but uses no intermediaries at all — only math and consensus. The relatively heavy cryptography needed in Zerocoin (and its successor, Zerocash) means that a separate block chain is the far more feasible route. As for the security mechanism, recall that the notion of burning a basecoin and getting a zerocoin in exchange for it are atomically coupled through the same transaction; and similarly for later redeeming a zerocoin. This is an example of atomicity.

# 11.4 When is Decentralization a Good Idea?

In this chapter so far, we have focused on the technical challenges of achieving decentralization. Now we're going to delve into questions of motivation. These questions are non-technical but often they're just as difficult to answer: Is decentralization a good idea? Is it economically feasible? What are the social consequences to decentralization?

Until now, we have used the term decentralization as a technical concept without being explicit about the fact that it is politically charged. When we talk about replacing traditional systems fully or partly with technological alternatives, we are really talking about redistributing power from well-established legal, social and financial institutions. Thus the idea of decentralization stems from Bitcoin's roots in the cypherpunk movement — a movement begun by nonconformists dreaming of cryptography's ability to empower individual autonomy. With the block chain, this ideal appear closer than ever. But is this ideal feasible or desirable?

Returning to our running example, there are two problems that the traditional institutions try to solve for car owners. The first is enforcing ownership, or essentially, preventing theft. The second is ensuring secure exchanges, or preventing someone from being ripped off during a sale. So to analyze how smart property fares compared to the existing system, we have to look at not just how efficient things are when everything goes right, but also, crucially, how bad things can get when something goes wrong.

## The challenge of real-world security

Defending against any form of theft — cars, art, money, etc. — is an exercise of prevention, detection and correction. Preventive security mechanisms try to stop theft before it happens, while detection mechanisms ensure theft is perceived so potential corrective measures can be taken to revert the damages of the theft and to punish the perpetrator (which could also serve as a deterrent to committing theft). Car locks and alarms are preventive mechanisms, while GPS tracing units (such as LoJack) can assist in detecting the theft and enabling law enforcement to recover the stolen car. The key insight is the car lock is just one small piece of deterrence to car theft — one piece of a large, intricate system involving police, insurance companies, courts, etc. If you lived in a lawless environment, a car lock by itself wouldn't be much of a deterrent to theft. Leaving your car locked on the street would ensure that it would be quickly stolen.

The model we have seen for smart property relies heavily on preventive mechanisms. We were able to achieve decentralization only because we equated possession with ownership — owning a car is essentially equivalent to knowing the private key corresponding to a designated transaction on a block chain. But this control mechanism is a poor replacement for our current mosaic of institutional support, as we'll explain.

If we reduce ownership to the problem of securing private keys, it raises the stakes for digital security, which is a difficult problem with humans being a weak link. Programmers have endeavored to write bug-free code for decades, but the challenge remains elusive. Designers of cryptosystems have tried for decades to get non-technical users to utilize and manage private keys in a way that resists both theft and accidental loss of keys, also with little progress. If the model of decentralization relies excessively on private keys, cars might get stolen by malware or in phishing attacks, and the loss of a key might turn your car into a giant brick. While there could be fallback mechanisms to cover these types of events, inevitably such mechanisms tend to lead us back toward intermediaries and centralized systems, chipping away at the benefits of the decentralized model that we were striving for.

Another area of property transfers that is fundamentally human-oriented is dealing with disputes that might arise over the terms of sale or other aspects of the transfer. If the real world, if the participants cannot reach a resolution, the issue will end up in court where a judge will methodically examine each bit of evidence, testimony, and written words to reach a nuanced ruling about the validity of the sale. It is tempting, particularly for technical people, to think of the law as a set of logical rules or algorithms that can produce a clear-cut ruling. However the reality of the legal system is that not only are laws and contracts verbose, they are ultimately subject to human interpretation and discretion, which is further removed from the notion of clear-cut logical rules. This is not a weakness. It allows resolving situations that are far more complex than what was anticipated by the individuals writing the law.

To drive home the mismatch between the security properties we get from the decentralized model and the security properties that we actually want, let's revisit the earlier example of decentralized crowd-funding. We saw a technical mechanism to ensure an entrepreneur cannot cash out on investments until the contributions sum to some pre-specified amount. However, this by no means prevents an entrepreneur who has successfully raised the funds from absconding with the money! In fact, even with the current centralized model, there have been numerous alleged scams on crowd-funding sites, resulting in several lawsuits. In a model where entrepreneurs are potentially anonymous and there is no deterrent effect from the threat of being sued, this problem is likely to be far worse. It is hard to imagine that there could be a technical solution to this problem. This is another case where the technology is only solving a small part of the problem, and frankly, not even the interesting part of the problem.

To recap, the interesting problems with smart property seem to be social problems, issues that arise when something goes wrong. Technology can ensure a very efficient transaction when all parties are satisfied, but it is not well-positioned to solve thorny disputes.

## The pros and cons of smart property

As argued, smart property has difficulty decentralizing the aspects of a system that traditionally require human intervention. In fact, automation may even make it more difficult by not composing well with mediation and other processes if they are layered on after the fact. Finally, it may create new categories of problems, such as requiring software security in addition to physical security in the case of a car.

These examples are, to a certain extent, cartoon versions of what a thorough proposal for smart property might look like. Many proposals in the Bitcoin community are more nuanced, but even in our simple setting, we can discern the advantages and disadvantages of smart property.

The main advantage of smart property is the efficiency of ownership transfer, which can be done from anywhere at any time. For sales of items less valuable than a car, maybe a smartphone or computer, disputes are unlikely to end up in court, and so nothing is lost in that regard. For such items, atomic transactions are a useful security feature.

Smart property through block chains also provide greater privacy, and even anonymity. While we've argued that it complicates dispute resolution, privacy is also beneficial in a society where consumer data is used by companies in ways that are unseen and likely unintended by making the purchases. In some cases, it might be important for the parties to a transaction to not disclose their identities, which is not feasible in a centralized intermediated model.

Finally, the decentralized model allows mediators to be chosen. Even if we are content with the legal system, often disputes are mediated by private companies like Visa or PayPal behind closed doors using a method that is hard to scrutinize. By using an alternative model where such mediation is opened up to competition, we can potentially bring more transparency and public oversight to the process.

## Crypto, the state, and the big opportunity

There is a striking parallel between the emergence of the modern state and the goals of the technology we have discussed in this chapter. In scaling society up from tribes and small groups, governments have had to confront precisely the problem of enabling secure commerce and other interactions between strangers. The methods may be very different but the goal is a shared one.

While a maximalist vision for decentralization might involve dismantling the state, this is not really viable vision, especially when others who share our democracy want one. However, decentralization through technology is not necessary in opposition to the state at all. In fact, they can be mutually beneficial. For example, assuming well-identified parties, transfers of smart property can use the block chain for efficient transfers and still use the court system if there is a dispute. We think the big opportunity for block-chain technology is implementing decentralization in a way that complement the functions of the state, rather than seeking to replace them.

It is tempting to think that things will get decentralized simply because the technology exists. But in practice, there needs to be a compelling economic reason, such as government regulation that is particularly onerous or inefficient, or a power imbalance that could lead to abuse. As one illustration of this, people in various African countries have adopted cell phone minutes as an ad-hoc currency that is outside of state control and less subject to abuses of power.

To summarize, we’ve shown the technical blueprint for decentralization in this chapter, and also critically examined the motivations behind decentralization. We encourage you to look for compelling use cases of decentralization, in particular ones that integrate into existing legal and regulatory practices.

# Conclusion to the book

Some people are excited about Bitcoin because of the underlying technology. Others are excited about its commercial possibilities, and yet others about its social and political implications. Reasonable people can disagree about the latter two, but we hope this book has convinced you that technologically, Bitcoin is deep, novel, interesting, and based on sound principles. Beyond Bitcoin there is a fascinating world of alternative cryptocurrency designs that we're just starting to explore, some of which might one day be more important than Bitcoin itself.

We got into Bitcoin because we believe in the power of its technology, and we think it's deeply connected to the rest of computer science. While we've highlighted how seemingly amazing new technology can struggle to displace established institutions, we believe that in the long run, people will continue to find new commercially and socially useful things to do with cryptocurrency technology. Even if your interest is primarily commercial, you'd do well to master the underlying technology — understanding its power and limitations will help you better weather the market's hype cycles.

We'll end with a few words about where to go from here. One of the best things about decentralization is that it's a great platform for experimentation and learning. Anyone can download and analyze Bitcoin's block chain, or build their own applications on top of it; we hope you'll take advantage of these opportunities.

We've created a number of online materials that complement this text. Our Coursera course contains video lectures that mirror the contents of this book. It also has quizzes and a series of programming assignments. Taking the course will also give you access to the forums where you'll find a community of like-minded learners.

While the first draft of this book is complete, it is a work in progress. We're watching developments in areas such as Ethereum, and whenever a body of scientific knowledge develops around a new area, we will release additional chapters. Check our course website!

# About the authors

**Arvind Narayanan** (Ph.D. 2009) is an Assistant Professor of Computer Science at Princeton. Narayanan leads the Princeton Web Transparency and Accountability project that aims to uncover how companies are collecting and using our personal information. He also leads a research group studying the security, anonymity, and stability of Bitcoin and cryptocurrencies. His doctoral research showed that data anonymization is broken in fundamental ways, for which he jointly received the 2008 Privacy Enhancing Technologies Award. You can follow him on Twitter at @random_walker.

**Joseph Bonneau** is a Technology Fellow at the Electronic Frontier Foundation and Postdoctoral Researcher at Stanford. In addition to researching Bitcoin and cryptocurrencies he has worked on passwords and web authentication, secure messaging tools, and HTTPS for secure web browsing. He received a PhD from the University of Cambridge under the supervision of Ross Anderson and an MS from Stanford under the supervision of Dan Boneh. Earlier he was as a Postdoctoral Fellow at CITP, Princeton and he has previously worked at Google, Yahoo, and Cryptography Research Inc.

**Edward W. Felten** is a Professor of Computer Science and Public Affairs at Princeton, and the founding Director of the Center for Information Technology Policy. In 2011-12 he served as the first Chief Technologist at the U.S. Federal Trade Commission. His research interests include computer security and privacy, and technology law and policy. He has published more than 100 papers in the research literature, and two books. His research on topics such as Internet security, privacy, copyright and copy protection, and electronic voting has been covered extensively in the popular press.

**Andrew Miller** is a computer science PhD student at the University of Maryland, and previously received his M.S. degree from the University of Central Florida. He has studied cryptocurrencies since 2011, and has authored scholarly papers on a wide range of original research, including new proof-of-work puzzle constructions, programming languages for block chain data structures, and peer-to-peer network measurement and simulation techniques. He is an Associate Director of the Initiative for Cryptocurrencies and Contracts (IC3) at Cornell and an advisor to the zcash project.

**Steven Goldfeder** is a PhD student in the Department of Computer Science at Princeton University, advised by Arvind Narayanan. He is a member of the Security & Privacy Research Group, a CITP Graduate Student Fellow, and a National Science Foundation Graduate Research Fellow. His research interests include cryptography, security, and privacy, especially decentralized digital currencies. His current work involves increasing the security of Bitcoin wallets.

**Jeremy Clark** is an Assistant Professor at the Concordia Institute for Information Systems Engineering in Montreal. He received his PhD from the University of Waterloo in 2011, where he applied cryptography to designing and deploying verifiable voting systems, including Scantegrity — the first use of an end-to-end verifiable system in a public sector election. He became interested in Bitcoin in 2010 and published one of the first academic papers in the area. Beyond research, he has worked with several municipalities on voting technology and testified to the Canadian Senate on Bitcoin.