

DIFFERENTIAL AND INTEGRAL CALCULUS, I

LECTURE NOTES (TEL AVIV UNIVERSITY, FALL 2009)

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PRELIMINARIES

Preparatory reading. These books are intended for high-school students who like math. All three books are great, my personal favorite is the first one.

- (1) R. Courant, H. Robbins, I. Stewart, What is mathematics, Oxford, 1996 (or earlier editions).
- (2) T. W. Korner, The pleasures of counting, Cambridge U. Press, 1996.
- (3) K. M. Ball, Strange curves, counting rabbits, and other mathematical explorations, Princeton University Press, 2003.

Reading. There are many good textbooks in analysis, though I am not going to follow any of them too closely. The following list reflects my personal taste:

- (1) V. A. Zorich, Mathematical analysis, vol.1, Springer, 2004.
- (2) A. Browder, Mathematical analysis. An introduction. Undergraduate Texts in Mathematics. Springer-Verlag, New York, 1996.
- (3) R. Courant and F. John, Introduction to calculus and analysis, vol.1, Springer, 1989 (or earlier editions).
- (4) D. Maizler, Infinitesimal calculus (in Hebrew).
- (5) G. M. Fihtengol'tz, Course of Differential and Integral Calculus, vol. I (in Russian)
- (6) E. Hairer, G. Wanner, Analysis by its history, Springer, 1996.

The last book gives a very interesting and motivated exposition of the main ideas of this course given in the historical perspective.

You may find helpful informal discussions of various ideas related to this course (as well to the other undergraduate courses) at the web page of Timothy Gowers:

www.dpmms.cam.ac.uk/~wtg10/mathindex.html

I suppose that the students attend in parallel with this course the course “Introduction to the set theory”, or the course “Discrete Mathematics”. The notes (in Hebrew) of Moshe Jarden might be useful:

www.math.tau.ac.il/~jarden/Courses/set.pdf

Problem books. For those of you who are interested to try to solve more difficult and interesting problems and exercises, I strongly recommend to look at two excellent collections of problems:

- (1) B. M. Makarov, M. G. Goluzina, A. A. Lodkin, A. N. Podkorytov, Selected problems in real analysis, American Mathematical Society, 1992.
- (2) G. Polya, G. Szegö, Problems and theorems in analysis (2 volumes) Springer, 1972 (there are earlier editions).

Basic notation.*Symbols from logic.*

\vee	or
\wedge	and
\neg	negation
\implies	yields
\iff	is equivalent to

Example: $(x^2 - 3x + 2 = 0) \iff ((x = 1) \vee (x = 2))$

Quantifiers:

\exists	exists
$\exists!$	exists and unique (warning: this notation isn't standard)
\forall	for every

Set-theoretic notation.

\in	belongs
\notin	does not belong
\subset	subset
\emptyset	empty set
\cap	intersection of sets
\cup	union of sets
$\#(X)$	cardinality of the set X
$X \setminus Y = \{x \in X : x \notin Y\}$	complement to Y in X

Example: $(X \subset Y) := \forall x ((x \in X) \implies (x \in Y))$

We shall freely operate with these notion during the course. Usually, the sets we deal with are subsets of the set of real numbers \mathbb{R} .

Subsets of reals:

\mathbb{N}	natural numbers (positive integers)
\mathbb{Z}	integers
$\mathbb{Z}_+ = \mathbb{N} \cup \{0\}$	non-negative integers
\mathbb{Q}	rational numbers
\mathbb{R}	real numbers
$[a, b] := \{x \in \mathbb{R} : a \leq x \leq b\}$	closed interval (one point sets are closed intervals as well)
$(a, b) := \{x \in \mathbb{R} : a < x < b\}$	open interval
$(a, b]$ and $[a, b)$	semi-open intervals

Sums and products.

$$\sum_{j=1}^n a_j = a_1 + a_2 + \dots + a_n$$

$$\prod_{j=1}^n a_j = a_1 \cdot a_2 \cdot \dots \cdot a_n$$

Some abbreviations.

iff “if and only if”

wlog “without loss of generality”

RHS, LHS “right-hand side”, “left-hand side”

qed “end of the proof”¹. Often is replaced by the box like this one: □

:= according to the definition (the same as $\stackrel{\text{def}}{=}$)

¹“quod erat demonstrandum” (in Latin), “which was to be demonstrated”

Basic Greek letters.

α	alpha
β	beta
γ, Γ	gamma
δ, Δ	delta
ε	epsilon
ζ	zeta
η	eta
θ, Θ	theta
ι	iota
κ	kappa
λ, Λ	lambda
μ	mu
ν	nu
ξ, Ξ	xi
π, Π	pi
ρ	rho
σ, Σ	sigma
τ	tau
υ, Υ	upsilon
φ, Φ	phi
χ	chi
ψ, Ψ	psi
ω, Ω	omega

Exercise: Translate from the Greek the word *μαθηματικά*.

1. REAL NUMBERS

1.1. Infinite decimal strings. All of you have an idea what are the real numbers. For instance, we often think of the real numbers as strings of elements of the set $\{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}$ preceded by a sign (we write only a minus sign, the absence of the sign means that the sign is positive). A finite string of elements of this set followed by a decimal point followed by an infinite string of elements of this set. If the string starts with zeroes, they can be removed: $0142.35000\dots = 142.35$, if the string has an infinite sequence of nines, the last element which differs from nine should be increased by one, and then the nines should be replaced by the zeroes: $13.4999999\dots = 13.5000\dots = 13.5$. We call such strings *finite*.

Then we can define what is the sum, the product and the quotient of two such strings, and we can compare the strings. It is not completely obvious, but you've certainly learnt this in the high-school how to do this for finite strings:

Exercise 1.1.1. Try to write down the “algorithms” for addition, multiplication and comparison of two *finite* decimal strings.

One may prefer to operate with strings which consist of zeroes and ones only. In other civilizations, people used to operate with expansions with a different base, say $\{0, 1, 2, 3, 4, 5, 6, \dots, 59\}$ (this base goes back to Babylon). Do they deal with *the same* set \mathbb{R} of real numbers? How to formalize this question? and how to answer it?

1.2. The axioms. We know that it is possible to add and multiply real numbers; that is,

$$\forall x, y \in \mathbb{R} \quad x + y, x \cdot y \in \mathbb{R}.$$

Let us write down the customary rules (called “axioms”):

Axioms of addition +.

- (+1) \exists the null element $0 \in \mathbb{R}$ such that $\forall x \in \mathbb{R}: x + 0 = 0 + x = x$;
- (+2) $\forall x \in \mathbb{R} \exists$ an element $-x \in \mathbb{R}$ such that $x + (-x) = (-x) + x = 0$;
- (+3) *associativity*: $\forall x, y, z \in \mathbb{R} \quad x + (y + z) = (x + y) + z$;
- (+4) *commutativity*: $\forall x, y \in \mathbb{R} \quad x + y = y + x$.

In “scientific words” these axioms mean that \mathbb{R} with addition is an *abelian group*.

Axioms of multiplication \cdot .

- (\cdot 1) \exists the unit element $1 \in \mathbb{R} \setminus \{0\}$ such that $\forall x \in \mathbb{R}: x \cdot 1 = 1 \cdot x = x$;
- (\cdot 2) $\forall x \in \mathbb{R} \setminus \{0\} \exists$ the inverse element x^{-1} such that $x \cdot x^{-1} = x^{-1} \cdot x = 1$;
- (\cdot 3) *associativity*: $\forall x, y, z \in \mathbb{R} \quad x \cdot (y \cdot z) = (x \cdot y) \cdot z$
- (\cdot 4) *commutativity*: $\forall x, y \in \mathbb{R} \quad x \cdot y = y \cdot x$.

This group of the axioms means that the set $\mathbb{R} \setminus \{0\}$ with the multiplication is also an abelian group.

Relation between addition and multiplication is given by

Distributive axiom. $\forall x, y, z \in \mathbb{R} \quad (x + y) \cdot z = x \cdot z + y \cdot z.$

Exercise 1.2.1. Prove that $a \cdot 0 = 0$. Prove that if $a \cdot b = 0$, then either $a = 0$, or $b = 0$.

Any set K with two operations satisfying all these axioms is called a *field*. The fields are studied in the courses in algebra.

Exercise 1.2.2. Construct a finite field with more than two elements.

Axioms of order \leq . Real numbers are equipped with another important structure: the order relation. Having two real numbers x and y we can always juxtapose them and tell whether they are equal or one of them is bigger than the other one. To make this formal, we need to check that the reals satisfy the third set of the axioms:

- (\leq_1) $\forall x \in \mathbb{R} \quad x \leq x;$
- (\leq_2) if $x \leq y$ and $y \leq x$, then $x = y;$
- (\leq_3) if $x \leq y$ and $y \leq z$, then $x \leq z;$
- (\leq_4) $\forall x, y \in \mathbb{R}$ either $x \leq y$ or $y \leq x.$

These axioms say that \mathbb{R} is a (linearly) ordered set. The next two axioms relate the order with addition and multiplication on \mathbb{R} :

- ($+, \leq$) if $x \leq y$, then $\forall z \in \mathbb{R} \quad x + z \leq y + z;$
- (\cdot, \leq) if $x \geq 0$ and $y \geq 0$, then $x \cdot y \geq 0.$

Now, we can say that \mathbb{R} is an *ordered field*.

Exercise 1.2.3. Let $x \geq y$. Prove that $x \cdot z \geq y \cdot z$ if $z > 0$ and $x \cdot z \leq y \cdot z$ if $z < 0$.

Exercise 1.2.4. Let $x \geq y > 0$. Prove that $x^2 \geq y^2$.

The axioms introduced above still are not enough to start the course of analysis.

Completeness axiom: if X and Y are non-empty subsets of \mathbb{R} such that

$$\forall x \in X \quad \forall y \in Y \quad x \leq y$$

then $\exists c \in \mathbb{R}$ such that

$$\forall x \in X \quad \forall y \in Y \quad x \leq c \leq y.$$

Intuitively, this should hold for reals, however, it would take some time to check it for the infinite decimals. I will not do this verification in my lectures. Later, we will learn several equivalent forms of this axiom, then the verification will be much easier, see Exercise 2.1.9.

Why do we call all these rules the *axioms*? Let us say that a set F equipped with two operations (call them “addition” and multiplication”) and with an order relation is a *complete ordered field* if it satisfies all the axioms given above. We know (or rather believe) that the reals give us an example of a complete ordered field. This is a good point to turn things around (as we often do in math), and to accept the following

Definition 1.2.5. A field of real numbers \mathbb{R} is a complete ordered field.

I.e., from now on, we will allow ourselves to freely use the axioms introduced above.

When we start with an abstract system of axioms two questions arise: First, *whether there exists an object which satisfies them?* or maybe, the axioms from our system contradict each other? Second, assuming that such an object exists, *whether it is unique?* Imagine two different objects called “real numbers”! In our case, the answers to the both questions are positive. Since the proofs are too long for the first acquaintance with analysis, we’ll skip them.

To prove existence, it suffices to check, for instance, that the infinite decimal strings satisfy these axioms. Note, that there are other constructions of the set of reals (like Dedekind cuts and Cauchy sequences of rationals). Luckily, all of them lead to the same object.

Suppose that we have two complete ordered fields, denote them \mathbb{R} and \mathbb{R}' . How to say that they are equivalent? Some thought gives us the answer: we call \mathbb{R} and \mathbb{R}' *equivalent* if there exist a one-to-one correspondence f between \mathbb{R} and \mathbb{R}' which preserves the arithmetic operations and the order relation; i.e.

$$\begin{aligned} f(x + y) &= f(x) + f(y), \\ f(x \cdot y) &= f(x) \cdot f(y), \\ x \leq y &\implies f(x) \leq f(y). \end{aligned}$$

It’s not very difficult to construct² such a map f . This construction leads to a theorem which says that *any two complete ordered field are equivalent*.

Natural and integer numbers. Naively, the set of natural numbers is the set of all real numbers of the form

$$1, 1 + 1, (1 + 1) + 1, ((1 + 1) + 1) + 1, \dots$$

A formal definitions is slightly more complicated.

Definition 1.2.6 (inductive sets). A set $X \subset \mathbb{R}$ is called *inductive* if

$$(x \in X) \implies (x + 1 \in X)$$

For instance, the set of all reals is inductive.

Definition 1.2.7 (natural numbers). The set of natural numbers \mathbb{N} is the intersection of all inductive sets that contains the element 1.

In other words, a real number x is natural if it belongs to *each* inductive set that contains 1.

Claim 1.2.8. *The set of natural numbers is inductive.*

Proof: Suppose $n \in \mathbb{N}$. Let X be an arbitrary inductive subset of \mathbb{R} that contains n . Since X is inductive, $n + 1$ is also in X . Hence, $n + 1$ belongs to each inductive subset of \mathbb{R} , whence, $n + 1 \in \mathbb{N}$; i.e., the set \mathbb{N} is inductive. \square

This definition provides a justification for the *principle of mathematical induction*. Suppose there is a proposition $P(n)$ whose truth depends on the natural numbers. The principle states that if we can prove the truth of $P(1)$ (“the base”), and that assuming the truth of $P(n)$ we can prove the truth of $P(n + 1)$, then $P(n)$ is true for all natural n .

²I suggest to the students with curiosity to build such a map yourselves.

Exercise 1.2.9. Prove:

- (i) any natural number can be represented as a sum of ones: $1 + 1 + \dots + 1$;
- (ii) if m and n are natural numbers, then either $|m - n| \geq 1$, or $m = n$.

Example 1.2.10 (Bernoulli's inequality). $\forall x > -1$ and $\forall n \in \mathbb{N}$

$$(1 + x)^n \geq 1 + nx.$$

The equality sign is possible only when either $n = 1$ or $x = 0$.

Proof: Fix $x > -1$. For $n = 1$, the LHS and the RHS equal $1 + x$. Hence, we've checked the base of the induction.

Assume that we know that

$$(1 + x)^n \geq 1 + nx.$$

Since $1 + x$ is a positive number, we can multiply this inequality by $1 + x$. We get

$$(1 + x)^{n+1} \geq (1 + nx)(1 + x) = 1 + (n + 1)x + nx^2.$$

If $x \neq 0$, the RHS is bigger than $1 + (n + 1)x$, and we are done. \square

Exercise 1.2.11. Prove that $\forall m, n \in \mathbb{N}$

$$\frac{1}{\sqrt[n]{1+m}} + \frac{1}{\sqrt[m]{1+n}} \geq 1.$$

Hint: Use Bernoulli's inequality.

Exercise 1.2.12. Suppose a_1, \dots, a_n are non-negative reals such that $S = a_1 + \dots + a_n < 1$. Prove that

$$1 + S \leq (1 + a_1) \cdot \dots \cdot (1 + a_n) \leq \frac{1}{1 - S}$$

and

$$1 - S \leq (1 - a_1) \cdot \dots \cdot (1 - a_n) \leq \frac{1}{1 + S}.$$

Exercise 1.2.13. Prove:

$$1^2 + 2^2 + \dots + n^2 = \frac{n(n+1)(2n+1)}{6}, \quad n \in \mathbb{N}.$$

Exercise 1.2.14. Prove that

$$2(\sqrt{n} - 1) < 1 + \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{3}} + \dots + \frac{1}{\sqrt{n}} < 2\sqrt{n}.$$

Hint: to prove the left inequality, set $X_n = 2\sqrt{n} - (1 + \frac{1}{\sqrt{2}} + \dots + \frac{1}{\sqrt{n}})$, and show that the sequence $X_n + \frac{1}{\sqrt{n}}$ does not increase.

Definition 1.2.15 (integers).

$$\mathbb{Z} = \left\{ x \in \mathbb{R} : (x \in \mathbb{N}) \vee (-x \in \mathbb{N}) \vee (x = 0) \right\}.$$

Remark: It is purely a matter of agreement that we start the set of natural numbers with 1. In some textbooks the set \mathbb{N} starts with 0.

In what follows, we denote the set of non-negative integers by $\mathbb{Z}_+ = \mathbb{N} \cup \{0\}$.

Rational numbers.

Definition 1.2.16.

$$\mathbb{Q} = \left\{ x = \frac{m}{n} : m, n \in \mathbb{Z}, n \neq 0 \right\}.$$

Exercise 1.2.17. Whether the set of integers \mathbb{Z} is a field? Whether the set of rationals \mathbb{Q} is a field?

Exercise 1.2.18. Check that the rationals \mathbb{Q} form an ordered field.

Exercise 1.2.19. Prove that the equation $s^2 = 2$ does not have a rational solution.

Exercise 1.2.20. Check that the field of rationals \mathbb{Q} doesn't satisfy the completeness axiom.

1.3. Application: solution of equation $s^n = a$.

Theorem 1.3.1. *For each $a > 0$ and each natural $n \in \mathbb{N}$, the equation $s^n = a$ has a unique positive solution s .*

Proof: Define the sets $X := \{x \in \mathbb{R} : x > 0, x^n < a\}$ and $Y := \{y \in \mathbb{R} : y > 0, y^n > a\}$. The both sets are not empty. For instance, to see that the set X is not empty, we take $t = 1 + 1/a$. Then $t^n \geq t > 1/a$, and $(1/t)^n < a$. Therefore, $1/t \in X$.

The completeness axiom can be applied to these sets since

$$\forall x \in X, y \in Y \quad (x^n < a < y^n) \implies (x < y).$$

By the axiom,

$$\exists s \quad \forall x \in X, \forall y \in Y \quad x \leq s \leq y.$$

We claim that $s^n = a$.

First, observe that X contains a positive number so that s is positive as well. Indeed, take $t = 1 + 1/a$. Then $t^n \geq t > 1/a$, and $(1/t)^n < a$. Therefore, $1/t \in X$.

Now, assume that $s^n < a$. Our aim is to find another value s_1 which is bigger than s but still $s_1^n < a$. Then $s_1 \in X$, that is, X has an element which is (strictly) bigger than s . Hence, contradiction.

To find such s_1 , we choose a small positive ϵ so that $0 < \epsilon < a - s^n$ and $\epsilon < na$. Then

$$s^n < a - \epsilon = a \left(1 - \frac{\epsilon}{a}\right) = a \left(1 - n \frac{\epsilon}{na}\right) \leq a \left(1 - \frac{\epsilon}{na}\right)^n$$

(at the last step we used Bernoulli's inequality). Put

$$s_1 = \frac{s}{1 - \epsilon/(na)}.$$

We see that $s_1 > s$ and still $s_1^n < a$. Therefore, $s^n \geq a$.

A similar argument shows that $s^n \leq a$. Now, we start with assumption that $s^n > a$. Then we take a small positive ϵ such that $0 < \epsilon < s^n - a$ and $\epsilon < ns^n$. We have

$$a < s^n - \epsilon = s^n \left(1 - \frac{\epsilon}{s^n}\right) = s^n \left(1 - n \frac{\epsilon}{ns^n}\right) \leq s^n \left(1 - \frac{\epsilon}{ns^n}\right)^n$$

(at the last step, we again used Bernoulli's inequality). Put $s_2 = s \left(1 - \frac{\epsilon}{ns^n}\right)$, then $s_2 < s$, and still $s_2^n > a$; i.e., $s_2 \in Y$, which again contradicts the choice of s . Therefore, $s^n = a$ proving existence of the solution.

To prove uniqueness, we suppose that there are two positive solutions to our equation: $s_1^n = s_2^n$, but $s_1 \neq s_2$. Then

$$0 = s_2^n - s_1^n = (s_2 - s_1)(s_2^{n-1} + s_2^{n-2}s_1 + \dots + s_2s_1^{n-2} + s_1^{n-1}),$$

whence (see Exercise 1.2.1), $s_2^{n-1} + s_2^{n-2}s_1 + \dots + s_2s_1^{n-2} + s_1^{n-1} = 0$. This is impossible since on the left-hand side we have a sum of positive real numbers. \square

Exercise 1.3.2. Let $a \in \mathbb{R}$, $n \in \mathbb{N}$. Prove that equation $s^n = a$ cannot have more than two *real* solutions.

1.4. **The distance on \mathbb{R} .** We also know how to measure the distance between two real numbers. Set

$$|x| = \begin{cases} x, & x \geq 0, \\ -x, & x < 0 \end{cases}$$

The value $d(x, y) = |x - y|$ is *the distance* between x and y . It enjoys the following properties:

positivity: $d(x, y) \geq 0$ and $d(x, y) = 0$ iff $x = y$;

symmetry: $d(x, y) = d(y, x)$;

triangle inequality: $d(x, y) \leq d(x, z) + d(z, y)$ with the equality sign iff the point z lies within the closed segment with the end-points x and y .

The first two properties are obvious. Let's prove the triangle inequality.

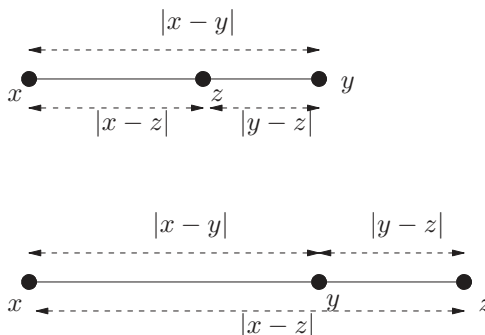


FIGURE 1. To the proof of triangle inequality

Let, say, $x < y$. If $z \in [x, y]$, then

$$d(x, y) = y - x = (y - z) - (z - x) = d(y, z) + d(x, z).$$

If z does not belong to the interval $[x, y]$, say $z > y$, then

$$d(x, y) = y - x < z - x = d(x, z) < d(x, z) + d(y, z).$$

Done! \square

Question: How the triangle inequality got its name?

There are other versions of the triangle inequality which we'll often use in this course:

$$|x + y| \leq |x| + |y|,$$

$$|x - y| \geq \left| |x| - |y| \right|,$$

and

$$|x_1 + \dots + x_n| \leq |x_1| + \dots + |x_n|.$$

We apply the name “triangle inequality” to these inequalities as well.

To get the first inequality, we add inequalities $x \leq |x|$ and $y \leq |y|$. We get $x + y \leq |x| + |y|$. Applying this to $-x$ and $-y$ instead of x and y , we get $-(x + y) \leq |x| + |y|$. These two inequalities together give us $|x + y| \leq |x| + |y|$.

To prove the second inequality, we assume that $|x| \geq |y|$. Then

$$|x| = |(x - y) + y| \leq |x - y| + |y|,$$

whence

$$|x - y| \geq |x| - |y| = \left| |x| - |y| \right|.$$

The third inequality follows from the first one by induction. □.

2. UPPER AND LOWER BOUNDS

2.1. Maximum/minimum supremum/infimum. The completeness axiom has a number of important corollaries which will be of frequent use during the whole course. We start with some definitions.

A subset $X \subset \mathbb{R}$ is *upper bounded* if $\exists c$ such that $\forall x \in X, x \leq c$. Any c with this property is called an *upper bound* (or a *majorant*) of X . A subset $X \subset \mathbb{R}$ is *lower bounded* if $\exists c$ such that $\forall x \in X, x \geq c$. Any c with this property is called a *lower bound* (or a *minorant*) of X . A set X is bounded if it is upper- and lower bounded.

Next, we define the *maximum* and *minimum* of a set X :

Definition 2.1.1 (maximum/minimum).

$$(a = \max X) := (a \in X \wedge \forall x \in X \quad (x \leq a)),$$

that is, a is a majorant of X and belongs to X . Similarly,

$$(a = \min X) := (a \in X \wedge \forall x \in X \quad (x \geq a)),$$

that is, a is a minorant of X and belongs to X .

If a set is unbounded from above, then certainly it does not have a maximum. However, even if X is upper bounded, the maximum does not have to exist: for example consider an open interval $(0, 1)$.

Example 2.1.2. The open interval $(0, 1)$ has nor maximum neither minimum.

Proof: Suppose that c is a majorant of $(0, 1)$. Then $c \geq 1$. Observe, that $(0, 1) \cap [1, \infty) = \emptyset$, hence, c cannot belong to $(0, 1)$. The proof that $(0, 1)$ has no minimum is similar. \square

Claim 2.1.3. If the maximum exists, then it is unique.

Proof: Suppose the set X has two different maxima: $a \neq b$. Then either $a < b$ or $b < a$. Assume, for instance, that $a < b$. Note that $b \in X$ since b is a maximum of X . Therefore, a does not majorize X . \square

Exercise 2.1.4. Each finite subset of \mathbb{R} has a maximum and a minimum.

Hint: use induction by the number of elements in the set.

Let $X \subset \mathbb{R}$ be an upper bounded set. Consider the set of all upper bounds of X :

$$M_X \stackrel{\text{def}}{=} \{c \in \mathbb{R} : \forall x \in X \quad x \leq c\}.$$

This set is not empty and is lower bounded (**why?**).

For instance, both for $X = [0, 1]$ and $X = (0, 1)$, we have $M_X = [1, +\infty)$.

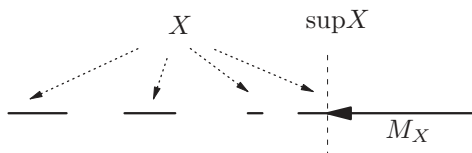


FIGURE 2. Supremum of the set X

Definition 2.1.5 (supremum). The *supremum* of X is the *least upper bound* of X , that is the minimum of the set M_X :

$$\sup X := \min M_X .$$

An equivalent way to pronounce the same definition is

$$s = \sup X \quad \text{iff} \quad (\forall x \in X \quad x \leq s) \wedge (\forall p < s \exists x' \in X \quad p < x') .$$

We see from the previous exercise that if the supremum exists, then it is unique.

Examples: $\sup[-1, 1] = \max[-1, 1] = 1$, $\sup[-1, 1) = 1$. In the second case the maximum does not exist.

Lemma 2.1.6 (existence of supremum). *For every non-empty upper bounded set $X \subset \mathbb{R}$, the supremum exists.*

Proof: Consider the set M_X of all upper bounds of X . We have to show that this set has a minimum.

Since X is upper bounded, $M_X \neq \emptyset$. Condition of the completeness axiom is fulfilled for the sets X and M_X . Therefore,

$$\exists s \in \mathbb{R} \quad \forall x \in X \quad \forall c \in M_X \quad x \leq s \leq c .$$

That is, s is an upper bound of X , and hence belongs to M_X . The same relation shows that s is a minorant of M_X . Therefore, $s = \min M_X$. \square

Now, let $X \subset \mathbb{R}$ be a lower bounded set. The *infimum* of X is the *greatest lower bound* of X , that is

$$\inf X := \max\{c \in \mathbb{R} : \forall x \in X \quad x \geq c\} .$$

If the infimum exists, it is unique.

Here is an equivalent way to word the same definition:

$$s = \inf X \quad \text{iff} \quad (\forall x \in X \quad x \geq s) \wedge (\forall p > s \exists x' \in X \quad x' < p) .$$

Exercise 2.1.7. Let $X \subset \mathbb{R}$ and let $-X := \{x \in \mathbb{R} : -x \in X\}$. Show $\inf X = \sup(-X)$. Deduce that every lower bounded set has an infimum.

It is interesting to note that existence of the supremum of an upper bounded set is *equivalent* to the completeness axiom:

Exercise 2.1.8. Let X and Y be non-empty subsets of \mathbb{R} such that

$$\forall x \in X \quad \forall y \in Y \quad x \leq y .$$

Then the set X is bounded from above. Set $c = \sup X$. Check that $\forall x \in X \quad \forall y \in Y$ one has $x \leq c \leq y$.

The meaning of the following exercise is to verify that any upper bounded set of infinite decimals has a supremum. I.e., the infinite decimals satisfy the completeness axiom.

To prove uniqueness of such k , suppose, that $k' \leq x < k' + 1$. Then k' belongs to the set $\{n \in \mathbb{Z} : n \leq x\}$, whence, $k' \leq k$. If $k' < k$, then by the exercise above, $k' \leq k - 1$, and hence $k' + 1 \leq k \leq x$. This contradiction shows that $k' = k$. \square

This number k is called an *integer part* of x and is denoted by $[x]$ (some CS folks call the same function a *floor function* and denote it by $\lfloor x \rfloor$ but we will not use this notation). The fractional part of x is the number $\{x\} : x - [x]$. It is also defined uniquely and is always in the semi-open interval $[0, 1)$.

Exercise 2.2.6. Draw the graph of the function $f(x) = \{10x\}$.

The following is a straightforward extension of the Archimedes principle: For every $h > 0$ and every $x \in \mathbb{R}$ there exists a unique $k \in \mathbb{Z}$ such that $(k - 1)h \leq x < kh$.

Claim 2.2.7. *Whatever small is a positive ϵ , there is a natural number n such that $0 < 1/n < \epsilon$.*

Proof: otherwise, $\forall n \in \mathbb{N}$ we have $1/n \geq \epsilon$, or $n \leq 1/\epsilon$, that is, the set of naturals \mathbb{N} is upper bounded which is impossible. \square

Claim 2.2.8. *Let $h \geq 0$ and $\forall n \in \mathbb{N} \quad h \leq 1/n$. Then $h = 0$.*

Proof: is the same as in in the previous claim: if $h > 0$, then $\forall n \in \mathbb{N} \quad n \leq 1/h$ and as above we arrive at the contradiction. \square

Claim 2.2.9. *Every open interval contains rationals:*

$$\forall (a, b) \subset \mathbb{R} \quad \exists r \in \mathbb{Q} \cap (a, b).$$

Proof: Choose $n \in \mathbb{N}$ such that $0 < 1/n < b - a$. Then choose $m \in \mathbb{Z}$ such that $\frac{m-1}{n} \leq a < \frac{m}{n}$ (we use the extended version of Archimedes principle with $h = \frac{1}{n}$). Take $r = \frac{m}{n}$. By construction, $r > a$.

If $r \geq b$, then $\frac{m-1}{n} < a < b \leq \frac{m}{n}$, and $b - a < \frac{1}{n}$ which contradicts the choice of n . \square

What about irrational numbers? Try to prove yourself that every open interval contains at least one irrational number or wait till the next lecture.

It is worth mentioning that one really needs the completeness axiom for derivation of these corollaries.

Consider a set of rational functions, that is functions represented as quotients of two polynomials: $r(x) = p(x)/q(x)$ (there could be points x where r is not defined. Two functions $r_1 = p_1/q_1$ and $r_2 = p_2/q_2$ are equal if $p_1q_2 - p_2q_1$ is a zero polynomial (that is, identically equals zero). Show that these functions form a field with usual addition and multiplication (that is, check the axioms). Now, introduce an order: let r_1 and r_2 be two rational functions. We say that $r_1 < r_2$ if there is an $x > 0$ such that $r_1(t) < r_2(t)$ for all $t \in (0, x)$.

Exercise* 2.2.10. Show that this is an ordered field (i.e., check the axioms).

The integers in this field are rational functions which identically equal an integer number. For example, the integer 7 is represented by a rational function $r = (7q)/q$ where q is an arbitrary polynomial.

Exercise* 2.2.11. Check that the rational function $r = 1/x$ is a majorant for the set of all integers in that field. In other words, the integers are bounded therein.

3. THREE BASIC LEMMAS:
CANTOR, HEINE-BOREL, BOLZANO-WEIERSTRASS

In this lecture we prove three fundamental lemmas. The most of the proofs in the rest of the course rely upon them.

3.1. The nested intervals principle.

Lemma 3.1.1 (Cantor). *Any nested sequence of closed intervals $I_1 \supset I_2 \supset \dots \supset I_n \supset I_{n+1} \supset \dots$ has a non-empty intersection:*

$$\bigcap_{n \geq 1} I_n \neq \emptyset.$$

In other words, $\exists c \in \mathbb{R}$ such that $\forall n \in \mathbb{N} \ c \in I_n$.

Proof: Let $I_n = [a_n, b_n]$. Clearly, $\forall m, n$ we have $a_m \leq b_n$ (otherwise, $I_m \cap I_n = [a_m, b_m] \cap [a_n, b_n] = \emptyset$). Consider the sets

$$A := \{a_m : m \in \mathbb{N}\}, \quad B := \{b_n : n \in \mathbb{N}\}.$$

Any element from the set B is an upper bound for the set A , that is the completeness axiom is applicable. It says:

$$\exists c \in \mathbb{R} : \forall m, n \in \mathbb{N} \quad a_m \leq c \leq b_n.$$

In particular,

$$a_n \leq c \leq b_n, \quad \forall n \in \mathbb{N},$$

proving the lemma. □

Clearly, the lemma fails if the nested intervals are open. E.g., $\bigcap_n (0, 1/n) = \emptyset$.

Question 3.1.2. Where in the proof of Cantor's lemma we used that the nested intervals are closed?

Exercise 3.1.3. *Whether the lemma holds true for semi-open nested intervals?*

Exercise 3.1.4. *In the assumptions of the Cantor lemma, $\bigcap_n I_n$ is always a closed interval.*

Sometimes, the following complement to the Cantor lemma is useful: *if, additionally, in the assumptions of the lemma, the lengths of the intervals I_n $|I_n| = b_n - a_n$ are getting closer and closer to zero (formally, $\forall \epsilon > 0 \ \exists k$ such that $|I_k| (= b_k - a_k) < \epsilon$,) then the intersection of I_j is a singleton:*

$$\bigcap_{j \geq 1} I_j = \{c\}.$$

Indeed, if there are two different points c_1 and c_2 in the intersection of I_j 's (and, say, $c_1 < c_2$), then

$$a_n \leq c_1 < c_2 \leq b_n, \quad \forall n \in \mathbb{N},$$

whence $|I_n| = b_n - a_n \geq c_2 - c_1$ which contradicts to the assumption.

3.2. The finite subcovering principle. To proceed further, we need several new definitions. Let Y be a subset of \mathbb{R} , and let $\mathcal{S} = \{X_\alpha\}_{\alpha \in A}$ be a collection of subsets of \mathbb{R} . We say that \mathcal{S} covers Y , if

$$Y \subset \bigcup_{\alpha \in A} X_\alpha.$$

In other words, for every point $y \in Y$, $\exists \alpha \in A$ such that $y \in X_\alpha$.

Examples:

1. Trivial coverings: let Y be an arbitrary subset of \mathbb{R} . Consider $\mathcal{S}_1 := \{\mathbb{R}\}$, that is, \mathcal{S}_1 consists of the one set \mathbb{R} . We get a covering. Another example is $\mathcal{S}_2 := \{y\}_{y \in Y}$, here \mathcal{S}_2 consists of all one-point sets, again we get a covering.
2. Let $Y = (0, 1)$ and $\mathcal{S} = \{X_1, X_2\}$, where $X_1 = [-1, 1/2]$ and $X_2 = [1/3, 2]$.
3. Let $Y = [0, 1]$, $\mathcal{S} = \{I_x\}_{x \in [0, 1]}$, where $I_x = (x - 1/4, x + 1/4)$.

Lemma 3.2.1 (Heine-Borel). *For any system of open intervals $\mathcal{S} = \{I\}$ which covers a closed interval J there is a finite subsystem which still covers J .*

In this case, we say that there exists a finite subcovering. Before going to the proof, we suggest to analyze the third example above and to choose a finite subcovering in that case.

Proof: We use a “bisection method”. Assume that the lemma is wrong. Then we construct inductively an infinite nested sequence of closed sub-intervals J_n of J such that $\forall n$ the intervals J_n cannot be covered by any finite subcollection of \mathcal{S} , and $|J_n| = 2^{-n}|J|$.

Start with $J_0 = J$ and dissect it onto two equal closed subintervals. Since J_0 has no finite subcovering, one of these two parts also has no finite subcovering. Call this part J_1 . Then $J_1 \subset J_0$, $|J_1| = 2^{-1}|J|$ and J_1 has no finite subcovering. Then we continue this dissection procedure.

According to the Cantor lemma (and its complement), the closed intervals J_n have one point intersection: $\bigcap_n J_n = \{c\}$. The point c belongs to J and therefore is covered by an open interval $I = (a, b)$ from the collection \mathcal{S} , that is $a < c < b$. Take $\epsilon = \min(b - c, c - a)$. We know that for some n the length of J_n (which is $2^{-n}|J|$) is less than ϵ , and that $c \in J_n$. Therefore, $J_n \subset (a, b) = I$. Hence, J_n has a finite subcovering from our subcollection, in fact a subcovering by one open interval I . We arrive at the contradiction which proves the lemma. \square

Exercise 3.2.2. Try to change assumptions of this lemma. Whether the result persists if the intervals in the covering are closed? What about coverings of an open interval by closed ones? or by open ones? Consider all three remaining cases.

3.3. The accumulation principle. We start with some definitions. Let x be a real number. Any open interval $I \ni x$ is called a *vicinity* (or *neighbourhood*) of x . The set $I \setminus \{x\}$ is called a *punctured vicinity* of x .

Let $X \subset \mathbb{R}$. A point p is called an *accumulation point* of X if any vicinity of p contains infinitely many points from X . Equivalently, any punctured vicinity of p contains at least one point of X .

Exercise 3.3.1. Proof equivalence of these definitions.

Exercise 3.3.2. Find accumulation points of the following sets:

$$\{1/n\}_{n \in \mathbb{N}}, \quad [a, b], \quad (-2, -1) \cup (1, 2), \quad \mathbb{Z}, \quad \mathbb{Q}, \quad \mathbb{R} \setminus \mathbb{Q}, \quad \mathbb{R}.$$

Lemma 3.3.3 (Bolzano-Weierstrass). *Each infinite bounded set $X \subset \mathbb{R}$ has an accumulation point.*

Proof: Let $X \subset [a, b] =: J$. Assume the assertion is wrong, that is each point $x \in J$ has a neighbourhood $U(x)$ which has a finitely many points in the intersection with X . The open intervals $\{U(x)\}_{x \in J}$ obviously cover J and by the Borel lemma we can chose a finite subcovering. That is,

$$X \subset J \subset \bigcup_{k=1}^N U(x_k),$$

and therefore the set X is finite:

$$\#(X) \leq \sum_{k=1}^N \#(X \cap U(x_k)) < \infty.$$

This contradicts the assumption and proves the lemma. \square

Exercise 3.3.4. Starting with the Bolzano-Weierstrass lemma, derive the existence of the supremum for every upper bounded subset of \mathbb{R} .

The meaning of this exercise is simple: the four principles (completeness, existence of the supremum, Borel's covering lemma, and Bolzano-Weierstrass' lemma) appear to be *equivalent* to each other.

Exercise 3.3.5. All real points are coloured in two colours: black and white, and the both colours were used. Prove that there are points of different colours at the distance less than 0.001.

3.4. Appendix: Countable and uncountable subsets of \mathbb{R} . Here we touch very briefly the notions of finite, infinite, countable and uncountable sets. You will learn more in the courses "Introduction to the set theory" or in "Discrete Mathematics". First, recall some terminology. A map $f: X \rightarrow Y$ is

injective (or "one-to-one") if

$$\forall x_1, x_2 \in X \quad x_1 \neq x_2 \implies f(x_1) \neq f(x_2);$$

i.e., injective maps define one-to-one correspondence between X and its image $f(X) \subset Y$.

surjective if

$$\forall y \in Y \quad \exists x \in X \quad f(x) = y;$$

i.e., surjective maps map X into the whole Y . In this case, we say that f maps X *onto* Y .

bijective if it is injective and surjective; that is, bijective maps define one-to-one correspondence between the sets X and Y .

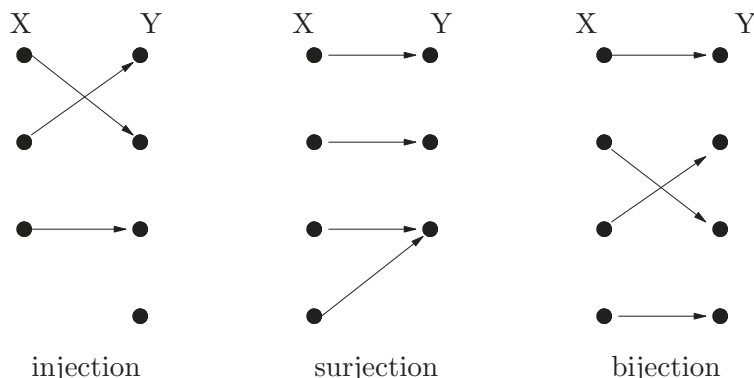


FIGURE 4. Injective, surjective, and bijective maps

Definition 3.4.1. A set X is called *finite* if there is a bijection between the set $\{1, 2, \dots, n\}$ and X . The number n is called a cardinality of a finite set X and denoted by $\#X$.

The emptyset \emptyset is also finite, and its cardinality equals 0.

Exercise 3.4.2. Any subset of a finite set is finite as well.

Definition 3.4.3. A set X is called countable if there exists a bijection $\theta: \mathbb{N} \rightarrow X$.

Claim 3.4.4. Any infinite subset $\mathbb{N}_1 \subset \mathbb{N}$ is countable.

Proof: we build the map $\theta: \mathbb{N} \rightarrow \mathbb{N}_1$ as follows:

$$\theta(1) = \min \mathbb{N}_1 ,$$

$$\theta(n) = \min \{ n \in \mathbb{N}_1 : n > \theta(n-1) \} = \min \mathbb{N}_1 \setminus \{ \theta(1), \dots, \theta(n-1) \} .$$

This map is injective since $n_1 < n_2$ yields $\theta(n_1) < \theta(n_2)$, and surjective since if $m \in \theta(\mathbb{N})$, then $\theta(n) \leq m$ for all $n \in \mathbb{N}$; i.e., the finite set $\{1, 2, \dots, m\}$ contains an infinite subset $\{ \theta(1), \theta(2), \dots, \theta(n), \dots \}$ which is the absurd. \square

Corollary 3.4.5. Any infinite subset of a countable set is countable.

Claim 3.4.6. The set of ordered pairs of positive integer numbers

$$\mathbb{N} \times \mathbb{N} \stackrel{\text{def}}{=} \{ (m, n) : m, n \in \mathbb{N} \}$$

is countable.

The proof of this claim follows by inspection of the infinite Cantor board (Figure 5) that explains how to build a bijection between the sets \mathbb{N} and $\mathbb{N} \times \mathbb{N}$. \square

Corollary 3.4.7. Any finite or countable union of countable sets is countable.

Proof: Let $\mathbb{N}_1 \subset \mathbb{N}$, and let $X = \bigcup_{m \in \mathbb{N}_1} X_m$ be a finite or countable union of countable sets. Let $X_m = \{ x_{m,1}, x_{m,2}, \dots, x_{m,n}, \dots \}$. Then $\psi: (m, n) \mapsto x_{m,n}$ defines a bijection between X and a subset of $\mathbb{N} \times \mathbb{N}$. The previous claims yield that X is countable. \square

22	30	39	49	60	72	85	
16	23	31	40	50	61	73	
11	17	24	32	41	51	62	
7	12	18	25	33	42	52	
4	8	13	19	26	34	43	
2	5	9	14	20	27	35	
1	3	6	10	15	21	28	

FIGURE 5. Cantor's board

Corollary 3.4.8. *The set of rational numbers is countable.*

Proof: Consider the countable sets

$$Q_m \stackrel{\text{def}}{=} \left\{ r = \frac{n}{m} : n \in \mathbb{Z} \right\}, \quad m \in \mathbb{N}.$$

(For instance, $Q_7 = \{\dots, -\frac{2}{7}, -\frac{1}{7}, 0, \frac{1}{7}, \frac{2}{7}, \dots\}$). Then

$$\mathbb{Q} = \bigcup_{m \in \mathbb{N}} Q_m$$

is a countable union of countable sets. Hence, it is countable. \square

Exercise 3.4.9. Write down an explicit formula for the bijection between the sets \mathbb{N} and $\mathbb{N} \times \mathbb{N}$.

Theorem 3.4.10 (Cantor). *Any interval (open, closed, or semi-open) of positive length contains uncountable many points.*

Proof: Since any interval of positive length contains a closed subinterval of positive length, it suffices to prove the statement for closed intervals. Suppose that the statement is not correct, i.e., there is a closed interval I_1 of positive length which contains countably many points: $I_1 = \{x_1, x_2, \dots, x_n, \dots\}$. Choose a closed subinterval $I_2 \subset I_1$ of positive length that does not contain the point x_1 . Then choose a closed subinterval of positive length $I_3 \subset I_2$ that does not contain the point x_2 , etc.

At the n -th step, having a closed interval of positive length I_n , we choose its closed subinterval $I_{n+1} \subset I_n$ of positive length that does not contain the point x_{n+1} . By Cantor's lemma, the intersection $\bigcap_j I_j$ is not empty. Take any point $c \in \bigcap_j I_j$. By construction, $c \in I_1$, but c differs from any of the points $x_1, x_2, \dots, x_n, \dots$. Contradiction!

\square

Exercise 3.4.11. The set of all irrational numbers is uncountable.

Exercise 3.4.12.

- i** Prove that it is possible to draw only countably many disjoint figures \mathcal{S} on the plane.
- ii*** Prove that it is possible to draw only countably many disjoint letters \mathcal{T} on the plane.

4. SEQUENCES AND THEIR LIMITS

4.1. The infinite sequence is a function defined on the set \mathbb{N} of natural numbers, $f: \mathbb{N} \rightarrow \mathbb{R}$. Such a function f can be written as a infinite string

$$\{f(1), f(2), f(3), \dots, f(n), \dots\}.$$

For historical reasons, in this case the argument is usually written as a subscript: $\{f_1, f_2, f_3, \dots, f_n, \dots\}$. A standard notation for such a string is $\{f_n\}_{n \in \mathbb{N}}$. The value f_n is called the n -th term of the sequence.

Examples:

Arithmetic progression

$$\{1, 2, 3, 4, 5, 6, \dots\},$$

or more generally

$$\{a, a + d, a + 2d, a + 3d, a + 4d, a + 5d, \dots\}.$$

Geometric progression

$$\{q^0, q^1, q^2, q^3, q^4, q^5, \dots\}$$

Definition 4.1.1 (convergence). A sequence $\{x_n\}$ converges to the limit a if

$$\forall \epsilon > 0 \quad \exists N \in \mathbb{N} \quad \text{such that} \quad \forall n \geq N \quad |x_n - a| < \epsilon.$$

In other words, whatever small ϵ is, only finitely many terms of the sequence do not belong to the interval $(a - \epsilon, a + \epsilon)$. If the sequence $\{x_n\}$ converges to the limit a , we

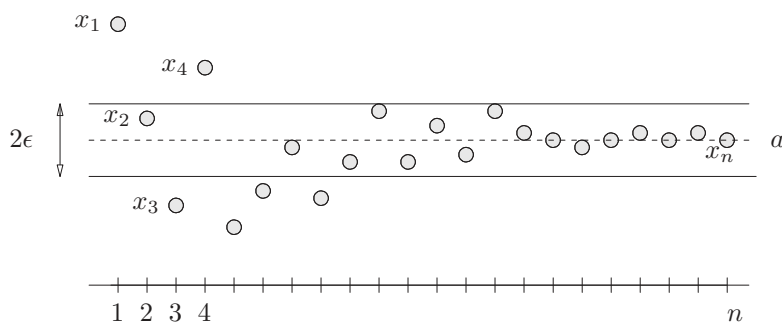


FIGURE 6. Convergent sequence

write

$$a = \lim_{n \rightarrow \infty} x_n,$$

or $x_n \rightarrow a$. If a sequence is not convergent, it is called *divergent*.

Examples:

- $\{1/n\}$, the sequence converges to zero;
- $\{(n+1)/n\}$, the sequence converges to one;
- $\{1, \frac{1}{2}, 3, \frac{1}{4}, 5, \frac{1}{6}, \dots\}$, the sequence is divergent;
- $\{1 + (-1)^n/n\}$, the sequence converges to one;

$\{\sin n/n\}$, the sequence converges to zero;
 $\{q^n\}$, the sequence converges to zero if $|q| < 1$, converges to one if $q = 1$, and is divergent in the other cases.

4.2. Fundamental properties of the limits.

(a) *If the limit exists, it is unique.*

Proof: Let a and b be limits of a sequence $\{x_n\}$. We have to prove that $a = b$. Given positive ϵ , we can find $N \in \mathbb{N}$ such that simultaneously $|x_N - a| < \epsilon$ and $|x_N - b| < \epsilon$. Therefore,

$$|a - b| = |(a - x_N) + (x_N - b)| \leq |x_N - a| + |x_N - b| < 2\epsilon.$$

Since this holds for an arbitrary positive ϵ , we conclude that $a = b$, completing the proof. \square

(b) *If a sequence converges, then it is bounded.*

Proof: Let a be a limit of a sequence $\{x_n\}$. Using the definition of convergence with $\epsilon = 1$, we find $N \in \mathbb{N}$ such that $|x_n - a| < 1$ for all $n \geq N$. Therefore, for these n 's, $|x_n| < |a| + 1$. Hence $\{x_n\}$ is bounded:

$$|x_n| \leq M := \max(|x_1|, |x_2|, \dots, |x_{N-1}|, |a| + 1), \quad \forall n \in \mathbb{N}.$$

\square

Note that the bounded sequence $\{(-1)^n\}$ diverges.

(c) *Let $\{x_n\}$ and $\{y_n\}$ be two sequences such that the set $\{n \in \mathbb{N} : x_n \neq y_n\}$ is finite, and let $\{x_n\}$ converges to a . Then $\{y_n\}$ converges to a as well.*

In other words, the limit depends only on a *tail* of the sequence. We leave this as an exercise.

Exercise 4.2.1. Prove that every convergent sequence has either the maximal term, or the minimal term, or the both ones. Provide examples for each of the three cases.

Exercise 4.2.2. Let a sequence $\{x_n\}$ converge to zero, and let a sequence $\{y\}$ be obtained from $\{x_n\}$ by a permutation of its terms, then $\{y_n\}$ converges to zero as well.

With sequences we can do the same operations as with functions: for example, we can add and multiply them termwise.

Theorem 4.2.3. *Let $a = \lim x_n$ and $b = \lim y_n$. Then*

- (i) $\lim(x_n \pm y_n) = a \pm b$;
- (ii) $\lim(x_n \cdot y_n) = a \cdot b$;
- (iii) if $b \neq 0$, then $\lim(x_n/y_n) = a/b$.

Proof:

(i) Given $\epsilon > 0$, we choose N_1 such that $|x_n - a| < \epsilon$ for all $n \geq N_1$ and choose N_2 such that $|y_n - b| < \epsilon$ for all $n \geq N_2$. Thus, for $n \geq N := \max(N_1, N_2)$, both inequalities hold. Therefore,

$$|(x_n \pm y_n) - (a \pm b)| \leq |x_n - a| + |y_n - b| < 2\epsilon,$$

proving the claim.

(ii) Since $\{x_n\}$ is convergent, it is bounded. Take $M = \sup |x_n|$. Given $\epsilon > 0$, choose values N_1 and N_2 such that for all $n \geq N_1$ we have $|x_n - a| < \epsilon$, and for all $n \geq N_2$ we have $|y_n - b| < \epsilon$. Then

$$\begin{aligned} |x_n \cdot y_n - a \cdot b| &= |x_n \cdot (y_n - b) + (x_n - a) \cdot b| \\ &\leq (\sup |x_n|) \cdot |y_n - b| + |b| \cdot |x_n - a| < M \cdot \epsilon + |b| \cdot \epsilon = (M + |b|)\epsilon. \end{aligned}$$

(iii) We start with a warning some terms of the sequence $\{y_n\}$ can vanish. A good news is that a number of vanishing terms of this sequence is always finite. So that, the sequence $\{x_n/y_n\}$ is well-defined for sufficiently large indices n .

Now, keeping in mind that (ii) has been proved already, we conclude that it suffices to prove (iii) only in a special case when $x_n = 1$ for all $n \in \mathbb{N}$. We have to estimate the quantity

$$\left| \frac{1}{y_n} - \frac{1}{b} \right| = \frac{|y_n - b|}{|y_n| \cdot |b|}.$$

Since the sequence $\{y_n\}$ has a non-zero limit, we can choose $N_1 \in \mathbb{N}$ such that $|y_n| \geq \delta (> 0)$ for all $n \geq N_1$. Then, given $\epsilon > 0$, we choose $N_2 \in \mathbb{N}$ such that $\forall n \geq N_2$ $|y_n - b| < \epsilon$. Therefore, $\forall n \geq N := \max(N_1, N_2)$

$$\left| \frac{1}{y_n} - \frac{1}{b} \right| < \frac{\epsilon}{\delta|b|},$$

completing the proof of the theorem. □

Exercise 4.2.4. Prove:

1. Let $a = \lim x_n$, $b = \lim y_n$ and $a < b$. Then $x_n < y_n$ for all sufficiently large indices n .
2. Let $a = \lim x_n$, $b = \lim y_n$ and $x_n \leq y_n$ for all sufficiently large indices n . Then $a \leq b$.

Theorem 4.2.5 (Two policemen, a.k.a. the sandwich). *Let*

$$x_n \leq c_n \leq y_n, \quad n \in \mathbb{N},$$

and let the sequences $\{x_n\}$ and $\{y_n\}$ converge to the same limit a . Then the sequence $\{c_n\}$ also converges to a .

Question: Explain, how the theorem got these names.

Proof: Given $\epsilon > 0$, choose the naturals N_1 and N_2 such that

$$\forall n \geq N_1 \quad a - \epsilon < x_n,$$

and

$$\forall n \geq N_2 \quad y_n < a + \epsilon.$$

Then for any $n \geq N := \max(N_1, N_2)$

$$a - \epsilon < c_n < a + \epsilon,$$

proving the convergence of $\{c_n\}$ to a . □

Definition 4.2.6 (monotonic sequence). A sequence $\{x_n\}$ does not decrease if

$$x_1 \leq x_2 \leq \dots \leq x_n \leq \dots$$

A sequence $\{x_n\}$ does not increase if

$$x_1 \geq x_2 \geq \dots \geq x_n \geq \dots$$

If the strong inequalities hold, we'll say correspondingly that the sequence increases/decreases. In any of these cases, a sequence is called *monotonic*.

The next result is fundamental:

Theorem 4.2.7. *Any upper bounded non-decreasing sequence $\{x_n\}$ converges, and*

$$\lim x_n = \sup x_n .$$

Proof: Take $a := \sup x_n$. According to the definition of the supremum, $x_n \leq a$ for each $n \in \mathbb{N}$, and given $\epsilon > 0$ there is an $N \in \mathbb{N}$ such that $x_N > a - \epsilon$. By monotonicity,

$$\forall n \geq N \quad x_n \geq x_N > a - \epsilon .$$

Therefore, for all sufficiently large indices n , $a - \epsilon < x_n \leq a$, proving the theorem. \square

This result is *equivalent* to the existence of the supremum of any upper bounded subset of the reals (and therefore, to all other equivalent forms of this statement we already know).

5. CONVERGENT SEQUENCES

5.1. Examples.

5.1.1. Fix $q > 1$ and consider a sequence with terms

$$x_n = \frac{n}{q^n}.$$

We shall prove that it converges to zero.

First, check that the sequence eventually (that is, for large enough n) decreases. Indeed,

$$\frac{x_{n+1}}{x_n} = \frac{n+1}{n \cdot q}.$$

If n is sufficiently large, the left hand side is less than one since $\lim(n+1)/n = 1$ and $q > 1$. That is, for large n , $x_{n+1} < x_n$.

Therefore, by the theorem from the previous lecture, the sequence $\{x_n\}$ converges to a non-negative limit a . Let us show that $a = 0$. We have

$$a = \lim x_{n+1} = \lim \left(\frac{n+1}{qn} \cdot x_n \right) = \frac{1}{q} \cdot \underbrace{\lim \frac{n+1}{n}}_{=1} \cdot \lim x_n = \frac{a}{q}.$$

Comparing the right and left hand sides, we conclude that $a = 0$. □

Corollary 5.1.1. $\lim \sqrt[n]{n} = 1$.

Indeed, taking into account the limit we've just computed, given $\epsilon > 0$ we can take N so large that $\forall n \geq N$

$$1 < n < (1 + \epsilon)^n.$$

Then

$$1 < \sqrt[n]{n} < 1 + \epsilon,$$

proving the convergence to one. □

Exercise 5.1.2. Let $M \in \mathbb{N}$, $a > 0$, and $q > 1$. Prove that

$$\lim \frac{n^M}{q^n} = 0 \quad \text{and} \quad \lim \sqrt[n]{a} = 1.$$

5.1.2. For each positive q ,

$$\lim_{n \rightarrow \infty} \frac{q^n}{n!} = 0.$$

We use a similar argument: first show that the sequence $x_n = q^n/n!$ eventually decays:

$$\frac{x_{n+1}}{x_n} = \frac{q^{n+1}}{q^n} \cdot \frac{n!}{(n+1)!} = \frac{q}{n+1} < 1,$$

if n is sufficiently large. Therefore, the sequence converges to a limit a . We check that a vanishes:

$$a = \lim x_{n+1} = \lim \frac{q}{n+1} \cdot x_n = 0 \cdot a = 0.$$

□

In the following example the sequence is defined *recurrently*.

5.1.3. Take $x_0 = 1$, $x_n = \sqrt{2 + x_{n-1}}$. We show that the sequence $\{x_n\}$ converges to 2. Less formally,

$$\sqrt{2 + \sqrt{2 + \dots \sqrt{2 + \dots}}} = 2.$$

First, using induction by n , we check that $1 \leq x_n < 2$ for all n . The base $n = 1$ of the induction is evident. Assume that the claims are verified for n , check that they hold for $n + 1$. Since $1 \leq x_n < 2$, we have $1 < x_{n+1} = \sqrt{2 + x_n} < \sqrt{4} = 2$, proving the claim for $n + 1$. Now, we check that the sequence $\{x_n\}$ increases, which is equivalent to $2 + x > x^2$ for $1 \leq x < 2$. This holds since the quadratic polynomial $x^2 - x - 2 = (x - 2)(x + 1)$ is negative for these x 's.

We conclude that $\{x_n\}$ is an increasing upper bounded sequence, so that, it has a limit which we call a . Then

$$a^2 = \lim_{n \rightarrow \infty} x_{n+1}^2 = 2 \lim_{n \rightarrow \infty} x_n = 2a,$$

so that $a = 2$. □

5.1.4.

$$\lim_{n \rightarrow \infty} \frac{1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n - 1)}{2 \cdot 4 \cdot 6 \dots \cdot 2n} = 0.$$

This follows from the following chain:

$$\left(\frac{1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n - 1)}{2 \cdot 4 \cdot 6 \dots \cdot 2n} \right)^2 = \frac{1 \cdot 3}{2 \cdot 2} \cdot \frac{3 \cdot 5}{4 \cdot 4} \cdot \dots \cdot \frac{(2n - 3)(2n - 1)}{(2n - 2)^2} \cdot \frac{2n - 1}{2n} \cdot \frac{1}{2n} < \frac{1}{2n}.$$

so that

$$(5.1.3) \quad \frac{1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n - 1)}{2 \cdot 4 \cdot 6 \dots \cdot 2n} < \frac{1}{\sqrt{2n}},$$

and the statement follows. □

It's worth to mention that the estimate (5.1.3) is not bad. In reality,

$$\lim_{n \rightarrow \infty} \sqrt{n} \frac{1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n - 1)}{2 \cdot 4 \cdot 6 \dots \cdot 2n} = \frac{1}{\sqrt{2\pi}}.$$

This follows from the Wallis formula which, hopefully, you will learn in the second semester.

Exercise 5.1.4. Find the limit

$$\lim_{n \rightarrow \infty} \left(\frac{1}{\sqrt{n^2 + 1}} + \frac{1}{\sqrt{n^2 + 2}} + \dots + \frac{1}{\sqrt{n^2 + n}} \right)$$

5.2. Two theorems. Now we prove two rather useful results. They assert that if $\{x_n\}$ is a convergent sequence, then sequences of arithmetic and geometric means must converge to the same limit.

Theorem 5.2.1. *Let $\lim x_n = a$. Then*

$$\lim_{n \rightarrow \infty} \frac{1}{n} \sum_{k=1}^n x_k = a.$$

Proof: Without loss of generality, we assume that $a = 0$, otherwise we just replace x_n by $x_n - a$. Put $M = \sup |x_n|$ (that is, $\sup\{|x_n|: n \in \mathbb{N}\}$). Given $\epsilon > 0$, find sufficiently large N such that $|x_k| < \epsilon$ for all $k \geq N$. Then

$$\left| \frac{1}{n} \sum_{k=1}^n x_k \right| \leq \frac{1}{n} \sum_{k=1}^n |x_k| = \frac{1}{n} \sum_{k=1}^N |x_k| + \frac{1}{n} \sum_{k=N+1}^n |x_k| \leq \frac{N \cdot M}{n} + \epsilon < 2\epsilon,$$

provided that $n \geq \frac{N \cdot M}{\epsilon}$. This proves the theorem. \square

Exercise 5.2.2. Prove or disprove the following statement: *If a sequence*

$$\frac{1}{n} \sum_{k=1}^n x_k$$

converges, then the sequence $\{x_k\}$ converges as well.

Exercise 5.2.3. If a sequence $\{x_n\}$ is such that $\lim(x_{n+1} - x_n) = c$, then

$$\lim \frac{x_n}{n} = c$$

as well.

Theorem 5.2.4. *Let x_n be a positive sequence such that $\lim x_n = a$. Then*

$$\lim_{n \rightarrow \infty} \sqrt[n]{x_1 x_2 \dots x_n} = a.$$

Proof: The idea of the proof is the same as in the previous theorem. First consider the case when the limit $a \neq 0$. Then without loss of generality, we assume that $a = 1$, otherwise we just replace x_n by x_n/a . Put $M = \sup |x_n|$, and $m = \inf |x_n|$. Observe that $m > 0$ (why?). Given $\epsilon > 0$, we have $1 - \epsilon < x_n < 1 + \epsilon$ for all sufficiently large $n > N$. Then

$$x_1 \cdot \dots \cdot x_n < M^N (1 + \epsilon)^{n-N} = \left(\frac{M}{1 + \epsilon} \right)^N (1 + \epsilon)^n$$

and

$$\sqrt[n]{x_1 x_2 \dots x_n} < Q^{1/n} (1 + \epsilon)$$

with $Q = (M/(1 + \epsilon))^N$. Since $Q^{1/n} \rightarrow 1$ as $n \rightarrow \infty$, we can choose N_1 (depending on ϵ and M) such that, for $n > N_1$, we have $Q^{1/n} < 1 + \epsilon$. Whence,

$$\sqrt[n]{x_1 x_2 \dots x_n} < (1 + \epsilon)^2$$

for $n > \max(N, N_1)$. Similarly

$$\sqrt[n]{x_1 x_2 \dots x_n} \geq (1 - \epsilon)^2$$

(check this!). If $\epsilon < 1$, these two estimates yield

$$-2\epsilon < (1 - \epsilon)^2 - 1 \leq \sqrt[n]{x_1 x_2 \dots x_n} - 1 \leq (1 + \epsilon)^2 - 1 < 3\epsilon,$$

completing the proof.

The case $a = 0$ is similar, and we leave it as an exercise. \square

Corollary 5.2.5. *Let $t_n > 0$ and*

$$\lim_{n \rightarrow \infty} \frac{t_{n+1}}{t_n} = c.$$

Then $\lim \sqrt[n]{t_n} = c$ as well.

Proof: we reduce this statement to Theorem 5.2.4. Put

$$x_1 := t_1, \quad x_n = \frac{t_n}{t_{n-1}}.$$

Then $t_n = x_1 \cdot x_2 \cdot \dots \cdot x_n$ and the statement follows from Theorem 5.2.4. \square

5.3. More examples.

5.3.1. Take in the previous corollary $t_n = \binom{2n}{n}$ (the binomial coefficient “choose n from $2n$ ”). The corollary is applicable since

$$\frac{t_{n+1}}{t_n} = \frac{(2n+2)!}{((n+1)!)^2} \cdot \frac{(n!)^2}{(2n)!} = \frac{(2n+1)(2n+2)}{(n+1)^2},$$

tends to 4 when $t \rightarrow \infty$. We obtain

$$\lim_{n \rightarrow \infty} \sqrt[n]{\binom{2n}{n}} = 4.$$

Exercise 5.3.1. For a (fixed) natural k , find

$$\lim_{n \rightarrow \infty} \sqrt[n]{\binom{kn}{n}}.$$

The next two limits are quite famous.

5.3.2. Let $x_0 > 0$ and

$$(5.3.2) \quad x_{n+1} := \frac{1}{2} \left(x_n + \frac{a}{x_n} \right), \quad a > 0.$$

Then the sequence $\{x_n\}$ converges to \sqrt{a} .

This is an iterative Newton method of finding square roots³. Note that the right-hand side of (5.3.2) is the arithmetic mean between two approximation to x_n and a/x_n to \sqrt{a} .

If we know that the sequence $\{x_n\}$ is convergent, then it is quite easy to guess that the limit is \sqrt{a} . Indeed, denote the limit c . Then using the recurrence from the definition of $\{x_n\}$, we get an equation

$$c = \frac{1}{2} \left(c + \frac{a}{c} \right).$$

That is, $c^2 = a$ and $c = \sqrt{a}$.

³known to Babylonians and to the first-century Greek mathematician Heron of Alexandria

Proof: in order to simplify recursion, let us replace x_n by

$$\xi_n := \frac{x_n - \sqrt{a}}{\sqrt{a}}.$$

Then $x_n = \sqrt{a}(1 + \xi_n)$. Let us find a recursion for ξ_n : substituting the previous formula into recursion for x_n , we get

$$\sqrt{a}(1 + \xi_{n+1}) = \frac{1}{2} \left(\sqrt{a}(1 + \xi_n) + \frac{a}{\sqrt{a}(1 + \xi_n)} \right).$$

Whence (after some simplifications)

$$\xi_{n+1} = \frac{\xi_n^2}{2(1 + \xi_n)}.$$

Next, observe that ξ_n are positive for any $n \in \mathbb{N}$. Indeed, $1 + \xi_0 = \frac{x_0}{\sqrt{a}} > 0$, so that $\xi_1 > 0$. Then $\xi_2 > 0$ etc. Therefore,

$$\xi_{n+1} < \frac{\xi_n^2}{2\xi_n} = \frac{\xi_n}{2} < \dots < \frac{\xi_1}{2^n}.$$

That is, ξ_n converges to zero and x_n converges to \sqrt{a} . □

The proof above also gives a convergence of the Newton algorithm with the rate of geometric progression:

$$|x_n - \sqrt{a}| < \frac{\text{Const}}{2^n} \sqrt{a}.$$

In fact, the convergence even faster (like q^{2^n} with some $q < 1$). This explain a remarkable efficiency of Newton's method.

Exercise 5.3.3. Try to give a better estimate of $|x_n - \sqrt{a}|$. Using Newton method (and calculator, if needed) find $\sqrt{111}$ with error of order 10^{-6} . How many iterations were you needed for that?

5.3.3. The sequence

$$x_n := \left(1 + \frac{1}{n}\right)^n$$

converges to a limit. To prove this, we define another sequence

$$y_n := \left(1 + \frac{1}{n}\right)^{n+1}.$$

We'll show that the sequence $\{y_n\}$ decays. Then since it is lower bounded ($y_n > 1$) it is convergent. Since

$$x_n = y_n \cdot \frac{n}{n+1}$$

and the second factor on the right hand side converges to one, x_n converges to the same limit as y_n .

To check that $\{y_n\}$ decays, we use Bernoulli's inequality. We have

$$\begin{aligned} \frac{y_{n-1}}{y_n} &= \frac{\left(1 + \frac{1}{n-1}\right)^n}{\left(1 + \frac{1}{n}\right)^{n+1}} = \frac{n^{2n+1}}{(n-1)^n(n+1)^{n+1}} \\ &= \frac{n^{2n}}{(n^2-1)^n} \cdot \frac{n}{n+1} = \left(1 + \frac{1}{n^2-1}\right)^n \cdot \frac{n}{n+1} \\ &\geq \left(1 + \frac{n}{n^2-1}\right) \cdot \frac{n}{n+1} > \left(1 + \frac{1}{n}\right) \cdot \frac{n}{n+1} = 1, \end{aligned}$$

completing the argument. \square

The limit of this sequence is denoted by e . This is one of the most important constants. It's easy to see that $2 \leq e < 3$. Indeed, by Bernoulli's inequality

$$x_n = \left(1 + \frac{1}{n}\right)^n \geq 1 + n \frac{1}{n} = 2.$$

To get the upper bound, note that

$$y_5 = \left(1 + \frac{1}{5}\right)^6 = \left(\frac{6}{5}\right)^6 = \frac{46656}{15625} < 3.$$

Since the sequence y_n decays, its limit is less than 3. The approximate value is $e \approx 2.718281828459\dots$. Later, we'll find another representation for this constant:

$$e = \lim_{n \rightarrow \infty} \left(1 + \frac{1}{1!} + \frac{1}{2!} + \dots + \frac{1}{n!}\right)$$

which is more convenient for numerical computation of e . We will also prove that e is an irrational number.

**6. CAUCHY'S SEQUENCES. UPPER AND LOWER LIMITS.
EXTENDED CONVERGENCE**

In this lecture, we continue our study of convergent sequences.

6.1. Cauchy's sequences. Suppose, we need to check that some sequence converges but we have no clue about its limiting value. The definition of the limit will not help us too much: it is not an easy task to verify it without a priori knowledge about the limit. It would be useful to have an equivalent definition of convergence which does not mention the limiting value at all.

Definition 6.1.1 (Cauchy's sequence). *A sequence $\{x_n\}$ is called Cauchy's sequence, if*

$$\forall \epsilon > 0 \quad \exists N \in \mathbb{N} \quad \text{such that} \quad \forall m, n \geq N \quad |x_n - x_m| < \epsilon. \quad (C)$$

Theorem 6.1.2 (Cauchy). *A sequence $\{x_n\}$ is convergent if and only if it is Cauchy's sequence.*

Proof: In one direction the result is clear: if the sequence $\{x_n\}$ converges to a limit a , then according to the definition of the limit,

$$\forall \epsilon > 0 \quad \exists N \in \mathbb{N} \quad \text{such that} \quad \forall m, n \geq N \\ |x_n - a| < \epsilon, \quad |x_m - a| < \epsilon,$$

and therefore

$$|x_n - x_m| = |(x_n - a) + (a - x_m)| < 2\epsilon,$$

proving that $\{x_n\}$ is Cauchy's sequence.

In the other direction, first, let us observe that the sequence $\{x_n\}$ is bounded: choose $N \in \mathbb{N}$ such that

$$x_N - 1 < x_m < x_N + 1$$

for all $m \geq N$. Then the bound for $|x_n|$ is

$$\sup_n |x_n| \leq \max\{|x_1|, |x_2|, \dots, |x_{N-1}|, |x_N| + 1\}.$$

Now, introduce the sequences

$$\underline{x}_n = \inf_{m \geq n} x_m, \quad \bar{x}_n = \sup_{m \geq n} x_m.$$

The values \underline{x}_n , and \bar{x}_n are finite since the sequence $\{x_n\}$ is bounded. Compare \underline{x}_n with \underline{x}_{n+1} : in the definition of \underline{x}_{n+1} we take an infimum over a smaller set, therefore, $\underline{x}_{n+1} \geq \underline{x}_n$. Similarly, $\bar{x}_{n+1} \leq \bar{x}_n$. Besides, we always have $\underline{x}_n \leq \bar{x}_n$. Summarizing,

$$\dots \leq \underline{x}_n \leq \underline{x}_{n+1} \leq \dots \leq \bar{x}_{n+1} \leq \bar{x}_n \leq \dots,$$

and we get a sequence of closed nested intervals $[\underline{x}_n, \bar{x}_n]$. By Cantor's lemma, the intersection of these intervals is not empty, so we choose

$$c \in \bigcap_{n \geq 1} [\underline{x}_n, \bar{x}_n]$$

as a candidate for $\lim x_n$. We claim that the sequence $\{x_n\}$ converges to c .

Note that the values c and x_n both belong to the interval $[\underline{x}_n, \bar{x}_n]$. Hence

$$|c - x_n| \leq \bar{x}_n - \underline{x}_n.$$

In order to estimate the difference on the left hand side, fix $\epsilon > 0$ and choose $N \in \mathbb{N}$ according to (C). Let $n \geq N$. Then for some $m \geq n$

$$\bar{x}_n (= \sup_{k \geq n} x_k) < x_m + \epsilon < x_n + 2\epsilon,$$

and similarly

$$\underline{x}_n > x_n - 2\epsilon.$$

Hence $\bar{x}_n - \underline{x}_n < (x_n + 2\epsilon) - (x_n - 2\epsilon) = 4\epsilon$, and $|c - x_n| < 4\epsilon$ completing the proof. \square

Example 6.1.3. Consider the sequence

$$S_n = 1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{n}.$$

Then

$$S_{2n} - S_n = \frac{1}{n+1} + \frac{1}{n+2} + \dots + \frac{1}{2n} > n \cdot \frac{1}{2n} = \frac{1}{2}.$$

Hence the sequence $\{S_n\}$ is not Cauchy's sequence and therefore is divergent.

Note that we can check divergence of this sequence without appeal to the Cauchy criterion. The property $S_{2n} - S_n \geq \frac{1}{2}$ we've established shows that the sequence S_n is unbounded.

6.2. Upper and lower limits. In the proof of the Cauchy theorem, for a given sequence $\{x_n\}$ bounded from above and from below, we defined two sequences $\{\underline{x}_n\}$ and $\{\bar{x}_n\}$. Sometimes, they are called the *lower and upper envelopes of the sequence* $\{x_n\}$.

Note that if the sequence $\{x_n\}$ does not decrease, then $\underline{x}_n = x_n$, and if the sequence $\{x_n\}$ does not increase, then $\bar{x}_n = x_n$.

Example 6.2.1.

(i) If $x_n = \frac{1}{n}$, then $\bar{x}_n = \frac{1}{n}$ while $\underline{x}_n = 0$.

(ii) If $x_n = (-1)^n$, then $\underline{x}_n = -1$ while $\bar{x}_n = 1$.

(iii) If $x_n = \frac{(-1)^n}{n}$, then

$$\{\underline{x}_n\} = \left\{-1, -\frac{1}{3}, -\frac{1}{3}, -\frac{1}{5}, -\frac{1}{5}, \dots\right\}, \quad \{\bar{x}_n\} = \left\{\frac{1}{2}, \frac{1}{2}, \frac{1}{4}, \frac{1}{4}, \frac{1}{6}, \frac{1}{6}, \dots\right\}.$$

In the course of the proof of Cauchy's theorem, we observed that

- (i) the sequence \underline{x}_n does not decrease;
- (ii) the sequence \bar{x}_n does not increase;
- (iii) $\forall m, n \quad \underline{x}_n \leq \bar{x}_m$

In particular, we see that the both envelopes are monotonic sequences, and therefore they converge when they are bounded. Now, we look more carefully at their limits.

Definition 6.2.2 (limsup, liminf). *If the sequence $\{x_n\}$ is upper bounded, then its upper limit (or limit superior) is*

$$\limsup_{n \rightarrow \infty} x_n := \lim_{n \rightarrow \infty} \bar{x}_n = \lim_{n \rightarrow \infty} \sup_{m \geq n} x_m .$$

If the sequence $\{x_n\}$ is not upper bounded, we say that its upper limit equals $+\infty$.

If the sequence $\{x_n\}$ is lower bounded, then its lower limit is

$$\liminf_{n \rightarrow \infty} x_n := \lim_{n \rightarrow \infty} \underline{x}_n = \lim_{n \rightarrow \infty} \inf_{m \geq n} x_m .$$

If the sequence $\{x_n\}$ is not lower bounded, we say that its lower limit equals $-\infty$.

We see that always $\liminf x_n \leq \limsup x_n$.

Deciphering the definition of the upper limit, we see that $\limsup x_n = L$ if and only if the following two conditions are fulfilled:

- (a) $\forall \epsilon > 0 \exists N \in \mathbb{N}$ such that $\forall n \geq N \ x_n < L + \epsilon$;
- (b) $\forall \epsilon > 0 \forall N \in \mathbb{N} \exists n > N$ such that $x_n > L - \epsilon$.

Indeed, condition (a) says that $\forall n \geq N \ \bar{x}_n < L + \epsilon$; i.e., that $\lim \bar{x}_n \leq L$, while condition (b) says that $\forall n \geq N \ \bar{x}_n \geq L$; i.e., that $\lim \bar{x}_n \geq L$.

Exercise 6.2.3. Formulate and prove the similar criterium for $\liminf x_n$.

Theorem 6.2.4. *A sequence $\{x_n\}$ converges to the limit a if and only if*

$$\liminf x_n = \limsup x_n = a . \tag{L}$$

In other words, the sequence $\{x_n\}$ converges to the limit a if and only if the envelopes $\{\bar{x}_n\}$ and $\{\underline{x}_n\}$ converge to the same limit a .

Proof: In one direction, since $\underline{x}_n \leq x_n \leq \bar{x}_n$, then (L) combined with the two policemen theorem give us convergence of $\{x_n\}$.

In the other direction, if $\{x_n\}$ converges to the limit a , then we fix $\epsilon > 0$ and choose $N \in \mathbb{N}$ such that $\forall m \geq N$ we have $|x_m - a| < \epsilon$. If $n \geq N$, then for some $m \geq n$ we have

$$a - \epsilon < x_n \leq \bar{x}_n < x_m + \epsilon < a + 2\epsilon ,$$

therefore $\limsup x_n = \lim \bar{x}_n = a$, and similarly $\liminf x_n = a$ proving (L). \square

Note that we use more or less the same argument as in the proof of Cauchy's theorem.

Exercise 6.2.5. Check that

$$\limsup(-x_n) = -\liminf x_n ;$$

and if $0 < a \leq x_n \leq b < \infty$,

$$\limsup 1/x_n = 1/\liminf x_n .$$

Prove the inequalities

$$\limsup(x_n + y_n) \leq \limsup x_n + \limsup y_n ,$$

$$\limsup(x_n \cdot y_n) \leq \limsup x_n \cdot \limsup y_n ,$$

(in the second inequality, we assume that $x_n, y_n > 0$). Show that, if one of the sequences $\{x_n\}$ or $\{y_n\}$ converges, then there is an equality sign in these inequalities.

Exercise 6.2.6. Let $0 < a \leq x_n \leq b < +\infty$. Show that

$$\limsup x_n \cdot \limsup \frac{1}{x_n} \geq 1.$$

Show that the equality sign is attained there if and only if the sequence $\{x_n\}$ is convergent.

Exercise 6.2.7. Let a_n be positive numbers such that

$$A_n = \sum_{k=1}^n a_k \rightarrow \infty, \quad n \rightarrow \infty.$$

For any sequence $\{t_n\}$ set

$$\tilde{t}_n = \frac{1}{A_n} \sum_{k=1}^n a_k t_k.$$

Then

$$\liminf t_n \leq \liminf \tilde{t}_n \leq \limsup \tilde{t}_n \leq \limsup t_n.$$

In particular, if $t_n \rightarrow L$, then $\tilde{t}_n \rightarrow L$. This extends Theorem 5.2.1 which corresponds to the case $a_n = 1$.

6.3. Convergence in wide sense.

Definition 6.3.1 (convergence to ∞). *The sequence x_n converges to ∞ , if*

$$\forall M < \infty \quad \exists N \in \mathbb{N} \quad \text{such that} \quad \forall n \geq N \quad |x_n| \geq M.$$

Of course, this just means that the sequence $\{1/x_n\}$ converges to zero and nothing else.

Definition 6.3.2 (convergence to $\pm\infty$). *The sequence $\{x_n\}$ converges to $+\infty$ if*

$$\forall M < \infty \quad \exists N \in \mathbb{N} \quad \text{such that} \quad \forall n \geq N \quad x_n \geq M,$$

and that a sequence $\{x_n\}$ converges to $-\infty$ if

$$\forall M > -\infty \quad \exists N \in \mathbb{N} \quad \text{such that} \quad \forall n \geq N \quad x_n \leq M,$$

Exercise 6.3.3. Give 3 examples of sequences $\{x_n\}$ satisfying each of the following properties:

- (i) $\{x_n\}$ converges to $+\infty$;
- (ii) $\{x_n\}$ converges to $-\infty$;
- (iii) $\{x_n\}$ converges to ∞ but converges neither to $+\infty$ nor to $-\infty$;
- (iv) $\{x_n\}$ is divergent in the wide sense.

(There should be 12 examples all together.)

Exercise 6.3.4. Extend Theorem 6.2.4 to the wide convergence.

Exercise 6.3.5 (Stoltz' lemma). Suppose the sequence $\{y_n\}$ increases and $\lim y_n = +\infty$. If there exists the limit

$$\lim \frac{x_{n+1} - x_n}{y_{n+1} - y_n} = L,$$

then

$$\lim \frac{x_n}{y_n} = L.$$

Here, L is a real number or $\pm\infty$.

Hint: use Exercise 6.2.7 with

$$a_k = y_k - y_{k-1}, \quad t_k = \frac{x_k - x_{k-1}}{y_k - y_{k-1}}$$

(for convenience, we set $x_0 = y_0 = 0$).

Exercise 6.3.6. Show that for each $p \in \mathbb{N}$,

$$\lim_{n \rightarrow \infty} \frac{1}{n^{p+1}} \sum_{k=1}^n k^p = \frac{1}{p+1}.$$

Hint: use Stoltz' lemma.

Exercise* 6.3.7. Let $x_n \leq \frac{1}{2}(x_{n-1} + x_{n-2})$. Show that the sequence $\{x_n\}$ is convergent (either to a finite number or to $-\infty$).

7. SUBSEQUENCES AND PARTIAL LIMITS.

7.1. Subsequences. Let $\{x_n\}$ be a sequence, we want to define its *subsequence*. In plain words, we write down the sequence $\{x_n\}$ as a string, and then drop out some elements from this string taking care that an infinite number of elements remain. What remains is called a *subsequence*. More formally, we take an increasing sequence $\{n_k\}$ of natural numbers ($n_1 < n_2 < \dots < n_k < \dots$) and form a new function $k \mapsto x_{n_k}$ defined on \mathbb{N} .

Exercise 7.1.1. Prove that any sequence contains a monotonic subsequence.

Exercise 7.1.2. Show that a monotonic sequence converges if it contains a convergent subsequence.

Our first result is a version of the Bolzano-Weierstrass lemma 3.3.3.

Lemma 7.1.3 (Bolzano-Weierstrass). *Each bounded sequence has a convergent subsequence.*

Proof: Let E be the set of all values attended by the sequence $\{x_n\}$. Consider two cases:

(a) The set E is finite. Then we can choose an infinite number of elements in our sequence which have the same value:

$$x_{n_1} = x_{n_2} = \dots = x_{n_k} = \dots = x \in E, \quad n_1 < n_2 < \dots < n_k < \dots$$

We get a subsequence $\{x_{n_k}\}$ converging to x .

(b) Now, assume that the set E is infinite. According to the Bolzano-Weierstrass lemma about accumulation points, E has an accumulation point x . Choose $n_1 \in \mathbb{N}$ such that $|x_{n_1} - x| < 1$. Then choose $n_2 > n_1$ such that $|x_{n_2} - x| < \frac{1}{2}$, etc. At the k -th step, choose $n_k > n_{k-1}$ such that $|x_{n_k} - x| < \frac{1}{k}$. Clearly, the subsequence $\{x_{n_k}\}$ converges to x . \square

Another proof of this lemma follows from the first exercise above combined with a theorem about convergence of monotonic bounded sequences we proved earlier.

It is not difficult to formulate and to prove a version of this lemma for the extended convergence:

Lemma 7.1.4 (Bolzano-Weierstrass for extended convergence). *Each sequence has a subsequence convergent in the wide sense.*

Exercise 7.1.5. Prove this lemma.

7.2. Partial limits. If a subsequence $\{x_{n_k}\}$ is convergent, then its limit is called a *partial limit* of $\{x_n\}$. It's not difficult to verify that if the original sequence $\{x_n\}$ converges to the limit a , then any of its subsequences also converges to a . Define the limit set $PL(\{x_n\})$ of all partial limits of the sequence $\{x_n\}$.

Theorem 7.2.1. *Let $\{x_n\}$ be a bounded sequence. Then*

$$\limsup x_n = \max\{c: c \in PL(\{x_n\})\},$$

and

$$\liminf x_n = \min\{c: c \in PL(\{x_n\})\}.$$

Proof: We'll prove only the first of these two relations, the proof of the second one is similar. In fact, we have to prove two statements: (α) any partial limit of $\{x_n\}$ does not exceed $\limsup x_n$ and (β) $\limsup x_n \in PL(\{x_n\})$.

Let us recall what we already know about the value $L = \limsup x_n$:

- (a) $\forall \epsilon > 0 \exists N \in \mathbb{N}$ such that $\forall n \geq N \ x_n < L + \epsilon$;
- (b) $\forall \epsilon > 0 \forall N \in \mathbb{N} \exists n > N$ such that $x_n > L - \epsilon$.

A minute reflection shows that (α) follows from (a) and then (β) follows from (a) and (b) (check this formally!) completing the proof. \square

In the previous lecture we proved that the sequence $\{x_n\}$ converges to a limit a if and only if

$$\liminf x_n = \limsup x_n = a.$$

Combining this with the theorem above, we obtain

Corollary 7.2.2. *A sequence $\{x_n\}$ converges if and only if the set of its limit set is a singleton: $PL(\{x_n\}) = \{a\}$. In this case, $a = \lim x_n$.*

Exercise 7.2.3. Find $\limsup x_n$, $\liminf x_n$, $\sup x_n$, $\inf x_n$, and the set $PL(\{x_n\})$ of all partial limits for the sequences

$$x_n = \cos^n \frac{n\pi}{4} \quad \text{and} \quad x_n = n^{(-1)^n n}.$$

Exercise 7.2.4. Construct a sequence whose set of partial limits coincides with the closed interval $[0, 1]$.

Exercise 7.2.5. (a) Show that there is no sequence $\{x_n\}$ with $PL(\{x_n\}) = (0, 1)$.

(b) Show that there is no sequence $\{x_n\}$ with $PL(\{x_n\}) = \{1, \frac{1}{2}, \dots, \frac{1}{n}, \dots\}$.

(c) Show that any accumulation point of the set $PL(\{x_n\})$ must belong to $PL(\{x_n\})$ as well.

Exercise 7.2.6. Suppose the subsequences $\{x_{2n}\}$ and $\{x_{2n+1}\}$ converge to the same limit. Show that the sequence $\{x_n\}$ converge.

Exercise 7.2.7. Let $\{x_n\}$ be a sequence such that $\forall n \geq 1 \ |x_{n+1} - x_n| \leq \frac{1}{2^n}$. Can this sequence be unbounded? Can this sequence be divergent? The same questions for $|x_{n+1} - x_n| \leq \frac{1}{n}$.

Problem 7.2.8. Let $\{x_n\}$ be a bounded sequence such that

$$\lim(x_n - x_{n-1}) = 0.$$

Show that the set $PL(\{x_n\})$ coincides with the (closed) interval

$$[\liminf x_n, \limsup x_n].$$

Problem* 7.2.9 (Fekete's lemma). Let a sequence $\{x_n\}$ satisfy $0 \leq x_{m+n} \leq x_m + x_n$, $\forall m, n \in \mathbb{N}$ (such sequences are called *subadditive*). Show that there exists the limit

$$\lim_{n \rightarrow \infty} \frac{x_n}{n} = \inf_{n \geq 1} \frac{x_n}{n}.$$

7.2.1. Appendix: *The continued fraction of the golden mean and the Fibonacci numbers.* Let

$$x_{n+1} = 1 + \frac{1}{x_n}, \quad x_0 = 1.$$

We shall show that $\lim x_n = \frac{\sqrt{5}+1}{2}$. (This number is called the *golden mean*.) In other words,

$$1 + \frac{1}{1 + \frac{1}{1 + \frac{1}{\dots}}} = \frac{\sqrt{5} + 1}{2}.$$

The expression on the left hand side is an example of a *continued fraction*.

First, let us write down several the beginning of the sequence $\{x_n\}$:

$$\begin{aligned} x_0 &= \frac{1}{1}, & x_1 &= 1 + \frac{1}{1} = \frac{2}{1}, & x_2 &= 1 + \frac{1}{2} = \frac{3}{2}, & x_3 &= 1 + \frac{2}{3} = \frac{5}{3}, \\ x_4 &= 1 + \frac{3}{5} = \frac{8}{5}, & x_5 &= 1 + \frac{5}{8} = \frac{13}{8}, & x_6 &= 1 + \frac{8}{13} = \frac{21}{13}, \dots \end{aligned}$$

Let $x_n = \frac{p_n}{q_n}$, p_n and q_n are mutually prime natural numbers. Then by induction

$$\begin{aligned} p_n &= p_{n-1} + p_{n-2}, & p_0 &= 1, & p_1 &= 2, \\ q_n &= q_{n-1} + q_{n-2}, & q_0 &= q_1 &= 1. \end{aligned}$$

We see that p_n and q_n are famous *Fibonacci numbers*. We conclude from these formulas that

$$q_n p_{n-1} - q_{n-1} p_n = -(q_{n-1} p_{n-2} - q_{n-2} p_{n-1}) = \dots = (-1)^n (q_1 p_0 - q_0 p_1) = (-1)^n \quad (A)$$

and that

$$q_n p_{n-2} - q_{n-2} p_n = q_{n-1} p_{n-2} - q_{n-2} p_{n-1} = (-1)^{n-1}. \quad (B)$$

From (A) we get

$$x_{n-1} - x_n = \frac{(-1)^n}{q_n q_{n-1}}, \quad (C)$$

from (B) we get

$$x_{n-2} - x_n = \frac{(-1)^{n-1}}{q_n q_{n-2}}. \quad (D)$$

Looking at (D), we conclude by induction that the subsequence $\{x_{2n}\}$ increases (and is < 2), while the subsequence $\{x_{2n+1}\}$ decreases (and is > 1). Therefore, the both subsequences converges. Further, the increasing sequence of natural numbers $\{q_n\}$ tends to $+\infty$, so looking at (C), we conclude that the subsequences $\{x_{2n}\}$ and $\{x_{2n+1}\}$ have the same limit α . From the initial recursion we see that α is a positive solution to the equation $\alpha = 1 + \frac{1}{\alpha}$, that is $\alpha = \frac{1+\sqrt{5}}{2}$.

Problem 7.2.10. Show that

$$1 + \frac{1}{2 + \frac{1}{2 + \frac{1}{\dots}}} = \sqrt{2}.$$

If you want to learn more about fascinated continued fractions, read section 1.6 of the book by Hairer and Wanner mentioned in the introduction.

8. INFINITE SERIES

8.1. Let $\{a_j\}$ be a sequence of real numbers, the sum $a_n + a_{n+1} + \dots + a_m$ is denoted by

$$\sum_{j=n}^m a_j = \sum_{n \leq j \leq m} a_j.$$

Our goal is to prescribe a meaning for the sum of all terms of the sequence $\{a_j\}$; i.e. to the expression

$$\sum_{j=1}^{\infty} a_j = a_1 + a_2 + \dots + a_n + \dots \quad (*)$$

called (*an infinite series*). Numbers a_j are called the *terms*.

Define a sequence of partial sums $S_n = \sum_{j=1}^n a_j$.

Definition 8.1.1. *The series $\sum_1^{\infty} a_j$ is called convergent if the sequence S_n of partial sums converges. In this case, the limiting value $S = \lim S_n$ is called the sum of the series: $\sum_1^{\infty} a_j = S$.*

Dealing with series, usually it is not very difficult to check convergence or divergence, to find the value of the sum is a much more delicate problem which we almost will not touch here. We start with several simple observations and examples.

1. *Convergence or divergence of the series depends on its tail only;* i.e. if two series have the same terms a_j for $j \geq j_0$ then they converge or diverge simultaneously.
2. *If the series (*) converges, then $\lim a_n = 0$.* Indeed, $a_n = S_{n+1} - S_n$ and therefore

$$\lim a_n = \lim(S_{n+1} - S_n) = \lim S_{n+1} - \lim S_n = S - S = 0.$$

8.2. Examples.

8.2.1. Geometric series. Let $a_j = q^{j-1}$. Then

$$S_n = \frac{1 - q^n}{1 - q},$$

and if $|q| < 1$ the series converges to $\frac{1}{1-q}$. In the case $|q| \geq 1$ the series is divergent.

8.2.2. Harmonic series. Let $a_j = \frac{1}{j}$. Then, as we know, $\lim S_n = +\infty$ and therefore the series is divergent. Later in this course, we will show that there exists the limit

$$\lim_{n \rightarrow \infty} (S_n - \log n) = \gamma,$$

called the *Euler constant*.

8.2.3. Let $a_j = (-1)^j$. Then $S_n = 0$ if n is even, and $S_n = 1$ if n is odd. Therefore, the series diverges.

8.2.4. Let

$$a_j = \frac{1}{(\alpha + j)(\alpha + j + 1)}.$$

Observe that

$$a_j = \frac{1}{\alpha + j} - \frac{1}{\alpha + j + 1},$$

so that

$$S_n = \sum_{j=1}^n \left[\frac{1}{\alpha + j} - \frac{1}{\alpha + j + 1} \right] = \frac{1}{\alpha + 1} - \frac{1}{\alpha + n + 1}$$

(such sums with cancelation of all intermediate terms are called sometimes *telescopic*). We see that the series converges to the value $\frac{1}{\alpha+1} = \lim S_n$.

8.2.5. Let

$$a_j = \frac{(-1)^{j-1}}{j}.$$

In this case, we consider separately partial sums with even and odd indices. We have

$$S_{2n} = \left(1 - \frac{1}{2}\right) + \left(\frac{1}{3} - \frac{1}{4}\right) + \dots + \left(\frac{1}{2n-1} - \frac{1}{2n}\right).$$

Therefore, the sequence S_{2n} increases. It is bounded from above by 1:

$$S_{2n} = 1 - \left(\frac{1}{2} - \frac{1}{3}\right) - \left(\frac{1}{4} - \frac{1}{5}\right) - \dots < 1.$$

Hence, $\{S_{2n}\}$ converges to the limit S . Further the sequence $\{S_{2n+1}\}$ converges to the same limit:

$$\lim S_{2n+1} = \lim \left(S_{2n} + \frac{(-1)^{2n}}{2n+1} \right) = \lim S_{2n} = S.$$

Therefore, the whole sequence S_n converges. As we have seen $S_{2n} \uparrow S$, it is not difficult to see that $S_{2n+1} \downarrow S$ (check this!).

The sum of this series is $S = \log 2$, we'll compute it later, in Section 23.3.

Definition 8.2.1. Suppose that the sequence of positive numbers a_j monotonically converges to 0. Then the series $\sum_{j \geq 0} (-1)^j a_j$ is called *the Leibniz series*.

Theorem 8.2.2 (Leibniz).

- (i) Each Leibniz series converges to a sum S ;
- (ii) $S_{2n} \downarrow S$ while $S_{2n+1} \uparrow S$;
- (iii) $|S - S_n| < a_{n+1}$; i.e., the error of approximation of the whole sum S by the n -th partial sum S_n does not exceed the first neglected term.

Proof of Theorem 8.2.2 repeats the argument from Example 8.2.5. We have $S_{2n} - S_{2n-2} = -a_{2n-1} + a_{2n} < 0$, and

$$S_{2n} = (a_0 - a_1) + (a_2 - a_3) + \dots + (a_{2n-2} - a_{2n-1}) + a_{2n} > 0.$$

Hence, $S_{2n} \downarrow S'$. Similarly, the sequence S_{2n-1} increases, and is $< a_0$. Hence $S_{2n-1} \downarrow S''$. Next, $S_{2n} - S_{2n-1} = a_{2n} \rightarrow 0$, whence, $S' = S''$.

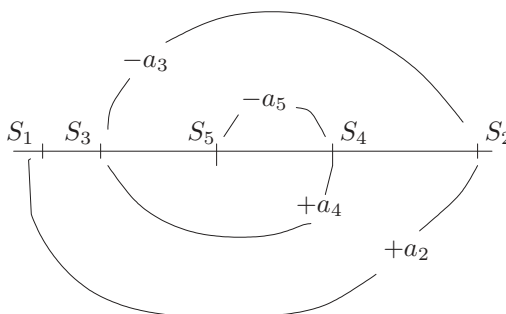


FIGURE 7. Leibniz' theorem

At last, the inequality $S_{2n} > S > S_{2n-1}$ together with $S_{2n} - S_{2n-1} = a_{2n}$ yield $S - S_{2n-1} < a_{2n}$, while the inequality $S_{2n} > S > S_{2n+1}$ together with $S_{2n} - S_{2n+1} = a_{2n+1}$ yield $S_{2n} - S < a_{2n+1}$. \square

8.3. Cauchy's criterion for convergence. Absolute convergence. Cauchy's criterion for convergence of sequences immediately gives us

Theorem 8.3.1 (Cauchy's criterion for the series convergence). *The series (*) converges if and only if $\forall \epsilon > 0 \exists N \in \mathbb{N}$ such that $\forall m \geq n \geq N$*

$$\underbrace{|a_{n+1} + a_{n+1} + \dots + a_m|}_{=S_m - S_n} < \epsilon.$$

Definition 8.3.2 (absolute convergence). The series $\sum a_j$ is called *absolutely convergent* if the series $\sum |a_j|$ converges. The series $\sum a_j$ is called *conditionally convergent* if it converges but not absolutely.

Claim 8.3.3. *If the series converges absolutely, then it converges in the usual sense.*

This follows at once from the Cauchy criterion. In the opposite direction the result is wrong: the series $\sum \frac{(-1)^j}{j}$ converges but not absolutely.

Till the end of this lecture we consider only series with positive terms.

8.4. Series with positive terms. Convergence tests. The theorem on convergence of upper bounded increasing sequences immediately gives us

Theorem 8.4.1. *The series with positive terms converges if and only if the sequence of its partial sums is upper bounded.*

An efficient way to check convergence or divergence of a series with positive terms is to compare it with another series with positive terms for which we convergence or divergence are known.

Corollary 8.4.2. *Let $0 < a_j \leq b_j, j \geq j_0$. If the series $\sum b_j$ converges, then the series $\sum a_j$ also converges. If the series $\sum a_j$ diverges, then the series $\sum b_j$ also diverges.*

This follows from Theorem 8.4.1. Sometimes, another form of the same result is useful:

Corollary 8.4.3. *If a_j and b_j are positive and*

$$0 < \liminf \frac{a_j}{b_j} \leq \limsup \frac{a_j}{b_j} < \infty,$$

then the series $\sum a_j$ and $\sum b_j$ converge or diverge simultaneously.

Usually, in applications of this corollary there exists the limit

$$\lim_{j \rightarrow \infty} \frac{a_j}{b_j} = L,$$

and we need only to check that $0 < L < +\infty$.

Example 8.4.4. The series

$$\sum_{j=1}^{\infty} \frac{1}{j^2}$$

converges. This we see by comparison with the convergent series

$$\sum_{j=1}^{\infty} \frac{1}{j(j+1)}.$$

In this case, the quotient of the terms tends to 1.

Example 8.4.5. The series

$$\sum_{j=1}^{\infty} \frac{\sqrt{j+1}}{j^{3/2}}$$

diverges. This we see by comparison with the divergent harmonic series $\sum_{j=1}^{\infty} \frac{1}{j}$.

The simplest way to check the convergence of the series with positive terms is to compare it with the geometric series.

Claim 8.4.6 (Cauchy's root test). *Set*

$$\alpha := \limsup \sqrt[j]{a_j}.$$

If $\alpha < 1$, then the series $\sum a_j$ converges. If $\alpha > 1$, then the series diverges.

Proof: Let $\alpha < 1$. Choose α' : $\alpha < \alpha' < 1$. Then according to the definition of the upper limit, $a_j < \alpha'^j$, $j \geq j_0$, and by Corollary 8.4.2 the series converges.

If $\alpha > 1$, then choose α' such that $1 < \alpha' < \alpha$, and by the definition of \limsup we see that there are arbitrary large indices j such that $a_j \geq \alpha'^j > 1$. Therefore, the sequence a_j does not tend to zero⁴, and the series $\sum a_j$ diverges. \square

Exercise 8.4.7 (D'Alembert's "ratio test"). Suppose $a_j > 0$ and there exists the limit

$$\beta = \lim_{j \rightarrow \infty} \frac{a_{j+1}}{a_j}.$$

If $\beta < 1$, then the series converges, if $\beta > 1$, the series diverges.

Hint: use Corollary 5.2.5.

⁴Moreover, $\limsup a_j = +\infty$.

Example 8.4.8. The series

$$\sum_{j \geq 2} \frac{1}{(\log j)^j}$$

converges by application of the Cauchy test.

Example 8.4.9. The series

$$\sum_{j \geq 1} \frac{x^j}{j!}$$

(absolutely) converges for any real x by application of the d’Alambert test.

Example 8.4.10. The series

$$\sum_{j \geq 1} \frac{x^j}{j^s}$$

converges for $x < 1$ and diverges for $x > 1$. This can be obtained easily by application of any of the two tests, and the answer does not depend on the choice of real s . In the remaining case $x = 1$ the answer depends on s . As we already know, the series diverges for $s = 1$ and therefore for all $s \leq 1$. A bit later, we’ll see that the series converges for all $s > 1$.

The both tests do not lead to any conclusion in the “boundary” case when α or β equal 1. In this case, the following theorem is very useful:

Theorem 8.4.11 (Cauchy’s compression). *Let a_j be a non-increasing sequence of positive numbers. Then the series $\sum_{j \geq 1} a_j$ converges and diverges simultaneously with the series $\sum_{k \geq 0} 2^k a_{2^k}$.*

Proof: Let s_n be a partial sum $\sum_{j=1}^n a_j$, let $A_k = 2^k a_{2^k}$, and let S_n be a partial sum $S_n = \sum_{k=0}^n A_k$. Since the terms a_j do not increase, for each $k \geq 0$ we have

$$\frac{1}{2} A_{k+1} = 2^k a_{2^{k+1}} \leq a_{2^k+1} + a_{2^k+2} + \dots + a_{2^{k+1}} \leq 2^k a_{2^k} = A_k.$$

Summing up these inequalities from $k = 0$ till $k = n$, we get

$$\frac{1}{2} (S_{n+1} - a_1) \leq s_{2^{n+1}} - a_1 \leq S_n.$$

This means that the increasing sequence of partial sums $\{s_n\}$ is bounded from above if and only if the increasing sequence of partial sums $\{S_n\}$ is bounded from above. Therefore, the sequences s_n and S_n converge and diverge simultaneously. \square

The theorem is useful since the new series $\sum_{k \geq 1} 2^k a_{2^k}$ usually has “better convergence” than the original one.

Example 8.4.12. The series

$$\sum_{n \geq 1} \frac{1}{n^s}$$

converges if and only if $s > 1$. Indeed, in this case the new series from Cauchy's theorem is

$$\sum_{k=1}^{\infty} 2^k \frac{1}{2^{ks}} = \sum_{k=1}^{\infty} 2^{k(1-s)}.$$

If $s > 1$, we get a convergent geometric series, if $s \leq 1$ the terms do not tend to zero and the series diverges.

Exercise 8.4.13. Check convergence or divergence of the series $\sum_{n \geq 1} a_n$ when

$$a_n = 2^n n! n^{-n}, \quad a_n = 3^n n! n^{-n}, \quad a_n = \frac{1}{\log n!} \quad (n \geq 2),$$

$$a_n = n^n e^{-n^{1.001}}, \quad a_n = \frac{n^{\log n}}{(\log n)^n}, \quad a_n = \frac{(n!)^2}{(2n)!},$$

$$a_n = (\sqrt{n+1} - \sqrt{n-1})^\alpha, \quad a_n = \frac{\sqrt{n+1} - \sqrt{n-1}}{n^\alpha} \quad (\alpha \in \mathbb{R}),$$

$$a_n = \frac{1}{n \log^a n}, \quad a_n = \frac{1}{n \log^a n \log \log^b n} \quad (a, b \in \mathbb{R})$$

Exercise 8.4.14. Suppose that $a_n \downarrow 0$, and $\sum a_n = +\infty$. Prove that

$$\sum \min(a_n, 1/n) = +\infty.$$

Hint: Use Cauchy's compression.

There are many interesting problems about the infinite series with positive terms. For instance,

Problem 8.4.15. Let $a_n \geq 0$ and the series $\sum a_n$ diverges.

(i) Show that the series $\sum \frac{a_n}{1+a_n}$ also diverges.

(ii) Let $S_n = a_1 + \dots + a_n$. Show that

$$(a) \quad \sum_{n \geq 1} \frac{a_n}{S_n} = +\infty; \quad (b) \quad \sum_{n \geq 1} \frac{a_n}{S_n^{1+\epsilon}} < \infty \quad \text{for each } \epsilon > 0.$$

9. REARRANGEMENT OF THE INFINITE SERIES

9.1. Be careful! Some operations customary for finite sums might be illegal for infinite convergent sums. To see this, let us return to the convergent series $\sum_{j \geq 1} (-1)^{j-1}/j$ and denote by S its sum. We have

$$\begin{aligned} 2S &= \frac{2}{1} - \frac{2}{2} + \frac{2}{3} - \frac{2}{4} + \frac{2}{5} - \frac{2}{6} + \frac{2}{7} \dots \\ &= \frac{2}{1} - \frac{1}{1} + \frac{2}{3} - \frac{1}{2} + \frac{2}{5} - \frac{1}{3} + \frac{2}{7} - \frac{1}{4} + \dots \end{aligned}$$

Consider separately the terms with even and odd denominators. The terms with even denominators are negative:

$$-\frac{1}{2}, \quad -\frac{1}{4}, \quad -\frac{1}{5}, \dots$$

There are two terms with any odd denominator, one term is positive, another one is negative, and the difference is positive:

$$\frac{2}{1} - \frac{1}{1} = \frac{1}{1}, \quad \frac{2}{3} - \frac{1}{3} = \frac{1}{3}, \quad \frac{2}{5} - \frac{1}{5} = \frac{1}{5}, \dots$$

Collecting the terms together in such a way that the denominators increase, we get

$$2S = \frac{1}{1} - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \frac{1}{5} - \frac{1}{6} + \dots = S.$$

Therefore, $S = 0$. On the other hand, this is definitely impossible, since the sequence S_{2n} increases to S , and $S_2 = \frac{1}{2}$, so that $S > \frac{1}{2}$.

Exercise 9.1.1. What was illegal in our sequence of operations?

9.2. Rearrangement of the series.

Definition 9.2.1. A sequence $\sum_{j \geq 1} b_j$ is a *rearrangement* of the sequence $\sum_{j \geq 1} a_j$ if every term in the first sequence appears exactly once in the second and conversely. In other words, there is a bijection $\varphi: \mathbb{N} \rightarrow \mathbb{N}$ such that $a_j = a_{\varphi(j)}$ for $j \in \mathbb{N}$.

Theorem 9.2.2 (Dirichlet). *After an arbitrary rearrangement of the terms, the absolutely convergent series $\sum_{j \geq 1} a_j$ converges to the same sum.*

Proof: First, we prove assume that $a_j \geq 0$. Set

$$S = \sum_{j=1}^{\infty} a_j, \quad S_n = \sum_{j=1}^n a_j.$$

Let $\{b_j\}$ be an arbitrary rearrangement of the sequence $\{a_j\}$. Set

$$S'_n = \sum_{j=1}^n b_j.$$

Then, for each $n \in \mathbb{N}$, $S'_n \leq S$. Hence, the series $\sum b_j$ converges to the sum S' , and $S' \leq S$.

In turn, the sequence a_j is a rearrangement of the sequence $\sum b_j$, whence $S \leq S'$. Hence, $S = S'$.

Now, we consider the general case when the terms a_j are real. First, we introduce a useful notation. For real a , we set $a^+ = \max(a, 0)$, and $a^- = \max(-a, 0) (= (-a)^+)$. Then $a = a^+ - a^-$ and $|a| = a^+ + a^-$. Using this notation and applying the special case proven above, we get

$$\begin{aligned} \sum b_j &= \sum (b_j^+ - b_j^-) = \sum b_j^+ - \sum b_j^- \\ &= \sum a_j^+ - \sum a_j^- = \sum (a_j^+ - a_j^-) = \sum a_j \end{aligned}$$

completing the proof. \square .

9.3. Rearrangement of conditionally convergent series. For conditionally convergent series the situation is very different.

Theorem 9.3.1 (B. Riemann). *Suppose that the series $\sum_{j \geq 1} a_j$ converges conditionally. Then given $-\infty \leq \alpha \leq \beta \leq +\infty$, there exists a rearrangement $\{b_j\}$ of the sequence $\{a_j\}$ such that*

$$\liminf s_n = \alpha, \quad \limsup s_n = \beta, \quad \text{where } s_n = \sum_{j=1}^n b_j.$$

Here is a striking

Corollary 9.3.2. *Suppose that the series $\sum_{j \geq 1} a_j$ converges conditionally. Then, given $s \in \mathbb{R}$, there exists a rearrangement $\{b_j\}$ of the sequence $\{a_j\}$ such that $\sum_{j \geq 1} b_j = s$.*

We start with a simple claim:

Claim 9.3.3. *Suppose that the series $\sum_{j \geq 1} a_j$ converges conditionally. Then*

$$\sum a_j^+ = \sum a_j^- = +\infty.$$

Proof of Claim 9.3.3: Suppose one of the sums, say the first one, converges. Since

$$\sum_{j=1}^n a_j^- = \sum_{j=1}^n a_j^+ - \sum_{j=1}^n a_j,$$

we conclude that the other sum also converges. Recalling that

$$\sum_{j=1}^n |a_j| = \sum_{j=1}^n a_j^+ + \sum_{j=1}^n a_j^-,$$

we conclude that the series $\sum |a_j|$ converges, which contradicts our assumption. \square

Proof of Theorem 9.3.1: we consider only the case when $-\infty < \alpha \leq \beta < +\infty$, leaving the other cases as exercises.

We split the set \mathbb{N} into two disjoint subsets: $\mathbb{N}^+ = \{j \in \mathbb{N} : a_j > 0\}$ and $\mathbb{N}^- = \{j \in \mathbb{N} : a_j \leq 0\}$. Let $n_1 < n_2 < \dots$ be the elements of the set \mathbb{N}^+ , and $m_1 < m_2 < \dots$ be the elements of the set \mathbb{N}^- . That is, $a_{n_1}, a_{n_2}, a_{n_3}, \dots$, are positive terms of the sequence a_j , and $a_{m_1}, a_{m_2}, a_{m_3}, \dots$, are negative terms of the same sequence. Since the series $\sum a_j$ converges, we have $\lim_j a_j = 0$, whence $\lim_j a_{n_j} = \lim_j a_{m_j} = 0$.

Now, the idea of the proof is very simple. First, we add the positive terms

$$a_{n_1} + a_{n_2} + \dots = b_1 + b_2 + \dots$$

and stop at the moment when their sum will increase β . This moment will occur since $\sum_j a_{n_j} = +\infty$. Suppose we took k_1 positive terms. Then the difference between the sum and β is $a_{n_{k_1}}$ at most. Then we start to add the negative terms

$$(a_{n_1} + \dots + a_{n_{k_1}}) + a_{m_1} + a_{m_2} + \dots = (b_1 + \dots + b_{k_1}) + b_{k_1+1} + b_{k_1+2} + \dots$$

and stop at the moment when the sum will be less than α . This is also possible due to divergence of the sum $\sum_j a_{m_j} = -\infty$. Suppose we took ℓ_1 negative terms. Then the difference between α and the sum is $-a_{m_{\ell_1}}$ at most. Then again we start to add positive terms

$$\begin{aligned} & (a_{n_1} + \dots + a_{n_{k_1}}) + (a_{m_1} + \dots + a_{m_{\ell_1}}) + a_{n_{k_1+1}} + a_{n_{k_1+2}} + \dots \\ & = (b_1 + \dots + b_{k_1}) + (b_{k_1+1} + \dots + b_{k_1+\ell_1}) + b_{k_1+\ell_1+1} + b_{k_1+\ell_1+2} + \dots \end{aligned}$$

and stop when the sum will be bigger than β , and continue in the same way. Then the partial sums of the new series oscillate between the numbers α and β , and since $\lim_j a_{n_j} = \lim_j a_{m_j} = 0$, the lower and upper bounds for this oscillation are closer and closer to α and β .

Now, we will try to make the proof more formal. We define the bijection $\varphi: \mathbb{N} \rightarrow \mathbb{N}$. We will do it in an infinite sequence of steps. Each step consists of two parts.

Step 1: We set

$$k_1 = \min \left\{ k: \sum_{j=1}^k a_{n_j} > \beta \right\}, \quad \ell_1 = \min \left\{ \ell: \sum_{j=1}^{k_1} a_{n_j} + \sum_{j=1}^{\ell} a_{m_j} < \alpha \right\},$$

and let

$$\varphi(j) = n_j, \text{ for } 1 \leq j \leq k_1, \quad \varphi(k_1 + j) = m_j, \text{ for } 1 \leq j \leq \ell_1.$$

At the first step, we use first $N_1^+ = k_1$ positive terms of the sequence $\{a_j\}$, first $N_1^- = \ell_1$ non-positive terms of the sequence $\{a_j\}$. The total number of the terms we use is $N_1 = N_1^+ + N_1^-$.

Proceeding the same way, at the t -th step we use k_t positive terms and ℓ_t non-positive terms. After the t -th step, $\varphi(j)$ is defined for $1 \leq j \leq N_t$, where $N_t = N_t^+ + N_t^-$, and

$$N_t^+ = \sum_{i=1}^t k_i, \quad N_t^- = \sum_{i=1}^t \ell_i.$$

It is easy to see that the construction yields three properties of the mapping φ :

- (i) $\varphi(j)$ is defined for all $j \in \mathbb{N}$;
- (ii) $\varphi(i) \neq \varphi(j)$ for $i \neq j$;
- (iii) for each $p \in \mathbb{N}$, there is j such that $\varphi(j) = p$.

That is, φ is a bijection of \mathbb{N} onto itself. Now, we set $b_j = a_{\varphi(j)}$, and denote

$$s_n = \sum_{j=1}^n b_j.$$

For every $t \in \mathbb{N}$, we have $s_{N_t} < \alpha$ and $s_{N_t+k_{t+1}} > \beta$. Therefore,

$$\liminf s_n \leq \alpha, \quad \limsup s_n \geq \beta.$$

To show the opposite inequalities, we note that

$$\alpha - |b_{N_t}| \leq s_N \leq \beta + |b_{N_t+k_{t+1}}| \quad \text{for } N_t \leq N \leq N_{t+1} - 1.$$

This is the place where we use our “stopping time rules”. Since $\lim b_j = 0$, we see that given $\epsilon > 0$, we have $\alpha - \epsilon \leq s_N \leq \beta + \epsilon$, provided that N is big enough. This completes the proof of Riemann’s theorem. \square

Exercise 9.3.4. Check the properties (i), (ii), (iii) from the proof.

Exercise 9.3.5. Check the remaining cases of Riemann’s theorem when either one of the values α and β , or both of them, are infinite.

Exercise 9.3.6. Suppose that the series $\sum_{j \geq 1} a_j$ converges and that $b_j = a_{\varphi(j)}$ with the bijection $\varphi: \mathbb{N} \rightarrow \mathbb{N}$ such that $\sup\{|\varphi(j) - j|: j \in \mathbb{N}\} < \infty$. Show that $\sum_{j \geq 1} b_j = \sum_{j \geq 1} a_j$.

10. LIMITS OF FUNCTIONS. BASIC PROPERTIES

10.1. Cauchy's definition of limit. Denote by $U_\delta^*(a) = \{x : 0 < |x - a| < \delta\}$ the punctured δ -neighbourhood of a .

Definition 10.1.1 (the limit according to Cauchy). Let $f : E \rightarrow \mathbb{R}$ be a function defined on a set $E \subset \mathbb{R}$, and let a be an accumulation point of E . We say that f has a limit L when x tends to a along E : $\lim_{E \ni x \rightarrow a} f(x) = L$, if

$$\forall \epsilon > 0 \quad \exists \delta > 0 \quad \text{such that} \quad \forall x \in U_\delta^*(a) \cap E \quad |f(x) - L| < \epsilon.$$

Usually, we deal with the case when the set E contains some punctured neighbourhood of a . Then we just say that f has a limit L at the point a : $\lim_{x \rightarrow a} f(x) = L$, or $f(x) \rightarrow L$ for $x \rightarrow a$.

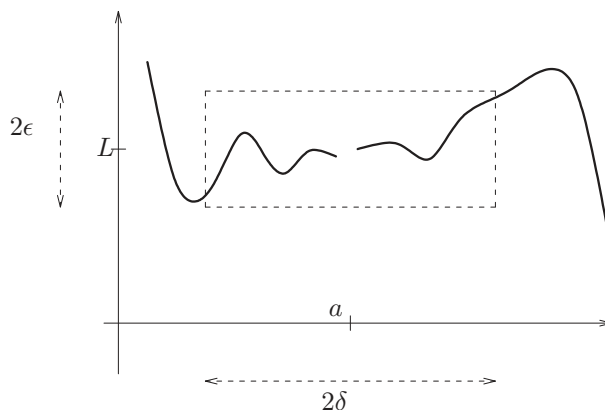


FIGURE 8. To the definition of the limit

Remarks:

i. Existence of the limit and its value do not depend on the value of the function $f(x)$ at the point $x = a$, moreover, the function f does not need to be defined at a at all. For example, the function $f : \mathbb{R} \setminus \{0\} \rightarrow \mathbb{R}$ defined by $f(x) = 2x + 1$, has the limit $\lim_{x \rightarrow 0} f(x) = 1$. If we consider the function $f_1(x) : \mathbb{R} \rightarrow \mathbb{R}$ which equals $f(x)$ for $x \neq 0$ and equals C at the origin, then its limit at the origin is the same for any C :

$$\lim_{x \rightarrow 0} f_1(x) = \lim_{x \rightarrow 0} f(x) = 1.$$

ii. If $E_1 \subset E$, a is an accumulation of E_1 (and therefore of E) and the limit $\lim_{E \ni x \rightarrow a} f(x)$ exists, then the limit of f along E_1 also exists and has the same value.

Example 10.1.2.

$$\lim_{x \rightarrow 0} x \sin \frac{1}{x} = 0.$$

More generally,

Claim 10.1.3. *If $\lim_{x \rightarrow a} f(x) = 0$, and a function g is bounded in a punctured neighbourhood $U^*(a)$ of a , then $\lim_{x \rightarrow a} f(x)g(x) = 0$.*

Proof: Indeed, set $M = \sup\{|g(x)| : x \in U^*(a)\}$, fix $\epsilon > 0$ and choose $\delta > 0$ such that

$$|f(x)| < \frac{\epsilon}{M} \quad \text{for} \quad x \in U_\delta^*(a).$$

We may always assume that $U_\delta^*(a) \subset U^*(a)$, otherwise we make δ smaller. Then

$$|f(x)g(x)| < \frac{\epsilon}{M} \cdot M = \epsilon, \quad x \in U_\delta^*(a),$$

and we are done. \square

In the example above, $f(x) = x$ and $g(x) = \sin \frac{1}{x}$.

Agreement. If $E = (a, b)$ ($b > a$), then we use notations

$$\lim_{x \downarrow a} f(x) = \lim_{x \rightarrow a+0} f(x) \stackrel{\text{def}}{=} \lim_{E \ni x \rightarrow a} f(x)$$

(this is called the limit from above, or the right limit). If $E = (b, a)$ ($b < a$), then we write

$$\lim_{x \uparrow a} f(x) = \lim_{x \rightarrow a-0} f(x) \stackrel{\text{def}}{=} \lim_{E \ni x \rightarrow a} f(x)$$

(this is called the limit from below, or the left limit).

Example 10.1.4. $f(x) = \text{sgn}(x)$. In this case the limit at the origin does not exist, however

$$\lim_{x \uparrow 0} \text{sgn}(x) = -1, \quad \lim_{x \downarrow 0} \text{sgn}(x) = +1.$$

Exercise 10.1.5. Suppose that the limits from above and from below exist and are equal. Then the usual limit exists as well and has the same value.

10.2. Heine's definition of limit. The next theorem shows the limit of functions can be defined using only the notion of limits of sequences.

Theorem 10.2.1. *Let a be an accumulation point of the set $C \subset \mathbb{R}$, and let $f: E \rightarrow \mathbb{R}$. Then the following two conditions are equivalent:*

$$(A) \quad \lim_{E \ni x \rightarrow a} f(x) = L,$$

and

(B) *for any sequence $\{x_n\}$ convergent to a and such that $x_n \in E \setminus \{a\}$ for each $n \in \mathbb{N}$, the sequence $\{f(x_n)\}$ converges to L .*

Proof: Implication (A) \Rightarrow (B) follows by straightforward inspection. We shall prove that (B) implies (A). Assume that (B) holds but (A) fails, that is

$$\exists \epsilon > 0 \quad \forall \delta > 0 \quad \exists x \in U_\delta^*(a) \quad |f(x) - L| \geq \epsilon.$$

Choosing here $\delta = \frac{1}{n}$ we get

$$\forall n \in \mathbb{N} \quad \exists x_n \quad \text{such that } 0 < |x_n - a| < \frac{1}{n} \quad \text{and} \quad |f(x_n) - L| \geq \epsilon.$$

We see that $f(x_n)$ does not converge to L and therefore we arrived at the contradiction. \square

Remark 10.2.2. In the theorem, we can replace (B) by a seemingly weaker condition (B') for any sequence $\{x_n\} \subset E \setminus \{a\}$ convergent to a the sequence $\{f(x_n)\}$ converges. This already yields (B): assume that (B) fails but (B') holds, i.e., there are two sequences $\{x'_n\}, \{x''_n\} \subset E \setminus \{a\}$, both are convergent to a , such that $\lim f(x'_n) = L'$ and $\lim f(x''_n) = L''$, where $L' \neq L''$. Take $x_n = x'_m$ for $n = 2m$ and $x_n = x''_m$ for $n = 2m + 1$. Then $x_n \rightarrow a$ but the sequence $f(x_n)$ has two limit points L' and L'' , and therefore it does not converge. We arrive at the contradiction which proves (B).

Example 10.2.3. Consider the Dirichlet function $\mathcal{D} : \mathbb{R} \rightarrow \mathbb{R}$ which equals 0 at irrational x and 1 at rational x . Then \mathcal{D} does not have a limit at *any* real point a . Indeed, take two sequences $\{x_n\} \subset \mathbb{Q}$ and $\{y_n\} \subset \mathbb{R} \setminus \mathbb{Q}$ converging to a . Then $\mathcal{D}(x_n) = 1$ for all n , hence $\lim \mathcal{D}(x_n) = 1$. Similarly, $\lim \mathcal{D}(y_n) = 0$.

Exercise 10.2.4. Show that

$$\mathcal{D}(x) = \lim_{m \rightarrow \infty} \left(\lim_{n \rightarrow \infty} \cos^{2n}(2\pi x m!) \right).$$

Theorem 10.2.1 will allow us to transfer all the properties of the limit of sequences we've already known to the limits of functions.

Corollary 10.2.5 (Cauchy's criterion). *The limit $\lim_{E \ni x \rightarrow a} f(x)$ exists if and only if*

$$\forall \epsilon > 0 \quad \exists \delta > 0 \quad \text{such that} \quad |f(x') - f(x'')| < \epsilon, \quad (C)$$

provided $x', x'' \in E$ and $0 < |x' - a| < \delta$, $0 < |x'' - a| < \delta$.

Here is a logic of the proof:

$$\begin{aligned} \exists \lim_{E \ni x \rightarrow a} f(x) &\Rightarrow (C) \\ &\Rightarrow \forall \{x_n\} \subset E \setminus \{a\} \text{ convergent to } a, \{f(x_n)\} \text{ is Cauchy's sequence} \\ &\Rightarrow (B') \Rightarrow \exists \lim_{E \ni x \rightarrow a} f(x). \end{aligned}$$

We leave the rest as an exercise. \square

Exercise 10.2.6. Prove that $\lim_{x \rightarrow 0} \sin \frac{1}{x}$ does not exist.

10.3. Limits and arithmetic operations. Set $(f + g)(x) = f(x) + g(x)$, $(f \cdot g)(x) = f(x) \cdot g(x)$, and $\left(\frac{f}{g}\right)(x) = \frac{f(x)}{g(x)}$.

Theorem 10.3.1. *Let the functions f and g be defined on a set $E \setminus \{a\}$ where $\{a\}$ is an accumulation point of E . Suppose that*

$$\lim_{E \ni x \rightarrow a} f(x) = A, \quad \text{and} \quad \lim_{E \ni x \rightarrow a} g(x) = B.$$

Then there exists the limits:

$$\text{a) } \lim_{E \ni x \rightarrow a} (f + g)(x) = A + B,$$

$$\text{b) } \lim_{E \ni x \rightarrow a} (f \cdot g)(x) = A \cdot B,$$

c) if $B \neq 0$ and $g(x) \neq 0$ for $x \in E$, then

$$\lim_{E \ni x \rightarrow a} \frac{f}{g}(x) = \frac{A}{B}.$$

This theorem can be checked using the definition of the limit, it also follows at once from the corresponding properties of the limits of sequences, so we shall not prove it here.

Example 10.3.2. Let m and n be positive integers. Then

$$\lim_{x \rightarrow 1} \frac{x^m - 1}{x^n - 1} = \lim_{x \rightarrow 1} \frac{1 + x + \dots + x^{m-1}}{1 + x + \dots + x^{n-1}} = \frac{m}{n}.$$

As a corollary, we obtain the value for another limit:

$$\lim_{x \rightarrow 1} \frac{x^{1/m} - 1}{x^{1/n} - 1} = \frac{n}{m}.$$

Indeed, we introduce a new variable $x = t^{mn}$, then $t \rightarrow 1$ for $x \rightarrow 1$ (why?), and

$$\lim_{x \rightarrow 1} \frac{x^{1/m} - 1}{x^{1/n} - 1} = \lim_{t \rightarrow 1} \frac{t^n - 1}{t^m - 1} = \frac{n}{m}.$$

10.4. The first remarkable limit: $\lim_{x \rightarrow 0} \frac{\sin x}{x} = 1$. Since the function $\frac{\sin x}{x}$ is even, it suffices to consider the case when $x \downarrow 0$. First, we prove the inequality

$$(*) \quad \sin x < x < \tan x$$

valid for $0 < x < \frac{\pi}{2}$. For that, consider the circle of radius one centered at O and two points A and B on that circle such that the angle $\angle AOB$ equals x radians. Let C be the intersection point of the tangent to the circle at A and the line containing the radius OB . Then

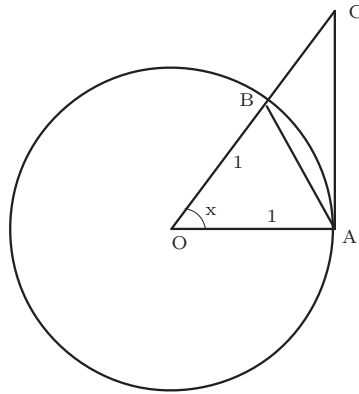


FIGURE 9. The triangles AOB and AOC

$$\triangle AOB \subset \text{sector } AOB \subset \triangle AOC,$$

so that

$$\text{Area}(\triangle AOB) < \text{Area}(\text{sector } AOB) < \text{Area}(\triangle AOC).$$

Computing the areas, we get

$$\frac{\sin x}{2} < \frac{x}{2} < \frac{\tan x}{2},$$

that is (*).

Dividing (*) by $\sin x$, we obtain

$$1 > \frac{\sin x}{x} > \cos x,$$

or

$$0 < 1 - \frac{\sin x}{x} < 1 - \cos x.$$

But

$$1 - \cos x = 2 \sin^2 \frac{x}{2} < 2 \left(\frac{x}{2}\right)^2 = \frac{x^2}{2}$$

(we have used the first inequality from (*)). So that

$$0 < 1 - \frac{\sin x}{x} < \frac{x^2}{2}.$$

This yields the limit in the box. Done! □

Corollary 10.4.1.

$$\lim_{n \rightarrow \infty} \left\{ \cos \frac{t}{2} \cdot \cos \frac{t}{2^2} \cdot \cos \frac{t}{2^3} \cdot \dots \cdot \cos \frac{t}{2^n} \right\} = \frac{\sin t}{t}.$$

Proof: Indeed,

$$\begin{aligned} \sin t &= 2 \cos \frac{t}{2} \sin \frac{t}{2} = 2^2 \cos \frac{t}{2} \cos \frac{t}{2^2} \sin \frac{t}{2^2} \\ &= \dots = 2^n \cos \frac{t}{2} \cos \frac{t}{2^2} \dots \cos \frac{t}{2^n} \sin \frac{t}{2^n}, \end{aligned}$$

so the product of cosines equals

$$\frac{\sin t}{2^n \sin \frac{t}{2^n}} = \frac{\sin t}{t} \cdot \frac{\frac{t}{2^n}}{\sin \frac{t}{2^n}}.$$

Notice, that the second factor converges to 1 since $\frac{t}{2^n}$ converges to 0. □

Exercise 10.4.2 (Vieta). Prove that

$$\frac{2}{\pi} = \frac{\sqrt{2}}{2} \frac{\sqrt{2 + \sqrt{2}}}{2} \frac{\sqrt{2 + \sqrt{2 + \sqrt{2}}}}{2} \dots$$

(the product on the RHS is infinite).

Hint: Let $t = 2/\pi$ in the previous corollary. Using induction, check that $\cos \frac{\pi}{2^{n+1}} =$

$$\frac{\sqrt{2 + \sqrt{2 + \dots + \sqrt{2}}}}{2}, \quad n \in \mathbb{N}, \text{ with } n \text{ square roots on the RHS.}$$

10.5. Limits at infinity and infinite limits. We extend the definition of limit to two cases: first, we allow the point a to be $\pm\infty$. Second, we allow the limit to be $\pm\infty$.

Definition 10.5.1. Let f be a function defined for $x > x_0$. We say that $\lim_{x \rightarrow +\infty} f(x) = L$ if

$$\forall \epsilon > 0 \quad \exists M \quad \forall x > M \quad |f(x) - L| < \epsilon.$$

If f is defined for $x < x_0$ we say that $\lim_{x \rightarrow -\infty} f(x) = L$ if

$$\forall \epsilon > 0 \quad \exists M \quad \forall x < -M \quad |f(x) - L| < \epsilon.$$

Exercise 10.5.2. Check that $\lim_{x \rightarrow +\infty} f(x) = \lim_{y \downarrow 0} f\left(\frac{1}{y}\right)$.

Example 10.5.3.

$$\lim_{x \rightarrow +\infty} \arctan x = \frac{\pi}{2}, \quad \lim_{x \rightarrow -\infty} \arctan x = -\frac{\pi}{2}.$$

Consider the first case. Fix $\epsilon > 0$ and choose $M = \tan(\frac{\pi}{2} - \epsilon)$. If $x > \tan(\frac{\pi}{2} - \epsilon)$, then $\arctan x > \frac{\pi}{2} - \epsilon$, and since $\arctan x$ is always less than $\frac{\pi}{2}$, we are done. The second case is similar to the first one. \square .

Definition 10.5.4. We say that $\lim_{E \ni x \rightarrow a} f(x) = +\infty$, if

$$\forall M > 0 \quad \exists \delta > 0 \quad \text{such that} \quad \forall x \in U_\delta^*(a) \quad f(x) > M.$$

Similarly, we say that $\lim_{E \ni x \rightarrow a} f(x) = -\infty$ if

$$\forall M > 0 \quad \exists \delta > 0 \quad \text{such that} \quad \forall x \in U_\delta^*(a) \quad f(x) < -M.$$

In both cases, $\lim_{E \ni x \rightarrow a} \frac{1}{f(x)} = 0$.

Example 10.5.5.

i

$$\lim_{x \downarrow 0} \frac{1}{\sin x} = +\infty, \quad \lim_{x \uparrow 0} \frac{1}{\sin x} = -\infty.$$

ii.

$$\lim_{x \rightarrow \pm\infty} x^3 = \pm\infty.$$

Example 10.5.6. Let $P(x) = a_p x^p + \dots$ and $Q(x) = b_q x^q + \dots$ be polynomials of degrees p and q . Then

$$\begin{aligned} \lim_{x \rightarrow +\infty} \frac{P(x)}{Q(x)} &= \lim_{x \rightarrow +\infty} \frac{a_p x^p + a_{p-1} x^{p-1} + \dots + a_0}{b_q x^q + b_{q-1} x^{q-1} + \dots + b_0} \\ &= \lim_{x \rightarrow +\infty} x^{p-q} \cdot \frac{a_p + a_{p-1} x^{-1} + \dots + a_0 x^{-p}}{b_q + b_{q-1} x^{-1} + \dots + b_0 x^{-q}}. \end{aligned}$$

The latter limit equals 0 if $p < q$, equals $+\infty$ if $p > q$ and a_p and b_q have the same signs, and $-\infty$ if they are of different signs, and equals the quotient $\frac{a_p}{b_q}$ of the leading coefficients if the polynomials have the same degrees $p = q$.

10.6. Limits of monotonic functions. Set $\sup_E f = \sup\{f(x) : x \in E\}$ if f is bounded from above on E , and $= +\infty$ otherwise, and set $\inf_E f = \inf\{f(x) : x \in E\}$ if f is bounded from below and $= -\infty$ otherwise.

Theorem 10.6.1. *Suppose $f: (a, b) \rightarrow \mathbb{R}$ does not decrease. Then the limits*

$$(1) \quad \lim_{x \uparrow b} f(x) = \sup_{(a,b)} f,$$

and

$$(2) \quad \lim_{x \downarrow a} f(x) = \inf_{(a,b)} f$$

exist.

Proof: We shall prove the first relation, proof of the second one is similar.

First, assume that f is bounded from above on (a, b) , then $\sup_{(a,b)} f < +\infty$. We fix $\epsilon > 0$ and use of the definition of the supremum. We find $x_0 < b$ such that $f(x_0) > \sup_{(a,b)} f - \epsilon$.

Since f does not decrease on the interval (a, b) , we have $f(x) \geq f(x_0)$ for $x \geq x_0$, so that

$$\sup_{(a,b)} f - \epsilon < f(x) \leq \sup_{(a,b)} f, \quad x_0 \leq x < b.$$

This proves (1) in the case when f is bounded from above.

Now, let f be unbounded from above. Then for any M we find x_0 such that $f(x_0) > M$, hence $f(x) > M$ for $x_0 \leq x < b$, and $\lim_{x \uparrow b} f(x) = +\infty$. \square

Exercise 10.6.2. Find the following limits:

$$\begin{aligned} & \lim_{x \downarrow 0} x \left[\frac{1}{x} \right], \quad \lim_{x \uparrow 0} x \left[\frac{1}{x} \right], \quad \lim_{x \rightarrow 0} \frac{\sqrt{1+x} - \sqrt{1-x}}{x}, \quad \lim_{x \rightarrow 0} x \cos \frac{1}{x}, \\ & \lim_{x \rightarrow +\infty} \left(\sqrt{x + \sqrt{x + \sqrt{x} - \sqrt{x}}} \right), \quad \lim_{x \rightarrow \pi} \frac{\sin x}{\pi - x}, \quad \lim_{x \rightarrow 0} \frac{x}{\tan x}, \\ & \lim_{x \rightarrow \pm\infty} \frac{x + \sin x}{x - \sin x}, \quad \lim_{x \downarrow 0} \frac{\sin x}{x^2}, \quad \lim_{x \rightarrow 0} \frac{1 - \cos x}{x^2}, \quad \lim_{x \rightarrow 0} \frac{\sin 5x - \sin 3x}{x}, \\ & \lim_{n \rightarrow \infty} \sin \pi \sqrt{n^2 + 1}, \quad \lim_{n \rightarrow \infty} \sin \pi (n^3 + 1)^{1/3}, \quad \lim_{n \rightarrow \infty} \underbrace{\sin \sin \dots \sin x}_{n \text{ times}}. \end{aligned}$$

11. THE EXPONENTIAL FUNCTION AND THE LOGARITHM

11.1. The function $t \mapsto a^t$. First, we recall the definition of the function $t \mapsto a^t$ for $a > 0$ and $t \in \mathbb{Z}$ that you've known from the high-school, then then we extend it to the set of all rational $t \in \mathbb{Q}$, and then to the whole real axis. The discussion will be brief.

11.1.1. $t \in \mathbb{Z}$. We set $a^0 = 1$, $a^t = \underbrace{a \cdot a \cdot \dots \cdot a}_{t \text{ times}}$, and $a^{-t} = \frac{1}{a^t}$ for $t \in \mathbb{N}$. This function

has the following properties

- (a) $a^m \cdot a^n = a^{m+n}$;
- (b) $(a^m)^n = a^{mn}$;
- (c) $a^n \cdot b^n = (ab)^n$;
- (d) for $n > 0$, $a^n < b^n$ if and only if $a < b$;
- (e) let $n < m$, then $a^n < a^m$ provided $a > 1$, and $a^n > a^m$ provided $a < 1$.

11.1.2. $t \in \mathbb{Q}$. Suppose $t = \frac{m}{n}$. Then we denote by $x = a^t$ a unique positive solution to the equation $x^n = a^m$. Note that with this definition

$$a^{\frac{m}{n}} = (a^m)^{\frac{1}{n}} = \left(a^{\frac{1}{n}}\right)^m$$

(why?).

First of all, we need to check that this definition is *correct*; i.e., that if we use a different representation $t = \frac{m'}{n'}$ then the answer will be the same. Let

$$x = a^{\frac{m}{n}}, \quad y = a^{\frac{m'}{n'}}$$

then

$$x^{nn'} = a^{mn'}, \quad y^{nn'} = a^{m'n}$$

Since $\frac{m'}{n'} = \frac{m}{n}$, we have $m'n = mn'$; i.e., $x^{nn'} = y^{nn'}$. Since the positive nn' -th root is unique, we get $x = y$. \square

Notice that the properties (a)–(e) formulated above hold true for the extension $t \mapsto a^t$, $t \in \mathbb{Q}$. We check only (a) and leave the rest as an exercise.

Claim 11.1.1. For $t_1, t_2 \in \mathbb{Q}$, $a^{t_1+t_2} = a^{t_1} \cdot a^{t_2}$.

Proof: Suppose

$$x_1 = a^{\frac{m_1}{n_1}}, \quad x_2 = a^{\frac{m_2}{n_2}}.$$

We need to check that

$$x_1 \cdot x_2 = a^{\frac{m_1}{n_1} + \frac{m_2}{n_2}}.$$

We have

$$x_1^{n_1 n_2} = a^{m_1 n_2}, \quad x_2^{n_1 n_2} = a^{m_2 n_1},$$

whence

$$(x_1 \cdot x_2)^{n_1 n_2} = a^{m_1 n_2} \cdot a^{m_2 n_1} = a^{m_1 n_2 + m_2 n_1}$$

(note that in the last equation, we've used the property (a) for integer t 's). That is

$$x_1 \cdot x_2 = a^{\frac{m_1 n_2 + m_2 n_1}{n_1 n_2}} = a^{\frac{m_1}{n_1} + \frac{m_2}{n_2}},$$

completing the proof. \square

We need one more property of the exponential function:

$$(f) \lim_{\mathbb{Q} \ni r \rightarrow t} a^r = a^t, t \in \mathbb{Q}.$$

Proof of (f): First, we prove (f) in a special case when $t = 0$; i.e, we prove that $\lim_{\mathbb{Q} \ni r \rightarrow 0} a^r = 1$. We prove it in the case $a > 1$, the case $a < 1$ is similar.

We use Heine's definition of the limit. Let $\{r_n\}$ be a sequence of rationals converging to 0. We fix an arbitrarily small $\epsilon > 0$ and choose $k \in \mathbb{N}$ such that

$$1 - \epsilon < a^{-1/k} < a^{1/k} < 1 + \epsilon$$

(why this is possible?). Then we choose $N \in \mathbb{N}$ such that for $n \geq N$,

$$-\frac{1}{k} < r_n < \frac{1}{k}.$$

Then we have

$$1 - \epsilon < a^{-1/k} \stackrel{(e)}{<} a^{r_n} \stackrel{(e)}{<} a^{1/k} < 1 + \epsilon,$$

proving the claim in the case $t = 0$.

Now, consider the general case. We have

$$\lim_{\mathbb{Q} \ni r \rightarrow t} a^r \cdot a^{-t} = \lim_{\mathbb{Q} \ni r \rightarrow t} a^{r-t} = \lim_{\mathbb{Q} \ni s \rightarrow 0} a^s = 1,$$

hence, the claim. \square

11.1.3. $t \in \mathbb{R}$. Assume again that $a > 1$. Given $t \in \mathbb{R}$, consider the numbers

$$s = \sup\{a^r : r \in \mathbb{Q}, r < t\}, \quad i = \inf\{a^q : q \in \mathbb{Q}, q > t\}.$$

It is not difficult to see that these two numbers must coincide. First note that $s \leq i$ (why?). Then, given $k \in \mathbb{N}$, choose the rationals r and q such that $r < t < q$ and $q - r < \frac{1}{k}$. Then

$$0 \leq i - s < a^q - a^r = a^r(a^{q-r} - 1) < s(a^{1/k} - 1).$$

Letting $k \rightarrow \infty$, we get $s = i$. \square

Definition 11.1.2. For $a > 1$ and for each $t \in \mathbb{R}$, we set $a^t = s = i$. If $a < 1$, then we set $a^t = \left(\frac{1}{a}\right)^{-t}$.

An equivalent definition says

$$a^t \stackrel{def}{=} \lim_{\mathbb{Q} \ni r \rightarrow t} a^r.$$

Exercise 11.1.3. Show that the limit on the right hand side exists, and prove the equivalence of these definitions.

This extends the function $t \mapsto a^t$ to the whole real axis preserving the properties (a)–(f):

- (a) $a^t \cdot a^s = a^{t+s}$;
- (b) $(a^t)^s = a^{ts}$;
- (c) $a^t \cdot b^t = (ab)^t$;
- (d) for $t > 0$, $a^t < b^t$ if and only if $a < b$, for $t < 0$, $a^t < b^t$ if and only if $a > b$.
- (e) let $t < s$, then $a^t < a^s$ provided $a > 1$, and $a^t > a^s$ provided $a < 1$;
- (f) $\lim_{s \rightarrow t} a^s = a^t$.

Exercise 11.1.4. Check the properties (a)–(f).

Next, we'll need one more property of the exponential function:

Claim 11.1.5. *The function $t \mapsto a^t$ maps \mathbb{R} onto \mathbb{R}_+ .*

I.e., for each positive y , there is $t \in \mathbb{R}$ such that $a^t = y$. Note, that due do monotonicity claimed in (e), if such a t exists then it must be unique.

Proof: Suppose that $a > 1$. Fix $y > 0$ and consider the sets

$$A_{<} = \{t \in \mathbb{R} : a^t < y\} \quad \text{and} \quad A_{>} = \{t \in \mathbb{R} : a^t > y\}.$$

The both sets are not empty, for instance, if we take a big enough $n \in \mathbb{N}$, then $-n \in A_{<}$ and $n \in A_{>}$. By (e), for each $t_1 \in A_{<}$ and $t_2 \in A_{>}$, we have $t_1 < t_2$. Therefore, by the completeness axiom, there exists $t \in \mathbb{R}$ such that $t_1 \leq t \leq t_2$ for each $t_1 \in A_{<}$ and each $t_2 \in A_{>}$. Let us show that $a^t = y$.

Suppose that $a^t < y$. Since $a^{t+1/n} \rightarrow a^t$ when $n \rightarrow \infty$, we can choose big enough n such that $t + \frac{1}{n} \in A_{<}$. This contradicts to our assumption that the point t separates the sets $A_{<}$ and $A_{>}$. Similarly, the assumption $a^t > y$ also leads to the contradiction. Thus, $a^t = y$, completing the proof. \square

The claim we've just proven allows us to define the inverse function to a^t which is called the *logarithmic function* $\log_a : \mathbb{R}_+ \mapsto \mathbb{R}$.

11.2. The logarithmic function $\log_a x$. This function is defined as inverse to the function $t \mapsto a^t$, that is $\log_a(a^t) = a^{\log_a t} = t$. It follows from the definition that $\log_a 1 = 0$ and $\log_a a = 1$. Now we list the basic properties of the logarithmic function:

- (i) $\log_a(xy) = \log_a x + \log_a y$;
- (ii) $\log_a(x^y) = y \log_a x$.
- (iii) if $x < y$, then $\log_a x < \log_a y$ provided $a > 1$, and $\log_a x > \log_a y$ provided $a < 1$;
- (iv) $\lim_{x \rightarrow y} \log_a x = \log_a y$;

Exercise 11.2.1. Check the properties (i)–(iv) of the logarithmic functions.

Another important property is

(v)

$$\log_a x = \frac{\log_b x}{\log_b a}.$$

Indeed, if $u = \log_b x$ and $v = \log_b a$, then $b^u = x$ and $b^v = a$. Now, we need to express the value $t = \log_a x$, that is the solution of the equation $a^t = x$ through u and v . We have $b^{vt} = a^t = x = b^u$, hence $vt = u$ and $t = \frac{u}{v}$ as we needed. \square

In particular, we see that

$$\log_a x = \frac{1}{\log_x a}.$$

If the basis a equals e , then we simply write $\log x = \log_e x$. Such logarithms are called the *natural* ones. The reason why the base e is important will be clear later (the base $a = 2$ is also very useful). It is worth to remember the special case of (v):

$$\log_a x = \frac{\log x}{\log a}$$

which allows to convert any logarithms to the natural ones.

Having the logarithms, we can define the power function $x \mapsto x^\alpha$ for $x > 0$ by

$$x^\alpha = e^{\alpha \log x}.$$

If $\alpha \in \mathbb{Z}$ this definition coincide with the one we know from the high-school (**why?**). If $\alpha > 0$ the function $x \mapsto x^\alpha$ increases, if $\alpha < 0$, then this function decreases.

It is important to remember that the exponential function grows at infinity faster than the power function:

Claim 11.2.2. For $a > 1$ and $p < \infty$,

$$(*) \quad \lim_{x \rightarrow +\infty} \frac{x^p}{a^x} = 0.$$

Proof: The relation $(*)$ easily follows from its special case for the sequences. We know that $n^p/a^n \rightarrow 0$, as $\mathbb{N} \ni n \rightarrow \infty$. Therefore, we can fix sufficiently small $\epsilon > 0$ and choose big enough N such that $\forall n > N$

$$\frac{n^{[p]+1}}{a^n} < \epsilon.$$

Then for $n = [x]$ (x is large enough) we have

$$0 < \frac{x^p}{a^x} < \frac{(n+1)^{[p]+1}}{a^{n+1}} \cdot a < a\epsilon.$$

Done! □

Corollary 11.2.3.

i. Setting in $(*)$ $a^x = t^\alpha$, we see that the logarithmic function grows slower than any power function:

$$\lim_{t \rightarrow +\infty} \frac{\log_a t}{t^\alpha} = \frac{1}{\alpha} \lim_{x \rightarrow +\infty} \frac{x}{a^x} = 0.$$

Here $\alpha > 0$, of course.

ii. Making the change of variables $s = \frac{1}{x}$, we arrive at another important limit:

$$\lim_{s \downarrow 0} s^\alpha |\log_a s| = 0.$$

Here again $\alpha > 0$.

Example 11.2.4.**i.**

$$\lim_{x \downarrow 0} x^x = \lim_{x \downarrow 0} e^{x \log x} = e^0 = 1.$$

ii.

$$\lim_{x \downarrow 0} x^{x^x} = \lim_{x \downarrow 0} e^{x^x \log x} = 0.$$

Now, the exponent tends to $-\infty$, hence the limit equals 0.

12. THE SECOND REMARKABLE LIMIT.
THE SYMBOLS “ o SMALL” AND “ \sim ”

12.1. $\lim_{x \rightarrow \pm\infty} \left(1 + \frac{1}{x}\right)^x = e.$

Proof: We already know the special case:

$$\lim_{n \rightarrow \infty} \left(1 + \frac{1}{n}\right)^n = e,$$

which is a definition of the number e . Now, let $x \rightarrow +\infty$, and let $n = [x]$ be the integer part of x . Then

$$\begin{aligned} \left(1 + \frac{1}{n+1}\right)^{n+1} \frac{n+1}{n+2} &= \left(1 + \frac{1}{n+1}\right)^n < \left(1 + \frac{1}{x}\right)^x \\ &< \left(1 + \frac{1}{n}\right)^{n+1} = \left(1 + \frac{1}{n}\right)^n \frac{n+1}{n}, \end{aligned}$$

and the result follows.

Now, consider the second case: $x \rightarrow -\infty$. We have

$$\lim_{x \rightarrow -\infty} \left(1 + \frac{1}{x}\right)^x = \lim_{y \rightarrow +\infty} \left(1 - \frac{1}{y}\right)^{-y},$$

and

$$\left(1 - \frac{1}{y}\right)^{-y} = \left(\frac{y}{y-1}\right)^y = \left(1 + \frac{1}{y-1}\right)^{y-1} \cdot \left(\frac{y}{y-1}\right).$$

Letting $y \rightarrow +\infty$, we see that the first factor on the right hand side converges to e , while the second factor converges to 1. Done! \square

Corollary 12.1.1.

$$\lim_{t \rightarrow 0} (1+t)^{\frac{1}{t}} = e$$

and

$$\lim_{t \rightarrow 0} \frac{\log(1+t)}{t} = 1.$$

Proof: To get the first limit put $x = 1/t$ in the 2nd remarkable limit. The second relation follows from the first one: if $y = (1+t)^{1/t} \rightarrow e$, then $\log y \rightarrow 1$, and $\log y$ is nothing but $\frac{1}{t} \log(1+t)$.

12.2. Infinitesimally small values and the symbols o and \sim . Here we develop a useful formalism which in many cases make the formulas simpler.

Definition 12.2.1. Let $E \subset \mathbb{R}$, and a be an accumulation point of E . The function $\alpha : E \rightarrow \mathbb{R}$ is called *infinitesimally small* at a , if

$$\lim_{E \ni x \rightarrow a} \alpha(x) = 0.$$

Let us make several trivial comments. If α and β are infinitesimally small at a , then their sum $\alpha + \beta$ is infinitesimally small as well. If α is infinitesimally small at a and β is bounded, then the product $\alpha \cdot \beta$ is infinitesimally small as well. At last, relation $f(x) = L + \alpha(x)$ where α is infinitesimally small at a is equivalent to $\lim_{x \rightarrow a} f(x) = L$.

Another notation for infinitesimally small values is $o(1)$ ("o small"). This notation is quite useful.

Definition 12.2.2. Let $f, g : E \rightarrow \mathbb{R}$, and let a be an accumulation point of E . We say that

$$f(x) = o(g(x)), \quad x \rightarrow a, \quad x \in E,$$

if $f(x) = \alpha(x)g(x)$, where α is infinitesimally small at a .

For instance,

$$x^2 = o(x), \quad x \rightarrow 0,$$

$$x = o(x^2), \quad x \rightarrow \pm\infty,$$

$$\frac{1}{x} = o\left(\frac{1}{x^2}\right), \quad x \rightarrow 0,$$

and

$$\frac{1}{x^2} = o\left(\frac{1}{x}\right), \quad x \rightarrow \pm\infty.$$

Definition 12.2.3. We say that the functions f and g are *equivalent* at a :

$$f \sim g, \quad x \rightarrow a, \quad x \in E,$$

if

$$\lim_{E \ni x \rightarrow a} \frac{f(x)}{g(x)} = 1.$$

Another way to express the same is to write

$$f(x) = g(x) + o(g(x)) = (1 + o(1))g(x), \quad x \rightarrow a, \quad x \in E.$$

Examples:

- (i) if $P_{n-1}(x)$ is a polynomial of degree $\leq n - 1$, then $x^n + P_{n-1}(x) \sim x^n$ for $x \rightarrow \pm\infty$.

The next relations hold for $x \rightarrow 0$:

- (ii) $x^2 + x \sim x$;
- (iii) $\sin x \sim x$;
- (iv) $\log(1 + x) \sim x$;
- (v) $e^x - 1 \sim x$;
- (vi) $(1 + x)^a - 1 \sim ax$.

Let us prove the last two relations: in (v) we introduce a new variable $t = \log(1+x)$, then (v) reduces to (iv). In (vi) we use both (iv) and (v):

$$\begin{aligned} \lim_{x \rightarrow 0} \frac{(1+x)^a - 1}{x} &= \lim_{x \rightarrow 0} \frac{e^{a \log(1+x)} - 1}{x} \\ &= \lim_{x \rightarrow 0} \frac{e^{a \log(1+x)} - 1}{a \log(1+x)} \cdot \frac{a \log(1+x)}{x} \\ &= \lim_{y \rightarrow 0} \frac{e^y - 1}{y} \cdot a \lim_{x \rightarrow 0} \frac{\log(1+x)}{x} = a. \end{aligned}$$

Exercise 12.2.4. Show that $\sqrt{x + \sqrt{x + \sqrt{x}}} \sim x^{\frac{1}{8}}$ for $x \rightarrow 0$, and is $\sim \sqrt{x}$ for $x \rightarrow +\infty$.

Exercise 12.2.5. Find the limits

$$\begin{aligned} \lim_{x \rightarrow \infty} \left(\frac{x^2 + 1}{x^2 - 1} \right)^{x^2}, \quad \lim_{x \rightarrow +\infty} (e^x - 1)^{1/x}, \quad \lim_{x \rightarrow 1} x^{x^{-1}}, \\ \lim \left(\frac{a^t + b^t}{2} \right)^{1/t} \quad (t \rightarrow +\infty, t \rightarrow -\infty, t \rightarrow 0). \end{aligned}$$

Exercise 12.2.6. Find the limits

$$\lim_{x \rightarrow 1} \left(\frac{m}{1-x^m} - \frac{n}{1-x^n} \right) \quad (m, n \in \mathbb{N}), \quad \lim_{x \rightarrow 0} \frac{\log \cos \alpha x}{\log \cos \beta x} \quad (\beta \neq 0).$$

Hint: in the first limit, write $x = 1+s$ and use that $(1+s)^n = 1 + ns + \frac{n(n-1)}{2}s^2 + o(s^2)$ for $s \rightarrow 0$ and $n \in \mathbb{N}$. In the second limit, use that $\cos x = 1 - \frac{1}{2}x^2 + o(x^2)$ for $x \rightarrow 0$.

Let

$$\lim_{x \rightarrow +\infty} f(x) = \lim_{x \rightarrow +\infty} g(x) = +\infty.$$

If $g(x) = o(f(x))$ for $x \rightarrow +\infty$, then we say that f grows faster at $+\infty$ than g (or, equivalently, that g grows slower at $+\infty$ than f). For example, for each $\alpha > 0$, and $p < \infty$, x^α grows faster than $\log^p x$, and for each $a > 1$, a^x grows faster than x^α .

Exercise* 12.2.7. Prove that for any sequence of functions

$$f_1(x), f_2(x), \dots, f_n(x), \dots \quad x_0 < x < +\infty,$$

such that

$$\lim_{x \rightarrow +\infty} f_n(x) = +\infty, \quad \forall n \in \mathbb{N},$$

it is possible to construct other two functions $\varphi(x)$ and $\psi(x)$ such that φ grows to $+\infty$ faster than any of f_n (i.e., for each n , $\lim_{x \rightarrow +\infty} (\varphi/f_n)(x) = +\infty$) and ψ grows to $+\infty$ slower than any of f_n (i.e., for each n , $\lim_{x \rightarrow +\infty} (\psi/f_n)(x) = 0$).

13. CONTINUOUS FUNCTIONS, I

13.1. Continuity.

Definition 13.1.1. The function f defined in a neighbourhood of a point a is called *continuous* at a if

$$f(a) = \lim_{x \rightarrow a} f(x).$$

In other words, $\forall \epsilon > 0$ exists $\delta > 0$ such that $\forall x \in U_\delta(a)$

$$|f(x) - f(a)| < \epsilon.$$

Here, as usual, $U_\delta(a) = \{t : |t - a| < \delta\}$ is a δ -neighbourhood of a .

If a function f is continuous at any point it is defined, we say that this function is continuous everywhere.

The function f can be defined only on a set E and $a \in E$. If a is an accumulation point of E then we say that f is *continuous at a along E* if

$$f(a) = \lim_{E \ni x \rightarrow a} f(x).$$

If a is an isolated point of E , then we also say that also f is continuous at a .

Examples:

- i. The constant function $f(x) = \text{const}$ is continuous everywhere.
- ii. The identity function $f(x) = x$ is continuous everywhere.
- iii. The function $f(x) = \sin x$ is continuous everywhere. Indeed, if $|x - a| < \epsilon$, then we get

$$\begin{aligned} |\sin x - \sin a| &= \left| 2 \cos \frac{x+a}{2} \sin \frac{x-a}{2} \right| \\ &\leq 2 \left| \sin \frac{x-a}{2} \right| \leq 2 \left| \frac{x-a}{2} \right| = |x-a| < \epsilon. \end{aligned}$$

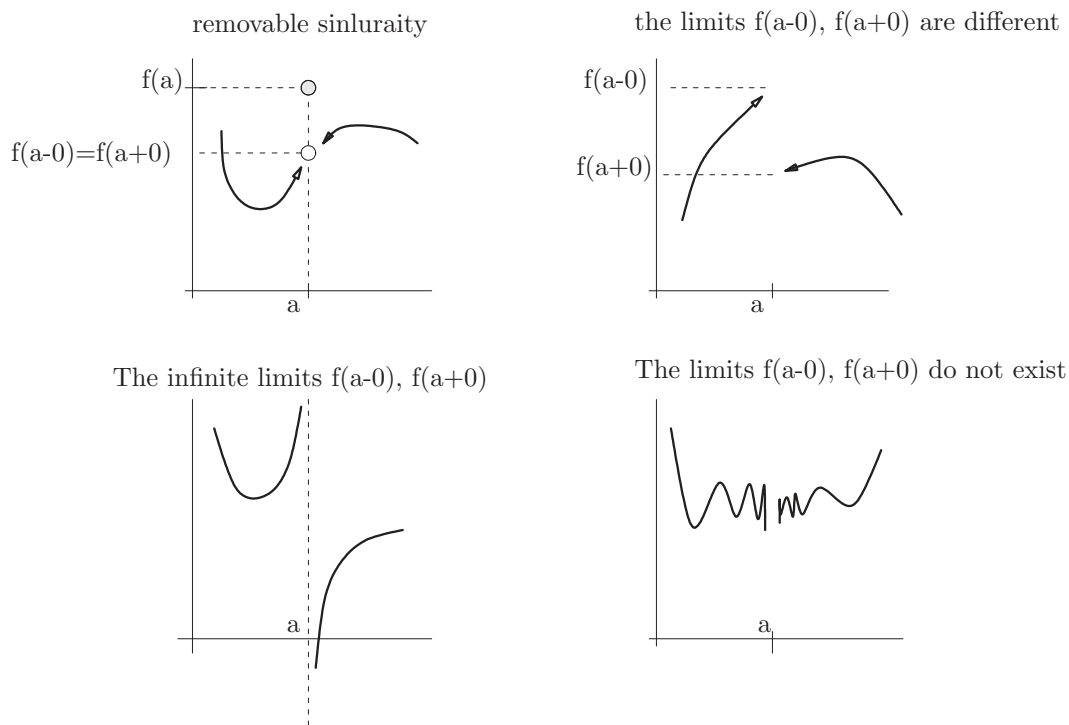
Similarly, the cosine function is continuous.

iv. The exponential function $x \mapsto a^x$ and the logarithmic function $x \mapsto \log x$ are continuous everywhere they are defined. This follows from the properties of these functions established in the previous lecture.

v. The function $f : [0, +\infty) \rightarrow [0, \infty)$ defined by $f(x) = e^{-1/x^2}$ for $x \neq 0$ and $f(0) = 0$ is continuous at every point of $[0, +\infty)$.

13.2. Points of discontinuity. There are various reasons for a function f to be discontinuous at a point a . We give here a brief classification of possible cases. In what follows, we'll use notations

$$f(a-0) = \lim_{x \uparrow a} f(x), \quad f(a+0) = \lim_{x \downarrow a} f(x).$$

FIGURE 10. Possible discontinuities at a

Removable discontinuity. We say that the function f has a *removable discontinuity* at the point a if the limits from above and from below at this point exist and have the same value: $f(a-0) = f(a+0)$. In this case, we can always define (or re-define) the function f at this point by the common value of these limits making the function continuous.

Examples:

- i. Let $f(x) = x$ for $x \neq 0$ and $f(0) = 10$. This function is clearly discontinuous at the origin. However, re-defining f at the origin by prescribing it the zero value, we obtain a continuous function at the origin.
- ii. Let $f(x) = x \sin \frac{1}{x}$ for $x \neq 0$. Again setting $f(0) = 0$, we get a continuous function.
- iii. Let $f(x) = \frac{\sin x}{x}$ for $x \neq 0$. Setting $f(0) = 1$, we get a continuous function.
- iv. Consider the Riemann function

$$\mathcal{R}(x) = \begin{cases} \frac{1}{n} & \text{if } x = \frac{m}{n} \in \mathbb{Q} \setminus \{0\}, (m, n) = 1 \\ 0 & \text{if } x \in \mathbb{R} \setminus \mathbb{Q} \text{ or } x = 0. \end{cases}$$

Here (m, n) is the greatest common divisor of m and n ; i.e., $(m, n) = 1$ means that m and n are mutually primes. We show that \mathcal{R} has a limit at any point $a \in \mathbb{R}$ and

$$(R) \quad \lim_{x \rightarrow a} \mathcal{R}(x) = 0.$$

We fix a and an arbitrary large natural number N . Consider the set

$$Q_N = \left\{ r = \frac{m}{n} : m \in \mathbb{Z}, n \in \mathbb{N}, (m, n) = 1, n \leq N \right\}.$$

If $r_1, r_2 \in Q_N$ and $r_1 \neq r_2$, then

$$|r_1 - r_2| = \left| \frac{m_1}{n_1} - \frac{m_2}{n_2} \right| = \frac{|m_1 n_2 - m_2 n_1|}{n_1 n_2} \geq \frac{1}{n_1 n_2} \geq \frac{1}{N^2}.$$

Hence, we can find a punctured neighbourhood $U^*(a)$ such that it contains *no* rational numbers from Q_N . This means that

$$\forall x \in U^*(a) \quad 0 \leq \mathcal{R}(x) < \frac{1}{N},$$

that is (R) holds. Relation (R) yields that Riemann's function is continuous at any irrational point and at the origin, and is discontinuous at any rational point except of $x = 0$. \square

Problem* 13.2.1. Whether there exists a function $f : \mathbb{R} \rightarrow \mathbb{R}$ continuous at all rational points and discontinuous at all irrational points?

Different one-sided limits. Another simple singularity appears when the function f has different one-sided limits at the point a , i.e., $f(a-0)$ and $f(a+0)$ exist but do not equal. It is also convenient to include into this group the case when at least one of these two limits is infinite.

For instance, if a discontinuity point of a monotonic function is not removable, then it must be of that kind.

Examples:

- i. $f(x) = \operatorname{sgn} x, a = 0$.
- ii. $f(x) = \tan x, a = \frac{\pi}{2}$.

Exercise 13.2.2. Give an example of the function $f : \mathbb{R} \rightarrow \mathbb{R}$ which is continuous at $\mathbb{R} \setminus \mathbb{Z}$ and discontinuous at all integer points.

Problem 13.2.3. The discontinuity set of an arbitrary monotonic function is at most countable.

At least one of the two one-sided limits does not exist. This are discontinuities of more complicated (hence, interesting!) nature.

Exercise 13.2.4. The function $f(x) = \sin \frac{1}{x}$ has no limits from the left and the right at the origin.

13.3. Local properties of continuous functions. Everywhere below we assume that the function $f : E \rightarrow \mathbb{R}$ is continuous at a . We list some simple *local* properties of f :

Local boundedness. There exists a neighbourhood $U(a)$ of a such that f is bounded in $E \cap U(a)$.

Local conservation of the sign. If $f(a) \neq 0$, then there exists a neighbourhood $U(a)$ of a where f has the same sign as at a :

$$\operatorname{sgn}f(x) = \operatorname{sgn}f(a), \quad \forall x \in E \cap U(a).$$

Arithmetic of continuous functions. If $g: E \rightarrow \mathbb{R}$ is continuous at a , then the functions $f + g$ and $f \cdot g$ are also continuous at a . If $g(x) \neq 0$ in a neighbourhood of a , then the quotient $\frac{f}{g}$ is also continuous at a .

Exercise 13.3.1. Prove these three properties.

Using these properties, we see for example, that every polynomial is a continuous function on \mathbb{R} and any rational function (that is the function of the form $R = \frac{P}{Q}$ where P and Q are polynomials) is continuous everywhere except of the zeroes of the denominator.

Continuity of the composition. If $f: E \rightarrow V$ is continuous at a , and $g: V \rightarrow \mathbb{R}$ is continuous at $b = f(a)$, then the composition $(g \circ f)(x)$ is continuous at a .

Proof: Indeed, fix $\epsilon > 0$ and choose $\delta > 0$ such that

$$|g(y) - g(b)| < \epsilon$$

provided $|y - b| < \delta$. Then having this δ choose an $\eta > 0$ such that

$$|f(x) - f(a)| < \delta$$

provided $|x - a| < \eta$. With this choice

$$|g(f(x)) - g(f(a))| = |g(y) - g(b)| < \epsilon.$$

Done! □

The last property implies continuity of the power function $x \mapsto x^\alpha = e^{\alpha \log x}$ on $(0, +\infty)$ for $\alpha < 0$ and on $[0, +\infty)$ for $\alpha > 0$. Using this fact, we prove now that

$$e^\lambda = \lim_{x \rightarrow \infty} \left(1 + \frac{\lambda}{x}\right)^x$$

for each $\lambda \in \mathbb{R}$. Indeed, we may assume that $\lambda \neq 0$ (if $\lambda = 0$ the formula is trivial). Then we introduce a new variable $t = \frac{x}{\lambda}$ which goes to ∞ with x . We have

$$\lim_{x \rightarrow \infty} \left(1 + \frac{\lambda}{x}\right)^x = \lim_{t \rightarrow \infty} \left[\left(1 + \frac{1}{t}\right)^t\right]^\lambda = \left[\lim_{t \rightarrow \infty} \left(1 + \frac{1}{t}\right)^t\right]^\lambda = e^\lambda.$$

The limit was interchanged with the brackets using continuity of the power function, the limit of the expression in the brackets equal e , as we know from the previous lecture.

Exercise 13.3.2. Suppose that the functions $f, g: E \rightarrow \mathbb{R}$ are continuous at a . Show that the functions $\max(f, g)(x)$ and $\min(f, g)(x)$ are also continuous at a . Deduce that if f is continuous at a , then $|f|$ is continuous at a as well.

Problem 13.3.3 (Cauchy's functional equation). Suppose $f: \mathbb{R} \rightarrow \mathbb{R}$ is a continuous function such that, for each $x, y \in \mathbb{R}$, $f(x + y) = f(x) + f(y)$. Then $f(x) = kx$ for some $k \in \mathbb{R}$.

I.e., the linear functions are the only continuous solutions of the functional equation $f(x + y) = f(x) + f(y)$.

Hint: First, using induction, check that $f(nx) = nf(x)$ for any $n \in \mathbb{Z}$. Then check that $f(\frac{m}{n}x) = \frac{m}{n}f(x)$. Then use the continuity of f .

Problem* 13.3.4. Prove the same under a weaker assumption that f is bounded from above in a neighbourhood of the origin.

Problem 13.3.5.

a. Suppose $f: \mathbb{R} \rightarrow \mathbb{R}$ is a continuous function that does not vanish identically and such that, for each $x, y \in \mathbb{R}$, one has $f(x + y) = f(x)f(y)$. Then $f(x) = e^{kx}$ for some $k \in \mathbb{R}$.

b. Formulate and prove a similar characterization of the logarithmic function $f(x) = k \log x$, and the power function $f(x) = x^k$ (in the both cases, $k \in \mathbb{R}$).

14. CONTINUOUS FUNCTIONS, II

14.1. Global properties of continuous functions. In what follows we denote by $C(E)$ the collection of all continuous functions on the set $E \subset \mathbb{R}$.

Theorem 14.1.1. *Let $f \in C[a, b]$ and let the values of the function f at the end-points have different signs: $f(a)f(b) < 0$. Then there exists an intermediate point $c \in (a, b)$ where the function f vanishes.*

Our intuitive understanding of the word “continuous” suggests that the result is correct: the graph of continuous function should be a “continuous curve” and we cannot connect a point above the x -axis with a point below x -axis by a continuous line which does not intersects the x -axis.

Proof: We construct inductively a sequence of nested intervals $I_n = [a_n, b_n]$, $I_0 \supset I_1 \supset \dots \supset I_n \supset \dots$ such that $|I_n| = 2^{-n}|I_0|$, and $f(a_n)f(b_n) < 0$.

Set $a_0 = a$, $b_0 = b$, and $I_0 = [a_0, b_0]$. As we know, at the end-points of I_0 the function f has different signs: $f(a_0)f(b_0) < 0$. Having the interval I_n , we consider its middle point ξ and check the sign of $f(\xi)$. If $f(\xi) = 0$, then the theorem is proven and there is no need in the further construction. If $f(\xi) \neq 0$, then either $f(a_n)$ or $f(b_n)$ has the opposite sign with $f(\xi)$. If $f(a_n)f(\xi) < 0$, then we set $a_{n+1} = a_n$, $b_{n+1} = \xi$, otherwise we set $a_{n+1} = \xi$, $b_{n+1} = b_n$. In any case, we get a new interval I_{n+1} with the same properties.

By Cantor’s lemma the intersection of the intervals I_n is a singleton set:

$$\{c\} = \bigcap_{n \geq 1} I_n.$$

We claim that the function f vanishes at c . By construction,

$$\lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} b_n = c.$$

By continuity of f

$$f^2(c) = \lim_{n \rightarrow \infty} f(a_n)f(b_n) \leq 0,$$

so that $f(c) = 0$. We are done. \square

The proof of this theorem is constructive, and it can be easily turned to a simple and effective numerical algorithm (called sometimes *bisection method*) for finding roots of equations.

The result can be put in a more general form:

Theorem 14.1.2 (Intermediate Value Property). *Let $f \in C[a, b]$, and let $f(a) = A$, $f(b) = B$, where $A \neq B$. Then for any intermediate value C between A and B (that is $A < C < B$ or $B < C < A$) there exists $c \in (a, b)$ such that $f(c) = C$.*

Proof: Consider a new function $f_1(x) = f(x) - C$. Its values at the end-points have different signs, so applying Theorem 1 we find a point $c \in (a, b)$ such that $f_1(c) = 0$, or $f(c) = C$. \square

Corollary 14.1.3. *For each polynomial P of odd degree there exists a point $\xi \in \mathbb{R}$ such that $P(\xi) = 0$.*

Proof: Let $P(x) = a_{2N-1}x^{2N-1} + \dots$ be a polynomial of degree $2N - 1$, i.e., $a_{2N-1} \neq 0$. Suppose, for instance, that $a_{2N-1} > 0$. Then $\lim_{x \rightarrow \pm\infty} P(x) = \pm\infty$. Therefore, we can find a sufficiently big positive M such that $P(M) > 0$ and $P(-M) < 0$. The rest follows from continuity of P and from the IVP-property. \square

Corollary 14.1.4. *If $f \in C(a, b)$ then the image $f(a, b)$ is an interval (maybe, infinite, semi-infinite, or a singleton).*

In the proof of this corollary we will use the following characteristics property of intervals: the set $Y \subset \mathbb{R}$ is an interval provided that for each pair of points $y_1, y_2 \in Y$, $y_1 < y_2$, we have $(y_1, y_2) \subset Y$.

Exercise 14.1.5. Check this!

Hint: consider the interval with end-points at $i = \inf Y$ and $s = \sup Y$.

Proof of Corollary 14.1.4: Take any two points $y_1 < y_2$ in $f(a, b)$. We need to check that $(y_1, y_2) \subset f(a, b)$. Since $y_1, y_2 \in f(a, b)$, there are points $\xi_1, \xi_2 \in (a, b)$ such that $f(\xi_i) = y_i$, $i = 1, 2$. Suppose, for instance, that $\xi_1 < \xi_2$. Then by the IVP-property, for any $y \in (y_1, y_2)$, there is $\xi \in (\xi_1, \xi_2)$ such that $f(\xi) = y$; i.e., $(y_1, y_2) \subset f(a, b)$. \square

Exercise 14.1.6. A point ξ is said to be a *fixed point* of the function f if $f(\xi) = \xi$.

i. Prove that any continuous function that maps the interval $[0, 1]$ into itself has a fixed point. In other words, if $f \in C[0, 1]$ and $0 \leq f(x) \leq 1$ for all $x \in [0, 1]$, then there exists a point $\xi \in [0, 1]$ such that $f(\xi) = \xi$.

ii. Let the function f be defined on $[a, b]$ and satisfy there

$$|f(x) - f(y)| \leq K|x - y|, \quad \forall x, y \in [a, b]$$

with some $K < 1$. Show that f has a *unique* fixed point at the interval $[a, b]$.

Exercise 14.1.7. Let P be a polygon in the plane. Prove that there is a vertical line which splits P onto two polygons of equal area.

Exercise 14.1.8. Let $a_1, a_2, a_3 > 0$, $\lambda_1 < \lambda_2 < \lambda_3$. Show that equation

$$\frac{a_1}{x - \lambda_1} + \frac{a_2}{x - \lambda_2} + \frac{a_3}{x - \lambda_3} = 0$$

has exactly 2 real solutions.

Exercise 14.1.9. Let $f \in C[0, 1]$, and $f(0) = f(1)$. Show that there exists $a \in [0, \frac{1}{2}]$ such that $f(a) = f(a + \frac{1}{2})$.

Theorem 14.1.10 (Weierstrass). *If $f \in C[a, b]$, then f is bounded on $[a, b]$ and attains there its maximum and minimum values.*

Proof: First, we prove the boundedness of f . In the previous lecture we proved local boundedness of continuous functions. Therefore, for each $x \in [a, b]$ there exists a neighbourhood $U(x)$ and a constant C_x such that

$$|f(y)| \leq C_x, \quad y \in U(x).$$

The neighbourhoods $\{U(x)\}_{x \in [a,b]}$ form a covering of $[a, b]$. Hence, using the Borel covering lemma we can find a finite sub-covering

$$[a, b] \subset \bigcup_{k=1}^N U(x_k)$$

Then

$$|f(x)| \leq \max\{C_{x_1}, \dots, C_{x_k}\}, \quad x \in [a, b],$$

that is. f is bounded on $[a, b]$.

Now we show that f achieves its maximum and minimum values. We'll show this only for the maximum value. The other case is similar. Let

$$M = \sup_{[a,b]} f.$$

By the definition of the supremum, there is a sequence $\{x_n\} \subset [a, b]$ such that

$$\lim_{n \rightarrow \infty} f(x_n) = M.$$

Since the sequence $\{x_n\}$ is bounded we can find a convergent subsequence

$$\{x_{n_i}\} \rightarrow x^* \in [a, b].$$

Then by continuity of f

$$f(x^*) = \lim_{i \rightarrow \infty} f(x_{n_i}) = M.$$

We are done. □

Remark 14.1.11. The both conclusions of the Weierstrass theorem may fail if f is continuous on an open interval (or on the whole real axis).

For instance, the function $f(x) = 1/x$ is continuous on the interval $(0, 1)$ but is unbounded there. The function $f(x) = x$ is bounded on the same interval but has no maximal and minimal values on that interval.

Combining the Weierstrass theorem and the IVP of continuous functions, we get

Corollary 14.1.12. *If $f \in C[a, b]$, then the image $f[a, b]$ is a closed interval with the end-points at $\min_{[a,b]} f$ and $\max_{[a,b]} f$.*

Exercise 14.1.13.

- i. Give an example of a bounded continuous function on \mathbb{R} which has no maximum and minimum.
- ii. Prove, that if $f \in C(\mathbb{R})$ is a positive function and $\lim_{x \rightarrow \infty} f(x) = 0$, then f attains its maximum value.

14.2. Uniform continuity.

Definition 14.2.1. The function $f : E \rightarrow \mathbb{R}$ is called *uniformly continuous on E* if $\forall \epsilon > 0 \exists \delta > 0$ such that the inequality

$$(\alpha) \quad |f(x) - f(y)| < \epsilon$$

holds $\forall x, y \in E$ provided that $|x - y| < \delta$.

It is instructive to compare this definition with the definition of continuity *everywhere on E* . The latter says that $\forall x \in E \forall \epsilon > 0 \exists \delta > 0$ (*depending on x and ϵ*) such that (α) holds provided that $|x - y| < \delta$. Here, δ depends on a point x . The uniform continuity guarantees the choice of δ which works everywhere on E , which is, at least formally, a stronger property than continuity everywhere.

In order to show that a continuous function f is not uniformly continuous, one has to find two sequences of points $\{x_n\}$ and $\{y_n\}$ in the domain of f such that $|x_n - y_n| \rightarrow 0$ but $|f(x_n) - f(y_n)| \geq \text{const}$.

Examples:

i. Consider the function $f(x) = \sin \frac{1}{x}$ on the set $E = (0, 1]$. The function is continuous (as a composition of two continuous functions) but not uniformly continuous. Indeed, consider two sequences of points: $x_n = (2\pi n)^{-1}$ and $y_n = [(2n + \frac{1}{2})\pi]^{-1}$. Clearly, $|x_n - y_n| \rightarrow 0$ but $f(x_n) = 1$, $f(y_n) = 0$.

ii. The identity function $f(x) = x$ is uniformly continuous everywhere on \mathbb{R} .

iii. The square function $f(x) = x^2$ is continuous on \mathbb{R} but not uniformly. Suppose $x_n = \sqrt{n+1}$ and $y_n = \sqrt{n}$. Then

$$|x_n - y_n| = \frac{1}{\sqrt{n+1} + \sqrt{n}} \rightarrow 0$$

but $f(x_n) - f(y_n) = 1$.

iv. The function $f(x) = \sqrt{x}$ is uniformly continuous on $\{x \geq 0\}$. This follows from inequality

$$|\sqrt{x} - \sqrt{y}| \leq \sqrt{|x - y|}, \quad x, y \geq 0.$$

To prove this inequality, we suppose that $y = x + h$ with $h > 0$. Then

$$\sqrt{y} - \sqrt{x} = \frac{h}{\sqrt{x+h} + \sqrt{x}} \leq \sqrt{h} = \sqrt{y-x}.$$

v. The function $f(x) = \frac{1}{x}$ is not uniformly continuous on $(0, 1]$. Indeed, consider the sequences $x_n = \frac{1}{2n}$ and $y_n = \frac{1}{2n+1}$, the difference between them converges to zero, but $f(y_n) - f(x_n) = 1$.

vi. The function $f(x) = \sin(x^2)$ is not uniformly continuous on \mathbb{R} . Choose $x_n = \sqrt{\frac{\pi}{2}(n+1)}$, $y_n = \sqrt{\frac{\pi}{2}n}$, then $|x_n - y_n| \rightarrow 0$ but $|f(x_n) - f(y_n)| = 1$.

Theorem 14.2.2 (Cantor). *If $f \in C[a, b]$, then f is uniformly continuous on $[a, b]$.*

Proof: Assume that f is not uniformly continuous on $[a, b]$, then, for some $\epsilon > 0$, one can find two sequences $\{x_n\}$ and $\{y_n\}$ such that $|x_n - y_n| \rightarrow 0$ but $|f(x_n) - f(y_n)| \geq \epsilon$. Passing to the subsequences, we may assume that $\{x_{n_k}\}$ and $\{y_{n_k}\}$ converge to $c \in [a, b]$. Then $|f(x_{n_k}) - f(y_{n_k})| \rightarrow 0$ and we arrive at the contradiction. \square

An alternative proof can be done using the Heine-Borel covering lemma.

Exercise 14.2.3. If $f \in C[a, b]$, then the functions

$$m(x) = \inf_{a \leq \xi \leq x} f(\xi), \quad \text{and} \quad M(x) = \sup_{a \leq \xi \leq x} f(\xi)$$

are also continuous on $[a, b]$.

Exercise 14.2.4.

- i. Let the function f be uniformly continuous on a bounded set E . Prove that f is bounded.
- ii. Let $f \in C(a, b)$ where (a, b) is a finite interval. Prove that f is uniformly continuous on (a, b) if and only if there exist the limiting values $f(a + 0)$ and $f(b - 0)$.
- iii. Let $f \in C(\mathbb{R})$ be bounded and monotonic. Prove that f is uniformly continuous.

Exercise 14.2.5. Check the uniform continuity of the following functions:

$$\log x, \quad x \in (0, 1]; \quad \frac{1}{\log x}, \quad x \in (0, 1); \quad x + \frac{x}{x+1}, \quad x \in [0, +\infty);$$

$$x \sin x; \quad \sin x^2; \quad \sin \sqrt{x} \quad (x \in \mathbb{R}).$$

Exercise 14.2.6. Let $f: E \rightarrow \mathbb{R}$, $E \subset \mathbb{R}$. Show that the function f is uniformly continuous on E if and only if

$$\omega_f(\delta) \stackrel{\text{def}}{=} \sup \{|f(x) - f(y)| : x, y \in E, |x - y| < \delta\} \rightarrow 0$$

for $\delta \rightarrow 0$.

14.3. Inverse functions. We start with a simple result (in fact, we've used it already):

Theorem 14.3.1. *Suppose the function $f : X \rightarrow \mathbb{R}$ is strongly monotonic, and $Y = fX$ is the range of f . Then there exists the inverse function $f^{-1} : Y \rightarrow X$ which is also strongly monotonic. It increases when f increases, and decreases when f decreases.*

The proof follows by a straightforward inspection and we skip it.

For continuous functions, strong monotonicity is also a necessary conditions for existence of the inverse function.

Theorem 14.3.2. *Let the function $f \in C[a, b]$ have an inverse function. Then f is strongly monotonic.*

Proof: First, observe that since f is invertible, for any $x, y \in [a, b]$, $f(x) \neq f(y)$.

Strongly monotonic functions have the following characteristic property: for each triple of points $x_1 < x_2 < x_3$ the value $f(x_2)$ must be belong to the open interval with the end-points at $f(x_1)$ and $f(x_3)$. Now, assume that the theorem is wrong and that there exists a triple $x_1 < x_2 < x_3$ such that, for example, $f(x_1) < f(x_3) < f(x_2)$ (the other cases are similar). Therefore, by the IVP-property there exists $\xi \in (x_1, x_2)$ such that $f(\xi) = f(x_3)$ which contradicts invertibility of f . \square

The next theorem says that for monotonic functions continuity is equivalent to the IVP-property.

Theorem 14.3.3. *Suppose $f : [a, b] \rightarrow \mathbb{R}$ is monotonic. Then f is continuous on $[a, b]$ if and only if the image $f[a, b]$ is a closed interval with the end-points at $f(a)$ and $f(b)$.*

Proof: If f is continuous, then by the IVP-property the image $f[a, b]$ contains any intermediate point between $f(a)$ and $f(b)$.

In the other direction, suppose $f[a, b]$ be a closed interval and suppose that f is discontinuous at $c \in [a, b]$. We assume that $c \in (a, b)$, the cases $c = a$, and $c = b$ are similar. By monotonicity of f , the one-sided limits $f(c - 0)$ and $f(c + 0)$ exist, and at least one of open intervals

$$(f(c), f(c + 0)), \quad (f(c - 0), f(c))$$

is not empty, let us call this interval I . The function f does not attain any value from this interval, on the other hand, $I \subset [f(a), f(b)]$. The contradiction proves the theorem. \square

Note that the theorem fails without monotonicity assumption:

Exercise 14.3.4. Consider the function

$$f(x) = \begin{cases} \sin \frac{1}{x} & x \in \mathbb{R} \setminus \{0\} \\ 0 & x = 0. \end{cases}$$

This function is discontinuous at the origin. Check that for any closed interval $I \subset \mathbb{R}$ the image fI is an interval as well.

Combining these theorems, we obtain

Corollary 14.3.5. *Let $f \in C[a, b]$ be strongly monotonic. Then the inverse function f^{-1} is also continuous and strongly monotonic.*

Proof: Indeed, by Theorem 14.3.1, the inverse function f^{-1} is strongly monotonic. Suppose for instance, that f and hence f^{-1} are (strongly) increasing functions. Let $\alpha = f(a)$ and $\beta = f(b)$. Then by the IVP-property $f[a, b] = [\alpha, \beta]$; i.e., $f^{-1}[\alpha, \beta] = [a, b]$, and by Theorem 14.3.3 the function f^{-1} must be continuous. \square

For example, the function $\arcsin x$ is continuous on $[-1, 1]$ and the function $\arctan x$ is continuous on \mathbb{R} .

In some sense, the continuity assumption in the last corollary is redundant:

Problem 14.3.6. Let $f: (a, b) \rightarrow \mathbb{R}$ be monotonic, and let the inverse f^{-1} be defined on a set E . Then f^{-1} is continuous on E .

Problem 14.3.7. Let $f: [0, 1] \rightarrow [0, 1]$ be a continuous increasing function. Then for each $x \in [0, 1]$ one of the following holds: either x is a fixed point of f (that is, $f(x) = x$), or the n -th iterate $f^n(x)$ converges to a fixed point of f when $n \rightarrow \infty$.

15. THE DERIVATIVE

15.1. Definition and some examples.

Definition 15.1.1 (The derivative). f be a function defined in an open neighbourhood U of a point $x \in \mathbb{R}$. The function f is called *differentiable at x* if there exists the limit

$$f'(x) = \lim_{y \rightarrow x} \frac{f(y) - f(x)}{y - x} = \lim_{\epsilon \rightarrow 0} \frac{f(x + \epsilon) - f(x)}{\epsilon}$$

called the *derivative of f at x* . The function f is differentiable on an open interval (a, b) if it is differentiable at every point $x \in (a, b)$.

Sometimes, we denote the differences by the symbols Δ :

$$\Delta x = y - x = \epsilon$$

and

$$\Delta f(x, \epsilon) = f(x + \epsilon) - f(x).$$

Notice that Δf is a function of two variables: x and $\Delta x = \epsilon$. In these notations

$$f'(x) = \lim_{\Delta x \rightarrow 0} \frac{\Delta f(x, \Delta x)}{\Delta x} = \frac{df}{dx},$$

where df and dx are (in the meantime) symbolic notations called the *differentials* of f and of x .

If the function f is defined on the closed interval $[a, b]$, then we say that f is differentiable at the end-points a and b if there exist one-sided limits:

$$f'(a+0) = \lim_{y \downarrow a} \frac{f(y) - f(a)}{y - a}, \quad f'(b-0) = \lim_{y \uparrow b} \frac{f(y) - f(b)}{y - b}.$$

It follows immediately from the definition, that if f is differentiable at x , then it must be continuous at x , otherwise, the limit in the definition of the derivative is infinite.

Examples:

(i) Let $f(x)$ be the constant function. Then $f'(x) = 0$ everywhere. Soon, we'll see that this property characterizes the constant functions: they are the only functions with the zero derivative.

(ii) Let $f(x) = x^n$, $n \in \mathbb{N}$. Then

$$\Delta f(x, \epsilon) = (x + \epsilon)^n - x^n = nx^{n-1}\epsilon + o(\epsilon), \quad \epsilon \rightarrow 0.$$

So that

$$f'(x) = \lim_{\epsilon \rightarrow 0} \frac{\Delta f(x, \epsilon)}{\epsilon} = \lim_{\epsilon \rightarrow 0} (nx^{n-1} + o(1)) = nx^{n-1}.$$

In particular, if the function $f(x)$ is linear, then its derivative is a constant function: $(ax + b)' = a$. We'll learn soon that the linear functions are the only functions with constant derivative.

(iii) Consider the sine-function $f(x) = \sin x$. Then

$$\Delta f(x, \epsilon) = \sin(x + \epsilon) - \sin x = 2 \sin \frac{\epsilon}{2} \cos \left(x + \frac{\epsilon}{2} \right),$$

and

$$(\sin x)' = \lim_{\epsilon \rightarrow 0} \left(\frac{\sin(\epsilon/2)}{\epsilon/2} \right) \cos \left(x + \frac{\epsilon}{2} \right) = \cos x.$$

In a similar way, one finds the derivative of the cosine function

$$(\cos x)' = -\sin x.$$

(iv) Next, consider the exponential function $f(x) = a^x$. Now

$$\Delta f = a^{x+\epsilon} - a^x = a^x (a^\epsilon - 1) = a^x (e^{\epsilon \log a} - 1),$$

and

$$\lim_{\epsilon \rightarrow 0} \frac{\Delta f(x, \epsilon)}{\epsilon} = a^x \lim_{\epsilon \rightarrow 0} \frac{e^{\epsilon \log a} - 1}{\epsilon} = a^x \log a \lim_{\delta \rightarrow 0} \frac{e^\delta - 1}{\delta} = a^x \log a.$$

Therefore,

$$(a^x)' = a^x \log a.$$

In particular,

$$(e^x)' = e^x.$$

This explains why in many situations it is simpler to work with the base e than with the other bases.

(v) Now, let $f(x) = x^\mu$, $x > 0$ (with $\mu \in \mathbb{R}$ and $\mu \neq 0$). Then

$$\begin{aligned} \Delta f(x, \epsilon) &= (x + \epsilon)^\mu - x^\mu = x^\mu \left\{ \left(1 + \frac{\epsilon}{x} \right)^\mu - 1 \right\} \\ &= x^\mu \left\{ 1 + \mu \frac{\epsilon}{x} + o(\epsilon) - 1 \right\} = \mu x^{\mu-1} \epsilon + o(\epsilon), \end{aligned}$$

and

$$(x^\mu)' = \mu x^{\mu-1}.$$

This computation extends example (ii).

(vi) Consider the logarithmic function $f(x) = \log_a |x|$ defined for $x \in \mathbb{R} \setminus \{0\}$. In this case,

$$\Delta f(x, \epsilon) = \log_a |x + \epsilon| - \log_a |x| = \log_a \left| 1 + \frac{\epsilon}{x} \right|.$$

If ϵ is sufficiently small: $|\epsilon| < |x|$, then the expression $1 + \epsilon/x$ is positive and

$$\Delta f(x, \epsilon) = \log_a \left(1 + \frac{\epsilon}{x} \right) = \frac{\log(1 + \epsilon/x)}{\log a} = \frac{\epsilon}{x \log a} + o(\epsilon).$$

Hence

$$(\log_a |x|)' = \frac{1}{x \log a}.$$

In particular,

$$(\log |x|)' = \frac{1}{x}.$$

(vii) At last, consider the function $f(x) = |x|$. It is easy to see directly from the definition that $f'(x) = \text{sgn}(x)$ for $x \neq 0$ and that f has no derivative at the origin.

15.2. Some rules. In this section we show several simple rules which help us to compute derivatives.

Theorem 15.2.1. *Let the functions f and g be defined on an interval (a, b) and suppose they are differentiable at the point $x \in (a, b)$. Then*

- (i) *the sum $f + g$ is differentiable at x and $(f + g)'(x) = f'(x) + g'(x)$;*
- (ii) *the product $f \cdot g$ is differentiable at x and*

$$(f \cdot g)'(x) = f'(x) \cdot g(x) + f(x) \cdot g'(x).$$

In particular, if c is a constant, then $(cf)'(x) = cf'(x)$.

- (iii) *if $g(x) \neq 0$, then the quotient $\frac{f}{g}$ is differentiable at x and*

$$\left(\frac{f}{g}\right)'(x) = \frac{f'(x)g(x) - f(x)g'(x)}{g^2(x)}.$$

Proof: The proof of (i) is obvious. Next,

$$\begin{aligned} (f \cdot g)(x + \epsilon) - (f \cdot g)(x) &= f(x + \epsilon)g(x + \epsilon) - f(x)g(x + \epsilon) + f(x)g(x + \epsilon) - f(x)g(x) \\ &= (f(x + \epsilon) - f(x))g(x + \epsilon) + f(x)(g(x + \epsilon) - g(x)) \end{aligned}$$

which readily gives us (ii).

Having (ii), it suffices to prove (iii) in a special case when f equals identically 1:

$$(iv) \quad \left(\frac{1}{g}\right)'(x) = -\frac{g'(x)}{g^2(x)}.$$

We have

$$\begin{aligned} \frac{1}{g(x + \epsilon)} - \frac{1}{g(x)} &= -\frac{g(x + \epsilon) - g(x)}{g(x + \epsilon)g(x)} \\ &= -\frac{g(x + \epsilon) - g(x)}{g^2(x)} \cdot \frac{g(x + \epsilon)}{g(x)}, \end{aligned}$$

which yields (iv). This proves the theorem. □

Example 15.2.2. Consider the function $f(x) = \tan x = \frac{\sin x}{\cos x}$. We have

$$f'(x) = \frac{\cos^2 x + \sin^2 x}{\cos^2 x} = \frac{1}{\cos^2 x}.$$

That is,

$$(\tan x)' = \frac{1}{\cos^2 x}.$$

Similarly,

$$(\cot x)' = -\frac{1}{\sin^2 x}.$$

Example 15.2.3. If

$$P(x) = \sum_{j=0}^n a_j x^j$$

is a polynomial of degree n , then

$$P'(x) = \sum_{i=0}^{n-1} (i+1)a_{i+1}x^i.$$

is a polynomial of degree $n-1$.

15.3. Derivative of the inverse function and of the composition.

Theorem 15.3.1. *Let the function $f: (a, b) \rightarrow \mathbb{R}$ be a continuous, strictly monotone function. Suppose f is differentiable at the point $x_0 \in (a, b)$ and $f'(x_0) \neq 0$. Then the inverse function $g = f^{-1}$ is differentiable at $y_0 = f(x_0)$ and*

$$g'(y_0) = \frac{1}{f'(x_0)}.$$

Symbolically, if $y = f(x)$, then $x = g(y)$ and

$$g'(y) = \frac{dx}{dy} = \frac{1}{\frac{dy}{dx}}.$$

Proof: Let $x = g(y)$. If $y \rightarrow y_0$, then $g(y) \rightarrow g(y_0)$ (since the function g is continuous at y_0) or, what is the same, $x \rightarrow x_0$. Then we have

$$\begin{aligned} \lim_{y \rightarrow y_0} \frac{g(y) - g(y_0)}{y - y_0} &= \lim_{x \rightarrow x_0} \frac{x - x_0}{f(x) - f(x_0)} \\ &= \lim_{x \rightarrow x_0} \frac{1}{\frac{f(x) - f(x_0)}{x - x_0}} = \frac{1}{f'(x_0)}, \end{aligned}$$

proving the theorem. □

Theorem 15.3.1 gives us the expression for $g'(y)$ in terms of the variable x , however, applying Theorem 15.3.1, we have to return to the variable y .

Examples:

i. Let $f(x) = \sin x$, $x \in [-\frac{\pi}{2}, +\frac{\pi}{2}]$.

$$(\arcsin y)' = \frac{1}{(\sin x)'} = \frac{1}{\cos x} = \frac{1}{\sqrt{1 - \sin^2 x}} = \frac{1}{\sqrt{1 - y^2}}.$$

Similarly,

$$(\arccos y)' = -\frac{1}{\sqrt{1 - y^2}}.$$

ii. Let $f(x) = \tan x$, $x \in (-\frac{\pi}{2}, \frac{\pi}{2})$. Then

$$(\arctan y)' = \frac{1}{(\tan x)'} = \cos^2 x = \frac{1}{1 + \tan^2 x} = \frac{1}{1 + y^2}.$$

Similarly,

$$(\operatorname{arccot} y)' = -\frac{1}{1+y^2}.$$

iii. Let $f(x) = a^x$. Then $g(y) = \log_a y$ and

$$(\log_a y)' = \frac{1}{a^x \log a} = \frac{1}{y \log a}.$$

(We've known already the answer in advance, of course).

Theorem 15.3.2 (The Chain Rule). *Let the function $y = f(x)$ be differentiable at the point x_0 and let the function $z = g(y)$ be differentiable at the point $y_0 = f(x_0)$. Then the composition function $g \circ f$ is differentiable at x_0 and*

$$(g \circ f)'(x_0) = g'(y_0)f'(x_0) = g'(f(x_0))f'(x_0).$$

Symbolically,

$$\frac{dz}{dx} = \frac{dz}{dy} \cdot \frac{dy}{dx}.$$

Proof: We have

$$\begin{aligned} \frac{(g \circ f)(x) - (g \circ f)(x_0)}{x - x_0} &= \frac{g(f(x)) - g(f(x_0))}{f(x) - f(x_0)} \cdot \frac{f(x) - f(x_0)}{x - x_0} \\ &= \frac{g(y) - g(y_0)}{y - y_0} \cdot \frac{f(x) - f(x_0)}{x - x_0}. \end{aligned}$$

If $x \rightarrow x_0$, then $y \rightarrow y_0$ (since the function f is continuous at x_0), and we see that the last expression tends to $g'(y_0)f'(x_0)$ proving the theorem. \square

The chain rule is easily extended to the composition of several functions: if $F = f_1 \circ f_2 \circ \dots \circ f_n$, then

$$F' = f_1'(f_2 \circ \dots \circ f_n) f_2'(f_3 \circ \dots \circ f_n) \dots f_n'.$$

This can be easily proved by induction with respect to n . In particular, if

$$F = f \circ f \circ \dots \circ f = f^{\circ n}$$

is the n -th iterate of the function f , then

$$F' = f'(f^{\circ(n-1)})f'(f^{\circ(n-2)})\dots f'(f)f'.$$

Examples:

i. The logarithmic derivative. Let $f(x) = \log g(x)$. Then

$$f'(x) = \frac{g'}{g}(x).$$

For example, if $P(x) = c(x - x_1)\dots(x - x_n)$ is a polynomial of degree n , then

$$\frac{P'}{P}(x) = \frac{1}{x - x_1} + \dots + \frac{1}{x - x_n}.$$

ii. If $f(x) = e^{g(x)}$, then $f'(x) = g'(x)e^{g(x)}$.

iii. If $f(x) = u(x)^{v(x)}$, then

$$f' = \left(e^{v \log u} \right)' = e^{v \log u} (v \log u)' = u^v \left(v' \log u + v \frac{u'}{u} \right).$$

For example,

$$(x^x)' = x^x \left(\log x + x \frac{1}{x} \right) = x^x (\log x + 1).$$

16. APPLICATIONS OF THE DERIVATIVE

The differential calculus was systematically developed by Newton and Leibnitz, however Archimedes, Fermat, Barrow and many other great mathematicians already used it in some concrete situations. In this lecture we bring just a few of numerous applications without trying to make the arguments completely formal.

16.1. Local linear approximation. Given a function $f : (a, b) \rightarrow \mathbb{R}$ and a point $x_0 \in (a, b)$, we want to find a linear approximation to the function f which will be good in a small neighbourhood of the point x_0 . More precisely, we are looking for the linear function $L(x) = c_0 + c_1(x - x_0)$ such that

$$f(x) = L(x) + o(x - x_0), \quad x \rightarrow x_0.$$

In the limit $x \rightarrow x_0$, we obtain condition: $f(x_0) = L(x_0)$ (of course, if the function f is continuous at x_0 , so let's assume that this is the case), that is $c_0 = f(x_0)$. Then

$$c_1 = \frac{f(x) - f(x_0)}{x - x_0} + o(1),$$

and in the limit we obtain $c_1 = f'(x_0)$ (provided that f is differentiable at x_0). Therefore, the linear function L equals

$$L(x) = f(x_0) + (x - x_0)f'(x_0),$$

and we obtain

$$f(x) = f(x_0) + (x - x_0)f'(x_0) + o(x - x_0), \quad x \rightarrow x_0.$$

Sometimes, the approximate equality

$$f(x) \approx f(x_0) + (x - x_0)f'(x_0)$$

can be used in order to find the numerical value of $f(x)$ if $f(x_0)$ is known. The closer x to x_0 , the better approximation we get. Consider two examples:

If $f(x) = \log x$ and $x_0 = 1$, then we get an approximation for small values of t :

$$\log(1 + t) \approx t$$

which shows, for example, that $\log 1.02 \approx 0.02$ while my calculator gives $\log 1.02 = 0.0198026$.

If $f(x) = \sqrt{x}$ and $x_0 = 100$, then $f(x_0) = 10$, $f'(x_0) = \frac{1}{20}$, so we get

$$\sqrt{100 + t} \approx 10 + \frac{t}{20}.$$

For example, $\sqrt{101} \approx 10.05$, and my calculator gives $\sqrt{101} = 10.049876$.

Exercise 16.1.1. Without using the calculator, find the approximate values of $\tan 44^\circ$ and of $\frac{1}{0.95^{13}}$. Check the results with the calculator.

Later, we'll develop further the idea of this section and find a polynomial $P(x)$ of degree $\leq n$ which locally approximate the function $f(x)$ in the following way:

$$f(x) = P(x) + o((x - x_0)^n), \quad x \rightarrow x_0.$$

16.2. The tangent line. Given a curve γ in the (x, y) -plane and a point $M_0(x_0, y_0)$ on γ , we want to draw through M_0 a tangent line to γ . For that, we consider another point $M_1(x_1, y_1)$ on γ which is sufficiently close to M_0 and draw the straight line Q through these points. The *tangent line* to γ at M_0 is a limiting position of this straight line when the point M_1 moves to M_0 along γ .

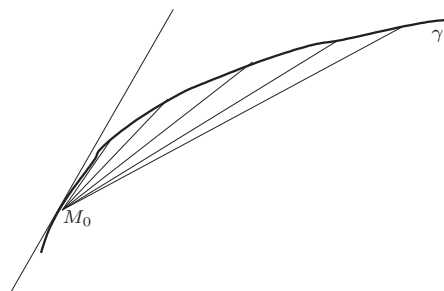


FIGURE 11. The tangent line to the curve γ

Now, assume that the line γ is a graph of the function $f(x)$, and let us find equation of the tangent line. The equation of the straight line Q is

$$y = f(x_0) + \frac{f(x_1) - f(x_0)}{x_1 - x_0}(x - x_0).$$

We see that if existence of the limiting equation as $x_1 \rightarrow x_0$ is equivalent to the differentiability of the function f at x_0 . The limiting equation is

$$y = f(x_0) + f'(x_0)(x - x_0).$$

This is the equation of the tangent line we were after. In particular, we see that the

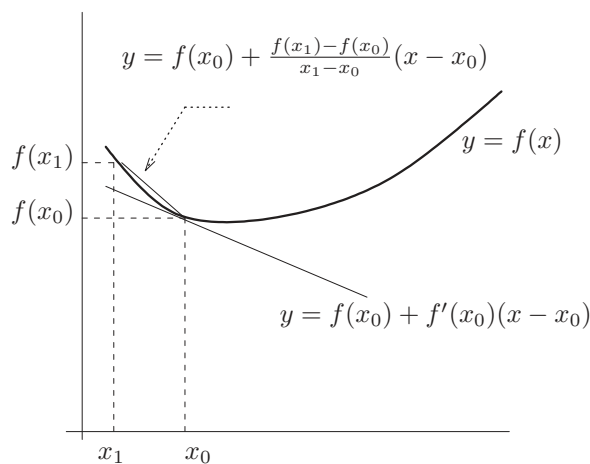


FIGURE 12. The tangent to the graph of the function f

slope of the tangent line at the point x_0 equals $f'(x_0)$.

Example 16.2.1. Let $f(x) = x^2 \sin \frac{1}{x}$ for $x \neq 0$ and $f(0) = 0$. This function is differentiable at the origin, and $f'(0) = \lim_{\epsilon \rightarrow 0} \epsilon \sin \frac{1}{\epsilon} = 0$. We see that the x -axis is the tangent line to the graph of f at the origin. Observe that in this example the graph of f has infinitely many intersections with the tangent line in any neighbourhood of the origin.

Exercise 16.2.2. Find the angles between the graphs of functions $y = 8 - x$ and $y = 4\sqrt{x+4}$ at the point of their intersection.

Exercise 16.2.3. Find the value of parameter a such that the graphs of the functions $y = ax^2$ and $y = \log x$ touch each other (i.e. have a joint tangent line).

16.3. Lagrange interpolation. From high school, we know that there is a unique straight line that passes through given two points in the plane, and we know how to write the equation of this line. Here, we consider a more general problem: *given a set of $n + 1$ points in the plane, $M_j(x_j, y_j)$, $0 \leq j \leq n$, find a polynomial $P(x)$ of degree $\leq n$ whose graph passes all these points; i.e.*

$$(a) \quad P(x_j) = y_j, \quad 0 \leq j \leq n.$$

A natural restriction is that the points x_j must be disjoint: $x_j \neq x_i$ for $j \neq i$.

To solve the problem we define the polynomial

$$Q(x) = (x - x_0)(x - x_1) \dots (x - x_n)$$

of degree n and observe that

$$(b) \quad \lim_{x \rightarrow x_j} \frac{Q(x)}{(x - x_j)Q'(x_j)} = \lim_{x \rightarrow x_j} \frac{Q(x) - Q(x_j)}{(x - x_j)Q'(x_j)} = 1.$$

Now, we can present the solution of the problem:

$$(c) \quad P(x) \stackrel{\text{def}}{=} \sum_{k=0}^n \frac{y_k Q(x)}{(x - x_k)Q'(x_k)}.$$

First of all, observe that P is indeed a polynomial of degree $\leq n$: since $Q(x)$ vanishes at x_k , the polynomial $Q(x)/(x - x_k)$ is a polynomial of degree n , so that P is a sum of $n + 1$ polynomials of degree n , and therefore has degree $\leq n$.

Now, we check that P satisfies conditions (b). When we plug $x = x_j$ in the right hand side of (c), we see that the terms with $k \neq j$ vanish (since the numerator vanishes and the denominator does not). Therefore, the only term with $k = j$ remains on the right hand side. Since this remaining term is a polynomial, it is a continuous function of x , so we can find its value at x_j using (b):

$$P(x_j) = \lim_{x \rightarrow x_j} \frac{y_j Q(x)}{(x - x_j)Q'(x_j)} = y_j.$$

Mention, that the solution P we have found is unique: if there are two solutions P_1 and P_2 satisfying (a), then their difference $P_1 - P_2$ vanishes at all $n + 1$ points x_j . Being a polynomial of degree $\leq n$, it must be the zero function.

It is also worth to mention another form of the formula (c):

$$(d) \quad \frac{P(x)}{Q(x)} = \sum_{k=0}^n \frac{P(x_k)}{(x - x_k)Q'(x_k)}$$

which provides the *partial fraction decomposition* of the rational function P/Q in the case when $\deg P < \deg Q$ and Q has only simple zeroes (the latter condition yields that Q' does not vanish at zeroes of Q).

Exercise 16.3.1 (Newton). Show that for $n \geq 1$

$$\sum_{j=0}^n \frac{x_j^p}{Q'(x_j)} = \begin{cases} 0, & 0 \leq p \leq n-1 \\ 1, & p = n. \end{cases}$$

Hint: in the case $p < n$, apply (d) to $P(x) = x^{p+1}$ and set $x = 0$. In the case $p = n$, apply (d) to $P(x) = x^n$, multiply the formula you get by x , and let $x \rightarrow \infty$.

16.3.1. Appendix: the Horner scheme. In the solution above we used two simple facts which you may not know yet:

16.3.2. If a polynomial Q of degree $n+1$ vanishes at x_j , then $Q(x) = (x - x_j)Q_1(x)$ where Q_1 is a polynomial of degree n .

16.3.3. If a polynomial of degree $\leq n$ vanishes at $n+1$ points, then it must be zero everywhere.

To prove these facts, you should recall the Horner scheme (a fast algorithm of a division of a polynomial by a linear factor) which you've probably known from the high-school. Here it is:

Claim 16.3.4 (Horner's scheme). Consider the polynomial $p(x) = \sum_{k=0}^n p_k x^k$ and the number $c \in \mathbb{R}$. Then there are another polynomial q and a constant $r \in \mathbb{R}$ such that

$$p(x) = (x - c)q(x) + r.$$

Here the degree of q is less than the degree of p by one, and $r = p(c)$.

Proof: We look for q at the form $q(x) = \sum_{k=0}^{n-1} q_k x^k$, we need to find the coefficients q_k . We have

$$p_n x^n + p_{n-1} x^{n-1} + \dots + p_1 x + p_0 = (x - c)(q_{n-1} x^{n-1} + \dots + q_1 x + q_0) + r,$$

which is equivalent to the chain of equations:

$$\begin{aligned} p_n &= q_{n-1} \\ p_{n-1} &= q_{n-2} - cq_{n-1} \\ p_{n-2} &= q_{n-3} - cq_{n-2} \\ &\dots \\ p_1 &= q_0 - cq_1 \\ p_0 &= r - cq_0. \end{aligned}$$

From here, we find one by one the coefficients q_k and the remainder r . □

This yields 16.3.2 and 16.3.3.

Remark 16.3.5. The Horner scheme works without any modifications for polynomials with coefficients in other fields different from \mathbb{R} . For instance, the coefficients p_k and the value c can be rational numbers. Then the polynomial q has rational coefficients and the value $r = p(c)$ is rational as well. Similarly, the coefficients of P might be complex numbers.

17. DERIVATIVES OF HIGHER ORDERS

17.1. Definition and examples. Let f be a function defined in a neighbourhood of a point x . The derivatives of higher orders of f at x are defined recurrently:

$$f''(x) = (f')'(x) = \frac{d^2 f}{dx^2}$$

(the *second order derivative*),

$$f'''(x) = (f'')'(x) = \frac{d^3 f}{dx^3}$$

(the *third order derivative*) etc, and

$$f^{(n)}(x) = (f^{(n-1)})'(x) = \frac{d^n f}{dx^n}$$

(the *derivative of order n*). Sometimes, it is convenient to agree that the zeroth order derivative is f itself: $f^{(0)} = f$, we'll follow this agreement.

Example 17.1.1. Let

$$P(x) = \sum_{k=0}^n c_k x^k$$

be a polynomial of degree n . Then differentiating P , we have:

$$\begin{aligned} P^{(0)}(x) &= P(x), & P(0) &= c_0; \\ P'(x) &= c_1 + 2c_2x + \dots + nc_nx^{n-1}, & P'(0) &= c_1; \\ P''(x) &= 2c_2 + 3 \cdot 2c_3x + \dots + n(n-1)c_nx^{n-2}, & P''(0) &= 2c_2; \\ P'''(x) &= 3 \cdot 2c_3 + \dots + n(n-1)(n-2)c_nx^{n-3}, & P'''(0) &= 3 \cdot 2c_3; \\ &\dots & & \\ P^{(n)}(x) &= n!c_n, & P^{(n)}(0) &= n!c_n; \\ P^{(k)}(x) &= 0, & & \text{for } k > n. \end{aligned}$$

We obtain

$$c_k = \frac{P^{(k)}(0)}{k!}, \quad k \in \mathbb{Z}_+,$$

and

$$P(x) = P(0) + \frac{P'(0)}{1!}x + \frac{P''(0)}{2!}x^2 + \dots + \frac{P^{(n)}(0)}{n!}x^n.$$

From here, we easily get a more general formula

$$P(x) = P(x_0) + \frac{P'(x_0)}{1!}(x - x_0) + \frac{P''(x_0)}{2!}(x - x_0)^2 + \dots + \frac{P^{(n)}(x_0)}{n!}(x - x_0)^n.$$

To prove it, we consider the polynomial $Q(x) = P(x + x_0)$, apply the previous boxed formula to the polynomial $Q(y)$, and then replace y by $x - x_0$.

We'll return to these formulas a bit later when we'll begin the study the Taylor expansion.

Exercise 17.1.2. Let $u(x)$ and $v(x)$ be twice differentiable non-vanishing functions of x , and let

$$g(x) = \log \frac{u(x)}{v(x)}.$$

Find $g''(x)$.

The next table gives expressions for the higher derivatives of some elementary functions. These expressions are of frequent use. The formulas can be easily checked by induction with respect to the order of derivative.

$f(x)$	$f'(x)$	$f''(x)$	...	$f^{(n)}(x)$
a^x	$a^x \log a$	$a^x \log^2 a$	...	$a^x \log^n a$
e^x	e^x	e^x	...	e^x
$\sin x$	$\cos x$	$-\sin x$	...	$\sin\left(x + \frac{n\pi}{2}\right)$
$\cos x$	$-\sin x$	$-\cos x$	...	$\cos\left(x + \frac{n\pi}{2}\right)$
x^μ	$\mu x^{\mu-1}$	$\mu(\mu-1)x^{\mu-2}$	...	$\mu(\mu-1)\dots(\mu-n+1)x^{\mu-n}$
$\log|x|$	$\frac{1}{x}$	$-\frac{1}{x^2}$	...	$(-1)^{n-1}(n-1)!x^{-n}$
$\frac{ax+b}{cx+d}$	$\frac{ad-bc}{(cx+d)^2}$	$-\frac{2c(ad-bc)}{(cx+d)^3}$	...	$\frac{(-1)^{n-1}c^{n-1}n!(ad-bc)}{(cx+d)^{n+1}}$
$\frac{1}{\sqrt{ax+b}}$	$-\frac{a}{2(ax+b)^{3/2}}$	$\frac{a^2 \cdot 3}{2^2(ax+b)^{5/2}}$	...	$\frac{(-1)^n a^n 1 \cdot 3 \cdot \dots \cdot (2n-1)}{2^n (ax+b)^{n+\frac{1}{2}}}$

Exercise 17.1.3. Find

$$\left(\frac{\log x}{x}\right)^{(n)}.$$

Example 17.1.4. Consider the function

$$f(x) = \frac{1}{x^2 - a^2}.$$

First, represent f in the form more convenient for differentiation:

$$f(x) = \frac{1}{2a} \left(\frac{1}{x-a} - \frac{1}{x+a} \right).$$

Making use of this form, we easily find that

$$f^{(n)}(x) = \frac{(-1)^n n!}{2a} \left(\frac{1}{(x-a)^{n+1}} - \frac{1}{(x+a)^{n+1}} \right).$$

Example 17.1.5. Let

$$f(x) = e^{ax} \sin bx.$$

Then

$$\begin{aligned} f'(x) &= ae^{ax} \sin bx + be^{ax} \cos bx \\ &= \sqrt{a^2 + b^2} \left\{ \frac{a}{\sqrt{a^2 + b^2}} \sin bx + \frac{b}{\sqrt{a^2 + b^2}} \cos bx \right\} e^{ax} \\ &= \sqrt{a^2 + b^2} \sin(bx + \varphi) e^{ax}, \end{aligned}$$

where φ is an “auxiliary phase” defined by

$$\sin \varphi = \frac{b}{\sqrt{a^2 + b^2}}, \quad \cos \varphi = \frac{a}{\sqrt{a^2 + b^2}}.$$

Differentiating further, we get

$$f^{(n)}(x) = (a^2 + b^2)^{\frac{n}{2}} \sin(bx + n\varphi) e^{ax}.$$

Functions which have derivatives of *any order* are called *infinitely differentiable*. The elementary functions are usually infinitely differentiable in the domain of definition. The set of infinitely differentiable functions on an interval I is denoted by $C^\infty(I)$.

Example 17.1.6. Consider the function

$$f(x) = \begin{cases} e^{-1/x^2} & \text{for } x \neq 0 \\ 0 & \text{for } x = 0. \end{cases}$$

We show that f is an infinitely differentiable function on \mathbb{R} and that

$$(1) \quad f^{(n)}(x) = \begin{cases} P_n\left(\frac{1}{x}\right) e^{-1/x^2}, & x \neq 0 \\ 0, & x = 0, \end{cases}$$

where $P_n(s)$ is a polynomial of degree $3n$ in s . We shall need a

Claim 17.1.7. For each p , $p < \infty$,

$$\lim_{x \rightarrow 0} x^{-p} e^{-1/x^2} = 0.$$

Proof of the claim: follows by the change of variable: set $t = 1/x^2$, then

$$\lim_{x \rightarrow 0} x^{-p} e^{-1/x^2} = \lim_{t \rightarrow +\infty} t^{p/2} e^{-t} = 0.$$

□

Making use of induction with respect to n , we see that (1) holds for all $n \geq 1$ with $P_0 = 1$ and

$$P_{n+1}(s) = 2s^3 P_n(s) - s^2 P_n'(s), \quad \deg P_{n+1} = \deg P_n + 3.$$

At the origin, using the claim and again the induction with respect to n , we have

$$f^{(n+1)}(0) = \lim_{x \rightarrow 0} \frac{f^{(n)}(x)}{x} = 0$$

This completes the argument. \square

Exercise 17.1.8. Build the non-negative infinitely differentiable function which vanishes outside of the interval $[0, 1]$ but does not vanish identically.

Exercise 17.1.9. Suppose

$$f(x) = \begin{cases} x^{2n} \sin \frac{1}{x} & \text{for } x \neq 0 \\ 0 & \text{for } x = 0. \end{cases}$$

Show that f is n times differentiable at the origin and $f^{(j)}(0) = 0$, $1 \leq j \leq n$. Show that the $n + 1$ -st derivative of f at the origin does not exist.

17.2. The Leibniz rule. We know that the product of two n times differentiable functions is n times differentiable as well. The Leibnitz formula gives an explicit expression for the n -th derivative of the product:

$$(uv)^{(n)} = \sum_{m=0}^n \binom{n}{m} u^{(n-m)} v^{(m)},$$

where, as usual, $\binom{n}{m}$ is the binomial coefficient “ n choose m ”.

Proof: We use induction with respect to n . For $n = 1$ the formula is correct. Suppose it is correct for the n -th derivative, and check its correctness for the $n + 1$ -st derivative:

$$\begin{aligned} (uv)^{(n+1)} &= \left(\sum_{m=0}^n \binom{n}{m} u^{(n-m)} v^{(m)} \right)' \\ &= \sum_{m=0}^n \binom{n}{m} u^{(n-m+1)} v^{(m)} + \sum_{m=0}^n \binom{n}{m} u^{(n-m)} v^{(m+1)} \\ &= u^{(n+1)} v^{(0)} + \sum_{m=1}^n \left(\binom{n}{m} + \binom{n}{m-1} \right) u^{(n+1-m)} v^{(m)} + u^{(0)} v^{(n+1)} \\ &= \sum_{m=0}^{n+1} \binom{n+1}{m} u^{(n+1-m)} v^{(m)}, \end{aligned}$$

completing the argument. \square

Exercise 17.2.1. Find $(x^2 \cos ax)^{(2008)}$.

Example 17.2.2. Find the n -th order derivative of $g(y) = \arctan y$ at $y = 0$. We'll show that

$$g^{(n)}(0) = \begin{cases} 0 & \text{for } n = 2m \\ (-1)^m (2m)! & \text{for } n = 2m + 1. \end{cases}$$

Indeed, since the function $\arctan y$ is odd, its derivatives of even order vanish at the origin (prove!), so we need to find only derivatives of odd orders. We have

$$g'(y)(1 + y^2) = 1.$$

Differentiating this equation $n = 2m$ times and using the Leibnitz rule, we get the recurrence relation

$$(1 + y^2)g^{(n+1)} + 2nyg^{(n)} + n(n-1)g^{(n-1)} = 0.$$

Substituting here $y = 0$, we get

$$g^{(2m+1)}(0) + 2m(2m-1)g^{(2m-1)} = 0.$$

Since $g'(0) = 1$, this yields the result. □

Exercise 17.2.3. Show that

$$\left. \frac{d^n \arcsin y}{dy^n} \right|_{y=0} = \begin{cases} 0 & \text{for } n = 2m \\ ((2m-1)!!)^2 & \text{for } n = 2m+1. \end{cases}$$

Here, $(2m-1)!! = 1 \cdot 3 \cdot 5 \cdot \dots \cdot (2m-1)$.

Hint: use that $(1-y^2)g''(y) - yg'(y) = 0$ for $g(y) = \arcsin y$.

Exercise 17.2.4. Function $y(x)$ satisfies the differential equation $y'' - xy = 0$ with $y(0) = 0$ and $y'(0) = 1$. Find the derivatives of all orders $y^{(n)}(0)$.

**18. BASIC THEOREMS OF THE DIFFERENTIAL CALCULUS:
FERMAT, ROLLE, LAGRANGE**

18.1. Theorems of Fermat and Rolle. Local extrema. We start with a simple

Claim 18.1.1. *Let the function f has the finite derivative at x_0 . If $f'(x_0) > 0$, then there exists a $\delta > 0$ such that*

$$(I) \quad \begin{cases} f(x) > f(x_0) & \text{for } x_0 < x < x_0 + \delta \\ f(x) < f(x_0) & \text{for } x_0 - \delta < x < x_0. \end{cases}$$

If $f'(x_0) < 0$, then

$$(II) \quad \begin{cases} f(x) < f(x_0) & \text{for } x_0 < x < x_0 + \delta \\ f(x) > f(x_0) & \text{for } x_0 - \delta < x < x_0. \end{cases}$$

Proof of the claim: If $f'(x_0) > 0$, using the definition of the limit, we choose a $\delta > 0$ such that

$$\frac{f(x) - f(x_0)}{x - x_0} > 0 \quad \text{for } 0 < |x - x_0| < \delta.$$

This is equivalent to (I). The second case is similar. □

In the case (I) we say that the function f *increases at x_0* , in the case (II) we say that the function f *decreases at x_0* .

Definition 18.1.2. We say that the function f has a *local extremum* at the point x_0 , if one of the following holds:

$$\begin{aligned} f(x) &\leq f(x_0), & \forall x \in U(x_0), \\ f(x) &\geq f(x_0), & \forall x \in U(x_0), \end{aligned}$$

where $U(x_0)$ is a neighbourhood of x_0 . In the first case, we say that f has a local maximum at x_0 , and a local minimum in the second case.

Theorem 18.1.3 (Fermat). *Let a function f be defined in a neighbourhood of a point x_0 , be differentiable at x_0 , and have a local extremum there. Then $f'(x_0) = 0$.*

The proof follows at once from the claim above. □

If $f'(x) = 0$ then the point x is called a *critical point* of the function f . The set of all critical points $\{x: f'(x) = 0\}$ is called sometimes a *stationary set* of the function f .

18.1.1. Classification of local extrema. Vanishing of the derivative is only a necessary condition for the local extremum, for example, consider the function $f(x) = x^3$ in a neighbourhood of the origin. Its derivative vanishes at the origin, but the function does not have a local extremum there.

Note that if f attains its extremal value on the edge of the interval, then the derivative does not have to vanish. For example, consider the identity function $f(x) = x$ on $[-1, 1]$.

The next figure explains how to recognize what happens at critical points.

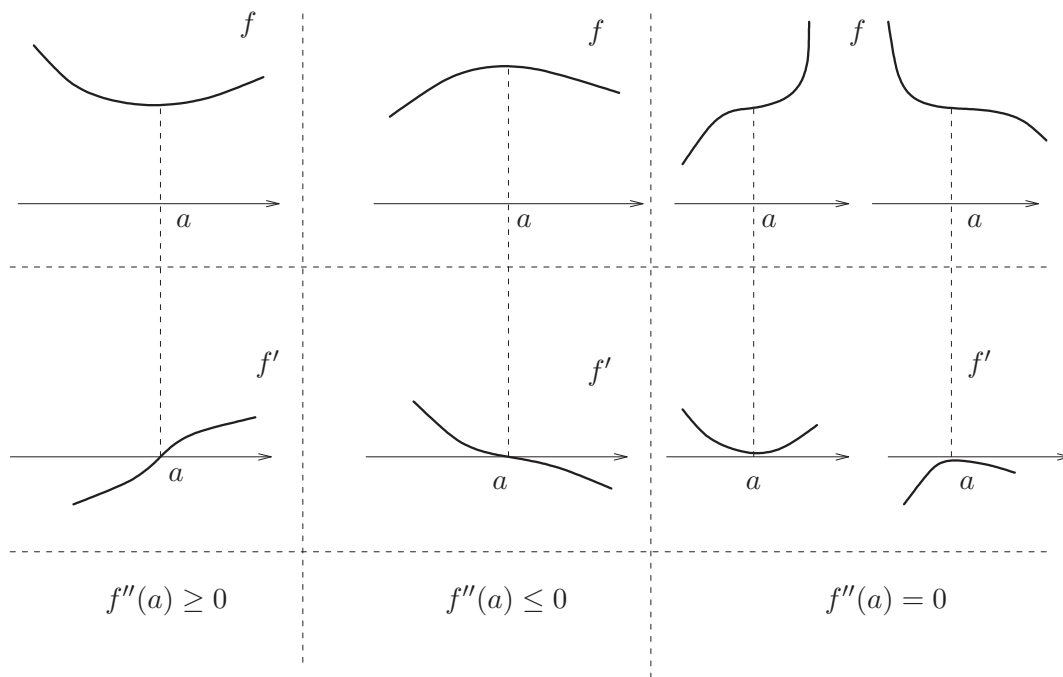


FIGURE 13. Classification of local extrema

Exercise 18.1.4. Find the critical points and their characters for the functions $f(x) = \frac{\log^2 x}{x}$, $x > 0$, and $g(x) = x(x-1)^{1/3}$, $x \in \mathbb{R}$. Sketch the graphs of these functions.

Hint: in the second example, the one-to-one change of variables $t = (x-1)^{1/3}$ simplifies the investigation.

18.1.2. Geometric applications. Now, we give two geometric applications of Fermat's theorem.

Question 18.1.5. Find x such that the rectangle on the following figure has the max-

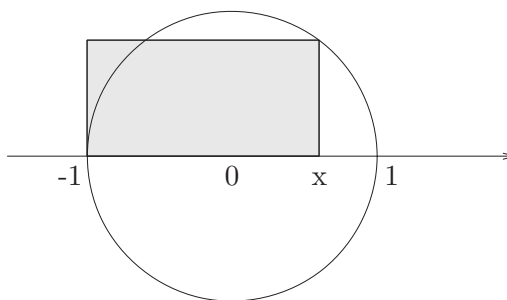


FIGURE 14

imal area (the radius of the circumference equals one).

To solve this question, denote by $S(x)$ the area which we need to maximize. Then $S(x) = (1+x)\sqrt{1-x^2}$. We need to maximize this function for $-1 \leq x \leq 1$. Since it is non-negative and vanishes at the end points $x = \pm 1$, it achieves its maximum at some inner point $x_0 \in (-1, 1)$. Then $S'(x_0) = 0$; i.e.,

$$\sqrt{1-x^2} - \frac{x(x+1)}{\sqrt{1-x^2}} = 0,$$

and we get equation

$$2x^2 + x - 1 = 0$$

with solutions $x_1 = \frac{1}{2}$ and $x_2 = -1$. The second root is irrelevant for us, and we see that the function S achieves its maximal value $\frac{3\sqrt{3}}{4}$ at the point $x = \frac{1}{2}$. \square

In the second application, we prove the Snellius Law of Refraction. Recall that Fermat's *principle of least action* in optics says that the path of a light ray is determined by the property that the time the light takes to go from point A to point B under the given condition must be the least possible.

Question 18.1.6 (The Law of Refraction). Given two points A and B on the opposite sides of the x -axis. Find the path from A to B that requires the shortest possible time if the velocity on one side of the x -axis is a and on the other side is b .

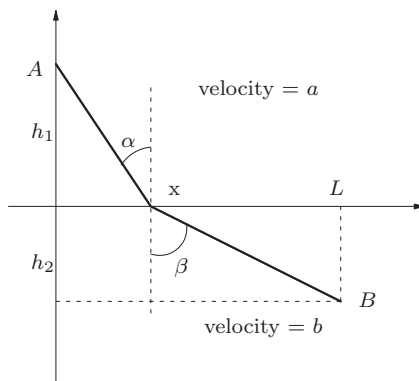


FIGURE 15. Law of refraction

If the light intersects the real axis at x , then the time it takes to go from A to B equals

$$T(x) = \frac{1}{a} \sqrt{h_1^2 + x^2} + \frac{1}{b} \sqrt{h_2^2 + (L-x)^2}.$$

We are looking for the minimum of this function. We have

$$T'(x) = \frac{1}{a} \frac{x}{\sqrt{h_1^2 + x^2}} - \frac{1}{b} \frac{L-x}{\sqrt{h_2^2 + (L-x)^2}}.$$

This function vanishes for

$$\frac{1}{a} \underbrace{\frac{x}{\sqrt{h_1^2 + x^2}}}_{=\sin \alpha} = \frac{1}{b} \underbrace{\frac{L-x}{\sqrt{h_2^2 + (L-x)^2}}}_{=\sin \beta}.$$

Hence, the answer:

$$\frac{\sin \alpha}{\sin \beta} = \frac{a}{b}.$$

It is easy to see that we've indeed found the minimum of T . For instance, since $T''(x) > 0$ everywhere (**check!**).

Hairer and Wanner write in their book (p. 93) that Fermat himself found the problem too difficult for analytical treatment, and that the computations were performed by Leibniz.

18.1.3. Rolle's theorem and its applications.

Theorem 18.1.7 (Rolle). *Let the function f be continuous on the closed interval $[a, b]$, be differentiable on the open interval (a, b) , and let $f(a) = f(b)$. Then there exists a point $c \in (a, b)$ such that $f'(c) = 0$.*

Proof: By the Weierstrass theorem, the continuous function f in the closed interval $[a, b]$ attains its maximal and minimal values:

$$f(x_{\min}) = \min_{x \in [a, b]} f(x), \quad f(x_{\max}) = \max_{x \in [a, b]} f(x).$$

Consider two cases:

(i) First, assume that $\min_{[a, b]} f = \max_{[a, b]} f$. Then f is the constant function and $f' = 0$ everywhere.

(ii) Now, suppose that $\min_{[a, b]} f \neq \max_{[a, b]} f$. Then at least one of the points x_{\min} , x_{\max} must belong to the *open* interval (a, b) , and by the Fermat theorem, the derivative of f vanishes at this point. \square

Exercise 18.1.8. Suppose f is a differentiable function on \mathbb{R} such that

$$\lim_{x \rightarrow -\infty} f(x) = \lim_{x \rightarrow +\infty} f(x) = 0.$$

Show that there exists a point $c \in \mathbb{R}$ such that $f'(c) = 0$.

Usually, counting zeroes of smooth functions, we are taking into account their *multiplicities*: if

$$f(c) = f'(c) = \dots = f^{(n-1)}(c) = 0, \quad \text{but } f^{(n)}(c) \neq 0,$$

then we say that f has zero of multiplicity n at c . If $n = 1$, we say that c is a *simple* zero of f . For example, the function $x \mapsto x^n$ ($n \in \mathbb{N}$) has zero of multiplicity n at the origin. The function $e^x - 1 - x$ has zero of multiplicity 2 at the origin.

Exercise 18.1.9. Construct a function the has zero of multiplicity m at $x = 0$ and n at $x = 1$. Construct a function the has zeroes of multiplicity 2 at each integer point.

Exercise 18.1.10.

i. (extension of Rolle's theorem)

Show that if the function f is continuous on the closed interval $[a, b]$, n times differentiable on the open interval (a, b) , and has $n + 1$ zeroes in (a, b) , then its n -th derivative has at least one zero in the open interval (a, b) .

ii. Show that if a polynomial P of degree n has n real zeroes, then its derivative has $n - 1$ real zeroes.

iii. Show that if a polynomial of degree n has at least $n + 1$ real zeroes, then it vanishes identically.

Problem 18.1.11. For non-zero c_1, c_2, \dots, c_n , and for pairwise distinct $\alpha_1, \alpha_2, \dots, \alpha_n$, prove that the equation

$$c_1x^{\alpha_1} + c_2x^{\alpha_2} + \dots + c_nx^{\alpha_n} = 0$$

has at most $n - 1$ zeroes in $(0, +\infty)$, and that the equation

$$c_1e^{\alpha_1s} + c_2e^{\alpha_2s} + \dots + c_ne^{\alpha_ns} = 0$$

has at most $n - 1$ real zeroes.

Hint: use induction with respect to n .

This bookkeeping can be made more accurate:

Problem* 18.1.12 (Descartes' sign rule). If $\alpha_1 < \alpha_2 < \dots < \alpha_n$, then the number of positive zeroes of the function

$$f(x) = \sum_{j=1}^n c_j x^{\alpha_j}$$

(with their multiplicities) does not exceed the number of changes of signs in the sequence of coefficients c_1, c_2, \dots, c_n .

18.2. Mean-value theorems.

Theorem 18.2.1 (Lagrange's mean value theorem). *Let the function f be continuous on the closed interval $[a, b]$ and differentiable on the open interval (a, b) . Then there is a point $c \in (a, b)$ such that*

$$f(b) - f(a) = f'(c)(b - a).$$

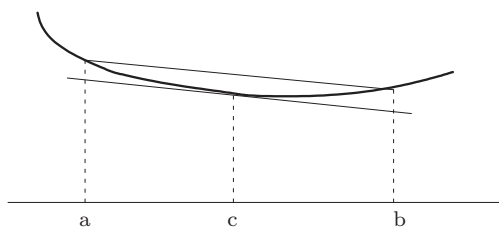


FIGURE 16. Lagrange's MVT

Proof: Notice, that in the special case $f(b) = f(a)$ the result coincides with the Rolle theorem. Now, using this special case we prove the general one. For this, define a linear function $L(x)$ that interpolates the values of f at the end-points:

$$L(x) = f(a) + \frac{f(b) - f(a)}{b - a}(x - a),$$

and set

$$F(x) = f(x) - L(x).$$

We have $F(a) = F(b) = 0$, so the Rolle theorem can be applied to F . We get an intermediate point $c \in (a, b)$ such that $F'(c) = 0$, or

$$f'(c) = L'(c) = \frac{f(b) - f(a)}{b - a},$$

completing the proof. \square

Corollary 18.2.2.

If the function f is differentiable on an open interval (a, b) and has a positive derivative there, then f is strictly increasing. If f' is negative, then f is strictly decreasing. If f' is non-negative, then f does not decrease, and if f' is not positive, then f does not increase.

If $f' \equiv 0$ on (a, b) , then f is a constant function.

If f is n times differentiable and $f^{(n)} \equiv 0$, then f is a polynomial of degree $n - 1$ or less.

Corollary 18.2.3. *If f is a differentiable function, and $f' = f$. Then $f(x) = Ce^x$ (C is a constant).*

Proof: Consider the function $F(x) = f(x)e^{-x}$. Then $F'(x) = f'(x)e^{-x} - f(x)e^{-x} = 0$, therefore, F is a constant function. \square

We've just learnt how to solve the simplest differential equations. The next problem looks more complicated (but in a year, after the course of ordinary differential equations you will recall it with a smile).

Problem 18.2.4. Let f be a twice differentiable function such that $f'' + f = 0$. Show that $f(x) = C_1 \sin x + C_2 \cos x$ where C_1 and C_2 are constants.

Hint: Let $g'' + g = 0$. Multiply the equation by $2g'$, deduce that $(g'^2 + g^2)' = 0$, hence $g'^2 + g^2$ is the constant function. Apply this to the function $g(x) = f(x) - (C_1 \sin x + C_2 \cos x)$ with appropriate C_1 and C_2 .

Exercise 18.2.5. Suppose f is a differentiable function on $[0, +\infty)$, $f(0) = 1$, and $f' \geq f$ everywhere. Show that $f(x) \geq e^x$ for $x \geq 0$.

Exercise 18.2.6. Let $f: (0, +\infty) \rightarrow \mathbb{R}$ be a twice differentiable function, such that $f''(x) > 0$ everywhere. Prove that for each $x > 0$,

$$f(2x) - f(x) < f(3x) - f(2x).$$

Exercise 18.2.7. Let the function f be defined on the interval I , and for some $\alpha > 1$ and $K < \infty$ satisfy

$$|f(x) - f(y)| \leq K|x - y|^\alpha, \quad \forall x, y \in I.$$

Then f is a constant function.

Problem 18.2.8. Prove that if f is an unbounded differentiable function on an interval (a, b) , then its derivative f' is also unbounded.

Whether the converse is true?

Problem 18.2.9. Prove that if f is a differentiable function on an interval (a, b) (finite or infinite) with the bounded derivative, then f is uniformly continuous on this interval.

Whether the converse is true; i.e. whether the uniformly continuous differentiable function must have a bounded derivative?

Note that the pointwise existence of f' does not guarantee that f' is continuous. For instance, the function

$$f(x) = \begin{cases} x^2 \sin(1/x), & x \neq 0, \\ 0, & x = 0 \end{cases}$$

is differentiable everywhere on \mathbb{R} , while its derivative

$$f'(x) = \begin{cases} 2x \sin(1/x) - \cos(1/x), & x \neq 0, \\ 0, & x = 0 \end{cases}$$

is discontinuous at the origin. Nevertheless, as the next theorem shows, the derivatives, like continuous functions, always possess the intermediate value property.

Theorem 18.2.10 (Darboux). *Let the function f be differentiable everywhere in the segment $[a, b]$. Then f' attains every intermediate value between $f'(a)$ and $f'(b)$.*

Proof: Suppose that $f'(a) < f'(b)$ and fix y such that $f'(a) < y < f'(b)$. By the definition of the derivative, we can find $h > 0$, such that

$$\frac{f(a+h) - f(a)}{h} < y, \quad \frac{f(b) - f(b-h)}{h} > y.$$

Define the function $g: [a, b-h] \rightarrow \mathbb{R}$,

$$g(t) \stackrel{\text{def}}{=} \frac{f(t+h) - f(t)}{h}, \quad g \in C[a, b-h].$$

Then $g(a) < y < g(b)$ and by the intermediate value property of continuous functions, there exists a point $c \in (a, b-h)$ such that

$$y = g(c) = \frac{f(c+h) - f(c)}{h}.$$

It remains to apply Lagrange's theorem (which does not require continuity of the derivative). By this theorem, there exists $x \in (c, c+h)$ such that $f(c+h) - f(c) = f'(x)h$. Then $f'(x) = g(c) = y$, completing the proof. \square

The next theorem slightly generalizes Lagrange's theorem:

Theorem 18.2.11 (Cauchy's extended mean value theorem). *Let f and g be continuous functions on $[a, b]$ differentiable in the open interval (a, b) . Then there exists a point $c \in (a, b)$ such that*

$$f'(c)[g(b) - g(a)] = g'(c)[f(b) - f(a)].$$

If $g' \neq 0$ on (a, b) , then $g(b) \neq g(a)$, and

$$\frac{f(b) - f(a)}{g(b) - g(a)} = \frac{f'(c)}{g'(c)}.$$

Proof: Notice, that if $g(x) = x$ then we get the previous result. The strategy of the proof is similar: define an auxiliary function

$$F(x) = f(x)[g(b) - g(a)] - g(x)[f(b) - f(a)].$$

We have $F(b) = F(a) = f(a)g(b) - f(b)g(a)$, and applying the Rolle theorem, we get the result. \square

Problem* 18.2.12.

i. Suppose f is infinitely differentiable function on the real axis such that

$$\forall x \in \mathbb{R} \quad \exists n \in \mathbb{Z}_+ \quad \forall m \geq n \quad f^{(m)}(x) = 0.$$

Then f is a polynomial.

ii. Suppose f is infinitely differentiable function on the real axis such that

$$\forall x \in \mathbb{R} \quad \exists n \in \mathbb{Z}_+ \quad f^{(n)}(x) = 0.$$

Then f is a polynomial.

19. APPLICATIONS OF FUNDAMENTAL THEOREMS

19.1. L'Hospital's rule. Here we bring a theorem which in many cases simplifies calculation of limits of the form " $\frac{0}{0}$ " and " $\frac{\infty}{\infty}$ ".

Theorem 19.1.1. Let $-\infty \leq a < b \leq +\infty$. Let f and g be differentiable functions defined on an interval (a, b) , and $g' \neq 0$ on (a, b) . Suppose that

$$(19.1.2) \quad \lim_{x \downarrow a} \frac{f'(x)}{g'(x)} = L \quad (-\infty \leq L \leq +\infty),$$

and that either

$$(19.1.3) \quad \lim_{x \downarrow a} f(x) = \lim_{x \downarrow a} g(x) = 0,$$

or

$$(19.1.4) \quad \lim_{x \downarrow a} |g(x)| = +\infty.$$

Then

$$(19.1.5) \quad \lim_{x \downarrow a} \frac{f(x)}{g(x)} = L.$$

Remarks:

(i) the same result holds for $x \uparrow b$;

(ii) it may look strange that in the case " $\frac{\infty}{\infty}$ " we required only that $|g(x)| = +\infty$ and have not said anything about the limiting value $f(a)$. However, as we will see in the proof, in this case, the assumptions of the theorem yield that $|f(a)| = \infty$.

Proof of l'Hospital's rule: Since $g' \neq 0$, by Darboux's theorem 18.2.10, either everywhere $g' > 0$, or everywhere $g' < 0$. We suppose that $g' > 0$ everywhere in (a, b) ; i.e., that the function $g(x)$ (strictly) increases with x . Therefore, by Cauchy's extended mean value theorem 18.2.11, that

$$(19.1.6) \quad \exists u \in (s, t) \quad \text{such that} \quad \frac{f(t) - f(s)}{g(t) - g(s)} = \frac{f'(u)}{g'(u)}.$$

We consider separately two cases: $L \in \mathbb{R}$ and $L = \pm\infty$. Each of these cases will have two subcases depending on the type of the uncertainty we deal with (" $\frac{0}{0}$ " or " $\frac{\infty}{\infty}$ ").

1st case: $L \in \mathbb{R}$. Fix $\epsilon > 0$. By (19.1.2),

$$\exists c \in (a, b) \quad \forall u \in (a, c) \quad L - \epsilon < \frac{f'(u)}{g'(u)} < L + \epsilon.$$

Then, by (19.1.6), we have

$$(19.1.7) \quad L - \epsilon < \frac{f(t) - f(s)}{g(t) - g(s)} < L + \epsilon,$$

provided that $a < s < t \leq c$.

Subcase 1a: “ $\frac{0}{0}$ ” uncertainty. Suppose that condition (19.1.3) holds. Letting $s \downarrow 0$ in (19.1.7), we get

$$L - \epsilon < \frac{f(t)}{g(t)} < L + \epsilon,$$

provided that $a < t < c$, whence, (19.1.5).

Subcase 1b: “ $\frac{\infty}{\infty}$ ” uncertainty. Now, we suppose that condition (19.1.4) holds. Since the function g increases, this means that $g(s) \downarrow -\infty$ when $s \downarrow a$. Choose $t \in (a, c)$ such that $g(t) < 0$. Then $g(s) < 0$ for $a < s < t$. Multiplying (19.1.7) $(g(s) - g(t))/g(s) > 0$, we get

$$(L - \epsilon) \left(1 - \frac{g(t)}{g(s)}\right) < \frac{f(s) - f(t)}{g(s)} < (L + \epsilon) \left(1 - \frac{g(t)}{g(s)}\right).$$

Given t , we find $d \in (a, t)$ such that

$$\left|\frac{f(t)}{g(s)}\right| < \epsilon \quad \text{and} \quad \frac{g(t)}{g(s)} < \epsilon \quad \text{for } a < s < d,$$

we get

$$(L - \epsilon)(1 - \epsilon) - \epsilon < \frac{f(s)}{g(s)} < (L + \epsilon)(1 + \epsilon) + \epsilon, \quad \text{for } a < s < d.$$

Therefore, $f(s)/g(s)$ tends to L as $s \downarrow a$.

2nd case: $L = \pm\infty$. Now, we briefly consider the case $L = +\infty$ (the case $L = -\infty$ is similar). Fix an arbitrarily large positive M . By (19.1.2),

$$\exists c \in (a, b) \quad \forall u \in (a, c) \quad \frac{f'}{g'}(u) > M.$$

Then, by (19.1.6),

$$\frac{f(t) - f(s)}{g(t) - g(s)} > M \quad \text{for } a < s < t < c.$$

The rest is very similar to the same case, and we leave to check the details to the students. \square

Examples:

i.

$$\lim_{x \rightarrow 0} \frac{\tan x - x}{x - \sin x} = \lim_{x \rightarrow 0} \frac{\frac{1}{\cos^2 x} - 1}{1 - \cos x} = \lim_{x \rightarrow 0} \frac{1}{\cos^2 x} \frac{1 - \cos^2 x}{1 - \cos x} = 2.$$

ii.

$$\begin{aligned} \lim_{x \rightarrow 0} \left(\frac{1}{x^2} - \cot^2 x \right) &= \lim_{x \rightarrow 0} \frac{\sin^2 x - x^2 \cos^2 x}{x^2 \sin^2 x} \\ &= \lim_{x \rightarrow 0} \frac{\sin x + x \cos x}{\sin x} \cdot \lim_{x \rightarrow 0} \frac{\sin x - x \cos x}{x^2 \sin x} \\ &= 2 \cdot \lim_{x \rightarrow 0} \frac{x \sin x}{2x \sin x + x^2 \cos x} = \frac{2}{3}. \end{aligned}$$

iii. Consider the limit

$$\lim_{x \rightarrow \infty} \frac{x + \sin x}{x - \sin x}.$$

This is a “ $\frac{\infty}{\infty}$ ”-type limit which equals 1 since

$$\frac{x + \sin x}{x - \sin x} = \frac{1 + \sin x/x}{1 - \sin x/x} = \frac{1 + o(1)}{1 + o(1)}, \quad x \rightarrow \infty.$$

On the other hand, differentiating the numerator and denominator, we get an expression

$$\frac{1 + \cos x}{1 - \cos x}$$

which obviously has no limit as $x \rightarrow \infty$.

Exercise 19.1.8. Find the limits

$$\lim_{x \rightarrow 0} \frac{a^x + a^{-x} - 2}{x^2} \quad (a > 0), \quad \lim_{x \rightarrow 0} \frac{a^x - b^x}{c^x - d^x} \quad (c \neq d).$$

Problem 19.1.9. Prove that if f is differentiable on $(a, +\infty)$ and

$$\lim_{x \rightarrow +\infty} f'(x) = 0,$$

then $f(x) = o(x)$ when $x \rightarrow +\infty$.

Problem 19.1.10. Prove that if the function f has the second derivative at x , then

$$f''(x) = \lim_{h \rightarrow 0} \frac{f(x+h) + f(x-h) - 2f(x)}{h^2}.$$

Whether existence of the limit on the right hand side yields existence of the second derivative of f at x ?

19.2. Appendix: Algebraic numbers. Lagrange’s MVT has a nice application in the algebraic number theory.

Definition 19.2.1. The number $t \in \mathbb{R}$ is *algebraic* if there exist $a_0, a_1, \dots, a_n \in \mathbb{Z}$, $a_n \neq 0$, with

$$\sum_{j=0}^n a_j t^j = 0.$$

The *degree* of the algebraic number t is the least possible n with this property.

The number $t \in \mathbb{R}$ is *transcendental* if it is not algebraic.

For instance, the rational numbers are algebraic numbers of degree 1, $\sqrt{2}$ is an algebraic number of degree 2. The number $10^{3/17}$ is also algebraic.

Note that if a rational number satisfies some algebraic equation with rational coefficients, then it satisfies another equation of the same degree with integer coefficients and hence is algebraic.

The first question is natural: *do the transcendental numbers exist?*

Exercise 19.2.2 (Cantor). The set of algebraic numbers is countable. Hence, the transcendental numbers exist.

Unfortunately, this neat argument does not give us explicit examples of transcendental numbers.

Theorem 19.2.3 (Liouville). *Suppose t is an algebraic number of degree $n \geq 2$. Then there exist a positive constant c (depending on t) such that*

$$\left|t - \frac{p}{q}\right| \geq \frac{c}{q^n}$$

for any $p, q \in \mathbb{Z}$.

The theorem says that algebraic numbers are badly approximated by the rational ones.

Proof: We assume that $\left|t - \frac{p}{q}\right| < 1$ (otherwise, any $c \leq 1$ works).

Suppose that $P(x) = \sum_{j=0}^n a_j x^j$ is a polynomial of degree n with integer coefficients such that $P(t) = 0$.

Claim 19.2.4. *The polynomial P cannot have rational roots.*

Proof of Claim: Indeed, suppose that $P\left(\frac{p}{q}\right) = 0$. Then

$$P(x) = P(x) - P\left(\frac{p}{q}\right) = \left(x - \frac{p}{q}\right)Q(x)$$

where Q is a polynomial with *rational* coefficients of degree $n - 1$. Since

$$Q(t) = \frac{P(t)}{t - p/q} = 0$$

we arrive at the contradiction (t cannot satisfy an algebraic equation of degree less than n). This proves the claim. \square

The claim yields that, for any integers p and q , the number $P(p/q)$ is a non-zero rational number of the form r/q^n with integer $r \neq 0$. Hence

$$\left|P\left(\frac{p}{q}\right)\right| \geq \frac{1}{q^n}.$$

Now, we have

$$\frac{1}{q^n} \leq \left|P\left(\frac{p}{q}\right)\right| = \left|P\left(\frac{p}{q}\right) - P(t)\right| \stackrel{\text{MVT}}{=} \left|\frac{p}{q} - t\right| |P'(\xi)|.$$

The point ξ lies in the interval with the end-points at t and p/q , hence, it belongs to the larger interval $(t - 1, t + 1)$. Denoting by M the maximum of $|P'|$ over the closed interval $[t - 1, t + 1]$, we get

$$\frac{1}{Mq^n} \leq \left|\frac{p}{q} - t\right|.$$

Hence, the result. \square

The numbers $t \in \mathbb{R}$ such that

$$\forall n \geq 2 \quad \exists \frac{p}{q} \in \mathbb{Q} \quad \left|t - \frac{p}{q}\right| \leq \frac{1}{q^n}$$

are called the *Liouville numbers*. The Liouville theorem says that they are transcendental.

Example 19.2.5. The number

$$t = \sum_{k=1}^{\infty} \frac{1}{10^{k!}}$$

is the Liouville number.

Indeed, let

$$\frac{p}{q} = \sum_{k=1}^n \frac{1}{10^{k!}}.$$

Then $q = 10^{n!}$, and

$$0 < t - \frac{p}{q} = \sum_{k=n+1}^{\infty} \frac{1}{10^{k!}} < \frac{2}{10^{(n+1)!}},$$

while

$$\frac{1}{q^n} = \frac{1}{10^{n \cdot n!}}.$$

Since $10^{n!} > 2$ (sic!), we have

$$10^{(n+1)!} = (10^{n!})^{n+1} > 2 \cdot 10^{n \cdot n!},$$

i.e.,

$$0 < t - \frac{p}{q} < \frac{1}{q^n}.$$

Done! □

It is worth mentioning that the numbers e and π are transcendental but the proofs are not so simple (they are due to Hermite and Lindemann) and they were found *after* Liouville proved his theorem.

20. INEQUALITIES

Here, we show how the differential calculus helps to prove useful inequalities.

20.1. $\frac{2}{\pi}x \leq \sin x \leq x$, $0 \leq x \leq \frac{\pi}{2}$. The right inequality we already know. In order to prove the left inequality, consider the function

$$\varphi(x) = \frac{\sin x}{x}, \quad 0 \leq x \leq \frac{\pi}{2}.$$

We have

$$\varphi'(x) = \frac{x \cos x - \sin x}{x^2} = \frac{\cos x}{x^2}(x - \tan x).$$

Since $x \leq \tan x$ on the interval $[0, \frac{\pi}{2})$, $\varphi'(x) \leq 0$. Therefore, the function φ does not increase, and

$$\varphi(x) \geq \varphi\left(\frac{\pi}{2}\right) = \frac{2}{\pi},$$

proving the inequality. □

Exercise 20.1.1. Show that the equality signs attains only at the end-points $x = 0$ and $x = \frac{\pi}{2}$.

Exercise 20.1.2. Show that

$$\pi < \frac{\sin \pi x}{x(1-x)} \leq 4$$

for $0 < x < 1$.

20.2. $\frac{x}{1+x} < \log(1+x) < x$, $x > -1$, $x \neq 0$. In order to prove the right inequality, consider the function $\psi(x) = \log(1+x) - x$. Its derivative equals

$$\psi'(x) = \frac{1}{1+x} - 1 = -\frac{x}{1+x}.$$

Therefore, the function ψ increases on $(-1, 0)$, has a local maximum at $x = 0$ and decreases for $x > 0$. At the end-points it equals $-\infty$:

$$\lim_{x \downarrow -1} \psi(x) = \lim_{x \uparrow +\infty} \psi(x) = -\infty.$$

So that, the function ψ attains its global maximum at the origin, and hence $\log(1+x) < x$ for $x > -1$, $x \neq 0$.

To prove the left inequality, we set

$$\psi(x) = \log(1+x) - \frac{x}{1+x}.$$

In this case,

$$\psi'(x) = \frac{1}{1+x} - \frac{1}{(1+x)^2} = \frac{x}{(1+x)^2}.$$

Now, ψ' is positive for $x > 0$, vanishes at the origin and is negative for $-1 < x < 0$. Therefore, ψ decreases for $-1 < x < 0$ and increases for $x > 0$. The limiting values of ψ equals $+\infty$:

$$\lim_{x \downarrow -1} \psi(x) = \lim_{x \uparrow +\infty} \psi(x) = +\infty.$$

So that, ψ attains its global minimum at the origin, and

$$\log(1+x) > \frac{x}{1+x}, \quad x > -1, \quad x \neq 0,$$

completing the argument. □

Exercise 20.2.1. Show that

$$\frac{a-b}{a} < \log \frac{a}{b} < \frac{a-b}{b}$$

for positive a and b .

The inequality we proved has an interesting application:

Corollary 20.2.2. *There exists the limit*

$$\gamma = \lim_{n \rightarrow \infty} \left(\sum_{j=1}^n \frac{1}{j} - \log n \right).$$

The constant γ is called the Euler constant. Its approximate value is $\gamma \approx 0.5772$.

Proof of Corollary: Consider the series

$$(S) \quad \sum_{j=1}^{\infty} \left(\frac{1}{j} - \log \frac{j+1}{j} \right).$$

We'll show that the terms of this series are positive and that the series is convergent.

Indeed,

$$\frac{1}{j+1} = \frac{1/j}{1+1/j} < \log \left(1 + \frac{1}{j} \right) < \frac{1}{j},$$

so that

$$0 < \frac{1}{j} - \log \left(1 + \frac{1}{j} \right) < \frac{1}{j} - \frac{1}{j+1} < \frac{1}{j^2},$$

and the series (S) converges since the series $\sum_{j \geq 1} \frac{1}{j^2}$ is convergent.

Denote by γ the sum of the series S . Then

$$\begin{aligned} \sum_{j=1}^n \frac{1}{j} &= \sum_{j=1}^n \left(\frac{1}{j} - \log \frac{j+1}{j} \right) + \log(n+1) \\ &= \gamma + o(1) + \log n + o(1) = \gamma + \log n + o(1), \quad n \rightarrow \infty, \end{aligned}$$

proving the corollary. □

20.3. Bernoulli's inequalities. We prove that for $x > 0$

$$\begin{aligned} x^\alpha - \alpha x &\leq 1 - \alpha, & 0 < \alpha < 1, \\ x^\alpha - \alpha x &\geq 1 - \alpha, & \alpha < 0, \text{ or } \alpha > 1, \end{aligned}$$

with strong inequalities for $x \neq 1$.

Consider the function

$$f(x) = x^\alpha - \alpha x + \alpha - 1, \quad x > 0.$$

Then $f'(x) = \alpha(x^{\alpha-1} - 1)$. If $0 < \alpha < 1$, then f' is positive on $(0, 1)$, vanishes at $x = 1$ and is negative for $x > 1$, and the limiting values of f are negative:

$$f(+0) = \alpha - 1 < 0,$$

$$\lim_{x \rightarrow +\infty} f(x) = -\infty.$$

So that

$$f(x) < f(1) = 0, \quad \text{for } x > 0, \quad x \neq 1.$$

Similarly, if $\alpha < 0$ or $\alpha > 1$, f decreases on $(0, 1)$ and increases on $(1, +\infty)$, and the limiting values of f are positive. So that, in this case

$$f(x) > f(1) = 0, \quad \text{for } x > 0, \quad x \neq 1,$$

completing the proof. \square

Exercise 20.3.1. Prove inequalities:

$$x^m(1-x)^n \leq \frac{m^m n^n}{(m+n)^{m+n}}, \quad m, n > 0, \quad 0 \leq x \leq 1,$$

$$(x+1)2^{-\frac{n-1}{n}} \leq (x^n+1)^{\frac{1}{n}} \leq x+1, \quad n \geq 1, \quad x > 0.$$

Exercise 20.3.2. Prove that equation $\log x = cx$

- (i) has no solutions if $c > \frac{1}{e}$;
- (ii) has a unique solution if $c = \frac{1}{e}$ or if $c \leq 0$;
- (iii) has two solutions if $0 < c < \frac{1}{e}$.

Exercise 20.3.3. Prove that equation $\log(1+x^2) = \arctan x$ has two real solutions.

20.4. Young's inequality. Here, we prove that

$$(Y) \quad ab \leq \frac{a^p}{p} + \frac{b^q}{q},$$

for $a, b > 0$, $\frac{1}{p} + \frac{1}{q} = 1$, $p, q > 1$, and the equality sign attains for $a^p = b^q$ only.

Introduce the function

$$h(a) = ab - \frac{a^p}{p}.$$

Then

$$h'(a) = b - a^{p-1}.$$

We see that

$$h'(a) \begin{cases} > 0, & \text{for } a < b^{1/(p-1)} \\ = 0, & \text{for } a = b^{1/(p-1)} \\ < 0, & \text{for } a > b^{1/(p-1)}. \end{cases}$$

Therefore,

$$h(a) \leq h\left(b^{1/(p-1)}\right) = b^{1+\frac{1}{p-1}} - \frac{b^{\frac{p}{p-1}}}{p} = \frac{b^q}{q},$$

and the equality sign attains only when $a = b^{1/(p-1)}$. This proves the statement. \square

If $p > 1$, the value $q = \frac{p}{p-1}$ is called sometimes the *dual* to p . I.e., if p and q are dual to each other, then $\frac{1}{p} + \frac{1}{q} = 1$.

Exercise 20.4.1. Prove the inequality

$$ab \leq e^a + b \log \frac{b}{e}, \quad a, b > 0.$$

20.5. Hölder's inequality. The Hölder inequality says that

$$(H) \quad \sum_{j=1}^n x_j y_j \leq \left(\sum_{j=1}^n x_j^p \right)^{1/p} \left(\sum_{j=1}^n y_j^q \right)^{1/q}$$

provided that $x_j, y_j \geq 0$, $p, q > 1$ and $\frac{1}{p} + \frac{1}{q} = 1$, with the equality sign only in the case when

$$\frac{x_j^p}{y_j^q} = \text{const}, \quad 1 \leq j \leq n.$$

When $p = q = 2$, with get the Cauchy-Schwarz inequality

$$\sum_{j=1}^n x_j y_j \leq \left(\sum_{j=1}^n x_j^2 \right)^{1/2} \left(\sum_{j=1}^n y_j^2 \right)^{1/2}.$$

Proof of (H): Set

$$X = \left(\sum_{j=1}^n x_j^p \right)^{1/p}, \quad Y = \left(\sum_{j=1}^n y_j^q \right)^{1/q}.$$

Applying the Young inequality (Y), we get

$$\frac{x_j}{X} \cdot \frac{y_j}{Y} \leq \frac{1}{p} \frac{x_j^p}{X^p} + \frac{1}{q} \frac{y_j^q}{Y^q}, \quad 1 \leq j \leq n.$$

Adding these inequalities, we obtain

$$\frac{1}{X \cdot Y} \sum_{j=1}^n x_j y_j \leq \frac{1}{p} \cdot 1 + \frac{1}{q} \cdot 1 = 1,$$

which yields (H).

There is the equality sign in (H) if and only if for each j we applied (Y) with the equality sign, that is

$$\left(\frac{x_j}{X} \right)^p = \left(\frac{y_j}{Y} \right)^q,$$

or setting $\lambda = X^p/Y^q$, we obtain

$$x_j^p = \lambda y_j^q, \quad 1 \leq j \leq n,$$

completing the argument. □

Exercise 20.5.1. Let $p > 1$, $q < 1$, and $\frac{1}{p} + \frac{1}{q} = 1$. Let $x_i > 0$, $y_i > 0$, and let the series $\sum_i x_i^p$ and $\sum_i y_i^q$ converge. The the series $\sum_i x_i y_i$ also converges and its sum does not exceed the product

$$\left(\sum_i x_i^p \right)^{1/p} \cdot \left(\sum_i y_i^q \right)^{1/q}.$$

20.6. Minkowski's inequality. Minkowski's inequality says

$$(M) \quad \left(\sum_{j=1}^n (x_j + y_j)^p \right)^{1/p} \leq \left(\sum_{j=1}^n x_j^p \right)^{1/p} + \left(\sum_{j=1}^n y_j^p \right)^{1/p}$$

provided that $x_j, y_j > 0$ and $p \geq 1$.

Proof of (M): Let the index q be dual to p . Then

$$\begin{aligned} \sum_{j=1}^n (x_j + y_j)^p &= \sum_{j=1}^n x_j (x_j + y_j)^{p-1} + \sum_{j=1}^n y_j (x_j + y_j)^{p-1} \\ &\leq \left(\sum_{j=1}^n x_j^p \right)^{1/p} \left(\sum_{j=1}^n (x_j + y_j)^{(p-1)q} \right)^{1/q} \\ &\quad + \left(\sum_{j=1}^n y_j^p \right)^{1/p} \left(\sum_{j=1}^n (x_j + y_j)^{(p-1)q} \right)^{1/q} \\ &= \left(\sum_{j=1}^n x_j^p \right)^{1/p} \left(\sum_{j=1}^n (x_j + y_j)^p \right)^{1/q} \\ &\quad + \left(\sum_{j=1}^n y_j^p \right)^{1/p} \left(\sum_{j=1}^n (x_j + y_j)^p \right)^{1/q}, \end{aligned}$$

whence (M) follows at once. □

We finish this lecture mentioning two beautiful and deep inequalities proven by Swedish mathematicians:

Problem* 20.6.1 (Carleman). Let $\sum_{j \geq 1} a_j$ be a convergent series with positive terms. Then the series

$$\sum_{j \geq 1} \{a_1 \dots a_j\}^{1/j}$$

also converges and its sum is

$$< e \sum_{j \geq 1} a_j.$$

The constant e in this inequality cannot be replaced by a smaller one.

Problem* 20.6.2 (Carlson).

$$\left(\sum_{j \geq 1} a_j \right)^4 \leq \pi^2 \left(\sum_{j \geq 1} a_j^2 \right) \left(\sum_{j \geq 1} j^2 a_j^2 \right).$$

The constant π on the right hand side is optimal.

Try to solve these with *some* constants on the right hand side. This is also not easy. If you want to learn more about the inequalities, you should look at the classical book: HARDY, LITTLEWOOD, POLYA "Inequalities" or at the recent book J.M.STEELE "Cachy-Schwarz master class".

21. CONVEX FUNCTIONS. JENSEN'S INEQUALITY

21.1. Definition. Let I be an interval, open or closed, finite or infinite. The function $f: I \rightarrow \mathbb{R}$ is called *convex* if its graph lies below the chord between any two points on the graph.

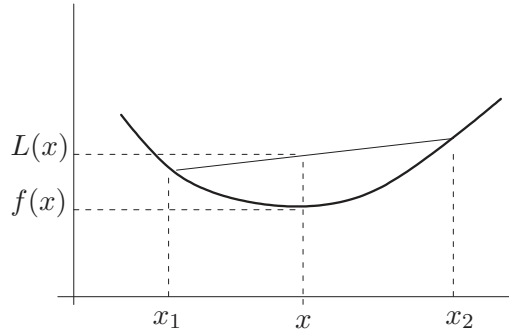


FIGURE 17. Convexity

Now, we'll find an analytic form of this condition. We fix two points $x_1, x_2 \in I$, $x_1 < x_2$, and let x be an intermediate point between x_1 and x_2 ; i.e. $x_1 \leq x \leq x_2$. Let $y = L(x)$ be an equation of the chord which joins the points $(x_1, f(x_1))$ and $(x_2, f(x_2))$. Then the definition says

$$f(x) \leq L(x) \quad \forall x \in [x_1, x_2].$$

The affine function L is given by the equation

$$L(x) = f(x_1) + \frac{f(x_2) - f(x_1)}{x_2 - x_1}(x - x_1),$$

so that we get the inequality

$$(a) \quad (x_2 - x)f(x) \leq (x_2 - x)f(x_1) + (x - x_1)f(x_2),$$

which holds for any triple of points $x_1 \leq x \leq x_2$ from I . We set

$$x = \lambda x_1 + (1 - \lambda)x_2, \quad \lambda = \frac{x_2 - x}{x_2 - x_1},$$

and get

$$(a') \quad f(\lambda x_1 + (1 - \lambda)x_2) \leq \lambda f(x_1) + (1 - \lambda)f(x_2)$$

for each $\lambda \in [0, 1]$ and each $x_1 < x_2$ in I . Obviously, (a) and (a') are equivalent. Taking $\lambda = \frac{1}{2}$, we get

$$f\left(\frac{x + y}{2}\right) \leq \frac{f(x) + f(y)}{2}$$

for each $x, y \in I$. This property is "almost equivalent" to convexity of f :

Exercise 21.1.1. If the function f is continuous on an interval I and if for any pair of points $x, y \in I$, $x < y$:

$$f\left(\frac{x+y}{2}\right) \leq \frac{f(x)+f(y)}{2},$$

then f is convex on I .

It is convenient way to rewrite condition (a) as a double inequality between the slopes of three chords which join the points $(x_1, f(x_1))$, $(x, f(x))$ and $(x_2, f(x_2))$ on the graph of f :

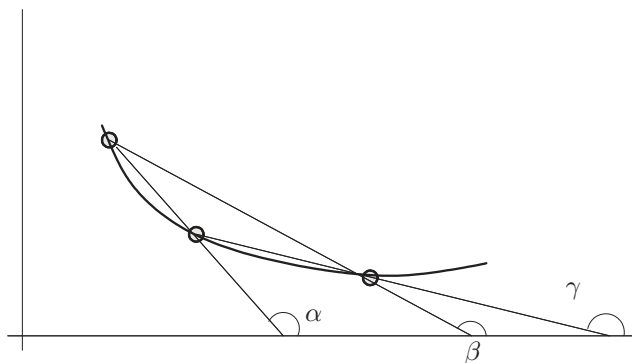


FIGURE 18. $\alpha < \beta < \gamma$

$$(b) \quad \frac{f(x) - f(x_1)}{x - x_1} \leq \frac{f(x_2) - f(x_1)}{x_2 - x_1} \leq \frac{f(x_2) - f(x)}{x_2 - x}.$$

Each of these two inequalities after a simple transformation reduces to (a).

Exercise 21.1.2. If f and g are two convex functions defined on the same interval I , then the functions $cf(x)$, where c is a positive constant, $f(x)+g(x)$ and $\max\{f(x), g(x)\}$ are convex as well.

From this exercise we see that the function $|x|$ is convex on \mathbb{R} , and more generally, if $L_1(x), \dots, L_n(x)$ are affine functions, then the function $\max_{1 \leq j \leq n} L_j(x)$ is also convex.

The other examples will be given a bit later after we'll find a simple way to verify that a twice-differentiable function is convex.

Problem 21.1.3 (Geometric meaning of convexity). The set $F \subset \mathbb{R}^2$ is called *convex* if, for any two points $A, B \in F$, the whole segment $[A, B]$ that connects these two points also belongs to F . For instance, the disk, the triangle and the rectangle are convex sets, while the annulus is not convex.

Suppose $f: I \rightarrow \mathbb{R}$, I is an open interval. Consider the set $\Gamma_+(f) = \{(x, y): x \in I, y \geq f(x)\}$. This is a set of points $P(x, y)$ that lie *above* the graph of f .

Prove that the function f is convex iff the set $\Gamma_+(f)$ is convex.

21.2. Fundamental properties of convex functions.

Claim 21.2.1. *Any convex function on an open interval is continuous.*

Proof: Fix two points $t, x \in I$, $t > x$ which are not the end-points of I . Choose a subinterval $[a, b] \subset I$ such that $[x, t] \subset (a, b)$. Then applying condition (b) to the triple $x < t < b$, we get

$$\frac{f(t) - f(x)}{t - x} \leq \frac{f(b) - f(x)}{b - x}$$

and applying condition (b) to the triple $a < x < t$, we get

$$\frac{f(x) - f(a)}{x - a} \leq \frac{f(t) - f(x)}{t - x}.$$

Thus

$$(t - x) \frac{f(x) - f(a)}{x - a} \leq f(t) - f(x) \leq (t - x) \frac{f(b) - f(x)}{b - x},$$

which yields continuity of f . □

Question 21.2.2. Suppose the function f is convex on a closed interval $[a, b]$. Whether it has to be continuous at the end-points a and b ?

Exercise 21.2.3. If f is convex and attains its maximum at the point x which is not an end-point of the interval I , then f is a constant function.

Claim 21.2.4. *Set*

$$m_f(x, y) = \frac{f(y) - f(x)}{y - x}.$$

If f is convex, then the functions $x \mapsto m_f(x, y)$ and $y \mapsto m_f(x, y)$ are increasing.

Proof: is a reformulation of (b). □

In the next claim, we'll use one-sided derivatives of the function f defined by

$$f'_+(x) = \lim_{t \downarrow x} \frac{f(t) - f(x)}{t - x}$$

(the right derivative) and

$$f'_-(x) = \lim_{t \uparrow x} \frac{f(t) - f(x)}{t - x}$$

(the left derivative). The (usual) derivative $f'(x)$ exists if and only if the right and left derivatives exist and equal to each other.

Claim 21.2.5. *If f is convex on I , then f has the right and left derivatives, and*

$$f'_-(x) \leq f'_+(x) \leq f'_-(y),$$

for any $x < y$, $x, y \in I$.

Proof: follows from the previous claim. □

Remark 21.2.6. The same argument shows that if f is convex on the closed interval $[a, b]$, then the one-sided derivatives $f'_+(a)$ and $f'_-(b)$ exist (finite or infinite), and

$$\begin{aligned} f'_+(a) &\leq f'_-(x), & \forall x \in (a, b], \\ f'_-(b) &\geq f'_+(x), & \forall x \in [a, b). \end{aligned}$$

Exercise 21.2.7. Prove that the set of points x where the derivative of a convex function does not exist is at most countable.

Claim 21.2.8. *If f is differentiable on I , then f is convex if and only if f' does not decrease.*

Proof: In one direction, this follows from the inequalities between the one-sided derivatives. Now, assume that f' does not decrease. Then using the Lagrange mean value theorem we get for any triple $x_1 < x < x_2$ there are points $\xi_1 \in (x_1, x)$, and $\xi_2 \in (x, x_2)$ such that

$$\frac{f(x) - f(x_1)}{x - x_1} = f'(\xi_1) \quad \text{and} \quad f'(\xi_2) = \frac{f(x_2) - f(x)}{x_2 - x}.$$

Since $f'(\xi_1) \leq f'(\xi_2)$, this yields inequality (a). □

Claim 21.2.9. *If f is twice differentiable on I , then it is convex if and only if $f'' \geq 0$.*

Proof: follows from the previous claim. □

Problem 21.2.10. Let $f \in C^2(\mathbb{R})$ and

$$\lim_{x \rightarrow +\infty} f(x) = \lim_{x \rightarrow -\infty} f(x) = 0.$$

Prove that there exist at least two points c_1 and c_2 such that

$$f''(c_1) = f''(c_2) = 0.$$

21.3. A function f is called *concave* if the function $-f$ is convex. The affine function is the only one which is convex and concave at the same time.

- The function $f(x) = x^a$ is convex on $[0, +\infty)$ for $a \geq 1$, is convex on $(0, +\infty)$ for $a \leq 0$, and is concave on $[0, +\infty)$ for $0 \leq a \leq 1$.
- The exponent $f(x) = a^x$ is a convex function on \mathbb{R} .
- The logarithmic function $f(x) = \log x$ is a concave function on $(0, +\infty)$.
- The function $f(x) = \sin x$ is concave on $[0, \pi]$ and convex on $[\pi, 2\pi]$.

Exercise 21.3.1. Suppose that $t \geq 1$. Show that

$$2t^p \leq (t-1)^p + (t+1)^p$$

for $p \geq 1$, and

$$2t^p \geq (t-1)^p + (t+1)^p$$

for $0 \leq p \leq 1$.

Exercise 21.3.2. Suppose f is a convex function. Show that if f increases, then the inverse function f^{-1} is concave, while if f decreases, f^{-1} is convex.

Problem 21.3.3. Suppose f is a convex function on \mathbb{R} bounded from above. Then f is a concave function.

If this question looks difficult, try to solve it assuming that f is differentiable on \mathbb{R} .

21.4. Jensen's inequality.

Theorem 21.4.1. Let f be a convex function in the interval I , and let $x_1, x_2, \dots, x_n \in I$. Then

$$(J) \quad f\left(\sum_{j=1}^n \alpha_j x_j\right) \leq \sum_{j=1}^n \alpha_j f(x_j)$$

provided that $\alpha_1, \dots, \alpha_n \geq 0$ and $\sum_{j=1}^n \alpha_j = 1$.

Proof: We shall use induction with respect to n . The case $n = 2$ corresponds to inequality (a') proved above.

Now, assuming that (J) is proven for $n - 1 \geq 2$, we prove it for $n \geq 3$. We assume that $\alpha_n > 0$ (if $\alpha_n = 0$, then we have already the result), and take $\beta = \alpha_2 + \dots + \alpha_n > 0$. Notice that $\alpha_1 + \beta = 1$ and that

$$\frac{\alpha_2}{\beta} + \dots + \frac{\alpha_n}{\beta} = 1.$$

Then applying (J) first with $n = 2$ and then with $n - 1$ we get

$$\begin{aligned} f(\alpha_1 x_1 + \dots + \alpha_n x_n) &= f\left(\alpha_1 x_1 + \beta \left(\frac{\alpha_2}{\beta} x_2 + \dots + \frac{\alpha_n}{\beta} x_n\right)\right) \\ &\leq \alpha_1 f(x_1) + \beta f\left(\frac{\alpha_2}{\beta} x_2 + \dots + \frac{\alpha_n}{\beta} x_n\right) \\ &\leq \alpha_1 f(x_1) + \dots + \alpha_n f(x_n), \end{aligned}$$

completing the proof. □

Problem 21.4.2. Prove that if $\alpha_j > 0$ for every j , then there is equality in (J) if and only if f is the affine function in the interval $[\min x_j, \max x_j]$.

Examples:

i. Take $f(x) = \log x$. This function is concave, so (J) works with the opposite inequality:

$$\alpha_1 \log x_1 + \dots + \alpha_n \log x_n \leq \log(\alpha_1 x_1 + \dots + \alpha_n x_n).$$

Taking the exponent of the both sides, we get

$$x_1^{\alpha_1} \cdot \dots \cdot x_n^{\alpha_n} \leq \alpha_1 x_1 + \dots + \alpha_n x_n,$$

provided that $\alpha_1, \dots, \alpha_n \geq 0$ and $\sum_{j=1}^n \alpha_j = 1$.

Consider a special case with

$$\alpha_1 = \alpha_2 = \dots = \alpha_n = \frac{1}{n}.$$

We get celebrated Cauchy's inequality between the geometric and arithmetic means:

$$\sqrt[n]{x_1 \cdot \dots \cdot x_n} \leq \frac{x_1 + \dots + x_n}{n}.$$

ii. Now, we apply the Jensen inequality to the function $f(x) = x^p$, $p > 1$, again with $\alpha_1 = \dots = \alpha_n = \frac{1}{n}$. Recall, that f is convex for such p 's. We obtain that for any $x_1, \dots, x_n > 0$

$$\frac{1}{n} \sum_{j=1}^n x_j \leq \left(\frac{1}{n} \sum_{j=1}^n x_j^p \right)^{1/p}, \quad p > 1.$$

Note that this inequality also follows from Hölder's inequality.

Problem 21.4.3. For $x_1, \dots, x_n > 0$ and $p \in \mathbb{R} \setminus \{0\}$, set

$$\mathcal{M}_p(x_1, \dots, x_n) = \left\{ \frac{1}{n} \sum_{j=1}^n x_j^p \right\}^{1/p}.$$

This quantity is called the p -th mean of the values x_1, x_2, \dots, x_n .

i. Find the limits

$$\lim_{p \rightarrow 0} \mathcal{M}_p(x_1, \dots, x_n), \quad \lim_{p \rightarrow +\infty} \mathcal{M}_p(x_1, \dots, x_n), \quad \text{and} \quad \lim_{p \rightarrow -\infty} \mathcal{M}_p(x_1, \dots, x_n).$$

ii. Show that the function $p \mapsto \mathcal{M}_p(x_1, \dots, x_n)$ is strictly increasing unless all x_j are equal, in that case $\mathcal{M}_p(x_1, \dots, x_n)$ is their common value for all p .

22. THE TAYLOR EXPANSION

In this lecture we develop the polynomial approximation to smooth functions which works both locally and globally.

22.1. Local polynomial approximation. Peano's theorem. The starting point of this lecture is the following

Problem. Let the function f has n derivatives⁵ at x_0 . Find the polynomial $P_n(x)$ of degree $\leq n$ such that

$$f(x) = P_n(x) + o((x - x_0)^n), \quad x \rightarrow x_0.$$

In the case $n = 1$, we know that the solution is given by the linear function

$$P_1(x) = f(x_0) + (x - x_0)f'(x_0).$$

Juxtaposing this with another formula

$$P(x) = \sum_{j=0}^n \frac{P^{(j)}(x_0)}{j!} (x - x_0)^j$$

which we proved in Section 17 for an arbitrary polynomial P of degree n , we can guess that the answer to our problem is given by the polynomial

$$P_n(x) = P_n(x; x_0, f) = \sum_{j=0}^n \frac{f^{(j)}(x_0)}{j!} (x - x_0)^j$$

called *the Taylor polynomial of degree n* of the function f at x_0 . The difference

$$R_n(x) = R_n(x; x_0, f) = f(x) - P_n(x)$$

called *the remainder*.

The Taylor polynomial of degree n *interpolates* at the point x_0 the value of f and of its first n derivatives:

$$P_n^{(j)}(x_0) = f^{(j)}(x_0), \quad 0 \leq j \leq n.$$

Therefore, the remainder vanishes at x_0 with its first n derivatives:

$$R_n^{(j)}(x_0) = 0, \quad 0 \leq j \leq n.$$

The following claim finishes the job:

Claim 22.1.1. *Suppose the function g has n derivatives at x_0 , and*

$$g(x_0) = g'(x_0) = \dots = g^{(n)}(x_0) = 0.$$

Then

$$g(x) = o((x - x_0)^n), \quad x \rightarrow x_0.$$

⁵This means that f is differentiable $n - 1$ times in a neighbourhood of x_0 and the n -th derivatives exists at x_0 .

Proof: We shall use induction in n . For $n = 1$, we have

$$\lim_{x \rightarrow x_0} \frac{g(x)}{x - x_0} = \lim_{x \rightarrow x_0} \frac{g(x) - g(x_0)}{x - x_0} = g'(x_0) = 0.$$

Now, having the claim for n , we'll prove it for $n + 1$, using the Lagrange mean value theorem:

$$g(x) - g(x_0) = g'(c)(x - x_0),$$

where c is an intermediate point between x_0 and x . By the inductive assumption,

$$g'(x) = o((x - x_0)^n), \quad x \rightarrow x_0,$$

hence

$$g'(c) = o((c - x_0)^n) = o((x - x_0)^n), \quad x \rightarrow x_0.$$

This proves the claim. □.

Theorem 22.1.2 (Peano). *Let the function f have n derivatives at x_0 . Then*

$$f(x) = \sum_{j=0}^n \frac{f^{(j)}(x_0)}{j!} (x - x_0)^j + o((x - x_0)^n), \quad x \rightarrow x_0.$$

Exercise 22.1.3. If the function f has n derivatives at x_0 , and

$$f(x) = Q(x) + o((x - x_0)^n), \quad x \rightarrow x_0,$$

where Q is a polynomial of degree n , then

$$Q(x) = \sum_{j=0}^n \frac{f^{(j)}(x_0)}{j!} (x - x_0)^j.$$

22.2. The Taylor remainder. Theorems of Lagrange and Cauchy. The Peano theorem shows that the Taylor polynomial $P_n(x)$ well approximates the function f *locally* in a small neighbourhood of x_0 (which generally speaking may shrink as $n \rightarrow \infty$). It appears, that in many cases $P_n(x)$ is close to f *globally*, that is in a fixed interval containing x_0 whose size does not depend on n . In order to prove this, we need to find a convenient expression good for the remainder $R_n(x)$.

First, we introduce some notations: let I be an interval (it can be open or close, finite or infinite). By $C^n(I)$ we denote the class of all n -times differentiable functions on I such that the n -th derivative is continuous on I . By $C^\infty(I)$ we denote the class of all infinitely differentiable functions on I .

Theorem 22.2.1. *Let $f \in C^n[x_0, x]$, and let $f^{(n+1)}$ exist on (x_0, x) . Let the function φ be continuous on $[x_0, x]$, be differentiable on (x_0, x) , and the derivative φ' do not vanish on (x_0, x) . Then there exists an intermediate point c between x_0 and x such that*

$$(R) \quad R_n(x) = \frac{\varphi(x) - \varphi(x_0)}{\varphi'(c)n!} f^{(n+1)}(c)(x - c)^n.$$

Proof: Fix x and consider the function

$$F(t) \stackrel{\text{def}}{=} f(x) - \left\{ f(t) + \frac{f'(t)}{1!}(x-t) + \dots + \frac{f^{(n)}(t)}{n!}(x-t)^n \right\}.$$

Then $F(x) = 0$, $F(x_0) = R_n(x; x_0)$, and

$$F'(t) = -\frac{f^{(n+1)}(t)}{n!}(x-t)^n.$$

So that

$$\frac{R_n(x; x_0)}{\varphi(x) - \varphi(x_0)} = -\frac{F(x) - F(x_0)}{\varphi(x) - \varphi(x_0)} \stackrel{\text{Cauchy's MVT}}{=} -\frac{F'(c)}{\varphi'(c)} = \frac{f^{(n+1)}(c)}{n!\varphi'(c)}(x-c)^n$$

completing the proof. □

In what follows, we use two special cases of (R). Taking

$$(L) \quad \varphi(t) = (x-t)^{n+1},$$

we arrive at the *Lagrange formula* for the remainder:

$$R_n(x) = \frac{(x-x_0)^{n+1}}{(n+1)!} f^{(n+1)}(c).$$

This immediately yields a good estimate of the remainder:

Corollary 22.2.2. *Suppose the function f is the same as in Theorem 2. Then*

$$|R_n(x)| \leq \frac{|x-x_0|^{n+1}}{(n+1)!} \sup_{c \in I} |f^{(n+1)}(c)|.$$

Taking in (R) $\varphi(t) = x-t$, we arrive at another representation for the remainder $R_n(x)$ called the *Cauchy formula*:

$$(C) \quad R_n(x) = \frac{(x-c)^n(x-x_0)}{n!} f^{(n+1)}(c),$$

which sometimes gives a better result than the Lagrange formula. The both forms will be extensively used in the next lecture.

Exercise 22.2.3. Find the approximation error:

$$\sqrt{1+x} \approx 1 + \frac{x}{2} - \frac{x^2}{8}, \quad 0 \leq x \leq 1.$$

Problem* 22.2.4. Suppose that the function f is twice differentiable on $[0, 1]$, $f(0) = f(1) = 0$, and $\sup |f''| \leq 1$. Show that $|f'| \leq \frac{1}{2}$ everywhere on $[0, 1]$.

Problem* 22.2.5 (Hadamard's inequality). Suppose that the function f is twice differentiable on \mathbb{R} , and set $M_k = \sup_{\mathbb{R}} |f^{(k)}|$, $k = 0, 1, 2$. Show that $M_1^2 \leq 2M_0M_2$.

In Lecture 16 we defined the Lagrange interpolation polynomial of degree n with the interpolation nodes at the pairwise distinct points $\{x_j\}_{0 \leq j \leq n}$:

$$L_n(x) = L_n(x; x_0, f) = \sum_{j=0}^n \frac{f(x_j)Q(x)}{Q'(x_j)(x - x_j)},$$

where

$$Q(x) = (x - x_0)(x - x_1)\dots(x - x_n).$$

Problem 22.2.6. Show that if $f \in C^n[a, b]$ and $f^{(n+1)}$ exists on (a, b) , then for any choice of nodes $\{x_j\} \subset [a, b]$ there exists a point $c \in (a, b)$ such that

$$f(x) - L_n(x) = \frac{Q(x)}{(n+1)!} f^{(n+1)}(c).$$

In particular,

$$\max_I |f - L_n| \leq \frac{\max_I |Q|}{(n+1)!} \sup_I |f^{(n+1)}|.$$

Hint: Take $r = f - L_n$, and consider the function

$$t \mapsto r(x)Q(t) - r(t)Q(x).$$

This function has $n+2$ zeroes on $[a, b]$, so that its $n+1$ -st derivative vanishes at an intermediate point c .

23. TAYLOR EXPANSIONS OF ELEMENTARY FUNCTIONS

Let f be a C^∞ -function on I . In many cases, using one of the formulas for the remainder, we can conclude that

$$\lim_{n \rightarrow \infty} R_n(x; x_0) = 0$$

for any point x from the interval $I \ni x_0$. This means that

$$(T) \quad f(x) = \sum_{j=0}^{\infty} \frac{f^{(j)}(x_0)}{j!} (x - x_0)^j, \quad x \in I.$$

The series on the right hand side is called the *Taylor series* of f at x_0 . The formula (T) says the Taylor series converges to f everywhere on I .

We should warn that even if the Taylor series converges, it does not have to represent the function f . For example, the Taylor series at the origin of the C^∞ -function

$$f(x) = \begin{cases} e^{-1/x^2}, & x \neq 0 \\ 0, & x = 0 \end{cases}$$

has only zero coefficients (since $f^{(j)}(0) = 0$, $j \geq 0$), and does not represent the function f anywhere outside the origin.

In the rest of this lecture we consider examples of the Taylor series for elementary functions. In all the examples below, we choose $x_0 = 0$ and set $R_n(x) = R_n(x; 0, f)$. Then using either Lagrange, or Cauchy, representation for the remainder R_n , we show that it converges to zero on an interval I .

23.1. The exponential function. We start with the exponential function $f(x) = e^x$. We will use a simple sufficient condition that follows from Lagrange's estimate for the remainder.

Lemma 23.1.1. *Suppose that $f \in C^\infty(I)$ and that there exists a positive constant C such that*

$$(23.1.2) \quad \sup_{j \geq 0} \sup_{x \in I} |f^{(j)}(x)| \leq C.$$

Then

$$f(x) = \sum_{j=0}^{\infty} \frac{f^{(j)}(x_0)}{j!} (x - x_0)^j, \quad x \in I.$$

Proof: By Lagrange's estimate for the remainder, we have

$$\sup_I |R_n| \leq \frac{C|x - x_0|^{n+1}}{(n+1)!},$$

and the right hand side converges to zero as $n \rightarrow \infty$. □

Clearly, this lemma can be applied to the exponential function, whence,

$$e^x = \sum_{j=0}^{\infty} \frac{x^j}{j!}, \quad x \in \mathbb{R}.$$

In particular, we obtain that

$$e = \sum_{j=0}^{\infty} \frac{1}{j!},$$

with a good estimate for the remainder:

$$0 < e - \sum_{j=0}^n \frac{1}{j!} < \frac{e}{(n+1)!} < \frac{3}{(n+1)!}.$$

Exercise 23.1.3. Which n one should take to compute e with error at most 10^{-10} ?

Claim 23.1.4. *The number e is irrational.*

Proof: Let $e = \frac{m}{n}$ and $s_n = \sum_{k=1}^n (k!)^{-1}$. Then

$$n!(e - s_n) = (n-1)!m - \sum_{k=1}^n \frac{n!}{k!}$$

is a natural number and hence is ≥ 1 . On the other hand,

$$\begin{aligned} n!(e - s_n) &= \frac{n!}{(n+1)!} + \frac{n!}{(n+2)!} + \frac{n!}{(n+3)!} + \dots \\ &= \frac{1}{n+1} + \frac{1}{(n+1)(n+2)} + \frac{1}{(n+1)(n+2)(n+3)} + \dots \\ &< \frac{1}{2} + \frac{1}{2^2} + \frac{1}{2^3} + \dots = 1. \end{aligned}$$

Contradiction! □

Exercise 23.1.5. Prove that $n! > \left(\frac{n}{e}\right)^n$.

Exercise 23.1.6.

(i) Find $\lim_{n \rightarrow \infty} \{en!\}$. Here, $\{ \cdot \}$ is a fractional part.

(ii) Show that $\lim_{n \rightarrow \infty} n \sin(2\pi en!) = 2\pi$.

23.2. The sine and cosine functions. In this case, the same Lemma 23.1.1 yields the formulas:

$$\sin x = \sum_{j=0}^{\infty} (-1)^j \frac{x^{2j+1}}{(2j+1)!}, \quad x \in \mathbb{R}$$

and

$$\cos x = \sum_{j=0}^{\infty} (-1)^j \frac{x^{2j}}{(2j)!}, \quad x \in \mathbb{R}.$$

Similar formulas hold for the hyperbolic sine and cosine:

$$\sinh x \stackrel{\text{def}}{=} \frac{e^x - e^{-x}}{2} = \sum_{j=0}^{\infty} \frac{x^{2j+1}}{(2j+1)!}, \quad x \in \mathbb{R},$$

and

$$\cosh x \stackrel{\text{def}}{=} \frac{e^x + e^{-x}}{2} = \sum_{j=0}^{\infty} \frac{x^{2j}}{(2j)!}, \quad x \in \mathbb{R}.$$

Exercise 23.2.1. Prove these two formulas using Lemma 23.1.1.

Exercise 23.2.2. Check that $\cosh^2 x - \sinh^2 x = 1$, and that the both functions satisfy the differential equation $f'' = f$.

Condition (23.1.2) is too restrictive.

Problem 23.2.3. Let I be an interval, and let $f \in C^\infty(I)$ satisfy

$$\sup_{x \in I} |f^{(j)}(x)| \leq C M^j j!, \quad j \in \mathbb{Z}_+,$$

with positive constants C and M .

(i) Show that the Taylor series of f at x_0 converges to f on the set $\{x \in I: |x - x_0| < M^{-1}\}$.

(ii) Show that if f vanishes with all its derivatives at some point x_0 of I :

$$f^{(n)}(x_0) = 0, \quad j \in \mathbb{Z}_+,$$

then f is the zero function.

(iii) Show that if f vanishes on a subset of I that has an accumulation point in I , then f is the zero function.

23.3. The logarithmic function. Consider the function $f(x) = \log(1 + x)$ defined for $x > -1$. We have

$$f^{(j)}(x) = (-1)^{j-1} \frac{(j-1)!}{(1+x)^j},$$

so that $f^{(j)}(0) = (-1)^{j-1}(j-1)!$. Lagrange's estimate for the remainder yields the convergence of the Taylor expansion for $0 \leq x \leq 1$:

$$\max_{0 \leq x \leq 1} |R_n(x)| \leq \frac{n!}{(n+1)!} = \frac{1}{n+1}.$$

Therefore, for $0 \leq x \leq 1$,

$$(23.3.1) \quad \log(1+x) = \sum_{j=1}^{\infty} (-1)^{j-1} \frac{x^j}{j}.$$

In particular, we find the formula which was promised in Lecture 8:

$$\log 2 = 1 - \frac{1}{2} + \frac{1}{3} - \frac{1}{4} + \dots$$

For $x > 1$ the Taylor series diverges (its terms tend to infinity with n). For the negative x 's, we have to use Cauchy's formula for the remainder. If $|x| < 1$, then for some intermediate c between 0 and x :

$$|R_n(x)| = \left| \frac{(x-c)^n x}{(1+c)^{n+1}} \right| = \left| \frac{x}{1+c} \right| \left| \frac{x-c}{1+c} \right|^n.$$

Claim 23.3.2.

$$\left| \frac{x-c}{1+c} \right| < |x|.$$

Proof of Claim: since c is an intermediate point between 0 and x , $|x - c| = |x| - |c|$. Then

$$\left| \frac{x - c}{1 + c} \right| = \frac{|x| - |c|}{|1 + c|} \leq \frac{|x| - |c|}{1 - |c|} < \frac{|x| - |c||x|}{1 - |c|} = |x|.$$

proving the claim. □

Making use of the claim, we continue the estimate for the remainder $R_n(x)$ and get

$$|R_n(x)| < |x|^{n+1}.$$

Since $|x| < 1$, we see that the remainder goes to zero with n . Therefore, the Taylor expansion converges to $\log(1 + x)$ for $-1 < x \leq 1$. □

It is curious, that the remainder in Cauchy's form gives us the result for $|x| < 1$ but to get the expansion at the end-point $x = 1$ we have to use Lagrange's estimate of the remainder.

There is another way to find the Taylor expansion for $\log(1 + x)$. The derivative of this function equals

$$\frac{1}{1 + x} = \sum_{j=0}^{\infty} (-1)^j x^j.$$

Recalling that $\log(1 + x) = 0$ at $x = 0$ and that $(x^{j+1})' = (j + 1)x^j$, we immediately arrive at the expansion (23.3.1). This idea will be justified in the second semester.

Exercise 23.3.3. Find the Taylor expansion of the function $\log \frac{1+x}{1-x}$ and investigate its convergence.

23.4. The binomial series. In this section, we consider the function $f(x) = (1 + x)^a$ defined for $x > -1$. Now,

$$f^{(j)}(x) = a(a - 1)\dots(a - j + 1)(1 + x)^{a-j},$$

and we get (at least, formally) the Newton formula

$$(1 + x)^a = \sum_{j=0}^{\infty} \frac{a(a - 1)\dots(a - j + 1)}{j!} x^j.$$

Of course, if $a \in \mathbb{N}$, then there are only finitely many non-zero terms in the series on the right hand side, and we arrive at the familiar binomial formula.

We shall prove convergence of this formula for $|x| < 1$. The formula is also valid at $x = 1$ and (for $a \geq 0$) at $x = -1$. This will follow from the Abel convergence theorem that you'll learn in the second semester course.

So we fix $s < 1$, assume that $|x| < s$, and estimate the remainder using the Cauchy formula:

$$\begin{aligned} |R_n(x)| &= \left| \frac{a(a-1)\dots(a-n)}{n!} (1+c)^{a-n-1} (x-c)^n x \right| \\ &= \left| a \left(1 - \frac{a}{1}\right) \dots \left(1 - \frac{a}{n}\right) \right| (1+c)^{a-1} \left| \frac{x-c}{1+c} \right|^n |x| \\ &\leq (1+c)^{a-1} \cdot \left| a \left(1 - \frac{a}{1}\right) \dots \left(1 - \frac{a}{n}\right) \right| |x|^{n+1} = (1+c)^{a-1} \cdot q_n \end{aligned}$$

(in the passage from the second to the third line we used the claim from the previous section). If n is big enough, we have

$$\frac{q_{n+1}}{q_n} = \left| \left(1 - \frac{a}{n+1}\right) x \right| \leq s < 1,$$

so that q_n and hence $R_n(x)$ tend to zero for $|x| < 1$.

23.5. The Taylor series for $\arctan x$. Let $f(x) = \arctan x$, $|x| \leq 1$. To arrive at the Taylor expansion, recall that

$$f'(x) = \frac{1}{1+x^2} = \sum_{j=0}^{\infty} (-1)^j x^{2j}.$$

Hence, the guess:

$$\arctan x = \sum_{j=0}^{\infty} (-1)^j \frac{x^{2j+1}}{2j+1}.$$

To justify our guess, we need to bound the remainder. For this, we need a formula for the j -th derivative $f^{(j)}(x)$.

Claim 23.5.1. For each $j \geq 1$,

$$(C) \quad f^{(j)} = (j-1)! \cos^j f \sin j \left(f + \frac{\pi}{2} \right).$$

Proof of the claim: We'll use the induction with respect to j . For $j = 1$ we have

$$f'(x) = \frac{1}{1+x^2} = \frac{1}{1+\tan^2 f} = \cos^2 f = \cos f \sin \left(f + \frac{\pi}{2} \right).$$

Suppose the claim is verified for $j = n$, then

$$\begin{aligned} f^{(n+1)} &= (n-1)! \cos^{n-1} f \cdot n f' \left\{ -\sin f \sin n \left(f + \frac{\pi}{2} \right) + \cos f \cos n \left(f + \frac{\pi}{2} \right) \right\} \\ &= n! \cos^{n+1} f \cos \left((n+1)f + n \frac{\pi}{2} \right) \\ &= n! \cos^{n+1} f \sin \left((n+1) \left(f + \frac{\pi}{2} \right) \right), \end{aligned}$$

proving the claim. □

Corollary 23.5.2. For each $n \geq 1$,

$$\sup_{[-1,1]} |f^{(n)}| \leq n!.$$

Then, by the Lagrange estimate for the remainder,

$$\sup_{x \in [-1,1]} |R_n(x)| \leq \frac{1}{(n+1)!} \sup_{[-1,1]} |f^{(n+1)}| \leq \frac{1}{n}.$$

That is, the Taylor expansion converges to $\arctan x$ everywhere on $[-1, 1]$.

Plugging the value $x = 0$ into (C), we get

$$f^{(j)}(0) = (j-1)! \sin \frac{j\pi}{2} = \begin{cases} (-1)^m (2m)!, & j = 2m + 1 \\ 0, & j = 2m \end{cases}$$

(we got this expression in Lecture 17 by a different calculation). So that we obtain the Taylor expansion for $\arctan x$

$$\arctan x = \sum_{j=0}^{\infty} (-1)^j \frac{x^{2j+1}}{2j+1}$$

valid on $[-1, 1]$.

Taking $x = 1$, we arrive at a remarkable formula of Leibnitz:

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots$$

Problem 23.5.3. Prove that

$$\arcsin x = x + \sum_{n=1}^{\infty} \frac{(2n-1)!!}{(2n)!!(2n+1)} x^{2n+1}, \quad -1 \leq x \leq 1.$$

Here,

$$(2n-1)!! = 1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n-1), \quad (2n)!! = 2 \cdot 4 \cdot \dots \cdot 2n.$$

Plugging $x = \frac{1}{2}$ into the expansion of $\arcsin x$, we get

$$\frac{\pi}{6} = \frac{1}{2} + \sum_{n=1}^{\infty} \frac{(2n-1)!!}{(2n)!!(2n+1)2^{2n+1}}.$$

This expansion of $\frac{\pi}{6}$ is essentially better than the previous one of $\frac{\pi}{4}$. Why?

23.6. Some computations. There are many elementary functions for which it is not easy to find a good expression for coefficients in the Taylor expansion. In most of applications, one usually needs only a few first terms in the Taylor expansion which can be found directly (sometimes, this requires a patience). Consider several examples:

23.6.1. $f(x) = \tan x$. This is an odd function, so in its Taylor expansion all even coefficients vanish. We'll find first three non-vanishing odd coefficients. We have

$$f'(x) = \sec^2 x, \quad f'(0) = 1,$$

then

$$\begin{aligned} f''(x) &= 2 \sin x \cos^{-3} x, \\ f'''(x) &= 2 \cos^{-2} x + 6 \sin^2 x \cos^{-4} x = -4 \cos^{-2} x + 6 \cos^{-4} x, \quad f'''(0) = 2, \\ f^{(iv)}(x) &= -8 \sin x \cos^{-3} x + 24 \sin x \cos^{-5} x, \end{aligned}$$

and at last

$$\begin{aligned} f^{(v)}(x) &= -8 \cos^{-2} x + 24 \sin^2 x \cos^{-4} x + 24 \cos^{-4} x + 120 \sin^2 \cos^{-6} x \\ &= 16 \cos^{-2} x - 120 \cos^{-4} x + 120 \cos^{-6} x, \end{aligned}$$

so that $f^{(v)}(0) = 16$. We find that

$$\tan x = x + \frac{1}{3}x^3 + \frac{2}{15}x^5 + o(x^6), \quad x \rightarrow 0.$$

Exercise 23.6.1. Find the approximation error

$$\tan x \approx x + \frac{x^3}{3}, \quad |x| \leq \frac{1}{10}.$$

23.6.2. $f(x) = \log \cos x$. Note that $f'(x) = -\tan x$, that $f(0) = 0$, and that f is an even function. Hence, we can use computation from the previous example. We get

$$f'(0) = 0, \quad f''(0) = -1, \quad f'''(0) = 0, \quad f^{(iv)}(0) = -2, \quad f^{(v)}(0) = 0.$$

Hence,

$$\log \cos x = -\frac{1}{2}x^2 - \frac{1}{12}x^4 + o(x^5) \quad x \rightarrow 0.$$

Exercise 23.6.2. Find the Taylor polynomials of degree n at the point x_0 to the following functions

$$\begin{array}{ll} \frac{1+x+x^2}{1-x+x^2} & (n=4, x_0=0) \qquad \sqrt[n]{a^m+x} \quad (a>0) \quad (n=4, x_0=0) \\ \sqrt{2x-x^2} & (n=3, x_0=1) \qquad e^{2x-x^2} \quad (n=4, x_0=0) \\ \sin(\sin x) & (n=3, x_0=0) \qquad x^x - 1 \quad (n=3, x_0=1). \end{array}$$

23.7. Application to the limits. In many cases, knowledge of the Taylor expansion simplifies computation of limits. For example, making use of the expansions of $\tan x$ and $\log \cos x$ we easily find

$$\lim_{x \rightarrow 0} \frac{\sin x - x}{\tan x - x} = \lim_{x \rightarrow 0} \frac{-x^3/6 + o(x^3)}{x^3/3 + o(x^3)} = -\frac{1}{2},$$

and

$$\lim_{x \rightarrow 0} \frac{\log \cos x}{x^2} = -\frac{1}{2}.$$

Exercise 23.7.1. Find the limits

$$\begin{array}{lll} \lim_{x \rightarrow 0} \frac{\sin x - \arcsin x}{\tan x - \arctan x} & \lim_{x \rightarrow 0} \left(\frac{\sin x}{x} \right)^{\frac{1}{1-\cos x}} & \lim_{x \rightarrow 0} \frac{\cos x - e^{-\frac{1}{2}x^2}}{x^4} \\ \lim_{x \rightarrow 0} \left(\frac{1}{x} - \frac{1}{\sin x} \right) & \lim_{x \rightarrow 1} \frac{1-x+\log x}{1-\sqrt{2x-x^2}} & \lim_{x \rightarrow +\infty} \left(\sqrt[6]{x^6+x^5} - \sqrt[6]{x^6-x^5} \right). \end{array}$$

24. THE COMPLEX NUMBERS

In this lecture we introduce the complex numbers and recall their basic properties.

24.1. Basic definitions and arithmetics. As you probably remember from the high-school, the complex numbers are the expressions $z = x + iy$ with $i^2 = -1$. We can add and multiply the complex numbers as follows

$$\begin{aligned}(x_1 + iy_1) + (x_2 + iy_2) &= (x_1 + x_2) + i(y_1 + y_2), \\ (x_1 + iy_1)(x_2 + iy_2) &= (x_1x_2 - y_1y_2) + i(x_1y_2 + x_2y_1).\end{aligned}$$

If $z = x + iy$, then the value $\bar{z} = x - iy$ is called *the conjugate* to z , x is *the real part* of z , $x = \operatorname{Re} z = \frac{z + \bar{z}}{2}$, and y is *the imaginary part* of z , $y = \operatorname{Im} z = \frac{z - \bar{z}}{2i}$. Note that $z\bar{z} = x^2 + y^2$ is always non-negative, and vanishes iff $z = 0$. The non-negative number $\sqrt{z\bar{z}}$ is called *the absolute value* of z , denoted $r = |z| = \sqrt{x^2 + y^2}$. If $z \neq 0$, then there is the inverse to z :

$$z^{-1} = \frac{1}{z} = \frac{\bar{z}}{z\bar{z}} = \frac{x - iy}{x^2 + y^2} = \frac{x}{x^2 + y^2} - i \frac{y}{x^2 + y^2}.$$

Then, for $z_2 \neq 0$, we can define

$$\frac{z_1}{z_2} = z_1 \cdot \frac{1}{z_2}.$$

I.e., the complex numbers form a field denoted by \mathbb{C} . Any real number x can be regarded as a complex number $x + i0$ with zero imaginary part. I.e., $\mathbb{R} \subset \mathbb{C}$.

Exercise 24.1.1. Check:

$$\overline{z_1 + z_2} = \bar{z}_1 + \bar{z}_2, \quad \overline{z_1 \cdot z_2} = \bar{z}_1 \cdot \bar{z}_2.$$

Claim 24.1.2 (Triangle inequality).

$$|z + w| \leq |z| + |w|.$$

Proof: We have

$$\begin{aligned}|z + w|^2 &= (z + w)\overline{(z + w)} = (z + w)(\bar{z} + \bar{w}) \\ &= z\bar{z} + w\bar{w} + z\bar{w} + w\bar{z} = |z|^2 + |w|^2 + 2\operatorname{Re}(z\bar{w}).\end{aligned}$$

Note that $-|a| \leq \operatorname{Re} a \leq |a|$, whence

$$|z + w|^2 \leq |z|^2 + |w|^2 + 2|z||w| = (|z| + |w|)^2.$$

Done! □

Exercise 24.1.3.

$$|z_1 + z_2|^2 + |z_1 - z_2|^2 = 2(|z_1|^2 + |z_2|^2).$$

Exercise 24.1.4 (Cauchy-Schwarz inequality).

$$\left| \sum z_j w_j \right|^2 \leq \left(\sum |z_j|^2 \right) \left(\sum |w_j|^2 \right).$$

24.2. Geometric representation of complex numbers. The argument. We can represent complex numbers by two-dimensional vectors:

$$z = x + iy \mapsto \begin{pmatrix} x \\ y \end{pmatrix}.$$

Then, the addition law for the complex numbers corresponds to the addition law for

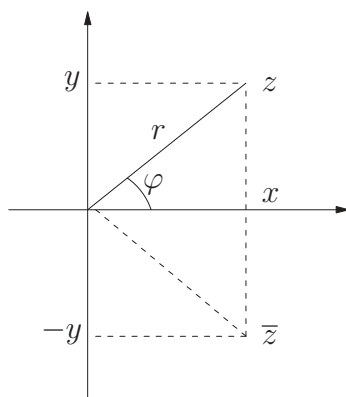


FIGURE 19. Complex plane

the vectors, and the absolute value of the complex number is the same as the length of the corresponding vector. However, the vector representation is not very convenient when we need to multiply the complex number. In this case, it is more convenient to use the polar coordinates.

Definition 24.2.1 (argument). For $z \neq 0$, the *argument* of z is the angle $\varphi = \arg z$ the point z is seen from the origin. The angle is measured counterclockwise, started with the positive ray.

We have

$$\begin{aligned} \tan \varphi &= \frac{y}{x}, \\ x &= r \cos \varphi, & y &= r \sin \varphi \end{aligned}$$

(as above, $r = |z|$), and

$$z = r(\cos \varphi + i \sin \varphi).$$

This representation is consistent with multiplication: if $z_j = r_j(\cos \varphi_j + i \sin \varphi_j)$, $j = 1, 2$, are non-zero complex numbers, then

$$z_1 \cdot z_2 = r_1 r_2 (\cos(\varphi_1 + \varphi_2) + i \sin(\varphi_1 + \varphi_2)).$$

I.e., multiplying the complex numbers, we multiply their absolute values and add their arguments.

Corollary 24.2.2 (Moivre). If $z = r(\cos \varphi + i \sin \varphi)$, then

$$z^n = r^n (\cos n\varphi + i \sin n\varphi), \quad n \in \mathbb{N}.$$

Warning: the angles are measured up to $2\pi k$, $k \in \mathbb{Z}$. Hence, the argument is not the number but rather a set of real numbers, such that the difference between any two numbers from this set equals $2\pi k$ with some integer k . The most popular choice for the representative from this set is $\varphi \in [0, 2\pi)$.

Example 24.2.3. Let us solve the equation $z^n = a$. Here, $n \in \mathbb{N}$. We suppose that $a \neq 0$, otherwise, the equation has only the zero solution. Denote $a = \rho(\cos \theta + i \sin \theta)$. Then

$$r^n(\cos n\varphi + i \sin n\varphi) = \rho(\cos \theta + i \sin \theta),$$

i.e., $r^n = \rho$ and $n\varphi = \theta + 2k\pi$ with some $k \in \mathbb{Z}$. Hence, $r = \sqrt[n]{\rho}$. The obvious solution for the second equation is $\varphi = \theta/n$. However, after a minute reflection we realize that it has n distinct solutions:

$$\varphi_k = \frac{\theta}{n} + \frac{2k\pi}{n}, \quad k = 0, 1, \dots, n-1.$$

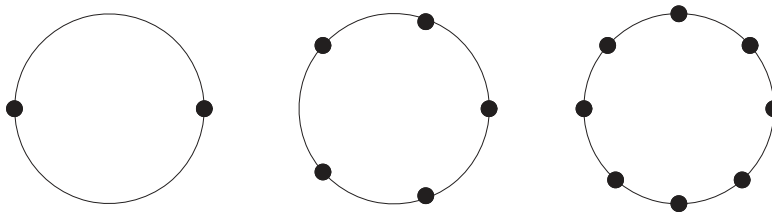


FIGURE 20. The roots of unity, $n = 2$, $n = 5$, and $n = 8$

Consider the special case $a = 1$. In this case, $\rho = 1$ and $\theta = 0$. We get n points

$$z_k = \cos\left(\frac{2k\pi}{n}\right) + i \sin\left(\frac{2k\pi}{n}\right), \quad k = 0, 1, \dots, n-1$$

called *the roots of unity*.

Exercise 24.2.4. Solve the equations $z^4 = i$, $z^2 = i$, $z^2 = 1 + i$. Find the absolute value and the argument of the solutions, as well as their real and imaginary parts. Mark the solutions on the complex plane.

Exercise 24.2.5. Let

$$\omega = \cos\left(\frac{2\pi}{n}\right) + i \sin\left(\frac{2\pi}{n}\right).$$

Compute the sums

$$1 + \omega + \omega^2 + \dots + \omega^{n-1} = ?,$$

$$1 + 2\omega + 3\omega^2 + \dots + n\omega^{n-1} = ?,$$

and

$$1 + \omega^h + \omega^{2h} + \dots + \omega^{(n-1)h} = ?$$

(h is a positive integer).

24.3. Convergence in \mathbb{C} . The *distance* between the complex numbers z_1 and z_2 is $|z_1 - z_2|$.

Definition 24.3.1. The sequence z_n converges to z (denoted by $z_n \rightarrow z$ or $z = \lim_{n \rightarrow \infty} z_n$), if $\lim_{n \rightarrow \infty} |z - z_n| = 0$.

Since

$$\max\{|x - x_n|, |y - y_n|\} \leq \underbrace{\sqrt{(x - x_n)^2 + (y - y_n)^2}}_{=|z - z_n|} \leq |x - x_n| + |y - y_n|,$$

the sequence z_n converges to z iff the corresponding real and imaginary parts converge:

$$x_n \rightarrow x, \quad y_n \rightarrow y.$$

Exercise 24.3.2. Check that the Cauchy criterion of convergence works for the complex sequences.

Definition 24.3.3 (continuity). The complex valued function f is continuous at z , if for each sequence $z_n \rightarrow z$, $f(z_n) \rightarrow f(z)$.

Exercise 24.3.4. Check that the sum and the product of continuous functions is continuous. Check that the quotient of continuous functions is continuous in the points where the denominator does not vanish.

Hint: the proofs are the same as in the real case.

We see that the polynomials are continuous functions in the whole complex plane. That's all we need to prove in the next lecture the fundamental theorem of algebra.

Exercise 24.3.5. If $f = u + iv$, then f is continuous iff its real and imaginary parts u and v are continuous. If f is continuous, then $|f|$ is also continuous.

25. THE FUNDAMENTAL THEOREM OF ALGEBRA AND ITS COROLLARIES

25.1. The theorem and its proof.

Theorem 25.1.1. *Any polynomial $P(z) = c_0 + c_1z + \dots + c_nz^n$ of positive degree has at least one zero in \mathbb{C} .*

Proof: WLOG, we assume that $c_n = 1$. Denote $m = \inf_{z \in \mathbb{C}} |P(z)|$.

Claim 25.1.2. *There is a sufficiently big R such that $|P(z)| > m + 1$ for $|z| > R$.*

Indeed, we have

$$P(z) = z^n \left(1 + \frac{c_{n-1}}{z} + \dots + \frac{c_0}{z^n} \right),$$

whence

$$\begin{aligned} |P(z)| &\geq |z|^n \left(1 - \left| \frac{c_{n-1}}{z} + \dots + \frac{c_0}{z^n} \right| \right) \\ &\geq |z|^n \left(1 - \underbrace{\left(\frac{|c_{n-1}|}{|z|} + \dots + \frac{|c_0|}{|z|^n} \right)}_{\leq 1/2} \right) \geq \frac{1}{2} |z|^n \stackrel{|z| \geq R}{\geq} \frac{1}{2} R^n \geq m + 1 \end{aligned}$$

provided that R is sufficiently big. □

Therefore, $m = \inf_{|z| \leq R} |P(z)|$. Next, using the Bolzano-Weierstrass lemma, we will check that the infimum is actually attained:

Claim 25.1.3. *There exists z_0 with $|z_0| \leq R$ such that $|P(z_0)| = m$.*

Indeed, choose a sequence of points z_k , $|z_k| \leq R$, such that

$$|P(z_k)| \leq m + \frac{1}{k}.$$

The sequences $x_k = \operatorname{Re} z_k$ and $y_k = \operatorname{Im} z_k$ are bounded $\max\{|x_k|, |y_k|\} \leq R$. Hence, they have convergent subsequences. Hence, the sequence $\{z_k\}$ has a convergent subsequence $z_{k_j} \rightarrow z_0$. Then by continuity of the polynomial P , we have

$$P(z_0) = \lim_{j \rightarrow \infty} P(z_{k_j}),$$

whence $|P(z_0)| = m$. □

Suppose that P does not have zeroes in \mathbb{C} , i.e., $m > 0$, and consider the polynomial

$$Q(z) \stackrel{\text{def}}{=} \frac{P(z + z_0)}{P(z_0)}.$$

Then $1 = Q(0) \leq |Q(z)|$, $z \in \mathbb{C}$.

To complete the proof, we show that there are points z where $|Q(z)| < Q(0)$. This will lead to the contradiction. We have

$$Q(z) = 1 + q_k z^k + q_{k+1} z^{k+1} + \dots + q_n z^n \quad \text{with} \quad |q_k| \neq 0.$$

Set $\psi = \arg q_k$ and consider the points z with $\arg z = \frac{\pi - \psi}{k}$. Then

$$\arg(q_k z^k) = \psi + (\pi - \psi) = \pi,$$

so that $q_k z^k = -r^k |q_k|$. Let's estimate $|Q(z)|$ assuming on each step that r is chosen sufficiently small:

$$\begin{aligned} |Q(z)| &\leq \left| 1 + q_k z^k \right| + |q_{k+1}| r^{k+1} + \dots + |q_n| r^n \\ &= 1 - r^k |q_k| + r^{k+1} |q_{k+1}| + \dots + r^n |q_n| \\ &= 1 - r^k \left(|q_k| - r |q_{k+1}| - \dots - r^{n-k} |q_n| \right) < 1, \end{aligned}$$

and we are done! \square

25.2. Factoring the polynomials. In Lecture 16, we discussed the Horner scheme of the polynomial division. This scheme also works for the polynomials with complex coefficients. It yields, that if P is a polynomial of degree $n \geq 1$, then

$$P(z) = (z - a)P_1(z) + P(a)$$

where P_1 is a polynomial of degree $n - 1$. In particular, if P vanishes at a , then

$$P(z) = (z - a)P_1(z).$$

Using induction with respect to the degree of P , we arrive at

Corollary 25.2.1 (factorization of polynomials). *Every polynomial of degree $n \geq 1$ can be factored:*

$$P(z) = c(z - z_1) \dots (z - z_n).$$

Note that some of the zeroes z_1, \dots, z_n of P may coincide. We say that a is a zero of P of multiplicity k if

$$P(z) = (z - a)^k P_1(z)$$

where the polynomial P_1 does not vanish at a . Usually, we count zeroes of the polynomials with their multiplicities⁶. Then we can write down the factorization in the following form

$$P(z) = c(z - z_1)^{k_1} \dots (z - z_m)^{k_m}$$

where the zeroes z_1, \dots, z_m are pairwise different, and $\sum k_j = n$.

Exercise 25.2.2. If a polynomial of degree P has more than n zeroes in \mathbb{C} (counting with the multiplicities), then it vanishes identically.

⁶For instance, the polynomial $P(z) = z(z - 1)^2(z - 2)^{10}$ has 1 zero at the origin, 2 zeroes at $z = 1$, and 10 zeroes at $z = 2$.

25.3. Rational functions. Partial fraction decomposition. *Rational functions* are functions represented as the quotients of the polynomials:

$$R(z) = \frac{P(z)}{Q(z)}.$$

Writing this representation we assume that the polynomials P and Q have no common zeroes. Then $\deg R \stackrel{\text{def}}{=} \max\{\deg P, \deg Q\}$. The rational functions form a *field* with usual addition and multiplication.

The rational function R is defined everywhere except of the zeroes of Q . The zeroes of the polynomial Q are called *the poles* of R . Note that a is a pole of R if and only if

$$\lim_{z \rightarrow a} |R(z)| = +\infty.$$

If a is a zero of Q of multiplicity k , then we say that the pole of R at a also has multiplicity k . The polynomials are the rational functions without poles.

Claim 25.3.1. *If a is a pole of R of multiplicity k , then there are the unique coefficients A_1, \dots, A_k such that*

$$R(z) - \left(\frac{A_1}{z-a} + \dots + \frac{A_k}{(z-a)^k} \right)$$

has no pole at a .

The sum on the RHS is called *the singular part* of R at a . We denote it by $S_a(z)$.

Proof:

i (existence): Consider the rational function $U(z) = (z-a)^k R(z)$, it has no pole at a . We set $A_k = U(a)$. Then

$$(z-a)^k R(z) - A_k = U(z) - A_k = (z-a)V(z)$$

where V is a rational function without pole at a , or

$$R(z) - \frac{A_k}{(z-a)^k} = \frac{V(z)}{(z-a)^{k-1}}$$

and the RHS has a pole at a of multiplicity $k-1$ or less. Then we apply the same procedure to the function V .

ii (uniqueness): Suppose that the expression

$$R(z) - \left(\frac{B_1}{z-a} + \dots + \frac{B_k}{(z-a)^k} \right)$$

also has no pole at a . Then the difference of the two expressions

$$F(z) = \frac{B_1 - A_1}{z-a} + \dots + \frac{B_k - A_k}{(z-a)^k}$$

also has no pole at a . Suppose that some $A_l \neq B_l$ and set $j = \max\{l: A_l \neq B_l\}$. Then

$$F(z) = \frac{1}{(z-a)^j} \underbrace{\{(B_j - A_j) + (B_{j-1} - A_{j-1})(z-a) + \dots + (B_1 - A_1)(z-a)^{j-1}\}}_{=T(z)} = \frac{T(z)}{(z-a)^j}$$

where T is a polynomial, and $T(a) = B_j - A_j \neq 0$ by our assumption. Hence, F has a pole at a , arriving at the contradiction. Hence, the claim. \square

Applying the claim, one by one, to all poles of R , we get

Theorem 25.3.2 (partial fraction decomposition). *Every rational function R can be uniquely represented in the following form:*

$$R(z) = \sum_a S_a(z) + W(z)$$

where the sum is taken over the set of all poles a of R , S_{a_j} are the corresponding singular parts, and W is a polynomial.

Exercise 25.3.3. If $R = \frac{P}{Q}$ where the polynomials P and Q has no common zeroes, then $\deg W = \deg P - \deg Q$, if the latter is non-negative; otherwise $W = 0$.

Example 25.3.4. Let

$$R(z) = \frac{z^4 + 1}{z(z+1)(z+2)}.$$

This function has simple poles at the points $z = 0, -1, -2$. Hence,

$$R(z) = \frac{A_0}{z} + \frac{A_{-1}}{z+1} + \frac{A_{-2}}{z+2} + W(z)$$

where W is a (linear) polynomial. We have

$$A_0 = \lim_{z \rightarrow 0} R(z)z = \lim_{z \rightarrow 0} \frac{z^4 + 1}{(z+1)(z+2)} = \frac{1}{2},$$

$$A_{-1} = \lim_{z \rightarrow -1} R(z)(z+1) = \lim_{z \rightarrow -1} \frac{z^4 + 1}{z(z+2)} = -2,$$

$$A_{-2} = \lim_{z \rightarrow -2} R(z)z = \lim_{z \rightarrow -2} \frac{z^4 + 1}{z(z+1)} = \frac{17}{2},$$

and

$$W(z) = \frac{z^4 + 1}{z(z+1)(z+2)} - \left(\frac{1}{2z} - \frac{2}{z+1} + \frac{17}{2(z+2)} \right) = \dots = z - 3,$$

and finally

$$\frac{z^4 + 1}{z(z+1)(z+2)} = \frac{1}{2z} - \frac{2}{z+1} + \frac{17}{2(z+2)} + z - 3.$$

There a more simple way to compute the linear polynomial $W(z) = az + b$:

$$a = \lim_{z \rightarrow \infty} \frac{R(z)}{z} = 1,$$

and

$$b = \lim_{z \rightarrow \infty} (R(z) - z) = \lim_{z \rightarrow \infty} \frac{z^4 + 1 - z^2(z+1)(z+2)}{z(z+1)(z+2)} = -3.$$

25.3.1. Simple poles and Lagrange interpolation. If the poles of R are *simple* (i.e., have multiplicity 1), then we get a representation of R as a sum of simple fractions and a polynomial:

$$(25.3.5) \quad R(z) = \sum_j \frac{A_j}{z - a_j} + W(z).$$

In this case⁷,

$$A_j = \lim_{z \rightarrow a_j} R(z)(z - a_j) = \lim_{z \rightarrow a_j} \frac{P(z)(z - a_j)}{Q(z)} = \frac{P(a_j)}{Q'(a_j)},$$

and we get

$$\frac{P(z)}{Q(z)} = \sum_j \frac{P(a_j)}{(z - a_j)Q'(a_j)} + W(z)$$

where the sum is taken over the zeroes of the polynomial Q . If $\deg P < \deg Q$, then W is zero, and we arrive at the Lagrange interpolation formula with nodes at the zeroes of Q proven in Lecture 15.

$$P(z) = \sum_j \frac{P(a_j)Q(z)}{(z - a_j)Q'(a_j)}.$$

That is, Lagrange interpolation formula is a special case of the partial fraction decomposition of rational functions!

⁷Here we use the derivative of the polynomial Q at $a \in \mathbb{C}$. It is defined as usual:

$$Q'(a) = \lim_{z \rightarrow a} \frac{Q(z) - Q(a)}{z - a}.$$

It is easy to see that this limit always exists. If

$$Q(z) = \sum_{0 \leq j \leq n} q_j z^j,$$

then

$$Q'(a) = \sum_{0 \leq j \leq n-1} (j+1)q_{j+1}a^j.$$

In algebra, the latter relation is considered as a definition of the derivative Q'

26. COMPLEX EXPONENTIAL FUNCTION

26.1. Absolutely convergent series. Here we deal with absolutely convergent series $\sum a_k$ with complex terms a_k .

26.1.1. Rearrangement of the series. Let us recall that a series $\sum a'_k$ is a *rearrangement* of the series $\sum a_k$ if every term in the first series appears exactly once in the second and conversely. In other words, there is a bijection $p: \mathbb{N} \rightarrow \mathbb{N}$ such that $a'_k = a_{p(k)}$.

Theorem 26.1.1 (Dirichlet). *If the series $\sum a_k$ is absolutely convergent, then all its rearrangements converge to the same sum.*

We've already proved this theorem for series with real terms (Theorem 9.2.2). For series with complex terms the proof is the same. We observe that

$$a_k = \alpha_k + i\beta_k = \alpha_k^+ - \alpha_k^- + i\beta_k^+ - i\beta_k^-$$

(here we've used notation $x^+ = \max\{x, 0\}$, $x^- = \max\{-x, 0\}$). Hence, we can represent the series $\sum a_k$ by a linear combination of four convergent series with non-negative terms:

$$\sum a_k = \sum \alpha_k^+ - \sum \alpha_k^- + i \sum \beta_k^+ - i \sum \beta_k^-.$$

Since all rearrangements of the series with positive terms converge to the same sum, the result follows. \square .

26.1.2. Multiplication of series. Having two absolutely convergent series

$$(A) \quad \sum_k a_k$$

and

$$(B) \quad \sum_l b_l,$$

we want to learn how to multiply them. Intuitively, the product (AB) should be a double sum

$$(AB) \quad \sum_{k,l} a_k b_l.$$

The first question is *how to understand this expression?* The second question is *does it converge to the product $A \cdot B$?*

Consider the two-dimensional array of all possible products $a_k b_l$:

$$\begin{array}{cccccc} a_1 b_1 & a_1 b_2 & a_1 b_3 & \dots & a_1 b_n & \dots \\ a_2 b_1 & a_2 b_2 & a_2 b_3 & \dots & a_2 b_n & \dots \\ a_3 b_1 & a_3 b_2 & a_3 b_3 & \dots & a_3 b_n & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ a_m b_1 & a_m b_2 & a_m b_3 & \dots & a_m b_n & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \end{array}$$

Recall that we know how enumerate the elements of this array by the naturals \mathbb{N} and each enumeration leads to a different series. Luckily, the previous theorem tells us, that

if the series we get in this way are absolutely convergent, then different enumerations will lead to the same answer, so we'll be able to choose the most convenient one.

Absolute convergence: observe that we can bound the finite sums

$$|a_{k_1}b_{l_1}| + \dots + |a_{k_s}b_{l_s}| \leq (|a_1| + \dots + |a_n|)(|b_1| + \dots + |b_n|)$$

with $n = \max\{k_1, \dots, k_s, l_1, \dots, l_s\}$. Hence, an arbitrary finite sum $|a_{k_1}b_{l_1}| + \dots + |a_{k_s}b_{l_s}|$ is bounded by $(\sum |a_k|)(\sum |b_l|)$. Therefore, for any rearrangement of the terms, the series (AB) is absolutely convergent, and its sum does not depend on the rearrangement.

Cauchy's product: the most popular rearrangement is the one called Cauchy's product:

$$a_1b_1 + (a_1b_2 + a_2b_1) + (a_1b_3 + a_2b_2 + a_3b_1) + \dots,$$

or

$$\sum_{k,l=1}^{\infty} a_k b_l = \sum_{n=1}^{\infty} \sum_{k+l=n} a_k b_l = \sum_{n=1}^{\infty} \sum_{k=1}^n a_k b_{n-k}.$$

Here is our chief example:

Example 26.1.2. Suppose we have two absolutely convergent Taylor series

$$\sum_{k=0}^{\infty} a_k z^k, \quad \sum_{l=0}^{\infty} b_l z^l.$$

Then their product is represented by another absolutely convergent Taylor series

$$\sum_{k=0}^{\infty} a_k z^k \cdot \sum_{l=0}^{\infty} b_l z^l = \sum_{n=0}^{\infty} c_n z^n$$

with

$$c_n = \sum_{k+l=n} a_k b_l.$$

26.2. The complex exponent. Define the functions

$$e^z \stackrel{\text{def}}{=} \sum_{n=0}^{\infty} \frac{z^n}{n!}, \quad \sin z \stackrel{\text{def}}{=} \sum_{n=0}^{\infty} (-1)^n \frac{z^{2n+1}}{(2n+1)!}, \quad \cos z \stackrel{\text{def}}{=} \sum_{n=0}^{\infty} (-1)^n \frac{z^{2n}}{(2n)!}.$$

First, note that the series on the RHS absolutely converge at any point $z \in \mathbb{C}$, and that for real z 's the new definitions coincide with the ones we know. Now, the miracle comes:

Claim 26.2.1 (Euler).

$$e^{iz} = \cos z + i \sin z, \quad z \in \mathbb{C}.$$

Proof: by inspection. We have

$$\begin{aligned} e^{iz} &= \sum_{n=0}^{\infty} \frac{(iz)^n}{n!} = \sum_{m=0}^{\infty} \overbrace{\frac{(iz)^{2m}}{(2m)!}}^{i^{2m}=(-1)^m} + \sum_{m=0}^{\infty} \overbrace{\frac{(iz)^{2m+1}}{(2m+1)!}}^{i^{2m+1}=i(-1)^m} \\ &= \sum_{m=0}^{\infty} (-1)^m \frac{z^{2m}}{(2m)!} + i \sum_{m=0}^{\infty} (-1)^m \frac{z^{2m+1}}{(2m+1)!} = \cos z + i \sin z. \end{aligned}$$

Done! □

Note that the cosine function is even, while the sine function is odd. Hence,

Corollary 26.2.2. $\cos z = \frac{e^{iz} + e^{-iz}}{2}, \sin z = \frac{e^{iz} - e^{-iz}}{2i}.$

Corollary 26.2.3. Any non-zero complex number z can be represented in the form $z = re^{i\varphi}$ where $r = |z|$, and $\varphi = \arg z$.

Corollary 26.2.4. $e^{2\pi i} = 1.$

Corollary 26.2.5 (Euler's formula). $e^{i\pi} = -1.$

This miraculous identity connects the numbers $e = \lim_{n \rightarrow \infty} (1 + \frac{1}{n})^n$, π defined as the quotient of the length of the circumference to its diameter, and $i = \sqrt{-1}$.

Exercise 26.2.6. Define

$$\sinh z \stackrel{\text{def}}{=} \sum_{n=0}^{\infty} \frac{z^{2n+1}}{(2n+1)!}, \quad \cosh z \stackrel{\text{def}}{=} \sum_{n=0}^{\infty} \frac{z^{2n}}{(2n)!}.$$

Check the following relations:

- i. $\cosh z = \frac{e^z + e^{-z}}{2}, \sinh z = \frac{e^z - e^{-z}}{2}.$
- ii. $\sin(iz) = i \sinh z, \cos(iz) = \cosh z.$
- iii. $\sin^2 z + \cos^2 z = 1, \cosh^2 z - \sinh^2 z = 1.$
- iv. $\sin(\frac{\pi}{2} - z) = \cos z.$

The fundamental properties of the exponential function e^x on the real axis are the functional equation $e^{x+y} = e^x \cdot e^y$ and the differential equation $(e^x)' = e^x$. As we know, each of these properties characterizes the exponential function. Now, we'll check that this two properties persist for the function e^z on \mathbb{C} .

Claim 26.2.7. $e^{z+w} = e^z \cdot e^w.$

Proof: by inspection.

$$\begin{aligned} e^z \cdot e^w &= \sum_{n=0}^{\infty} \sum_{k+l=n} \frac{z^k}{k!} \cdot \frac{w^l}{l!} \\ &= \sum_{n=0}^{\infty} \sum_{k=0}^n \frac{z^k}{k!} \cdot \frac{w^{n-k}}{(n-k)!} \\ &= \sum_{n=0}^{\infty} \frac{1}{n!} \sum_{k=0}^n \binom{n}{k} z^k w^{n-k} \\ &= \sum_{n=0}^{\infty} \frac{(z+w)^n}{n!} = e^{z+w} \end{aligned}$$

and we are done. □

Corollary 26.2.8. $e^{z+2\pi i} = e^z$; i.e., e^z is a periodic function with the period $2\pi i$.

The function $f: \mathbb{C} \rightarrow \mathbb{C}$ is said to be (complex) differentiable at the point z if there exists the limit

$$f'(z) = \lim_{\mathbb{C} \ni \epsilon \rightarrow 0} \frac{f(z + \epsilon) - f(z)}{\epsilon}.$$

It is important that the limit does not depend on the direction at which ϵ approaches 0.

Claim 26.2.9. *The function e^z is differentiable in \mathbb{C} and $(e^z)' = e^z$.*

Proof: We have

$$\frac{e^{z+\epsilon} - e^z}{\epsilon} = e^z \frac{e^\epsilon - 1}{\epsilon}.$$

Note that

$$\left| \frac{e^\epsilon - 1}{\epsilon} - 1 \right| \leq \sum_{n=1}^{\infty} \frac{|\epsilon|^n}{(n+1)!} = o(1)$$

as $\epsilon \rightarrow 0$. Done! □