Analysis 1 – Practicals

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1 Exercise 1

Exercise 1. Let p, q and r be statements. Prove the distributive law using the truth table:

$$p \wedge (q \vee r) \Leftrightarrow (p \wedge q) \vee (p \wedge r)$$

p	q	r	$(q \vee r)$	$(p \wedge (q \vee r))$	$(p \wedge q)$	$(p \wedge r)$	$(p \wedge q) \vee (p \wedge r)$
0	0	0	0	0	0	0	0
0	0	1	1	0	0	0	0
0	1	0	1	0	0	0	0
0	1	1	1	0	0	0	0
1	0	0	0	0	0	0	0
1	0	1	1	1	0	1	1
1	1	0	1	1	1	0	1
1	1	1	1	1	1	1	1

Therefore the truthtable of both statements is equivalent. Two boolean statements are equivalent iff their truthtable is equivalent.

2 Exercise 2

Exercise 2. Formalize the following colloquial combination of statements p, q and r in propositional calculus. Furthermore always create the negation:

- "Under the assumption, that p or q holds, we conclude that r cannot be true."
- "It's a requirement for r, that p and q hold."
- "p or q holds, but p and q exclude each other"

- "Under the assumption, that p or q holds, we conclude that r cannot be true."

  $$(p \vee q) \rightarrow \neg r$$

  Negation: $(p \vee q) \wedge r$
- "It's a requirement for r, that p and q hold."

  $$r \rightarrow (p \wedge q)$$

  Negation: $r \wedge (\neg p \vee \neg q)$
- "p or q holds, but p and q exclude each other"

  $$(p \vee q) \wedge \neg(p \wedge q)$$

  $$\Leftrightarrow (p \dot{\vee} q) \Leftrightarrow (p \oplus q)$$

  Negation: $p \leftrightarrow q$

3 Exercise 3

Exercise 3. Mister Travelmuch bought a Eurail ticket in August 1980 and has organized a large journey. When moving flats, he list his photo album, he tries to remember, which cities of Paris, Madrid and Rome he visited.

He remembers:

- If he was not in Madrid, then he was in Paris and Rome.
- If he was in Paris, he was not in Madrid and not in Rome.
- If he was not in Paris, he was also not in Rome.

Use appropriate variables for the statements and help Mister Travelmuch determining which cities (or city) he visited in 1980.

Let M, P and R be visits to Madrid, Pairs and Rome respectively. We formalize:

$$\begin{aligned}\neg M &\implies (P \wedge R)\\ P &\implies (\neg M \wedge \neg R)\\ \neg P &\implies \neg R\end{aligned}$$

As far as all three conditions need to be satisfied, we conjoint them:

$$[\neg M \to (P \wedge R)] \wedge [P \to (\neg M \wedge \neg R)] \wedge [\neg P \to \neg R]$$

We apply $(a \to b) \Leftrightarrow (\neg a \vee b)$ to all three statements:

$$[\neg(\neg M) \vee (P \wedge R)] \wedge [\neg P \vee (\neg M \wedge \neg R)] \wedge [\neg(\neg P) \vee \neg R]$$

...and $\neg(\neg A) \Leftrightarrow A$:

$$[M \vee (P \wedge R)] \wedge [\neg P \vee (\neg M \wedge \neg R)] \wedge [P \vee \neg R]$$

...and the distributive law holds:

$$[(M \vee P) \wedge (M \vee R)] \wedge [(\neg P \wedge \neg M) \vee (\neg P \wedge \neg R)] \wedge [P \vee \neg R]$$

We reorder statements:

$$[(M \vee P) \wedge (M \vee R) \wedge (P \vee \neg R)] \wedge [(\neg P \wedge \neg M) \vee (\neg P \wedge \neg R)]$$

...and again the distributive law:

$$[(M \vee P) \wedge (M \vee R) \wedge (P \vee \neg R) \wedge (\neg P \wedge \neg M)] \vee [(M \vee P) \wedge (M \vee R) \wedge (P \vee \neg R) \wedge (\neg P \wedge \neg R)]$$

$$[(M \vee P) \wedge \neg P \wedge \neg M] \vee [(M \vee P) \wedge (M \vee R) \wedge (P \vee \neg R) \wedge (\neg P \wedge \neg R)]$$

The left-hand side cannot be satisfied, but $M \wedge \neg P \wedge \neg R$ holds for the right side. So,

- In 1980, he was in Madrid.
- In 1980, he was not in Paris.
- In 1980, he was not in Rome.

4 Exercise 4

Exercise 4. Let X be a set. Formalize the following colloquial combination of statements $p(x)$, $q(x)$, $r(x)$ and $s(x, y)$ with the help of quantifiers. Also create the negation:

1. "For all elements x of the set X for which $p(x)$ holds, also $q(x)$ or $r(x)$ holds."
2. "For all x in X, there is one y in Y such that $s(x, y)$ holds."
3. "If $p(x)$ is not wrong for all x in X, then $q(y)$ is true for at least one y in Y."

1. “For all elements x of the set X for which $p(x)$ holds, also $q(x)$ or $r(x)$ holds.”

$$\forall x \in X : p(x) \to q(x) \vee r(x)$$

$$\text{negation: } \exists x \in X : p(x) \wedge (\neg q(x) \wedge \neg r(x))$$

2. “For all x in X, there is one y in Y such that $s(x, y)$ holds.”

$$\forall x \in X \exists y \in Y : s(x, y)$$

$$\text{negation: } \exists x \in X \forall y \in Y : \neg s(x, y)$$

3. “If $p(x)$ is not wrong for all x in X, then $q(y)$ is true for at least one y in Y.”

$$(\exists x \in X : p(x)) \to (\exists y \in X : q(y))$$

$$\text{negation: } (\exists x \in X : p(x)) \wedge (\forall y \in X : \neg q(y))$$

5 Exercise 5

Exercise 5. Prove in three ways (direct, indirect, by contradiction):

$$\forall x \in \mathbb{R} : x^3 + 2x > 0 \Rightarrow x > 0$$

Consider ϕ to be given and φ to be our conclusion. Then the three ways of proving work as follows:

Direct proof $\phi \implies \varphi$

Indirect proof $\neg\varphi \implies \neg\phi$
Because $\varphi \vee \neg\phi \Leftrightarrow \neg\phi \vee \varphi \Leftrightarrow \phi \to \varphi$.

Proof by contradiction $(\neg(\phi \implies \varphi) \implies \bot) \implies (\phi \implies \varphi)$
Because $((\phi \to \varphi) \vee \bot) \to (\phi \to \varphi) \Leftrightarrow (\phi \to \varphi) \to (\phi \to \varphi)$.

Direct proof Assume,

$$x(x^2 + 2) > 0$$

This requires that

- both factors are non-zero
- and
  - both factors are negative, or
  - both factors are positive

So,

$$(x \neq 0 \wedge (x^2 + 2) \neq 0) \wedge \big[(x < 0 \wedge (x^2 + 2) < 0) \vee (x > 0 \wedge (x^2 + 2) > 0)\big]$$

As far as a square cannot be negative, $(x^2 + 2) < 0$ does not hold.

$$(x \neq 0 \wedge (x^2 + 2) \neq 0) \wedge \big[(x > 0 \wedge (x^2 + 2) > 0)\big]$$

Therefore it must hold that

$$(x \neq 0) \wedge (x^2 + 2 \neq 0) \wedge (x > 0) \wedge (x^2 + 2 > 0)$$

And so it holds that $x > 0$.

Indirect proof Assume $x \leq 0$. Then $x \cdot x^2 \leq 0$. And also $x \cdot (x^2 + 2) \leq 0$. Which is $x^3 + 2x \leq 0$.

Proof by contradiction Assume $x(x^2+2) > 0 \implies x \leq 0$.

$$\forall x \in \mathbb{R} : x \cdot \underbrace{(x^2+2)}_{\geq 2} > 0 \implies x \leq 0$$
$$\forall x \in \mathbb{R} : \underbrace{x}_{\Rightarrow \geq 0} \cdot \underbrace{(x^2+2)}_{\geq 2} > 0 \implies x \leq 0$$
$$\forall x \in \mathbb{R} : x > 0 \implies x \leq 0$$
$$\lightning$$
$$\Rightarrow \forall x \in \mathbb{R} : x \cdot (x^2+2) > 0 \implies x > 0$$

6 Exercise 6

Exercise 6. Let p, q and r be statements. Show that

- $(p \implies q) \iff \neg(p \implies \neg q)$ "proof by contradiction"
- $[p \implies (q \vee r)] \iff [(p \wedge \neg q) \implies r]$

6.1 Exercise 6a

$$(p \implies q) \iff \neg(p \wedge \neg q)$$
$$(\neg p \vee q) \iff (\neg p \vee q)$$

6.2 Exercise 6b

$$(p \to (q \vee r)) \iff ((p \wedge \neg q) \to r)$$
$$\neg p \vee (q \vee r) \iff \neg(p \wedge \neg q) \vee r$$
$$(\neg p \vee q) \vee r \iff (\neg p \vee q) \vee r$$

7 Exercise 7

Exercise 7. Let A, B, C and D be sets. Prove that

- $(A \setminus B) \cap (A \setminus C) = A \setminus (B \cup C)$
- $(A \setminus B) \cap (C \setminus D) = (A \setminus D) \cap (C \setminus B)$
- $B \subseteq A \implies B = A \setminus (A \setminus B)$

7.1 Exercise 7a

$$(A \setminus B) \cap (A \setminus C) = A \setminus (B \cup C)$$

Let a be a variable which is true if the considered element is contained in A. $\neg a$ is analogously not. Same for b and c. Then:

$$(a \wedge \neg b) \wedge (a \wedge \neg c) = a \wedge \neg(b \vee c)$$
$$a \wedge \neg b \wedge a \wedge \neg c = a \wedge (\neg b \wedge \neg c)$$
$$a \wedge \neg b \wedge \neg c = a \wedge \neg b \wedge \neg c$$
$$\top = \top$$

7.2 Exercise 7b

$$(A \setminus B) \cap (C \setminus D) = (A \setminus D) \cap (C \setminus B)$$
$$(a \wedge \neg b) \wedge (c \wedge \neg d) = (a \wedge \neg d) \wedge (c \wedge \neg b)$$
$$a \wedge \neg b \wedge \neg c = a \wedge \neg b \wedge \neg c$$
$$\top = \top$$

7.3 Exercise 7c

$$B \subseteq A \Rightarrow B = A \setminus (A \setminus B)$$

$$\forall x \in X : (x \in B \Rightarrow x \in A) \implies \left[x \in B \leftrightarrow x \in A \wedge (\underbrace{x \notin A}_{\perp} \vee x \in B))) \right]$$
$$\forall x \in X : (x \in B \Rightarrow x \in A) \implies [x \in B \leftrightarrow x \in A \wedge x \in B]$$
$$\forall x \in X : (x \in B \Rightarrow x \in A) \implies \left[(x \in B \rightarrow \implies x \in A \wedge \underbrace{x \in B}_{\top}) \wedge \underbrace{(x \in A \wedge x \in B \implies x \in B)}_{\top} \right]$$
$$\forall x \in X : (x \in B \Rightarrow x \in A) \implies (x \in B \rightarrow x \in A)$$
$$\forall x \in X : (x \in B \Rightarrow x \in A) \implies \top$$
$$\top$$

8 Exercise 8

Exercise 8. Let X be a set with $X \neq \emptyset$ and $X \neq \{\emptyset\}$. Of which of the following sets is (a) the set X, (b) the set $\{X\}$, element of subset?

S op	$x \in S$	$X \subseteq S$
$\{\{X\}, X\}$	✓(2nd arg)	✗(recursive def required)
X	✗(recursive def required)	✓($X = X$)
$\emptyset \cap \{X\} = \emptyset$	✗	✗(unless $X = \emptyset$)
$\{X\} \setminus \{\{X\}\} = \{X\}$	✓(1st arg)	✗(recursive definition required)
$\{X\} \cup X$	✓(1st arg)	✓($X = X$)
$\{X\} \cup \{\emptyset\}$	✓(1st arg)	✗(recursive definition required)

9 Exercise 9

$(0, \infty)$ is the set $\mathbb{R}_{>0}$

9.1 Exercise 9a

Prove in three ways the following statement:

$$\forall x \in (0, \infty) \forall y \in (0, \infty) : x \neq y \implies \frac{x}{y} + \frac{y}{x} > 2$$

direct proof

$$
\begin{aligned}
x &\neq y \\
x - y &\neq 0 \\
(x-y)^2 &\neq 0 \\
(x-y)^2 &> 0 \\
x^2 - 2xy + y^2 &> 0 && x, y \in \mathbb{R}_{>0} \Rightarrow xy > 0 \\
\frac{x^2}{xy} - \frac{2xy}{xy} + \frac{y^2}{xy} &> 0 \\
\frac{x}{y} - 2 + \frac{y}{x} &> 0 \\
\frac{x}{y} + \frac{y}{x} &> 2
\end{aligned}
$$

indirect proof

$$
\begin{aligned}
\forall x \in (0,\infty) \forall y \in (0,\infty) : \frac{x}{y} + \frac{y}{x} &\leq 2 \Rightarrow x = y \\
\frac{x^2}{xy} + \frac{y^2}{xy} &\leq 2 \\
x^2 + y^2 &\leq 2xy \\
x^2 - 2xy + y^2 &\leq 0 \\
(x-y)^2 &\leq 0 (x-y)^2 && = 0 \\
x - y &= 0 \\
x &= y
\end{aligned}
$$

proof by contradiction

$$
\forall x \in (0,\infty) \forall y \in (0,\infty) : x \neq y \Rightarrow \frac{x}{y} + \frac{y}{x} \leq 2
$$

9.2 Exercise 9b

9.3 Exercise 9c

10 Reminder

If $n < m$, then the ***empty sum*** $\sum_{k=m}^{n} a_k$ has value 0, and the ***empty product*** $\prod_{k=m}^{n} a_k$ has value 1.

11 Exercise 18

Exercise 9. Let $n \in \mathbb{N}_+$. Show that

$$\prod_{k=2}^{n}\left(1-\frac{1}{k}\right)=\frac{1}{n}.$$

Induction base $n = 1$

$$\prod_{k=2}^{1}\cdots = 1 = \frac{1}{1} \qquad \checkmark$$

Induction step $n \to n+1$

$$\begin{aligned}
\prod_{k=2}^{n+1}\left(1-\frac{1}{k}\right) &= \frac{1}{n+1}\\
\prod_{k=2}^{n}\left(1-\frac{1}{k}\right)\left(1-\frac{1}{n+1}\right) &= \frac{1}{n+1}\\
\frac{1}{n}\left(1-\frac{1}{n+1}\right) &= \frac{1}{n+1}\\
\frac{1}{n}\cdot\frac{n+1-1}{n+1} &= \frac{1}{n+1}\\
\frac{n}{n} &= 1 \qquad \checkmark
\end{aligned}$$

Actually, can be rewritten as

$$\begin{aligned}
&\prod_{k=2}^{n}\left(\frac{k-1}{k}\right)\\
&= \frac{1}{2}\cdot\frac{2}{3}\cdot\frac{3}{4}\cdot\frac{4}{5}\cdots\frac{n-1}{n}\\
&= \frac{1}{n}
\end{aligned}$$

So this is the multiplication equivalent of telescoping sums.

12 Exercise 19

Exercise 10. X and Y are non-empty sets and $f : X \to Y$ is a mapping. Furthermore let $A \subseteq X$ and $B \subseteq Y$.

1. Prove that $A \subseteq f^{-1}(f(A))$ and $B \supseteq f(f^{-1}(B))$
2. Show (by providing counterexamples) that in the inclusions of (1) no equivalence is given.

12.1 Exercise 19.1

Show that,

$$a \in A \Rightarrow a \in f^{-1}(f(A))$$

So we take a and map it to the codomain:

$$f(a) \in f(A)$$

We denote the result as y:

$$y \coloneqq f(a)$$

Because

$$f^{-1}(x) = \{x \in A \,|\, f(x) \in B\}$$

we know that a originates from:

$$a \in f^{-1}(f(A))$$

It is very important here to distinguish between ***domain/codomain*** and ***function/inverse function.*** Because an inverse function implies that the corresponding function is injective. Assuming this fact, the exercise is immediate. But we are talking about domains and co-domains here.

As second exercise we need to show that,

$$B \supseteq f\left(f^{-1}(B)\right)$$

We need the definition that,

$$f^{-1}(B) = \{x' \in X \,|\, f(x') \in B\}$$

$$y' \in f(f^{-1}(B))$$

Does $y' \in B$ hold? Yes, because ...

$$\begin{aligned} y' \in f\left(f^{-1}(B)\right) &\Rightarrow \exists x' \in f^{-1}(B) \\ &\Rightarrow y' \in B \end{aligned}$$

12.2 Exercise 19.2

Show that,

$$\exists f : A \subsetneq f^{-1}(f(A))$$

We use a surjective, but not injective function.

$$\begin{aligned} f : \{1, 2\} &\to \{a\} \\ 1 &\mapsto a \\ 2 &\mapsto a \end{aligned}$$

$$\begin{aligned} A &= \{1\} \\ f(A) &= \{a\} \\ f^{-1}(f(A)) &= \{1, 2\} \end{aligned}$$

Show that,

$$\exists f : A \subsetneq f(f^{-1}(A))$$

We use an injective, but not surjective function.

$$\begin{aligned} f : \{1\} &\to \{a, b\} \\ 1 &\mapsto a \end{aligned}$$

$$\begin{aligned} B &= \{b\} \\ f^{-1}(B) &= \emptyset \\ f(f^{-1}(B)) &= \emptyset \end{aligned}$$

13 Exercise 20

Exercise 11. Prove the following variant of Bernoulli's inequality: For $x \in \mathbb{R}$ with $0 < x < 1$ and $n \in \mathbb{N}_+$ it holds that

$$(1-x)^n < \frac{1}{1+nx}.$$

$$\begin{aligned}
(1+x)^n &\geq 1+nx \\
\frac{(1+x)^n}{1+nx} &\geq \frac{1+nx}{1+nx} \\
\frac{(1+x)^n}{1+nx} &\geq 1 \\
\frac{(1-x)^n(1+x)^n}{(1-x)^n(1+nx)} &\geq 1 \\
\frac{(1-x)^n(1+x)^n}{(1+nx)} &\geq (1-x)^n \\
\frac{((1-x)(1+x))^n}{(1+nx)} &\geq (1-x)^n \\
\frac{\left(1-x^2\right)^n}{(1+nx)} &\geq (1-x)^n \\
\frac{\overbrace{\left(1-x^2\right)^n}^{\text{interval } (0,1)}}{(1+nx)} &\geq (1-x)^n \\
\frac{1}{(1+nx)} &> (1-x)^n
\end{aligned}$$

14 Exercise 21

Exercise 12. X and Y are nonempty sets and $f : X \to Y$ is a mapping.

a) Show that the following holds: For all $A, B \subseteq X$

$$f(A \cap B) \subseteq f(A) \cap f(B).$$

b) Show that the following statements are equivalent:

1. f is injective.
2. For all $A, B \subseteq X$ it holds that $f(A \cap B) \supseteq f(A) \cap f(B)$
3. For all $A, B \subseteq X$ it holds that $f(A \cap B) = f(A) \cap f(B)$

14.1 Exercise 21a

Let $C = A \cap B$. Case distinction:

$A = B = C$

$$\begin{aligned}
f(A \cap B) &= \{f(x) \mid x \in A\} \\
f(A) \cap f(B) &= f(A) \\
&= \{f(x) \mid x \in A\}
\end{aligned}$$

$C = A \dot{\vee} C = B$ wlog. $C = A$.

$$\begin{aligned}
f(A \cap B) &= f(A) \\
&= \{f(x) \mid x \in A\} \\
f(A) \cap f(B) &= \{f(x) \mid x \in A\} \cap \{f(x) \mid x \in B\} \\
&= \{f(x) \mid x \in A \wedge x \notin (B \setminus A)\} \\
&= \{f(x) \mid x \in A\}
\end{aligned}$$

$C = \emptyset$

$$\begin{aligned}
f(A \cap B) &= f(\emptyset) \\
&= \emptyset \\
f(A) \cap f(B) &= \{f(x) \mid x \in A\} \cap \{f(x) \mid x \in B\}
\end{aligned}$$

So,

$$C \neq \emptyset \Rightarrow f(A \cap B) = f(A) \cap f(B)$$

But if $C = 0$, we get zero values on the left-hand side and zero to $|A| + |B|$ values on the right-hand side. So,

$$C = \emptyset \Rightarrow f(A \cap B) \subseteq f(A) \cap f(B)$$

14.2 Exercise 21b

We prove 3 with 1:

Let $C = A \cap B$. f is injective, meaning

$$\forall x_1, x_2 \in X : x_1 \neq x_2 \Rightarrow f(x_1) \cap f(x_2)$$

Case distinction:

$A = B = C$

$$\begin{aligned}
f(A \cap B) &= \{f(x) \mid x \in A\} \\
f(A) \cap f(B) &= f(A) \\
&= \{f(x) \mid x \in A\}
\end{aligned}$$

$C = A \dot{\vee} C = B$

wlog. $C = A$ meaning $A \subsetneq B$

$$\begin{aligned}
f(A \cap B) &= f(A) \\
&= \{f(x) \mid x \in A\} \\
f(A) \cap f(B) &= \{f(x) \mid x \in A\} \cap \{f(x) \mid x \in B\} \\
&= \{f(x) \mid x \in A \wedge x \notin (B \setminus A)\} \\
&= \{f(x) \mid x \in A\}
\end{aligned}$$

$C = \emptyset$

$$\begin{aligned}
f(A \cap B) &= f(\emptyset) \\
&= \emptyset \\
f(A) \cap f(B) &= \emptyset
\end{aligned}$$

Every element in A is distinct from values in B. Therefore $\forall x_1 \in A, x_2 \in B : f(x_1) \neq f(x_2)$ because of injectivity. The intersection of all $f(x_i)$ is therefore empty.

15 Exercise 22

Exercise 13. Let $n \in \mathbb{N}$. Use the following idea to derive an equation for the sum of powers of three.

$$\sum_{k=1}^{n} \left(k^4 - (k-1)^4\right)$$

This sum can be written in two different ways:

- As telescoping sum (the initial and trailing value will be left)
- (First resolve the parentheses.) As combination of sums of the third, second, first and zero-th power. With that (and known equations for sums of smaller powers) we can compute $\sum_{k=1}^{n} k^3$.

We look at the telescoping sum:

$$\begin{aligned}
\sum_{k=1}^{n}(k^4 - (k-1)^4) &= \left(1^4 - (1-1)^4\right) + \left(2^4 - (2-1)^4\right) + \left(3^4 - (3-1)^4\right) \\
&\quad + \cdots + \left((n-1)^4 - ((n-1)-1)^4\right) + \left(n^4 - (n-1)^4\right) \\
&= -0^4 + n^4 \\
&= n^4
\end{aligned}$$

Then we use the combination of sums of lower powers.

$$\begin{aligned}
\sum_{k=1}^{n}(k^4 - (k-1)^4) &= \sum_{k=1}^{n}(k^4 - (k^4 - 4k^3 + 6k^2 - 4k + 1)) \\
&= \sum_{k=1}^{n}(k^4 - k^4 + 4k^3 - 6k^2 + 4k - 1) \\
&= \sum_{k=1}^{n}(4k^3 - 6k^2 + 4k - 1) \\
&= \sum_{k=1}^{n} 4k^3 - \sum_{k=1}^{n} 6k^2 + \sum_{k=1}^{n} 4k - \sum_{k=1}^{n} 1 \\
&= \sum_{k=1}^{n} 4k^3 - 6\frac{2n^3 + 3n^2 + n}{6} + 4\frac{n(n+1)}{2} - n \\
&= \sum_{k=1}^{n} 4k^3 - 2n^3 - n^2
\end{aligned}$$

Therefore,

$$\begin{aligned}
n^4 &= \sum_{k=1}^{n} 4k^3 - 2n^3 - n^2 \\
\sum_{k=1}^{n} 4k^3 &= n^4 + 2n^3 + n^2 \\
\sum_{k=1}^{n} k^3 &= \frac{n^4 + 2n^3 + n^2}{4}
\end{aligned}$$

16 Exercise 23

Exercise 14. Let $n \in \mathbb{N}$. Prove that

$$\sum_{k=0}^{n} \binom{n}{k} = 2^n$$

and if $n \geq 1$,

$$\sum_{k=0}^{n} (-1)^k \binom{n}{k} = 0$$

Binomial theorem with $x = 1, y = 1$:

$$\sum_{k=0}^{n} \binom{n}{k} 1^n 1^{n-k} = (1+1)^n$$
$$\sum_{k=0}^{n} \binom{n}{k} = 2^n$$

If $n \geq 1$,

$$\begin{aligned}
\sum_{k=0}^{n} (-1)^k \binom{n}{k} &= \sum_{k=0}^{n} (-1)^k \left(\binom{n-1}{k} + \binom{n-1}{k-1} \right) \\
&= \sum_{k=0}^{n} (-1)^k \binom{n-1}{k} + \sum_{k=0}^{n} (-1)^k \binom{n-1}{k-1} \\
&= (-1)^n \binom{n-1}{n} + \sum_{k=0}^{n-1} (-1)^k \binom{n-1}{k} + \sum_{k=0}^{n} (-1)^k \binom{n-1}{k-1} \\
&= \underbrace{(-1)^n \binom{n-1}{n}}_{0} + \sum_{k=0}^{n-1} (-1)^k \binom{n-1}{k} + \sum_{k=1}^{n} (-1)^k \binom{n-1}{k-1} + \underbrace{(-1)^0 \binom{n-1}{-1}}_{0} \\
&= \sum_{k=0}^{n-1} (-1)^k \binom{n-1}{k} + \sum_{k=0}^{n-1} (-1)^{k+1} \binom{n-1}{k} \\
&= \sum_{k=0}^{n-1} (-1)^k \binom{n-1}{k} - (-1) \sum_{k=0}^{n-1} (-1)^{k+1} \binom{n-1}{k} \\
&= \sum_{k=0}^{n-1} (-1)^k \binom{n-1}{k} - \sum_{k=0}^{n-1} (-1)^{k+2} \binom{n-1}{k} \\
&= \sum_{k=0}^{n-1} (-1)^k \binom{n-1}{k} - \sum_{k=0}^{n-1} (-1)^{k} \binom{n-1}{k} \\
&= 0
\end{aligned}$$

17 Exercise 24

Exercise 15. Let $k, n \in \mathbb{N}_+$ with $k \leq n$. Determine the number of vectors of length k with pairwise different entries from $M_n = \{1, 2, \ldots, n\}$.

This question is covered by the field of combinatorics.

$$(a_0, a_1, a_2, \ldots) \neq (a_0, a_2, a_1, \ldots)$$

The order of elements is relevant. Therefore a variation, not combination, is given. The number of combinations without repetitions would be given by the binomial coefficient $\binom{n}{k}$ (the number of ways to choose k of n elements disregarding their order). For variations the formula n^k holds to select k elements among n arbitrarily often (hence with repetition).

We model the given situation as

- "variation without repetition"
- i.e. "k-permutations of n"
- i.e. the k-th falling factorial power $n^{\underline{k}}$ of n

The formula is given by,

$$P_k^n = \frac{n!}{(n-k)!}$$

We can estimate it in the following way: Consider a combination without repetition represented by the formula $\binom{n}{k}$:

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$

So because we have a variation, not combination, the order of elements is relevant. Therefore given some combination, there are $k!$ possible arrangements. Given the vector (and also combination) $(1, 2, 3)$ there are $k!$ possible arrangements (variations) $\{(1, 2, 3), (1, 3, 2), (2, 1, 3), (2, 3, 1), (3, 1, 2), (3, 2, 1)\}$. Indeed it holds that

$$\frac{3!}{(3-3)!} = \frac{6}{1} = 6$$

This argument explains why $k!$ in the denominator is omitted for variations w/o repetitions.

combinations	variations					
(123)	(123)	(132)	(213)	(231)	(312)	(321)
(124)	(124)	(142)	(214)	(241)	(412)	(421)
(134)	(134)	(143)	(314)	(341)	(413)	(431)
(234)	(234)	(243)	(324)	(342)	(423)	(432)

Table 1: Combinations and variations for $n = 4$ of $k = 3$

18 Exercise 25

Exercise 16. Let K be a field and $a, b, c \in K$. Show (using the field axioms):

(a) $-(-a) = a$.

(b) $(-a)(-b) = ab$.

(c) $a + b = a + c \Rightarrow b = c$.

(d) From $a \neq 0$ and $ab = ac$ follows $b = c$.

(e) Is $a \neq 0$, then there is exactly one $x \in K$ with $ax + b = c$.

The field axioms are defined as follows:

A1 $\forall a, b \in K : a + b = b + a$

A2 $\forall a, b, c \in K : (a + b) + c = a + (b + c)$

A3 $\exists 0 \in K \forall a \in K : a + 0 = a$

A4 $\forall a \in K \exists \tilde{a} : a + \tilde{a} = 0$

M1 $\forall a, b \in K : a \cdot b = b \cdot a$

M2 $\forall a, b, c \in K : a \cdot (b \cdot c) = (a \cdot b) \cdot c$

M3 $\exists 1 \in K : a \cdot 1 = a \forall a \in K$ (neutral element)

M4 $\forall a \in K \setminus \{0\} \, \exists \hat{a} : \hat{a} \cdot a = 1$

D $\forall a, b, c \in K : a \cdot (b + c) = a \cdot b + a \cdot c$

18.1 Exercise 25.a

$$\begin{aligned} A4 &\Rightarrow \forall a \in K \exists -a : a + (-a) = 0 \\ \text{equivalence} &\Rightarrow a + (-a) - (-a) = 0 - (-a) \\ A1 &\Rightarrow a + (-a) - (-a) = -(-a) + 0 \\ A3 &\Rightarrow a + (-a) - (-a) = -(-a) \\ A4 &\Rightarrow a + 0 = -(-a) \\ A3 &\Rightarrow a = -(-a) \end{aligned}$$

18.2 Exercise 25.b

We have proven in the lecture: **M5**: $-a = (-1) \cdot a$

First, we show **M7**

$$\begin{aligned} &= a \cdot (-a) \\ M5 &\Rightarrow a \cdot (-1) \cdot a \\ M1 &\Rightarrow (-1) \cdot a \cdot a \\ &\Rightarrow -(a \cdot a) \end{aligned}$$

Secondly, we show (actually we have already shown that in the lecture) **M6**

$$\begin{aligned} D &\Rightarrow \forall a, b, c \in K : a \cdot (b + c) = a \cdot b + a \cdot c \\ &\quad [\text{we choose} \quad a := a, \quad b := a, \quad c := (-a)] \\ &\Rightarrow a \cdot (a + (-a)) = a \cdot a + a \cdot (-a) \\ A3 &\Rightarrow a \cdot 0 = a \cdot a + a \cdot (-a) \\ \text{previous theorem} &\Rightarrow a \cdot 0 = a \cdot a + (-(a \cdot a)) \\ A4 &\Rightarrow a \cdot 0 = 0 \end{aligned}$$

Finally, we show

$$\begin{aligned}
\text{previous theorem} \Rightarrow & (-a) \cdot 0 = 0 \\
A4 \Rightarrow & (-a) \cdot (b + (-b)) = 0 \\
D \Rightarrow & (-a) \cdot b + (-a)(-b) = 0 \\
\text{equivalence} \Rightarrow & ab + (-a)b + (-a)(-b) = ab + 0 \\
M1 \Rightarrow & ab + (-a)b + (-a)(-b) = 0 + ab \\
A3 \Rightarrow & ab + (-a)b + (-a)(-b) = ab \\
M6 \Rightarrow & ab - ab + (-a)(-b) = ab \\
A4 \Rightarrow & 0 + (-a)(-b) = ab \\
A3 \Rightarrow & (-a)(-b) = ab
\end{aligned}$$

18.3 Exercise 25.c

$$\begin{aligned}
& a + b = a + c \\
\text{equivalence} \Rightarrow & a + b + (-a) = a + c + (-a) \\
A1 \Rightarrow & (a + (-a)) + b = (a + (-a)) + c \\
A4 \Rightarrow & 0 + b = 0 + c \\
A3 \Rightarrow & b = c
\end{aligned}$$

18.4 Exercise 25.d

$$\begin{aligned}
& a \neq 0 \wedge ab = ac \\
\text{equivalence} \Rightarrow & aba^{-1} = aca^{-1} \\
M1 \Rightarrow & aa^{-1}b = aa^{-1}c \\
M4 \Rightarrow & 1b = 1c \\
M3 \Rightarrow & b = c
\end{aligned}$$

18.5 Exercise 25.e

Proof by contradiction. Assume $x_1, x_2 \in K$ with $x_1 \neq x_2$ then $\exists r \in K$:

$$ax_1 = r \qquad ax_2 = r$$

$$ax_1 = ax_2$$

$$\begin{aligned}
& \Rightarrow ax_1 = ax_2 \\
\text{equivalence} \Rightarrow & a^{-1}ax_1 = a^{-1}ax_2 \\
M4 \Rightarrow & 1x_1 = 1x_2 \\
M3 \Rightarrow & x_1 = x_2
\end{aligned}$$

This is a contradiction to our assumption $x_1 \neq x_2$. Therefore x is distinct.

19 Exercise 26

Exercise 17. Let $n \in \mathbb{N}_+$. Prove that

$$\sum_{k=0}^{n} \binom{2n}{2k} = \sum_{k=1}^{n} \binom{2n}{2k-1} = 2^{2n-1}.$$

19.1 Exercise 26.1: $\sum_{k=0}^{n} \binom{2n}{2k} = \sum_{k=1}^{n} \binom{2n}{2k-1}$ - approach 1

Proof.

$$\begin{aligned}
\sum_{k=0}^{n} \binom{2n}{2k} &= \sum_{k=1}^{n-1} \binom{2n}{2k} + 1 + 1 \\
&= \sum_{k=1}^{n-1} \left[\binom{2n-1}{2k} + \binom{2n-1}{2k-1} \right] + 1 + 1 \\
&= \sum_{k=1}^{n-1} \binom{2n-1}{2k} + \sum_{k=1}^{n-1} \binom{2n-1}{2k-1} + 1 + 1 \\
&= \sum_{k=2}^{n} \binom{2n-1}{2(k-1)} + \sum_{k=1}^{n-1} \binom{2n-1}{2k-1} + 1 + 1 \\
&= \sum_{k=1}^{n} \binom{2n-1}{2k-2} + \sum_{k=1}^{n-1} \binom{2n-1}{2k-1} + 1 \\
&= \sum_{k=1}^{n-1} \binom{2n-1}{2k-2} + \sum_{k=1}^{n-1} \binom{2n-1}{2k-1} + \binom{2n-1}{2n-2} + 1 \\
&= \sum_{k=1}^{n-1} \left[\binom{2n-1}{2k-2} + \binom{2n-1}{2k-1} \right] + \binom{2n-1}{2n-2} + 1 \\
&= \sum_{k=1}^{n-1} \binom{2n}{2k-1} + \left[1 + \binom{2n-1}{2n-2} \right] \\
&= \sum_{k=1}^{n-1} \binom{2n}{2k-1} + \left[\binom{2n-1}{2n-1} + \binom{2n-1}{2n-2} \right] \\
&= \sum_{k=1}^{n-1} \binom{2n}{2k-1} + \binom{2n}{2n-1} \\
&= \sum_{k=1}^{n} \binom{2n}{2k-1}
\end{aligned}$$

□

19.2 Exercise 26.1: $\sum_{k=0}^{n} \binom{2n}{2k} = \sum_{k=1}^{n} \binom{2n}{2k-1}$ - approach 2

Proof. Idea: Consider $(1-1)^{2n}$ and split even/odd ks.

$$
\begin{aligned}
(1-1)^{2n} &= \sum_{k=0}^{2n} \binom{2n}{k} (-1)^k 1^{2n-k} && \text{[binomial theorem]} \\
0 &= \sum_{k=0}^{n} \binom{2n}{2k} (-1)^{2k} + \sum_{k=1}^{n} \binom{2n}{2k-1} (-1)^{2k-1} \\
&= \sum_{k=0}^{n} \binom{2n}{2k} + \sum_{k=1}^{n} \binom{2n}{2k-1} (-1) && \text{[$(-1)^{\text{even}}$ is 1, $(-1)^{\text{odd}}$ is -1]} \\
&= \sum_{k=0}^{n} \binom{2n}{2k} - \sum_{k=1}^{n} \binom{2n}{2k-1} \\
\sum_{k=1}^{n} \binom{2n}{2k-1} &= \sum_{k=0}^{n} \binom{2n}{2k}
\end{aligned}
$$

□

19.3 Exercise 26.2: $\sum_{k=0}^{n} \binom{2n}{2k}$

Proof. Idea: Consider $(1+1)^{2n}$ and odd+even provides the factor 2 we need to divide with.

$$
\begin{aligned}
(1+1)^{2n} &= \sum_{k=0}^{2n} \binom{2n}{k} 1^k 1^{2n-k} && \text{[binomial theorem]} \\
2^{2n} &= \sum_{k=0}^{2n} \binom{2n}{k} \\
&= \sum_{k=0}^{n} \binom{2n}{2k} + \sum_{k=1}^{n} \binom{2n}{2k-1} && \text{[split even and odd]} \\
&= \sum_{k=0}^{n} \binom{2n}{2k} + \sum_{k=0}^{n} \binom{2n}{2k} && \text{[from previous result]} \\
&= 2 \sum_{k=0}^{n} \binom{2n}{2k} \\
\frac{2^{2n}}{2} &= \sum_{k=0}^{n} \binom{2n}{2k} \\
2^{2n-1} &= \sum_{k=0}^{n} \binom{2n}{2k}
\end{aligned}
$$

□

20 Exercise 27

Exercise 18. Let $x \in \mathbb{R} \setminus \{0\}$. Show: Let $x + \frac{1}{x} \in \mathbb{Z}$, then $x^n + \frac{1}{x^n} \in \mathbb{Z}$ for all $n \in \mathbb{N}$ (Remark: Consider $(x + \frac{1}{x})^n$.)

So we need to show that,

$$x \in \mathbb{R} \setminus \{0\} : \forall n \in \mathbb{N} : x + \frac{1}{x} \in \mathbb{Z} \implies x^n + \frac{1}{x^n} \in \mathbb{Z}$$

First we need to cover some fundamentals,

- $a, b \in \mathbb{Z} \implies (a+b) \in \mathbb{Z}$
- $a, b \in \mathbb{Z} \implies (a \cdot b) \in \mathbb{Z} \implies \forall n \in \mathbb{N} : a^n \in \mathbb{Z}$

Proof. **IB**: $n = 0$

$$
\begin{aligned}
\forall x \in \mathbb{R} \setminus \{0\} : x + \frac{1}{x} \in \mathbb{Z} \\
&\Rightarrow x = 1 : 1 + \frac{1}{1} \in \mathbb{Z} \\
&\Rightarrow \forall x \in \mathbb{R} \setminus \{0\} : x^0 + \frac{1}{x^0} \in \mathbb{Z} \\
&\Rightarrow \forall x \in \mathbb{R} \setminus \{0\} : n = 0 : x^n + \frac{1}{x^n} \in \mathbb{Z}
\end{aligned}
$$

IB: $n = 1$

$$
\begin{aligned}
\forall x \in \mathbb{R} \setminus \{0\} : x + \frac{1}{x} \in \mathbb{Z} \\
&\Rightarrow \forall x \in \mathbb{R} \setminus \{0\} : x^1 + \frac{1}{x^1} \in \mathbb{Z} \\
&\Rightarrow \forall x \in \mathbb{R} \setminus \{0\} : n = 1 : x^n + \frac{1}{x^n} \in \mathbb{Z}
\end{aligned}
$$

IS: $n \to n+1$ Okay, how does the induction step for an implication look like?

$$
\begin{aligned}
((a \to b) \to (a \to d)) &= \neg(\neg a \lor b) \lor (\neg a \lor d) \\
&= (a \land \neg b) \lor \neg a \lor d \\
&= ((a \lor \neg a) \land (\neg a \lor \neg b)) \lor d \\
&= (\neg a \lor \neg b) \lor d \\
&= (a \land b) \to d
\end{aligned}
$$

Therefore we can assume

$$\left(x + \frac{1}{x} \in \mathbb{Z}\right) \land \left(x^n + \frac{1}{x^n} \in \mathbb{Z}\right)$$

and need to prove that this follows:

$$x^{n+1} + \frac{1}{x^{n+1}} \in \mathbb{Z}$$

$$
\begin{aligned}
\left(x^n + \frac{1}{x^n} \in \mathbb{Z}\right) &= \left(x^n + \frac{1}{x^n}\right)\left(x + \frac{1}{x}\right) \in \mathbb{Z} \\
&= \left(x^n \cdot x + \frac{1}{x^n} \cdot x + x^n \cdot \frac{1}{x} + \frac{1}{x^n} \cdot \frac{1}{x}\right) \in \mathbb{Z} \\
&= \left(x^{n+1} + x^{-n+1} + x^{n-1} + x^{-n-1}\right) \in \mathbb{Z} \\
&= \left(x^{n+1} + x^{-n-1} + x^{n-1} + x^{-n+1}\right) \in \mathbb{Z} \\
&= \left(x^{n+1} + \frac{1}{x^{n+1}}\right) + \underbrace{\left(x^{n-1} + \frac{1}{x^{n-1}}\right)}_{\substack{\in\mathbb{Z} \text{ because of induction hypothesis} \\ \text{and we have a 2-step induction}}} \in \mathbb{Z} \\
&= \left(x^{n+1} + \frac{1}{x^{n+1}}\right) \in \mathbb{Z}
\end{aligned}
$$

$\square$

21 Exercise 28

Exercise 19. Let K be an ordered field and $a, b \in K_+$. Show:

$$a < b \Rightarrow a^2 < b^2$$

Especially the mapping $f : K_+ \cup \{0\} \to K_+ \cup \{0\}, a \mapsto a^2$ is injective.

We already know,

U1 $\forall a, b \in K : a < b \Leftrightarrow b > a$

U2 $\forall a \in K : a^2 = a \cdot a$

U3 $\forall c \in K_+ : a > b \Rightarrow ac > bc$

M1 $\forall a, b \in K : a \cdot b = b \cdot a$

Proof.

$$\begin{aligned}
a < b: \quad & U1 \Rightarrow b > a \\
& U1 \Rightarrow b \cdot a > a \cdot a && \text{[yes, } a \text{ originates from } K_+\text{]} \\
& U2 \Rightarrow b \cdot a > a^2 \\
b > a: \quad & U1 \Rightarrow b \cdot b > a \cdot b && \text{[yes, } b \text{ originates from } K_+\text{]} \\
& U2 \Rightarrow b^2 > a \cdot b \\
& M1 \Rightarrow b^2 > b \cdot a \\
b^2 > b \cdot a \wedge b \cdot a > a^2: \quad & U3 \Rightarrow b^2 > a^2 \\
& U1 \Rightarrow a^2 < b^2 \\
& \Rightarrow \forall a, b \in K_+ : a < b \Rightarrow a^2 < b^2
\end{aligned}$$

□

Injectivity:

$$\forall a_1, a_2 \in K_+ \cup \{0\} : a_1 \neq a_2 \Rightarrow a_1^2 \neq a_2^2$$

Proof. First we consider $a = 0$. In this case, $a = 0$ and $a^2 = a \cdot a = 0 \cdot 0 = 0$ according to the axiom $0 \cdot a = 0$ we have proven in the lecture. So for $a = 0$, there is only one a for which the square is zero, which is 0.

We can proceed in K_+. Proof by contradiction:

$$\exists a_1, a_2 \in K_+ : a_1 \neq a_2 \Rightarrow a_1^2 = a_2^2$$

$$a_1 \neq a_2 \Leftrightarrow a_1 < a_2 \dot{\vee} a_1 > a_2$$

because a_1 and a_2 are elements of an ordered field.

Case 1: $a_1 < a_2$

$$a_1 < a_2 \Rightarrow a_1^2 < a_2^2$$

Case 2: $a_1 > a_2$

$$a_1 > a_2 \Rightarrow a_1^2 > a_2^2$$

Therefore either $a_1^2 < a_2^2$ or $a_1^2 > a_2^2$. So

$$a_1^2 \neq a_2^2$$

This contradicts and therefore $\nexists a_1, a_2 \in K_+ : a_1 \neq a_2 \Rightarrow a_1^2 = a_2^2$ or because we covered $a = 0$,

$$\nexists a_1, a_2 \in K_+ \cup \{0\} : a_1 \neq a_2 \Rightarrow a_1^2 = a_2^2$$

□

22 Exercise 29

Exercise 20. Let K be an ordered field and $a, b \in K$. Show:

$$|\, a+b \,| = |\, a \,| + |\, b \,| \Leftrightarrow ab \geq 0$$

Triangular inequality:

$$\forall a, b \in K : |\, a+b \,| \leq |\, a \,| + |\, b \,|$$

Absolute values are defined with,

$$|\, a \,| = \begin{cases} a & a \in K_+ \\ 0 & a = 0 \\ -a & a \in K_- \end{cases}$$

Proof. Case distinction:

$a = 0, b = 0$

$$\begin{aligned} |\, a+b \,| &\leq |\, a \,| + |\, b \,| \\ |\, a+0 \,| &\leq |\, a \,| + |\, 0 \,| \\ A3 \Rightarrow |\, a \,| &\leq |\, a \,| + 0 \\ A3 \Rightarrow |\, a \,| &= |\, a \,| \end{aligned}$$

$a > 0, b = 0$

$$\begin{aligned} |\, a+b \,| &\leq |\, a \,| + |\, b \,| \\ |\, a+0 \,| &\leq |\, a \,| + |\, 0 \,| \\ A3 \Rightarrow |\, a \,| &\leq |\, a \,| + 0 \\ A3 \Rightarrow |\, a \,| &= |\, a \,| \end{aligned}$$

$a = 0, b > 0$

$$\begin{aligned} |\, a+b \,| &\leq |\, a \,| + |\, b \,| \\ |\, 0+b \,| &\leq |\, 0 \,| + |\, b \,| \\ A3 \Rightarrow |\, b \,| &\leq 0 + |\, b \,| \\ A3 \Rightarrow |\, b \,| &= |\, b \,| \end{aligned}$$

$a > 0, b > 0$

$$\begin{aligned} \underbrace{|\, a+b \,|}_{\in K_+} &\leq \underbrace{|\, a \,|}_{\in K_+} + \underbrace{|\, b \,|}_{\in K_+} \\ (a+b) &\leq (a) + (b) \\ A2 \Rightarrow a+b &\leq a+b \\ a+b &= a+b \end{aligned}$$

$\square$

23 Exercise 33

$$[a_n, b_n], [c_n, d_n], a_n \leq \alpha \leq b_n, c_n \leq \gamma \leq d_n$$
$$\forall \varepsilon > 0 \exists N(\varepsilon) : |\, a_n - b_n \,| < \varepsilon \forall n \geq N(\varepsilon)$$
$$\left[\frac{1}{b_n}, \frac{1}{a_n}\right] \to \frac{1}{b_n} \leq \frac{1}{b_{n+1}} \leq \frac{1}{\alpha} \leq \frac{1}{a_{n+1}} \leq \frac{1}{a_n}$$
$$\left| \frac{1}{b_n} - \frac{1}{a_n} \right| = \frac{a_n - b_n}{a_n b_n} = \frac{|\, a_n - b_n \,|}{|\, a_n \,|\,|\, b_n \,|} \leq \frac{\varepsilon}{|\, a_1 \,|\, \alpha} = \varepsilon'$$

Important: our approximation $a_n \geq a_1 > 0$ and $b_n \geq \alpha$ is independent of n!

$$\forall \varepsilon' > 0 \exists N(\varepsilon') : \left| \frac{1}{b_n} - \frac{1}{a_n} \right| < \varepsilon'$$

$$|\, a_n c_n - b_n d_n \,| = |\, a_n c_n - \alpha c_n + \alpha c_n - \alpha c_n + \alpha\gamma - b_n\gamma + b_n\gamma - b_n d_n \,|$$
$$\leq \underbrace{|\, a_n - \alpha \,|}_{<\varepsilon} \underbrace{|\, c_n \,|}_{\leq\gamma} + |\, \alpha \,| \underbrace{|\, c_n - \gamma \,|}_{<\varepsilon} + \underbrace{|\, \gamma \,|}_{1} \underbrace{|\, \alpha - b_n \,|}_{<\varepsilon} + \underbrace{|\, b_n \,|}_{b_1} \underbrace{|\, \gamma - d_n \,|}_{<\varepsilon} < \varepsilon \underbrace{(2\gamma + \alpha + b_1)}_{=c} = \varepsilon'$$

24 Exercise 35

This exercise was delayed until 26th of November 2015 (later then the other exercises here).

$$(a_n)_{n\in\mathbb{N}} \text{ is sequence with } \lim_{n\to\infty} a_n = a \in \mathbb{R}$$
$$(b_n)_{n\in\mathbb{N}} \text{ is sequence with } \lim_{n\to\infty} b_n = b \in \mathbb{R}$$

Furthermore $b \neq 0$.

24.1 Part 1

$$\lim_{n\to\infty} a_n = a \wedge \lim_{n\to\infty} b_n = b \neq 0$$

Let $\varepsilon > 0$ be arbitrary.

Claim: $\exists k \in \mathbb{N} \forall n \geq k : |\, b_n \,| > \frac{|\, b \,|}{2}$.

Proof: Let $\varepsilon > 0$. Consider $\varepsilon = \frac{|\, b \,|}{2}$.

For $\varepsilon = \frac{|\, b \,|}{2} > 0$:

$$\exists k \in \mathbb{N} : \forall n \geq k : |\, b_n - b \,| < \frac{|\, b \,|}{2} = \varepsilon$$

$$\begin{aligned}\forall n \geq k : |\, b_n \,| = |\, b_n - b + b \,| \geq & \left|\, |\, b \,| - \underbrace{|\, b - b_n \,|}_{< \frac{|\, b \,|}{2}} \,\right| \\ & > |\, b \,| - |\, b - b_n \,| \\ & > |\, b \,| - \frac{|\, b \,|}{2} \\ & = \frac{|\, b \,|}{2}\end{aligned}$$

Claim:

$$\text{sequence } \left(\frac{1}{b_n}\right)_{n\in\mathbb{N}} \wedge \exists \lim \left(\frac{1}{b_n}\right) = \frac{1}{b}$$

Proof: For $\frac{\varepsilon |\, b\, |^2}{2}$:

$$\exists N \in \mathbb{N} : \forall n \geq N : |\, b_n - b\, | < \frac{\varepsilon\, |\, b\, |^2}{2}$$

It holds that $\forall n \geq N$:

$$\left| \frac{1}{b_n} - \frac{1}{b} \right| = \left| \frac{b - b_n}{b_n \cdot b} \right| = \frac{|\, b - b_n\, |}{|\, b_n\, | \cdot |\, b\, |} < \frac{\varepsilon \cdot \frac{|\, b\, |^2}{2}}{\frac{|\, b\, |}{b}\, |\, b\, |} = \varepsilon$$

$$\lim_{n\to\infty} \frac{a_n}{b_n} = \lim_{n\to\infty} a_n \cdot \lim_{n\to\infty} \frac{1}{b_n} = a \cdot \frac{1}{b} \cdot \frac{a}{b}$$

Or a direct proof:

$$\begin{aligned}
\left| \frac{a_n}{b_n} - \frac{a}{b} \right| &= \left| \frac{a_n b - a b_n}{b_n b} \right| \\
&= \frac{|\, a_n b - ab + ab - a b_n\, |}{|\, b_n\, |\, |\, b\, |} \\
&\leq \frac{|\, b\, |\, |\, a_n - a\, | + |\, a\, |\, |\, b_n - b\, |}{\frac{|\, b\, |}{2} \cdot |\, b\, |} \\
&\leq C \cdot \varepsilon
\end{aligned}$$

24.2 Part 2

25 Exercise 36

$$A = \left\{ \frac{1}{2^m} + \frac{1}{n} \,\middle|\, m, n \in \mathbb{N}_+ \right\}$$

Assumption: $\min a = 0$

$$0 \notin A$$

$$\frac{1}{2^N} + \frac{1}{N} < 2\varepsilon$$

$$\forall \varepsilon > 0 \exists N \in \mathbb{N}_+ : (m \geq N \Rightarrow \left| \frac{1}{2^m} - 0 \right| < \varepsilon)$$

$$\frac{1}{2^N} < \varepsilon$$

$$n \geq N \Rightarrow \left| \frac{1}{n} - 0 \right| < \varepsilon$$

Assume $\exists s > 0$ is our lower bound.

$$\exists m : \frac{1}{2^m} < \frac{s}{2} = \varepsilon$$

$$\varepsilon = \frac{s}{2} : \exists N : \frac{1}{N} < \frac{S}{2}$$

$$\rightarrow \underbrace{\frac{1}{sm} + \frac{1}{N}}_{\in A} < s$$

$$\Rightarrow \inf A = 0$$

Remark: When starting this exercise, always estimate whether a maximum/minimum exists. If so, you can save time to prove supremum/infimum.

$$\frac{1}{2^{m+1}} < \frac{1}{2^m} \forall m$$

$$\frac{1}{N+1} < \frac{1}{N} \forall N$$

Therefore $\max A$ is when m, n is as small as possible:

$$\frac{1}{2} + \frac{1}{1} = \frac{3}{2}$$

$$\max(A) = \frac{3}{2} = \sup(A)$$

$$B = \left\{ \frac{x}{1+x} \,\middle|\, x \in \mathbb{R}, x \geq 0 \right\}$$

$\min(B) = 0$ because $0 \leq \frac{x}{1+x} \forall x \geq 0 \land \left. \frac{x}{1+x} \right|_{x=0} = 0$.

$$\frac{x}{1+x} < 1 \Leftrightarrow x < 1 + x \Leftrightarrow 0 < 1 \forall x \geq 0$$

Is 1 an upper bound and $1 \notin B$?

Assume $\exists s < 1$:

$$\frac{x}{1+x} \leq s$$
$$x \leq s(1+x)$$
$$x(1-s) \leq 0$$
$$1 - s > 0$$
$$\Rightarrow \sup(B) = 1 \land \nexists \max(B)$$

26 Exercise 37

$$I = [a, b) = \{x \in \mathbb{R} \mid a \leq x < b\}$$
$$a = \min [a, b) \Rightarrow a \text{ is } \inf([a, b))$$
$$a \in [a, b) : \forall x \in [a, b) : a \leq x \Rightarrow \min(I) = a \Rightarrow \inf(I) = a$$

b is upper bound:

$$b \notin [a, b) \text{ by definition } \forall x \in [a, b) : b > x$$

Claim: b is the smallest upper bound.
Assume: $\exists b' < b : b'$ is upper bound.

$$b' \in [a, b) \qquad \underbrace{\grave{}}_{\text{because } \mathbb{R} \text{ is complete}}$$

27 Exercise 38

> **Exercise 21.** Let A and B two non-empty, bounded by below subseteq of $\mathbb{R}$. Prove that
>
> $$\inf(A \cup B) = \min \{\inf(A), \inf(B)\}$$

Without loss of generality, $\inf A \leq \inf B$:

Let $a \in A$ and $b \in B$ arbitrary. This implies that $a \geq \inf A$ and $b \geq \inf B \geq \inf A$.

$$\Rightarrow \forall x \in (A \cup B) : x \geq \inf A$$

$$\Rightarrow \inf(A) \geq \inf(A \cup B)$$

Because extending a set A with additional elements, the infimum cannot be increased, but only decreased.

$$\Rightarrow \inf(A) \leq \inf(A \cup B)$$

$$x \in A : \inf\{\inf A, \inf B\} \leq \inf(A) \leq x$$
$$x \in B : \inf\{\inf A, \inf B\} \leq \inf(B) \leq x$$
$$\forall x \in A \cup B : \underbrace{\min\{\inf A, \inf B\}}_{\text{lower bound}} \leq x$$

$$\Rightarrow \inf(A \cup B) \leq \min\{\inf(A), \inf(B)\}$$

$$\Rightarrow \inf(A) = \inf(A \cup B)$$

28 Exercise 39

28.1 Exercise 39a

$$\sup_{y \in Y} \inf_{x \in X} f(x,y) \leq \inf_{x \in X} \sup_{y \in Y} f(x,y)$$
$$\underbrace{\inf_{x \in X} f(x,y) \leq f(x,y)}_{\sup_{y \in Y}} \leq \sup_{y \in Y} f(x,y)$$
$$\sup_{y \in Y} \inf_{x \in X} f(x,y) \leq \sup_{y \in Y} f(x,y)$$
$$\sup_{y \in Y} \inf_{x \in X} f(x,y) = \inf_{x \in X} \sup_{y \in Y} \inf_{x \in X} f(x,y) \leq \inf_{x \in X} \sup_{y \in Y} f(x,y) \quad \checkmark$$

28.2 Exercise 39b

$$f : (x,y) \mapsto 1_{\{x \geq 0, y \geq 0\} \cup \{x < 0, y < 0\}}$$
$$\sup_{y \in Y} f(x,y) = 1 \forall x$$
$$\inf_{x \in X} \sup_{y \in Y} f(x,y) = 1$$
$$\inf_{x \in X} f(x,y) = 0 \forall y \in [-1,1]$$
$$\sup_{y \in Y} \inf_{x \in X} f(x,y) = 0 < 1$$

29 Exercise 40

29.1 Exercise 40.a.1

$$\frac{5+i}{2+3i} \cdot \frac{2-3i}{2-3i} = \frac{10-15i+2i-3i^2}{-6i+4+6i-9i^2} = \frac{10-13i+3}{4+9} = \frac{13-13i}{13} = 1-i$$

29.2 Exercise 40.a.2

$$z^2 = \frac{1+\sqrt{3}i}{2}$$
$$z^2 = \pm\sqrt{\frac{1}{2} + \frac{\sqrt{3}i}{2}}$$
$$z^2 = \pm\sqrt{\frac{9+6\sqrt{3}i-3}{12}}$$
$$z^2 = \pm\sqrt{\frac{(3+\sqrt{3}i)^2}{12}}$$
$$z^2 = \pm\frac{3+\sqrt{3}i}{\sqrt{12}}$$
$$z^2 = \pm\left(\frac{\sqrt{3}}{2} + i\frac{1}{2}\right)$$

29.3 Exercise 40.b.1

$$M_1 = \left\{ z \in \mathbb{C} \setminus \{0\} \,\middle|\, \left|\frac{1}{z}\right| < 2 \right\}$$
$$\left|\frac{1}{z}\right| = \left|\frac{1}{a+bi}\right| = \frac{|\,1\,|}{|\,a+bi\,|} = \frac{1}{\sqrt{a^2+b^2}}$$
$$\Rightarrow \frac{1}{\sqrt{a^2+b^2}} < 2$$
$$\Rightarrow \frac{1}{2} < \sqrt{a^2+b^2}$$
$$\Rightarrow \frac{1}{4} < a^2+b^2$$

Illustrated we draw a circle originating in $(0,0)$ with radius $\frac{1}{2}$. The solution set is the whole plane excluding everything what is part of the circle.

29.4 Exercise 40.b.2

$$M_2 = \{z \in \mathbb{C} \,|\, \Im((1+i)z) = 0\}$$
$$\Im(z+zi)$$

TODO

30 Exercise 41

$$A_n := (-\infty, a_n)_{n\in\mathbb{N}} \qquad A := \bigcup_{n\in\mathbb{N}} A_n$$
$$B_n := (b_n, \infty)_{n\in\mathbb{N}} \qquad B := \bigcup_{n\in\mathbb{N}} B_n$$

$$\forall n \in \mathbb{N} : x \in I_n$$

Show that $x = \sup A = \inf B$.

Because I_n are nested intervals it holds that

$$a_1 \leq \cdots \leq a_n \leq a_{n+1} \leq x$$

Because

$$\forall \varepsilon > 0 \exists N : N \geq n : 0 \leq x - a_x \leq b_n - a_n \leq \varepsilon$$

it holds that

$$x = \sup(a_n)$$

Let $y \in A$.

$$\exists n \in \mathbb{N} : y \in A_n \Rightarrow y < a_n \leq x$$
$$\Rightarrow y \in A : y < x$$

Therefore x is an upper bound. Is it the only upper bound?

Assume another upper bound x' exists.

$$x' < x = \lim) n \to \infty a_n$$
$$\Rightarrow \exists N \in \mathbb{N} : x' < a_n \qquad \forall n \geq M$$
$$\varepsilon = \frac{x - x'}{2}$$
$$\Rightarrow \exists y \in A_{n+1}$$
$$y > x'$$

This is a contradiction and therefore x is the distinct upper bound.

The proof for the infimum works analogously.

It only remains to show that $x \notin A$.

$$\forall a_n \neq x \Rightarrow \exists a_{n+k} : a_n < a_{n+k}$$

31 Exercise 42

Give the limes for the following sequences:

31.1 Exercise 42.a

$$a_n = \frac{5n+2}{3n+7}$$

$$\begin{aligned}
\lim_{n\to\infty} a_n &= \frac{5n+2}{3n+7} \\
&= \frac{\lim_{n\to\infty} 5n+2}{\lim_{n\to\infty} 3n+7} \\
&= \frac{\lim_{n\to\infty} 5n + \lim_{n\to\infty} 2}{\lim_{n\to\infty} 3n + \lim_{n\to\infty} 7} \\
&= \frac{n(5+\frac{2}{n})}{n(3+\frac{7}{n})} \\
&= \frac{5 + \overbrace{\frac{2}{n}}^{\to 0}}{3 + \underbrace{\frac{7}{n}}_{\to 0}} \\
&= \frac{5}{3}
\end{aligned}$$

This works only if the denominator is non-zero. $\lim_{n\to\infty}(3 + \frac{7}{n})$ turns out to be non-zero.

31.2 Exercise 42.b

$$b_n = \frac{2n^2 - 4n + 5}{n^3 + 2\sqrt{n}}$$

First, we make a remark, that $\lim_{n\to\infty} \frac{1}{n^2} = 0$. Why, because

$$\lim_{n\to\infty} \frac{1}{n^2} = \left(\lim_{n\to\infty} \frac{1}{n}\right) \cdot \left(\lim_{n\to\infty} \frac{1}{n}\right) = 0$$

This can be generalized for $\lim_{n\to\infty} \frac{1}{n^k} = 0$ with $k \in \mathbb{N}_+$.

$$\begin{aligned}
\lim_{n\to\infty} b_n &= \frac{2n^2 - 4n + 5}{n^3 + 2\sqrt{n}} \\
&= \frac{n^3 \cdot \left(\frac{2}{n} - \frac{4}{n^2} + \frac{5}{n^2}\right)}{n^3 \cdot \left(1 + 2\frac{n^{0.5}}{n^3}\right)} \\
&= \frac{\frac{2}{n} - \frac{4}{n^2} + \frac{5}{n^3}}{1 + 2 \cdot \frac{1}{n^{2.5}}} \\
&= \frac{\frac{2}{n} - \frac{4}{n^2} + \frac{5}{n^3}}{\frac{n^{2.5}}{n^{2.5}}} \\
&= \frac{2n^{1.5} - 4n^{0.5} + 5n^{0.5}}{n^{2.5} + 2} \cdot \frac{\frac{1}{n^{2.5}}}{\frac{1}{n^{2.5}}} \\
&= \frac{2n^{-1} - 4n^{-2} + 5n^{-3}}{1 + 2n^{-2.5}} \\
&= \frac{0}{1}
\end{aligned}$$

Or generally:

$$2n^2 - 4n + 5 \le 2n^2 + 4n^2 + 5n^2 \le 11n^2$$

$$0 \le b_n \le \frac{11n^2}{n^3} = \underbrace{\frac{11}{n}}_{\to 0}$$

31.3 Exercise 42.c

$$c_n = \sqrt{4n^2 + 2n + 3}$$

$$\begin{aligned}
c_n &= \sqrt{4n^2 + 2n + 3} \cdot \frac{\sqrt{4n^2 + 2n + 3}}{\sqrt{4n^2 + 2n + 3} + 2n} \\
&= \dots \\
&= \frac{2 + \frac{3}{n}}{\sqrt{4 + \frac{2}{n} + \frac{3}{n^2}} + 2} \\
&= \frac{2}{4} \\
&= \frac{1}{2}
\end{aligned}$$

31.4 Exercise 42.d

$$d_n = \binom{n}{k} n^{-k} \text{ with } n \in \mathbb{N} \text{ for a fixed } k \in \mathbb{N}_+$$

$$\begin{aligned}
d_n &= \binom{n}{k} n^{-k} \\
&= \frac{n!}{k!(n-k)!n^k} \\
&= \frac{n \cdot (n-1) \cdot \dots \cdot 1}{k!(n-k)!n^k} \\
&= \frac{n \cdot (n-1) \cdot \dots \cdot 1}{k!(n-k)!n^k} \\
&= \frac{(1-\frac{1}{n})(1-\frac{2}{n}) \cdot \dots \cdot (1-\frac{k-1}{n}) \cdot (n-k) \cdot \dots \cdot 1}{k!(n-k)!} \\
&= \frac{(n-k)!}{k!(n-k)!} \\
&= \frac{1}{k!}
\end{aligned}$$

Or better we write:

$$\begin{aligned}
\frac{n!}{k!(n-k)!} &= \frac{\prod_{i=0}^{n-1}(n-i)}{\prod_{j=k}^{n-1}(n-j)} \\
&= \frac{1}{k!} \prod_{j=0}^{k-1} (n-j) n^{-k} \\
&= \frac{1}{k!} \prod_{j=0}^{k-1} \left[(n-j) \cdot \frac{1}{n} \right] \\
&= \frac{1}{k!} \prod_{j=0}^{k-1} \left(1 - \frac{j}{n} \right) \\
\lim_{n\to\infty} \frac{1}{k!} \prod_{j=0}^{k-1} \left(1 - \frac{j}{n} \right) &= \frac{1}{k!} \lim_{n\to\infty} \prod_{j=0}^{k-1} \left(1 - \frac{j}{n} \right) && \text{[if limes exist]} \\
&= \frac{1}{k!} \prod_{j=0}^{k-1} \underbrace{\lim_{n\to\infty} \left(1 - \frac{j}{n} \right)}_{=1} \\
&= \frac{1}{k!} \forall j = 0, \dots, k-1
\end{aligned}$$

32 Exercise 43

Exercise 22. Let $(a_n)_{n\in\mathbb{N}}$ be a sequence in $\mathbb{R}_+$ with $\lim_{n\to\infty} \frac{a_{n+1}}{a_n} = q$. Prove that

$$(a_n)_{n\in\mathbb{N}} \begin{cases} \text{converges} & \text{if } q < 1 \\ \text{diverges} & \text{if } q > 1 \end{cases}$$

In case $q = 1$ no statement about the convergence of $(a_n)_{n\in\mathbb{N}}$ can be made.

$$\lim_{n\to\infty} \frac{a_{n+1}}{a_n} = q$$

32.1 Examples for $q = 1$

$$a_n = \frac{1}{n+1} \qquad \frac{a_{n+1}}{a_n}\frac{n+1}{n+2} \to_{n\to\infty} 1 \qquad a_m \searrow 0$$

$$a_n = n+1 \qquad \frac{a_{n+1}}{a_n} = \frac{n+2}{n+1} \to_{n\to\infty} 1 \qquad a_n \nearrow 0$$

32.2 Proof for $q < 1$

$$\exists \underbrace{\varepsilon}_{=\frac{q+1}{2}-a} > 0 : q + \varepsilon < 1$$

If n is sufficiently large:

$$\left| \frac{a_{n+1}}{a_n} - q \right| < \varepsilon \Rightarrow \frac{a_{n+1}}{a_n} \in (q-\varepsilon, q+\varepsilon)$$

$$\begin{gathered} 0 \le a_{n+1} \le (q+\varepsilon)a_n \\ 0 \le a_{n+2} \le (q+\varepsilon)^2 a_n \\ \dots \\ 0 \le a_{n+k} \le (q+\varepsilon)^k a_n \end{gathered}$$

By induction it holds that

$$0 \le a_{n+k} \le \underbrace{(q+\varepsilon)}_{\tilde{q}<1}{}^k a_1 \to_{k\to\infty} 0$$

This follows from the squeeze theorem.

$$\forall q > 1 \exists \varepsilon > 0 : q - \varepsilon > 1$$

$$\begin{gathered} a_{n+1} > (q-\varepsilon)a_n \\ a_{n+k} > \underbrace{(q-\varepsilon)}_{\tilde{q}>1}{}^k a_n \end{gathered}$$

$$\begin{gathered} \lim_{n\to\infty} \tilde{q}^k = +\infty \\ \tilde{q} > 1 \end{gathered}$$

33 Exercise 44

> **Exercise 23.** Let $(a_n)_{n\in\mathbb{N}}$ be a zero sequence in $\mathbb{R}$ and $(b_n)_{n\in\mathbb{N}}$ a bounded sequence in $\mathbb{R}$. Prove that $(a_n b_n)_{n\in\mathbb{N}}$ is a zero sequence.

Because $(b_n)_{n\in\mathbb{N}}$ is bounded some d exists such that

$$\forall \varepsilon > 0 : \exists N \in \mathbb{N} : n \ge N : |\, a_n - 0 \,| < \varepsilon$$

Consider $\lim_{n\to\infty}(a_n \cdot b_n) = 0$.

We need to show that

$$\forall \varepsilon > 0 \exists N \in \mathbb{N} : n \ge N : |\, a_n \cdot b_n - 0 \,| < \varepsilon \cdot d$$

Where $\varepsilon \cdot d$ is epsilon multiplied with constant d. This is a hand-crafted value (meaning that we selected it intentionally and will turn out to solve our problem). Now we elaborate on the relation:

$$\begin{aligned} |\, a_n \cdot b_n \,| &< \varepsilon \cdot d \\ |\, a_n \,| \cdot |\, b_n \,| &< \varepsilon \cdot d \\ |\, a_n \,| \cdot d &< \varepsilon \cdot d \\ |\, a_n \,| &< \varepsilon \end{aligned}$$

Because $a_n < \varepsilon$ it holds that some constant exists for a sufficiently large N such that $|\, a_n \cdot b_n \,|$ is always smaller than some constant ε.