Theory of Computer Science

B1. Propositional Logic I

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B1.1 Motivation

Why Logic?

- formalizing mathematics
  - What is a true statement?
  - What is a valid proof?
- basis of many tools in computer science
  - design of digital circuits
  - semantics of databases; query optimization
  - meaning of programming languages
  - verification of safety-critical hardware/software
  - knowledge representation in artificial intelligence
  - logic-based programming languages (e.g. Prolog)
  - ...

Application: Logic Programming I

Declarative approach: Describe what to accomplish
not how to accomplish it.

Example (Map Coloring)

Color each region in a map with a limited number of colors
so that no two adjacent regions have the same color.

CC BY-SA 3.0 Wikimedia Commons (TUBS)

This is a hard problem!

Application: Logic Programming II

Prolog program

```
color(red). color(blue). color(green). color(yellow).

neighbor(StateAColor, StateBColor) :-
    color(StateAColor), color(StateBColor),
    StateAColor \= StateBColor.

switzerland(AG, AI, AR, BE, BL, BS, FR, GE, GL, GR,
            JU, LU, NE, NW, OW, SG, SH, SO, SZ, TG,
            TI, UR, VD, VS, ZG, ZH) :-
    neighbor(AG, BE), neighbor(AG, BL), neighbor(AG, LU),
    ...
    neighbor(UR, VS), neighbor(VD, VS), neighbor(ZH, ZG).
```

What Logic is About

General Question:

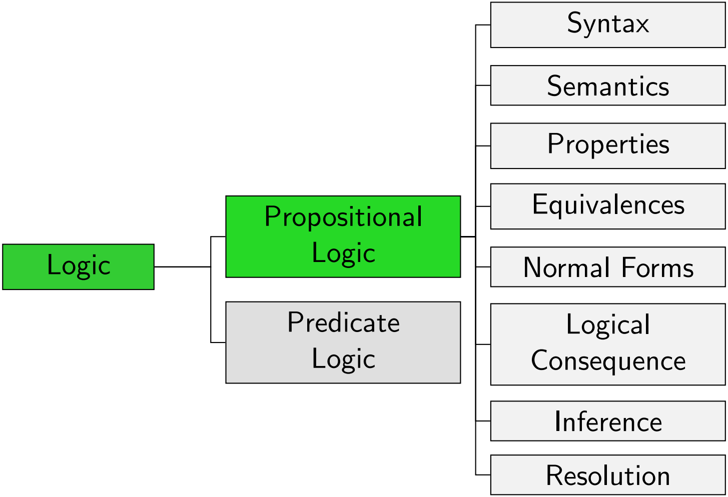
- Given some knowledge about the world (a knowledge base)
- what can we derive from it?
- And on what basis may we argue?

$\rightsquigarrow$ logic

Goal: "mechanical" proofs

- formal "game with letters"
- detached from a concrete meaning

Logic: Overview



Task

What's the secret of your long life?

I am on a strict diet: If I don't drink beer to a meal, then I always eat fish. Whenever I have fish and beer with the same meal, I abstain from ice cream. When I eat ice cream or don't drink beer, then I never touch fish.

Simplify this advice!

Exercise from U. Schöning: Logik für Informatiker
Picture courtesy of graur razvan ionut / FreeDigitalPhotos.net

Propositional Logic

Propositional logic is a simple logic without numbers or objects.

Building blocks of propositional logic:

- propositions are statements that can be either true or false
- atomic propositions cannot be split into sub-propositions
- logical connectives connect propositions to form new ones

German: Aussagenlogik, Aussage, atomare Aussage, Junktoren

Examples for Building Blocks

If I don't drink beer to a meal, then I always eat fish. Whenever I have fish and beer with the same meal, I abstain from ice cream. When I eat ice cream or don't drink beer, then I never touch fish.

- Every sentence is a proposition that consists of sub-propositions (e. g., "eat ice cream or don't drink beer").
- atomic propositions "drink beer", "eat fish", "eat ice cream"
- logical connectives "and", "or", negation, "if, then"

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Examples for Building Blocks

If I don't drink beer to a meal, then I always eat fish. Whenever I have fish and beer with the same meal, I abstain from ice cream. When I eat ice cream or don't drink beer, then I never touch fish.

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Problems with Natural Language

> If I don't drink beer to a meal, then I always eat fish.
> Whenever I have fish and beer with the same meal, I abstain from ice cream.
> When I eat ice cream or don't drink beer, then I never touch fish.

- "irrelevant" information

Exercise from U. Schöning: Logik für Informatiker
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Problems with Natural Language

If I don't drink beer, then I eat fish.
Whenever I have fish and beer, I abstain from ice cream.
When I eat ice cream or don't drink beer, then I never touch fish.

- "irrelevant" information
- different formulations for the same connective/proposition

Exercise from U. Schöning: Logik für Informatiker
Picture courtesy of graur razvan ionut / FreeDigitalPhotos.net

Problems with Natural Language

If not DrinkBeer, then EatFish.
If EatFish and DrinkBeer,
then not EatIceCream.
If EatIceCream or not DrinkBeer,
then not EatFish.

- "irrelevant" information
- different formulations for the same connective/proposition

Exercise from U. Schöning: Logik für Informatiker
Picture courtesy of graur razvan ionut / FreeDigitalPhotos.net

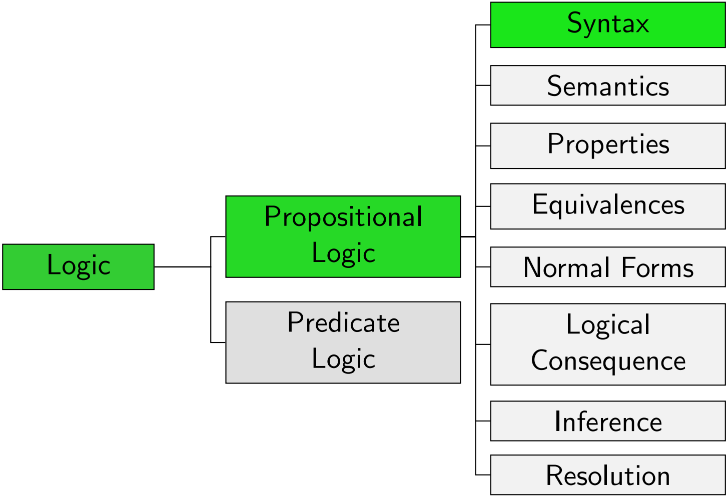
What is Next?

- What are meaningful (well-defined) sequences of atomic propositions and connectives?
  "if then EatIceCream not or DrinkBeer and" not meaningful
  $\rightarrow$ syntax
- What does it mean if we say that a statement is true?
  Is "DrinkBeer and EatFish" true?
  $\rightarrow$ semantics
- When does a statement logically follow from another?
  Does "EatFish" follow from "if DrinkBeer, then EatFish"?
  $\rightarrow$ logical entailment

German: Syntax, Semantik, logische Folgerung

B1.2 Syntax

Logic: Overview



Syntax of Propositional Logic

Definition (Syntax of Propositional Logic)

Let A be a set of atomic propositions. The set of propositional formulas (over A) is inductively defined as follows:

- Every atom $a \in A$ is a propositional formula over A.
- If φ is a propositional formula over A, then so is its negation $\neg\varphi$.
- If φ and ψ are propositional formulas over A, then so is the conjunction $(\varphi \land \psi)$.
- If φ and ψ are propositional formulas over A, then so is the disjunction $(\varphi \lor \psi)$.

The implication $(\varphi \rightarrow \psi)$ is an abbreviation for $(\neg\varphi \lor \psi)$.
The biconditional $(\varphi \leftrightarrow \psi)$ is an abbrev. for $((\varphi \rightarrow \psi) \land (\psi \rightarrow \varphi))$.
German: atomare Aussage, aussagenlogische Formel, Atom, Negation, Konjunktion, Disjunktion, Implikation, Bikonditional

Syntax: Examples

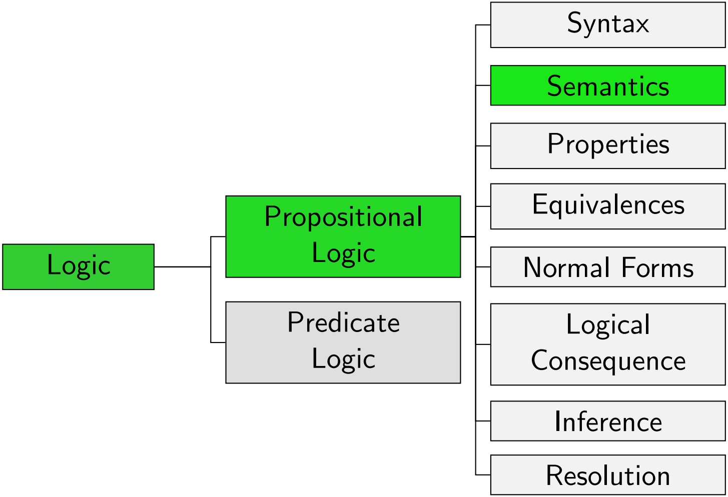
Which of the following sequences of symbols are propositional formulas over the set of all possible letter sequences?

- $(\mathrm{A} \land (\mathrm{B} \lor \mathrm{C}))$
- $((\mathrm{EatFish} \land \mathrm{DrinkBeer}) \rightarrow \neg\mathrm{EatIceCream})$
- $\neg(\land \mathrm{Rain} \lor \mathrm{StreetWet})$
- $\neg(\mathrm{Rain} \lor \mathrm{StreetWet})$
- $\neg(\mathrm{A} = \mathrm{B})$
- $(\mathrm{A} \land \neg(\mathrm{B} \leftrightarrow)\mathrm{C})$
- $(\mathrm{A} \lor \neg(\mathrm{B} \leftrightarrow \mathrm{C}))$
- $((\mathrm{A} \leq \mathrm{B}) \land \mathrm{C})$
- $((\mathrm{A}_1 \land \mathrm{A}_2) \lor \neg(\mathrm{A}_3 \leftrightarrow \mathrm{A}_2))$

Which kinds of formula are they (atom, conjunction, ...)?

B1.3 Semantics

Logic: Overview



Meaning of Propositional Formulas?

So far propositional formulas are only symbol sequences without any meaning.

For example, what does this mean:
$((\mathsf{EatFish} \land \mathsf{DrinkBeer}) \rightarrow \neg\mathsf{EatIceCream})$?

▷ We need semantics!

Semantics of Propositional Logic

Definition (Semantics of Propositional Logic)

A truth assignment (or interpretation) for a set of atomic propositions A is a function $\mathcal{I} : A \to \{0, 1\}$.

A propositional formula φ (over A) holds under $\mathcal{I}$ (written as $\mathcal{I} \models \varphi$) according to the following definition:

$$
\begin{array}{lll l}
\mathcal{I} \models a & \text{iff} & \mathcal{I}(a) = 1 & \text{(for } a \in A) \\
\mathcal{I} \models \neg\varphi & \text{iff} & \text{not } \mathcal{I} \models \varphi & \\
\mathcal{I} \models (\varphi \land \psi) & \text{iff} & \mathcal{I} \models \varphi \text{ and } \mathcal{I} \models \psi & \\
\mathcal{I} \models (\varphi \lor \psi) & \text{iff} & \mathcal{I} \models \varphi \text{ or } \mathcal{I} \models \psi &
\end{array}
$$

Question: should we define semantics of $(\varphi \to \psi)$ and $(\varphi \leftrightarrow \psi)$?

German: Wahrheitsbelegung/Interpretation, φ gilt unter $\mathcal{I}$

Semantics of Propositional Logic: Terminology

- For $\mathcal{I} \models \varphi$ we also say $\mathcal{I}$ is a model of φ and that φ is true under $\mathcal{I}$.
- If φ does not hold under $\mathcal{I}$, we write this as $\mathcal{I} \not\models \varphi$ and say that $\mathcal{I}$ is no model of φ and that φ is false under $\mathcal{I}$.
- Note: $\models$ is not part of the formula but part of the meta language (speaking about a formula).

German: $\mathcal{I}$ ist ein/kein Modell von φ; φ ist wahr/falsch unter $\mathcal{I}$; Metasprache

Semantics: Example (1)

$A = \{\text{DrinkBeer}, \text{EatFish}, \text{EatIceCream}\}$

$\mathcal{I} = \{\text{DrinkBeer} \mapsto 1, \text{EatFish} \mapsto 0, \text{EatIceCream} \mapsto 1\}$

$\varphi = (\neg\text{DrinkBeer} \rightarrow \text{EatFish})$

Do we have $\mathcal{I} \models \varphi$?

Semantics: Example (2)

Goal: prove $\mathcal{I} \models \varphi$.

Let us use the definitions we have seen:

$$\begin{aligned}\mathcal{I} \models \varphi \text{ iff } & \mathcal{I} \models (\neg \mathsf{DrinkBeer} \rightarrow \mathsf{EatFish}) \\ \text{iff } & \mathcal{I} \models (\neg\neg \mathsf{DrinkBeer} \lor \mathsf{EatFish}) \\ \text{iff } & \mathcal{I} \models \neg\neg \mathsf{DrinkBeer} \text{ or } \mathcal{I} \models \mathsf{EatFish}\end{aligned}$$

This means that if we want to prove $\mathcal{I} \models \varphi$, it is sufficient to prove

$$\mathcal{I} \models \neg\neg \mathsf{DrinkBeer}$$

or to prove

$$\mathcal{I} \models \mathsf{EatFish}.$$

We attempt to prove the first of these statements.

Semantics: Example (3)

New goal: prove $\mathcal{I} \models \neg\neg\text{DrinkBeer}$.

We again use the definitions:

$$\begin{aligned}\mathcal{I} \models \neg\neg\text{DrinkBeer} &\text{ iff not } \mathcal{I} \models \neg\text{DrinkBeer}\\ &\text{ iff not not } \mathcal{I} \models \text{DrinkBeer}\\ &\text{ iff } \mathcal{I} \models \text{DrinkBeer}\\ &\text{ iff } \mathcal{I}(\text{DrinkBeer}) = 1\end{aligned}$$

The last statement is true for our interpretation $\mathcal{I}$.

To write this up as a proof of $\mathcal{I} \models \varphi$,
we can go through this line of reasoning back-to-front,
starting from our assumptions and ending with the conclusion
we want to show.

Semantics: Example (4)

Let $\mathcal{I} = \{\text{DrinkBeer} \mapsto 1, \text{EatFish} \mapsto 0, \text{EatIceCream} \mapsto 1\}$.

Proof that $\mathcal{I} \models (\neg\text{DrinkBeer} \rightarrow \text{EatFish})$:

(1) We have $\mathcal{I} \models \text{DrinkBeer}$
(uses defn. of $\models$ for atomic props. and fact $\mathcal{I}(\text{DrinkBeer}) = 1$).

(2) From (1), we get $\mathcal{I} \not\models \neg\text{DrinkBeer}$
(uses defn. of $\models$ for negations).

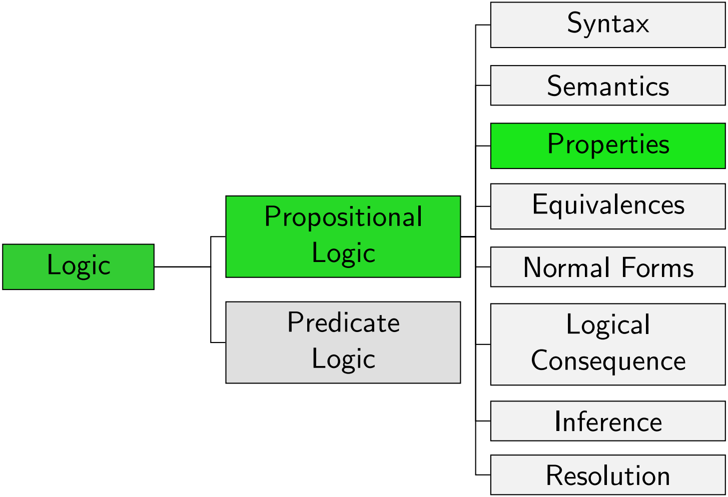
(3) From (2), we get $\mathcal{I} \models \neg\neg\text{DrinkBeer}$
(uses defn. of $\models$ for negations).

(4) From (3), we get $\mathcal{I} \models (\neg\neg\text{DrinkBeer} \vee \psi)$ for all formulas ψ,
in particular $\mathcal{I} \models (\neg\neg\text{DrinkBeer} \vee \text{EatFish})$
(uses defn. of $\models$ for disjunctions).

(5) From (4), we get $\mathcal{I} \models (\neg\text{DrinkBeer} \rightarrow \text{EatFish})$
(uses defn. of "$\rightarrow$"). □

B1.4 Properties of Propositional Formulas

Logic: Overview



Properties of Propositional Formulas

A propositional formula φ is

- satisfiable if φ has at least one model
- unsatisfiable if φ is not satisfiable
- valid (or a tautology) if φ is true under every interpretation
- falsifiable if φ is no tautology

German: erfüllbar, unerfüllbar, gültig/eine Tautologie, falsifizierbar

How can we show that a formula has one of these properties?

Examples

- Show that $(A \land B)$ is satisfiable.
  $\mathcal{I} = \{A \mapsto 1, B \mapsto 1\}$ (+ simple proof that $\mathcal{I} \models (A \land B)$)
- Show that $(A \land B)$ is falsifiable.
  $\mathcal{I} = \{A \mapsto 0, B \mapsto 1\}$ (+ simple proof that $\mathcal{I} \not\models (A \land B)$)
- Show that $(A \land B)$ is not valid.
  Follows directly from falsifiability.
- Show that $(A \land B)$ is not unsatisfiable.
  Follows directly from satisfiability.

So far all proofs by specifying one interpretation.

How to prove that a given formula is valid/unsatisfiable/
not satisfiable/not falsifiable?

$\rightsquigarrow$ must consider all possible interpretations

Truth Tables

Evaluate for all possible interpretations
if they are models of the considered formula.

$\mathcal{I}(\mathsf{A})$	$\mathcal{I} \models \neg\mathsf{A}$
0	Yes
1	No

$\mathcal{I}(\mathsf{A})$	$\mathcal{I}(\mathsf{B})$	$\mathcal{I} \models (\mathsf{A} \wedge \mathsf{B})$
0	0	No
0	1	No
1	0	No
1	1	Yes

$\mathcal{I}(\mathsf{A})$	$\mathcal{I}(\mathsf{B})$	$\mathcal{I} \models (\mathsf{A} \vee \mathsf{B})$
0	0	No
0	1	Yes
1	0	Yes
1	1	Yes

Truth Tables in General

Similarly in the case where we consider a formula whose building blocks are themselves arbitrary unspecified formulas:

$\mathcal{I} \models \varphi$	$\mathcal{I} \models \psi$	$\mathcal{I} \models (\varphi \wedge \psi)$
No	No	No
No	Yes	No
Yes	No	No
Yes	Yes	Yes

Truth Tables for Properties of Formulas

Is $\varphi = ((A \rightarrow B) \vee (\neg B \rightarrow A))$ valid, unsatisfiable, ...?

$\mathcal{I}(A)$	$\mathcal{I}(B)$	$\mathcal{I} \models \neg B$	$\mathcal{I} \models (A \rightarrow B)$	$\mathcal{I} \models (\neg B \rightarrow A)$	$\mathcal{I} \models \varphi$
0	0	Yes	Yes	No	Yes
0	1	No	Yes	Yes	Yes
1	0	Yes	No	Yes	Yes
1	1	No	Yes	Yes	Yes

Connection Between Formula Properties and Truth Tables

A propositional formula φ is

- satisfiable if φ has at least one model
  $\rightsquigarrow$ result in at least one row is "Yes"
- unsatisfiable if φ is not satisfiable
  $\rightsquigarrow$ result in all rows is "No"
- valid (or a tautology) if φ is true under every interpretation
  $\rightsquigarrow$ result in all rows is "Yes"
- falsifiable if φ is no tautology
  $\rightsquigarrow$ result in at least one row is "No"

Main Disadvantage of Truth Tables

How big is a truth table with n atomic propositions?

1	2 interpretations (rows)
2	4 interpretations (rows)
3	8 interpretations (rows)
n	??? interpretations

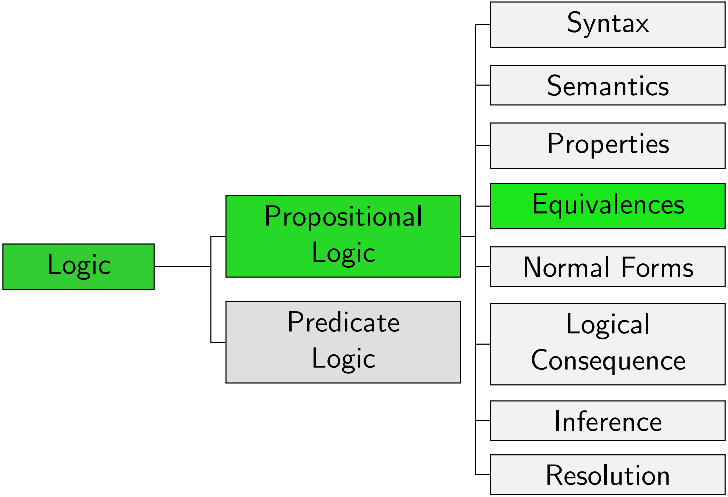
Some examples: $2^{10} = 1024$, $2^{20} = 1048576$, $2^{30} = 1073741824$

$\rightsquigarrow$ not viable for larger formulas; we need a different solution

- more on difficulty of satisfiability etc.: Part E of this course
- practical algorithms: Foundations of AI course

B1.5 Equivalences

Logic: Overview



Equivalent Formulas

Definition (Equivalence of Propositional Formulas)

Two propositional formulas φ and ψ over A are (logically) equivalent ($\varphi \equiv \psi$) if for all interpretations $\mathcal{I}$ for A it is true that $\mathcal{I} \models \varphi$ if and only if $\mathcal{I} \models \psi$.

German: logisch äquivalent

Equivalent Formulas: Example

$$((\varphi \lor \psi) \lor \chi) \equiv (\varphi \lor (\psi \lor \chi))$$

$\mathcal{I} \models \varphi$	$\mathcal{I} \models \psi$	$\mathcal{I} \models \chi$	$\mathcal{I} \models (\varphi \lor \psi)$	$\mathcal{I} \models (\psi \lor \chi)$	$\mathcal{I} \models ((\varphi \lor \psi) \lor \chi)$	$\mathcal{I} \models (\varphi \lor (\psi \lor \chi))$
No	No	No	No	No	No	No
No	No	Yes	No	Yes	Yes	Yes
No	Yes	No	Yes	Yes	Yes	Yes
No	Yes	Yes	Yes	Yes	Yes	Yes
Yes	No	No	Yes	No	Yes	Yes
Yes	No	Yes	Yes	Yes	Yes	Yes
Yes	Yes	No	Yes	Yes	Yes	Yes
Yes	Yes	Yes	Yes	Yes	Yes	Yes

Some Equivalences (1)

$$(\varphi \land \varphi) \equiv \varphi$$
$$(\varphi \lor \varphi) \equiv \varphi \qquad \text{(idempotence)}$$

$$(\varphi \land \psi) \equiv (\psi \land \varphi)$$
$$(\varphi \lor \psi) \equiv (\psi \lor \varphi) \qquad \text{(commutativity)}$$

$$((\varphi \land \psi) \land \chi) \equiv (\varphi \land (\psi \land \chi))$$
$$((\varphi \lor \psi) \lor \chi) \equiv (\varphi \lor (\psi \lor \chi)) \qquad \text{(associativity)}$$

German: Idempotenz, Kommutativität, Assoziativität

Some Equivalences (2)

$$(\varphi \land (\varphi \lor \psi)) \equiv \varphi$$
$$(\varphi \lor (\varphi \land \psi)) \equiv \varphi \qquad \text{(absorption)}$$

$$(\varphi \land (\psi \lor \chi)) \equiv ((\varphi \land \psi) \lor (\varphi \land \chi))$$
$$(\varphi \lor (\psi \land \chi)) \equiv ((\varphi \lor \psi) \land (\varphi \lor \chi)) \qquad \text{(distributivity)}$$

German: Absorption, Distributivität

Some Equivalences (3)

$$\neg\neg\varphi \equiv \varphi \qquad \text{(Double negation)}$$

$$\neg(\varphi \land \psi) \equiv (\neg\varphi \lor \neg\psi)$$
$$\neg(\varphi \lor \psi) \equiv (\neg\varphi \land \neg\psi) \qquad \text{(De Morgan's rules)}$$

$$(\varphi \lor \psi) \equiv \varphi \text{ if } \varphi \text{ tautology}$$
$$(\varphi \land \psi) \equiv \psi \text{ if } \varphi \text{ tautology} \qquad \text{(tautology rules)}$$

$$(\varphi \lor \psi) \equiv \psi \text{ if } \varphi \text{ unsatisfiable}$$
$$(\varphi \land \psi) \equiv \varphi \text{ if } \varphi \text{ unsatisfiable} \qquad \text{(unsatisfiability rules)}$$

German: Doppelnegation, De Morgansche Regeln, Tautologieregeln, Unerfüllbarkeitsregeln

Substitution Theorem

Theorem (Substitution Theorem)

Let φ and φ' be equivalent propositional formulas over A. Let ψ be a propositional formula with (at least) one occurrence of the subformula φ.

Then ψ is equivalent to ψ', where ψ' is constructed from ψ by replacing an occurrence of φ in ψ with φ'.

German: Ersetzbarkeitstheorem

(without proof)

Application of Equivalences: Example

$$
\begin{aligned}
(P \land (\neg Q \lor P)) &\equiv ((P \land \neg Q) \lor (P \land P)) && \text{(distributivity)} \\
&\equiv ((P \land \neg Q) \lor P) && \text{(idempotence)} \\
&\equiv (P \lor (P \land \neg Q)) && \text{(commutativity)} \\
&\equiv P && \text{(absorption)}
\end{aligned}
$$

Summary

- propositional logic based on atomic propositions
- syntax defines what well-formed formulas are
- semantics defines when a formula is true
- interpretations are the basis of semantics
- satisfiability and validity are important properties of formulas
- truth tables systematically consider all possible interpretations
- truth tables are only useful for small formulas
- Logical equivalence describes when formulas are semantically indistinguishable.
- Equivalence rewriting is used to simplify formulas and to bring them in normal forms (next lecture).