

# Discrete Mathematics in Computer Science

## D2. Properties of Formulas and Equivalences

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## D2.1 Properties of Propositional Formulas

## D2.2 Equivalences

# D2.1 Properties of Propositional Formulas

# The Story So Far

- ▶ **propositional logic** based on atomic propositions
- ▶ **syntax**: which formulas are well-formed?
- ▶ **semantics**: when is a formula true?
- ▶ **interpretations**: important basis of semantics

# Reminder: 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  $\varphi$  is a propositional formula over  $A$ , then so is its **negation**  $\neg\varphi$ .
- ▶ If  $\varphi$  and  $\psi$  are propositional formulas over  $A$ , then so is the **conjunction**  $(\varphi \wedge \psi)$ .
- ▶ If  $\varphi$  and  $\psi$  are propositional formulas over  $A$ , then so is the **disjunction**  $(\varphi \vee \psi)$ .

The **implication**  $(\varphi \rightarrow \psi)$  is an abbreviation for  $(\neg\varphi \vee \psi)$ .

The **biconditional**  $(\varphi \leftrightarrow \psi)$  is an abbrev. for  $((\varphi \rightarrow \psi) \wedge (\psi \rightarrow \varphi))$ .

# Reminder: Semantics of Propositional Logic

## Definition (Semantics of Propositional Logic)

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

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

$\mathcal{I} \models a$	iff	$\mathcal{I}(a) = 1$	(for $a \in A$ )
$\mathcal{I} \models \neg\varphi$	iff	not $\mathcal{I} \models \varphi$	
$\mathcal{I} \models (\varphi \wedge \psi)$	iff	$\mathcal{I} \models \varphi$ and $\mathcal{I} \models \psi$	
$\mathcal{I} \models (\varphi \vee \psi)$	iff	$\mathcal{I} \models \varphi$ or $\mathcal{I} \models \psi$	

# Properties of Propositional Formulas

A propositional formula  $\varphi$  is

- ▶ **satisfiable** if  $\varphi$  has at least one model
- ▶ **unsatisfiable** if  $\varphi$  is not satisfiable
- ▶ **valid** (or a **tautology**) if  $\varphi$  is true under every interpretation
- ▶ **falsifiable** if  $\varphi$  is no tautology

**German:** erfüllbar, unerfüllbar, allgemeingültig/eine Tautologie, falsifizierbar

# Examples

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

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

$\leadsto$  must consider **all possible** interpretations



# Truth Tables

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

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

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

$\mathcal{I}(A)$	$\mathcal{I}(B)$	$\mathcal{I} \models (A \vee B)$
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  $\varphi$  is

- ▶ **satisfiable** if  $\varphi$  has at least one model  
     $\rightsquigarrow$  result in at least one row is “Yes”
- ▶ **unsatisfiable** if  $\varphi$  is not satisfiable  
     $\rightsquigarrow$  result in all rows is “No”
- ▶ **valid** (or a **tautology**) if  $\varphi$  is true under every interpretation  
     $\rightsquigarrow$  result in all rows is “Yes”
- ▶ **falsifiable** if  $\varphi$  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:  $2^{10} = 1024$ ,  $2^{20} = 1048576$ ,  $2^{30} = 1073741824$

↪ not viable for larger formulas; we need a different solution

- ▶ more on difficulty of satisfiability etc.:  
Theory of Computer Science course
- ▶ practical algorithms: Foundations of AI course

## D2.2 Equivalences

# Equivalent Formulas

## Definition (Equivalence of Propositional Formulas)

Two propositional formulas  $\varphi$  and  $\psi$  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

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

$\mathcal{I} \models \varphi$	$\mathcal{I} \models \psi$	$\mathcal{I} \models \chi$	$\mathcal{I} \models (\varphi \vee \psi)$	$\mathcal{I} \models (\psi \vee \chi)$	$\mathcal{I} \models ((\varphi \vee \psi) \vee \chi)$	$\mathcal{I} \models (\varphi \vee (\psi \vee \chi))$
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)

$$(\varphi \wedge \varphi) \equiv \varphi$$

$$(\varphi \vee \varphi) \equiv \varphi$$

(idempotence)

$$(\varphi \wedge \psi) \equiv (\psi \wedge \varphi)$$

$$(\varphi \vee \psi) \equiv (\psi \vee \varphi)$$

(commutativity)

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

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

(associativity)

**German:** Idempotenz, Kommutativität, Assoziativität

## Some Equivalences (2)

$$(\varphi \wedge (\varphi \vee \psi)) \equiv \varphi$$

$$(\varphi \vee (\varphi \wedge \psi)) \equiv \varphi \quad (\text{absorption})$$

$$(\varphi \wedge (\psi \vee \chi)) \equiv ((\varphi \wedge \psi) \vee (\varphi \wedge \chi))$$

$$(\varphi \vee (\psi \wedge \chi)) \equiv ((\varphi \vee \psi) \wedge (\varphi \vee \chi)) \quad (\text{distributivity})$$

**German:** Absorption, Distributivität

## Some Equivalences (3)

$$\neg\neg\varphi \equiv \varphi \quad (\text{double negation})$$

$$\neg(\varphi \wedge \psi) \equiv (\neg\varphi \vee \neg\psi)$$

$$\neg(\varphi \vee \psi) \equiv (\neg\varphi \wedge \neg\psi) \quad (\text{De Morgan's rules})$$

$$(\varphi \vee \psi) \equiv \varphi \text{ if } \varphi \text{ tautology}$$

$$(\varphi \wedge \psi) \equiv \psi \text{ if } \varphi \text{ tautology} \quad (\text{tautology rules})$$

$$(\varphi \vee \psi) \equiv \psi \text{ if } \varphi \text{ unsatisfiable}$$

$$(\varphi \wedge \psi) \equiv \varphi \text{ if } \varphi \text{ unsatisfiable} \quad (\text{unsatisfiability rules})$$

**German:** Doppelnegation, De Morgansche Regeln,  
Tautologieregeln, Unerfüllbarkeitsregeln

# Substitution Theorem

## Theorem (Substitution Theorem)

*Let  $\varphi$  and  $\varphi'$  be equivalent propositional formulas over  $A$ .*

*Let  $\psi$  be a propositional formula with (at least) one occurrence of the subformula  $\varphi$ .*

*Then  $\psi$  is equivalent to  $\psi'$ , where  $\psi'$  is constructed from  $\psi$  by replacing an occurrence of  $\varphi$  in  $\psi$  with  $\varphi'$ .*

German: Ersetzbarkeitstheorem

(without proof)

## Application of Equivalences: Example

$$\begin{aligned}(P \wedge (Q \vee \neg P)) &\equiv ((P \wedge Q) \vee (P \wedge \neg P)) && \text{(distributivity)} \\ &\equiv ((P \wedge \neg P) \vee (P \wedge Q)) && \text{(commutativity)} \\ &\equiv (P \wedge Q) && \text{(unsatisfiability rule)}\end{aligned}$$