PROPOSITIONAL LOGIC IN NON-CNF

VL Logik: WS 2019/20

(Version 2019.3)

Martina Seidl (martina.seidl@jku.at),
Armin Biere (biere@jku.at)
Institut für Formale Modelle und Verifikation
Example: Party Planning

We want to plan a party.

Unfortunately, the selection of the guests is not straightforward.

We have to consider the following rules.

1. If two people are married, we have to invite them both or none of them. Alice is married to Bob and Cecile is married to David.
2. If we invite Alice then we also have to invite Cecile. Cecile does not care if we invite Alice but not her.
3. David and Eva can't stand each other, so it is not possible to invite both. One of them should be invited.
4. We want to invite Bob and Fred.

Question: Can we find a guest list?
Party Planning with Propositional Logic

- **propositional variables:**
  - inviteAlice, inviteBob, inviteCecile, inviteDavid, inviteEva, inviteFred

- **constraints:**
  1. invite married: inviteAlice $\leftrightarrow$ inviteBob, inviteCecile $\leftrightarrow$ inviteDavid
  2. if Alice then Cecile: inviteAlice $\rightarrow$ inviteCecile
  3. either David or Eva: $\neg$ (inviteEva $\leftrightarrow$ inviteDavid)
  4. invite Bob and Fred: inviteBob $\land$ inviteFred

- **encoding in propositional logic:**
  
  $$(\text{inviteAlice }\leftrightarrow \text{inviteBob}) \land (\text{inviteCecile }\leftrightarrow \text{inviteDavid}) \land \\
  (\text{inviteAlice }\rightarrow \text{inviteCecile}) \land \neg (\text{inviteEva }\leftrightarrow \text{inviteDavid}) \land \\
  \text{inviteBob} \land \text{inviteFred}$$
The set $\mathcal{L}$ of well-formed propositional formulas is the smallest set such that

1. $\top, \bot \in \mathcal{L}$;
2. $\mathcal{P} \subseteq \mathcal{L}$ where $\mathcal{P}$ is the set of atomic propositions (atoms, variables);
3. if $\phi \in \mathcal{L}$ then $(\neg \phi) \in \mathcal{L}$;
4. if $\phi, \psi \in \mathcal{L}$ then $(\phi \circ \psi) \in \mathcal{L}$ with $\circ \in \{\lor, \land, \leftrightarrow, \rightarrow\}$.

$\mathcal{L}$ is the language of propositional logic. The elements of $\mathcal{L}$ are propositional formulas.
Rules of Precedence

To reduce the number of parenthesis, we use the following conventions (in case of doubt, uses parenthesis!):

- $\neg$ is stronger than $\land$
- $\land$ is stronger than $\lor$
- $\lor$ is stronger than $\rightarrow$
- $\rightarrow$ is stronger than $\leftrightarrow$
- Binary operators of same strength are assumed to be left parenthesized (also called “left associative”)

Example:

- $\neg a \land b \lor c \rightarrow d \leftrightarrow f$ is the same as (((((\neg a) \land b) \lor c) \rightarrow d) \leftrightarrow f).
- $a' \lor a'' \lor a''' \land b' \lor b''$ is the same as (((a' \lor a'') \lor (a''' \land b')) \lor b'').
- $a' \land a'' \land a''' \lor b' \land b''$ is the same as (((a' \land a'') \land a''') \lor (b' \land b'')).
Excursus: Rooted Tree

A rooted tree is a special kind of graph of the following shape:

- A single vertex \( v \) is a tree.
  
  The vertex \( v \) is the root of this tree.

- Let \( t_1, \ldots, t_n \) be \( n \) trees, such that
  
  - \( t_1 \) has root \( v_1 \)
  
  - \( \ldots \)
  
  - \( t_n \) has root \( v_n \).

  Further, let \( v \) be a vertex not occurring in \( t_1, \ldots, t_n \). We obtain a tree with root \( v \) if we add edges from \( v \) to \( v_1, \ldots, v_n \).

  The vertices \( v_1, \ldots, v_n \) are called children of \( v \).

- Nothing else is a tree.

A node without children is called leaf.
**Formula Tree**

- formulas have a tree structure
  - **inner nodes**: connectives
  - **leaves**: truth constants, variables

- **default**: inner nodes have one child node (negation) or two nodes as children (other connectives).

- tree structure reflects the use of parenthesis

- **simplification**: disjunction and conjunction may be considered as \( n \)-ary operators, i.e., if a node \( N \) and its child node \( C \) are of the same kind of connective (conjunction / disjunction), then the children of \( C \) can become direct children of \( N \) and the \( C \) is removed.
The formula

\[(a \lor (b \lor \neg c)) \leftrightarrow (\top \land ((a \rightarrow \neg b) \lor (\bot \lor a \lor b)))\]

has the formula tree
The formula

\[(a \lor (b \lor \neg c)) \leftrightarrow (\top \land ((a \rightarrow \neg b) \lor (\bot \lor a \lor b)))\]

has the simplified formula tree
Subformulas

An immediate subformula is defined as follows:

- truth constants and atoms have no immediate subformula.
- only immediate subformula of \( \neg \phi \) is \( \phi \).
- formula \( \phi \circ \psi \) (\( \circ \in \{\land, \lor, \leftrightarrow, \rightarrow\} \)) has immediate subformulas \( \phi \) and \( \psi \).

Informal: a subformula is a formula that is part of a formula

The set of subformulas of a formula \( \phi \) is the smallest set \( S \) with

1. \( \phi \in S \)
2. if \( \psi \in S \) then all immediate subformulas of \( \psi \) are in \( S \)

The subformulas of \( (a \lor b) \rightarrow (c \land \neg\neg d) \) are

\[ \{a, b, c, d, \neg d, \neg \neg d, a \lor b, c \land \neg \neg d, (a \lor b) \rightarrow (c \land \neg \neg d)\} \]
Excursus: Backus-Naur Form (BNF)

- notation technique for describing the syntax of a language
- elements:
  - non-terminal symbols (variables): enclosed in brackets ⟨⟩
  - ::= indicates the definition of a non-terminal symbol
  - the symbol | means “or”
  - all other symbols stand for themselves (sometimes they are quoted, e.g., “->”)

example: definition of the language of decimal numbers in BNF:

⟨number⟩ ::= ⟨integer⟩ “.” ⟨integer⟩

⟨integer⟩ ::= ⟨digit⟩ | ⟨digit⟩ ⟨integer⟩

⟨digit⟩ ::= 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 0

some words: 0.0, 1.1, 123.546, 01.10000, …
Limboole

- SAT-solver
- available at http://fmv.jku.at/limboole/
- input format in BNF:

\[
\langle expr \rangle ::= \langle iff \rangle \\
\langle iff \rangle ::= \langle implies \rangle \mid \langle implies \rangle "<->" \langle implies \rangle \\
\langle implies \rangle ::= \langle or \rangle \mid \langle or \rangle "->\" \langle or \rangle \mid \langle or \rangle "<-" \langle or \rangle \\
\langle or \rangle ::= \langle and \rangle \mid \langle and \rangle "|" \langle and \rangle \\
\langle and \rangle ::= \langle not \rangle \mid \langle not \rangle "&" \langle not \rangle \\
\langle not \rangle ::= \langle basic \rangle \mid "!" \langle not \rangle \\
\langle basic \rangle ::= \langle var \rangle \mid "(" \langle expr \rangle ")"
\]

where 'var' is a string over letters, digits, and \(-\_@\)

In Limboole the formula \((a \lor b) \rightarrow (c \land \neg \neg d)\) is represented as

\(((a \mid b) \rightarrow (c \& !!d))\)
Negation

- unary connective \( \neg \) (operator with exactly one argument)
- negating the truth value of its argument
- alternative notation: \( !\phi, \phi, -\phi, NOT\phi \)

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<thead>
<tr>
<th>( \phi )</th>
<th>( \neg\phi )</th>
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Example:
- If the atom “It rains.” is true then the negation “It does not rain.” is false.
- If atom \( a \) is true then \( \neg a \) is false.
- If formula \( ((a \lor x) \land y) \) is true then formula \( \neg ((a \lor x) \land y) \) is false.
- If formula \( ((b \rightarrow y) \land z) \) is true then formula \( \neg ((b \rightarrow y) \land z) \) is false.
Conjunction

- A conjunction is true iff both arguments are true.
- Alternative notation for $\phi \land \psi$: $\phi \& \psi$, $\phi \psi$, $\phi \ast \psi$, $\phi \cdot \psi$, $\phi \text{AND} \psi$.
- For $(\phi_1 \land \ldots \land \phi_n)$ we also write $\land_{i=1}^{n} \phi_i$.

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>$\phi \land \psi$</th>
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**Truth table:**

**Set view:**

**Example:**

- $(a \land \neg a)$ is always false.
- $(\top \land a)$ is true if $a$ is true. $(\bot \land \phi)$ is always false.
- If $(a \lor b)$ is true and $(\neg c \lor d)$ is true then $(a \lor b) \land (\neg c \lor d)$ is true.
Disjunction

- a disjunction is true iff at least one of the arguments is true
- alternative notation for \( \phi \lor \psi \): \( \phi | \psi \), \( \phi + \psi \), \( \phi \text{OR} \psi \)
- For \( \phi_1 \lor \ldots \lor \phi_n \) we also write \( \lor_{i=1}^{n} \phi_i \).

truth table:

<table>
<thead>
<tr>
<th>( \phi )</th>
<th>( \psi )</th>
<th>( \phi \lor \psi )</th>
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<tbody>
<tr>
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Example:

- \( (a \lor \neg a) \) is always true.
- \( (\top \lor a) \) is always true. \( (\bot \lor a) \) is true if \( a \) is true.
- If \( (a \rightarrow b) \) is true and \( (\neg c \rightarrow d) \) then \( (a \rightarrow b) \lor (\neg c \rightarrow d) \) is true.
Implication

- An implication is true iff the first argument is false or both arguments are true (Ex falso quodlibet.)
- Alternative notation: $\phi \supset \psi, \phi \text{ IMPL } \psi$

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<tr>
<th>$\phi$</th>
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<th>$\phi \rightarrow \psi$</th>
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Truth table:

Set view:

Example:
- If atom "It rains." is true and atom "The street is wet." is true then the statement "If it rains, the street is wet." is true.
- $(\perp \rightarrow a)$ and $(a \rightarrow a)$ are always true. $\top \rightarrow \phi$ is true if $\phi$ is true.
Equivalence

- true iff both subformulas have the same value
- alternative notation: $\phi = \psi$, $\phi \equiv \psi$, $\phi \sim \psi$

Truth table:

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<tr>
<th>$\phi$</th>
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<th>$\phi \leftrightarrow \psi$</th>
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Example:
- The formula $a \leftrightarrow a$ is always true.
- The formula $a \leftrightarrow b$ is true iff $a$ is true and $b$ is true or $a$ is false and $b$ is false.
- $\top \leftrightarrow \bot$ is never true.
The Logic Connectives at a Glance

<table>
<thead>
<tr>
<th>φ</th>
<th>ψ</th>
<th>⊤</th>
<th>⊥</th>
<th>¬φ</th>
<th>φ ∧ ψ</th>
<th>φ ∨ ψ</th>
<th>φ → ψ</th>
<th>φ ←→ ψ</th>
<th>φ ⊕ ψ</th>
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Example:

<table>
<thead>
<tr>
<th>φ</th>
<th>ψ</th>
<th>¬(¬φ ∧ ¬ψ)</th>
<th>¬φ ∨ ψ</th>
<th>(φ → ψ) ∧ (ψ → φ)</th>
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Observation: connectives can be expressed by other connectives.
Other Connectives

- there are 16 different functions for binary connectives
- so far, we had $\land$, $\lor$, $\leftrightarrow$, $\rightarrow$
- further connectives:
  - $\phi \leftrightarrow \psi$ (also $\oplus$, xor, antivalence)
  - $\phi \uparrow \psi$ (nand, Sheffer Stroke Function)
  - $\phi \downarrow \psi$ (nor, Pierce Function)

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>$\phi \leftrightarrow \psi$</th>
<th>$\phi \uparrow \psi$</th>
<th>$\phi \downarrow \psi$</th>
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- nor and nand can express every other boolean function (i.e., they are functional complete)
- often used for building digital circuits (like processors)
Propositional Formulas and Digital Circuits

- **and gate**
  - Inputs: A, B
  - Output: A AND B

- **nand gate**
  - Inputs: A, B
  - Output: NOT (A AND B)

- **or gate**
  - Inputs: A, B
  - Output: A OR B

- **nor gate**
  - Inputs: A, B
  - Output: NOT (A OR B)

- **xor gate**
  - Inputs: A, B
  - Output: A XOR B

- **not gate**
  - Input: A
  - Output: NOT A
Example of a Digital Circuit: Half Adder

<table>
<thead>
<tr>
<th>$x$</th>
<th>$y$</th>
<th>$c$</th>
<th>$s$</th>
</tr>
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<tbody>
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</table>

From the truth table, we see that

$c \iff x \land y$

and

$s \iff x \oplus y.$
<table>
<thead>
<tr>
<th>operator</th>
<th>logic</th>
<th>circuits</th>
<th>Java</th>
<th>Python</th>
<th>Limboole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \top )</td>
<td>1</td>
<td>true</td>
<td>true</td>
<td>–</td>
</tr>
<tr>
<td>0</td>
<td>( \bot )</td>
<td>0</td>
<td>false</td>
<td>false</td>
<td>–</td>
</tr>
<tr>
<td>negation</td>
<td>( \neg \phi )</td>
<td>( !\phi )</td>
<td>( \neg \phi )</td>
<td>( !\phi )</td>
<td>not ( \phi )</td>
</tr>
<tr>
<td>conjunction</td>
<td>( \phi \land \psi )</td>
<td>( \phi \psi )</td>
<td>( \phi \cdot \psi )</td>
<td>( \phi &amp;&amp; \psi )</td>
<td>( \phi \ \text{and} \ \psi )</td>
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<tr>
<td>disjunction</td>
<td>( \phi \lor \psi )</td>
<td>( \phi + \psi )</td>
<td>( \phi \parallel \psi )</td>
<td>( \phi \ \text{or} \ \psi )</td>
<td>( \phi \</td>
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<tr>
<td>exclusive or</td>
<td>( \phi \leftrightarrow \psi )</td>
<td>( \phi \oplus \psi )</td>
<td>( \phi \neq \psi )</td>
<td>( \phi \neq \psi )</td>
<td>–</td>
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<tr>
<td>implication</td>
<td>( \phi \rightarrow \psi )</td>
<td>( \phi \supset \psi )</td>
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<td>( \phi \rightarrow \psi )</td>
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<tr>
<td>equivalence</td>
<td>( \phi \leftrightarrow \psi )</td>
<td>( \phi = \psi )</td>
<td>( \phi \ == \ \psi )</td>
<td>( \phi \ == \ \psi )</td>
<td>( \phi \ == \ \psi )</td>
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</table>

**Example:**
- \((a \lor (b \lor \neg c)) \leftrightarrow (\top \land ((a \rightarrow \neg b) \lor (c \lor a \lor b)))\)
- \((a + (b + \bar{c})) = c \ ((a \supset \neg b) + (0 + a + b))\)
- \((a \parallel (b \parallel !c)) == (c \&\& (\neg a \\&\& \neg b) \parallel (\text{false} \parallel a \parallel b))\)
## All 16 Binary Functions

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>constant 0</th>
<th>nor</th>
<th>xor</th>
<th>nand</th>
<th>and</th>
<th>equivalence</th>
<th>implication</th>
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Assignment

■ a variable can be assigned one of two values from the two-valued domain $\mathbb{B}$, where $\mathbb{B} = \{1, 0\}$

■ the mapping $\nu : \mathcal{P} \rightarrow \mathbb{B}$ is called assignment, where $\mathcal{P}$ is the set of atomic propositions

■ we sometimes write an assignment $\nu$ as set $V$ with $V \subseteq \mathcal{P} \cup \{-x| x \in \mathcal{P}\}$ such that
  - $x \in V$ iff $\nu(x) = 1$
  - $\neg x \in V$ iff $\nu(x) = 0$

■ for $n$ variables, there are $2^n$ assignments possible

■ an assignment corresponds to one line in the truth table
Semantics of Propositional Logic

Given assignment $\nu : \mathcal{P} \rightarrow \mathbb{B}$, the interpretation $[.]_\nu : \mathcal{L} \rightarrow \mathbb{B}$ is defined by:

- $[\top]_\nu = 1$, $[\bot]_\nu = 0$
- if $x \in \mathcal{P}$ then $[x]_\nu = \nu(x)$
- $[\neg \phi]_\nu = 1$ iff $[\phi]_\nu = 0$
- $[\phi \lor \psi]_\nu = 1$ iff $[\phi]_\nu = 1$ or $[\psi]_\nu = 1$

What about the other connectives?
Simple Algorithm for Satisfiability Checking

1. **Algorithm**: evaluate

   **Data**: formula $\phi$

   **Result**: 1 iff $\phi$ is satisfiable

2. if $\phi$ contains a variable $x$ then
   
   pick $v \in \{\top, \bot\}$

   /* replace $x$ by truth constant $v$, evaluate resulting formula */

   if evaluate($\phi[x \leftarrow v]$) then return 1;

   else return evaluate($\phi[x \leftarrow \overline{v}]$);

else

   switch $\phi$ do

   case $\top$ do return 1;

   case $\bot$ do return 0;

   case $\neg \psi$ do return !evaluate($\psi$) /* true iff $\psi$ is false */;

   case $\psi' \land \psi''$ do

   return evaluate($\psi'$) && evaluate($\psi''$) /* true iff both $\psi'$ and $\psi''$ are true */

   case $\psi' \lor \psi''$ do

   return evaluate($\psi'$) || evaluate($\psi''$) /* true iff $\psi'$ or $\psi''$ is true */
Satisfying/Falsifying Assigments

■ An assignment is called
  □ satisfying a formula \( \phi \) iff \([\phi]_\nu = 1\).
  □ falsifying a formula \( \phi \) iff \([\phi]_\nu = 0\).

■ A satisfying assignment for \( \phi \) is a model of \( \phi \).

■ A falsifying assignment for \( \phi \) is a counter-model of \( \phi \).

Example:

For formula \(((x \land y) \lor \neg z)\),

■ \(\{\neg x, y, z\}\) is a counter-model,

■ \(\{x, y, z\}\) is a model.

■ \(\{x, y, \neg z\}\) is another model.
Properties of Propositional Formulas (1/3)

- formula $\phi$ is **satisfiable** iff there exists interpretation $[.]_\nu$ with $[\phi]_\nu = 1$
  check with limboole -s

- formula $\phi$ is **valid** iff for all interpretations $[.]_\nu$ it holds that $[\phi]_\nu = 1$
  check with limboole

- formula $\phi$ is **refutable** iff exists interpretation $[.]_\nu$ with $[\phi]_\nu = 0$
  check with limboole

- formula $\phi$ is **unsatisfiable** iff $[\phi]_\nu = 0$ for all interpretations $[.]_\nu$
  check with limboole -s
Properties of Propositional Formulas (2/3)

- A valid formula is called **tautology**.
- An unsatisfiable formula is called **contradiction**.

**Example:**

- $\top$ is valid.
- $\bot$ is unsatisfiable.
- $(a \lor \neg b) \land (\neg a \lor b)$ is refutable.
- $a \rightarrow b$ is satisfiable.
- $a \leftrightarrow \neg a$ is a contradiction.
- $(a \lor \neg b) \land (\neg a \lor b)$ is satisfiable.
Properties of Propositional Formulas (3/3)

- A satisfiable formula is
  - possibly valid
  - possibly refutable
  - not unsatisfiable.

- A valid formula is
  - satisfiable
  - not refutable
  - not unsatisfiable.

- A refutable formula is
  - possibly satisfiable
  - possibly unsatisfiable
  - not valid.

- An unsatisfiable formula is
  - refutable
  - not valid
  - not satisfiable.

Example:

- satisfiable, but not valid: \( a \leftrightarrow b \)
- satisfiable and refutable: \((a \lor b) \land (\neg a \lor c)\)
- valid, not refutable \( \top \lor (a \land \neg a) \); not valid, refutable \( (\bot \lor b) \)
Further Connections between Formulas

- A formula $\phi$ is valid iff $\neg \phi$ is unsatisfiable.

- A formula $\phi$ is satisfiable iff $\neg \phi$ is not valid.

- The formulas $\phi$ and $\psi$ are equivalent iff $\phi \leftrightarrow \psi$ is valid.

- The formulas $\phi$ and $\psi$ are equivalent iff $\neg (\phi \leftrightarrow \psi)$ is unsatisfiable.

- A formula $\phi$ is satisfiable iff $\phi \leftrightarrow \bot$. 
Semantic Equivalence

Two formula $\phi$ and $\psi$ are \textit{semantically equivalent} (written as $\phi \iff \psi$) iff for all interpretations $[.]_\nu$ it holds that $[\phi]_\nu = [\psi]_\nu$.

- $\iff$ is a \textit{meta-symbol}, i.e., it is not part of the language.
- \textit{natural language}: if and only if (iff)
- $\phi \iff \psi$ iff $\phi \leftrightarrow \psi$ is valid, i.e., we can express semantics by means of syntactics.
- If $\phi$ and $\psi$ are not equivalent, we write $\phi \not\iff \psi$.

Example:
- $a \lor \neg a \not\iff b \rightarrow \neg b$
- $a \lor \neg a \iff b \lor \neg b$
- $(a \lor b) \land \neg(a \lor b) \iff \bot$
- $a \iff (b \iff c)) \iff ((a \iff b) \iff c$
Examples of Semantic Equivalences (1/2)

| $\phi \land \psi \iff \psi \land \phi$ | $\phi \lor \psi \iff \psi \lor \phi$ | commutativity |
| $\phi \land (\psi \land \gamma) \iff (\phi \land \psi) \land \gamma$ | $\phi \lor (\psi \lor \gamma) \iff (\phi \lor \psi) \lor \gamma$ | associativity |
| $\phi \land (\phi \lor \psi) \iff \phi$ | $\phi \lor (\phi \land \psi) \iff \phi$ | absorption |
| $\phi \land (\psi \lor \gamma) \iff (\phi \land \psi) \lor (\phi \land \gamma)$ | $\phi \lor (\psi \land \gamma) \iff (\phi \lor \psi) \land (\phi \lor \gamma)$ | distributivity |
| $\neg (\phi \land \psi) \iff \neg \phi \lor \neg \psi$ | $\neg (\phi \lor \psi) \iff \neg \phi \land \neg \psi$ | laws of De Morgan |
| $\phi \iff \psi \iff (\phi \rightarrow \psi) \land (\psi \rightarrow \phi)$ | $\phi \iff \psi \iff (\phi \land \psi) \lor (\neg \phi \land \neg \psi)$ | synt. equivalence |
### Examples of Semantic Equivalences (2/2)

<table>
<thead>
<tr>
<th>$\phi \lor \psi \Leftrightarrow \neg \phi \rightarrow \psi$</th>
<th>$\phi \rightarrow \psi \Leftrightarrow \neg \psi \rightarrow \neg \phi$</th>
<th>implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi \land \neg \phi \Leftrightarrow \perp$</td>
<td>$\phi \lor \neg \phi \Leftrightarrow \top$</td>
<td>complement</td>
</tr>
<tr>
<td>$\neg \neg \phi \Leftrightarrow \phi$</td>
<td></td>
<td>double negation</td>
</tr>
<tr>
<td>$\phi \land \top \Leftrightarrow \phi$</td>
<td>$\phi \lor \bot \Leftrightarrow \phi$</td>
<td>neutrality</td>
</tr>
<tr>
<td>$\phi \lor \top \Leftrightarrow \top$</td>
<td>$\phi \land \bot \Leftrightarrow \bot$</td>
<td></td>
</tr>
<tr>
<td>$\neg \top \Leftrightarrow \bot$</td>
<td>$\neg \bot \Leftrightarrow \top$</td>
<td></td>
</tr>
</tbody>
</table>
Negation Normal Form (1/2)

Negation Normal Form (NNF) is defined as follows:

- Literals and truth constants are in NNF;
- \( \phi \circ \psi (\circ \in \{\lor, \land\}) \) is in NNF iff \( \phi \) and \( \psi \) are in NNF;
- no other formulas are in NNF.

In other words: A formula in NNF contains only conjunctions, disjunctions, and negations and negations only occur in front of variables and constants.
Negation Normal Form (2/2)

If a formula is in negation normal form then

- in the formula tree, nodes with negation symbols only occur directly before leaves.
- there are no subformulas of the form \( \neg \phi \) where \( \phi \) is something else than a variable or a constant.
- it does not contain NAND, NOR, XOR, equivalence, and implication connectives.

**Example:** The formula \(((x \lor \neg x_1) \land (x \lor (\neg z \lor \neg x_1)))\) is in NNF but
\n\(\neg(((x \lor \neg x_1) \land (x \lor (\neg z \lor \neg x_1)))\) is not in NNF.
Conjunctive Normal Form (CNF)

A propositional formula is in conjunctive normal form (CNF) iff it is a conjunction of clauses.

A formula in conjunctive normal form is

- in negation normal form
- \( \top \) if it contains no clauses
- easy to check whether it can be refuted

remark: CNF is the input of most SAT-solvers (DIMACS format)
Disjunctive Normal Form (DNF)

A propositional formula is in disjunctive normal form (DNF) if it is a disjunction of cubes.

A formula in disjunctive normal form is

- in negation normal form
- \( \bot \) if it contains no cubes
- easy to check whether it can be satisfied
Examples for CNF and DNF

### Examples CNF

- $\top$
- $\bot$
- $a$
- $\neg a$

- $l_1 \land l_2 \land l_3$
- $l_1 \lor l_2 \lor l_3$
- $(a_1 \lor \neg a_2) \land (a_1 \lor b_2 \lor a_2) \land a_2$
- $((l_{11} \lor \ldots \lor l_{1m_1}) \land \ldots \land (l_{n1} \lor \ldots \lor l_{nm_n}))$

### Examples DNF

- $\top$
- $\bot$
- $a$
- $\neg a$

- $l_1 \land l_2 \land l_3$
- $l_1 \lor l_2 \lor l_3$
- $(a_1 \land \neg a_2) \lor (a_1 \land b_2 \land a_2) \lor a_2$
- $((l_{11} \land \ldots \land l_{1m_1}) \lor \ldots \lor (l_{n1} \land \ldots \land l_{nm_n}))$
Representing Functions as CNFs

**Problem**: Given the truth table of a Boolean function \( \phi \). How is the function represented in propositional logic?

**Solution (in CNF):**

1. Represent each assignment \( \nu \) where \( \phi \) has value 0 as clause:
   - If variable \( x \) is 1 in \( \nu \), add \( \neg x \) to clause.
   - If variable \( x \) is 0 in \( \nu \), add \( x \) to clause.

2. Connect all clauses by conjunction.

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>( \phi )</th>
<th>clauses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( a \lor b \lor c )</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>( a \lor \neg b \lor \neg c )</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>( \neg a \lor b \lor \neg c )</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>( \neg a \lor \neg b \lor c )</td>
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<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
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<tr>
<td>1</td>
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<td>1</td>
<td>1</td>
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<td>1</td>
<td></td>
</tr>
</tbody>
</table>

\[ \phi = (a \lor b \lor c) \land (a \lor \neg b \lor \neg c) \land (\neg a \lor b \lor \neg c) \land (\neg a \lor \neg b \lor c) \]
Representing Functions as DNFs

Problem: Given the truth table of a Boolean function $\phi$. How is the function represented in propositional logic?

Solution (in DNF):

1. Represent each assignment $\nu$ where $\phi$ has value 1 as cube:
   - If variable $x$ is 1 in $\nu$, add $x$ to cube.
   - If variable $x$ is 0 in $\nu$, add $\neg x$ to cube.

2. Connect all cubes by disjunction.

<table>
<thead>
<tr>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$\phi$</th>
<th>cubes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\neg a \land \neg b \land c$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>$\neg a \land b \land \neg c$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>$\neg a \land \neg b \land \neg c$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>$a \land \neg b \land \neg c$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$a \land \neg b \land \neg c$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$a \land b \land \neg c$</td>
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<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$a \land b \land \neg c$</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>$a \land b \land c$</td>
</tr>
</tbody>
</table>

$\phi = \left( \neg a \land \neg b \land c \right) \lor \left( \neg a \land b \land \neg c \right) \lor \left( a \land \neg b \land \neg c \right) \lor \left( a \land b \land c \right)$
Functional Completeness

- In propositional logic there are
  - 2 functions of arity 0 (\(\top, \bot\))
  - 4 functions of arity 1 (e.g., not)
  - 16 functions of arity 2 (e.g., and, or, ...)
  - \(2^n\) functions of arity \(n\).

- A function of arity \(n\) has \(2^n\) different combinations of arguments (lines in the truth table).

- A functions maps its arguments either to 1 or 0.

A set of functions is called functional complete for propositional logic iff it is possible to express all other functions of propositional logic with functions from this set.

\(\{\neg, \wedge\}, \{\neg, \vee\}, \{\text{nand}\}\) are functional complete.
Logic Entailment

Let $\phi_1, \ldots, \phi_n, \psi$ be propositional formulas. Then $\phi_1, \ldots, \phi_n$ entail $\psi$ (written as $\phi_1, \ldots, \phi_n \models \psi$) iff $[\phi_1]_\nu = 1, \ldots, [\phi_n]_\nu = 1$ implies that $[\psi]_\nu = 1$.

Informal meaning: True premises derive a true conclusion.

- $\models$ is a meta-symbol, i.e., it is not part of the language.
- $\phi_1, \ldots, \phi_n \models \psi$ iff $(\phi_1 \land \ldots \land \phi_n) \rightarrow \psi$ is valid, i.e., we can express semantics by means of syntactics.
- If $\phi_1, \ldots, \phi_n$ do not entail $\psi$, we write $\phi_1, \ldots, \phi_n \not\models \psi$.

Example:

- $a \models a \lor b$
- $\models a \lor \neg a$
- $a, a \rightarrow b \models b$
- $a, b \models a \land b$
- $\not\models a \land \neg a$
- $\bot \models a \land \neg a$
Formula Strength

- Formulas $\phi$ and $\psi$ are equally strong iff $\phi \models \psi$ and $\psi \models \phi$
- Formula $\phi$ is stronger than formula $\psi$ iff $\phi \models \psi$
- Formula $\psi$ is weaker than formula $\phi$ iff $\phi \models \psi$

Examples

- $a \oplus b$ is stronger than $a \lor b$
- $a \land b$ is stronger than $a \lor b$
- $\bot$ is the strongest formula
- $\top$ is the weakest formula
Satisfiability Equivalence

Two formulas $\phi$ and $\psi$ are satisfiability-equivalent (written as $\phi \iff_{SAT} \psi$) iff both formulas are satisfiable or both are contradictory.

- Satisfiability-equivalent formulas are not necessarily satisfied by the same assignments.
- Satisfiability equivalence is a weaker property than semantic equivalence.
- Often sufficient for simplification rules: If the complicated formula is satisfiable then also the simplified formula is satisfiable.
Example: Satisfiability Equivalence

positive pure literal elimination rule:

If a variable $x$ occurs in a formula but $\neg x$ does not occur in the formula, then $x$ can be substituted by $\top$. The resulting formula is satisfiability-equivalent.

Example:

- $x \Leftrightarrow_{SAT} \top$, but $x \not\Leftrightarrow \top$
- $(a \land b) \lor (\neg c \land a) \Leftrightarrow_{SAT} b \lor \neg c$, but $(a \land b) \lor (\neg c \land a) \not\Leftrightarrow b \lor \neg c$