PROPOSITIONAL LOGIC II

VL Logik: WS 2018/19
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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.
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 ↔ inviteBob, inviteCecile ↔ inviteDavid
  2. if Alice then Cecile: inviteAlice → inviteCecile
  3. either David or Eva: ¬ (inviteEva ↔ inviteDavid)
  4. invite Bob and Fred: inviteBob ∧ inviteFred

- **encoding in propositional logic:**

  \[
  (inviteAlice ↔ inviteBob) ∧ (inviteCecile ↔ inviteDavid) ∧
  (inviteAlice → inviteCecile) ∧ ¬ (inviteEva ↔ inviteDavid) ∧
  inviteBob ∧ inviteFred
  \]
Syntax of Propositional Logic

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!):

- ¬ is stronger than ∧
- ∧ is stronger than ∨
- ∨ is stronger than →
- → is stronger than ↔
- 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'')).
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

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

has the formula tree

![Formula Tree Diagram]
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:

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

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 \& \text{!!}d))\)
Negation

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

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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 $\phi \land \psi$: $\phi \& \psi$, $\phi \psi$, $\phi * \psi$, $\phi \cdot \psi$, $\phi \text{AND} \psi$.
- For $(\phi_1 \land \ldots \land \phi_n)$ we also write $\land_{i=1}^n \phi_i$.

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

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 $\phi \lor \psi$: $\phi | \psi$, $\phi + \psi$, $\phi OR \psi$.
- For $(\phi_1 \lor \ldots \lor \phi_n)$ we also write $\bigvee_{i=1}^{n} \phi_i$.

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>$\phi \lor \psi$</th>
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<tbody>
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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: $\phi \supset \psi$, $\phi$ IMPL $\psi$

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>$\phi \rightarrow \psi$</th>
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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.
- $(\bot \rightarrow a)$ 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

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\psi$</th>
<th>$\phi \leftrightarrow \psi$</th>
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<tbody>
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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>T</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>
<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
  - Symbol: \( \land \)

- **nand gate**
  - Inputs: A, B
  - Symbol: \( \overline{\land} \)

- **or gate**
  - Inputs: A, B
  - Symbol: \( \lor \)

- **nor gate**
  - Inputs: A, B
  - Symbol: \( \overline{\lor} \)

- **xor gate**
  - Inputs: A, B
  - Symbol: \( \oplus \)

- **not gate**
  - Input: A
  - Symbol: \( \overline{A} \)
Example of a Digital Circuit: Half Adder

<table>
<thead>
<tr>
<th>$x$</th>
<th>$y$</th>
<th>$c$</th>
<th>$s$</th>
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<tbody>
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From the truth table, we see that

\[ c \leftrightarrow x \land y \]

and

\[ s \leftrightarrow x \oplus y. \]
## Different Notations

<table>
<thead>
<tr>
<th>operator</th>
<th>logic</th>
<th>circuits</th>
<th>C/C++/Java/C#</th>
<th>VHDL</th>
<th>Limboole</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>( \top )</td>
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<td>true</td>
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</tr>
<tr>
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<td>( \perp )</td>
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<td>false</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>negation</td>
<td>( \neg \phi )</td>
<td>( \bar{\phi} )</td>
<td>!( \phi )</td>
<td>not ( \phi )</td>
<td>!( \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 \ and \ \psi )</td>
</tr>
<tr>
<td>disjunction</td>
<td>( \phi \lor \psi )</td>
<td>( \phi + \psi )</td>
<td>( \phi \</td>
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<td>\psi )</td>
</tr>
<tr>
<td>exclusive or</td>
<td>( \phi \leftrightarrow \psi )</td>
<td>( \phi \oplus \psi )</td>
<td>( \phi \not\leftrightarrow \psi )</td>
<td>( \phi \ xor \ \psi )</td>
<td>–</td>
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<tr>
<td>implication</td>
<td>( \phi \rightarrow \psi )</td>
<td>( \phi \supset \psi )</td>
<td>–</td>
<td>–</td>
<td>( \phi \rightarrow \psi )</td>
</tr>
<tr>
<td>equivalence</td>
<td>( \phi \leftrightarrow \psi )</td>
<td>( \phi = \psi )</td>
<td>( \phi \ == \psi )</td>
<td>( \phi \ xnor \ \psi )</td>
<td>( \phi \ &lt;-&gt; \psi )</td>
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</tbody>
</table>

### Example:

- \((a \lor (b \lor \neg c)) \leftrightarrow (\top \land ((a \rightarrow \neg b) \lor (c \lor a \lor b)))\)
- \((a + (b + \bar{c})) = c ((a \supset \neg b) + (0 + a + b))\)
- \((a \parallel (b \parallel \neg c)) = ((c \& \& ((a \parallel \neg b) \parallel (false \parallel a \parallel b)))\)}
## 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 $V \subseteq \mathcal{P} \cup \{\neg x | x \in \mathcal{P}\}$ 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 \( \nu : \mathcal{P} \to \mathbb{B} \), the interpretation \([\cdot]_\nu : \mathcal{L} \to \mathbb{B}\) 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
   3 pick $v \in \{\top, \bot\}$
   4 /* replace $x$ by truth constant $v$, evaluate resulting formula */
   5 if evaluate($\phi[x|v]$) then return 1;
   6 else return evaluate($\phi[x|\neg v]$);

else

8 switch $\phi$ do
   9 case $\top$ do return 1;
   10 case $\bot$ do return 0;
   11 case $\neg \psi$ do return $\neg$ evaluate($\psi$) /* true iff $\psi$ is false */;
   12 case $\psi' \land \psi''$ do
      13 return evaluate($\psi'$) && evaluate($\psi''$) /* true iff both $\psi'$ and $\psi''$ are true */;
   14 case $\psi' \lor \psi''$ do
      15 return evaluate($\psi'$) || evaluate($\psi''$) /* true iff $\psi'$ or $\psi''$ is true */;
Satisfying/Falsifying Assignments

- 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
  - not possible 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 $\phi \leftrightarrow \bot$. 