



# Semantics and Verification of Software

Winter Semester 2017/18

Lecture 2: Operational Semantics of WHILE I  
(Evaluation of Expressions)

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<http://moves.rwth-aachen.de/teaching/ws-1718/sv-sw/>

# Recap: Syntax of WHILE

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## Outline of Lecture 2

Recap: Syntax of WHILE

Operational Semantics of WHILE

Evaluation of Arithmetic Expressions

Excursus: Proof by Structural Induction

Evaluation of Boolean Expressions

# Recap: Syntax of WHILE

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## Syntactic Categories

**WHILE**: simple imperative programming language without procedures or advanced data structures

Syntactic categories:

Category	Domain	Meta variable
Numbers	$\mathbb{Z} = \{0, 1, -1, \dots\}$	$z$
Truth values	$\mathbb{B} = \{\text{true}, \text{false}\}$	$t$
Variables	$Var = \{x, y, \dots\}$	$x$
Arithmetic expressions	$AExp$ (next slide)	$a$
Boolean expressions	$BExp$ (next slide)	$b$
Commands (statements)	$Cmd$ (next slide)	$c$

# Recap: Syntax of WHILE

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## Syntax of WHILE Programs

### Definition (Syntax of WHILE)

The **syntax of WHILE Programs** is defined by the following context-free grammar:

$$a ::= z \mid x \mid a_1 + a_2 \mid a_1 - a_2 \mid a_1 * a_2 \in AExp$$
$$b ::= t \mid a_1 = a_2 \mid a_1 > a_2 \mid \neg b \mid b_1 \wedge b_2 \mid b_1 \vee b_2 \in BExp$$
$$c ::= \text{skip} \mid x := a \mid c_1 ; c_2 \mid \text{if } b \text{ then } c_1 \text{ else } c_2 \text{ end} \mid \text{while } b \text{ do } c \text{ end} \in Cmd$$

**Remarks:** we assume that

- the syntax of numbers, truth values and variables is predefined (i.e., no “lexical analysis”)
- the syntactic interpretation of ambiguous constructs (expressions) is uniquely determined (by brackets or priorities)

# Operational Semantics of WHILE

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  - G.D. Plotkin: *A structural approach to operational semantics*, DAIMI FN-19, Computer Science Department, Aarhus University, 1981



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- Employs **derivation rules** of the form

$$\text{(Name)} \frac{\text{Premise(s)}}{\text{Conclusion}} \quad [\text{side conditions}]$$

- meaning: if every premise [and all side conditions] are fulfilled, then conclusion can be drawn
- a rule with no premises is called an **axiom**

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- meaning: if every premise [and all side conditions] are fulfilled, then conclusion can be drawn
  - a rule with no premises is called an **axiom**
- Derivation rules can be composed to form **derivation trees** with axioms as leafs (formal definition later)

# Evaluation of Arithmetic Expressions

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# Evaluation of Arithmetic Expressions

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## Program States

- **Meaning of expression** = its value (in the usual sense)
- Depends on the **values of the variables** in the expression

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### Definition 2.1 (Program state)

A **(program) state** is an element of the set

$$\Sigma := \{\sigma \mid \sigma : \text{Var} \rightarrow \mathbb{Z}\},$$

called the **state space**.

Thus  $\sigma(x)$  denotes the value of  $x \in \text{Var}$  in state  $\sigma \in \Sigma$ .

# Evaluation of Arithmetic Expressions

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## Evaluation of Arithmetic Expressions I

**Remember:**  $a ::= z \mid x \mid a_1 + a_2 \mid a_1 - a_2 \mid a_1 * a_2 \in AExp$

# Evaluation of Arithmetic Expressions

## Evaluation of Arithmetic Expressions I

**Remember:**  $a ::= z \mid x \mid a_1 + a_2 \mid a_1 - a_2 \mid a_1 * a_2 \in AExp$

Definition 2.2 (Evaluation relation for arithmetic expressions)

If  $a \in AExp$  and  $\sigma \in \Sigma$ , then  $\langle a, \sigma \rangle$  is called a **configuration**.

Expression  $a$  **evaluates to**  $z \in \mathbb{Z}$  in state  $\sigma$  (notation:  $\langle a, \sigma \rangle \rightarrow z$ ) if this relationship is derivable by means of the following rules:

Axioms:

$$\frac{}{\langle z, \sigma \rangle \rightarrow z} \quad \frac{}{\langle x, \sigma \rangle \rightarrow \sigma(x)}$$

Rules:

$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 + a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 + z_2$$

$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 - a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 - z_2$$

$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 * a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 \cdot z_2$$

# Evaluation of Arithmetic Expressions

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## Evaluation of Arithmetic Expressions II

### Example 2.3

$a = (x+3) * (y-2)$ ,  $\sigma(x) = 3$ ,  $\sigma(y) = 9$ :

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# Evaluation of Arithmetic Expressions

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## Evaluation of Arithmetic Expressions II

### Example 2.3

$a = (x+3) * (y-2), \sigma(x) = 3, \sigma(y) = 9:$

$$\frac{}{\langle (x+3) * (y-2), \sigma \rangle \rightarrow}$$

# Evaluation of Arithmetic Expressions

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## Evaluation of Arithmetic Expressions II

### Example 2.3

$a = (x+3) * (y-2)$ ,  $\sigma(x) = 3$ ,  $\sigma(y) = 9$ :

$$\frac{\frac{\langle x+3, \sigma \rangle \rightarrow \quad \quad \quad \langle y-2, \sigma \rangle \rightarrow}{\langle (x+3) * (y-2), \sigma \rangle \rightarrow}}{\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 * a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 \cdot z_2}$$

# Evaluation of Arithmetic Expressions

## Evaluation of Arithmetic Expressions II

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$a = (x+3) * (y-2)$ ,  $\sigma(x) = 3$ ,  $\sigma(y) = 9$ :

$$\frac{\frac{\langle x, \sigma \rangle \rightarrow \quad \langle 3, \sigma \rangle \rightarrow}{\langle x+3, \sigma \rangle \rightarrow} \quad \frac{\quad \quad \quad}{\langle y-2, \sigma \rangle \rightarrow}}{\langle (x+3) * (y-2), \sigma \rangle \rightarrow}$$
$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1+a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 + z_2$$

# Evaluation of Arithmetic Expressions

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## Evaluation of Arithmetic Expressions II

### Example 2.3

$a = (x+3) * (y-2)$ ,  $\sigma(x) = 3$ ,  $\sigma(y) = 9$ :

$$\frac{\frac{\frac{\langle x, \sigma \rangle \rightarrow 3}{\langle x+3, \sigma \rangle \rightarrow}}{\langle (x+3) * (y-2), \sigma \rangle \rightarrow}}{\langle x, \sigma \rangle \rightarrow \sigma(x)}$$

# Evaluation of Arithmetic Expressions

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# Evaluation of Arithmetic Expressions

## Evaluation of Arithmetic Expressions II

### Example 2.3

$a = (x+3) * (y-2)$ ,  $\sigma(x) = 3$ ,  $\sigma(y) = 9$ :

$$\frac{\frac{\langle x, \sigma \rangle \rightarrow 3 \quad \langle 3, \sigma \rangle \rightarrow 3}{\langle x+3, \sigma \rangle \rightarrow 6} \quad \langle y-2, \sigma \rangle \rightarrow}{\langle (x+3) * (y-2), \sigma \rangle \rightarrow}$$
$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1+a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 + z_2$$

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$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 - a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 - z_2$$

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# Evaluation of Arithmetic Expressions

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# Evaluation of Arithmetic Expressions

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$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 - a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 - z_2$$

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$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 * a_2, \sigma \rangle \rightarrow z} \quad \text{where } z := z_1 \cdot z_2$$

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**Here:** structure of derivation tree = structure of program fragment  
(not generally true)

# Evaluation of Arithmetic Expressions

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## Free Variables I

First formal result: value of an expression only depends on valuation of variables which occur (freely) in the expression

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### Definition 2.4 (Free variables)

The set of **free variables** of an expression is given by the function

$$FV : AExp \rightarrow 2^{Var}$$

where

$$\begin{array}{ll} FV(z) := \emptyset & FV(a_1 + a_2) := FV(a_1) \cup FV(a_2) \\ FV(x) := \{x\} & FV(a_1 - a_2) := FV(a_1) \cup FV(a_2) \\ & FV(a_1 * a_2) := FV(a_1) \cup FV(a_2) \end{array}$$

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Result will be shown by **structural induction** on the expression

# Excursus: Proof by Structural Induction

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Recap: Syntax of WHILE

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**Excursus: Proof by Structural Induction**

Evaluation of Boolean Expressions



# Excursus: Proof by Structural Induction

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## Excursus: Proof by Structural Induction I

### Proof principle

**Given:** an inductive set, i.e., a set  $S$  whose elements are either

- atomic or
- obtained from atomic elements by (finite) application of certain operations

**To show:** property  $P(s)$  applies to every  $s \in S$

**Proof:** we verify:

**Induction base:**  $P(s)$  holds for every atomic element  $s$

**Induction hypothesis:** assume that  $P(s_1)$ ,  $P(s_2)$  etc.

**Induction step:** then also  $P(f(s_1, \dots, s_n))$  holds for every operation  $f$  of arity  $n$

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**Remark:** structural induction is a special case of **well-founded induction**

# Excursus: Proof by Structural Induction

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## Excursus: Proof by Structural Induction II

Application: natural numbers (“mathematical induction”)

Definition:  $\mathbb{N}$  is the least set which

- contains 0 and
- contains  $n + 1$  whenever  $n \in \mathbb{N}$

Induction base:  $P(0)$  holds

Induction hypothesis:  $P(n)$  holds

Induction step:  $P(n + 1)$  holds

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Induction base:  $P(0)$  holds

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Induction step:  $P(n + 1)$  holds

**Generalization:** complete (strong, course-of-values) induction

- induction step:  $P(0), P(1), \dots, P(n) \Rightarrow P(n + 1)$
- corresponds to well-founded induction over natural numbers

## Excursus: Proof by Structural Induction

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### Excursus: Proof by Structural Induction III

#### Example 2.5 (Mathematical induction)

We prove that  $P(n) : \sum_{i=1}^n i = \frac{n(n+1)}{2}$  holds for every  $n \in \mathbb{N}$ .

## Excursus: Proof by Structural Induction

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## Excursus: Proof by Structural Induction

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Assume  $P(n)$ :  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$

## Excursus: Proof by Structural Induction

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Assume  $P(n)$ :  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$

Show  $P(n+1)$ :  $\sum_{i=1}^{n+1} i = \sum_{i=1}^n i + (n+1)$



# Excursus: Proof by Structural Induction

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## Excursus: Proof by Structural Induction III

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$P(0)$  holds:  $\sum_{i=1}^0 i = 0 = \frac{0(0+1)}{2} \checkmark$

Assume  $P(n)$ :  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$

Show  $P(n+1)$ :  $\sum_{i=1}^{n+1} i = \sum_{i=1}^n i + (n+1)$   
 $= \frac{n(n+1)}{2} + (n+1)$

## Excursus: Proof by Structural Induction

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### Excursus: Proof by Structural Induction III

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Show  $P(n+1)$ :  $\sum_{i=1}^{n+1} i = \sum_{i=1}^n i + (n+1)$   
 $= \frac{n(n+1)}{2} + (n+1)$   
 $= \frac{n(n+1)}{2} + \frac{2(n+1)}{2}$

# Excursus: Proof by Structural Induction

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## Excursus: Proof by Structural Induction III

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$P(0)$  holds:  $\sum_{i=1}^0 i = 0 = \frac{0(0+1)}{2} \checkmark$

Assume  $P(n)$ :  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$

Show  $P(n+1)$ :  $\sum_{i=1}^{n+1} i = \sum_{i=1}^n i + (n+1)$   
 $= \frac{n(n+1)}{2} + (n+1)$   
 $= \frac{n(n+1)}{2} + \frac{2(n+1)}{2}$   
 $= \frac{(n+2)(n+1)}{2}$

## Excursus: Proof by Structural Induction

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### Excursus: Proof by Structural Induction III

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Assume  $P(n)$ :  $\sum_{i=1}^n i = \frac{n(n+1)}{2}$

Show  $P(n+1)$ :  $\sum_{i=1}^{n+1} i = \sum_{i=1}^n i + (n+1)$   
 $= \frac{n(n+1)}{2} + (n+1)$   
 $= \frac{n(n+1)}{2} + \frac{2(n+1)}{2}$   
 $= \frac{(n+2)(n+1)}{2}$   
 $= \frac{(n+1)((n+1)+1)}{2} \checkmark$

## Excursus: Proof by Structural Induction

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### Excursus: Proof by Structural Induction IV

#### Application: arithmetic expressions (Def. 1.2)

Definition:  $AExp$  is the least set which

- contains all integers  $z \in \mathbb{Z}$  and all variables  $x \in Var$  and
- contains  $a_1 + a_2$ ,  $a_1 - a_2$  and  $a_1 * a_2$  whenever  $a_1, a_2 \in AExp$

Induction base:  $P(z)$  and  $P(x)$  holds (for every  $z \in \mathbb{Z}$  and  $x \in Var$ )

Induction hypothesis:  $P(a_1)$  and  $P(a_2)$  holds

Induction step:  $P(a_1 + a_2)$ ,  $P(a_1 - a_2)$  and  $P(a_1 * a_2)$  holds

# Excursus: Proof by Structural Induction

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## Free Variables II

### Lemma 2.6

Let  $a \in AExp$  and  $\sigma, \sigma' \in \Sigma$  such that  $\sigma(x) = \sigma'(x)$  for every  $x \in FV(a)$ . Then, for every  $z \in \mathbb{Z}$ ,

$$\langle a, \sigma \rangle \rightarrow z \iff \langle a, \sigma' \rangle \rightarrow z.$$

# Excursus: Proof by Structural Induction

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$$\langle a, \sigma \rangle \rightarrow z \iff \langle a, \sigma' \rangle \rightarrow z.$$

Proof.

by **structural induction** on  $a$  (on the board)



# Evaluation of Boolean Expressions

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Evaluation of Boolean Expressions



# Evaluation of Boolean Expressions

## Evaluation of Boolean Expressions I

Definition 2.7 ((Strict) evaluation relation for Boolean expressions)

For  $b \in BExp$ ,  $\sigma \in \Sigma$ , and  $t \in \mathbb{B}$ , the **evaluation relation**  $\langle b, \sigma \rangle \rightarrow t$  is defined by:

$$\begin{array}{c} \frac{\langle t, \sigma \rangle \rightarrow t}{\langle a_1, \sigma \rangle \rightarrow z \ \langle a_2, \sigma \rangle \rightarrow z} \quad \frac{\langle a_1, \sigma \rangle \rightarrow z_1 \ \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 = a_2, \sigma \rangle \rightarrow \text{true}} \text{ if } z_1 \neq z_2 \\ \frac{\langle a_1, \sigma \rangle \rightarrow z_1 \ \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 > a_2, \sigma \rangle \rightarrow \text{true}} \text{ if } z_1 > z_2 \quad \frac{\langle a_1, \sigma \rangle \rightarrow z_1 \ \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 > a_2, \sigma \rangle \rightarrow \text{false}} \text{ if } z_1 \leq z_2 \\ \frac{\langle b, \sigma \rangle \rightarrow \text{false}}{\langle \neg b, \sigma \rangle \rightarrow \text{true}} \quad \frac{\langle b, \sigma \rangle \rightarrow \text{true}}{\langle \neg b, \sigma \rangle \rightarrow \text{false}} \\ \frac{\langle b_1, \sigma \rangle \rightarrow \text{true} \ \langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{true}} \quad \frac{\langle b_1, \sigma \rangle \rightarrow \text{true} \ \langle b_2, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \\ \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \ \langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \quad \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \ \langle b_2, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \end{array}$$

( $\vee$  analogously)

# Evaluation of Boolean Expressions

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## Evaluation of Boolean Expressions II

### Remarks:

- Binary Boolean operators  $\wedge$  and  $\vee$  are interpreted as **strict**, i.e., always evaluate both arguments.

Important in situations like

```
while p <> nil and p^.key < val do ...!
```

(see following slides for alternatives)

# Evaluation of Boolean Expressions

---

## Evaluation of Boolean Expressions II

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```
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(see following slides for alternatives)

- $FV : BExp \rightarrow 2^{Var}$  can be defined in analogy to Def. 2.4.

# Evaluation of Boolean Expressions

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## Evaluation of Boolean Expressions II

### Remarks:

- Binary Boolean operators  $\wedge$  and  $\vee$  are interpreted as **strict**, i.e., always evaluate both arguments.

Important in situations like

```
while p <> nil and p^.key < val do ...!
```

(see following slides for alternatives)

- $FV : BExp \rightarrow 2^{Var}$  can be defined in analogy to Def. 2.4.
- Lemma 2.6 holds analogously for Boolean expressions, i.e., the value of  $b \in BExp$  does not depend on variables in  $Var \setminus FV(b)$ .

# Evaluation of Boolean Expressions

## Evaluation of Boolean Expressions III

### Definition 2.8 (Sequential evaluation of Boolean expressions)

For  $b \in BExp$ ,  $\sigma \in \Sigma$ , and  $t \in \mathbb{B}$ , the **sequential evaluation relation**  $\langle b, \sigma \rangle \rightarrow t$  is defined by the following rules:

$$\frac{\langle b_1, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \quad \frac{\begin{array}{c} \vdots \\ \langle b_1, \sigma \rangle \rightarrow \text{true} \end{array} \quad \langle b_2, \sigma \rangle \rightarrow t}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow t}$$
$$\frac{\langle b_1, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow \text{true}} \quad \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \quad \langle b_2, \sigma \rangle \rightarrow t}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow t}$$

# Evaluation of Boolean Expressions

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$$\frac{\langle b_1, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow \text{true}} \quad \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \quad \langle b_2, \sigma \rangle \rightarrow t}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow t}$$

**Remarks:** yields same result as strict evaluation for our simple language

- (Boolean) expressions have no side effects (assignments, exceptions, ...)
- evaluation always terminates

# Evaluation of Boolean Expressions

## Evaluation of Boolean Expressions IV

### Definition 2.9 (Parallel evaluation of Boolean expressions)

For  $b \in BExp$ ,  $\sigma \in \Sigma$ , and  $t \in \mathbb{B}$ , the **parallel evaluation relation**  $\langle b, \sigma \rangle \rightarrow t$  is defined by the following rules:

$$\begin{array}{c} \vdots \\ \frac{\langle b_1, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \quad \frac{\langle b_2, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \\ \frac{\langle b_1, \sigma \rangle \rightarrow \text{true} \quad \langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{true}} \\ \frac{\langle b_1, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow \text{true}} \quad \frac{\langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow \text{true}} \\ \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \quad \langle b_2, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \vee b_2, \sigma \rangle \rightarrow \text{false}} \end{array}$$