

Semantics and Verification of Software

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

Thomas Noll

Lehrstuhl für Informatik 2
(Software Modeling and Verification)

RWTH Aachen University

`noll@cs.rwth-aachen.de`

`http://www-i2.informatik.rwth-aachen.de/i2/svsw08/`

Winter semester 2008/09

- 1 Repetition: Syntax of WHILE
- 2 Operational Semantics of WHILE
- 3 Evaluation of Arithmetic Expressions
- 4 Excursus: Proof by Structural Induction
- 5 Evaluation of Boolean Expressions
- 6 Execution of Statements

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	$AExp$	a
Boolean expressions	$BExp$	b
Commands (statements)	Cmd	c

Definition (Syntax of WHILE)

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

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

Remarks: we assume that

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

- 1 Repetition: Syntax of WHILE
- 2 Operational Semantics of WHILE
- 3 Evaluation of Arithmetic Expressions
- 4 Excursus: Proof by Structural Induction
- 5 Evaluation of Boolean Expressions
- 6 Execution of Statements

Operational Semantics of WHILE

- Idea: define meaning of programs by specifying its behaviour being executed on an (abstract) machine

Operational Semantics of WHILE

- Idea: define meaning of programs by specifying its behaviour being executed on an (abstract) machine
- Here: evaluation/execution relation for program fragments (expressions, statements)

Operational Semantics of WHILE

- Idea: define meaning of programs by specifying its behaviour being executed on an (abstract) machine
- Here: evaluation/execution relation for program fragments (expressions, statements)
- Approach based on Structural Operational Semantics (SOS)

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

Operational Semantics of WHILE

- Idea: define meaning of programs by specifying its behaviour being executed on an **(abstract) machine**
- Here: **evaluation/execution relation** for program fragments (expressions, statements)
- Approach based on **Structural Operational Semantics (SOS)**

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

- Employs **derivation rules** of the form

$$\text{Name} \frac{\text{Premise(s)}}{\text{Conclusion}}$$

- meaning: if every premise is fulfilled, then conclusion can be drawn
- a rule with no premises is called an **axiom**

Operational Semantics of WHILE

- Idea: define meaning of programs by specifying its behaviour being executed on an (abstract) machine
- Here: evaluation/execution relation for program fragments (expressions, statements)
- Approach based on Structural Operational Semantics (SOS)

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

- Employs derivation rules of the form

$$\text{Name} \frac{\text{Premise(s)}}{\text{Conclusion}}$$

- meaning: if every premise is 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)

- 1 Repetition: Syntax of WHILE
- 2 Operational Semantics of WHILE
- 3 Evaluation of Arithmetic Expressions**
- 4 Excursus: Proof by Structural Induction
- 5 Evaluation of Boolean Expressions
- 6 Execution of Statements

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

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

Definition 2.1 (Program state)

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

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

called the **state space**.

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

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 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 σ (notation: $\langle a, \sigma \rangle \rightarrow z$) if this relationship is derivable by means of the following rules:

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

Example 2.3

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

Example 2.3

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

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

Example 2.3

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

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

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

Example 2.3

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

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

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

Example 2.3

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

$$\begin{array}{c}
 \frac{\frac{\langle x, \sigma \rangle \rightarrow 3}{\langle x+3, \sigma \rangle \rightarrow} \quad \frac{\langle 3, \sigma \rangle \rightarrow}{\langle y-2, \sigma \rangle \rightarrow}}{\langle (x+3)*(y-2), \sigma \rangle \rightarrow}
 \end{array}$$

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

Example 2.3

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

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

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\quad} \quad \overline{\quad}}{\overline{\langle y-2, \sigma \rangle \rightarrow \quad}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow \quad}}$$

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

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\langle y, \sigma \rangle \rightarrow} \quad \overline{\langle 2, \sigma \rangle \rightarrow}}{\overline{\langle y-2, \sigma \rangle \rightarrow}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow}}$$

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

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\langle y, \sigma \rangle \rightarrow 9} \quad \overline{\langle 2, \sigma \rangle \rightarrow}}{\overline{\langle y-2, \sigma \rangle \rightarrow}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow}}$$
$$\frac{}{\overline{\langle x, \sigma \rangle \rightarrow \sigma(x)}}$$

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\langle y, \sigma \rangle \rightarrow 9} \quad \overline{\langle 2, \sigma \rangle \rightarrow 2}}{\overline{\langle y-2, \sigma \rangle \rightarrow}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow}}$$
$$\frac{}{\overline{\langle z, \sigma \rangle \rightarrow z}}$$

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\langle y, \sigma \rangle \rightarrow 9} \quad \overline{\langle 2, \sigma \rangle \rightarrow 2}}{\overline{\langle y-2, \sigma \rangle \rightarrow 7}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow}}$$

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

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\langle y, \sigma \rangle \rightarrow 9} \quad \overline{\langle 2, \sigma \rangle \rightarrow 2}}{\overline{\langle y-2, \sigma \rangle \rightarrow 7}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow 42}}$$

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

Example 2.3

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

$$\frac{\frac{\overline{\langle x, \sigma \rangle \rightarrow 3} \quad \overline{\langle 3, \sigma \rangle \rightarrow 3}}{\overline{\langle x+3, \sigma \rangle \rightarrow 6}} \quad \frac{\overline{\langle y, \sigma \rangle \rightarrow 9} \quad \overline{\langle 2, \sigma \rangle \rightarrow 2}}{\overline{\langle y-2, \sigma \rangle \rightarrow 7}}}{\overline{\langle (x+3)*(y-2), \sigma \rangle \rightarrow 42}}$$

Here: structure of derivation tree = structure of program fragment
(generally not the case)

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

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

Definition 2.4 (Free variables)

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

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

where

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

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

Definition 2.4 (Free variables)

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

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

where

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

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

- 1 Repetition: Syntax of WHILE
- 2 Operational Semantics of WHILE
- 3 Evaluation of Arithmetic Expressions
- 4 Excursus: Proof by Structural Induction
- 5 Evaluation of Boolean Expressions
- 6 Execution of Statements

Proof principle

Given: an inductive set, i.e., a set S

- which contains certain atomic elements and
- which is closed under 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

Application: natural numbers (“complete 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

Example 2.5

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

Example 2.5

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

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

Example 2.5

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

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

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

Example 2.5

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

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

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

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

Example 2.5

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

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

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

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

Example 2.5

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

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

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

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

Example 2.5

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

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

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

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

Example 2.5

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

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

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

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

$$\begin{aligned} &= \frac{n(n+1)}{2} + (n+1) \\ &= \frac{n(n+1)}{2} + \frac{2(n+1)}{2} \\ &= \frac{(n+2)(n+1)}{2} \\ &= \frac{(n+1)((n+1)+1)}{2} \quad \checkmark \end{aligned}$$

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

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 $z \in \mathbb{Z}$,

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

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 $z \in \mathbb{Z}$,

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

Proof.

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



- 1 Repetition: Syntax of WHILE
- 2 Operational Semantics of WHILE
- 3 Evaluation of Arithmetic Expressions
- 4 Excursus: Proof by Structural Induction
- 5 Evaluation of Boolean Expressions**
- 6 Execution of Statements

Evaluation of Boolean Expressions I

Remember: $b ::= t \mid a_1 = a_2 \mid a_1 > a_2 \mid \neg b \mid b_1 \wedge b_2 \mid b_1 \vee b_2 \in BExp$

Evaluation of Boolean Expressions I

Remember: $b ::= t \mid a_1 = a_2 \mid a_1 > a_2 \mid \neg b \mid b_1 \wedge b_2 \mid b_1 \vee b_2 \in BExp$

Definition 2.7 (Evaluation relation for Boolean expressions)

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

$$\begin{array}{c} \frac{}{\langle t, \sigma \rangle \rightarrow t} \\[10pt] \frac{\langle a_1, \sigma \rangle \rightarrow z \quad \langle a_2, \sigma \rangle \rightarrow z}{\langle a_1 = a_2, \sigma \rangle \rightarrow \text{true}} \qquad \frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 = a_2, \sigma \rangle \rightarrow \text{false}} \text{ if } z_1 \neq z_2 \\[10pt] \frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 > a_2, \sigma \rangle \rightarrow \text{true}} \text{ if } z_1 > z_2 \qquad \frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 > a_2, \sigma \rangle \rightarrow \text{false}} \text{ if } z_1 \leq z_2 \\[10pt] \frac{\langle b, \sigma \rangle \rightarrow \text{false}}{\langle \neg b, \sigma \rangle \rightarrow \text{true}} \qquad \frac{\langle b, \sigma \rangle \rightarrow \text{true}}{\langle \neg b, \sigma \rangle \rightarrow \text{false}} \\[10pt] \frac{\langle b_1, \sigma \rangle \rightarrow \text{true} \quad \langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{true}} \qquad \frac{\langle b_1, \sigma \rangle \rightarrow \text{true} \quad \langle b_2, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \\[10pt] \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \quad \langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \qquad \frac{\langle b_1, \sigma \rangle \rightarrow \text{false} \quad \langle b_2, \sigma \rangle \rightarrow \text{false}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}} \end{array}$$

($\vee$ analogously)

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 1st exercise sheet for non-strict evaluation)

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 1st exercise sheet for non-strict evaluation)

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

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 1st exercise sheet for non-strict evaluation)

- $FV : BExp \rightarrow 2^{Var}$ 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 $Var \setminus FV(b)$.

- 1 Repetition: Syntax of WHILE
- 2 Operational Semantics of WHILE
- 3 Evaluation of Arithmetic Expressions
- 4 Excursus: Proof by Structural Induction
- 5 Evaluation of Boolean Expressions
- 6 Execution of Statements

Effect of statement = transformation of program state

Effect of statement = transformation of program state

Example:

$$\langle x := 2+3, \sigma \rangle \rightarrow \sigma[x \mapsto 5]$$

where for every $\sigma \in \Sigma$, $x, y \in Var$, and $z \in \mathbb{Z}$:

$$\sigma[x \mapsto z](y) := \begin{cases} z & \text{if } y = x \\ \sigma(y) & \text{otherwise} \end{cases}$$

Remember:

$c ::= \text{skip} \mid x := a \mid c_1; c_2 \mid \text{if } b \text{ then } c_1 \text{ else } c_2 \mid \text{while } b \text{ do } c \in \text{Cmd}$

Execution of Statements

Remember:

$c ::= \text{skip} \mid x := a \mid c_1; c_2 \mid \text{if } b \text{ then } c_1 \text{ else } c_2 \mid \text{while } b \text{ do } c \in \text{Cmd}$

Definition 2.8 (Execution relation for statements)

For $c \in \text{Cmd}$ and $\sigma, \sigma' \in \Sigma$, the **execution relation** $\langle c, \sigma \rangle \rightarrow \sigma'$ is defined by the following rules:

$$\begin{array}{lcl} \text{(skip)} \frac{}{\langle \text{skip}, \sigma \rangle \rightarrow \sigma} & \text{(asn)} \frac{\langle a, \sigma \rangle \rightarrow z}{\langle x := a, \sigma \rangle \rightarrow \sigma[x \mapsto z]} \\ \text{(seq)} \frac{\langle c_1, \sigma \rangle \rightarrow \sigma' \quad \langle c_2, \sigma' \rangle \rightarrow \sigma''}{\langle c_1; c_2, \sigma \rangle \rightarrow \sigma''} & \text{(if-t)} \frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_1, \sigma \rangle \rightarrow \sigma'}{\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'} \\ \text{(if-f)} \frac{\langle b, \sigma \rangle \rightarrow \text{false} \quad \langle c_2, \sigma \rangle \rightarrow \sigma'}{\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'} & \text{(wh-f)} \frac{\langle b, \sigma \rangle \rightarrow \text{false}}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma} \\ \text{(wh-t)} \frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c, \sigma \rangle \rightarrow \sigma' \quad \langle \text{while } b \text{ do } c, \sigma' \rangle \rightarrow \sigma''}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma''} \end{array}$$