

Semantics and Verification of Software

Lecture 3: Operational Semantics of WHILE

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- 1 Repetition: Evaluation and Execution Relations
- 2 An Execution Example
- 3 Determinism of Evaluation/Execution

Evaluation of Arithmetic Expressions

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

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

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

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

Evaluation of Boolean Expressions

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 (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:

$$\overline{\langle t, \sigma \rangle \rightarrow t}$$

$$\frac{\langle a_1, \sigma \rangle \rightarrow z \quad \langle a_2, \sigma \rangle \rightarrow z}{\langle a_1 = a_2, \sigma \rangle \rightarrow \text{true}}$$

$$\langle a_1 = a_2, \sigma \rangle \rightarrow \text{true}$$

$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 = a_2, \sigma \rangle \rightarrow \text{false}} \text{ if } z_1 \neq z_2$$

$$\langle a_1 = a_2, \sigma \rangle \rightarrow \text{false}$$

$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 > a_2, \sigma \rangle \rightarrow \text{true}} \text{ if } z_1 > z_2$$

$$\langle a_1 > a_2, \sigma \rangle \rightarrow \text{true}$$

$$\frac{\langle a_1, \sigma \rangle \rightarrow z_1 \quad \langle a_2, \sigma \rangle \rightarrow z_2}{\langle a_1 > a_2, \sigma \rangle \rightarrow \text{false}} \text{ if } z_1 \leq z_2$$

$$\langle a_1 > a_2, \sigma \rangle \rightarrow \text{false}$$

$$\frac{\langle b, \sigma \rangle \rightarrow \text{false}}{\langle \neg b, \sigma \rangle \rightarrow \text{true}}$$

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$$\frac{\langle b_1, \sigma \rangle \rightarrow \text{true} \quad \langle b_2, \sigma \rangle \rightarrow \text{true}}{\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{true}}$$

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$$\langle b_1 \wedge b_2, \sigma \rangle \rightarrow \text{false}$$

($\vee$ analogously)

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 (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:

$$\begin{array}{c} \frac{}{\langle \text{skip}, \sigma \rangle \rightarrow \sigma} \text{ (skip)} \qquad \frac{\langle a, \sigma \rangle \rightarrow z}{\langle x := a, \sigma \rangle \rightarrow \sigma[x \mapsto z]} \text{ (asgn)} \\[10pt] \frac{\langle c_1, \sigma \rangle \rightarrow \sigma' \quad \langle c_2, \sigma' \rangle \rightarrow \sigma''}{\langle c_1; c_2, \sigma \rangle \rightarrow \sigma''} \text{ (seq)} \qquad \frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_1, \sigma \rangle \rightarrow \sigma'}{\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'} \text{ (if-t)} \\[10pt] \frac{\langle b, \sigma \rangle \rightarrow \text{false} \quad \langle c_2, \sigma \rangle \rightarrow \sigma'}{\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'} \text{ (if-f)} \qquad \frac{\langle b, \sigma \rangle \rightarrow \text{false}}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma} \text{ (wh-f)} \\[10pt] \frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c, \sigma \rangle \rightarrow \sigma' \quad \langle \text{while } b \text{ do } c, \sigma' \rangle \rightarrow \sigma''}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma''} \text{ (wh-t)} \end{array}$$

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Example 3.4

- $c := y := 1; \text{ while } \underbrace{\neg(x=1)}_b \text{ do } \underbrace{y := y * x}_{c_1}; \underbrace{x := x - 1}_{c_2}$
 $\underbrace{\hspace{10em}}_{c_0}$
- Claim: $\langle c, \sigma \rangle \rightarrow \sigma_{1,6}$ for every $\sigma \in \Sigma$ with $\sigma(x) = 3$
- Notation: $\sigma_{i,j}$ means $\sigma(x) = i, \sigma(y) = j$
- Derivation tree: on the board

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This operational semantics is well defined in the following sense:

Theorem 3.5

*The execution relation for statements is **deterministic**, i.e., whenever $c \in \text{Cmd}$ and $\sigma, \sigma', \sigma'' \in \Sigma$ such that $\langle c, \sigma \rangle \rightarrow \sigma'$ and $\langle c, \sigma \rangle \rightarrow \sigma''$, then $\sigma' = \sigma''$.*

The proof is based on the corresponding result for expressions.

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The proof is based on the corresponding result for expressions.

Lemma 3.6

- ① For every $a \in AExp$, $\sigma \in \Sigma$, and $z, z' \in \mathbb{Z}$: $\langle a, \sigma \rangle \rightarrow z$ and $\langle a, \sigma \rangle \rightarrow z'$ implies $z = z'$.
- ② For every $b \in BExp$, $\sigma \in \Sigma$, and $t, t' \in \mathbb{B}$: $\langle b, \sigma \rangle \rightarrow t$ and $\langle b, \sigma \rangle \rightarrow t'$ implies $t = t'$.

Remark: Lemma 3.6 is **not** implied by Lemma 2.6
(“ $\sigma|_{FV(a)} = \sigma'|_{FV(a)} \implies (\langle a, \sigma \rangle \rightarrow z \iff \langle a, \sigma' \rangle \rightarrow z)$ ”)!)

The latter just implies

$$\{z \in \mathbb{Z} \mid \langle a, \sigma \rangle \rightarrow z\} = \{z \in \mathbb{Z} \mid \langle a, \sigma' \rangle \rightarrow z\}$$

while Lemma 3.6 states that

$$|\{z \in \mathbb{Z} \mid \langle a, \sigma \rangle \rightarrow z\}| \leq 1.$$

Lemma 3.6

- 1 For every $a \in AExp$, $\sigma \in \Sigma$, and $z, z' \in \mathbb{Z}$: $\langle a, \sigma \rangle \rightarrow z$ and $\langle a, \sigma \rangle \rightarrow z'$ implies $z = z'$.
- 2 For every $b \in BExp$, $\sigma \in \Sigma$, and $t, t' \in \mathbb{B}$: $\langle b, \sigma \rangle \rightarrow t$ and $\langle b, \sigma \rangle \rightarrow t'$ implies $t = t'$.

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while Lemma 3.6 states that

$$|\{z \in \mathbb{Z} \mid \langle a, \sigma \rangle \rightarrow z\}| \leq 1.$$

Application: Boolean expressions (Def. 1.2)

Definition: $BExp$ is the least set which

- contains the truth values $t \in \mathbb{B}$ and, for every $a_1, a_2 \in AExp$, $a_1 = a_2$ and $a_1 > a_2$, and
- contains $\neg b_1$, $b_1 \wedge b_2$ and $b_1 \vee b_2$ whenever $b_1, b_2 \in BExp$

Induction base: $P(t)$, $P(a_1 = a_2)$ and $P(a_1 > a_2)$ holds
(for every $t \in \mathbb{B}$, $a_1, a_2 \in AExp$)

Induction hypothesis: $P(b_1)$ and $P(b_2)$ holds

Induction step: $P(\neg b_1)$, $P(b_1 \wedge b_2)$ and $P(b_1 \vee b_2)$ holds

Proof (Lemma 3.6).

- 1 by structural induction on a (omitted)
- 2 by structural induction on b (omitted)

Excursus: Proof by Structural Induction IV

Application: Boolean expressions (Def. 1.2)

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Proof (Lemma 3.6).

- 1 by structural induction on a (omitted)
- 2 by structural induction on b (omitted)

- How to prove that $\langle c, \sigma \rangle \rightarrow \sigma'$ is deterministic (Theorem 3.5)?
- Idea: use **induction on the syntactic structure** of c

Application: syntax of WHILE statements (Def. 1.2)

Definition: Cmd is the least set which

- contains **skip** and, for every $x \in Var$ and $a \in AExp$,
 $x := a$, and
- contains $c_1; c_2$, **if** b **then** c_1 **else** c_2 and
while b **do** c_1 whenever $b \in BExp$ and $c_1, c_2 \in Cmd$

Induction base: $P(\text{skip})$ and $P(x := a)$ holds
(for every $x \in Var$ and $a \in AExp$)

Induction hypothesis: $P(c_1)$ and $P(c_2)$ holds

Induction step: $P(c_1; c_2)$, $P(\text{if } b \text{ then } c_1 \text{ else } c_2)$ and
 $P(\text{while } b \text{ do } c_1)$ holds

Determinism of Execution Relation III

Remark:

- But: **proof of Theorem 3.5 fails!**
- Problematic case:

$c = \text{while } b \text{ do } c_0 \text{ where } \langle b, \sigma \rangle \rightarrow \text{true}$

- Here $\langle c, \sigma \rangle \rightarrow \sigma'$ and $\langle c, \sigma \rangle \rightarrow \sigma''$ yield $\sigma_1, \sigma_2 \in \Sigma$ such that

$$\frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_0, \sigma \rangle \rightarrow \sigma_1 \quad \langle c, \sigma_1 \rangle \rightarrow \sigma'}{\langle c, \sigma \rangle \rightarrow \sigma'} \text{ (wh-t)}$$

and

$$\frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_0, \sigma \rangle \rightarrow \sigma_2 \quad \langle c, \sigma_2 \rangle \rightarrow \sigma''}{\langle c, \sigma \rangle \rightarrow \sigma''} \text{ (wh-t)}$$

- c_0 proper substatement of c
 $\implies$ induction hypothesis yields $\sigma_1 = \sigma_2$
- c **not** proper substatement of $c \implies$ **conclusion $\sigma' = \sigma''$ invalid!**

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$$\frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_0, \sigma \rangle \rightarrow \sigma_2 \quad \langle c, \sigma_2 \rangle \rightarrow \sigma''}{\langle c, \sigma \rangle \rightarrow \sigma''} \text{ (wh-t)}$$

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Determinism of Execution Relation III

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- Here $\langle c, \sigma \rangle \rightarrow \sigma'$ and $\langle c, \sigma \rangle \rightarrow \sigma''$ yield $\sigma_1, \sigma_2 \in \Sigma$ such that

$$\frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_0, \sigma \rangle \rightarrow \sigma_1 \quad \langle c, \sigma_1 \rangle \rightarrow \sigma'}{\langle c, \sigma \rangle \rightarrow \sigma'} \text{ (wh-t)}$$

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$$\frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_0, \sigma \rangle \rightarrow \sigma_2 \quad \langle c, \sigma_2 \rangle \rightarrow \sigma''}{\langle c, \sigma \rangle \rightarrow \sigma''} \text{ (wh-t)}$$

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and

$$\frac{\langle b, \sigma \rangle \rightarrow \text{true} \quad \langle c_0, \sigma \rangle \rightarrow \sigma_2 \quad \langle c, \sigma_2 \rangle \rightarrow \sigma''}{\langle c, \sigma \rangle \rightarrow \sigma''} \text{ (wh-t)}$$

- c_0 proper substatement of c
 $\implies$ induction hypothesis yields $\sigma_1 = \sigma_2$
- c **not** proper substatement of $c \implies$ **conclusion $\sigma' = \sigma''$ invalid!**

Application: derivation trees of execution relation (Def. 3.3)

- (skip): for every $\sigma \in \Sigma$, $\frac{}{\langle \text{skip}, \sigma \rangle \rightarrow \sigma}$ is a derivation tree for $\langle \text{skip}, \sigma \rangle \rightarrow \sigma$
- (asgn): if s is a derivation tree for $\langle a, \sigma \rangle \rightarrow z$ (Def. 2.3), then $\frac{s}{\langle x := a, \sigma \rangle \rightarrow \sigma[x \mapsto z]}$ is a derivation tree for $\langle x := a, \sigma \rangle \rightarrow \sigma[x \mapsto z]$
- (seq): if s_1 and s_2 are derivation trees for $\langle c_1, \sigma \rangle \rightarrow \sigma'$ and, respectively, $\langle c_2, \sigma' \rangle \rightarrow \sigma''$, then $\frac{s_1 \quad s_2}{\langle c_1; c_2, \sigma \rangle \rightarrow \sigma''}$ is a derivation tree for $\langle c_1; c_2, \sigma \rangle \rightarrow \sigma''$
- (if-t): if s_1 and s_2 are derivation trees for $\langle b, \sigma \rangle \rightarrow \text{true}$ (Def. 2.7) and, respectively, $\langle c_1, \sigma \rangle \rightarrow \sigma'$, then $\frac{s_1 \quad s_2}{\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'}$ is a derivation tree for $\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'$
- (if-f): analogously
- (wh-t): if s_1 , s_2 and s_3 are derivation trees for $\langle b, \sigma \rangle \rightarrow \text{true}$ (Def. 2.7), $\langle c, \sigma \rangle \rightarrow \sigma'$ and $\langle \text{while } b \text{ do } c, \sigma' \rangle \rightarrow \sigma''$, respectively, then $\frac{s_1 \quad s_2 \quad s_3}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma''}$ is a derivation tree for $\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma''$
- (wh-f): if s is a derivation tree for $\langle b, \sigma \rangle \rightarrow \text{false}$ (Def. 2.7), then $\frac{s}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma}$ is a derivation tree for $\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma$

Application: derivation trees of execution relation (continued)

Induction base: $P\left(\frac{}{\langle \text{skip}, \sigma \rangle \rightarrow \sigma}\right)$ holds for every $\sigma \in \Sigma$, and $P(s)$ holds for every derivation tree s for an arithmetic or Boolean expression.

Induction hypothesis: $P(s_1)$, $P(s_2)$ und $P(s_3)$ holds.

Induction step: it also holds that

$$(\text{asgn}): P\left(\frac{s_1}{\langle x := a, \sigma \rangle \rightarrow \sigma[x \mapsto z]}\right)$$

$$(\text{seq}): P\left(\frac{s_1 \quad s_2}{\langle c_1; c_2, \sigma \rangle \rightarrow \sigma''}\right)$$

$$(\text{if-t}): P\left(\frac{s_1 \quad s_2}{\langle \text{if } b \text{ then } c_1 \text{ else } c_2, \sigma \rangle \rightarrow \sigma'}\right)$$

(if-f): analogously

$$(\text{wh-t}): P\left(\frac{s_1 \quad s_2 \quad s_3}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma''}\right)$$

$$(\text{wh-f}): P\left(\frac{s_1}{\langle \text{while } b \text{ do } c, \sigma \rangle \rightarrow \sigma}\right)$$

Proof.

To show:

$$\langle c, \sigma \rangle \rightarrow \sigma', \langle c, \sigma \rangle \rightarrow \sigma'' \implies \sigma' = \sigma''$$

(by structural induction on derivation trees; on the board)

