

Semantics and Verification of Software

Lecture 25: Provably Correct Implementation II (Compiler Correctness)

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Lehrstuhl für Informatik 2
(Software Modeling and Verification)

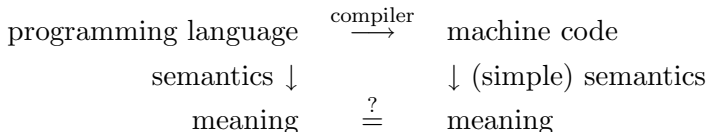
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- 1 Repetition: Abstract Machine & Compiler
- 2 Another Execution Example
- 3 Proof of Compiler Correctness



To do:

- Definition of **abstract machine**
- Definition (operational) **semantics of machine instructions**
- Definition of **translation** WHILE $\rightarrow$ machine code (“compiler”)
- **Proof:** semantics of generated machine code = semantics of original source code

The Abstract Machine

Definition

The **abstract machine (AM)** is given by

- **configurations** of the form $\langle d, e, \sigma \rangle \in Cnf$ where
 - $d \in Code$ is the **sequence** of instructions (code) to be executed
 - $e \in Stk := (\mathbb{Z} \cup \mathbb{B})^*$ is the **evaluation stack**
 - $\sigma \in \Sigma := (Var \rightarrow \mathbb{Z})$ is the **(storage) state**

(thus $Cnf = Code \times Stk \times \Sigma$)

- **final configurations** of the form $\langle \varepsilon, e, \sigma \rangle$
- **code sequences** and **instructions**:

$$d ::= \varepsilon \mid i : d$$

$$i ::= \text{PUSH}(z) \mid \text{ADD} \mid \text{MULT} \mid \text{SUB} \mid \\ \text{TRUE} \mid \text{FALSE} \mid \text{EQ} \mid \text{GT} \mid \text{AND} \mid \text{OR} \mid \text{NEG} \mid \\ \text{LOAD}(x) \mid \text{STORE}(x) \mid \text{NOOP} \mid \text{BRANCH}(d, d) \mid \text{LOOP}(d, d)$$

(where $z \in \mathbb{Z}$ and $x \in Var$)

Translation of Arithmetic Expressions

Definition

The translation function

$$\mathfrak{T}_a[\cdot] : AExp \rightarrow Code$$

is given by

$$\begin{aligned}\mathfrak{T}_a[z] &:= \text{PUSH}(z) \\ \mathfrak{T}_a[x] &:= \text{LOAD}(x) \\ \mathfrak{T}_a[a_1 + a_2] &:= \mathfrak{T}_a[a_2] : \mathfrak{T}_a[a_1] : \text{ADD} \\ \mathfrak{T}_a[a_1 - a_2] &:= \mathfrak{T}_a[a_2] : \mathfrak{T}_a[a_1] : \text{SUB} \\ \mathfrak{T}_a[a_1 * a_2] &:= \mathfrak{T}_a[a_2] : \mathfrak{T}_a[a_1] : \text{MULT}\end{aligned}$$

Example

$$\begin{aligned}\mathfrak{T}_a[x + 1] &= \mathfrak{T}_a[x] : \mathfrak{T}_a[1] : \text{ADD} \\ &= \text{LOAD}(x) : \text{PUSH}(1) : \text{ADD}\end{aligned}$$

Definition

The translation function

$$\mathfrak{T}_b[\cdot] : BExp \rightarrow Code$$

is given by

$$\begin{aligned}\mathfrak{T}_b[\text{true}] &:= \text{TRUE} \\ \mathfrak{T}_b[\text{false}] &:= \text{FALSE} \\ \mathfrak{T}_b[a_1 = a_2] &:= \mathfrak{T}_a[a_2] : \mathfrak{T}_a[a_1] : \text{EQ} \\ \mathfrak{T}_b[a_1 > a_2] &:= \mathfrak{T}_a[a_2] : \mathfrak{T}_a[a_1] : \text{GT} \\ \mathfrak{T}_b[\neg b] &:= \mathfrak{T}_b[b] : \text{NEG} \\ \mathfrak{T}_b[b_1 \wedge a_2] &:= \mathfrak{T}_b[b_2] : \mathfrak{T}_b[b_1] : \text{AND} \\ \mathfrak{T}_b[b_1 \vee a_2] &:= \mathfrak{T}_b[b_2] : \mathfrak{T}_b[b_1] : \text{OR}\end{aligned}$$

Translation of Statements

Definition

The translation function $\mathfrak{T}_c[\cdot] : \text{Cmd} \rightarrow \text{Code}$ is given by

$$\begin{aligned}\mathfrak{T}_c[\text{skip}] &:= \text{NOOP} \\ \mathfrak{T}_c[x := a] &:= \mathfrak{T}_a[a] : \text{STORE}(x) \\ \mathfrak{T}_c[c_1; c_2] &:= \mathfrak{T}_c[c_1] : \mathfrak{T}_c[c_2] \\ \mathfrak{T}_c[\text{if } b \text{ then } c_1 \text{ else } c_2] &:= \mathfrak{T}_b[b] : \text{BRANCH}(\mathfrak{T}_c[c_1], \mathfrak{T}_c[c_2]) \\ \mathfrak{T}_c[\text{while } b \text{ do } c] &:= \text{LOOP}(\mathfrak{T}_b[b], \mathfrak{T}_c[c])\end{aligned}$$

Example (Factorial program)

$$\begin{aligned}&\mathfrak{T}_c[y:=1; \text{while } \neg(x=1) \text{ do } (y:=y*x; x:=x-1)] \\&= \mathfrak{T}_c[y:=1] : \mathfrak{T}_c[\text{while } \neg(x=1) \text{ do } (y:=y*x; x:=x-1)] \\&= \mathfrak{T}_a[1] : \text{STORE}(y) : \text{LOOP}(\mathfrak{T}_b[\neg(x=1)], \mathfrak{T}_c[y:=y*x; x:=x-1]) \\&= \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(\mathfrak{T}_b[x=1] : \text{NEG}, \mathfrak{T}_c[y:=y*x] \mathfrak{T}_c[x:=x-1]) \\&\vdots \\&= \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(\text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}, \\&\quad \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \\&\quad \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x))\end{aligned}$$

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Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and
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$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \quad , \quad \varepsilon, \sigma \quad \rangle$

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$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and
 $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and
 $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and
 $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and
 $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and
 $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad \varepsilon, \sigma$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	$, \quad \varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad \varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad 2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad \text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad \text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	$, \quad \varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad \varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$, \quad 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	$, \quad \varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad \varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad 1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$, \quad 1 : 1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1 : 1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1 : 1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, ε, σ	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $2 : 1, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1 : 2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2, \sigma[y \mapsto 1]$	$\rangle$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $2 : 1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	, $1, \sigma[y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $1 : 1, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{true}, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	, $\text{false}, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$
$\triangleright \langle \text{NOOP} \rangle$	, $\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$	$\rangle$

Execution of Factorial Program

Example 25.1 (Factorial program)

Let $\sigma \in \Sigma$ with $\sigma(x) = 2$, $d_1 := \text{PUSH}(1) : \text{LOAD}(x) : \text{EQ} : \text{NEG}$, and $d_2 := \text{LOAD}(x) : \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x)$.

$\langle \text{PUSH}(1) : \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	ε, σ
$\triangleright \langle \text{STORE}(y) : \text{LOOP}(d_1, d_2) \rangle$	$1, \sigma$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	$\varepsilon, \sigma[y \mapsto 1]$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$\varepsilon, \sigma[y \mapsto 1]$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$1, \sigma[y \mapsto 1]$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$2 : 1, \sigma[y \mapsto 1]$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$\text{false}, \sigma[y \mapsto 1]$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$\text{true}, \sigma[y \mapsto 1]$
$\triangleright \langle d_2 : \text{LOOP}(d_1, d_2) \rangle$	$\varepsilon, \sigma[y \mapsto 1]$
$\triangleright \langle \text{LOAD}(y) : \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$2, \sigma[y \mapsto 1]$
$\triangleright \langle \text{MULT} : \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$1 : 2, \sigma[y \mapsto 1]$
$\triangleright \langle \text{STORE}(y) : \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$2, \sigma[y \mapsto 1]$
$\triangleright \langle \text{PUSH}(1) : \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$\varepsilon, \sigma[y \mapsto 2]$
$\triangleright \langle \text{LOAD}(x) : \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$1, \sigma[y \mapsto 2]$
$\triangleright \langle \text{SUB} : \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$2 : 1, \sigma[y \mapsto 2]$
$\triangleright \langle \text{STORE}(x) : \text{LOOP}(d_1, d_2) \rangle$	$1, \sigma[y \mapsto 2]$
$\triangleright \langle \text{LOOP}(d_1, d_2) \rangle$	$\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle d_1 : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle \text{LOAD}(x) : \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$1, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle \text{EQ} : \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$1 : 1, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle \text{NEG} : \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$\text{true}, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle \text{BRANCH}(d_2 : \text{LOOP}(d_1, d_2), \text{NOOP}) \rangle$	$\text{false}, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle \text{NOOP} \rangle$	$\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$
$\triangleright \langle \varepsilon \rangle$	$\varepsilon, \sigma[x \mapsto 1, y \mapsto 2]$

- 1 Repetition: Abstract Machine & Compiler
- 2 Another Execution Example
- 3 Proof of Compiler Correctness

Definition (Repetition: Semantics of arithm. expr. (Def. 4.4))

The (denotational) semantic functional for arithmetic expressions,

$$\mathcal{A}[\![\cdot]\!] : AExp \rightarrow (\Sigma \rightarrow \mathbb{Z}),$$

is given by:

$$\begin{array}{ll} \mathcal{A}[\![z]\!]\sigma := z & \mathcal{A}[\![a_1 + a_2]\!]\sigma := \mathcal{A}[\![a_1]\!]\sigma + \mathcal{A}[\![a_2]\!]\sigma \\ \mathcal{A}[\![x]\!]\sigma := \sigma(x) & \mathcal{A}[\![a_1 - a_2]\!]\sigma := \mathcal{A}[\![a_1]\!]\sigma - \mathcal{A}[\![a_2]\!]\sigma \\ & \mathcal{A}[\![a_1 * a_2]\!]\sigma := \mathcal{A}[\![a_1]\!]\sigma * \mathcal{A}[\![a_2]\!]\sigma \end{array}$$

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Lemma 25.2 (Correctness of $\mathcal{T}_a[\![\cdot]\!]$)

For every $a \in AExp$ and $\sigma \in \Sigma$,

$$\langle \mathcal{T}_a[\![a]\!], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, \mathcal{A}[\![a]\!]\sigma, \sigma \rangle$$

Correctness of $\mathcal{T}_a[\![\cdot]\!]$

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Proof.

by induction on the syntactic structure of a (on the board)



Definition (Semantics of Boolean expressions (Def. 4.5))

The (denotational) semantic functional for Boolean expressions,

$$\mathfrak{B}[\![\cdot]\!] : BExp \rightarrow (\Sigma \rightarrow \mathbb{B}),$$

is given by:

$$\begin{aligned}\mathfrak{B}[\![t]\!]\sigma &:= t \\ \mathfrak{B}[\![a_1 = a_2]\!]\sigma &:= \begin{cases} \text{true} & \text{if } \mathfrak{A}[\![a_1]\!]\sigma = \mathfrak{A}[\![a_2]\!]\sigma \\ \text{false} & \text{otherwise} \end{cases} \\ \mathfrak{B}[\![a_1 > a_2]\!]\sigma &:= \begin{cases} \text{true} & \text{if } \mathfrak{A}[\![a_1]\!]\sigma > \mathfrak{A}[\![a_2]\!]\sigma \\ \text{false} & \text{otherwise} \end{cases} \\ \mathfrak{B}[\![\neg b]\!]\sigma &:= \begin{cases} \text{true} & \text{if } \mathfrak{B}[\![b]\!]\sigma = \text{false} \\ \text{false} & \text{otherwise} \end{cases} \\ \mathfrak{B}[\![b_1 \wedge b_2]\!]\sigma &:= \begin{cases} \text{true} & \text{if } \mathfrak{B}[\![b_1]\!]\sigma = \mathfrak{B}[\![b_2]\!]\sigma = \text{true} \\ \text{false} & \text{otherwise} \end{cases} \\ \mathfrak{B}[\![b_1 \vee b_2]\!]\sigma &:= \begin{cases} \text{false} & \text{if } \mathfrak{B}[\![b_1]\!]\sigma = \mathfrak{B}[\![b_2]\!]\sigma = \text{false} \\ \text{true} & \text{otherwise} \end{cases}\end{aligned}$$

Lemma 25.3 (Correctness of $\mathfrak{T}_b[\![\cdot]\!]$)

For every $b \in BExp$ and $\sigma \in \Sigma$,

$$\langle \mathfrak{T}_b[\![b]\!], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, \mathfrak{B}[\![b]\!] \sigma, \sigma \rangle$$

Lemma 25.3 (Correctness of $\mathfrak{T}_b[\![\cdot]\!]$)

For every $b \in BExp$ and $\sigma \in \Sigma$,

$$\langle \mathfrak{T}_b[b], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, \mathfrak{B}[b]\sigma, \sigma \rangle$$

Proof.

by induction on the syntactic structure of b (omitted) □

Definition (Repetition: Operational functional (Def. 4.1))

The **functional of the operational semantics**,

$$\mathfrak{D}[\cdot] : Cmd \rightarrow (\Sigma \dashrightarrow \Sigma),$$

assigns to every statement $c \in Cmd$ a partial state transformation

$\mathfrak{D}[c] : \Sigma \dashrightarrow \Sigma$, which is defined as follows:

$$\mathfrak{D}[c]\sigma := \begin{cases} \sigma' & \text{if } \langle c, \sigma \rangle \rightarrow \sigma' \text{ for some } \sigma' \in \Sigma \\ \text{undefined} & \text{otherwise} \end{cases}$$

Definition (Repetition: Operational functional (Def. 4.1))

The **functional of the operational semantics**,

$$\mathfrak{O}[\cdot] : Cmd \rightarrow (\Sigma \dashrightarrow \Sigma),$$

assigns to every statement $c \in Cmd$ a partial state transformation

$\mathfrak{O}[c] : \Sigma \dashrightarrow \Sigma$, which is defined as follows:

$$\mathfrak{O}[c]\sigma := \begin{cases} \sigma' & \text{if } \langle c, \sigma \rangle \rightarrow \sigma' \text{ for some } \sigma' \in \Sigma \\ \text{undefined} & \text{otherwise} \end{cases}$$

Definition (Repetition: Semantics of machine code (Def. 24.8))

The **semantics of an instruction sequence** is given by the mapping

$$\mathfrak{M}[\cdot] : Code \rightarrow (\Sigma \dashrightarrow \Sigma),$$

defined by

$$\mathfrak{M}[d]\sigma := \begin{cases} \sigma' & \text{if } \langle d, \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, e, \sigma' \rangle \\ \text{undefined} & \text{otherwise} \end{cases}$$

Theorem 25.4 (Correctness of $\mathfrak{T}_c[\cdot]$)

For every $c \in \text{Cmd}$,

$$\mathfrak{D}[c] = \mathfrak{M}[\mathfrak{T}_c[c]].$$

Theorem 25.4 (Correctness of $\mathfrak{T}_c[\cdot]$)

For every $c \in \text{Cmd}$,

$$\mathfrak{D}[\![c]\!] = \mathfrak{M}[\![\mathfrak{T}_c[\![c]\!]]\!].$$

Proof carried out in two parts. First step: from source to machine code

Lemma 25.5

For every $c \in \text{Cmd}$ and $\sigma, \sigma' \in \Sigma$,

$$\langle c, \sigma \rangle \rightarrow \sigma' \text{ implies } \langle \mathfrak{T}_c[\![c]\!], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, \varepsilon, \sigma' \rangle.$$

Correctness of $\mathfrak{T}_c[\cdot]$ II

Theorem 25.4 (Correctness of $\mathfrak{T}_c[\cdot]$)

For every $c \in \text{Cmd}$,

$$\mathfrak{D}[c] = \mathfrak{M}[\mathfrak{T}_c[c]].$$

Proof carried out in two parts. First step: from source to machine code

Lemma 25.5

For every $c \in \text{Cmd}$ and $\sigma, \sigma' \in \Sigma$,

$$\langle c, \sigma \rangle \rightarrow \sigma' \text{ implies } \langle \mathfrak{T}_c[c], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, \varepsilon, \sigma' \rangle.$$

Proof.

by induction on the derivation tree of $\langle c, \sigma \rangle \rightarrow \sigma'$ (on the board) □

Second step: from machine to source code

Lemma 25.6

For every $c \in \text{Cmd}$, $\sigma, \sigma' \in \Sigma$, and $e \in \text{Stk}$,

$$\langle \mathcal{T}_c[\![c]\!], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, e, \sigma' \rangle \text{ implies } \langle c, \sigma \rangle \rightarrow \sigma' \text{ and } e = \varepsilon.$$

Second step: from machine to source code

Lemma 25.6

For every $c \in \text{Cmd}$, $\sigma, \sigma' \in \Sigma$, and $e \in \text{Stk}$,

$$\langle \mathcal{T}_c[\![c]\!], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, e, \sigma' \rangle \text{ implies } \langle c, \sigma \rangle \rightarrow \sigma' \text{ and } e = \varepsilon.$$

Proof.

by induction on the length of the computation sequence

$$\langle \mathcal{T}_c[\![c]\!], \varepsilon, \sigma \rangle \triangleright^* \langle \varepsilon, e, \sigma' \rangle \text{ (omitted)}$$

