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Titolo della tesi



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Abstract

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Acknowledgments

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Chapter 1

Framework

1.1 The Imp language

We denote by \mathbb{Z} the set of integers with the usual order, extended with bottom and top elements $-\infty$ and $+\infty$, s.t. $-\infty \leq z \leq +\infty \quad \forall z \in \mathbb{Z}$. We also extend addition and subtraction by letting, for $z \in \mathbb{Z}$ $+\infty + z = +\infty$ $-z = +\infty$ and $-\infty + z = -\infty$ $-z = -\infty$. We focus on the following non-deterministic language.

$$\begin{aligned} \text{Exp} \ni e &::= x \in S \mid x \in [a, b] \mid x \leq k \mid x > k \mid \text{true} \mid \text{false} \mid \\ &\quad x := k \mid x := y + k \mid x := y - k \\ \text{Imp}_{\neq \star} \ni D &::= e \mid D + D \mid D; D \\ \text{Imp} \ni C &::= D \mid C^* \mid \text{fix}(C) \end{aligned}$$

where $x, y \in \text{Var}$ a finite set of variables of interest, i.e., the variables appearing in the considered program, $S \subseteq \mathbb{Z}$ is (possibly empty) subset of numbers, $a \in \mathbb{Z} \cup \{-\infty\}$, $b \in \mathbb{Z} \cup \{+\infty\}$, $a \leq b$, $k \in \mathbb{Z}$ is any finite integer constant.

1.1.1 Syntactic sugar

We define some syntactic sugar for the language. In the next chapters we'll often use the syntactic sugar instead of its real equivalent for the sake of simplicity.

$$\begin{aligned} x \in S \vee x \in S &= (x \in S) + (x \in S) \\ x \in S \wedge x \in S &= (x \in S); (x \in S) \\ x \notin S &= x \in \neg S \\ \text{if } b \text{ then } C_1 \text{ else } C_2 &= (e; C_1) + (\neg e; C_2) \\ \text{while } b \text{ do } C &= \text{fix}(e; C); \neg e \\ x++ &= x := x + 1 \end{aligned}$$

1.2 Semantics

The first building block is that of environments, mapst from the set of variables to their value.

Definition 1.1 (Environments). Environments are (total) maps from variables to (numerical) values

$$\text{Env} \triangleq \{\rho \mid \rho : \text{Var} \rightarrow \mathbb{Z}\}$$

Definition 1.2 (Semantics of Basic Expressions). For basic expressions $e \in \text{Exp}$ the concrete semantics $\llbracket \cdot \rrbracket : \text{Exp} \rightarrow \text{Env} \rightarrow \text{Env} \cup \{\perp\}$ is inductively defined as follows:

$$\begin{aligned}
\llbracket x \in S \rrbracket \rho &\triangleq \begin{cases} \rho & \rho(x) \in S \\ \perp & \text{otherwise} \end{cases} \\
\llbracket x \in [a, b] \rrbracket \rho &\triangleq \begin{cases} \rho & \rho(x) \in [a, b] \\ \perp & \text{otherwise} \end{cases} \\
\llbracket x \leq k \rrbracket \rho &\triangleq \begin{cases} \rho & \rho(x) \leq k \\ \perp & \text{otherwise} \end{cases} \\
\llbracket x > k \rrbracket \rho &\triangleq \begin{cases} \rho & \rho(x) > k \\ \perp & \text{otherwise} \end{cases} \\
\llbracket \text{true} \rrbracket \rho &\triangleq \rho \\
\llbracket \text{false} \rrbracket \rho &\triangleq \perp \\
\llbracket x := k \rrbracket \rho &\triangleq \rho[x \mapsto k] \\
\llbracket x := y + k \rrbracket \rho &\triangleq \rho[x \mapsto \rho(y) + k] \\
\llbracket x := y - k \rrbracket \rho &\triangleq \rho[x \mapsto \rho(y) - k]
\end{aligned}$$

The next building block is the concrete collecting semantics for the language, it associates each program in Imp to a function which, given a set of initial environments X “collects” the set of terminal states produced by executing the program from X .

Definition 1.3 (Concrete collecting semantics). Let $\mathbb{C} \triangleq \langle 2^{\text{Env}}, \subseteq \rangle$ be a complete lattice called *concrete collecting domain*. The concrete collecting semantics for Imp is given by the total mapping

$$\langle \cdot \rangle : \text{Imp} \rightarrow \mathbb{C} \rightarrow \mathbb{C}$$

which maps each program $C \in \text{Imp}$ to a total mapping over the complete lattice \mathbb{C} ,

$$\langle C \rangle : \mathbb{C} \rightarrow \mathbb{C}$$

inductively defined as follows: given $X \in 2^{\text{Env}}$

$$\begin{aligned}
\langle e \rangle X &\triangleq \{ \llbracket e \rrbracket \rho \mid \rho \in X, \llbracket e \rrbracket \rho \neq \perp \} \\
\langle C_1 + C_2 \rangle X &\triangleq \langle C_1 \rangle X \cup \langle C_2 \rangle X \\
\langle C_1; C_2 \rangle X &\triangleq \langle C_2 \rangle (\langle C_1 \rangle X) \\
\langle C^* \rangle X &\triangleq \bigcup_{i \in \mathbb{N}} \langle C \rangle^i X \\
\langle \text{fix}(C) \rangle X &\triangleq \text{lfp}(\lambda Y \in 2^{\text{Env}}. (\langle C \rangle X \cup Y))
\end{aligned}$$

This concrete semantics is additive, meaning that the Kleene star (C^*) and the fixpoint ($\text{fix}(C)$) have the same concrete semantics $\langle C^* \rangle = \langle \text{fix}(C) \rangle$. This will not be the case for the abstract semantics (cf. example ??), where the Kleene star can be more precise than the fixpoint semantics, but harder to compute and, as such, less suited for analysis. For the concrete semantics, however, since they are the same in the latter proofs we’ll only explore the case C^* since it captures also $\text{fix}(C)$.

Along with the collecting semantics we also define a one step transition relation.

Definition 1.4 (Program State). Program states are tuples of programs and program environments:

$$\text{State} \triangleq \text{Imp} \times \text{Env}$$

Definition 1.5 (Small step semantics). The small step transition relation \rightarrow : $\text{State} \times (\text{State} \cup \text{Env})$ is a small step semantics for the Imp language. It is defined based on the following rules

$$\frac{\langle e \rangle \rho \neq \perp}{\langle e, \rho \rangle \rightarrow \langle e \rangle \rho} \text{ expr}$$

$$\frac{}{\langle C_1 + C_2, \rho \rangle \rightarrow \langle C_1, \rho \rangle} \text{ sum}_1 \quad \frac{}{\langle C_1 + C_2, \rho \rangle \rightarrow \langle C_2, \rho \rangle} \text{ sum}_2$$

$$\frac{\langle C_1, \rho \rangle \rightarrow \langle C'_1, \rho' \rangle}{\langle C_1; C_2, \rho \rangle \rightarrow \langle C'_1; C_2, \rho' \rangle} \text{ comp}_1 \quad \frac{\langle C_1, \rho \rangle \rightarrow \rho'}{\langle C_1; C_2, \rho \rangle \rightarrow \langle C_2, \rho' \rangle} \text{ comp}_2$$

$$\frac{}{\langle C^*, \rho \rangle \rightarrow \langle C; C^*, \rho \rangle} \text{ star} \quad \frac{}{\langle C^*, \rho \rangle \rightarrow \rho} \text{ star}_{\text{fix}}$$

Notation 1.1. We write $\langle C, \rho \rangle \rightarrow^* \langle C'', \rho'' \rangle$ meaning

$$\exists k \in \mathbb{N} \mid \underbrace{\langle C, \rho \rangle \rightarrow \langle C', \rho' \rangle \rightarrow \cdots \rightarrow \langle C'', \rho'' \rangle}_{k \text{ transitions}}$$

Lemma 1.1 (Collecting and small step link). For any $C \in \text{Imp}, X \in 2^{\text{Env}}$

$$\langle C \rangle X = \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C, \rho \rangle \rightarrow^* \rho_t \}$$

Therefore $\langle C \rangle X = \emptyset \iff \nexists \rho_t \in \text{Env}, \rho \in X \text{ s.t. } \langle C, \rho \rangle \rightarrow^* \rho_t$.

Proof. by induction on C :

Base case:

$C \equiv e$: $\langle e \rangle X = \{ \langle e \rangle \rho \mid \rho \in X \wedge \langle e \rangle \rho \neq \perp \}$, $\forall \rho \in X. \langle e, \rho \rangle \rightarrow \langle e \rangle \rho$ if $\langle e \rangle \rho \neq \perp$ because of the expr rule

$$\langle e \rangle X = \{ \langle e \rangle \rho \mid \rho \in X \wedge \langle e \rangle \rho \neq \perp \} = \{ \rho_t \in \text{Env} \mid \rho \in X, \langle e, \rho \rangle \rightarrow \rho_t \}$$

Inductive cases:

1. $C \equiv C_1 + C_2$: $\langle C_1 + C_2 \rangle X = \langle C_1 \rangle X \cup \langle C_2 \rangle X$, $\forall \rho \in X. \langle C_1 + C_2, \rho \rangle \rightarrow \langle C_1, \rho \rangle \vee \langle C_1 + C_2, \rho \rangle \rightarrow \langle C_2, \rho \rangle$ respectively according to rules sum_1 and sum_2 . By inductive hypothesis

$$\langle C_1 \rangle X = \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1, \rho \rangle \rightarrow^* \rho_t \} \quad \langle C_2 \rangle X = \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_2, \rho \rangle \rightarrow^* \rho_t \}$$

Therefore

$$\begin{aligned} \langle C_1 + C_2 \rangle X &= \langle C_1 \rangle X \cup \langle C_2 \rangle X && \text{(by definition)} \\ &= \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1, \rho \rangle \rightarrow^* \rho_t \} \cup \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_2, \rho \rangle \rightarrow^* \rho_t \} && \text{(by ind. hp)} \\ &= \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1, \rho \rangle \rightarrow^* \rho_t \vee \langle C_2, \rho \rangle \rightarrow^* \rho_t \} \\ &= \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1 + C_2, \rho \rangle \rightarrow^* \rho_t \} \end{aligned}$$

2. $C \equiv C_1; C_2$: $\langle C_1; C_2 \rangle X = \langle C_2 \rangle (\langle C_1 \rangle X)$. By inductive hp $\langle C_1 \rangle X = \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1, \rho \rangle \rightarrow^* \rho_t \} = Y$, by inductive hp again $\langle C_2 \rangle Y = \{ \rho_t \in \text{Env} \mid \rho \in Y, \langle C_2, \rho \rangle \rightarrow^* \rho_t \}$. Therefore

$$\begin{aligned} \langle C_1; C_2 \rangle X &= \langle C_2 \rangle (\langle C_1 \rangle X) && \text{(by definition)} \\ &= \{ \rho_t \in \text{Env} \mid \rho_x \in \{ \rho_x \mid \rho \in X, \langle C_1, \rho \rangle \rightarrow^* \rho_x \}, \langle C_2, \rho_x \rangle \rightarrow^* \rho_t \} && \text{(by ind. hp)} \\ &= \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1, \rho \rangle \rightarrow^* \rho_x \wedge \langle C_2, \rho_x \rangle \rightarrow^* \rho_t \} && \text{(by definition)} \\ &= \{ \rho_t \in \text{Env} \mid \rho \in X, \langle C_1; C_2, \rho \rangle \rightarrow^* \rho_t \} \end{aligned}$$

$$3. C \equiv C^* : \langle C^* \rangle X = \cup_{i \in \mathbb{N}} \langle C \rangle^i X$$

$$\begin{aligned} \langle C^* \rangle X &= X \cup \langle C \rangle X \cup \langle C \rangle^2 X \cup \dots && \text{(by definition)} \\ &= X \cup \{\rho_t \in \text{Env} \mid \rho \in X, \langle C, \rho \rangle \rightarrow^* \rho_t\} \cup \{\rho_t \in 2^{\text{Env}} \mid \rho \in X, \langle C; C, \rho \rangle \rightarrow^* \rho_t\} \cup \dots && \text{(by ind. hp)} \\ &= \cup_{i \in \mathbb{N}} \{\rho_t \in \text{Env} \mid \rho \in X, \langle C^i, \rho \rangle \rightarrow^* \rho_t\} \\ &= \{\rho_t \in \text{Env} \mid \rho \in X, \forall i \in \mathbb{N} \langle C^i, \rho \rangle \rightarrow^* \rho_t\} \\ &= \{\rho_t \in \text{Env} \mid \rho \in X, \langle C^*, \rho \rangle \rightarrow^* \rho_t\} \end{aligned}$$

□

We can notice that $\langle C \rangle X = \emptyset \iff \nexists \rho_t \in \text{Env}, \rho \in X \mid \langle C, \rho \rangle \rightarrow^* \rho_t$.

1.3 Transition system

With the set of states **State**, the set of environments **Env** and the small operational semantics \rightarrow we define a transition system:

Definition 1.6 (Transition system).

$$\langle \text{State} \cup \text{Env}, \text{Env}, \rightarrow \rangle$$

is a transition system for the language **Imp**

Definition 1.7 (Reductions). Given a program $C \in \text{Imp}$ we define its reductions $\text{red}(C)$ as

$$\text{red}(C) = \{C' \mid \langle C, \rho \rangle \rightarrow^* \langle C', \rho' \rangle \text{ for some } \rho\}$$

Lemma 1.2. Given a program $C \in \text{Imp}$, for $\text{red}(C)$ it holds that

$$\begin{aligned} \text{red}(e) &= \emptyset \\ \text{red}(C_1 + C_2) &= \{C_1, C_2\} \cup \text{red}(C_1) \cup \text{red}(C_2) \\ \text{red}(C_1; C_2) &= \{C_2\} \cup \text{red}(C_2) \cup \{C'_1; C_2 \mid C'_1 \in \text{red}(C_1)\} \\ \text{red}(C^*) &= \{C; C^*\} \cup \{C'; C^* \mid C' \in \text{red}(C)\} \end{aligned}$$

Proof. By definition:

- $C \equiv e$, and $\text{red}(e) = \{C' \mid \langle e, \rho \rangle \rightarrow \langle C', \rho' \rangle \text{ for some } \rho\}$. But because of expr rule, either $\langle e, \rho \rangle \rightarrow \langle e \rangle \rho$ (if $\langle e \rangle \rho \neq \perp$) or $\langle e, \rho \rangle \nrightarrow$ (if $\langle e \rangle \rho = \perp$), therefore $\nexists C' \mid \langle e, \rho \rangle \rightarrow \langle C', \rho' \rangle$ for some ρ , therefore

$$\text{red}(e) = \emptyset$$

- $C \equiv C_1 + C_2$ and $\text{red}(C_1 + C_2) = \{C' \mid \langle C_1 + C_2, \rho \rangle \rightarrow \langle C', \rho' \rangle \text{ for some } \rho\}$. By sum_1 $\langle C_1 + C_2, \rho \rangle \rightarrow \langle C_1, \rho \rangle$ and by sum_2 $\langle C_1 + C_2, \rho \rangle \rightarrow \langle C_2, \rho \rangle$. Therefore

$$\text{red}(C_1 + C_2) = \{C_1, C_2\} \cup \text{red}(C_1) \cup \text{red}(C_2)$$

- $C \equiv C_1; C_2$. In this case by comp_1 if $\langle C_1, \rho \rangle \rightarrow \langle C'_1, \rho' \rangle$ then $\langle C_1; C_2, \rho \rangle \rightarrow \langle C'_1; C_2, \rho' \rangle$. By comp_2 if $\langle C_1, \rho \rangle \rightarrow \rho'$ then $\langle C_1; C_2, \rho \rangle \rightarrow \langle C_2, \rho' \rangle$. Therefore

$$\text{red}(C_1; C_2) = \{C_2\} \cup \text{red}(C_2) \cup \{C'_1; C_2 \mid C'_1 \in \text{red}(C_1)\}$$

- $C \equiv C^*$. In this case by star $\langle C^*, \rho \rangle \rightarrow \langle C; C^*, \rho \rangle$ or by star_{fix} $\langle C^*, \rho \rangle \rightarrow \rho$. therefore

$$\text{red}(C^*) = \{C; C^*\} \cup \{C'; C^* \mid C' \in \text{red}(C)\}$$

□

Lemma 1.3. $\forall C \in \text{Imp}$ $\text{red}(C)$ is finite.

Proof. We work by induction on C :

Base case:

$C \equiv e$. Because of lemma 1.2 $\text{red}(e) = \emptyset$ which is finite.

Inductive cases:

- $C \equiv C_1 + C_2$. By lemma 1.2 $\text{red}(C_1 + C_2) = \{C_1, C_2\} \cup \text{red}(C_1) \cup \text{red}(C_2)$, which is finite as it is union of finite sets.
- $C \equiv C_1; C_2$ By lemma 1.2 $\text{red}(C_1; C_2) = \{C_2\} \cup \text{red}(C_2) \cup \{C'_1; C_2 \mid C'_1 \in \text{red}(C_1)\}$. Both $\text{red}(C_1)$ and $\text{red}(C_2)$ are finite by inductive hypothesis, and therefore the union of finite sets is finite..
- $C \equiv C^*$. By lemma 1.2 $\text{red}(C^*) = \{C; C^*\} \cup \{C'; C^* \mid C' \in \text{red}(C)\}$. $\text{red}(C)$ is finite by inductive hypothesis, and therefore the union of finite sets is finite.

□

Definition 1.8 (Paths). Let $\text{State}^\infty \triangleq \text{State}^+ \cup \text{State}^\omega$ be the set of all infinitary sequences of states (both finite and infinite). Then the set of *paths* in the transition system is

$$\text{Path}^\infty = \{\tau \in \text{State}^\infty \mid \forall i \in [1, |\tau|). \tau_i \rightarrow \tau_{i+1}\}$$

1.4 Functions in Imp

Since we're usually dealing with a finite number of free variables in our programs, we can without loss of generality refer to (input) variables as x_n with $n \in \mathbb{N}$. Therefore the collections of states $X \in 2^{\text{Env}}$ will look like

$$[x_1 \mapsto v_1, x_2 \mapsto v_2, \dots, x_n \mapsto v_n, y \mapsto v_y, z \mapsto v_z, \dots]$$

(since we're interested in finite programs, we can have only a finite set of free variables per program).

Notation 1.2 (Program input). Let $C \in \text{Imp}$ be a program, $(a_1, \dots, a_k) \in \mathbb{N}^\omega$ be a sequence of natural numbers. We indicate the sequence of \rightarrow transitions starting from the state $\langle C, [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \rangle$ as

$$C(a_1, \dots, a_k)$$

Notation 1.3 (Existential termination). We write

$$C(a_1, \dots, a_k) \downarrow \iff \langle C \rangle \{ [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \}$$

meaning that in the transition system at least one path leads to a final environment ρ_t . Dually a program $C(a_1, \dots, a_k) \uparrow$ iff there's no path that lead to a final environment ρ_t .

Notation 1.4 (Universal termination). We write

$$C(a_1, \dots, a_k) \Downarrow \iff \forall \langle C, [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \rangle \rightarrow^* \rho_t \text{ for some } \rho_t \in \text{Env}$$

meaning that in the transition system every path leads to a final environment ρ_t . Dually a program $C(a_1, \dots, a_k) \Uparrow$ iff at least one path does not lead to a final environment ρ_t .

Notation 1.5 (Program output). We say

$$C(a_1, \dots, a_n) \downarrow b \iff \exists \langle C, [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \rangle \rightarrow^* \rho_t \text{ s.t. } \rho_t(y) = b$$

$$C(a_1, \dots, a_n) \Downarrow b \iff \forall \langle C, [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \rangle \rightarrow^* \rho_t \text{ s.t. } \rho_t(y) = b$$

We consider the variable y as an output register for the program.

Observation 1.1. notice that this means, by lemma 1.1 that

$$C(a_1, \dots, a_k) \downarrow b \iff \exists \rho_t \in \langle C \rangle \{ [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \} . \rho_t(y) = b$$

$$C(a_1, \dots, a_k) \Downarrow b \iff \forall \rho_t \in \langle C \rangle \{ [x_1 \mapsto a_1, \dots, x_k \mapsto a_k] \} . \rho_t(y) = b$$

Definition 1.9 (Imp computability). let $f : \mathbb{N}^k \rightarrow \mathbb{N}$ be a function. f is Imp computable if

$$\exists C \in \text{Imp} \mid \forall (a_1, \dots, a_k) \in \mathbb{N}^k \wedge b \in \mathbb{N}$$

$$C(a_1, \dots, a_k) \downarrow b \iff (a_1, \dots, a_k) \in \text{dom}(f) \wedge f(a_1, \dots, a_k) = b$$

We argue that the class of function computed by Imp is the same as the set of partially recursive functions $\mathbb{N} \xrightarrow{r} \mathbb{N}$ (as defined in [Cut80]). To do that we have to prove that it contains the zero, successor and projection functions and it is closed under composition, primitive recursion and unbounded minimalization.

Lemma 1.4 (Imp functions richness). *The class of Imp-computable function is rich.*

Proof. We'll proceed by proving that Imp has each and every one of the basic functions (zero, successor, projection).

- The zero function:

$$\begin{aligned} z : \mathbb{N}^k &\rightarrow \mathbb{N} \\ (x_1, \dots, x_k) &\mapsto 0 \end{aligned}$$

is Imp-computable:

$$z(a_1, \dots, a_k) \triangleq y := 0$$

- The successor function

$$\begin{aligned} s : \mathbb{N} &\rightarrow \mathbb{N} \\ x_1 &\mapsto x_1 + 1 \end{aligned}$$

is Imp-computable:

$$s(a_1) \triangleq y := x_1 + 1$$

- The projection function

$$\begin{aligned} U_i^k : \mathbb{N}^k &\rightarrow \mathbb{N} \\ (x_1, \dots, x_k) &\mapsto x_i \end{aligned}$$

is Imp-computable:

$$U_i^k(a_1, \dots, a_k) \triangleq y := x_i + 0$$

We'll then prove that it is closed under composition, primitive recursion and unbounded minimalization.

Lemma 1.5. *let $f : \mathbb{N}^k \rightarrow \mathbb{N}$, $g_1, \dots, g_k : \mathbb{N}^n \rightarrow \mathbb{N}$ and consider the composition*

$$\begin{aligned} h : \mathbb{N}^k &\rightarrow \mathbb{N} \\ \vec{x} &\mapsto f(g_1(\vec{x}), \dots, g_k(\vec{x})) \end{aligned}$$

h is Imp-computable.

Proof. Since by hp $f, g_n \forall n \in [1, k]$ are computable, we'll consider their programs $F, G_n \forall n \in [1, k]$. Now consider the program

$$\begin{aligned}
&G_1(\vec{x}); \\
&y_1 := y + 0; \\
&G_2(\vec{x}); \\
&y_2 := y + 0; \\
&\dots; \\
&G_k(\vec{x}); \\
&y_k := y + 0; \\
&F(y_1, y_2, \dots, y_k);
\end{aligned}$$

Which is exactly h . Therefore Imp is closed under generalised composition. \square

Lemma 1.6. *Given $f : \mathbb{N}^k \rightarrow \mathbb{N}$ and $g : \mathbb{N}^{k+2} \rightarrow \mathbb{N}$ Imp computable, we argue that $h : \mathbb{N}^{k+1} \rightarrow \mathbb{N}$*

$$\begin{cases} h(\vec{x}, 0) = f(\vec{x}) \\ h(\vec{x}, y + 1) = g(\vec{x}, y, h(\vec{x}, y)) \end{cases}$$

defined through primitive recursion is Imp-computable.

Proof. We want a program to compute $h : \mathbb{N}^{k+1} \rightarrow \mathbb{N}$. By hypothesis we have programs F, G to compute respectively $f : \mathbb{N}^k \rightarrow \mathbb{N}$ and $g : \mathbb{N}^{k+2} \rightarrow \mathbb{N}$. Consider the program $H(\vec{x}, x_{k+1})$:

$$\begin{aligned}
&s := 0; \\
&F(\vec{x}); \\
&(x_{k+1} \notin [0, 0]; G(\vec{x}, s, y); s := s + 1; x_{k+1} := x_{k+1} - 1)^*; \\
&x_{k+1} \in [0, 0];
\end{aligned}$$

which computes exactly h . Therefore Imp is closed under primitive recursion. \square

Lemma 1.7. *Let $f : \mathbb{N}^{k+1} \rightarrow \mathbb{N}$ be a Imp-computable function. Then the function $h : \mathbb{N}^k \rightarrow \mathbb{N}$ defined through unbounded minimalization*

$$h(\vec{x}) = \mu y. f(\vec{x}, y) = \begin{cases} \text{least } z \text{ s.t.} & \begin{cases} f(\vec{x}, z) = 0 \\ f(\vec{x}, z) \downarrow & f(\vec{x}, z') \neq 0 \quad \forall z < z' \end{cases} \\ \uparrow & \text{otherwise} \end{cases} \quad (1.1)$$

is Imp-computable.

Proof. Let F be the program for the computable function f with ariety $k + 1$, $\vec{x} = (x_1, x_2, \dots, x_k)$. Consider the program $H(\vec{x})$

$$\begin{aligned}
&z := 0; \\
&F(\vec{x}, z); \\
&(y \notin [0, 0]; z := z + 1; F(\vec{x}, z))^*; \\
&y \in [0, 0]; \\
&y := z + 0;
\end{aligned}$$

Which outputs the least z s.t. $F(\vec{x}, z) \downarrow 0$, and loops forever otherwise. Imp is therefore closed under bounded minimalization. \square

Since has the zero function, the successor function, the projections function and is closed under composition, primitive recursion and unbounded minimalization, the class of Imp-computable functions is rich. \square

Since it is rich and $\mathbb{N} \xrightarrow{r} \mathbb{N}$ is the least class of rich functions, $\mathbb{N} \xrightarrow{r} \mathbb{N} \subseteq \text{Imp}_f$ holds. Therefore we can say

$$f \in \mathbb{N}^k \xrightarrow{r} \mathbb{N} \Rightarrow \exists C \in \text{Imp} \mid C(a_1, \dots, a_k) \downarrow b \iff f(a_1, \dots, a_k) \downarrow b$$

From this we get a couple of facts that derive from well known computability results:

- deciding whether $\langle C \rangle X \neq \emptyset$ (i.e., $C(a_1, \dots, a_k) \Downarrow$) is the same as deciding $x \in \text{dom}(f)$ for some $f \in \mathbb{N}^k \xrightarrow{r} \mathbb{N}$, which is undecidable (from the input problem in [Cut80, p. 104])
- dually, deciding whether $\langle C \rangle X = \emptyset$ (i.e., $C(a_1, \dots, a_k) \Uparrow$) is also undecidable. The set of functions $f \in \mathbb{N}^k \xrightarrow{r} \mathbb{N}$ s.t. $f(x) \uparrow \forall x \in \mathbb{N}^k$ is not trivial and saturated, therefore it is not recursive (by Rice's theorem [Ric53]).

1.5 Deciding invariant finiteness

Lemma 1.8. *If $C \in \text{Imp}_{\neq \star}$, and a finite $X \in 2^{\text{env}}$ then*

$$\langle C \rangle X \text{ is finite}$$

Proof. By induction on the program C :

Base case:

$C \equiv e$, therefore $\langle e \rangle X = \{\langle e \rangle \rho \mid \rho \in X, \langle e \rangle \rho \neq \perp\}$, which is finite, since X is finite.

Inductive cases:

1. $C \equiv C_1 + C_2$, therefore $\langle C_1 + C_2 \rangle X = \langle C_1 \rangle X \cup \langle C_2 \rangle X$. By inductive hypothesis, both $\langle C_1 \rangle X, \langle C_2 \rangle X$ are finite, as they're sub expressions of C . Since the union of finite sets is finite, $\langle C_1 + C_2 \rangle X$ is finite.
2. $C \equiv C_1; C_2$, therefore $\langle C_1; C_2 \rangle X = \langle C_2 \rangle (\langle C_1 \rangle X)$. By inductive hypothesis $\langle C_1 \rangle X = Y$ is finite. Again by inductive hypothesis $\langle C_2 \rangle Y$ is finite.

□

Lemma 1.9. *Given $C \in \text{Imp}_{\neq \star}$, and a finite $X \in 2^{\text{env}}$, the predicate " $\langle C^* \rangle X$ is finite" is undecidable.*

Proof. Suppose we can decide $\langle C^* \rangle X$ is finite. We show that we in that case we would be also able to decide whether $C^*(a_1, \dots, a_k) \Downarrow$, which is undecidable. Let $X = \{[x_1 \mapsto a_1, \dots, x_k \mapsto a_k]\}$ with $a_1, \dots, a_k \in \mathbb{Z}$.

- In case $\langle C^* \rangle X$ is infinite, then it must be that $\forall i \in \mathbb{N} \langle C \rangle^{k+1} X \not\subseteq \bigcup_{i=0}^k \langle C \rangle^i X$, otherwise we would reach a fixpoint and $\langle C^* \rangle X$ would be finite. Since each application of C must create an unempty set of new environments we can build the inductive sequence of sets of environments

$$\begin{aligned} Y_0 &= X \\ Y_{k+1} &= (\langle C \rangle Y_k) \setminus Y_k \end{aligned}$$

and $\forall \rho' \in Y_{k+1} \exists \rho \in Y_k \mid \rho' \in \langle C \rangle \{\rho\}$ by definition. This means that there is an infinite path in the transition system, and therefore $C^*(a_1, \dots, a_k) \uparrow$ which means that $C^*(a_1, \dots, a_k) \Downarrow$ is false.

□

Chapter 2

Intervals

2.1 Interval Analysis

We define *interval analysis* of the above language Imp in a standard way, taking the best correct approximations (bca) for the basic expressions in Exp .

Definition 2.1 (Integer intervals). We call

$$\text{Int} \triangleq \{[a, b] \mid a \in \mathbb{Z} \cup \{-\infty\} \wedge b \in \mathbb{Z} \cup \{+\infty\} \wedge a \leq b\} \cup \{\perp\}$$

set of integer intervals.

Definition 2.2 (Concretization map). We define the *concretization map* $\gamma : \text{Int} \rightarrow 2^{\mathbb{Z}}$ as

$$\begin{aligned} \gamma([a, b]) &\triangleq \{x \in \mathbb{Z} \mid a \leq x \leq b\} \\ \gamma(\perp) &\triangleq \emptyset \end{aligned}$$

Observation 2.1. $\langle \text{Int}, \sqsubseteq \rangle$ is a complete lattice where for all $I, J \in \text{Int}$, $I \sqsubseteq J$ iff $\gamma(I) \subseteq \gamma(J)$.

Definition 2.3 (Abstract integer domain). Let $\text{Int}_* \triangleq \text{Int} \setminus \{\perp\}$. The abstract domain \mathbb{A} for program analysis is the variable-wise lifting of Int_* :

$$\mathbb{A} \triangleq (\text{Var} \rightarrow \text{Int}_*) \cup \{\perp\}$$

where the intervals for a given variable are always nonempty, while \perp represents the empty set of environments. Thus, the corresponding concretization is defined as follows:

Definition 2.4 (Interval concretization). We define the *concretization map* for the abstract domain \mathbb{A} $\gamma_{\text{Int}} : \mathbb{A} \rightarrow 2^{\text{Env}}$ as

$$\begin{aligned} \gamma_{\text{Int}}(\perp) &\triangleq \emptyset \\ \forall \eta \neq \perp \quad \gamma_{\text{Int}}(\eta) &\triangleq \{\rho \in \text{Env} \mid \forall x \in \text{Var} \ \rho(x) \in \gamma(\eta(x))\} \end{aligned}$$

Observation 2.2. If we consider the ordering \sqsubseteq on \mathbb{A} s.t.

$$\forall \eta, \vartheta \in \mathbb{A} \quad \eta \sqsubseteq \vartheta \iff \gamma_{\text{Int}}(\eta) \subseteq \gamma_{\text{Int}}(\vartheta)$$

then $\langle \mathbb{A}, \sqsubseteq \rangle$ is a complete lattice.

Definition 2.5 (Interval sharpening). For a nonempty interval $[a, b] \in \text{Int}$ and $c \in \mathbb{Z}$, we define two operations raising \uparrow the lower bound to c and lowering \downarrow the upper bound to c , respectively:

$$\begin{aligned} [a, b] \uparrow c &\triangleq \begin{cases} [\max\{a, c\}, b] & \text{if } c \leq b \\ \perp & \text{if } c > b \end{cases} \\ [a, b] \downarrow c &\triangleq \begin{cases} [a, \min\{b, c\}] & \text{if } c \geq a \\ \perp & \text{if } c < a \end{cases} \end{aligned}$$

Observe that $\max([a, b] \downarrow c) \leq c$ always holds. □

Definition 2.6 (Interval addition and subtraction). For a nonempty interval $[a, b] \in \text{Int}$ and $c \in \mathbb{Z}$ define $[a, b] \pm c \triangleq [a \pm c, b \pm c]$ (recall that $\pm\infty + c = \pm\infty - c = \pm\infty$). \square

Observe that for every interval $[a, b] \in \text{Int}$ and $c \in \mathbb{Z}$

$$\max([a, b] \uparrow c) \leq b \quad \text{and} \quad \max([a, b] \downarrow c) \leq c$$

that trivially holds by defining $\max(\perp) \triangleq 0$ (i.e., 0 is the maximum of an empty interval).

The *interval semantics* of Imp is defined as the strict (i.e., preserving \perp) extension of the following function $\llbracket \cdot \rrbracket : \text{exp} \cup \text{Imp} \rightarrow \mathbb{A} \rightarrow \mathbb{A}$. For all $\eta : \text{Var} \rightarrow \text{Int}_*$,

$$\begin{aligned} \llbracket \mathbf{x} \in S \rrbracket \eta &\triangleq \begin{cases} \eta[\mathbf{x} \mapsto \eta(\mathbf{x}) \cap \text{Int}(S)] & \text{if } \eta(\mathbf{x}) \cap \text{Int}(S) \neq \perp \\ \perp & \text{otherwise} \end{cases} \\ \llbracket \mathbf{x} \in [a, b] \rrbracket \eta &\triangleq \begin{cases} \eta[\mathbf{x} \mapsto \eta(\mathbf{x}) \cap [a, b]] & \text{if } \eta(\mathbf{x}) \cap [a, b] \neq \perp \\ \perp & \text{otherwise} \end{cases} \\ \llbracket \mathbf{x} \leq k \rrbracket \eta &\triangleq \begin{cases} \eta[\mathbf{x} \mapsto \eta(\mathbf{x}) \downarrow k] & \text{if } \eta(\mathbf{x}) \downarrow k \neq \perp \\ \perp & \text{otherwise} \end{cases} \\ \llbracket \mathbf{x} > k \rrbracket \eta &\triangleq \begin{cases} \eta[\mathbf{x} \mapsto \eta(\mathbf{x}) \uparrow k + 1] & \text{if } \eta(\mathbf{x}) \downarrow k \neq \perp \\ \perp & \text{otherwise} \end{cases} \\ \llbracket \text{true} \rrbracket \eta &\triangleq \eta \\ \llbracket \text{false} \rrbracket \eta &\triangleq \perp \\ \llbracket \mathbf{x} := k \rrbracket \eta &\triangleq \eta[\mathbf{x} \mapsto [k, k]] \\ \llbracket \mathbf{x} := \mathbf{y} + k \rrbracket \eta &\triangleq \eta[\mathbf{x} \mapsto \eta(\mathbf{y}) + k] \\ \llbracket \mathbf{x} := \mathbf{x} - k \rrbracket \eta &\triangleq \eta[\mathbf{x} \mapsto \eta(\mathbf{y}) - k] \\ \llbracket \mathbf{C}_1 + \mathbf{C}_2 \rrbracket \eta &\triangleq \llbracket \mathbf{C}_1 \rrbracket \eta \sqcup \llbracket \mathbf{C}_2 \rrbracket \eta \\ \llbracket \mathbf{C}_1; \mathbf{C}_2 \rrbracket \eta &\triangleq \llbracket \mathbf{C}_2 \rrbracket (\llbracket \mathbf{C}_1 \rrbracket \eta) \\ \llbracket \mathbf{C}^* \rrbracket \eta &\triangleq \bigsqcup_{i \in \mathbb{N}} \llbracket \mathbf{C} \rrbracket^i(\eta) \\ \llbracket \text{fix}(\mathbf{C}) \rrbracket \eta &\triangleq \text{lfp} \lambda \mu. (\eta \sqcup \llbracket \mathbf{C} \rrbracket \mu) \end{aligned}$$

The semantics is well-defined, because of the following lemma:

Lemma 2.1. *for all $\mathbf{C} \in \text{Imp}$,*

$$\llbracket \mathbf{C} \rrbracket : \mathbb{A} \rightarrow \mathbb{A}$$

is monotone.

Proof. What we have to prove is that given $\eta, \vartheta \in \mathbb{A}$, with $\eta \sqsubseteq \vartheta$ then $\forall \mathbf{C} \in \text{Imp} \llbracket \mathbf{C} \rrbracket \eta \sqsubseteq \llbracket \mathbf{C} \rrbracket \vartheta$. We'll work by induction on the grammar of \mathbf{C} :

Base cases:

We avoid cases where $\eta = \perp$ and $\llbracket \mathbf{C} \rrbracket \eta = \perp$ as $\forall \vartheta \in \mathbb{A} \perp \sqsubseteq \vartheta$ and it becomes trivially true.

- $\mathbf{C} \equiv \mathbf{x} \in S$. Then

$$\begin{aligned} \llbracket \mathbf{x} \in S \rrbracket \eta &= \eta[\mathbf{x} \mapsto \eta(\mathbf{x}) \cap \text{Int}(S)] \\ \llbracket \mathbf{x} \in S \rrbracket \vartheta &= \vartheta[\mathbf{x} \mapsto \vartheta(\mathbf{x}) \cap \text{Int}(S)] \end{aligned}$$

Since $\eta(x) \sqcap \text{Int}(S) \neq \perp$ and $\eta \sqsubseteq \vartheta$, then $\vartheta(x) \sqcap \text{Int}(S) \neq \perp$. We can see that

$$\begin{aligned}
\eta \sqsubseteq \vartheta &\iff \gamma(\eta) \subseteq \gamma(\vartheta) \\
&\iff \{x \in \mathbb{Z} \mid x \in \eta(\mathbf{x})\} \subseteq \{x \in \mathbb{Z} \mid x \in \vartheta(\mathbf{x})\} \\
&\iff \{x \in \mathbb{Z} \mid x \in \eta(\mathbf{x})\} \cap \{x \in \mathbb{Z} \mid x \in \text{Int}(S)\} \subseteq \{x \in \mathbb{Z} \mid x \in \vartheta(\mathbf{x})\} \cap \{x \in \mathbb{Z} \mid x \in \text{Int}(S)\} \\
&\iff \{x \in \mathbb{Z} \mid x \in \eta(\mathbf{x}) \wedge x \in \text{Int}(S)\} \subseteq \{x \in \mathbb{Z} \mid x \in \vartheta(\mathbf{x}) \wedge x \in \text{Int}(S)\} \\
&\iff \{x \in \mathbb{Z} \mid x \in \eta(\mathbf{x}) \sqcap \text{Int}(S)\} \subseteq \{x \in \mathbb{Z} \mid x \in \vartheta(\mathbf{x}) \sqcap \text{Int}(S)\} \\
&\iff \gamma_{\text{Int}}(\eta[x \mapsto \eta(\mathbf{x}) \sqcap \text{Int}(S)](\mathbf{x})) \subseteq \gamma_{\text{Int}}(\vartheta[x \mapsto \vartheta(\mathbf{x}) \sqcap \text{Int}(S)](\mathbf{x})) \\
&\iff \llbracket \mathbf{x} \in S \rrbracket \eta \sqsubseteq \llbracket \mathbf{x} \in S \rrbracket \vartheta
\end{aligned}$$

- for the base cases $\mathbf{x} \in [a, b]$, $\mathbf{x} \leq k$, $\mathbf{x} > k$ we can use the same proceedings;
- $C \equiv \text{true}$. Then $\llbracket \text{true} \rrbracket \eta = \eta \sqsubseteq \vartheta = \llbracket \text{true} \rrbracket \vartheta$;
- $C \equiv \text{false}$. Then $\llbracket \text{false} \rrbracket \eta = \perp \sqsubseteq \perp = \llbracket \text{false} \rrbracket \vartheta$;
- $C \equiv \mathbf{x} := k$. Then

$$\begin{aligned}
\eta \sqsubseteq \vartheta &\iff \gamma_{\text{Int}}(\eta) \subseteq \gamma_{\text{Int}}(\vartheta) \\
&\iff \{\rho \in \text{Env} \mid \forall \mathbf{x} \in \text{Var} \rho(\mathbf{x}) \in \gamma(\eta(\mathbf{x}))\} \subseteq \{\rho \in \text{Env} \mid \forall \mathbf{x} \in \text{Var} \rho(\mathbf{x}) \in \gamma(\vartheta(\mathbf{x}))\} \\
&\iff \forall \mathbf{x} \in \text{Var}, \rho \in \text{Env} \quad \rho(\mathbf{x}) \in \gamma(\eta(\mathbf{x})) \Rightarrow \rho(\mathbf{x}) \in \gamma(\vartheta(\mathbf{x}))
\end{aligned} \tag{2.1}$$

Notice that

$$\begin{aligned}
\llbracket \mathbf{x} := k \rrbracket \eta &= \eta[\mathbf{x} \mapsto [k, k]] \\
\llbracket \mathbf{x} := k \rrbracket \vartheta &= \vartheta[\mathbf{x} \mapsto [k, k]]
\end{aligned}$$

because of equation 2.1 in this case we know that $\forall \mathbf{y} \in \text{Var}, \mathbf{y} \neq \mathbf{x} \rho(\mathbf{y}) \in \gamma(\eta(\mathbf{y})) \Rightarrow \rho(\mathbf{y}) \in \gamma(\vartheta(\mathbf{y}))$. For \mathbf{x} it holds that $\rho(\mathbf{x}) \in \gamma([k, k]) \Rightarrow \rho(\mathbf{x}) \in \gamma([k, k])$ and therefore

$$\begin{aligned}
\forall \mathbf{y} \in \text{Var}, \rho \in \text{Env} \quad \rho(\mathbf{y}) \in \gamma(\eta[\mathbf{x} \mapsto [k, k]](\mathbf{y})) &\Rightarrow \rho(\mathbf{y}) \in \gamma(\vartheta[\mathbf{x} \mapsto [k, k]](\mathbf{y})) \\
&\iff \gamma_{\text{Int}}(\llbracket \mathbf{x} := k \rrbracket \eta) \subseteq \gamma_{\text{Int}}(\llbracket \mathbf{x} := k \rrbracket \vartheta) \\
&\iff \llbracket \mathbf{x} := k \rrbracket \eta \sqsubseteq \llbracket \mathbf{x} := k \rrbracket \vartheta
\end{aligned}$$

- For $C \equiv \mathbf{x} := \mathbf{y} + k$, $\mathbf{x} := \mathbf{y} - k$ the procedure is the same.

Recursive cases:

- $C \equiv C_1 + C_2$. Then

$$\begin{aligned}
\llbracket C_1 + C_2 \rrbracket \eta &= \llbracket C_1 \rrbracket \eta \sqcup \llbracket C_2 \rrbracket \eta \\
&\sqsubseteq \llbracket C_1 \rrbracket \vartheta \sqcup \llbracket C_2 \rrbracket \vartheta && \text{by inductive hp.} \\
&= \llbracket C_1 + C_2 \rrbracket \vartheta
\end{aligned}$$

- $C \equiv C_1; C_2$. Then

$$\begin{aligned}
\llbracket C_1; C_2 \rrbracket \eta &= \llbracket C_2 \rrbracket (\llbracket C_1 \rrbracket \eta) \\
\alpha = \llbracket C_1 \rrbracket \eta &\sqsubseteq \llbracket C_1 \rrbracket \vartheta = \beta && \text{by inductive hp.} \\
\llbracket C_2 \rrbracket \alpha &\sqsubseteq \llbracket C_2 \rrbracket \beta && \text{by inductive hp.} \\
\llbracket C_2 \rrbracket (\llbracket C_1 \rrbracket \eta) &\sqsubseteq \llbracket C_2 \rrbracket (\llbracket C_1 \rrbracket \vartheta) && \text{by substitution}
\end{aligned}$$

- C^* . Then by inductive hypothesis $\forall i \in \mathbb{N}. \llbracket C \rrbracket^i \eta \sqsubseteq \llbracket C \rrbracket^i \vartheta$, which means

$$\llbracket C^* \rrbracket \eta = \bigsqcup_{i \in \mathbb{N}} \llbracket C \rrbracket^i \eta \sqsubseteq \bigsqcup_{i \in \mathbb{N}} \vartheta = \llbracket C^* \rrbracket \vartheta.$$

□

Theorem 1 (Correctness). *For all $C \in \text{Imp}$ and $\eta \in \mathbb{A}$, $\langle C \rangle \gamma(\eta) \subseteq \gamma(\llbracket C \rrbracket \eta)$ holds.*

Sempre per induzione?

Proof.

□

Remark 2.1. Let us remark that in case we were interested in studying termination of the abstract interpreter, we could assume that the input of a program will always be a finite interval in such a way that nontermination can be identified with the impossibility of converging to a finite interval for some variable. In fact, starting from an environment η which maps each variable to a finite interval, $\llbracket C \rrbracket \eta$ might be infinite on some variable when C includes a either Kleene or fix iteration which does not converge in finitely many steps.

2.1.1 Computing the interval semantics

In this section we argue that for the language Imp the interval abstract semantics is computable in finite time without widening.

Observe that the exact computation provides, already for our simple language, a precision which is not obtainable with (basic) widening and narrowing. In the example below the semantics maps x and y to $[0, 2]$ and $[6, 8]$ resp., while widening/narrowing to $[0, \infty]$ and $[6, \infty]$

```
x:=0;
y:=0;
while (x<=5) do
  if (y=0) then
    y=y+1;
  endif;
  if (x==0) then
    x:=y+7;
  endif;
done;
end
```

Of course, for the collecting semantics this is not the case. Already computing a finite upper bound for loop invariants when they are finite is impossible as this would allow to decide termination. In fact, if the invariant is infinite then the loop diverges. If it is finite, then the number of possible states is finite and this termination can be decided as non-termination reduces to the presence of a cycle, as shown with lemma 1.9.

Problem 2.1 (Termination of interval analysis). Given $C \in \text{Imp}$, $\eta \in \mathbb{A}$, decide: $\langle C \rangle \eta =? \top$

First, given a program, we associate each variable with a *single bound*, which captures both an *upper bound*, for which the rough idea is that, whenever a variable is beyond that bound, the behaviour of the program with respect to that variable becomes stable and an *increment bound* which captures the largest increment or decrement that can affect a variable.

Definition 2.7 (Program bound). The *bound* associated with a command $C \in \text{Imp}$ is a natural

number, denoted $(C)^b \in \mathbb{N}$, defined inductively as follows:

$$\begin{aligned}
(x \in S)^b &\triangleq \begin{cases} \min(S) & \text{if } \max(S) = \infty \\ \max(S) & \text{if } \max(S) \in \mathbb{N} \end{cases} \\
(x \in [a, b])^b &\triangleq \begin{cases} a & \text{if } b = \infty \\ b & \text{if } b \in \mathbb{N} \end{cases} \\
(x \leq k)^b &\triangleq k \\
(x > k)^b &\triangleq k \\
(\text{true})^b &\triangleq 0 \\
(\text{false})^b &\triangleq 0 \\
(x := k)^b &\triangleq k \\
(x := y + k)^b &\triangleq k \\
(x := y - k)^b &\triangleq k \\
(C_1 + C_2)^b &\triangleq (C_1)^b + (C_2)^b \\
(C_1; C_2)^b &\triangleq (C_1)^b + (C_2)^b \\
(C^*)^b &\triangleq (|\text{vars}(C)| + 1)(C)^b
\end{aligned}$$

where $\text{vars}(C)$ denotes the set of variables occurring in C .

Definition 2.8 (Bound Environment). A bound environment (benv for short) is a total function $b : \text{Var} \rightarrow \mathbb{N}$. We define $\mathbf{bEnv} \triangleq \{b \mid b : \text{Var} \rightarrow \mathbb{N}\}$. Each command $C \in \text{Imp}$ induces a benv transformer $[C]^b : \mathbf{bEnv} \rightarrow \mathbf{bEnv}$, which is defined inductively as follows:

$$\begin{aligned}
[x \in S]^b b &\triangleq \begin{cases} b[x \mapsto b(x) + \min(S)] & \text{if } \max(S) = \infty \\ b[x \mapsto b(x) + \max(S)] & \text{if } \max(S) \in \mathbb{N} \end{cases} \\
[x := k]^b b &\triangleq b[x \mapsto b(x) + k] \\
[x := y + k]^b b &\triangleq b[x \mapsto b(x) + b(y) + k] \\
[x := y - k]^b b &\triangleq b[x \mapsto b(x) + b(y) + k] \\
[C_1 + C_2]^b b &\triangleq \lambda x. ([C_1]^b b)(x) + ([C_2]^b b)(x) \\
[C_1; C_2]^b b &\triangleq \lambda x. ([C_1]^b b)(x) + ([C_2]^b b)(x) \\
[\text{fix}(C)]^b b &\triangleq \lambda x. (|\text{vars}(C)| + 1)([C]^b b)(x)
\end{aligned}$$

where $\text{vars}(C)$ denotes the set of variables occurring in C .

Lemma 2.2. For all $C \in \text{Imp}$, $(C)^b = \sum_{x \in \text{vars}(C)} ([C]^b b_0)(x)$, with $b_0 \triangleq \lambda x. 0$.

Proof. By induction on $C \in \text{Imp}$. The base cases are clear.

$(C_1 + C_2)$:

$$\begin{aligned}
(C_1 + C_2)^b &= \\
(C_1)^b + (C_2)^b &= \quad [\text{by inductive hypothesis}] \\
\sum_{\mathbf{x} \in \text{vars}(C_1)} ([C]^b b_0)(\mathbf{x}) + \sum_{\mathbf{x} \in \text{vars}(C_2)} ([C]^b b_0)(\mathbf{x}) &= \\
\sum_{\mathbf{x} \in \text{vars}(C_1) \cap \text{vars}(C_2)} ([C_1]^b b_0)(\mathbf{x}) + ([C_2]^b b_0)(\mathbf{x}) + \\
\sum_{\mathbf{x} \in \text{vars}(C_1) \setminus \text{vars}(C_2)} ([C_1]^b b_0)(\mathbf{x}) + \\
\sum_{\mathbf{x} \in \text{vars}(C_2) \setminus \text{vars}(C_1)} ([C_2]^b b_0)(\mathbf{x}) &= \\
[C_1 + C_2]^b b_0
\end{aligned}$$

$(C_1; C_2)$: identical to $(C_1 + C_2)$.

$(\text{fix}(C))$:

$$\begin{aligned}
(\text{fix}(C))^b &= \\
|\text{vars}(C) + 1|(C)^b &= \quad [\text{by inductive hypothesis}] \\
|\text{vars}(C) + 1| \sum_{\mathbf{x} \in \text{vars}(C)} ([C]^b b_0)(\mathbf{x}) &= \\
\sum_{\mathbf{x} \in \text{vars}(C)} |\text{vars}(C) + 1| ([C]^b b_0)(\mathbf{x}) &= \\
[\text{fix}(C)]^b b_0
\end{aligned}$$

□

Chapter 3

Non relational collecting

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