

Abstract interpretation with bounded numeric intervals

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- 1** The Language
 - Arithmetic Expressions
 - Boolean Expressions

- 2** Implementation
 - The Bounded Intervals Domain
 - Abstract States
 - Abstract Semantics

- 3** Performing Analysis

The language is a variation of the While language seen in class. It differs on:

- it admits some syntactic sugar (it's not minimal);
- its semantic functions model divergence and state changes in both arithmetic and boolean expressions.

$$\begin{aligned} AExp ::= & n \mid x \mid -e \mid (e) \mid [e_1, e_2] \\ & \mid e_1 + e_2 \mid e_1 - e_2 \mid e_1 * e_2 \mid e_1 / e_2 \\ & \mid x++ \mid ++x \mid x-- \mid --x \end{aligned}$$

The syntax allows arithmetic expression that change the state, such as $x++$ and $x--$.

The operator $(\cdot/\cdot) : \mathbb{N} \rightarrow \mathbb{N} \rightarrow \mathbb{N}$ returns the quotient of the two arguments. It's undefined when the second argument is 0.

$$\mathcal{A} : AExp \rightarrow State \hookrightarrow \mathbb{Z} \times State$$

$$\mathcal{A}[[n]]\varphi = (n_{\mathbb{Z}}, \varphi)$$

$$\mathcal{A}[[x]]\varphi = (\varphi(x), \varphi)$$

$$\mathcal{A}[(e)]\varphi = \mathcal{A}[[e]]\varphi$$

$$\mathcal{A}[-e]\varphi = \begin{cases} (-a, \varphi') & \mathcal{A}[[e]]\varphi = (a, \varphi') \\ \uparrow & (\mathcal{A}[[e]]\varphi) \uparrow \end{cases}$$

$$\mathcal{A}[[e_1, e_2]]\varphi = (a, \varphi'')$$

$$\text{where } (a_1, \varphi') = \mathcal{A}[[e_1]]\varphi$$

$$(a_2, \varphi'') = \mathcal{A}[[e_2]]\varphi'$$

a is a random number between a_1 and a_2

$\mathcal{A} : AExp \rightarrow State \hookrightarrow \mathbb{Z} \times State$

$$\mathcal{A}[\![e_1/e_2]\!] \varphi = \begin{cases} (a_1 \div a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ & \wedge a_2 \neq 0 \\ \uparrow & \text{otherwise} \end{cases}$$
$$\mathcal{A}[\![e_1 \text{ op } e_2]\!] \varphi = \begin{cases} (a_1 \text{ op } a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$\mathcal{A} : AExp \rightarrow State \hookrightarrow \mathbb{Z} \times State$

$$\mathcal{A}[[x++]]\varphi = (\varphi(x), \varphi[x \mapsto x + 1])$$

$$\mathcal{A}[[++x]]\varphi = \text{let } \varphi' = \varphi[x \mapsto x + 1] \\ \text{in } (\varphi'(x), \varphi')$$

$$\mathcal{A}[[x--]]\varphi = (\varphi(x), \varphi[x \mapsto x - 1])$$

$$\mathcal{A}[[--x]]\varphi = \text{let } \varphi' = \varphi[x \mapsto x - 1] \\ \text{in } (\varphi'(x), \varphi')$$

$$\begin{aligned} BExp ::= & \text{true} \mid \text{false} \mid (b) \mid b_1 \text{ and } b_2 \mid b_1 \text{ or } b_2 \\ & \mid e_1 = e_2 \mid e_1 \neq e_2 \mid e_1 < e_2 \mid e_1 \geq e_2 \\ & \mid e_1 > e_2 \mid e_1 \leq e_2 \end{aligned}$$

The operator $(\neg \cdot) : \mathbb{T} \rightarrow \mathbb{T}$ is not in the minimal definition: it is defined as syntactic sugar later on.

Operators between booleans short-circuit evaluation:

$$\mathcal{B} : BExp \rightarrow State \hookrightarrow \mathbb{T} \times State$$

$$\mathcal{B}[\![\text{true}]\!] \varphi = (\mathbf{tt}, \varphi)$$

$$\mathcal{B}[\![\text{false}]\!] \varphi = (\mathbf{ff}, \varphi)$$

$$\mathcal{B}[\![b]\!] \varphi = \mathcal{B}[\![b]\!] \varphi$$

$$\mathcal{B}[\![b_1 \text{ and } b_2]\!] \varphi = \begin{cases} (\mathbf{ff}, \varphi') & \mathcal{B}[\![b_1]\!] \varphi = (\mathbf{ff}, \varphi') \\ \mathcal{B}[\![b_2]\!] \varphi' & \mathcal{B}[\![b_1]\!] \varphi = (\mathbf{tt}, \varphi') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[\![b_1 \text{ or } b_2]\!] \varphi = \begin{cases} (\mathbf{tt}, \varphi') & \mathcal{B}[\![b_1]\!] \varphi = (\mathbf{tt}, \varphi') \\ \mathcal{B}[\![b_2]\!] \varphi' & \mathcal{B}[\![b_1]\!] \varphi = (\mathbf{ff}, \varphi') \\ \uparrow & \text{otherwise} \end{cases}$$

Comparison operators propagate the state transition(s):

$$\mathcal{B} : BExp \rightarrow State \hookrightarrow \mathbb{T} \times State$$

$$\mathcal{B}[\![e_1 = e_2]\!] \varphi = \begin{cases} (a_1 = a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[\![e_1 \neq e_2]\!] \varphi = \begin{cases} (a_1 \neq a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$\mathcal{B} : BExp \rightarrow State \hookrightarrow \mathbb{T} \times State$

$$\mathcal{B}[[e_1 < e_2]]\varphi = \begin{cases} (a_1 < a_2, \varphi'') & \mathcal{A}[[e_1]]\varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[[e_2]]\varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[[e_1 \geq e_2]]\varphi = \begin{cases} (a_1 \geq a_2, \varphi'') & \mathcal{A}[[e_1]]\varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[[e_2]]\varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$\mathcal{B} : BExp \rightarrow State \hookrightarrow \mathbb{T} \times State$

$$\mathcal{B}[[e_1 > e_2]]\varphi = \begin{cases} (a_1 > a_2, \varphi'') & \mathcal{A}[[e_1]]\varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[[e_2]]\varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[[e_1 \leq e_2]]\varphi = \begin{cases} (a_1 \leq a_2, \varphi'') & \mathcal{A}[[e_1]]\varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[[e_2]]\varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

Rule

Since boolean expressions induce state transitions, the evaluation order and quantity must be preserved in the desugared code.

This is the reason why we couldn't model the operators $(\cdot > \cdot)$, $(\cdot \leq \cdot) : \mathbb{N} \rightarrow \mathbb{N} \rightarrow \mathbb{T}$ as syntactic sugar. There is no way to encode those operators only with $(\cdot < \cdot)$, $(\cdot \geq \cdot)$, $(\cdot = \cdot)$ and $(\cdot \neq \cdot)$ respecting this rule.

$$\text{not true} \stackrel{\text{def}}{=} \text{false}$$

$$\text{not false} \stackrel{\text{def}}{=} \text{true}$$

$$\text{not } (b_1 \text{ and } b_2) \stackrel{\text{def}}{=} \text{not } b_1 \text{ or not } b_2$$

$$\text{not } (b_1 \text{ or } b_2) \stackrel{\text{def}}{=} \text{not } b_1 \text{ and not } b_2$$

$$\text{not } e_1 = e_2 \stackrel{\text{def}}{=} e_1 \neq e_2$$

$$\text{not } e_1 \neq e_2 \stackrel{\text{def}}{=} e_1 = e_2$$

$$\text{not } e_1 < e_2 \stackrel{\text{def}}{=} e_1 \geq e_2$$

$$\text{not } e_1 \geq e_2 \stackrel{\text{def}}{=} e_1 < e_2$$

$$\text{not } e_1 > e_2 \stackrel{\text{def}}{=} e_1 \leq e_2$$

$$\text{not } e_1 \leq e_2 \stackrel{\text{def}}{=} e_1 > e_2$$

While ::= $x := e$ | skip | $\{S\}$ | $S_1 ; S_2$
| if b then S_1 else S_2 | while b do S

$\mathcal{S}_{ds} : \text{While} \rightarrow \text{State} \hookrightarrow \text{State}$

$$\mathcal{S}_{ds}[\![x := e]\!] \varphi = \begin{cases} \varphi'[x \mapsto a] & \mathcal{A}[\![e]\!] \varphi = (a, \varphi') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{S}_{ds}[\![\text{skip}]\!] \varphi = \varphi$$

$$\mathcal{S}_{ds}[\![\{S\}]\!] \varphi = \mathcal{S}_{ds}[\![S]\!] \varphi$$

$\mathcal{S}_{ds} : \text{While} \rightarrow \text{State} \hookrightarrow \text{State}$

$$\mathcal{S}_{ds} \llbracket S_1 ; S_2 \rrbracket \varphi = (\mathcal{S}_{ds} \llbracket S_2 \rrbracket \circ \mathcal{S}_{ds} \llbracket S_1 \rrbracket) \varphi$$

$$\mathcal{S}_{ds} \llbracket \text{if } b \text{ then } S_1 \text{ else } S_2 \rrbracket \varphi = \text{cond}(\mathcal{B} \llbracket b \rrbracket, \mathcal{S}_{ds} \llbracket S_1 \rrbracket, \mathcal{S}_{ds} \llbracket S_2 \rrbracket)$$

$$\mathcal{S}_{ds} \llbracket \text{while } b \text{ do } S \rrbracket \varphi = \text{FIX}(\lambda g. \text{cond}(\mathcal{B} \llbracket b \rrbracket, g \circ \mathcal{S}_{ds} \llbracket S \rrbracket, \text{id}))$$

Where

$$\text{cond}(\text{pred}, g_1, g_2) = \begin{cases} g_1(\varphi') & \text{pred}(\varphi) = (\mathbf{tt}, \varphi') \\ g_2(\varphi') & \text{pred}(\varphi) = (\mathbf{ff}, \varphi') \\ \uparrow & \text{otherwise} \end{cases}$$

$$I_{m,n} \subset \wp(\mathbb{Z}) \text{ with } m, n \in \mathbb{Z} \cup -\infty, \infty$$

$$\begin{aligned} I_{m,n} = & \{\mathbb{Z}, \emptyset\} \cup \{\{z\} \mid z \in \mathbb{Z}\} \\ & \cup \{\{x \mid w \leq x \leq z\} \mid x, w, z \in \mathbb{Z} \text{ s.t. } m \leq w \leq z \leq n\} \\ & \cup \{\{x \mid x \leq z\} \mid x, z \in \mathbb{Z} \text{ s.t. } m \leq z \leq n\} \\ & \cup \{\{x \mid x \geq z\} \mid x, z \in \mathbb{Z} \text{ s.t. } m \leq z \leq n\} \end{aligned}$$

Bounded Intervals - Properties (1)



$I_{m,n}$ is partially ordered

$$i_1 \leq i_2 \iff i_1 \subseteq i_2$$

$I_{m,n}$ is a complete lattice

$$\perp_{I_{m,n}} = \emptyset$$

$$\top_{I_{m,n}} = \mathbb{Z}$$

$$\vee_{I_{m,n}} = \cup$$

$$\wedge_{I_{m,n}} = \cap$$

- $I_{m,n}$ has no infinite ascending chains when $m \neq -\infty \wedge n \neq \infty$:
 - when $m, n \in \mathbb{N}$ the fixed-point iteration sequence induced by $\mathcal{D}^\# \llbracket S_1 \rrbracket s \ \forall s \in \mathbb{S}_A, S_1 \in \mathbf{While}$ converges in finite time;
 - otherwise, we must make use of the widening operator $\nabla : \mathbb{S}_A \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A$ in order to enforce convergence.
- $I_{m,n}$ has no infinite descending chains:
 - any descending greatest fixed-point search converges in finite time;
 - there is no need for a narrowing operator $\Delta : \mathbb{S}_A \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A$.

We define for any abstract domain A , which is a complete lattice as well, the abstract state type $\mathbb{S}_A = \text{Map}(\text{Var}, A)$.

Assumption

When a variable is used before its definition, then its value is assumed to be “unknown” (\top_A). This is due to the fact that we assume that all referenced variables in the program are initialized.

Moreover, $\perp_{\mathbb{S}_A}$ represents an abnormal termination (no update operation can be performed over this state):

$$s(x) = \begin{cases} a & (x, a) \in s \\ \top_A & \text{otherwise} \end{cases}$$
$$s[x \mapsto a] = \begin{cases} \perp_{\mathbb{S}_A} & s = \perp_{\mathbb{S}_A} \\ \{(k, v) \mid (k, v) \in s, k \neq x\} & a \neq \top_A, s \neq \perp_{\mathbb{S}_A} \\ \{(k, v) \mid (k, v) \in s, k \neq x\} & \text{otherwise} \end{cases}$$

\mathbb{S}_A is partially ordered

$$s_1 \leq_{\mathbb{S}_A} s_2 \iff s_1(x) \leq_A s_2(x) \quad \forall x \in \text{Var}$$

\mathbb{S}_A is a complete lattice

$$\perp_{\mathbb{S}_A} = \{(x, \perp_A) \mid x \in \text{Var}\}$$

$$\top_{\mathbb{S}_A} = \emptyset$$

$$s_1 \vee_{\mathbb{S}_A} s_2 = \{(var, a_1 \vee_A a_2) \mid (var, a_1) \in s_1, (var, a_2) \in s_2\}$$

$$s_1 \wedge_{\mathbb{S}_A} s_2 = \{(var, a_1 \wedge_A a_2) \mid (var, a_1) \in s_1, (var, a_2) \in s_2\} \\ \cup \{e \mid e \in s_1, e \notin s_2\} \cup \{e \mid e \notin s_1, e \in s_2\}$$

The abstract semantic functions are:

- $\mathcal{A}^\sharp : AExp \rightarrow \mathbb{S}_A \rightarrow A \times \mathbb{S}_A$:
 - the first element of the tuple approximates the possible results of the arithmetic expression;
 - the second element approximates the possible states after the transition induced by the expression;
- $\mathcal{B}^\sharp : BExp \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A \times \mathbb{S}_A$:
 - the first element of the tuple approximates the states where the boolean expression can evaluate to **tt**;
 - the second element approximates the states where the boolean expression can evaluate **ff**.

This function returns two states, instead of one, in order to preserve the short circuit behavior of boolean operators along with a compositional definition.

- $\mathcal{D}^\sharp : While \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A$.

$$\mathcal{A}^\# : AExpr \rightarrow \mathbb{S}_A \rightarrow I_{m,n} \times \mathbb{S}_A$$

$$\mathcal{A}^\# \llbracket n \rrbracket s^\# = (\{n_{\mathbb{Z}}\}, s^\#)$$

$$\mathcal{A}^\# \llbracket x \rrbracket s^\# = (s^\#(x), s^\#)$$

$$\mathcal{A}^\# \llbracket (e) \rrbracket s^\# = \mathcal{A}^\# \llbracket e \rrbracket s^\#$$

$$\mathcal{A}^\# \llbracket -e \rrbracket s^\# = (-a^\#, s_1^\#)$$

$$\text{where } (a^\#, s_1^\#) = \mathcal{A}^\# \llbracket e \rrbracket s^\#$$

$$\mathcal{A}^\# \llbracket [e_1, e_2] \rrbracket s^\# = (\{a_1^\#, \dots, a_2^\#\}, s_2^\#)$$

$$\text{where } (a_1^\#, s_1^\#) = \mathcal{A}^\# \llbracket e_1 \rrbracket s^\#$$

$$(a_2^\#, s_2^\#) = \mathcal{A}^\# \llbracket e_2 \rrbracket s_1^\#$$

$$\mathcal{A}^\# : AExpr \rightarrow \mathbb{S}_A \rightarrow I_{m,n} \times \mathbb{S}_A$$

$$\begin{aligned}\mathcal{A}^\# \llbracket e_1 \text{ op } e_2 \rrbracket s^\# &= (a_1^\# \text{ op}_{I_{m,n}} a_2^\#, s_2^\#) \\ \text{where } (a_1^\#, s_1^\#) &= \mathcal{A}^\# \llbracket e_1 \rrbracket s^\# \\ (a_2^\#, s_2^\#) &= \mathcal{A}^\# \llbracket e_2 \rrbracket s_1^\#\end{aligned}$$

$$\mathcal{A}^\sharp : AExpr \rightarrow \mathbb{S}_A \rightarrow I_{m,n} \times \mathbb{S}_A$$

$$\mathcal{A}^\sharp \llbracket x++ \rrbracket s^\sharp = (s^\sharp(x), s^\sharp[x \mapsto x + I_{m,n} 1])$$

$$\mathcal{A}^\sharp \llbracket ++x \rrbracket s^\sharp = (s_1^\sharp(x), s_1^\sharp)$$

$$\text{where } s^\sharp[x \mapsto x + I_{m,n} 1] = s_1^\sharp$$

$$\mathcal{A}^\sharp \llbracket x-- \rrbracket s^\sharp = (s^\sharp(x), s^\sharp[x \mapsto x - I_{m,n} 1])$$

$$\mathcal{A}^\sharp \llbracket --x \rrbracket s^\sharp = (s_1^\sharp(x), s_1^\sharp)$$

$$\text{where } s^\sharp[x \mapsto x - I_{m,n} 1] = s_1^\sharp$$

$$\mathcal{B}^\sharp : BExp \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A \times \mathbb{S}_A$$

$$\mathcal{B}^\sharp[\text{true}]s^\sharp = (s^\sharp, \perp_{\mathbb{S}_A})$$

$$\mathcal{B}^\sharp[\text{false}]s^\sharp = (\perp_{\mathbb{S}_A}, s^\sharp)$$

$$\mathcal{B}^\sharp[(b)]s^\sharp = \mathcal{B}^\sharp[b]s^\sharp$$

$$\mathcal{B}^\sharp[b_1 \text{ and } b_2]s^\sharp = \begin{cases} (\mathbf{ff}, s_1^\sharp) & \mathcal{B}^\sharp[b_1]s^\sharp = (\mathbf{ff}, s_1^\sharp) \\ \mathcal{B}^\sharp[b_2]s_1^\sharp & \mathcal{B}^\sharp[b_1]s^\sharp = (\mathbf{tt}, s_1^\sharp) \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}^\sharp[b_1 \text{ or } b_2]s^\sharp = \begin{cases} (\mathbf{tt}, s_1^\sharp) & \mathcal{B}^\sharp[b_1]s^\sharp = (\mathbf{tt}, s_1^\sharp) \\ \mathcal{B}^\sharp[b_2]s_1^\sharp & \mathcal{B}^\sharp[b_1]s^\sharp = (\mathbf{ff}, s_1^\sharp) \\ \uparrow & \text{otherwise} \end{cases}$$

Comparison operators propagate the state transition(s):

$$\mathcal{B} : BExpr \rightarrow State \hookrightarrow \mathbb{T} \times State$$

$$\mathcal{B}[\![e_1 = e_2]\!] \varphi = \begin{cases} (a_1 = a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[\![e_1 \neq e_2]\!] \varphi = \begin{cases} (a_1 \neq a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$\mathcal{B} : BExpr \rightarrow State \hookrightarrow \mathbb{T} \times State$

$$\mathcal{B}[\![e_1 < e_2]\!] \varphi = \begin{cases} (a_1 < a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[\![e_1 \geq e_2]\!] \varphi = \begin{cases} (a_1 \geq a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$\mathcal{B} : BExpr \rightarrow State \hookrightarrow \mathbb{T} \times State$

$$\mathcal{B}[\![e_1 > e_2]\!] \varphi = \begin{cases} (a_1 > a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$$\mathcal{B}[\![e_1 \leq e_2]\!] \varphi = \begin{cases} (a_1 \leq a_2, \varphi'') & \mathcal{A}[\![e_1]\!] \varphi = (a_1, \varphi') \\ & \wedge \mathcal{A}[\![e_2]\!] \varphi' = (a_2, \varphi'') \\ \uparrow & \text{otherwise} \end{cases}$$

$\mathcal{D}^\# : \text{While} \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A$

$$\mathcal{D}^\# \llbracket x := e \rrbracket s^\# \stackrel{\text{def}}{=} \begin{cases} s'^\# [x \mapsto a] & (a, s'^\#) = \mathcal{A}^\# \llbracket e \rrbracket s^\# \\ & \wedge a \neq \perp_A \\ \perp_{\mathbb{S}_A} & \text{otherwise} \end{cases}$$

$$\mathcal{D}^\# \llbracket \text{skip} \rrbracket s^\# \stackrel{\text{def}}{=} s^\#$$

$$\mathcal{D}^\# \llbracket S_1 ; S_2 \rrbracket s^\# \stackrel{\text{def}}{=} (\mathcal{D}^\# \llbracket S_1 \rrbracket \circ \mathcal{D}^\# \llbracket S_2 \rrbracket) s^\#$$

$$\mathcal{D}^\# : \mathbf{While} \rightarrow \mathbb{S}_A \rightarrow \mathbb{S}_A$$

$$\mathcal{D}^\#[\text{if } b \text{ then } S_1 \text{ else } S_2]s^\# \stackrel{\text{def}}{=} (\mathcal{B}^\#[S_1]s_{\text{tt}}^\#) \vee_{\mathbb{S}_A} (\mathcal{B}^\#[S_2]s_{\text{ff}}^\#)$$

$$\text{where } (s_{\text{tt}}^\#, s_{\text{ff}}^\#) = \mathcal{B}^\#[b]s^\#$$

$$\mathcal{D}^\#[\text{while } b \text{ do } S]s^\# \stackrel{\text{def}}{=} \pi_2(\mathcal{B}^\#[b](\text{GFP}_{\text{FIX } F}(\lambda s. s \wedge_{\mathbb{S}_A} F s)))$$

$$\text{where } F : \mathbb{S}_A \rightarrow \mathbb{S}_A$$

$$F s = s^\# \vee_{\mathbb{S}_A} (\mathcal{D}^\#[S] \circ \pi_1 \circ \mathcal{B}^\#[b]s)$$

Where $\text{FIX } F$ refers to the fixed point of the function F and $\text{GFP}_s f$ is the greatest fixed point of f found starting from s .

Widened invariant refinition

Since $I_{m,n}$ has infinitely ascending chains, $\text{FIX } F$ might diverge.

Therefore, in the implementation, we make use of a widened iteration sequence.

The **widened invariant** resulting from (possibly) widened $\text{FIX } F$ is later refined with the GFP of $\lambda s.s \wedge_{\mathbb{S}_A} F s$.

This is sound:

- the widened invariant $s^{*\sharp}$ is a sound over-approximation of the smallest loop invariant s^* ;
- $s^* = F s^*$, so $s^* = s^* \wedge_{\mathbb{S}_A} F s^*$: therefore $\lambda s.s \wedge_{\mathbb{S}_A} F s$ (descending monotone) is a sound filtering of those states not in s^* .

Therefore, GFP F starting from $s^{*\sharp}$ is the most precise refinement of the widened invariant.

The program runs with the command

```
$ cabal run ai -- path/to/file.whl
```

This command will read the file given as input and as output:

- it will output the invariant after the last program point;
- it will rewrite the input into a file called as the input plus `.inv`, with the invariants as comments at any program point.

The program points are located along with the statements:

- the terminals $x:=e$ and `skip` are followed by one program point;
- the `then` and `else` sub-statements in the branch statement are preceded by one program point each;
- while statements are preceded by a program point, whose invariant is the loop invariant of that loop;
- the `do` sub-statement in the loop statement is preceded by one program point;
- while statements are followed by one program point, which is the invariant after the loop exit.

Input

```
x := 0;
while x < 10 do {
    x := x + 2
}
```

Output

```
x := 0; // {"x": [0, 0]}
skip; // {"x": [0, 11]}
while x < 10 do {
    skip; // {"x": [0, 9]}
    x := (x + 2); // {"x": [2, 11]}
};
skip; // {"x": [10, 11]}
```

Input

```
x := 10;  
while x > 0 do x := x + 1;  
y := 0
```

Output

```
x := 10; // {"x": [10, 10]}  
skip; // {"x": [10, Inf]}  
while x > 0 do {  
  skip; // {"x": [10, Inf]}  
  x := (x + 1); // {"x": [11, Inf]}  
};  
skip; // BOTTOM STATE  
y := 0; // BOTTOM STATE
```

Input

```
x := [-10, 10];  
if x / 2 = x then y := x else y := 0
```

Output

```
x := [(-10), 10]; // {"x": [-10, 10]}  
if (x / 2) = x then {  
  skip; // {"x": [-1, 0]}  
  y := x; // {"y": [-1, 0], "x": [-1, 0]}  
} else {  
  skip; // {"x": [-10, 10]}  
  y := 0; // {"y": [0, 0], "x": [-10, 10]}  
};  
skip; // {"y": [-1, 0], "x": [-10, 10]}
```