Semantica big-step

$$\textbf{(B-Num)}\frac{-}{\langle n, s\rangle \Downarrow n} \qquad \textbf{(B-Loc)}\frac{-}{\langle l, s\rangle \Downarrow s(l)} \qquad \textbf{(B-Skip)}\frac{-}{\langle \text{skip}, s\rangle \Downarrow s} \qquad \textbf{(B-Add)}\frac{\langle E_1, s\rangle \Downarrow n_1 \quad \langle E_2, s\rangle \Downarrow n_2}{\langle E_1 + E_2\rangle \Downarrow n_3} n_3 = \mathtt{add}(n_1, n_2)$$

$$\textbf{(B-Assign)}\frac{\langle E, s\rangle \Downarrow n}{\langle l := e, s\rangle \Downarrow s[l \mapsto n]} \qquad \textbf{(B-Assign.s)}\frac{\langle E, s\rangle \Downarrow n}{\langle l := e, s\rangle \Downarrow \langle \text{skip}, s[l \mapsto n]\rangle} \qquad \textbf{(B-Seq)}\frac{\langle C_1, s\rangle \Downarrow s_1 \quad \langle C_2, s_1\rangle \Downarrow s'}{\langle C_1; C_2, s\rangle \Downarrow s'} \qquad \textbf{(B-Seq.s)}\frac{\langle C_1, s\rangle \Downarrow \langle \text{skip}, s_1\rangle \quad \langle C_2, s_1\rangle \Downarrow \langle r, s'\rangle}{\langle C_1; C_2, s\rangle \Downarrow \langle r, s'\rangle}$$

$$\textbf{(B-If.T)}\frac{\langle B, s\rangle \Downarrow \mathtt{true} \quad \langle C_1, s\rangle \Downarrow s'}{\langle \text{if } B \text{ then } C_1 \text{ else } C_2, s\rangle \Downarrow s'} \qquad \textbf{(B-If.T)}\frac{\langle B, s\rangle \Downarrow \mathtt{true} \quad \langle C_1, s\rangle \Downarrow \langle r, s'\rangle}{\langle \text{if } B \text{ then } C_1 \text{ else } C_2, s\rangle \Downarrow \langle r, s'\rangle} \qquad \textbf{(B-If.F)}\frac{\langle B, s\rangle \Downarrow \mathtt{false} \quad \langle C_2, s\rangle \Downarrow s'}{\langle \text{if } B \text{ then } C_1 \text{ else } C_2, s\rangle \Downarrow s'} \qquad \textbf{(B-If.F)}\frac{\langle B, s\rangle \Downarrow \mathtt{false} \quad \langle C_2, s\rangle \Downarrow \langle r, s'\rangle}{\langle \text{if } B \text{ then } C_1 \text{ else } C_2, s\rangle \Downarrow \langle r, s\rangle}$$

$$\textbf{(B-While.T)}\frac{\langle B, s\rangle \Downarrow \mathtt{true} \quad \langle C, s\rangle \Downarrow s_1 \quad \langle \text{while } B \text{ do } C, s_1\rangle \Downarrow s'}{\langle \text{while } B \text{ do } C, s\rangle \Downarrow s'} \qquad \textbf{(B-While.F)}\frac{\langle B, s\rangle \Downarrow \mathtt{false}}{\langle \text{while } B \text{ do } C, s\rangle \Downarrow s} \qquad \textbf{(B-Do)}\frac{\langle B, s\rangle \Downarrow v_1 \quad \langle C, s\rangle \Downarrow v_2}{\langle \text{do } E \text{ return } C, s\rangle \Downarrow v_2}$$

$$\textbf{(B-While.UN)}\frac{\langle \text{if } B \text{ then } (C; \text{while } B \text{ do } C) \text{ else skip}, s\rangle \Downarrow r, s'}{\langle \text{while } B \text{ do } C, s\rangle \Downarrow r, s'} \qquad \textbf{(B-Await)}\frac{\langle B, s\rangle \Downarrow \mathtt{true}, s_1 \quad \langle C, s_1\rangle \twoheadrightarrow^* \langle \text{skip}, s'\rangle}{\langle \text{await } B \text{ protect } C \text{ end}, s\rangle \twoheadrightarrow \langle \text{skip}, s'\rangle}$$

$$\textbf{(B-Let-CBV)}\frac{P \Downarrow m \quad E\{^m/_x\} \Downarrow n}{\text{let } x = P \text{ in } E \Downarrow n} \qquad \textbf{(B-Let-CBN)}\frac{E\{^P/_x\} \Downarrow n}{\text{let } x = P \text{ in } E \Downarrow n} \qquad \textbf{(B-Fn)}\frac{-}{\langle \text{fn } x \colon T \;\Rightarrow\; e, s\rangle \twoheadrightarrow \langle \text{fn } x \colon T \;\Rightarrow\; e, s\rangle}$$

$$\textbf{(B-App-CBV)}\frac{E_1 \Downarrow \text{fn } x \colon T \Rightarrow E \qquad E\{^{E_2}/_x\} \Downarrow n}{E_1 E_2 \Downarrow n} \qquad \textbf{(B-App-CBN)}\frac{E_1 \Downarrow \text{fn } x \colon T \Rightarrow E \qquad E_2 \Downarrow v \qquad E\{^v/_x\} \Downarrow n}{E_1 E_2 \Downarrow n}$$

Semantica small-step

Grammatica delle espressioni

$$\mathsf{op} ::= + \mid \geqslant$$

$$e \in \text{Exp} ::= n \mid b \mid e \text{ op } e \mid \text{if } e \text{ then } e \text{ else } e \mid l := e \mid !l \mid \text{skip} \mid e; e \mid \text{while } e \text{ do } e \mid \text{fn } x : T \Rightarrow e \mid e_1 e_2 \mid \text{let } x : T = e \text{ in } e \mid e \oplus e \mid e \| e \mid$$
$$\text{await } e \text{ protect } e \text{ end} \mid \#\text{lab } e$$

Regole per la semantica

$$\textbf{S-Left}\ \frac{E_1 \rightarrow E_1'}{E_1 + E_2 \rightarrow E_1' + E_2}$$

$$\textbf{S-N.Right}\ \frac{E_2 \rightarrow E_2'}{n_1 + E_2 \rightarrow n_1 + E_2'}$$

$$\textbf{S-Add}\ \frac{-}{n_1 + n_2 \rightarrow n_3}\ n_3 = \mathsf{add}(n_1, n_2)$$

$$\textbf{S-Left}\ \frac{E_1 \rightarrow_{ch} E_1'}{E_1 + E_2 \rightarrow_{ch} E_1' + E_2}$$

$$\textbf{S-Right}\ \frac{E_2 \rightarrow_{ch} E_2'}{E_1 + E_2 \rightarrow_{ch} E_1 + E_2'}$$

$$\textbf{op+}\ \frac{-}{\langle n_1 + n_2, s\rangle \rightarrow \langle n, s\rangle}\ n = \mathsf{add}(n_1, n_2)$$

$$\textbf{op-geq}\ \frac{-}{\langle n_1 \geqslant n_2, s\rangle \rightarrow \langle b, s\rangle}\ b = \mathsf{geq}(n_1, n_2)$$

$$\textbf{op1}\ \frac{\langle e_1, s\rangle \rightarrow \langle e_1', s'\rangle}{\langle e_1 + e_2, s\rangle \rightarrow \langle e_1' + e_2, s'\rangle}$$

$$\textbf{op2}\ \frac{\langle e_2, s\rangle \rightarrow \langle e_2', s'\rangle}{\langle v + e_2, s\rangle \rightarrow \langle v + e_2', s\rangle}$$

$$\textbf{op1b}\ \frac{\langle e_2, s\rangle \rightarrow \langle e_2', s'\rangle}{\langle e_1 + e_2, s\rangle \rightarrow \langle e_1 + e_2', s'\rangle}$$

$$\textbf{op2b}\ \frac{\langle e_1, s\rangle \rightarrow \langle e_1', s'\rangle}{\langle e_1 + v, s\rangle \rightarrow \langle e_1' + v', s'\rangle}$$

$$\textbf{deref1}\ \frac{-}{\langle !l, s\rangle \rightarrow \langle v, s\rangle}\ \text{if } l \in \mathsf{dom}(s) \wedge s(l) = v$$

$$\textbf{deref2}\ \frac{\langle e, s\rangle \rightarrow \langle e', s'\rangle}{\langle !e, s\rangle \rightarrow \langle !e', s'\rangle}$$

$$\textbf{ref1}\ \frac{-}{\langle \text{ref } v, s\rangle \rightarrow \langle l, s[l \mapsto v]\rangle}\ l \notin \mathsf{dom}(s)$$

$$\textbf{ref2}\ \frac{\langle e, s\rangle \rightarrow \langle e', s'\rangle}{\langle \text{ref } e, s\rangle \rightarrow \langle \text{ref } e', s\rangle}$$

$$\textbf{assign1}\ \frac{-}{\langle l := v, s\rangle \rightarrow \langle \text{skip}, s[l \mapsto v]\rangle}\ \text{if } l \in \mathsf{dom}(s)$$

$$\textbf{assign2}\ \frac{\langle e, s\rangle \rightarrow \langle e', s'\rangle}{\langle l := e, s\rangle \rightarrow \langle l := e', s\rangle}$$

$$\textbf{assign3}\ \frac{\langle e_1, s\rangle \rightarrow \langle e_1', s'\rangle}{\langle e_1 := e_2, s\rangle \rightarrow \langle e_1' := e_2, s'\rangle}$$

$$\textbf{if-tt}\ \frac{-}{\langle \text{if } \mathsf{true} \text{ then } e_1 \text{ else } e_2, s\rangle \rightarrow \langle e_1, s\rangle}$$

$$\textbf{if-ff}\ \frac{-}{\langle \text{if } \mathsf{false} \text{ then } e_1 \text{ else } e_2, s\rangle \rightarrow \langle e_2, s\rangle}$$

$$\textbf{if}\ \frac{\langle e, s\rangle \rightarrow \langle e', s'\rangle}{\langle \text{if } e \text{ then } e_1 \text{ else } e_2, s\rangle \rightarrow \langle \text{if } e' \text{ then } e_1 \text{ else } e_2, s\rangle}$$

$$\textbf{while}\ \frac{-}{\langle \text{while } e \text{ do } e_1, s\rangle \rightarrow \langle \text{if } e \text{ then } (e_1; \text{while } e \text{ do } e_1) \text{ else skip}, s\rangle}$$

$$\textbf{assign1b}\ \frac{-}{\langle l := n, s\rangle \rightarrow \langle n, s[l \mapsto n]\rangle}\ l \in \mathsf{dom}(s)$$

$$\textbf{seq.skip}\ \frac{-}{\langle \text{skip}; e_2, s\rangle \rightarrow \langle e_2, s\rangle}$$

$$\textbf{seq}\ \frac{\langle e_1, s\rangle \rightarrow \langle e_1', s\rangle}{\langle e_1; e_2, s\rangle \rightarrow \langle e_1'; e_2, s'\rangle}$$

$$\textbf{seq.skipb}\ \frac{-}{\langle v; e_2, s\rangle \rightarrow \langle e_2, s\rangle}$$

$$\textbf{record1}\ \frac{\langle e_i, s\rangle \to \langle e_i', s'\rangle}{\langle\{lab_1 = v_1, \dots, lab_i = e_i, \dots, lab_k = e_k\}, s\rangle \to \langle\{lab_1 = v_1, \dots, lab_i = e_i', \dots, lab_k = e_k\}, s'\rangle}$$

$$\textbf{record2}\ \frac{-}{\langle \#lab_i\ \{lab_1 = v_1, \dots, lab_i = e_i, \dots, lab_k = e_k\}, s\rangle \to \langle v_i, s\rangle} \qquad \textbf{record3}\ \frac{\langle e, s\rangle \to \langle e', s'\rangle}{\langle \#lab\ e, s\rangle \to \langle \#lab\ e', s'\rangle}$$

$$\textbf{par-L}\ \frac{\langle e_1, s\rangle \to \langle e_1', s'\rangle}{\langle e_1 \| e_2, s\rangle \to \langle e_1' \| e_2, s'\rangle} \qquad \textbf{par-R}\ \frac{\langle e_2, s\rangle \to \langle e_2', s'\rangle}{\langle e_1 \| e_2, s\rangle \to \langle e_1 \| e_2', s'\rangle} \qquad \textbf{end-L}\ \frac{-}{\langle skip \| e, s\rangle \to \langle e, s\rangle} \qquad \textbf{end-R}\ \frac{-}{\langle e \| skip, s\rangle \to \langle e, s\rangle}$$

$$\textbf{await}\ \frac{\langle e_1, s\rangle \to^* \langle true, s'\rangle \qquad \langle e_2, s'\rangle \to^* \langle skip, s''\rangle}{\langle await\ e_1\ protect\ e_2\ end, s\rangle \to \langle skip, s''\rangle} \qquad \textbf{ChoiceL}\ \frac{\langle e_1, s\rangle \to \langle e_1', s'\rangle}{\langle e_1 \oplus e_2, s\rangle \to \langle e_1', s'\rangle} \qquad \textbf{ChoiceR}\ \frac{\langle e_2, s\rangle \to \langle e_2', s'\rangle}{\langle e_1 \oplus e_2, s\rangle \to \langle e_2', s'\rangle}$$

Grammatica dei tipi

$$T ::= \text{int} \mid \text{bool} \mid \text{unit} \mid T_1 \to T_2 \mid T_1 + T_2 \mid T_1 * T_2 \mid \text{ref } T \mid \{lab_1 : T_1, \dots, lab_k : T_k\}$$

Regole per il Tipaggio

Tipi primitivi e operatori

$$\textbf{(int)}\ \frac{-}{\Gamma \vdash n : \text{int}}\ \text{for } n \in \mathbb{Z} \qquad \textbf{(bool)}\ \frac{-}{\Gamma \vdash b : \text{bool}}\ \text{for } n \in \{true, false\} \qquad \textbf{(op +)}\ \frac{\Gamma \vdash e_1 : \text{int} \qquad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 + e_2 : \text{int}} \qquad \textbf{(op *)}\ \frac{\Gamma \vdash e_1 : \text{int} \qquad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 * e_2 : \text{int}}$$

$$\textbf{(op or)}\ \frac{\Gamma \vdash e_1 : \text{bool} \qquad \Gamma \vdash e_2 : \text{bool}}{\Gamma \vdash e_1\ or\ e_2 : \text{bool}} \qquad \textbf{(op and)}\ \frac{\Gamma \vdash e_1 : \text{bool} \qquad \Gamma \vdash e_2 : \text{bool}}{\Gamma \vdash e_1\ and\ e_2 : \text{bool}} \qquad \textbf{(op} \geqslant\textbf{)}\ \frac{\Gamma \vdash e_1 : \text{int} \qquad \Gamma \vdash e_2 : \text{int}}{\Gamma \vdash e_1 \geqslant e_2 : \text{bool}}$$

$$\textbf{(skip)}\ \frac{-}{\Gamma \vdash skip : unit} \qquad \textbf{(seq)}\ \frac{\Gamma \vdash e_1 : unit \qquad \Gamma \vdash e_2 : T}{\Gamma \vdash e_1; e_2 : T} \qquad \textbf{(if)}\ \frac{\Gamma : e_1 : \text{bool} \quad \Gamma \vdash e_2 : T \quad \Gamma \vdash e_3 : T}{\Gamma \vdash \text{if } e_1 \text{ then } e_2 \text{ else } e_3 : T} \qquad \textbf{(while)}\ \frac{\Gamma \vdash e_1 : \text{bool} \qquad \Gamma \vdash e_2 : T}{\Gamma \vdash \text{while } e_1 \text{ do } e_2 : T}$$

$$\textbf{(let)}\ \frac{\Gamma \vdash e_1 : T \qquad \Gamma, x : T \vdash e_2 : T'}{\Gamma \vdash \text{let } x : T = e_1 \text{ in } e_2 : T'}$$

Referenze

$$\textbf{(ref)}\ \frac{\Gamma \vdash e : T}{\Gamma \vdash \text{ref } e : \text{ref } T} \qquad \textbf{(deref)}\ \frac{\Gamma \vdash e : \text{ref } T}{\Gamma \vdash !e : T} \qquad \textbf{(assign)}\ \frac{\Gamma \vdash e_1 : \text{ref } T \quad \Gamma \vdash e_2 : T}{\Gamma \vdash (e_1 := e_2) : \text{unit}} \qquad \textbf{(loc)}\ \frac{-}{\Gamma \vdash l : \text{ref } T}\ \Gamma(l) = \text{ref } T$$

Funzioni

$$\textbf{(var)}\,\frac{-}{\Gamma \vdash : \mathsf{T}} \text{ if } \Gamma(x) = \mathsf{T} \qquad \textbf{(fn)}\,\frac{\Gamma, x\colon \mathsf{T} \vdash e\colon \mathsf{T}'}{\Gamma \vdash (\mathsf{fn}\ x\colon \mathsf{T}\ \Rightarrow\ e)\colon \mathsf{T} \to \mathsf{T}'} \qquad \textbf{(app)}\,\frac{\Gamma \vdash e_1\colon \mathsf{T} \to \mathsf{T}' \qquad \Gamma \vdash e_2\colon \mathsf{T}}{\Gamma \vdash e_1 e_2\colon \mathsf{T}'}$$

Record

$$\textbf{(record)}\,\frac{\Gamma \vdash e_1\colon \mathsf{T}_1\ \ldots\ \Gamma \vdash e_k\colon \mathsf{T}_k}{\Gamma \vdash \{\mathrm{lab}_1 = e_1, \ldots, \mathrm{lab}_k = e_k\} : \{\mathrm{lab}_1\colon \mathsf{T}_1, \ldots, \mathrm{lab}_k\colon \mathsf{T}_k\}} \qquad \textbf{(recordproj)}\,\frac{\Gamma \vdash e\colon \{\mathrm{lab}_1\colon \mathsf{T}_1, \ldots, \mathrm{lab}_k\colon \mathsf{T}_k\}}{\Gamma \vdash \#\mathrm{lab}_i\ e\colon \mathsf{T}_i}$$

Concorrenza

$$\textbf{(T-sq1)}\,\frac{\Gamma \vdash e_1\colon \mathrm{unit} \qquad \Gamma \vdash e_2\colon \mathrm{unit}}{\Gamma \vdash e_1; e_2\colon \mathrm{unit}} \qquad \textbf{(T-sq2)}\,\frac{\Gamma \vdash e_1\colon \mathrm{proc} \qquad \Gamma \vdash e_2\colon \mathrm{proc}}{\Gamma \vdash e_1; e_2\colon \mathrm{proc}} \qquad \textbf{(T-par)}\,\frac{\Gamma \vdash e_1\colon \mathsf{T}_1 \qquad \Gamma \vdash e_2\colon \mathsf{T}_2}{\Gamma \vdash e_1 \| e_2\colon \mathrm{proc}}\ \mathsf{T}_1, \mathsf{T}_2 \in \{\mathrm{unit}, \mathrm{proc}\}$$

$$\textbf{(T-await)}\,\frac{\Gamma \vdash e_1\colon \mathrm{bool} \qquad \Gamma \vdash e_2\colon \mathrm{unit}}{\Gamma \vdash \mathrm{await}\ e_1\ \mathrm{protect}\ e_2\ \mathrm{end}\colon \mathrm{unit}} \qquad \textbf{(T-choice)}\,\frac{\Gamma \vdash e_1\colon \mathrm{unit} \qquad \Gamma \vdash e_2\colon \mathrm{unit}}{\Gamma \vdash e_1 \oplus e_2\colon \mathrm{unit}}$$

Sottotipaggio

$$\textbf{(sub)}\,\frac{\Gamma \vdash e\colon \mathsf{T} \qquad \mathsf{T} <: \mathsf{T}'}{\Gamma \vdash e\colon \mathsf{T}'} \qquad \textbf{(s-refl)}\,\frac{-}{\mathsf{T} <: \mathsf{T}} \qquad \textbf{(s-trans)}\,\frac{\mathsf{T} <: \mathsf{T}' \qquad \mathsf{T}' <: \mathsf{T}''}{\mathsf{T} <: \mathsf{T}''}$$

Sottotipaggio dei record

$$\textbf{(rec-perm)}\,\frac{\pi \text{ una permutazione di } 1, 2, \ldots, k}{\{p_1\colon \mathsf{T}_1, \ldots, p_k\colon \mathsf{T}_k\} <: \{p_{\pi(1)}\colon \mathsf{T}_{\pi(1)}, \ldots, p_{\pi(k)}\colon \mathsf{T}_{\pi(k)}\}} \qquad \textbf{(rec-width)}\,\frac{-}{\{p_1\colon \mathsf{T}_1, \ldots, p_k\colon \mathsf{T}_k, p_{k+1}\colon \mathsf{T}_{k+1}, \ldots, p_z\colon \mathsf{T}_z\} <: \{p_1\colon \mathsf{T}_1, \ldots, p_k\colon \mathsf{T}_k\}}$$

$$\textbf{(rec-depth)}\,\frac{\mathsf{T}_1 <: \mathsf{T}_1'\ \ldots\ \mathsf{T}_k <: \mathsf{T}_k'}{\{p_1\colon \mathsf{T}_1, \ldots, p_k\colon \mathsf{T}_k\} <: \{p_1\colon \mathsf{T}_1', \ldots, p_k\colon \mathsf{T}_k'\}}$$

Sottotipaggio delle funzioni

$$\textbf{(fun-sub)}\,\frac{\mathsf{T}_1 :\ > \mathsf{T}_1' \qquad \mathsf{T}_2 <: \mathsf{T}_2'}{\mathsf{T}_1 \to \mathsf{T}_2 <: \mathsf{T}_1' \to \mathsf{T}_2'}$$

Sottotipaggio somma e prodotto

$$\textbf{(prod-sub)}\,\frac{\mathsf{T}_1 <: \mathsf{T}_1' \qquad \mathsf{T}_2 <: \mathsf{T}_2'}{\mathsf{T}_1 * \mathsf{T}_2 <: \mathsf{T}_1' * \mathsf{T}_2'} \qquad \textbf{(sum-sub)}\,\frac{\mathsf{T}_1 <: \mathsf{T}_1' \qquad \mathsf{T}_2 <: \mathsf{T}_2'}{\mathsf{T}_1 + \mathsf{T}_2 <: \mathsf{T}_1' + \mathsf{T}_2'}$$