Appendix A

Eva’s Specifications

A.1 Abstract Syntax

⟨*program*⟩ ::= ⟨*stmt*⟩ | ⟨*program*⟩ ⟨*stmt*⟩

⟨*stmt*⟩ ::= ⟨*def-stmt*⟩ | ⟨*type-stmt*⟩ | ⟨*import-stmt*⟩

⟨*def-stmt*⟩ ::= ‘`def`’ ⟨*lower-str*⟩ ⟨*opt-curly-parameters*⟩ ⟨*opt-arguments*⟩ ⟨*opt-box*⟩ ⟨*opt-arguments*⟩
‘=’ ⟨*exp*⟩

⟨*opt-curly-parameters*⟩ ::= ‘’ | ‘`{`’ ⟨*parameters*⟩ ‘`}`’

⟨*parameters*⟩ ::= ⟨*parameter*⟩ | ⟨*parameters*⟩ ‘`,`’ ⟨*parameter*⟩

⟨*parameter*⟩ ::= ⟨*opt-property*⟩ ⟨*lower-str*⟩

⟨*opt-property*⟩ ::= ‘’ |‘`Stable`’ | ‘`Limit`’ | ‘`Stable Limit`’ | ‘`CStable`’ | ‘`CStable Limit`’

⟨*opt-arguments*⟩ ::= ‘’ | ⟨*arguments*⟩

⟨*arguments*⟩ ::= ⟨*argument*⟩ | ⟨*argument*⟩ ⟨*arguments*⟩

⟨*argument*⟩ ::= ⟨*lower-str*⟩ ⟨*ascription*⟩

⟨*opt-box*⟩ ::= ‘’ | ‘#’

⟨*exp*⟩ ::= ⟨*opt-dotted-lower-str*⟩ ⟨*opt-curly-type-list*⟩ | ⟨*number*⟩ | ‘`()`’ | ‘`(`’ ⟨*exp*⟩ ‘`)`’
| ‘`fun`’ ⟨*arguments*⟩ ‘=>’ ⟨*exp*⟩
| ⟨*exp*⟩ ⟨*exp*⟩
| ‘`nfix`’ ⟨*lower-str*⟩ ⟨*ascription*⟩ ‘=>’ ⟨*exp*⟩
| ‘`let`’ ⟨*lower-str*⟩ ⟨*opt-arguments*⟩ ⟨*opt-box*⟩ ⟨*opt-arguments*⟩ ‘=’ ⟨*exp*⟩ ‘`in`’ ⟨*exp*⟩
| ⟨*exp*⟩ ‘`‘`’ ⟨*exp*⟩ ‘`‘`’ ⟨*exp*⟩ | ‘`suc`’ ⟨*expression*⟩ | ‘`true`’ | ‘`false`’
| ‘`if`’ ⟨*exp*⟩ ‘`then`’ ⟨*exp*⟩ ‘`else`’ ⟨*exp*⟩
| ⟨*unary-exp-op*⟩ ⟨*exp*⟩ | ⟨*exp*⟩ ⟨*binary-exp-op*⟩ ⟨*exp*⟩
| ‘`(`’ ⟨*exp*⟩ ‘`,`’ ⟨*exp*⟩ ‘`)`’ |
| ‘`let`’ ‘`(`’ ⟨*wc-var*⟩ ‘`,`’ ⟨*wc-var*⟩ ‘`)`’ ‘=’ ⟨*exp*⟩ ‘`in`’ ⟨*exp*⟩
| ‘`inl`’ ⟨*exp*⟩ ⟨*ascription*⟩ | ‘`inr`’ ⟨*exp*⟩ ⟨*ascription*⟩
| ‘`match`’ ⟨*exp*⟩ ‘`with`’ ‘`|`’ ‘`inl`’ ⟨*wc-var*⟩ ‘=>’ ⟨*exp*⟩ ‘`|`’ ‘`inr`’ ⟨*wc-var*⟩ ‘=>’ ⟨*exp*⟩
| ‘`[]`’ ⟨*ascription*⟩ | ‘`[`’ ⟨*list-elems*⟩ ‘`]`’
| ‘`let`’ ⟨*wc-var*⟩ ‘`:::`’ ⟨*wc-var*⟩ ‘=’ ⟨*exp*⟩ ‘`in`’ ⟨*exp*⟩

| ‘primrec’ ⟨exp⟩ ‘with’ ‘|’ ‘0’ ‘=>’ ⟨exp⟩ ‘|’ ‘suc’ ⟨wc-var⟩ ‘,’ ⟨wc-var⟩ ‘=>’ ⟨exp⟩
| ‘primrec’ ⟨exp⟩ ‘with’ ‘|’ ‘[]’ ‘=>’ ⟨exp⟩ ‘|’ ⟨wc-var⟩ ‘::’ ⟨wc-var⟩ ‘,’ ⟨wc-var⟩ ‘=>’ ⟨exp⟩
| ‘now’ ⟨exp⟩ ⟨ascription⟩ | ‘wait’ ⟨exp⟩ ⟨exp⟩
| ‘urec’ ⟨exp⟩ ‘with’ ‘|’ ‘now’ ⟨wc-var⟩ ‘=>’ ⟨exp⟩ ‘|’ ‘wait’ ⟨wc-var⟩ ⟨wc-var⟩ ‘,’ ⟨wc-var⟩ ‘=>’ ⟨exp⟩
| ‘into’ ⟨exp⟩ ⟨ascription⟩

⟨opt-dotted-lower-str⟩ ::= ⟨lower-str⟩ | ⟨upper-str⟩ ‘.’ ⟨lower-str⟩

⟨opt-curly-type-list⟩ ::= ‘’ | ‘{’ ⟨type-list⟩ ‘}’

⟨type-list⟩ ::= ⟨type⟩ | ⟨type⟩ ‘,’ ⟨type-list⟩

⟨unary-exp-op⟩ ::= ‘not’ | ‘fst’ | ‘snd’ | ‘>’ | ‘@’ | ‘<’ | ‘#’ | ‘?’ | ‘out’ | ‘suc’

⟨binary-exp-op⟩ ::= ‘+’ | ‘-’ | ‘*’ | ‘/’ | ‘%’ | ‘^’ | ‘and’ | ‘or’ | ‘==’ | ‘!=’ | ‘::’ | ‘++’ | ‘:::’

⟨list-elems⟩ ::= ⟨exp⟩ | ⟨exp⟩ ‘,’ ⟨list-elems⟩

⟨wc-var⟩ ::= ‘_’ | ⟨lower-str⟩

⟨ascription⟩ ::= ‘:’ | ⟨type⟩

⟨type-stmt⟩ ::= ‘type’ ⟨upper-str⟩ ⟨opt-round-arguments⟩ ‘=’ ⟨type⟩

⟨opt-round-arguments⟩ ::= ‘’ | ‘(’ ⟨lower-str-list⟩ ‘)’

⟨lower-str-list⟩ ::= ⟨lower-str⟩ | ⟨lower-str⟩ ‘,’ ⟨lower-str-list⟩

⟨type⟩ ::= ⟨opt-dotted-upper-str⟩ ⟨opt-round-type-list⟩ | ⟨lower-str⟩ | ‘(’ ⟨type⟩ ‘)’
| ‘Unit’ | ‘Nat’ | ‘Bool’ | ‘List’ ‘(’ ⟨type⟩ ‘)’
| ‘NFix’ ⟨lower-str⟩ ‘-->’ ⟨type⟩
| ⟨unary-type-op⟩ ⟨type | <type⟩ ⟨binary-type-op⟩ ⟨type⟩

⟨opt-round-type-list⟩ ::= ‘’ | ‘(’ ⟨type-list⟩ ‘)’

⟨opt-dotted-upper-str⟩ ::= ⟨upper-str⟩ | ⟨upper-str⟩ ‘.’ ⟨upper-str⟩

⟨unary-type-op⟩ ::= ‘>’ | ‘@’ | ‘#’

⟨binary-type-op⟩ ::= ‘->’ | ‘Until’ | ‘+’ | ‘*’

⟨import-stmt⟩ ::= ‘import’ ⟨file-path⟩ ⟨opt-name⟩

⟨opt-name⟩ ::= ‘’ | ‘as’ ⟨upper-str⟩

A.2 Definitions

$$
\begin{array}{rcl}
\text{Types } A\ B\ C & ::= & x \mid \texttt{Unit} \mid \texttt{Nat} \mid \texttt{Bool} \mid \texttt{List}(A) \mid \texttt{NFix}\ \ x \longrightarrow A \\
& & \mid {>}A \mid \texttt{@}A \mid \#A \mid A \to A \mid A\ \ \texttt{Until}\ \ A \mid A+A \mid A*A \\
\text{Expressions } e & ::= & x \mid n \mid \texttt{()} \mid \texttt{fun}\ \ x : A \Rightarrow e \mid e\ e \mid \texttt{let}\ \ x = e\ \ \texttt{in}\ \ e \\
& & \mid e+e \mid e-e \mid e*e \mid e/e \mid e\%e \mid e\hat{\ }e \mid \texttt{suc}\ \ e \\
& & \mid \texttt{primrec}\ \ e\ \ \texttt{with|0} \Rightarrow e\texttt{|suc}\ \ x,x \Rightarrow e \\
& & \mid \texttt{true} \mid \texttt{false} \mid \texttt{if}\ \ e\ \ \texttt{then}\ \ e\ \ \texttt{else}\ \ e \mid e\ \ \texttt{and}\ \ e \mid e\ \ \texttt{or}\ \ e \mid \texttt{not}\ \ e \\
& & \mid e == e \mid e! = e \\
& & \mid (e,e) \mid \texttt{fst}\ \ e \mid \texttt{snd}\ \ e \\
& & \mid \texttt{inl}\ \ e : A \mid \texttt{inr}\ \ e : A \mid \texttt{match}\ \ e\ \ \texttt{with|inl}\ \ x \Rightarrow e\texttt{|inr}\ \ x \Rightarrow e \\
& & \mid \texttt{[]} : A \mid [e,\ldots,e] \mid e :: e \mid e{+}{+}e \\
& & \mid \texttt{primrec}\ \ e\ \ \texttt{with|[]} \Rightarrow e \texttt{|} x :: x,x \Rightarrow e \\
& & \mid {>}e \mid \texttt{@}e \mid {<}e \mid \#e \mid ?e \mid \texttt{nfix}\ \ x : A \Rightarrow e \mid e\texttt{:::}e \mid \texttt{let}\ \ x\texttt{:::}x = e\ \ \texttt{in}\ \ e \\
& & \mid \texttt{now}\ \ e : A \mid \texttt{wait}\ \ e\ e \mid \texttt{urec}\ \ e\ \ \texttt{with|now}\ \ \Rightarrow e\texttt{|wait}\ \ x\ x,x \Rightarrow e \\
& & \mid \texttt{into}\ \ e : A \mid \texttt{out}\ \ e \\
\text{Type Properties } \omega & ::= & \texttt{None} \mid \texttt{Stable} \mid \texttt{Limit} \mid \texttt{CStable} \mid \texttt{Both} \mid \texttt{CBoth} \\
\text{Type Contexts } \Theta & ::= & \cdot \mid \Theta, (x,\omega) \\
\text{Term Variable Contexts } \Gamma & ::= & \cdot \mid \Gamma, x : A \mid \Gamma, \# \mid \Gamma, \checkmark_{>} \mid \Gamma, \checkmark_{@} \\
\text{Values } v\ w & ::= & \texttt{()} \mid n \mid \texttt{fun}\ \ x : A \Rightarrow e \mid (v,v) \mid \texttt{inl}\ \ v \mid \texttt{inr}\ \ v \\
& & \mid \texttt{true} \mid \texttt{false} \mid \texttt{[]} : A \mid [v,\ldots,v] \\
& & \mid \#e \mid \texttt{@}e \mid {>}e \mid \texttt{nfix}\ \ x : A \Rightarrow e \mid l \mid \texttt{into}\ \ v : A \mid \texttt{now}\ \ v : A \mid \texttt{wait}\ \ v\ v \\
\text{Heaps } \eta & ::= & \{l \mapsto v, \ldots, l \mapsto v\} \\
\text{Stores } \sigma & ::= & \cdot \mid \eta \mid \eta \checkmark \eta \\
\text{Value types } U\ V & ::= & \texttt{Unit} \mid \texttt{Nat} \mid \texttt{Bool} \mid \texttt{List}(U) \mid U*U \mid U+U \\
\texttt{Str}(A) & ::= & \texttt{NFix}\ \ x \longrightarrow (A*x) \\
\texttt{Fair}(A,B) & ::= & \texttt{NFix}\ \ x \longrightarrow A\ \ \texttt{Until}\ \ (B*{>}(B\ \ \texttt{Until}\ \ (A*x)))
\end{array}
$$

A.3 Judgement for Types

$$\frac{(x,\omega) \in \Theta}{\Theta \vdash x \text{ type}}$$

$$\frac{}{\Theta \vdash \texttt{Unit} \text{ type}} \qquad \frac{}{\Theta \vdash \texttt{Nat} \text{ type}} \qquad \frac{}{\Theta \vdash \texttt{Bool} \text{ type}} \qquad \frac{\Theta \vdash A \text{ type}}{\Theta \vdash \texttt{List}(A) \text{ type}}$$

$$\frac{\Theta, (x, \texttt{Limit}) \vdash A \text{ type}}{\Theta \vdash \texttt{NFix}\ \ x \longrightarrow A \text{ type}} \qquad \frac{\Theta \vdash A \text{ type}}{\Theta \vdash {>}A \text{ type}} \qquad \frac{\Theta \vdash A \text{ type}}{\Theta \vdash @A \text{ type}} \qquad \frac{\Theta \vdash A \text{ type}}{\Theta \vdash \#A \text{ type}}$$

$$\frac{\Theta \vdash A \text{ type} \qquad \Theta \vdash A' \text{ type}}{\Theta \vdash A\ \ \texttt{Until}\ \ A' \text{ type}} \qquad \frac{\Theta \vdash A \text{ type} \qquad \Theta \vdash A' \text{ type}}{\Theta \vdash A + A' \text{ type}} \qquad \frac{\Theta \vdash A \text{ type} \qquad \Theta \vdash A' \text{ type}}{\Theta \vdash A * A' \text{ type}}$$

$$\frac{(x,\omega) \in \Theta \qquad \omega \in \{\texttt{Stable}, \texttt{Both}, \texttt{CStable}, \texttt{CBoth}\}}{\Theta \vdash x \text{ stable}}$$

$$\frac{}{\Theta \vdash \texttt{Unit} \text{ type}} \qquad \frac{}{\Theta \vdash \texttt{Nat} \text{ stable}} \qquad \frac{}{\Theta \vdash \texttt{Bool} \text{ stable}}$$

$$\frac{\Theta \vdash A \text{ stable}}{\Theta \vdash \texttt{List}(A) \text{ stable}} \qquad \frac{}{\Theta \vdash \#A \text{ stable}}$$

$$\frac{\Theta \vdash A \text{ stable} \qquad \Theta \vdash A' \text{ stable}}{\Theta \vdash A + A' \text{ stable}} \qquad \frac{\Theta \vdash A \text{ stable} \qquad \Theta \vdash A' \text{ stable}}{\Theta \vdash A * A' \text{ stable}}$$

$$\frac{(x,\omega) \in \Theta \qquad \omega \in \{\texttt{Limit}, \texttt{Both}, \texttt{CBoth}\}}{\Theta \vdash x \text{ limit}}$$

$$\frac{}{\Theta \vdash \texttt{Unit} \text{ limit}} \qquad \frac{}{\Theta \vdash \texttt{Nat} \text{ limit}} \qquad \frac{}{\Theta \vdash \texttt{Bool} \text{ limit}} \qquad \frac{\Theta \vdash A \text{ limit}}{\Theta \vdash \texttt{List}(A) \text{ limit}}$$

$$\frac{\Theta, (x, \texttt{Limit}) \vdash A \text{ limit}}{\Theta \vdash \texttt{NFix}\ \ x \longrightarrow A \text{ limit}} \qquad \frac{\Theta \vdash A \text{ type}[1]}{\Theta \vdash {>}A \text{ limit}} \qquad \frac{\Theta \vdash A \text{ limit}}{\Theta \vdash @A \text{ limit}} \qquad \frac{\Theta \vdash A \text{ limit}}{\Theta \vdash \#A \text{ limit}}$$

$$\frac{\Theta \vdash A \text{ type}[1] \qquad \Theta \vdash A' \text{ limit}}{\Theta \vdash A \longrightarrow A' \text{ limit}} \qquad \frac{\Theta \vdash A \text{ limit} \qquad \Theta \vdash A' \text{ limit}}{\Theta \vdash A + A' \text{ limit}} \qquad \frac{\Theta \vdash A \text{ limit} \qquad \Theta \vdash A' \text{ limit}}{\Theta \vdash A * A' \text{ limit}}$$

[1] Not a typo

$$\frac{(x,\omega) \in \Theta \qquad \omega \in \{\texttt{CStable}, \texttt{CBoth}\}}{\Theta \vdash x \text{ comparable}}$$

$$\frac{}{\Theta \vdash \texttt{Unit} \text{ comparable}} \qquad \frac{}{\Theta \vdash \texttt{Nat} \text{ comparable}} \qquad \frac{}{\Theta \vdash \texttt{Bool} \text{ comparable}}$$

$$\frac{\Theta \vdash A \text{ comparable}}{\Theta \vdash \texttt{List}(A) \text{ comparable}}$$

$$\frac{\Theta \vdash A \text{ comparable} \qquad \Theta \vdash A' \text{ comparable}}{\Theta \vdash A + A' \text{ comparable}} \qquad \frac{\Theta \vdash A \text{ comparable} \qquad \Theta \vdash A' \text{ comparable}}{\Theta \vdash A * A' \text{ comparable}}$$

A.4 Judgement for Context

$$\frac{}{\Theta \vdash \cdot \text{ ctx}} \qquad \frac{\Theta \vdash \Gamma \text{ ctx} \qquad \Theta \vdash A \text{ type}}{\Theta \vdash \Gamma, x : A \text{ ctx}} \qquad \frac{\Theta \vdash \Gamma \text{ ctx} \qquad \# \notin \Gamma}{\Theta \vdash \Gamma, \# \text{ ctx}}$$

$$\frac{\Theta \vdash \Gamma \text{ ctx} \qquad \# \in \Gamma \qquad \text{tick-free}(\Gamma)}{\Theta \vdash \Gamma, \checkmark_{>} \text{ ctx}} \qquad \frac{\Theta \vdash \Gamma \text{ ctx} \qquad \# \in \Gamma \qquad \text{tick-free}(\Gamma)}{\Theta \vdash \Gamma, \checkmark_{@} \text{ ctx}}$$

A.5 Typing Rules

$$\frac{\text{token-free}(\Gamma') \quad \vee \quad \Theta \vdash A \text{ stable}}{\Theta; \Gamma, x : A, \Gamma' \vdash x : A} \qquad \frac{}{\Theta; \Gamma \vdash n : \texttt{Nat}} \qquad \frac{}{\Theta; \Gamma \vdash () : \texttt{Nat}}$$

$$\frac{\begin{array}{c}\Theta; \Gamma, x : A \vdash e : B \\ \text{tick-free}(\Gamma) \\ \Theta \vdash A \text{ type}\end{array}}{\Theta; \Gamma \vdash \texttt{fun} \;\; x : A \Rightarrow e : B} \qquad \frac{\Theta; \Gamma \vdash e : A \longrightarrow B \qquad \Theta; \Gamma \vdash e' : A}{\Theta; \Gamma \vdash e \; e' : B}$$

$$\frac{\begin{array}{c}\Theta; \Gamma \vdash e : A \\ \Theta; \Gamma, x : A \vdash e' : B\end{array}}{\Theta; \Gamma \vdash \texttt{let} \;\; x = e \;\; \texttt{in} \;\; e' : B}$$

$$\frac{\begin{array}{c}\Theta; \Gamma \vdash e : \texttt{Nat} \\ \Theta; \Gamma \vdash e' : \texttt{Nat} \\ op \in \{+, -, *, /, \%, \hat{}\,\}\end{array}}{\Theta; \Gamma \vdash e \; op \; e' : \texttt{Nat}} \qquad \frac{\Theta; \Gamma \vdash e : \texttt{Nat}}{\Theta; \Gamma \vdash \texttt{suc} \;\; e : \texttt{Nat}}$$

$$\frac{\begin{array}{c}\Theta; \Gamma \vdash e : \texttt{Nat} \\ \Theta; \Gamma \vdash e_1 : A \\ \Theta; \Gamma, x : \texttt{Nat}, y : A \vdash e_2 : A\end{array}}{\Theta; \Gamma \vdash \texttt{primrec} \;\; e \;\; \texttt{with} \;\; | \texttt{0} \Rightarrow e_1 \,|\, \texttt{suc} \;\; x, y \Rightarrow e_2 : A}$$

$$\frac{}{\Theta;\Gamma \vdash \mathtt{true} : \mathtt{Bool}} \qquad \frac{}{\Theta;\Gamma \vdash \mathtt{false} : \mathtt{Bool}} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e : \mathtt{Bool} \\ \Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : A\end{array}}{\Theta;\Gamma \vdash \mathtt{if}\ e\ \mathtt{then}\ e_1\ \mathtt{else}\ e_2 : A}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : \mathtt{Bool} \\ \Theta;\Gamma \vdash e_2 : \mathtt{Bool}\end{array}}{\Theta;\Gamma \vdash e_1\ \mathtt{and}\ e_2 : \mathtt{Bool}} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : \mathtt{Bool} \\ \Theta;\Gamma \vdash e_2 : \mathtt{Bool}\end{array}}{\Theta;\Gamma \vdash e_1\ \mathtt{or}\ e_2 : \mathtt{Bool}} \qquad \frac{\Theta;\Gamma \vdash e : \mathtt{Bool}}{\Theta;\Gamma \vdash \mathtt{not}\ e : \mathtt{Bool}}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : A \\ \Theta \vdash A \text{ comparable}\end{array}}{\Theta;\Gamma \vdash e_1 == e_2 : \mathtt{Bool}} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : A \\ \Theta \vdash A \text{ comparable}\end{array}}{\Theta;\Gamma \vdash e_1 != e_2 : \mathtt{Bool}}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : B\end{array}}{\Theta;\Gamma \vdash (e_1, e_2) : A * B} \qquad \frac{\Theta;\Gamma \vdash e : A * B}{\Theta;\Gamma \vdash \mathtt{fst}\ e : A} \qquad \frac{\Theta;\Gamma \vdash e : A * B}{\Theta;\Gamma \vdash \mathtt{snd}\ e : B}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e : A \\ \Theta \vdash A + B \text{ type}\end{array}}{\Theta;\Gamma \vdash \mathtt{inl}\ e : A + B : A + B} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e : B \\ \Theta \vdash A + B \text{ type}\end{array}}{\Theta;\Gamma \vdash \mathtt{inr}\ e : A + B : A + B}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e : A + B \\ \Theta;\Gamma, x : A \vdash e_1 : C \\ \Theta;\Gamma, y : B \vdash e_2 : C\end{array}}{\Theta;\Gamma \vdash \mathtt{match}\ e\ \mathtt{with|inl}\ x \Rightarrow e_1 \,|\, \mathtt{inr}\ y \Rightarrow e_2 : C}$$

$$\frac{\Theta \vdash \mathtt{List}(A) \text{ type}}{\Theta;\Gamma \vdash \mathtt{[]} : \mathtt{List}(A) : \mathtt{List}(A)} \qquad \frac{\Theta;\Gamma \vdash e_i : A \qquad (\forall i = 1, \ldots, n)}{\Theta;\Gamma \vdash [e_1, \ldots, e_n] : \mathtt{List}(A)}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : \mathtt{List}(A)\end{array}}{\Theta;\Gamma \vdash e_1 \mathtt{::} e_2 : \mathtt{List}(A)} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : \mathtt{List}(A) \\ \Theta;\Gamma \vdash e_2 : \mathtt{List}(A)\end{array}}{\Theta;\Gamma \vdash e_1 {+}{+} e_2 : \mathtt{List}(A)}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e : \mathtt{List}(A) \\ \Theta;\Gamma \vdash e_1 : B \\ \Theta;\Gamma, x : A, y : \mathtt{List}(A), z : B \vdash e_2 : B\end{array}}{\Theta;\Gamma \vdash \mathtt{primrec}\ e\ \mathtt{with|[]} \Rightarrow e_1 \,|\, x \mathtt{::} y, z \Rightarrow e_2 : B}$$

$$\frac{\Theta;\Gamma,\checkmark_{>} \vdash e : A}{\Theta;\Gamma \vdash {>}e : {>}A} \qquad \frac{\Theta;\Gamma,\checkmark_{\texttt{@}} \vdash e : A}{\Theta;\Gamma \vdash \texttt{@}e : \texttt{@}A} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e : m\ A \\ m \le m' \quad \vee \quad \Theta \vdash A \text{ limit}\end{array}}{\Theta;\Gamma,\checkmark_{m'},\Gamma' \vdash {<}e : A}\ (\text{where } \texttt{@} \le\ >)$$

$$\frac{\Theta;\Gamma,\text{token-less-stable}(\Gamma') \vdash e : \#A}{\Theta;\Gamma,\#,\Gamma' \vdash ?e : A} \qquad \frac{\Theta;\Gamma,\# \vdash e : A}{\Theta;\Gamma \vdash \#e : \#A} \qquad \frac{\begin{array}{c}\Theta;\Gamma,x : \#{>}A,\# \vdash e : A \\ \Theta \vdash \#A \text{ type}\end{array}}{\Theta;\Gamma \vdash \texttt{nfix}\ \ x : \#A \Rightarrow e : \#A}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : {>}\texttt{Str}(A)\end{array}}{\Theta;\Gamma \vdash e_1 \texttt{:::} e_2 : \texttt{Str}(A)} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : \texttt{Str}(A) \\ \Theta;\Gamma,x : A,y : {>}(\texttt{Str}(A)) \vdash e_2 : B\end{array}}{\Theta;\Gamma \vdash \texttt{let}\ \ x \texttt{:::} y = e_1\ \ \texttt{in}\ \ e_2 : B}$$

$$\frac{\Theta;\Gamma \vdash e : B}{\Theta;\Gamma \vdash \texttt{now}\ \ e : A\ \ \texttt{Until}\ \ B : A\ \ \texttt{Until}\ \ B} \qquad \frac{\begin{array}{c}\Theta;\Gamma \vdash e_1 : A \\ \Theta;\Gamma \vdash e_2 : \texttt{@}(A\ \ \texttt{Until}\ \ B)\end{array}}{\Theta;\Gamma \vdash \texttt{wait}\ \ e_1\, e_2 : A\ \ \texttt{Until}\ \ B}$$

$$\frac{\begin{array}{c}\Theta;\Gamma,\#,\Gamma' \vdash e : A\ \ \texttt{Until}\ \ B \\ \Theta;\Gamma,\#,\text{token-less-stable}(\Gamma'),x : B \vdash e_1 : C \\ \Theta;\Gamma,\#,\text{token-less-stable}(\Gamma'),x' : A,y : \texttt{@}(A\ \ \texttt{Until}\ \ B),z : \texttt{@}C \vdash e_2 : C\end{array}}{\Theta;\Gamma,\#,\Gamma' \vdash \texttt{urec}\ \ e\ \ \texttt{with|now}\ \ x \Rightarrow e_1 \texttt{|wait}\ \ x'\ y,z \Rightarrow e_2 : C}$$

$$\frac{\begin{array}{c}\Theta;\Gamma \vdash e : A[{>}(\texttt{NFix}\ \ x \longrightarrow A)/x] \\ \Theta \vdash \texttt{NFix}\ \ x \longrightarrow A \text{ type}\end{array}}{\Theta;\Gamma \vdash \texttt{into}\ \ e : \texttt{NFix}\ \ x \longrightarrow A : \texttt{NFix}\ \ x \longrightarrow A} \qquad \frac{\Theta;\Gamma \vdash e : \texttt{NFix}\ \ x \longrightarrow A}{\Theta;\Gamma \vdash \texttt{out}\ \ e : A[{>}(\texttt{NFix}\ \ x \longrightarrow A)/x]}$$

A.6 Evaluation Semantics

$$\frac{}{\langle v;\sigma\rangle \Downarrow \langle v;\sigma\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle \texttt{fun}\ x : A \Rightarrow e_1';\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle \\ \langle e_1'[v/x];\sigma''\rangle \Downarrow \langle v';\sigma'''\rangle\end{array}}{\langle e_1\ e_2;\sigma\rangle \Downarrow \langle v';\sigma'''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle v;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle \texttt{fun}\ x : A \Rightarrow e_2';\sigma''\rangle \\ \langle e_2'[v/x];\sigma''\rangle \Downarrow \langle v';\sigma'''\rangle\end{array}}{\langle \texttt{let}\ x = e_1\ \texttt{in}\ e_2;\sigma\rangle \Downarrow \langle v';\sigma'''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle m;\sigma''\rangle \\ v = n+m\end{array}}{\langle e_1+e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle m;\sigma''\rangle \\ v = \max(0,n-m)\end{array}}{\langle e_1-e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle m;\sigma''\rangle \\ v = n\times m\end{array}}{\langle e_1*e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle m;\sigma''\rangle \\ v = \lfloor n/(\max(1,m))\rfloor\end{array}}{\langle e_1*e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle m;\sigma''\rangle \\ v = n \bmod (\max(1,m))\end{array}}{\langle e_1\%e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle m;\sigma''\rangle \\ v = n\hat{}m\end{array}}{\langle e_1\hat{}e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}\ \text{where } 0\hat{}0 = 1$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \\ v = n+1\end{array}}{\langle \texttt{suc}\ e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle 0;\sigma'\rangle \\ \langle e_1;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle\end{array}}{\langle \texttt{primrec}\ e\ \texttt{with}\ \texttt{|0} \Rightarrow e_1 \texttt{|suc}\ x,y \Rightarrow e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle n;\sigma'\rangle \qquad (\text{with n} \neq 0) \\ \langle \texttt{primrec}\ n-1\ \texttt{with}\ \texttt{|0} \Rightarrow e_1 \texttt{|suc}\ x,y \Rightarrow e_2;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle \\ \langle e_2[n-1/x,v/y];\sigma''\rangle \Downarrow \langle v';\sigma'''\rangle\end{array}}{\langle \texttt{primrec}\ e\ \texttt{with}\ \texttt{|0} \Rightarrow e_1 \texttt{|suc}\ x,y \Rightarrow e_2;\sigma\rangle \Downarrow \langle v';\sigma'''\rangle}$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle \texttt{true};\sigma'\rangle \\ \langle e_1;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle\end{array}}{\langle \texttt{if}\ e\ \texttt{then}\ e_1\ \texttt{else}\ e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle \texttt{false};\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle\end{array}}{\langle \texttt{if}\ e\ \texttt{then}\ e_1\ \texttt{else}\ e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \\ v = v_1\&\&v_2\end{array}}{\langle e_1\ \texttt{and}\ e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \\ v = v_1||v_2\end{array}}{\langle e_1\ \texttt{or}\ e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle \\ v' = !v\end{array}}{\langle \texttt{not}\ e;\sigma\rangle \Downarrow \langle v';\sigma'\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \\ v_1 = v_2\end{array}}{\langle e_1 == e_2;\sigma\rangle \Downarrow \langle \texttt{true};\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \\ v_1 \neq v_2\end{array}}{\langle e_1 == e_2;\sigma\rangle \Downarrow \langle \texttt{false};\sigma''\rangle}$$

$$\frac{\langle \texttt{not}\ (e_1 == e_2);\sigma\rangle \Downarrow \langle v;\sigma'\rangle}{\langle e_1 ! = e_2;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}$$

$$\frac{\langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \quad \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle}{\langle (e_1,e_2);\sigma\rangle \Downarrow \langle (v_1,v_2);\sigma''\rangle} \qquad \frac{\langle e;\sigma\rangle \Downarrow \langle (v_1,v_2);\sigma'\rangle}{\langle \texttt{fst}\ e;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle} \qquad \frac{\langle e;\sigma\rangle \Downarrow \langle (v_1,v_2);\sigma'\rangle}{\langle \texttt{snd}\ e;\sigma\rangle \Downarrow \langle v_2;\sigma'\rangle}$$

$$\frac{\langle e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}{\langle \texttt{inl}\ e : A;\sigma\rangle \Downarrow \langle \texttt{inl}\ v : A;\sigma'\rangle} \qquad \frac{\langle e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}{\langle \texttt{inr}\ e : A;\sigma\rangle \Downarrow \langle \texttt{inr}\ v : A;\sigma'\rangle}$$

$$\frac{\langle e;\sigma\rangle \Downarrow \langle \texttt{inl}\ v : A;\sigma'\rangle \quad \langle e_1[v/x];\sigma'\rangle \Downarrow \langle v';\sigma''\rangle}{\langle \texttt{match}\ e\ \texttt{with|inl}\ x \Rightarrow e_1 \texttt{|inr}\ y \Rightarrow e_2;\sigma\rangle \Downarrow \langle v';\sigma''\rangle}$$

$$\frac{\langle e;\sigma\rangle \Downarrow \langle \texttt{inr}\ v : A;\sigma'\rangle \quad \langle e_2[v/y];\sigma'\rangle \Downarrow \langle v';\sigma''\rangle}{\langle \texttt{match}\ e\ \texttt{with|inl}\ x \Rightarrow e_1 \texttt{|inr}\ y \Rightarrow e_2;\sigma\rangle \Downarrow \langle v';\sigma''\rangle}$$

$$\frac{\langle e_i;\sigma_{i-1}\rangle \Downarrow \langle v_i;\sigma_i\rangle \qquad (\forall i = 1,\ldots,n)}{\langle \texttt{[}e_1,\ldots,e_n\texttt{]};\sigma_0\rangle \Downarrow \langle \texttt{[}v_1,\ldots,v_n\texttt{]};\sigma_n\rangle} \qquad \frac{\langle e_1;\sigma\rangle \Downarrow \langle v;\sigma'\rangle \quad \langle e_2;\sigma'\rangle \Downarrow \langle \texttt{[}v_1,\ldots,v_n\texttt{]};\sigma''\rangle}{\langle e_1 \texttt{::} e_2;\sigma\rangle \Downarrow \langle \texttt{[}v,v_1,\ldots,v_n\texttt{]};\sigma''\rangle}$$

$$\frac{\langle e_1;\sigma\rangle \Downarrow \langle \texttt{[}v_1,\ldots,v_n\texttt{]};\sigma'\rangle \quad \langle e_2;\sigma'\rangle \Downarrow \langle \texttt{[}w_1,\ldots,w_m\texttt{]};\sigma''\rangle}{\langle e_1 \texttt{++} e_2;\sigma\rangle \Downarrow \langle \texttt{[}v_1,\ldots,v_n,w_1,\ldots,w_m\texttt{]};\sigma''\rangle}$$

$$\frac{\langle e;\sigma\rangle \Downarrow \langle \texttt{[]} : A;\sigma'\rangle \quad \langle e_1;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle}{\langle \texttt{primrec}\ e\ \texttt{with |[]} \Rightarrow e_1 | x \texttt{::} y, z \Rightarrow e_2;\sigma\rangle \Downarrow \langle v;\sigma''\rangle}$$

$$\frac{\begin{array}{c}\langle e;\sigma\rangle \Downarrow \langle \texttt{[}v_1,\ldots,v_n\texttt{]};\sigma'\rangle \qquad (\text{with n} \neq 0) \\ \langle \texttt{primrec [}v_2,\ldots,v_n\texttt{] with |[]} \Rightarrow e_1 | x \texttt{::} y, z \Rightarrow e_2;\sigma'\rangle \Downarrow \langle v;\sigma''\rangle \\ \langle e_2[v_1/x, \texttt{[}v_2,\ldots,v_n\texttt{]}/y, v/z];\sigma''\rangle \Downarrow \langle v';\sigma'''\rangle\end{array}}{\langle \texttt{primrec}\ e\ \texttt{with |[]} \Rightarrow e_1 | x \texttt{::} y, z \Rightarrow e_2;\sigma\rangle \Downarrow \langle v;\sigma'''\rangle}$$

$$\frac{\begin{array}{c} l = \mathrm{alloc}(\sigma) \\ \sigma \neq \cdot \end{array}}{\langle \texttt{>}e;\sigma\rangle \Downarrow \langle l;\sigma + \{l \mapsto e\}\rangle} \qquad \frac{\begin{array}{c} l = \mathrm{alloc}(\sigma) \\ \sigma \neq \cdot \end{array}}{\langle \texttt{@}e;\sigma\rangle \Downarrow \langle l;\sigma + l \mapsto e\rangle} \qquad \frac{\begin{array}{c} \langle e;\eta_N\rangle \Downarrow \langle l;\eta'_N\rangle \\ \langle \eta'_N(l);(\eta'_N \checkmark \eta_L)\rangle \Downarrow \langle v;\sigma'\rangle \end{array}}{\langle \texttt{<}e;(\eta_N \checkmark \eta_L)\rangle \Downarrow \langle v;\sigma'\rangle}$$

$$\frac{\begin{array}{c} \langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \end{array}}{\langle e_1 \texttt{:::} e_2;\sigma\rangle \Downarrow \langle \texttt{into}\ (v_1, v_2) : A;\sigma''\rangle}$$ [1]

$$\frac{\begin{array}{c} \langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2[\texttt{fst(out}\ v_1)/x, \texttt{snd(out}\ v_1)/y];\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \end{array}}{\langle \texttt{let}\ x \texttt{:::} y = e_1\ \texttt{in}\ e_2;\sigma\rangle \Downarrow \langle v_2;\sigma''\rangle}$$

$$\frac{\begin{array}{c} \langle e;\cdot\rangle \Downarrow \langle \texttt{\#}e';\cdot\rangle \\ \langle e';\sigma\rangle \Downarrow \langle v;\sigma'\rangle \\ \sigma \neq \cdot \end{array}}{\langle \texttt{?}e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle} \qquad \frac{\begin{array}{c} \langle e;\cdot\rangle \Downarrow \langle \texttt{nfix}\ x : A \Rightarrow e';\cdot\rangle \\ \langle e'[\texttt{\#(>(?nfix}\ x : A \Rightarrow e'))/x];\sigma\rangle \Downarrow \langle v;\sigma'\rangle \\ \sigma \neq \cdot \end{array}}{\langle \texttt{?}e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}$$

$$\frac{\langle e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}{\langle \texttt{now}\ e;\sigma\rangle \Downarrow \langle \texttt{now}\ v;\sigma'\rangle} \qquad \frac{\begin{array}{c} \langle e_1;\sigma\rangle \Downarrow \langle v_1;\sigma'\rangle \\ \langle e_2;\sigma'\rangle \Downarrow \langle v_2;\sigma''\rangle \end{array}}{\langle \texttt{wait}\ e_1\ e_2;\sigma\rangle \Downarrow \langle \texttt{wait}\ v_1\ v_2;\sigma''\rangle}$$

$$\frac{\begin{array}{c} \langle e;\sigma\rangle \Downarrow \langle \texttt{now}\ v;\sigma'\rangle \\ \langle e_1[v/x];\sigma'\rangle \Downarrow \langle v';\sigma''\rangle \end{array}}{\langle \texttt{urec}\ e\ \texttt{with|now}\ x \Rightarrow e_1 \texttt{|wait}\ x'\ y, z \Rightarrow e_2;\sigma\rangle \Downarrow \langle v';\sigma''\rangle}$$

$$\frac{\begin{array}{c} \langle e;\sigma\rangle \Downarrow \langle \texttt{wait}\ v_1\ v_2;\sigma'\rangle \\ l = \mathrm{alloc}(\sigma') \\ \langle e_2[v_1/x', v_2/y, l/z];\sigma' + \{l \mapsto (\texttt{urec}\ \texttt{<}v_2\ \texttt{with|now}\ x \Rightarrow e_1 \texttt{|wait}\ x'\ y, z \Rightarrow e_2)\}\rangle \Downarrow \langle v';\sigma''\rangle \end{array}}{\langle \texttt{urec}\ e\ \texttt{with|now}\ x \Rightarrow e_1 \texttt{|wait}\ x'\ y, z \Rightarrow e_2;\sigma\rangle \Downarrow \langle v';\sigma''\rangle}$$

$$\frac{\langle e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}{\langle \texttt{into}\ e;\sigma\rangle \Downarrow \langle \texttt{into}\ v;\sigma'\rangle} \qquad \frac{\langle e;\sigma\rangle \Downarrow \langle \texttt{into}\ v;\sigma'\rangle}{\langle \texttt{out}\ e;\sigma\rangle \Downarrow \langle v;\sigma'\rangle}$$

[1]Type ascription A not important

A.7 Step Semantics

$$\frac{\langle e; \eta\checkmark\rangle \Downarrow \langle v \mathtt{:::} w; \eta_N \checkmark \eta_L\rangle}{\langle e; \eta\rangle \overset{v}{\Longrightarrow}_{\mathtt{Safe}} \langle \mathtt{<}w; \eta_L\rangle}$$

$$\frac{\langle e; \eta\checkmark\rangle \Downarrow \langle \mathtt{wait}\ \ v\ w; \eta_N \checkmark \eta_L\rangle}{\langle e; \eta\rangle \overset{v}{\Longrightarrow}_{\mathtt{Lively}} \langle \mathtt{<}w; \eta_L\rangle} \qquad \frac{\langle e; \eta\checkmark\rangle \Downarrow \langle \mathtt{now}\ \ v; \eta_N \checkmark \eta_L\rangle}{\langle e; \eta\rangle \overset{v}{\Longrightarrow}_{\mathtt{Lively}} \langle \mathtt{HALT}; \eta_L\rangle}$$

$$\frac{\langle e; \eta\rangle \overset{v}{\Longrightarrow}_{\mathtt{Lively}} \langle e'; \eta'\rangle}{\langle e; \eta; 1\rangle \overset{\mathtt{inl}\ v}{\Longrightarrow}_{\mathtt{Fair}} \langle e'; \eta'; 1\rangle} \qquad \frac{\langle e; \eta\rangle \overset{v}{\Longrightarrow}_{\mathtt{Lively}} \langle e'; \eta'\rangle}{\langle e; \eta; 2\rangle \overset{\mathtt{inr}\ v}{\Longrightarrow}_{\mathtt{Fair}} \langle e'; \eta'; 2\rangle}$$

$$\frac{\langle e; \eta\rangle \overset{(v,w)}{\Longrightarrow}_{\mathtt{Lively}} \langle \mathtt{HALT}; \eta'\rangle}{\langle e; \eta; 1\rangle \overset{\mathtt{inr}\ v}{\Longrightarrow}_{\mathtt{Fair}} \langle \mathtt{<}w; \eta'; 2\rangle} \qquad \frac{\langle e; \eta\rangle \overset{(v,w)}{\Longrightarrow}_{\mathtt{Lively}} \langle \mathtt{HALT}; \eta'\rangle}{\langle e; \eta; 2\rangle \overset{\mathtt{inl}\ v}{\Longrightarrow}_{\mathtt{Fair}} \langle \mathtt{out}(\mathtt{<}w); \eta'; 1\rangle}$$

$$\frac{\begin{array}{c}\langle e; (\eta + \{l \mapsto v \mathtt{:::} l'\})\checkmark\{l' \mapsto ()\}\rangle \Downarrow \langle v' \mathtt{:::} w; \eta_N \checkmark (\eta_L + \{l' \mapsto ()\})\rangle \\ l' = \mathrm{alloc}(\eta\checkmark)\end{array}}{\langle e; \eta; l\rangle \overset{v/v'}{\Longrightarrow}_{\mathtt{ISafe}} \langle \mathtt{<}w; \eta_L; l'\rangle}$$

$$\frac{\begin{array}{c}\langle e; (\eta + \{l \mapsto v \mathtt{:::} l'\})\checkmark\{l' \mapsto ()\}\rangle \Downarrow \langle \mathtt{wait}\ \ v'\ w; \eta_N \checkmark (\eta_L + \{l' \mapsto ()\})\rangle \\ l' = \mathrm{alloc}(\eta\checkmark)\end{array}}{\langle e; \eta; l\rangle \overset{v/v'}{\Longrightarrow}_{\mathtt{ILively}} \langle \mathtt{<}w; \eta_L; l'\rangle}$$

$$\frac{\begin{array}{c}\langle e; (\eta + \{l \mapsto v \mathtt{:::} l'\})\checkmark\{l' \mapsto ()\}\rangle \Downarrow \langle \mathtt{now}\ \ v'; \eta_N \checkmark (\eta_L + \{l' \mapsto ()\})\rangle \\ l' = \mathrm{alloc}(\eta\checkmark)\end{array}}{\langle e; \eta; l\rangle \overset{v/v'}{\Longrightarrow}_{\mathtt{ILively}} \langle \mathtt{HALT}; \eta_L; l'\rangle}$$

$$\frac{\langle e; \eta; l\rangle \overset{v/v'}{\Longrightarrow}_{\mathtt{ILively}} \langle e'; \eta'; l'\rangle}{\langle e; \eta; l; 1\rangle \overset{v/\mathtt{inl}\ v'}{\Longrightarrow}_{\mathtt{IFair}} \langle e'; \eta'; l'; 1\rangle} \qquad \frac{\langle e; \eta; l\rangle \overset{v/v'}{\Longrightarrow}_{\mathtt{ILively}} \langle e'; \eta'; l'\rangle}{\langle e; \eta; l; 2\rangle \overset{v/\mathtt{inr}\ v'}{\Longrightarrow}_{\mathtt{IFair}} \langle e'; \eta'; l'; 2\rangle}$$

$$\frac{\langle e; \eta; l\rangle \overset{v/(v',w)}{\Longrightarrow}_{\mathtt{ILively}} \langle \mathtt{HALT}; \eta'; l'\rangle}{\langle e; \eta; l; 1\rangle \overset{v/\mathtt{inr}\ v'}{\Longrightarrow}_{\mathtt{IFair}} \langle \mathtt{adv}\ \ w; \eta'; l'; 2\rangle} \qquad \frac{\langle e; \eta; l\rangle \overset{v/(v',w)}{\Longrightarrow}_{\mathtt{ILively}} \langle \mathtt{HALT}; \eta'; l'\rangle}{\langle e; \eta; l; 2\rangle \overset{v/\mathtt{inr}\ v'}{\Longrightarrow}_{\mathtt{IFair}} \langle \mathtt{out}(\mathtt{adv}\ \ w); \eta'; l'; 1\rangle}$$

A.8 Fundamental Theorems of Eva

A.8.1 Safe Interpreter

If $\cdot;\cdot \vdash e : \#\mathtt{Str}(A)$, then there is an infinite sequence of reduction steps:

$$\langle ?e;\emptyset\rangle \xRightarrow{v_1}_{\mathtt{Safe}} \langle e_1;\eta_1\rangle \xRightarrow{v_2}_{\mathtt{Safe}} \langle e_2;\eta_2\rangle \xRightarrow{v_3}_{\mathtt{Safe}} \cdots$$

Moreover, if A is a value type, then $\cdot;\cdot \vdash v_i : A$ for all $i \geq 1$.

A.8.2 Lively Interpreter

If $\cdot;\cdot \vdash e : \#(A\ \ \mathtt{Until}\ \ B)$, then there is a finite sequence of reduction steps:

$$\langle ?e;\emptyset\rangle \xRightarrow{v_1}_{\mathtt{Lively}} \langle e_1;\eta_1\rangle \xRightarrow{v_2}_{\mathtt{Lively}} \langle e_2;\eta_2\rangle \xRightarrow{v_3}_{\mathtt{Lively}} \cdots \xRightarrow{v_n}_{\mathtt{Lively}} \langle \mathtt{HALT};\eta_n\rangle$$

Moreover, if A and B are value types, then $\cdot;\cdot \vdash v_i : A$ for all $0 < i < n$, and $\cdot;\cdot \vdash v_n : B$.

A.8.3 Fair Interpreter

If $\cdot;\cdot \vdash e : \#\mathtt{Fair}(A,B)$, then there is an infinite sequence of reduction steps:

$$\langle \mathtt{out}(?e);\emptyset;1\rangle \xRightarrow{v_1}_{\mathtt{Fair}} \langle e_1;\eta_1;p_1\rangle \xRightarrow{v_2}_{\mathtt{Fair}} \langle e_2;\eta_2;p_2\rangle \xRightarrow{v_3}_{\mathtt{Fair}} \cdots$$

such that for each $p \in \{1,2\}$, we have $p_i = p$ for infinitely many $i \geq 1$. Moreover, if A and B are value types, then $\cdot;\cdot \vdash v_i : A+B$ for all $i \geq 1$.

A.8.4 ISafe Interpreter

If $\cdot;\cdot \vdash e : \#(\mathtt{Str}(A) \to \mathtt{Str}(B))$, then there is an infinite sequence of reduction steps:

$$\langle (?e)\ (<l_0);\emptyset;l_0\rangle \xRightarrow{v_1/v_1'}_{\mathtt{ISafe}} \langle e_1;\eta_1;l_1\rangle \xRightarrow{v_2/v_2'}_{\mathtt{ISafe}} \langle e_2;\eta_2;l_2\rangle \xRightarrow{v_3/v_3'}_{\mathtt{ISafe}} \cdots$$

Moreover, if B is a value type, then $\cdot;\cdot \vdash v_i' : B$ for all $i \geq 1$.

A.8.5 ILively Interpreter

If $\cdot;\cdot \vdash e : \#(\mathtt{Str}(A) \to (B\ \ \mathtt{Until}\ \ C))$, then there is a finite sequence of reduction steps:

$$\langle (?e)\ (<l_0);\emptyset;l_0\rangle \xRightarrow{v_1/v_1'}_{\mathtt{ILively}} \langle e_1;\eta_1;l_1\rangle \xRightarrow{v_2/v_2'}_{\mathtt{ILively}} \langle e_2;\eta_2;l_2\rangle \xRightarrow{v_3/v_3'}_{\mathtt{ILively}} \cdots \xRightarrow{v_n/v_n'}_{\mathtt{ILively}} \langle \mathtt{HALT};\eta_n;l_n\rangle$$

Moreover, if B and C are value types, then $\cdot;\cdot \vdash v_i' : B$ for all $0 < i < n$, and $\cdot;\cdot \vdash v_n' : C$.

A.8.6 IFair Interpreter

If $\cdot;\cdot \vdash e : \#(\mathtt{Str}(A) \to \mathtt{Fair}(B,C))$, then there is an infinite sequence of reduction steps:

$$\langle \mathtt{out}((?e)\ (<l_0));\emptyset;l_0;1\rangle \xRightarrow{v_1/v_1'}_{\mathtt{IFair}} \langle e_1;\eta_1;l_1;p_1\rangle \xRightarrow{v_2/v_2'}_{\mathtt{IFair}} \langle e_2;\eta_2;l_2;p_2\rangle \xRightarrow{v_3/v_3'}_{\mathtt{IFair}} \cdots$$

such that for each $p \in \{1,2\}$, we have $p_i = p$ for infinitely many $i \geq 1$. Moreover, if B and C are value types, then $\cdot;\cdot \vdash v_i' : B+C$ for all $i \geq 1$.