

1 Grammar

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|---|--------------------|--|------------------------|
| $e ::= x$ | $exprs.$ | $\varepsilon ::= \{\bar{r}.\pi\}$ | $effects$ |
| $\quad $ $\quad r$ | | $\tau ::= \{\bar{r}\}$ | $types$ |
| $\quad $ $\quad \lambda x : \tau. e$ | | $\quad $ $\quad \tau \rightarrow \tau$ | |
| $\quad $ $\quad ee$ | | $\hat{\tau} ::= \{\bar{r}\}$ | $labelled\ types$ |
| $\quad $ $\quad e.\pi$ | | $\quad $ $\quad \hat{\tau} \rightarrow \hat{\tau} ! \varepsilon$ | |
| $\hat{e} ::= x$ | $labelled\ exprs.$ | $\Gamma ::= \emptyset$ | $type\ ctx.$ |
| $\quad $ $\quad r$ | | $\quad $ $\quad \Gamma, x : \tau$ | |
| $\quad $ $\quad \lambda x : \hat{\tau}. \hat{e}$ | | $\hat{\Gamma} ::= \emptyset$ | $labelled\ type\ ctx.$ |
| $\quad $ $\quad \hat{e}.\hat{e}$ | | $\quad $ $\quad \hat{\Gamma}, x : \hat{\tau}$ | |
| $\quad $ $\quad \hat{e}.\pi$ | | | |
| $\quad $ $\quad \text{import}(\varepsilon) x = \hat{e} \text{ in } e$ | | | |

2 Functions

Definition ($\text{annot} :: \tau \times \varepsilon \rightarrow \hat{\tau}$)

1. $\text{annot}(\{\bar{r}\}, _) = \{\bar{r}\}$
2. $\text{annot}(\tau_1 \rightarrow \tau_2, \varepsilon) = \text{annot}(\tau_1, \varepsilon) \rightarrow \text{annot}(\tau_2, \varepsilon) ! \varepsilon$

Definition ($\text{annot} :: e \times \varepsilon \rightarrow \hat{e}$)

1. $\text{annot}(x, _) = x$
2. $\text{annot}(r, _) = r$
3. $\text{annot}(e_1 e_2, \varepsilon) = \text{annot}(e_1) \text{annot}(e_2)$
4. $\text{annot}(e.\pi, \varepsilon) = \text{annot}(e).\pi$
5. $\text{annot}(\lambda x : \tau. e, \varepsilon) = \lambda x : \text{annot}(\tau, \varepsilon). \text{annot}(e, \varepsilon)$

Definition ($\text{erase} :: \hat{\tau} \rightarrow \tau$)

1. $\text{erase}(\{\bar{r}\}, _) = \{\bar{r}\}$
2. $\text{erase}(\hat{\tau}_1 \rightarrow \hat{\tau}_2 ! \varepsilon) = \text{erase}(\hat{\tau}_1) \rightarrow \text{erase}(\hat{\tau}_2)$

Definition ($\text{erase} :: \hat{e} \rightarrow e$)

1. $\text{erase}(x) = x$
2. $\text{erase}(r) = r$
3. $\text{erase}(e_1 e_2) = \text{erase}(e_1) \text{erase}(e_2)$
4. $\text{erase}(e.\pi) = \text{erase}(e).\pi$
5. $\text{erase}(\lambda x : \hat{\tau}. \hat{e}) = \lambda x : \text{erase}(\hat{\tau}). \text{erase}(\hat{e})$

Definition ($\text{effects} :: \tau \rightarrow \varepsilon$)

1. $\text{effects}(\{\bar{r}\}) = \{r.\pi \mid r \in \bar{r}, \pi \in \Pi\}$
2. $\text{effects}(\hat{\tau}_1 \rightarrow \hat{\tau}_2 ! \varepsilon) = \varepsilon \cup \text{effects}(\hat{\tau}_2) \cup \text{ho-effects}(\hat{\tau}_1)$

Definition ($\text{ho-effects} :: \tau \rightarrow \varepsilon$)

1. $\text{ho-effects}(\hat{\tau}_1 \rightarrow \hat{\tau}_2 ! \varepsilon) = \text{ho-effects}(\hat{\tau}_2) \cup \text{effects}(\tau_1)$
2. $\text{ho-effects}(\{\bar{r}\}) = \emptyset$

3 Static Rules

$$\boxed{\hat{I} \vdash \hat{e} : \hat{\tau} \text{ with } \varepsilon}$$

$$\frac{\hat{I} \vdash \hat{e} : \hat{\tau} \text{ with } \varepsilon_1 \quad \varepsilon = \text{effects}(\hat{\tau}) \quad \text{ho-safe}(\hat{\tau}, \varepsilon) \quad x : \text{erase}(\hat{\tau}) \vdash e : \tau}{\hat{I} \vdash \text{import}(\varepsilon) \ x = \hat{e} \text{ in } e : \text{annot}(\hat{\tau}, \varepsilon) \text{ with } \varepsilon \cup \varepsilon_1} \text{ (T-MODULE)}$$

$$\boxed{\text{safe}(\tau, \varepsilon)}$$

$$\frac{}{\text{safe}(\{\bar{r}\}, \varepsilon)} \text{ (SAFE-RESOURCE)} \quad \frac{\varepsilon \subseteq \varepsilon_2 \quad \text{safe}(\hat{\tau}_2, \varepsilon) \quad \text{ho-safe}(\hat{\tau}, \varepsilon)}{\text{safe}(\hat{\tau}_1 \rightarrow \hat{\tau}_2 ! \varepsilon_2, \varepsilon)} \text{ (SAFE-ARROW)}$$

$$\boxed{\text{ho-safe}(\hat{\tau}, \varepsilon)}$$

$$\frac{}{\text{ho-safe}(\{\bar{r}\}, \varepsilon)} \text{ (HOSAFE-RESOURCE)} \quad \frac{\text{ho-safe}(\hat{\tau}_2, \varepsilon) \quad \text{safe}(\hat{\tau}_1, \varepsilon)}{\text{ho-safe}(\hat{\tau}_1 \rightarrow \hat{\tau}_2 ! \varepsilon_2, \varepsilon)} \text{ (HOSAFE-ARROW)}$$

4 Dynamic Rules

$$\boxed{\hat{e} \longrightarrow \hat{e} \mid \varepsilon}$$

$$\frac{}{\text{import}(\varepsilon) \ x = \hat{v} \text{ in } e \longrightarrow [\hat{v}, x] \text{annot}(e, \varepsilon) \mid \emptyset} \text{ (E-MODULE)}$$

$$\boxed{e \longrightarrow e \mid \varepsilon}$$

$$\frac{e_1 \longrightarrow e'_1.\pi \mid \varepsilon}{e_1.\pi \longrightarrow e'_1.\pi \mid \varepsilon} \text{ (E-OPERATION1)} \quad \frac{r \in R \quad \pi \in \Pi}{v_1.\pi \longrightarrow \text{unit} \mid \{r.\pi\}} \text{ (E-OPERATION2)}$$

$$\frac{e_1 e_2 \longrightarrow e'_1 e_2 \mid \varepsilon}{e_1 \longrightarrow e'_1 \mid \varepsilon} \text{ (E-APP1)} \quad \frac{v_1 e_2 \longrightarrow e_1 e'_2 \mid \varepsilon}{e_2 \longrightarrow e'_2 \mid \varepsilon} \text{ (E-APP2)}$$

$$\frac{}{(\lambda x : \tau. e) v_2 \longrightarrow [v_2/x] e \mid \emptyset} \text{ (E-APP3)}$$