

Algebraic Data Types for Hazel

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1 Syntax

$$\begin{aligned}
 \text{HTyp} \quad \tau &::= \emptyset \mid \tau \rightarrow \tau \mid \alpha \mid \mu\pi.\tau \mid +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \mid \langle \rangle \mid \langle \alpha \rangle \\
 \text{HTypPat} \quad \pi &::= \alpha \mid \langle \rangle \\
 \text{HExp} \quad e &::= \emptyset \mid x \mid \lambda x:\tau.e \mid e(e) \mid e:\tau \mid \text{inj}_C(e) \mid \text{roll}(e) \mid \text{unroll}(e) \\
 &\quad \mid \langle \rangle^u \mid \langle e \rangle^u \mid \langle e \rangle^u \blacktriangleright \\
 \text{IHExp} \quad d &::= \emptyset \mid x \mid \lambda x:\tau.d \mid d(d) \mid \text{inj}_C^\tau(d) \mid \text{roll}^{\mu\alpha.\tau}(d) \mid \text{unroll}(d) \\
 &\quad \mid d\langle \tau \Rightarrow \tau \rangle \mid d\langle \tau \Rightarrow \langle \rangle \not\Rightarrow \tau \rangle \mid \langle \rangle_\sigma^u \mid \langle d \rangle_\sigma^u \mid \langle d \rangle_\sigma^u \blacktriangleright \\
 \text{HTag} \quad C &::= \mathbf{C} \mid \langle \rangle^u \mid \langle \mathbf{C} \rangle^u
 \end{aligned}$$

1.1 Context Extension

We write Θ, π to denote the extension of type variable context Θ with optional type variable name π .

$$\Theta, \pi = \begin{cases} \Theta, \alpha & \pi = \alpha \\ \Theta & \pi = \langle \rangle \end{cases}$$

2 Static Semantics

$$\boxed{[\tau/\pi]\tau' = \tau''} \quad \tau'' \text{ is obtained by substituting } \tau \text{ for } \pi \text{ in } \tau'$$

$$\begin{aligned}
 [\tau/\langle \rangle]\tau' &= \tau' \\
 [\tau/\alpha]\emptyset &= \emptyset \\
 [\tau/\alpha](\tau_1 \rightarrow \tau_2) &= [\tau/\alpha]\tau_1 \rightarrow [\tau/\alpha]\tau_2 \\
 [\tau/\alpha]\alpha &= \tau \\
 [\tau/\alpha]\alpha_1 &= \tau' && \text{when } \alpha \neq \alpha_1 \\
 [\tau/\alpha]\mu\alpha_1.\tau_2 &= \mu\alpha_1.[\tau/\alpha]\tau_2 && \text{when } \alpha \neq \alpha_1 \text{ and } \alpha_1 \notin \text{FV}(\tau) \\
 [\tau/\alpha]\mu\langle \rangle.\tau_2 &= \mu\langle \rangle.[\tau/\alpha]\tau_2 \\
 [\tau/\alpha]+\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} &= +\{C_i([\tau/\alpha]\tau_i)\}_{C_i \in \mathcal{C}} \\
 [\tau/\alpha]\langle \rangle &= \langle \rangle \\
 [\alpha'/\alpha]\langle \alpha \rangle &= \langle \alpha' \rangle \\
 [\alpha'/\alpha]\langle \alpha' \rangle &= \langle \alpha' \rangle && \text{when } \alpha \neq \alpha'
 \end{aligned}$$

$$\boxed{\Theta \vdash \tau \text{ valid}} \quad \tau \text{ is a valid type}$$

$$\begin{array}{c}
 \text{TVUNIT} \\
 \hline
 \Theta \vdash \emptyset \text{ valid} \\
 \\
 \text{TVARR} \quad \frac{\Theta \vdash \tau_1 \text{ valid} \quad \Theta \vdash \tau_2 \text{ valid}}{\Theta \vdash \tau_1 \rightarrow \tau_2 \text{ valid}} \quad \text{TVVAR} \quad \frac{\alpha \in \Theta}{\Theta \vdash \alpha \text{ valid}} \quad \text{TVREC} \quad \frac{\Theta, \pi \vdash \tau \text{ valid}}{\Theta \vdash \mu\pi.\tau \text{ valid}} \quad \text{TVSUM} \quad \frac{\{\Theta \vdash \tau_i \text{ valid}\}_{C_i \in \mathcal{C}}}{\Theta \vdash +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \text{ valid}} \\
 \\
 \text{TVEHOLE} \quad \frac{}{\Theta \vdash \langle \rangle \text{ valid}} \quad \text{TVNEHOLE} \quad \frac{\alpha \notin \Theta}{\Theta \vdash \langle \alpha \rangle \text{ valid}}
 \end{array}$$

$\boxed{\tau \sim \tau'}$ τ and τ' are consistent

$$\begin{array}{c}
\text{TCREFL} \quad \frac{}{\tau \sim \tau} \quad \text{TCEHOLE1} \quad \frac{}{\llbracket \cdot \rrbracket \sim \tau} \quad \text{TCEHOLE2} \quad \frac{}{\tau \sim \llbracket \cdot \rrbracket} \quad \text{TCNEHOLE1} \quad \frac{}{\llbracket \alpha \rrbracket \sim \tau} \quad \text{TCNEHOLE2} \quad \frac{}{\tau \sim \llbracket \alpha \rrbracket} \quad \text{TCARR} \quad \frac{\tau_1 \sim \tau'_1 \quad \tau_2 \sim \tau'_2}{\tau_1 \rightarrow \tau_2 \sim \tau'_1 \rightarrow \tau'_2} \\
\\
\text{TCREC} \quad \frac{\tau \sim \tau'}{\mu\pi.\tau \sim \mu\pi.\tau'} \quad \text{TCRECHOLE1} \quad \frac{\alpha \notin \text{FV}(\tau) \quad \tau \sim \tau'}{\mu\llbracket \cdot \rrbracket.\tau \sim \mu\alpha.\tau'} \quad \text{TCRECHOLE2} \quad \frac{\alpha \notin \text{FV}(\tau) \quad \tau \sim \tau'}{\mu\alpha.\tau \sim \mu\llbracket \cdot \rrbracket.\tau'} \quad \text{TCSUM} \quad \frac{\{\tau_i \sim \tau'_i\}_{C_i \in \mathcal{C}}}{+\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \sim +\{C_i(\tau'_i)\}_{C_i \in \mathcal{C}}}
\end{array}$$

2.1 Bidirectional Typing

We call $[\mu\pi.\tau/\pi]\tau$ the *unrolling* of recursive type $\mu\pi.\tau$.

Theorem 1 (Synthetic Type Validity). *If $\Gamma \vdash e \Rightarrow \tau$ then $\emptyset \vdash \tau$ valid.*

Theorem 2 (Consistency Preserves Validity). *If $\Theta \vdash \tau$ valid and $\tau \sim \tau'$ then $\Theta \vdash \tau'$ valid.*

$\boxed{\tau \blacktriangleright_{\rightarrow} \tau_1 \rightarrow \tau_2}$ τ has matched arrow type $\tau_1 \rightarrow \tau_2$

$$\begin{array}{c}
\text{MAHOLE} \quad \frac{}{\llbracket \cdot \rrbracket \blacktriangleright_{\rightarrow} \llbracket \cdot \rrbracket \rightarrow \llbracket \cdot \rrbracket} \quad \text{MAARR} \quad \frac{}{\tau_1 \rightarrow \tau_2 \blacktriangleright_{\rightarrow} \tau_1 \rightarrow \tau_2}
\end{array}$$

$\boxed{\tau \blacktriangleright_{\mu} \mu\pi.\tau'}$ τ has matched recursive type $\mu\pi.\tau'$

$$\begin{array}{c}
\text{MRREC} \quad \frac{}{\mu\pi.\tau \blacktriangleright_{\mu} \mu\pi.\tau} \quad \text{MRHOLE} \quad \frac{}{\llbracket \cdot \rrbracket \blacktriangleright_{\mu} \mu\llbracket \cdot \rrbracket.\llbracket \cdot \rrbracket}
\end{array}$$

$\boxed{\Gamma \vdash e \Rightarrow \tau}$ e synthesizes type τ

$$\begin{array}{c}
\text{SUNIT} \quad \frac{}{\Gamma \vdash \emptyset \Rightarrow \emptyset} \quad \text{SVAR} \quad \frac{x : \tau \in \Gamma}{\Gamma \vdash x \Rightarrow \tau} \quad \text{SVARFREE} \quad \frac{x \notin \text{dom}(\Gamma)}{\Gamma \vdash \langle x \rangle^u \Rightarrow \llbracket \cdot \rrbracket} \quad \text{SLAM} \quad \frac{\emptyset \vdash \tau \text{ valid} \quad \Gamma, x : \tau \vdash e \Rightarrow \tau'}{\Gamma \vdash \lambda x : \tau. e \Rightarrow \tau \rightarrow \tau'} \\
\\
\text{SAPP} \quad \frac{\Gamma \vdash e_1 \Rightarrow \tau_1 \quad \tau_1 \blacktriangleright_{\rightarrow} \tau_2 \rightarrow \tau \quad \Gamma \vdash e_2 \Leftarrow \tau_2}{\Gamma \vdash e_1(e_2) \Rightarrow \tau} \quad \text{SAPPNOTARR} \quad \frac{\Gamma \vdash e_1 \Rightarrow \tau_1 \quad \tau_1 \approx \llbracket \cdot \rrbracket \rightarrow \llbracket \cdot \rrbracket \quad \Gamma \vdash e_2 \Leftarrow \llbracket \cdot \rrbracket}{\Gamma \vdash \langle e_1 \rangle^u \blacktriangleright (e_2) \Rightarrow \llbracket \cdot \rrbracket} \\
\\
\text{SASC} \quad \frac{\emptyset \vdash \tau \text{ valid} \quad \Gamma \vdash e \Leftarrow \tau}{\Gamma \vdash e : \tau \Rightarrow \tau} \quad \text{SROLLERR} \quad \frac{\Gamma \vdash e \Leftarrow \llbracket \cdot \rrbracket}{\Gamma \vdash \langle \text{roll}(e) \rangle^u \Rightarrow \mu\llbracket \cdot \rrbracket.\llbracket \cdot \rrbracket} \quad \text{SUNROLL} \quad \frac{\Gamma \vdash e \Rightarrow \tau \quad \tau \blacktriangleright_{\mu} \mu\pi.\tau'}{\Gamma \vdash \text{unroll}(e) \Rightarrow [\mu\pi.\tau'/\pi]\tau'} \\
\\
\text{SUNROLLNOTREC} \quad \frac{\Gamma \vdash e \Rightarrow \tau \quad \tau \approx \mu\llbracket \cdot \rrbracket.\llbracket \cdot \rrbracket}{\Gamma \vdash \text{unroll}(\langle e \rangle^u \blacktriangleright) \Rightarrow \llbracket \cdot \rrbracket} \quad \text{SINJERR} \quad \frac{\Gamma \vdash e \Leftarrow \llbracket \cdot \rrbracket}{\Gamma \vdash \langle \text{inj}_C(e) \rangle^u \Rightarrow \llbracket \cdot \rrbracket} \quad \text{SEHOLE} \quad \frac{}{\Gamma \vdash \llbracket \cdot \rrbracket^u \Rightarrow \llbracket \cdot \rrbracket} \quad \text{SNEHOLE} \quad \frac{}{\Gamma \vdash \langle e \rangle^u \Rightarrow \llbracket \cdot \rrbracket}
\end{array}$$

$\boxed{\Gamma \vdash e \Leftarrow \tau}$ e analyzes against type τ

$$\begin{array}{c}
\text{AROLL} \\
\frac{\tau \blacktriangleright_{\mu} \mu\pi.\tau' \quad \Gamma \vdash e \Leftarrow [\mu\pi.\tau'/\pi]\tau'}{\Gamma \vdash \mathbf{roll}(e) \Leftarrow \tau}
\end{array}
\quad
\begin{array}{c}
\text{AROLLNOTREC} \\
\frac{\tau \approx \mu(\emptyset).\emptyset \quad \Gamma \vdash e \Leftarrow \emptyset}{\Gamma \vdash (\mathbf{roll}(e))^u \Leftarrow \tau}
\end{array}
\quad
\begin{array}{c}
\text{AINJHOLE} \\
\frac{\Gamma \vdash e \Leftarrow \emptyset}{\Gamma \vdash \mathbf{inj}_C(e) \Leftarrow \emptyset}
\end{array}$$

$$\begin{array}{c}
\text{AINJ} \\
\frac{C_j \in \mathcal{C} \quad \Gamma \vdash e \Leftarrow \tau_j}{\Gamma \vdash \mathbf{inj}_{C_j}(e) \Leftarrow +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}}}
\end{array}
\quad
\begin{array}{c}
\text{AINJTAGErr} \\
\frac{C \notin \mathcal{C} \quad \Gamma \vdash e \Leftarrow \emptyset}{\Gamma \vdash \mathbf{inj}_C(e) \Leftarrow +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}}}
\end{array}$$

$$\begin{array}{c}
\text{AINJUNEXPECTEDBODY} \\
\frac{C_j \in \mathcal{C} \quad \tau_j = \emptyset \quad e \neq \emptyset \quad \Gamma \vdash e \Leftarrow \emptyset}{\Gamma \vdash (\mathbf{inj}_{C_j}(e))^u \Leftarrow +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}}}
\end{array}
\quad
\begin{array}{c}
\text{AINJEXPECTEDBODY} \\
\frac{C_j \in \mathcal{C} \quad \tau_j \neq \emptyset}{\Gamma \vdash (\mathbf{inj}_{C_j}(\emptyset))^u \Leftarrow +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}}}
\end{array}$$

$$\begin{array}{c}
\text{ASUBSUME} \\
\frac{\Gamma \vdash e \Rightarrow \tau' \quad \tau' \sim \tau}{\Gamma \vdash e \Leftarrow \tau}
\end{array}$$

2.2 Typed Elaboration

Theorem 3 (Synthetic Typed Elaboration Validity). *If $\Gamma \vdash e \Rightarrow \tau \rightsquigarrow d \dashv \Delta$ then $\emptyset \vdash \tau$ valid.*

$\boxed{\Gamma \vdash e \Rightarrow \tau \rightsquigarrow d \dashv \Delta}$ e synthesizes type τ and elaborates to d

$$\begin{array}{c}
\text{ESUNIT} \\
\frac{}{\Gamma \vdash \emptyset \Rightarrow \emptyset \rightsquigarrow \emptyset \dashv \emptyset}
\end{array}
\quad
\begin{array}{c}
\text{ESVAR} \\
\frac{x : \tau \in \Gamma}{\Gamma \vdash x \Rightarrow \tau \rightsquigarrow x \dashv \emptyset}
\end{array}
\quad
\begin{array}{c}
\text{ESVARFREE} \\
\frac{x \notin \text{dom}(\Gamma)}{\Gamma \vdash (x)^u \Rightarrow \emptyset \rightsquigarrow (x)_{\text{id}(\Gamma)}^u \dashv u :: \emptyset [\Gamma]}
\end{array}$$

$$\begin{array}{c}
\text{ESAPP} \\
\frac{\Gamma \vdash e_1 \Rightarrow \tau_1 \quad \tau_1 \blacktriangleright_{\rightarrow} \tau_2 \rightarrow \tau \quad \Gamma \vdash e_1 \Leftarrow \tau_2 \rightarrow \tau \rightsquigarrow d_1 : \tau'_1 \dashv \Delta_1 \quad \Gamma \vdash e_2 \Leftarrow \tau_2 \rightsquigarrow d_2 : \tau'_2 \dashv \Delta_2}{\Gamma \vdash e_1(e_2) \Rightarrow \tau \rightsquigarrow (d_1 \langle \tau'_1 \Rightarrow \tau_1 \rangle)(d_2 \langle \tau'_2 \Rightarrow \tau_2 \rangle) \dashv \Delta_1 \cup \Delta_2}
\end{array}$$

$$\begin{array}{c}
\text{ESLAM} \\
\frac{\emptyset \vdash \tau \text{ valid} \quad \Gamma, x : \tau \vdash e \Rightarrow \tau' \rightsquigarrow d \dashv \Delta}{\Gamma \vdash \lambda x : \tau. e \Rightarrow \tau \rightarrow \tau' \rightsquigarrow \lambda x : \tau. d \dashv \Delta}
\end{array}$$

$$\begin{array}{c}
\text{ESAPPNOTARR} \\
\frac{\Gamma \vdash e_1 \Rightarrow \tau_1 \rightsquigarrow d_1 \dashv \Delta_1 \quad \tau_1 \approx \emptyset \rightarrow \emptyset \quad \Gamma \vdash e_2 \Leftarrow \emptyset \rightsquigarrow d_2 : \tau'_2 \dashv \Delta_2}{\Gamma \vdash (e_1)^{u \blacktriangleright} (e_2) \Rightarrow \emptyset \rightsquigarrow (d_1)_{\text{id}(\Gamma)}^{u \blacktriangleright} (d_2 \langle \tau'_2 \Rightarrow \emptyset \rangle) \dashv \Delta_1 \cup \Delta_2, u :: \emptyset \rightarrow \emptyset [\Gamma]}
\end{array}$$

$$\begin{array}{c}
\text{ESAsc} \\
\frac{\emptyset \vdash \tau \text{ valid} \quad \Gamma \vdash e \Leftarrow \tau \rightsquigarrow d : \tau' \dashv \Delta}{\Gamma \vdash e : \tau \Rightarrow \tau \rightsquigarrow d \langle \tau' \Rightarrow \tau \rangle \dashv \Delta}
\end{array}$$

$$\begin{array}{c}
\text{ESROLLERR} \\
\frac{\Gamma \vdash e \Leftarrow \emptyset \rightsquigarrow d : \tau \dashv \Delta}{\Gamma \vdash (\mathbf{roll}(e))^u \Rightarrow \mu(\emptyset).\emptyset \rightsquigarrow (\mathbf{roll}^{\mu(\emptyset).\emptyset}(d \langle \tau \Rightarrow \emptyset \rangle))_{\text{id}(\Gamma)}^u \dashv \Delta, u :: \mu(\emptyset).\emptyset [\Gamma]}
\end{array}$$

$$\begin{array}{c}
\text{ESUNROLL} \\
\frac{\Gamma \vdash e \Rightarrow \tau \rightsquigarrow d \dashv \Delta \quad \tau \blacktriangleright_{\mu} \mu\pi.\tau'}{\Gamma \vdash \mathbf{unroll}(e) \Rightarrow [\mu\pi.\tau'/\pi]\tau' \rightsquigarrow \mathbf{unroll}(d \langle \tau \Rightarrow \mu\pi.\tau' \rangle) \dashv \Delta}
\end{array}$$

$$\frac{\text{ESUnrollNotRec} \quad \Gamma \vdash e \Rightarrow \tau \rightsquigarrow d \dashv \Delta \quad \tau \approx \mu(\emptyset).\emptyset}{\Gamma \vdash \text{unroll}(\langle e \rangle^u) \Rightarrow \emptyset \rightsquigarrow \text{unroll}(\langle d \rangle_{\text{id}(\Gamma)}^u) \dashv \Delta, u :: \mu(\emptyset).\emptyset[\Gamma]}$$

$$\frac{\text{ESInjErr} \quad \Gamma \vdash e \Leftarrow \emptyset \rightsquigarrow d : \tau \dashv \Delta \quad \tau' = +\{C(\tau)\}}{\Gamma \vdash \langle \text{inj}_C(e) \rangle^u \Rightarrow \emptyset \rightsquigarrow \langle \text{inj}_C^{\tau'}(d \langle \tau \Rightarrow \emptyset \rangle) \rangle_{\text{id}(\Gamma)}^u \dashv \Delta, u :: \emptyset[\Gamma]} \quad \text{ESEHole} \quad \frac{}{\Gamma \vdash \emptyset^u \Rightarrow \emptyset \rightsquigarrow \emptyset_{\text{id}(\Gamma)}^u \dashv u :: \emptyset[\Gamma]}$$

$$\frac{\text{ESNEHole} \quad \Gamma \vdash e \Rightarrow \tau \rightsquigarrow d \dashv \Delta}{\Gamma \vdash \langle e \rangle^u \Rightarrow \emptyset \rightsquigarrow \langle d \rangle_{\text{id}(\Gamma)}^u \dashv \Delta, u :: \emptyset[\Gamma]}$$

$$\boxed{\Gamma \vdash e \Leftarrow \tau_1 \rightsquigarrow d : \tau_2 \dashv \Delta} \quad e \text{ analyzes against type } \tau_1 \text{ and elaborates to } d \text{ of consistent type } \tau_2$$

$$\frac{\text{EARoll} \quad \tau \blacktriangleright_{\mu} \mu\pi.\tau' \quad \Gamma \vdash e \Leftarrow [\mu\pi.\tau'/\pi]\tau' \rightsquigarrow d : \tau'' \dashv \Delta}{\Gamma \vdash \text{roll}(e) \Leftarrow \tau \rightsquigarrow \text{roll}^{\mu\pi.\tau'}(d \langle \tau'' \Rightarrow [\mu\pi.\tau'/\pi]\tau' \rangle) : \mu\pi.\tau' \dashv \Delta}$$

$$\frac{\text{EARollNotRec} \quad \tau \approx \mu(\emptyset).\emptyset \quad \Gamma \vdash e \Leftarrow \emptyset \rightsquigarrow d : \tau' \dashv \Delta}{\Gamma \vdash \langle \text{roll}(e) \rangle^u \Leftarrow \tau \rightsquigarrow \langle \text{roll}^{\mu(\emptyset).\emptyset}(d) \rangle_{\text{id}(\Gamma)}^u : \mu(\emptyset).\emptyset \dashv \Delta, u :: \mu(\emptyset).\emptyset[\Gamma]}$$

$$\frac{\text{EAINjHole} \quad \Gamma \vdash e \Leftarrow \emptyset \rightsquigarrow d : \tau \dashv \Delta \quad \tau' = +\{C(\tau)\}}{\Gamma \vdash \text{inj}_C(e) \Leftarrow \emptyset \rightsquigarrow \text{inj}_C^{\tau'}(d) : \tau' \dashv \Delta} \quad \text{EAINj} \quad \frac{\tau = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \quad C_j \in \mathcal{C} \quad \Gamma \vdash e \Leftarrow \tau_j \rightsquigarrow d : \tau'_j \dashv \Delta}{\Gamma \vdash \text{inj}_{C_j}(e) \Leftarrow \tau \rightsquigarrow \text{inj}_{C_j}^{\tau'}(d \langle \tau'_j \Rightarrow \tau_j \rangle) : \tau \dashv \Delta}$$

$$\frac{\text{EAINjTagErr} \quad C \notin \mathcal{C} \quad \Gamma \vdash e \Leftarrow \emptyset \rightsquigarrow d : \tau \dashv \Delta \quad \tau' = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \cup \{C(\tau)\}}{\Gamma \vdash \text{inj}_C(e) \Leftarrow +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \rightsquigarrow \text{inj}_C^{\tau'}(d \langle \tau \Rightarrow \emptyset \rangle) : +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \dashv \Delta}$$

$$\frac{\text{EAINjUnexpectedBody} \quad \tau = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \quad C_j \in \mathcal{C} \quad \tau_j = \emptyset \quad e \neq \emptyset}{\Gamma \vdash e \Leftarrow \emptyset \rightsquigarrow d : \tau_j \dashv \Delta \quad \tau' = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C} \setminus C_j} \cup \{C_j(\tau_j)\}} \quad \frac{}{\Gamma \vdash \langle \text{inj}_{C_j}(e) \rangle^u \Leftarrow \tau \rightsquigarrow \langle \text{inj}_{C_j}^{\tau'}(d) \rangle_{\text{id}(\Gamma)}^u : \tau \dashv \Delta, u :: \tau[\Gamma]}$$

$$\frac{\text{EAINjExpectedBody} \quad \tau = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \quad C_j \in \mathcal{C} \quad \tau_j \neq \emptyset \quad \tau' = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C} \setminus C_j} \cup \{C_j(\emptyset)\}}{\Gamma \vdash \langle \text{inj}_{C_j}(\emptyset) \rangle^u \Leftarrow \tau \rightsquigarrow \langle \text{inj}_{C_j}^{\tau'}(\emptyset) \rangle_{\text{id}(\Gamma)}^u : \tau \dashv \Delta, u :: \tau[\Gamma]}$$

$$\frac{\text{EASubsume} \quad e \neq \emptyset^u \quad e \neq \langle e' \rangle^u \quad \Gamma \vdash e \Rightarrow \tau' \rightsquigarrow d \dashv \Delta \quad \tau \sim \tau'}{\Gamma \vdash e \Leftarrow \tau \rightsquigarrow d : \tau' \dashv \Delta} \quad \text{EAEHole} \quad \frac{}{\Gamma \vdash \emptyset^u \Leftarrow \tau \rightsquigarrow \emptyset_{\text{id}(\Gamma)}^u : \tau \dashv u :: \tau[\Gamma]}$$

$$\frac{\text{EANEHole} \quad \Gamma \vdash e \Rightarrow \tau' \rightsquigarrow d \dashv \Delta}{\Gamma \vdash \langle e \rangle^u \Leftarrow \tau \rightsquigarrow \langle d \rangle_{\text{id}(\Gamma)}^u : \tau \dashv u :: \tau[\Gamma]}$$

2.3 Type Assignment

$\boxed{\Delta; \Gamma \vdash d : \tau}$ d is assigned type τ

$$\begin{array}{c}
\text{TUNIT} \\
\frac{}{\Delta; \Gamma \vdash \emptyset : \emptyset}
\\
\text{TAVAR} \\
\frac{x : \tau \in \Gamma}{\Delta; \Gamma \vdash x : \tau}
\\
\text{TALAM} \\
\frac{\emptyset \vdash \tau \text{ valid} \quad \Delta; \Gamma, x : \tau \vdash d : \tau'}{\Delta; \Gamma \vdash \lambda x : \tau. d : \tau \rightarrow \tau'}
\\
\text{TAPP} \\
\frac{\Delta; \Gamma \vdash d_1 : \tau_2 \rightarrow \tau \quad \Delta; \Gamma \vdash d_2 : \tau_2}{\Delta; \Gamma \vdash d_1(d_2) : \tau}
\\
\text{TROLL} \\
\frac{\emptyset \vdash \mu\pi.\tau \text{ valid} \quad \Delta; \Gamma \vdash d : [\mu\pi.\tau/\pi]\tau}{\Delta; \Gamma \vdash \text{roll}^{\mu\pi.\tau}(d) : \mu\pi.\tau}
\\
\text{TUNROLL} \\
\frac{\Delta; \Gamma \vdash d : \mu\pi.\tau}{\Delta; \Gamma \vdash \text{unroll}(d) : [\mu\pi.\tau/\pi]\tau}
\\
\text{TINJ} \\
\frac{\tau = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \quad C_j \in \mathcal{C} \quad \Delta; \Gamma \vdash d : \tau_j}{\Delta; \Gamma \vdash \text{inj}_{C_j}^\tau(d) : \tau}
\\
\text{TAEHOLE} \\
\frac{u :: \tau[\Gamma'] \in \Delta \quad \Delta; \Gamma \vdash \sigma : \Gamma'}{\Delta; \Gamma \vdash \langle\!\!\langle d \rangle\!\!\rangle_\sigma^u : \tau}
\\
\text{TNEHOLE} \\
\frac{\Delta; \Gamma \vdash d : \tau' \quad u :: \tau[\Gamma'] \in \Delta \quad \Delta; \Gamma \vdash \sigma : \Gamma'}{\Delta; \Gamma \vdash \langle\!\!\langle d \rangle\!\!\rangle_\sigma^u : \tau}
\\
\text{TAMHOLE} \\
\frac{\Delta; \Gamma \vdash d : \tau' \quad u :: \tau[\Gamma'] \in \Delta \quad \Delta; \Gamma \vdash \sigma : \Gamma'}{\Delta; \Gamma \vdash \langle\!\!\langle d \rangle\!\!\rangle_\sigma^{u\blacktriangleright} : \tau}
\\
\text{TACAST} \\
\frac{\Delta; \Gamma \vdash d : \tau_1 \quad \tau_1 \sim \tau_2}{\Delta; \Gamma \vdash d \langle \tau_1 \Rightarrow \tau_2 \rangle : \tau_2}
\\
\text{TAFALIEDCAST} \\
\frac{\Delta; \Gamma \vdash d : \tau_1 \quad \tau_1 \text{ ground} \quad \tau_2 \text{ ground} \quad \tau_1 \neq \tau_2}{\Delta; \Gamma \vdash d \langle \tau_1 \Rightarrow \langle\!\!\langle \rangle\!\!\rangle \not\Rightarrow \tau_2 \rangle : \tau_2}
\end{array}$$

3 Dynamic Semantics

$\boxed{\tau \text{ ground}}$ τ is a ground type

$$\begin{array}{c}
\text{GARR} \\
\frac{}{\langle\!\!\langle \rangle\!\!\rangle \rightarrow \langle\!\!\langle \rangle\!\!\rangle \text{ ground}}
\\
\text{GREC} \\
\frac{}{\mu\langle\!\!\langle \rangle\!\!\rangle.\langle\!\!\langle \rangle\!\!\rangle \text{ ground}}
\\
\text{GSUM} \\
\frac{\{\tau_i = \emptyset \vee \tau_i = \langle\!\!\langle \rangle\!\!\rangle\}_{C_i \in \mathcal{C}}}{+\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \text{ ground}}
\end{array}$$

$\boxed{\tau \blacktriangleright_{\text{ground}} \tau'}$ τ has matched ground type τ'

$$\begin{array}{c}
\text{MGARR} \\
\frac{\tau_1 \rightarrow \tau_2 \neq \langle\!\!\langle \rangle\!\!\rangle \rightarrow \langle\!\!\langle \rangle\!\!\rangle}{\tau_1 \rightarrow \tau_2 \blacktriangleright_{\text{ground}} \langle\!\!\langle \rangle\!\!\rangle \rightarrow \langle\!\!\langle \rangle\!\!\rangle}
\\
\text{MGREC} \\
\frac{\tau \neq \langle\!\!\langle \rangle\!\!\rangle}{\mu\pi.\tau \blacktriangleright_{\text{ground}} \mu\langle\!\!\langle \rangle\!\!\rangle.\langle\!\!\langle \rangle\!\!\rangle}
\\
\text{MGSUM} \\
\frac{+\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \neq +\{C_i(\tau'_i)\}_{C_i \in \mathcal{C}} \quad \{(\tau_i = \emptyset \implies \tau'_i = \emptyset) \wedge (\tau_i \neq \emptyset \implies \tau'_i = \langle\!\!\langle \rangle\!\!\rangle)\}_{C_i \in \mathcal{C}}}{+\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \blacktriangleright_{\text{ground}} +\{C_i(\tau'_i)\}_{C_i \in \mathcal{C}}}
\end{array}$$

$\boxed{d \text{ final}}$ d is final

$$\begin{array}{c}
\text{FBOXEDVAL} \\
\frac{d \text{ boxedval}}{d \text{ final}}
\\
\text{FINDET} \\
\frac{d \text{ indet}}{d \text{ final}}
\end{array}$$

$\boxed{d \text{ val}}$ d is a value

$$\begin{array}{c} \text{VUNIT} \\ \hline \emptyset \text{ val} \end{array} \quad \begin{array}{c} \text{VLAM} \\ \hline \lambda x:\tau. d \text{ val} \end{array} \quad \begin{array}{c} \text{VROLL} \\ d \text{ val} \\ \hline \text{roll}^{\mu\pi.\tau}(d) \text{ val} \end{array} \quad \begin{array}{c} \text{VINJ} \\ d \text{ val} \\ \hline \text{inj}_C^\tau(d) \text{ val} \end{array}$$

$\boxed{d \text{ boxedval}}$ d is a boxed value

$$\begin{array}{c} \text{BVVAL} \\ d \text{ val} \\ \hline d \text{ boxedval} \end{array} \quad \begin{array}{c} \text{BVROLL} \\ d \text{ boxedval} \\ \hline \text{roll}^{\mu\pi.\tau}(d) \text{ boxedval} \end{array} \quad \begin{array}{c} \text{BVINJ} \\ d \text{ boxedval} \\ \hline \text{inj}_C^\tau(d) \text{ boxedval} \end{array} \quad \begin{array}{c} \text{BVARRCAST} \\ \tau_1 \rightarrow \tau_2 \neq \tau_3 \rightarrow \tau_4 \quad d \text{ boxedval} \\ \hline d\langle \tau_1 \rightarrow \tau_2 \Rightarrow \tau_3 \rightarrow \tau_4 \rangle \text{ boxedval} \end{array}$$

$$\begin{array}{c} \text{BVRECCAST} \\ \mu\pi.\tau \neq \mu\pi'.\tau' \quad d \text{ boxedval} \\ \hline d\langle \mu\pi.\tau \Rightarrow \mu\pi'.\tau' \rangle \text{ boxedval} \end{array} \quad \begin{array}{c} \text{BVSUMCAST} \\ \tau = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \\ \tau' = +\{C_i(\tau'_i)\}_{C_i \in \mathcal{C}} \\ \tau \neq \tau' \quad d \text{ boxedval} \\ \hline d\langle \tau \Rightarrow \tau' \rangle \text{ boxedval} \end{array} \quad \begin{array}{c} \text{BVHOLECAST} \\ d \text{ boxedval} \quad \tau \text{ ground} \\ \hline d\langle \tau \Rightarrow \emptyset \rangle \text{ boxedval} \end{array}$$

$\boxed{d \text{ indet}}$ d is indeterminate

$$\begin{array}{c} \text{IEHOLE} \\ \emptyset_\sigma^u \text{ indet} \end{array} \quad \begin{array}{c} \text{INEHOLE} \\ d \text{ final} \\ \hline \emptyset_\sigma^u \text{ indet} \end{array} \quad \begin{array}{c} \text{IAPP} \\ d_1 \neq d'_1 \langle \tau_1 \rightarrow \tau_2 \Rightarrow \tau_3 \rightarrow \tau_4 \rangle \quad d_1 \text{ indet} \quad d_2 \text{ final} \\ \hline d_1(d_2) \text{ indet} \end{array} \quad \begin{array}{c} \text{IROLL} \\ d \text{ indet} \\ \hline \text{roll}^{\mu\pi.\tau}(d) \text{ indet} \end{array}$$

$$\begin{array}{c} \text{IUNROLL} \\ d \text{ indet} \\ \hline \text{unroll}(d) \text{ indet} \end{array} \quad \begin{array}{c} \text{IINJ} \\ d \text{ indet} \\ \hline \text{inj}_C^\tau(d) \text{ indet} \end{array} \quad \begin{array}{c} \text{IINJHOLE} \\ C \neq \mathbf{C} \quad d \text{ final} \\ \hline \text{inj}_C^\tau(d) \text{ indet} \end{array} \quad \begin{array}{c} \text{ICASTGROUNDHOLE} \\ d \text{ indet} \quad \tau \text{ ground} \\ \hline d\langle \tau \Rightarrow \emptyset \rangle \text{ indet} \end{array}$$

$$\begin{array}{c} \text{ICASTHOLEGROUND} \\ d \neq d' \langle \tau' \Rightarrow \emptyset \rangle \quad d \text{ indet} \quad \tau \text{ ground} \\ \hline d\langle \emptyset \Rightarrow \tau \rangle \text{ indet} \end{array} \quad \begin{array}{c} \text{ICASTARR} \\ \tau_1 \rightarrow \tau_2 \neq \tau_3 \rightarrow \tau_4 \quad d \text{ indet} \\ \hline d\langle \tau_1 \rightarrow \tau_2 \Rightarrow \tau_3 \rightarrow \tau_4 \rangle \text{ indet} \end{array} \quad \begin{array}{c} \text{ICASTREC} \\ \mu\pi.\tau \neq \mu\pi'.\tau' \quad d \text{ indet} \\ \hline d\langle \mu\pi.\tau \Rightarrow \mu\pi'.\tau' \rangle \text{ indet} \end{array}$$

$$\begin{array}{c} \text{ICASTSUM} \\ \tau = +\{C_i(\tau_i)\}_{C_i \in \mathcal{C}} \\ \tau' = +\{C_i(\tau'_i)\}_{C_i \in \mathcal{C}} \\ \tau \neq \tau' \quad d \text{ indet} \\ \hline d\langle \tau \Rightarrow \tau' \rangle \text{ indet} \end{array} \quad \begin{array}{c} \text{IFAILEDCAST} \\ d \text{ final} \quad \tau_1 \text{ ground} \quad \tau_2 \text{ ground} \quad \tau_1 \neq \tau_2 \\ \hline d\langle \tau_1 \Rightarrow \emptyset \nRightarrow \tau_2 \rangle \text{ indet} \end{array}$$

$\boxed{d \longrightarrow d'}$ d takes an instruction transition to d'

$$\begin{array}{c} \text{ITAPP} \\ [d_2 \text{ final}] \\ \hline (\lambda x:\tau. d_1)(d_2) \longrightarrow [d_2/x]d_1 \end{array} \quad \begin{array}{c} \text{ITUNROLL} \\ [d \text{ final}] \\ \hline \text{unroll}(\text{roll}^{\mu\pi.\tau}(d)) \longrightarrow d \end{array}$$

$$\begin{array}{c} \text{ITAPPCAST} \\ [d_1 \text{ final}] \quad [d_2 \text{ final}] \quad \tau_1 \rightarrow \tau_2 \neq \tau'_1 \rightarrow \tau'_2 \\ \hline d_1 \langle \tau_1 \rightarrow \tau_2 \Rightarrow \tau'_1 \rightarrow \tau'_2 \rangle (d_2) \longrightarrow (d_1(d_2 \langle \tau'_1 \Rightarrow \tau_1 \rangle)) \langle \tau_2 \Rightarrow \tau'_2 \rangle \end{array}$$

$$\begin{array}{c} \text{ITUNROLLCAST} \\ [d \text{ final}] \quad \mu\pi.\tau \neq \mu\pi'.\tau' \\ \hline \text{unroll}(d\langle \mu\pi.\tau \Rightarrow \mu\pi'.\tau' \rangle) \longrightarrow \text{unroll}(d)\langle [\mu\pi.\tau/\pi]\tau \Rightarrow [\mu\pi'.\tau'/\pi']\tau' \rangle \end{array} \quad \begin{array}{c} \text{ITCASTID} \\ [d \text{ final}] \\ \hline d\langle \tau \Rightarrow \tau \rangle \longrightarrow d \end{array}$$

$$\frac{\text{ITCASTSUCCEED} \quad [d \text{ final}] \quad \tau \text{ ground}}{d\langle \tau \Rightarrow \emptyset \Rightarrow \tau \rangle \longrightarrow d} \quad \frac{\text{ITCASTFAIL} \quad [d \text{ final}] \quad \tau_1 \neq \tau_2 \quad \tau_1 \text{ ground} \quad \tau_2 \text{ ground}}{d\langle \tau_1 \Rightarrow \emptyset \Rightarrow \tau_2 \rangle \longrightarrow d\langle \tau_1 \Rightarrow \emptyset \nRightarrow \tau_2 \rangle}$$

$$\frac{\text{ITGROUND} \quad [d \text{ final}] \quad \tau \blacktriangleright_{\text{ground}} \tau'}{d\langle \tau \Rightarrow \emptyset \rangle \longrightarrow d\langle \tau \Rightarrow \tau' \Rightarrow \emptyset \rangle} \quad \frac{\text{ITEXPAND} \quad [d \text{ final}] \quad \tau \blacktriangleright_{\text{ground}} \tau'}{d\langle \emptyset \Rightarrow \tau \rangle \longrightarrow d\langle \emptyset \Rightarrow \tau' \Rightarrow \tau \rangle}$$

$$\text{EvalCtx } \mathcal{E} ::= \circ \mid \mathcal{E}(d) \mid d(\mathcal{E}) \mid \text{roll}^{\mu\pi.\tau}(\mathcal{E}) \mid \text{unroll}(\mathcal{E}) \mid \text{inj}_C^\tau(\mathcal{E}) \mid \langle \mathcal{E} \rangle_\sigma^u \mid \langle \mathcal{E} \rangle_\sigma^{u\blacktriangleright} \mid \mathcal{E}\langle \tau \Rightarrow \tau \rangle \mid \mathcal{E}\langle \tau \Rightarrow \emptyset \nRightarrow \tau \rangle$$

$$\boxed{d = \mathcal{E}\{d'\}} \quad d \text{ is obtained by placing } d' \text{ at the mark in } \mathcal{E}$$

$$\begin{array}{c} \text{FHOUTER} \quad \frac{}{d = \circ\{d\}} \quad \text{FHAPP1} \quad \frac{d_1 = \mathcal{E}\{d'_1\}}{d_1(d_2) = \mathcal{E}(d_2)\{d'_1\}} \quad \text{FHAPP2} \quad \frac{[d_1 \text{ final}] \quad d_2 = \mathcal{E}\{d'_2\}}{d_1(d_2) = d_1(\mathcal{E})\{d'_2\}} \quad \text{FHROLL} \quad \frac{d = \mathcal{E}\{d'\}}{\text{roll}^{\mu\pi.\tau}(d) = \text{roll}^{\mu\pi.\tau}(\mathcal{E})\{d'\}} \\[10pt] \text{FHUNROLL} \quad \frac{d = \mathcal{E}\{d'\}}{\text{unroll}(d) = \text{unroll}(\mathcal{E})\{d'\}} \quad \text{FHINJ} \quad \frac{d = \mathcal{E}\{d'\}}{\text{inj}_C^\tau(d) = \text{inj}_C^\tau(\mathcal{E})\{d'\}} \quad \text{FNEHOLEINSIDE} \quad \frac{d = \mathcal{E}\{d'\}}{\langle d \rangle_\sigma^u = \langle \mathcal{E} \rangle_\sigma^u\{d'\}} \quad \text{FMHOLEINSIDE} \quad \frac{d = \mathcal{E}\{d'\}}{\langle d \rangle_\sigma^{u\blacktriangleright} = \langle \mathcal{E} \rangle_\sigma^{u\blacktriangleright}\{d'\}} \\[10pt] \text{FHCASINSIDE} \quad \frac{d = \mathcal{E}\{d'\}}{d\langle \tau_1 \Rightarrow \tau_2 \rangle = \mathcal{E}\langle \tau_1 \Rightarrow \tau_2 \rangle\{d'\}} \quad \text{FHFAILEDCAST} \quad \frac{d = \mathcal{E}\{d'\}}{d\langle \tau_1 \Rightarrow \emptyset \nRightarrow \tau_2 \rangle = \mathcal{E}\langle \tau_1 \Rightarrow \emptyset \nRightarrow \tau_2 \rangle\{d'\}} \end{array}$$

$$\boxed{d \mapsto d'} \quad d \text{ steps to } d'$$

$$\frac{\text{STEP} \quad d = \mathcal{E}\{d_0\} \quad d_0 \longrightarrow d'_0 \quad d' = \mathcal{E}\{d'_0\}}{d \mapsto d'}$$