1 構文

Type Variable	$\ni$	X, Y, Z	
Term Variable	$\ni$	x, y, z	
Type	$\ni$	S, T, U	$::= \quad X \mid \mathrm{I} \mid T \oplus T \mid T \otimes T \mid T \multimap T \mid \mu X.T$
Term	$\ni$	s, t, u	$::= \quad x \mid () \mid \mathrm{inl}\ t \mid \mathrm{inl}\ t \mid t \times t \mid t \mapsto t \mid \mathrm{fold}_T\ t \mid \mathrm{trace}_T\ t \mid t \parallel t \mid t \mathbin{;} t \mid \varnothing \mid \mathrm{id} \mid t^{\dagger}$
Expression	$\ni$	e, f, g	$::= \quad t \mid e\ @\ e$
Type Context	$\ni$	Θ	$::= \quad \mid \Theta, X$
Term Context	$\ni$	Γ	$::= \quad \mid \Gamma, t : T$
Type Judgement	$\ni$	$\Theta \vdash T$	
Term Judgement	$\ni$	$\Gamma \vdash t : T$	
Expression Judgement	$\ni$	$\vdash e : T$	
Reduction	$\ni$	$t \Rrightarrow t$	

図 1　Syntax

2 型の構成

$$\frac{}{\Theta, X \vdash X} \quad \frac{}{\Theta \vdash I} \quad \frac{\Theta \vdash T_1 \qquad \Theta \vdash T_2}{\Theta \vdash T_1 \oplus T_2 :} \quad \frac{\Theta \vdash T_1 \qquad \Theta \vdash T_2}{\Theta \vdash T_1 \otimes T_2 :} \quad \frac{\Theta \vdash T_1 \qquad \Theta \vdash T_2}{\Theta \vdash T_1 \multimap T_2} \quad \frac{\Theta, X \vdash T}{\Theta \vdash \mu X.T}$$

図 2　Formation rules

$$\begin{aligned}
[\ ](X) &= X \\
[\sigma, X \to T](X) &= T \\
[\sigma, X' \to S](X) &= X \\
[\sigma](\mathrm{I}) &= \mathrm{I} \\
[\sigma](T_1 \oplus T_2) &= [\sigma](T_1) \oplus [\sigma](T_2) \\
[\sigma](T_1 \otimes T_2) &= [\sigma](T_1) \otimes [\sigma](T_2) \\
[\sigma](T_1 \multimap T_2) &= [\sigma](T_1) \multimap [\sigma](T_2) \\
[\sigma](\mu X.T) &= \mu X.[\sigma](T)
\end{aligned}$$

図 3　Type Substitution

3　型検査

$$\text{Variable}\ \frac{}{x : T \ \vdash\ x : T} \qquad \frac{\Gamma_2, \Gamma_1 \ \vdash\ t : T}{\Gamma_1, \Gamma_2 \ \vdash\ t : T}\ \text{Exchange}$$

$$I_L\ \frac{\Gamma \ \vdash\ t : T}{\Gamma, () : I \ \vdash\ t : T} \qquad \frac{}{\vdash\ () : I}\ I_R$$

$$\oplus_{L_l}\ \frac{\Gamma, t_1 : T_1 \ \vdash\ t : T}{\Gamma, \mathrm{inl}\ t_1 : T_1 \oplus T_2 \ \vdash\ t : T} \qquad \frac{\Gamma \ \vdash\ t_1 : T_1}{\Gamma \ \vdash\ \mathrm{inl}\ t_1 : T_1 \oplus T_2}\ \oplus_{R_l}$$

$$\oplus_{L_r}\ \frac{\Gamma, t_2 : T_2 \ \vdash\ t : T}{\Gamma, \mathrm{inr}\ t_2 : T_1 \oplus T_2 \ \vdash\ t : T} \qquad \frac{\Gamma \ \vdash\ t_2 : T_2}{\Gamma \ \vdash\ \mathrm{inr}\ t_2 : T_1 \oplus T_2}\ \oplus_{R_r}$$

$$\otimes_L\ \frac{\Gamma, t_1 : T_1, t_2 : T_2 \ \vdash\ t : T}{\Gamma, t_1 \times t_2 : T_1 \otimes T_2 \ \vdash\ t : T} \qquad \frac{\Gamma_1 \ \vdash\ t_1 : T_1 \qquad \Gamma_2 \ \vdash\ t_2 : T_2}{\Gamma_1, \Gamma_2 \ \vdash\ t_1 \times t_2 : T_1 \otimes T_2}\ \otimes_R$$

$$\multimap_L\ \frac{\Gamma_1 \ \vdash\ t_1 : T_1 \qquad \Gamma_2, t_2 : T_2 \ \vdash\ t : T}{\Gamma_1, \Gamma_2, t_1 \mapsto t_2 : T_1 \multimap T_2 \ \vdash\ t : T} \qquad \frac{\Gamma, t_1 : T_1 \ \vdash\ t_2 : T_2}{\Gamma \ \vdash\ t_1 \mapsto t_2 : T_1 \multimap T_2}\ \multimap_R$$

$$\mu_L\ \frac{\Gamma, u : [X \to \mu X.U]U \ \vdash\ t : T}{\Gamma, \mathrm{fold}_{\mu X.U}\ u : \mu X.U \ \vdash\ t : T} \qquad \frac{\Gamma \ \vdash\ t : [X \to \mu X.T]T}{\Gamma \ \vdash\ \mathrm{fold}_{\mu X.T}\ t : \mu X.T}\ \mu_R$$

$$\text{Trace}_L\ \frac{\Gamma, u : S \oplus U_1 \multimap S \oplus U_2 \ \vdash\ t : T}{\Gamma, \mathrm{trace}_S\ u : U_1 \multimap U_2 \ \vdash\ t : T} \qquad \frac{\Gamma \ \vdash\ t : U \oplus T_1 \multimap U \oplus T_2}{\Gamma \ \vdash\ \mathrm{trace}_U\ t : T_1 \multimap T_2}\ \text{Trace}_R$$

$$\text{Par}_L\ \frac{\Gamma, t_1 : U \ \vdash\ t : T \qquad \Gamma, t_2 : U \ \vdash\ t : T}{\Gamma, t_1 \parallel t_2 : U \ \vdash\ t : T} \qquad \frac{\Gamma \ \vdash\ t_1 : T \qquad \Gamma \ \vdash\ t_2 : T}{\Gamma \ \vdash\ t_1 \parallel t_2 : T}\ \text{Par}_R$$

$$\text{Seq}_L\ \frac{\Gamma, t_1 : T_1 \multimap T_2, t_2 : T_2 \multimap T_3 \ \vdash\ t : T}{\Gamma, t_1 \fatsemi t_2 : T_1 \multimap T_3 \ \vdash\ t : T} \qquad \frac{\Gamma_1 \ \vdash\ t_1 : T_1 \multimap T_2 \qquad \Gamma_2 \ \vdash\ t_2 : T_2 \multimap T_3}{\Gamma_1, \Gamma_2 \ \vdash\ t_1 \fatsemi t_2 : T_1 \multimap T_3}\ \text{Seq}_R$$

$$\dagger_L\ \frac{\Gamma, u : T_2 \multimap T_1 \ \vdash\ t : T}{\Gamma, u^{\dagger} : T_1 \multimap T_2 \ \vdash\ t : T} \qquad \frac{\Gamma \ \vdash\ t : T_2 \multimap T_1}{\Gamma \ \vdash\ t^{\dagger} : T_1 \multimap T_2}\ \dagger_R$$

$$\text{id}_L\ \frac{\Gamma \ \vdash\ t : T}{\Gamma, \mathrm{id} : U \multimap U \ \vdash\ t : T} \qquad \frac{}{\vdash\ \mathrm{id} : T \multimap T}\ \text{id}_R$$

$$\varnothing_{\mathrm{L}}\ \frac{\Gamma \ \vdash\ t : T}{\Gamma, \varnothing : U \ \vdash\ t : T} \qquad \frac{}{\Gamma \ \vdash\ \varnothing : T}\ \varnothing_{\mathrm{R}}$$

$$\frac{\vdash\ f : T_1 \multimap T_2 \qquad \vdash\ e : T_1}{\vdash\ f\ @\ e : T_2}\ \text{App}$$

図 4　Typing rules

$$\vdash\ t : T \triangleright$$

$$\text{Variable}\ \frac{\Gamma(x) = T}{\Gamma \vdash x : T \triangleright \Gamma \setminus x}$$

$$I_L\ \frac{\Gamma \vdash t : T \triangleright \Gamma'}{\Gamma, () : I \vdash t : T \triangleright \Gamma'} \qquad \frac{}{\Gamma \vdash () : I \triangleright \Gamma}\ I_R$$

$$\oplus_{L_l}\ \frac{\Gamma, t_1 : T_1 \vdash t : T \triangleright \Gamma'}{\Gamma, \mathrm{inl}\ t_1 : T_1 \oplus T_2 \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t_1 : T_1 \triangleright \Gamma'}{\Gamma \vdash \mathrm{inl}\ t_1 : T_1 \oplus T_2 \triangleright \Gamma'}\ \oplus_{R_l}$$

$$\oplus_{L_r}\ \frac{\Gamma, t_2 : T_2 \vdash t : T \triangleright \Gamma'}{\Gamma, \mathrm{inr}\ t_2 : T_1 \oplus T_2 \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t_2 : T_2 \triangleright \Gamma'}{\Gamma \vdash \mathrm{inr}\ t_2 : T_1 \oplus T_2 \triangleright \Gamma'}\ \oplus_{R_r}$$

$$\otimes_L\ \frac{\Gamma, t_1 : T_1, t_2 : T_2 \vdash t : T \triangleright \Gamma'}{\Gamma, t_1 \times t_2 : T_1 \otimes T_2 \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t_1 : T_1 \triangleright \Gamma' \qquad \Gamma' \vdash t_2 : T_2 \triangleright \Gamma''}{\Gamma \vdash t_1 \times t_2 : T_1 \otimes T_2 \triangleright \Gamma''}\ \otimes_R$$

$$\multimap_L\ \frac{\Gamma \vdash t_1 : T_1 \triangleright \Gamma' \qquad \Gamma', t_2 : T_2 \vdash t : T \triangleright \Gamma''}{\Gamma, t_1 \mapsto t_2 : T_1 \multimap T_2 \vdash t : T \triangleright \Gamma''} \qquad \frac{\Gamma, t_1 : T_1 \vdash t_2 : T_2 \triangleright \Gamma'}{\Gamma \vdash t_1 \mapsto t_2 : T_1 \multimap T_2 \triangleright \Gamma'}\ \multimap_R$$

$$\mu_L\ \frac{\Gamma, u : [X \to \mu X.U]U \vdash t : T \triangleright \Gamma'}{\Gamma, \mathrm{fold}_{\mu X.U}\ u : \mu X.U \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t : [X \to \mu X.T]T \triangleright \Gamma'}{\Gamma \vdash \mathrm{fold}_{\mu X.T}\ t : \mu X.T \triangleright \Gamma'}\ \mu_R$$

$$\mathrm{Trace}_L\ \frac{\Gamma, u : S \oplus U_1 \multimap S \oplus U_2 \vdash t : T \triangleright \Gamma'}{\Gamma, \mathrm{trace}_S\ u : U_1 \multimap U_2 \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t : U \oplus T_1 \multimap U \oplus T_2 \triangleright \Gamma'}{\Gamma \vdash \mathrm{trace}_U\ t : T_1 \multimap T_2 \triangleright \Gamma'}\ \mathrm{Trace}_R$$

$$\mathrm{Par}_L\ \frac{\Gamma, t_1 : U \vdash t : T \triangleright \Gamma' \qquad \Gamma, t_2 : U \vdash t : T \triangleright \Gamma'}{\Gamma, t_1 \parallel t_2 : U \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t_1 : T \triangleright \Gamma' \qquad \Gamma \vdash t_2 : T \triangleright \Gamma'}{\Gamma \vdash t_1 \parallel t_2 : T \triangleright \Gamma'}\ \mathrm{Par}_R$$

$$\mathrm{Seq}_L\ \frac{\Gamma, t_1 : T_1 \multimap T_2, t_2 : T_2 \multimap T_3 \vdash t : T \triangleright \Gamma'}{\Gamma, t_1 \fatsemi t_2 : T_1 \multimap T_3 \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t_1 : T_1 \multimap T_2 \triangleright \Gamma' \qquad \Gamma' \vdash t_2 : T_2 \multimap T_3 \triangleright \Gamma''}{\Gamma \vdash t_1 \fatsemi t_2 : T_1 \multimap T_3 \triangleright \Gamma''}\ \mathrm{Seq}_R$$

$$\dagger_L\ \frac{\Gamma, u : T_2 \multimap T_1 \vdash t : T \triangleright \Gamma'}{\Gamma, u^\dagger : T_1 \multimap T_2 \vdash t : T \triangleright \Gamma'} \qquad \frac{\Gamma \vdash t : T_2 \multimap T_1 \triangleright \Gamma'}{\Gamma \vdash t^\dagger : T_1 \multimap T_2 \triangleright \Gamma'}\ \dagger_R$$

$$\mathrm{id}_L\ \frac{\Gamma \vdash t : T \triangleright \Gamma'}{\Gamma, \mathrm{id} : U \multimap U \vdash t : T \triangleright \Gamma'} \qquad \frac{}{\Gamma \vdash \mathrm{id} : T \multimap T \triangleright \Gamma}\ \mathrm{id}_R$$

$$\varnothing_{\mathrm{L}}\ \frac{\Gamma \vdash t : T \triangleright \Gamma'}{\Gamma, \varnothing : U \vdash t : T \triangleright \Gamma'} \qquad \frac{}{\Gamma \vdash \varnothing : T \triangleright \Gamma}\ \varnothing_{\mathrm{R}}$$

$$\frac{\vdash f : T_1 \multimap T_2 \triangleright \qquad \vdash e : T_1 \triangleright}{\vdash f\ @\ e : T_2 \triangleright}\ \mathrm{App}$$

図 5　Syntax–Directed Typing rules

4 型推論

$$
\begin{aligned}
\mathit{unify} &:= \text{Set of Constraint} \to \text{Substitution} \\
\mathit{unify}(\{\}) &= [\,] \\
\mathit{unify}(\{X = T\} \cup C) &= \mathit{unify}([X \to T]C) \circ [X \to T] \\
\mathit{unify}(\{T = X\} \cup C) &= \mathit{unify}([X \to T]C) \circ [X \to T] \\
\mathit{unify}(\{S_1 \oplus S_2 = T_1 \oplus T_2\} \cup C) &= \mathit{unify}(C \cup \{S_1 = T_1, S_2 = T_2\}) \\
\mathit{unify}(\{S_1 \otimes S_2 = T_1 \otimes T_2\} \cup C) &= \mathit{unify}(C \cup \{S_1 = T_1, S_2 = T_2\}) \\
\mathit{unify}(\{S_1 \multimap S_2 = T_1 \multimap T_2\} \cup C) &= \mathit{unify}(C \cup \{S_1 = T_1, S_2 = T_2\}) \\
\mathit{unify}(\{\mu X.S = \mu Y.T\} \cup C) &= \mathit{unify}(C \cup \{X = Y, S = T\})
\end{aligned}
$$

図 6　単一化

$$\vdash t : X \triangleright \ \mid C$$

$$\text{Variable}\ \frac{\Gamma(x) = V_2}{\Gamma \vdash x : V_1 \triangleright \Gamma \setminus (x : T) \mid \{V_1 = V_2\}}$$

$$I_L\ \frac{\Gamma \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, () : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = I\}} \qquad \frac{}{\Gamma \vdash () : V \triangleright \Gamma \mid \{V = I\}}\ I_R$$

$$\oplus_{L_l}\ \frac{\Gamma, t_1 : X_1 \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, \text{inl}\ t_1 : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X_1 \oplus X_2\}} \qquad \frac{\Gamma \vdash t_1 : X_1 \triangleright \Gamma' \mid C}{\Gamma \vdash \text{inl}\ t_1 : V \triangleright \Gamma' \mid C \cup \{V = X_1 \oplus X_2\}}\ \oplus_{R_l}$$

$$\oplus_{L_r}\ \frac{\Gamma, t_2 : X_2 \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, \text{inr}\ t_2 : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X_1 \oplus X_2\}} \qquad \frac{\Gamma \vdash t_2 : X_2 \triangleright \Gamma' \mid C}{\Gamma \vdash \text{inr}\ t_2 : V \triangleright \Gamma' \mid C \cup \{X_1 \oplus X_2\}}\ \oplus_{R_r}$$

$$\otimes_L\ \frac{\Gamma, t_1 : X_1, t_2 : X_2 \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, t_1 \times t_2 : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X_1 \otimes X_2\}} \qquad \frac{\Gamma \vdash t_1 : X_1 \triangleright \Gamma' \mid C_1 \qquad \Gamma' \vdash t_2 : X_2 \triangleright \Gamma'' \mid C_2}{\Gamma \vdash t_1 \times t_2 : V \triangleright \Gamma'' \mid C_1 \cup C_2 \cup \{V = X_1 \otimes X_2\}}\ \otimes_R$$

$$\multimap_L\ \frac{\Gamma \vdash t_1 : X_1 \triangleright \Gamma' \mid C_1 \qquad \Gamma', t_2 : X_2 \vdash t : T \triangleright \Gamma'' \mid C_2}{\Gamma, t_1 \mapsto t_2 : V \vdash t : T \triangleright \Gamma'' \mid C_1 \cup C_2 \cup \{V = X_1 \multimap X_2\}} \qquad \frac{\Gamma, t_1 : X_1 \vdash t_2 : X_2 \triangleright \Gamma' \mid C}{\Gamma \vdash t_1 \mapsto t_2 : V \triangleright \Gamma' \mid C \cup \{V = X_1 \multimap X_2\}}\ \multimap_R$$

$$\mu_L\ \frac{\Gamma, u : [Y \to \mu Y.U]U \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, \text{fold}_{\mu Y.U}\ u : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = \mu Y.U\}} \qquad \frac{\Gamma \vdash t : [X \to \mu X.T]T \triangleright \Gamma' \mid C}{\Gamma \vdash \text{fold}_{\mu X.T}\ t : V \triangleright \Gamma' \mid C \cup \{V = \mu X.T\}}\ \mu_R$$

$$\text{Trace}_L\ \frac{\Gamma, u : U \oplus X_1 \multimap U \oplus X_2 \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, \text{trace}_U\ u : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X_1 \multimap X_2\}} \qquad \frac{\Gamma \vdash t : T \oplus X_1 \multimap T \oplus X_2 \triangleright \Gamma' \mid C}{\Gamma \vdash \text{trace}_T\ t : V \triangleright \Gamma' \mid C \cup \{V = X_1 \multimap X_2\}}\ \text{Trace}_R$$

$$\text{Par}_L\ \frac{\Gamma, t_1 : X \vdash t : T \triangleright \Gamma' \mid C_1 \qquad \Gamma, t_2 : X \vdash t : T \triangleright \Gamma' \mid C_2}{\Gamma, t_1 \parallel t_2 : V \vdash t : T \triangleright \Gamma' \mid C_1 \cup C_2 \cup \{V = X\}} \qquad \frac{\Gamma \vdash t_1 : X \triangleright \Gamma' \mid C_1 \qquad \Gamma \vdash t_2 : X \triangleright \Gamma' \mid C_2}{\Gamma \vdash t_1 \parallel t_2 : V \triangleright \Gamma' \mid C_1 \cup C_2 \cup \{V = X\}}\ \text{Par}_R$$

$$\text{Seq}_L\ \frac{\Gamma, t_1 : X_1 \multimap X_2, t_2 : X_2 \multimap X_3 \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, t_1 \mathbin{⨟} t_2 : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X_1 \multimap X_3\}} \qquad \frac{\Gamma \vdash t_1 : X_1 \multimap X_2 \triangleright \Gamma' \mid C_1 \qquad \Gamma' \vdash t_2 : X_2' \multimap X_3 \triangleright \Gamma'' \mid C_2}{\Gamma \vdash t_1 \mathbin{⨟} t_2 : V \triangleright \Gamma'' \mid C_1 \cup C_2 \cup \{V = X_1 \multimap X_3\}}\ \text{Seq}_R$$

$$\dagger_L\ \frac{\Gamma, u : X_2 \multimap X_1 \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, u^\dagger : \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X_1 \multimap X_2\}} \qquad \frac{\Gamma \vdash t : X_2 \multimap X_1 \triangleright \Gamma' \mid C}{\Gamma \vdash t^\dagger : V \triangleright \Gamma' \mid C \cup \{V = X_1 \multimap X_2\}}\ \dagger_R$$

$$\text{id}_L\ \frac{\Gamma \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, \text{id} : V \vdash t : T \triangleright \Gamma' \mid C \cup \{V = X \multimap X\}} \qquad \frac{}{\Gamma \vdash \text{id} : V \triangleright \Gamma \mid \{V = X \multimap X\}}\ \text{id}_R$$

$$\varnothing_{\mathrm{L}}\ \frac{\Gamma \vdash t : T \triangleright \Gamma' \mid C}{\Gamma, \varnothing : V \vdash t : T \triangleright \Gamma' \mid C\{V = X\}} \qquad \frac{}{\Gamma \vdash \varnothing : V \triangleright \Gamma \mid \{V = X\}}\ \varnothing_{\mathrm{R}}$$

$$\frac{\vdash f : X_1 \multimap X_2 \triangleright \ \mid C_1 \qquad \vdash e : X_1 \triangleright \ \mid C_2}{\vdash f\ @\ e : V \triangleright \ \mid C_1 \cup C_2 \cup \{V = X_2\}}\ \text{App}$$

図 7　Type Inference rules

5　表示的意味論

$$
\begin{aligned}
[\![\Theta \vdash T]\!] &: \mathcal{V}^{|\Theta|} \to \mathcal{V} \\
[\![\Theta \vdash X_i]\!] &:= \Pi_i \\
[\![\Theta \vdash \mathrm{I}]\!] &:= K_I \\
[\![\Theta \vdash T_1 \oplus T_2]\!] &:= \oplus \circ \langle [\![\Theta \vdash T_1]\!], [\![\Theta \vdash T_2]\!] \rangle \\
[\![\Theta \vdash T_1 \otimes T_2]\!] &:= \otimes \circ \langle [\![\Theta \vdash T_1]\!], [\![\Theta \vdash T_2]\!] \rangle \\
[\![\Theta \vdash T_1 \multimap T_2]\!] &:= \otimes \circ \langle [\![\Theta \vdash T_1]\!]^{\star}, [\![\Theta \vdash T_2]\!] \rangle \\
[\![\Theta \vdash \mu X.T]\!] &:= [\![\Theta, X \vdash T]\!]^{\sharp} \\
[\![\Theta \vdash T[X \to U]]\!] &:= [\![\Theta \vdash T]\!] \circ \langle Id, [\![\Theta \vdash U]\!] \rangle \\
[\![T]\!] &:= [\![\ \vdash T]\!](*) \in Obj(\mathcal{V})
\end{aligned}
$$

図 8　Type Interpretation

$$
\begin{aligned}
[\![\Gamma]\!] &\in Obj(\mathcal{V}) \\
[\![]\!] &:= I \\
[\![\Gamma, () : \mathrm{I}]\!] &:= [\![\Gamma]\!] \\
[\![\Gamma, \mathrm{inl}\ t_1 : T_1 \oplus T_2]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \oplus [\![T_2]\!]) \\
[\![\Gamma, \mathrm{inr}\ t_2 : T_1 \oplus T_2]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \oplus [\![T_2]\!]) \\
[\![\Gamma, t_1 \times t_2 : T_1 \otimes T_2]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \otimes [\![T_2]\!]) \\
[\![\Gamma, t_1 \mapsto t_2 : T_1 \multimap T_2]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \multimap [\![T_2]\!]) \\
[\![\Gamma, \mathrm{fold}_{\mu X.T}\ u : \mu X.T]\!] &:= [\![\Gamma]\!] \otimes [\![\mu X.T]\!] \\
[\![\Gamma, \mathrm{trace}_T\ t : T_1 \multimap T_2]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \multimap [\![T_2]\!]) \\
[\![\Gamma, t_1 \parallel t_2 : T]\!] &:= [\![\Gamma]\!] \otimes [\![T]\!] \\
[\![\Gamma, t_1 \fatsemi t_2 : T_1 \multimap T_3]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \multimap [\![T_3]\!]) \\
[\![\Gamma, t^{\dagger} : T_1 \multimap T_2]\!] &:= [\![\Gamma]\!] \otimes ([\![T_1]\!] \multimap [\![T_2]\!]) \\
[\![\Gamma, \mathrm{id} : T \multimap T]\!] &:= [\![\Gamma]\!] \\
[\![\Gamma, \varnothing : T]\!] &:= [\![\Gamma]\!] \\
[\![f\ @\ e : T]\!] &:= [\![\Gamma]\!] \otimes [\![T]\!]
\end{aligned}
$$

図 9　Context Interpretation

$$
\begin{aligned}
\llbracket \Gamma \vdash t : T \rrbracket &: \llbracket \Gamma \rrbracket \to \llbracket T \rrbracket \\
\llbracket x : T \ \vdash \ x : T \rrbracket &:= \llbracket T \rrbracket \xrightarrow{id_{\llbracket T \rrbracket}} \llbracket T \rrbracket \\
\llbracket \Gamma_1, \Gamma_2 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma_1 \rrbracket \otimes \llbracket \Gamma_2 \rrbracket \xrightarrow{\sigma_{\llbracket \Gamma_1 \rrbracket, \llbracket \Gamma_2 \rrbracket}} \llbracket \Gamma_2 \rrbracket \otimes \llbracket \Gamma_1 \rrbracket \xrightarrow{\llbracket \Gamma_2, \Gamma_1 \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma, () : \mathrm{I} \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes I \xrightarrow{\rho_{\llbracket \Gamma \rrbracket}} \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \ \vdash \ () : \mathrm{I} \rrbracket &:= \llbracket \rrbracket \xrightarrow{id_I} \llbracket \mathrm{I} \rrbracket \\
\llbracket \Gamma, \mathrm{inl}\ t_1 : T_1 \oplus T_2 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes (\llbracket T_1 \rrbracket \oplus \llbracket T_2 \rrbracket) \xrightarrow{id_{\llbracket \Gamma \rrbracket} \otimes \pi_1} \llbracket \Gamma \rrbracket \otimes \llbracket T_1 \rrbracket \xrightarrow{\llbracket \Gamma, t_1 : T_1 \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ \mathrm{inl}\ t_1 : T_1 \oplus T_2 \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t_1 : T_1 \rrbracket} \llbracket T_1 \rrbracket \xrightarrow{\iota_1} \llbracket T_1 \rrbracket \oplus \llbracket T_2 \rrbracket \\
\llbracket \Gamma, \mathrm{inr}\ t_2 : T_1 \oplus T_2 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes (\llbracket T_1 \rrbracket \oplus \llbracket T_2 \rrbracket) \xrightarrow{id_{\llbracket \Gamma \rrbracket} \otimes \pi_2} \llbracket \Gamma \rrbracket \otimes \llbracket T_2 \rrbracket \xrightarrow{\llbracket \Gamma, t_2 : T_2 \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ \mathrm{inr}\ t_1 : T_1 \oplus T_2 \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t_2 : T_2 \rrbracket} \llbracket T_2 \rrbracket \xrightarrow{\iota_2} \llbracket T_1 \rrbracket \oplus \llbracket T_2 \rrbracket \\
\llbracket \Gamma, t_1 \times t_2 : T_1 \otimes T_2 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes (\llbracket T_1 \rrbracket \otimes \llbracket T_2 \rrbracket) \xrightarrow{\llbracket \Gamma, t_1 : T_1, t_2 : T_2 \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma_1, \Gamma_2 \ \vdash \ t_1 \times t_2 : T_1 \otimes T_2 \rrbracket &:= \llbracket \Gamma_1 \rrbracket \otimes \llbracket \Gamma_2 \rrbracket \xrightarrow{\llbracket \Gamma_1 \vdash t_1 : T_1 \rrbracket \otimes \llbracket \Gamma_1 \vdash t_2 : T_2 \rrbracket} \llbracket T_1 \rrbracket \otimes \llbracket T_2 \rrbracket \\
\llbracket \Gamma_1, \Gamma_2, t_1 \mapsto t_2 : T_1 \multimap T_2 \ \vdash \ t : T \rrbracket &:= \Big(\llbracket \Gamma_1 \rrbracket \otimes \llbracket \Gamma_2 \rrbracket \otimes (\llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket) \cong \llbracket \Gamma_1 \rrbracket \otimes (\llbracket \Gamma_2 \rrbracket \otimes \llbracket T_2 \rrbracket) \otimes \llbracket T_1 \rrbracket^{\star} \to \llbracket T \rrbracket \Big) \\
&\cong \Big(\llbracket \Gamma_1 \rrbracket \otimes (\llbracket \Gamma_2 \rrbracket \otimes \llbracket T_2 \rrbracket) \xrightarrow{\llbracket \Gamma_1 \vdash t_1 : T_1 \rrbracket \otimes \llbracket \Gamma_2, t_2 : T_2 \vdash t : T \rrbracket} \llbracket T_1 \rrbracket \otimes \llbracket T \rrbracket \Big) \\
\llbracket \Gamma \ \vdash \ t_1 \mapsto t_2 : T_1 \multimap T_2 \rrbracket &:= \llbracket \Gamma \rrbracket \to \llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket \cong \Big(\llbracket \Gamma \rrbracket \otimes \llbracket T_1 \rrbracket \xrightarrow{\llbracket \Gamma, t_1 : T_1 \vdash t_2 : T_2 \rrbracket} \llbracket T_2 \rrbracket \Big) \\
\llbracket \Gamma, \mathrm{fold}_{\mu X.U}\ u : \mu X.U \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes \llbracket \mu X.U \rrbracket \xrightarrow{id_{\llbracket \Gamma \rrbracket} \otimes unfold_{\mu X.U}} \llbracket \Gamma \rrbracket \otimes \llbracket [X \to \mu X.U](U) \rrbracket \\
&\xrightarrow{\llbracket \Gamma, u : [X \to \mu X.U](U) \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ \mathrm{fold}_{\mu X.T}\ t : \mu X.T \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t : [X \to \mu X.T](T) \rrbracket} \llbracket [X \to \mu X.T](T) \rrbracket \xrightarrow{fold_{\mu X.T}} \llbracket \mu X.T \rrbracket \\
\llbracket \Gamma, \mathrm{trace}_U\ u : T_1 \multimap T_2 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes (\llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket) \xrightarrow{id_{\llbracket \Gamma \rrbracket} \otimes Tr^{\llbracket U \rrbracket}_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket}(\llbracket \Gamma, t : (U \oplus T_1) \multimap (U \oplus T_2) \vdash t : T \rrbracket)} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ \mathrm{trace}_U\ t : T_1 \multimap T_2 \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{Tr^{\llbracket U \rrbracket}_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket}(\llbracket \Gamma \vdash t : U \oplus T_1 \multimap U \oplus T_2 \rrbracket)} \llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket \\
\llbracket \Gamma, t_1 \parallel t_2 : U \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes \llbracket U \rrbracket \xrightarrow{id_{\llbracket \Gamma \rrbracket} \otimes (\llbracket \Gamma, t_1 : U \vdash t : T \rrbracket + \llbracket \Gamma, t_2 : U \vdash t : T \rrbracket)} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ t_1 \parallel t_2 : T \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t_1 : T \rrbracket + \llbracket \Gamma \vdash t_2 : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma, t_1 \fatsemi t_2 : T_1 \multimap T_3 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes (\llbracket T_1 \rrbracket \multimap \llbracket T_3 \rrbracket) \\
&\xrightarrow{id_{\Gamma} \otimes decomp_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket, \llbracket T_3 \rrbracket}} \llbracket \Gamma \rrbracket \otimes ((\llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket) \otimes (\llbracket T_2 \rrbracket \multimap \llbracket T_3 \rrbracket)) \\
&\xrightarrow{\llbracket \Gamma, t_1 : T_1 \multimap T_2, t_2 : T_2 \multimap T_3 \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma_1, \Gamma_2 \ \vdash \ t_1 \fatsemi t_2 : T_1 \multimap T_3 \rrbracket &:= \llbracket \Gamma_1 \rrbracket \otimes \llbracket \Gamma_2 \rrbracket \xrightarrow{\llbracket \Gamma_1 \vdash t_1 : T_1 \multimap T_2 \rrbracket \otimes \llbracket \Gamma_2 \vdash t_2 : T_2 \multimap T_3 \rrbracket} (\llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket) \otimes (\llbracket T_2 \rrbracket \multimap \llbracket T_3 \rrbracket) \\
&\xrightarrow{comp_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket, \llbracket T_3 \rrbracket}} \llbracket T_1 \rrbracket \multimap \llbracket T_3 \rrbracket \\
\llbracket \Gamma, u^{\dagger} : T_1 \multimap T_2 \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \otimes (\llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket) \xrightarrow{id_{\llbracket \Gamma \rrbracket} \otimes dagger_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket}} \llbracket \Gamma \rrbracket \otimes (\llbracket T_2 \rrbracket \multimap \llbracket T_1 \rrbracket) \xrightarrow{\llbracket \Gamma, u : T_2 \multimap T_1 \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ t^{\dagger} : T_1 \multimap T_2 \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t : T_2 \multimap T_1 \rrbracket} \llbracket T_2 \rrbracket \multimap \llbracket T_1 \rrbracket \xrightarrow{dagger_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket}} \llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket \\
\llbracket \Gamma, \mathrm{id} : U \multimap U \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \ \vdash \ \mathrm{id} : T \multimap T \rrbracket &:= \llbracket \rrbracket \to \llbracket T \rrbracket \multimap \llbracket T \rrbracket \cong \Big(\llbracket T \rrbracket \xrightarrow{id_{\llbracket T \rrbracket}} \llbracket T \rrbracket \Big) \\
\llbracket \Gamma, \varnothing : U \ \vdash \ t : T \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{\llbracket \Gamma \vdash t : T \rrbracket} \llbracket T \rrbracket \\
\llbracket \Gamma \ \vdash \ \varnothing : T \rrbracket &:= \llbracket \Gamma \rrbracket \xrightarrow{0_{\llbracket \Gamma \rrbracket, \llbracket T \rrbracket}} \llbracket T \rrbracket \\
\llbracket \ \vdash \ t \ @ \ t_1 : T_2 \rrbracket &:= \llbracket \rrbracket \xrightarrow{\llbracket \vdash t : T_1 \multimap T_2 \rrbracket \otimes \llbracket \vdash t_1 : T_1 \rrbracket} (\llbracket T_1 \rrbracket \multimap \llbracket T_2 \rrbracket) \otimes \llbracket T_1 \rrbracket \xrightarrow{eval_{\llbracket T_1 \rrbracket, \llbracket T_2 \rrbracket}} \llbracket T_2 \rrbracket
\end{aligned}
$$

図 10　Term Interpretation

6 操作的意味論

$$\sigma_1 \cup^{\times}_{\perp} \sigma_2 := \begin{cases} \perp & \text{if } \sigma_1 = \perp \vee \sigma_2 = \perp \\ \sigma_1 \cup \sigma_2 & \text{otherwise} \end{cases}$$

$$\sigma_1 \cup^{+}_{\perp} \sigma_2 := \begin{cases} \perp & \text{if } \sigma_1 = \perp \wedge \sigma_2 = \perp \\ \sigma_1 & \text{if } \sigma_2 = \perp \\ \sigma_2 & \text{if } \sigma_1 = \perp \\ \sigma_1 \cup \sigma_2 & \text{otherwise} \end{cases}$$

$$\sigma_1 \ltimes_{\perp} \sigma_2 := \begin{cases} \sigma_1 & \text{if } \sigma_1 \neq \perp \\ \sigma_2 & \text{if } \sigma_1 = \perp \wedge \sigma_2 \neq \perp \\ \perp & \text{otherwise} \end{cases}$$

図 11 Operations on Environment σ

$$\begin{aligned}
x \triangleright t &:= [x \to t] \\
() \triangleright () &:= [\,] \\
\mathrm{inl}\ t \triangleright \mathrm{inl}\ u &:= t \triangleright u \\
\mathrm{inl}\ t \triangleright \mathrm{inr}\ u &:= \perp \\
\mathrm{inr}\ t \triangleright \mathrm{inr}\ u &:= t \triangleright u \\
\mathrm{inr}\ t \triangleright \mathrm{inl}\ u &:= \perp \\
t_1 \times t_2 \triangleright u_1 \times u_2 &:= (t_1 \triangleright u_1) \cup^{\times}_{\perp} (t_2 \triangleright u_2) \\
t_1 \mapsto t_2 \triangleright u_1 \mapsto u_2 &:= (t_1 \triangleright u_1) \cup^{\times}_{\perp} (t_2 \triangleright u_2) \\
\mathrm{fold}_T\ t \triangleright \mathrm{fold}_T\ u &:= t \triangleright u \\
\mathrm{trace}_T\ t \triangleright \mathrm{trace}_T\ u &:= t \triangleright u \\
t \triangleright u_1 \parallel u_2 &:= (t \triangleright u_1) \cup^{+}_{\perp} (t \triangleright u_2) \\
t_1 \parallel t_2 \triangleright u &:= (t_1 \triangleright u) \ltimes_{\perp} (t_2 \triangleright u) \\
t_1 \mathbin{⨟} t_2 \triangleright u_1 \mathbin{⨟} u_2 &:= (t_1 \triangleright u_1) \cup^{\times}_{\perp} (t_2 \triangleright u_2) \\
t \mathbin{⨟} x \triangleright u &:= x \triangleright t^{\dagger} \mathbin{⨟} u \\
x \mathbin{⨟} t \triangleright u &:= x \triangleright u \mathbin{⨟} t^{\dagger} \\
t^{\dagger} \triangleright u &:= t \triangleright u^{\dagger} \\
\mathrm{id} \triangleright \mathrm{id} &:= [\,] \\
\varnothing \triangleright u &:= \perp \\
t \triangleright \varnothing &:= \perp
\end{aligned}$$

図 12 Constructing Environment

$$\begin{aligned}
[\,](x) &:= \varnothing \\
[\sigma, x \to t](x) &:= t \\
[\sigma, x' \to t](x) &:= \varnothing \\
[\sigma](()) &:= () \\
[\sigma](\mathrm{inl}\ t) &:= \mathrm{inl}\ [\sigma](t) \\
[\sigma](\mathrm{inr}\ t) &:= \mathrm{inr}\ [\sigma](t) \\
[\sigma_1, \sigma_2](t_1 \times t_2) &:= [\sigma](t_1) \times [\sigma](t_2) \\
[\sigma_1, \sigma_2](t_1 \mapsto t_2) &:= [\sigma](t_1) \mapsto [\sigma](t_2) \\
[\sigma](\mathrm{fold}_T\ t) &:= \mathrm{fold}_T\ [\sigma](t) \\
[\sigma](\mathrm{trace}_T\ t) &:= \mathrm{trace}_T\ [\sigma](t) \\
[\sigma_1, \sigma_2](t_1 \parallel t_2) &:= [\sigma](t_1) \parallel [\sigma](t_2) \\
[\sigma](t_1 \mathbin{⨟} t_2) &:= [\sigma](t_1) \mathbin{⨟} [\sigma](t_2) \\
[\sigma](t^{\dagger}) &:= [\sigma](t)^{\dagger} \\
[\sigma](\mathrm{id}) &:= \mathrm{id} \\
[\,](\varnothing) &:= \varnothing \\
[\perp](t) &:= \varnothing
\end{aligned}$$

図 13 Consumption of Environment

$$
\begin{aligned}
\varnothing \parallel t &\Rrightarrow t \\
(t_1 \parallel t_2) \parallel t_3 &\Rrightarrow t_1 \parallel (t_2 \parallel t_3) \\
t_1 \parallel t_2 &\Rrightarrow t_2 \parallel t_1 \\
t \parallel t &\Rrightarrow t \\
\mathrm{id} \mathbin{;} t &\Rrightarrow t \\
t \mathbin{;} \mathrm{id} &\Rrightarrow t \\
(t_1 \mathbin{;} t_2) \mathbin{;} t_3 &\Rrightarrow t_1 \mathbin{;} (t_2 \mathbin{;} t_3) \\
\varnothing \mathbin{;} t &\Rrightarrow \varnothing \\
t \mathbin{;} \varnothing &\Rrightarrow \varnothing \\
(t_1 \parallel t_2) \mathbin{;} t_3 &\Rrightarrow (t_1 \mathbin{;} t_3) \parallel (t_2 \mathbin{;} t_3) \\
t_1 \mathbin{;} (t_2 \parallel t_3) &\Rrightarrow (t_1 \mathbin{;} t_2) \parallel (t_1 \mathbin{;} t_3)
\end{aligned}
$$

$$
\begin{aligned}
\varnothing^\dagger &\Rrightarrow \varnothing \\
\mathrm{id}^\dagger &\Rrightarrow \mathrm{id} \\
()^\dagger &\Rrightarrow () \\
(t_1 \parallel t_2)^\dagger &\Rrightarrow t_1^\dagger \parallel t_2^\dagger \\
(t_1 \mathbin{;} t_2)^\dagger &\Rrightarrow t_1^\dagger \mathbin{;} t_2^\dagger \\
(\mathrm{inl}\ t)^\dagger &\Rrightarrow \mathrm{inl}\ t^\dagger \\
(\mathrm{inr}\ t)^\dagger &\Rrightarrow \mathrm{inr}\ t^\dagger \\
(t_1 \times t_2)^\dagger &\Rrightarrow t_1^\dagger \times t_2^\dagger \\
(t_1 \mapsto t_2)^\dagger &\Rrightarrow t_1^\dagger \mapsto t_2^\dagger \\
(\mathrm{fold}_T\ t)^\dagger &\Rrightarrow \mathrm{fold}_T\ t^\dagger \\
(\mathrm{trace}_T\ t)^\dagger &\Rrightarrow \mathrm{trace}_T\ t^\dagger \\
(t^\dagger)^\dagger &\Rrightarrow t
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{inl}\ \varnothing &\Rrightarrow \varnothing \\
\mathrm{inr}\ \varnothing &\Rrightarrow \varnothing \\
\varnothing \times t &\Rrightarrow \varnothing \\
t \times \varnothing &\Rrightarrow \varnothing \\
\varnothing \mapsto t &\Rrightarrow \varnothing \\
t \mapsto \varnothing &\Rrightarrow \varnothing \\
\mathrm{fold}_T\ \varnothing &\Rrightarrow \varnothing \\
\mathrm{trace}_T\ \varnothing &\Rrightarrow \varnothing
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{inl}\ (t_1 \parallel t_2) &\Rrightarrow \mathrm{inl}\ t_1 \parallel \mathrm{inl}\ t_2 \\
\mathrm{inr}\ (t_1 \parallel t_2) &\Rrightarrow \mathrm{inr}\ t_1 \parallel \mathrm{inr}\ t_2 \\
(t_1 \parallel t_2) \times t_3 &\Rrightarrow (t_1 \times t_3) \parallel (t_2 \times t_3) \\
t_1 \times (t_2 \parallel t_3) &\Rrightarrow (t_1 \times t_2) \parallel (t_1 \times t_3) \\
(t_1 \parallel t_2) \mapsto t_3 &\Rrightarrow (t_1 \mapsto t_3) \parallel (t_2 \mapsto t_3) \\
t_1 \mapsto (t_2 \parallel t_3) &\Rrightarrow (t_1 \mapsto t_2) \parallel (t_1 \mapsto t_3) \\
\mathrm{fold}_T\ (t_1 \parallel t_2) &\Rrightarrow \mathrm{fold}_T\ t_1 \parallel \mathrm{fold}_T\ t_2
\end{aligned}
$$

$$
\begin{aligned}
t_1 \Rrightarrow t_1' \implies t_2 \Rrightarrow t_2' &\implies t_1 \parallel t_2 \Rrightarrow t_1' \parallel t_2' \\
t_1 \Rrightarrow t_1' \implies t_2 \Rrightarrow t_2' &\implies t_1 \mathbin{;} t_2 \Rrightarrow t_1' \mathbin{;} t_2' \\
t \Rrightarrow t' &\implies \mathrm{inl}\ t \Rrightarrow \mathrm{inl}\ t' \\
t \Rrightarrow t' &\implies \mathrm{inr}\ t \Rrightarrow \mathrm{inr}\ t' \\
t_1 \Rrightarrow t_1' \implies t_2 \Rrightarrow t_2' &\implies t_1 \times t_2 \Rrightarrow t_1' \times t_2' \\
t_1 \Rrightarrow t_1' \implies t_2 \Rrightarrow t_2' &\implies t_1 \mapsto t_2 \Rrightarrow t_1' \mapsto t_2' \\
t \Rrightarrow t' &\implies \mathrm{fold}_T\ t \Rrightarrow \mathrm{fold}_T\ t' \\
t \Rrightarrow t' &\implies \mathrm{trace}_T\ t \Rrightarrow \mathrm{trace}_T\ t' \\
t_1 \Rrightarrow t_1' \implies t_2 \Rrightarrow t_2' &\implies t_1 \mathbin{@} t_2 \Rrightarrow t_1' \mathbin{@} t_2'
\end{aligned}
$$

$$
(t_1 \mapsto t_2) \mathbin{@} t \Rrightarrow (t_1 \triangleright t)\ t_2
$$

$$
\begin{aligned}
t_1 \not\Rrightarrow \varnothing &\implies (t_1 \parallel t_2) \mathbin{@} t \Rrightarrow t_1 \mathbin{@} t \\
t_1 \Rrightarrow \varnothing &\implies (t_1 \parallel t_2) \mathbin{@} t \Rrightarrow t_2 \mathbin{@} t
\end{aligned}
$$

$$
\begin{aligned}
\varnothing \mathbin{@} t &\Rrightarrow \varnothing \\
t \mathbin{@} \varnothing &\Rrightarrow \varnothing \\
\mathrm{id} \mathbin{@} t &\Rrightarrow t
\end{aligned}
$$

$$
\begin{aligned}
t \mathbin{@} (t_1 \parallel t_2) &\Rrightarrow (t \mathbin{@} t_1) \parallel (t \mathbin{@} t_2) \\
t_1 \mathbin{;} t_2 \mathbin{@} t &\Rrightarrow t_2 \mathbin{@} (t_1 \mathbin{@} t)
\end{aligned}
$$

$$
\begin{aligned}
t \mathbin{@} (\mathrm{inr}\ u) \Rrightarrow \mathrm{inr}\ u' &\implies (\mathrm{trace}_T\ t) \mathbin{@} u \Rrightarrow u' \\
t \mathbin{@} (\mathrm{inr}\ u) \Rrightarrow \mathrm{inl}\ u' \implies (\mathrm{trace}_T\ t) \mathbin{@} (\mathrm{inl}\ u') \Rrightarrow u'' &\implies (\mathrm{trace}_T\ t) \mathbin{@} u \Rrightarrow u'' \\
t \mathbin{@} (\mathrm{inl}\ u) \Rrightarrow \mathrm{inl}\ u' \implies (\mathrm{trace}_T\ t) \mathbin{@} (\mathrm{inl}\ u') \Rrightarrow u'' &\implies (\mathrm{trace}_T\ t) \mathbin{@} u \Rrightarrow u'' \\
t \mathbin{@} (\mathrm{inl}\ u) \Rrightarrow \mathrm{inr}\ u' &\implies (\mathrm{trace}_T\ t) \mathbin{@} (\mathrm{inl}\ u) \Rrightarrow u'
\end{aligned}
$$

図 14 Reduction

7 評価戦略