Transactional Events: Implementation Dynamics

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April 7, 2006

$(\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \xrightarrow{a} \mathbb{K}'; \mathbb{L}'; \mathbb{B}'; \mathcal{T}')$

$$
\begin{array}{lrcl}
\textit{Synchronous Evaluation Contexts} & M^{Evt} & ::= & [] \mid \mathsf{thenEvt}\ M_1^{Evt}\ e_2 \mid \mathsf{catchEvt}\ M_1^{Evt}\ e_2 \\
\textit{Concurrent Evaluation Contexts} & M^{IO} & ::= & [] \mid \mathsf{bindIO}\ M_1^{IO}\ e_2 \mid \mathsf{catchIO}\ M_1^{IO}\ e_2
\end{array}
$$

$$
\begin{array}{lrcl}
\text{Boolean} & \mathscr{b} & ::= & \mathit{true} \mid \mathit{false} \\
\text{Boolean Flag Map} & \mathbb{B} & ::= & \{\mathbb{b} \mapsto \mathscr{b}, \ldots\}
\end{array}
$$

$$
\begin{array}{lrcl}
\text{Completed Search List Map} & \mathbb{L} & ::= & \{\mathbb{l} \mapsto \{\langle \rho, \mathbb{b}_\rho \rangle, \ldots\}, \ldots\}
\end{array}
$$

$$
\begin{array}{lrcl}
\text{Path Element} & \overline{\rho} & ::= & \mathsf{Left} \mid \mathsf{Right} \mid \mathsf{Send}(\theta, \mathbb{b}_\theta, \rho_\theta, \mathbb{l}_\theta; \mathbb{l}) \mid \mathsf{Recv}(\theta, \mathbb{b}_\theta, \rho_\theta, \mathbb{l}_\theta; \mathbb{l}) \\
\text{Path} & \rho & ::= & \bullet \mid \overline{\rho}{:}\rho
\end{array}
$$

$$
\begin{array}{lrcl}
\text{Channel Send Set} & \mathscr{s}_{\mathsf{S}} & ::= & \{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO} \rangle, \ldots\} \\
\text{Channel Receive Set} & \mathscr{s}_{\mathsf{R}} & ::= & \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO} \rangle, \ldots\} \\
\text{Channel Map} & \mathbb{K} & ::= & \{\kappa \mapsto \langle \mathscr{s}_{\mathsf{S}}, \mathscr{s}_{\mathsf{R}} \rangle, \ldots\}
\end{array}
$$

$$
\begin{array}{llcll}
\textit{Threads} & T & ::= & \langle \theta, e \rangle & \text{Concurrent thread} \\
 & & \mid & \langle \theta, \mathbb{b}_\theta, \rho, e, M^{IO} \rangle & \text{Search thread} \\
 & & \mid & \langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO} \rangle^? & \text{Completed search thread (pending commit search)} \\
 & & \mid & \langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO} \rangle & \text{Completed search thread (completed commit search)} \\
\textit{Thread Groups} & \mathcal{T} & ::= & \{T, \ldots\} &
\end{array}
$$

$$\textit{Actions} \quad a \quad ::= \quad ?c \mid !c \mid \epsilon$$

$$\rho_1 \succeq \rho_2 \quad \text{iff} \quad \exists \rho.\ \rho_1 = \rho\rho_2$$

$$
\begin{array}{rcl}
\mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \bullet \rangle) & = & \emptyset \\
\mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \mathsf{Left}{:}\rho \rangle) & = & \mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \rho \rangle) \\
\mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \mathsf{Right}{:}\rho \rangle) & = & \mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \rho \rangle) \\
\mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \mathsf{Send}(\theta', \mathbb{b}'_\theta, \rho', \mathbb{l}'; \mathbb{l}){:}\rho \rangle) & = & \{\langle \theta', \mathbb{b}'_\theta, \mathsf{Recv}(\theta, \mathbb{b}_\theta, \rho, \mathbb{l}; \mathbb{l}'){:}\rho' \rangle\} \cup \mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \rho \rangle) \cup \mathsf{Dep}(\langle \theta', \mathbb{b}'_\theta, \rho' \rangle) \\
\mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \mathsf{Recv}(\theta', \mathbb{b}'_\theta, \rho', \mathbb{l}'; \mathbb{l}){:}\rho \rangle) & = & \{\langle \theta', \mathbb{b}'_\theta, \mathsf{Send}(\theta, \mathbb{b}_\theta, \rho, \mathbb{l}; \mathbb{l}'){:}\rho' \rangle\} \cup \mathsf{Dep}(\langle \theta, \mathbb{b}_\theta, \rho \rangle) \cup \mathsf{Dep}(\langle \theta', \mathbb{b}'_\theta, \rho' \rangle)
\end{array}
$$

$$
\begin{array}{l}
\mathsf{Coherent}(\langle \theta_1, \mathbb{b}_{\theta 1}, \rho_1 \rangle, \langle \theta_2, \mathbb{b}_{\theta 2}, \rho_2 \rangle) \quad \text{iff} \\
\quad \theta_1 \neq \theta_2 \\
\quad \wedge \forall \langle \theta, \mathbb{b}, \rho \rangle \in \mathsf{Dep}(\langle \theta_2, \mathbb{b}_{\theta 2}, \rho_2 \rangle).\ \theta_1 = \theta \Rightarrow \mathbb{b}_{\theta 1} = \mathbb{b} \wedge \rho_1 \succeq \rho \\
\quad \wedge \forall \langle \theta, \mathbb{b}, \rho \rangle \in \mathsf{Dep}(\langle \theta_1, \mathbb{b}_{\theta 1}, \rho_1 \rangle).\ \theta_2 = \theta \Rightarrow \mathbb{b}_{\theta 2} = \mathbb{b} \wedge \rho_2 \succeq \rho \\
\quad \wedge \forall \langle \theta_a, \mathbb{b}_a, \rho_a \rangle \in \mathsf{Dep}(\langle \theta_1, \mathbb{b}_{\theta 1}, \rho_1 \rangle).\ \forall \langle \theta_b, \mathbb{b}_b, \rho_b \rangle \in \mathsf{Dep}(\langle \theta_2, \mathbb{b}_{\theta 2}, \rho_2 \rangle).\ \theta_a = \theta_2 \Rightarrow \mathbb{b}_a = \mathbb{b}_b \wedge (\rho_a \succeq \rho_b \vee \rho_b \succeq \rho_a)
\end{array}
$$

IOEval

$$\frac{e \hookrightarrow e'}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[e] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[e'] \rangle\}}$$

IOBindUnit

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{bindIO}\ (\texttt{unitIO}\ e_1)\ e_2] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[e_2\ e_1] \rangle\}}$$

IOBindThrow

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{bindIO}\ (\texttt{throwIO}\ e_1)\ e_2] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{throwIO}\ e_1] \rangle\}}$$

IOCatchUnit

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{catchIO}\ (\texttt{unitIO}\ e_1)\ e_2] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{unitIO}\ e_1] \rangle\}}$$

IOCatchThrow

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{catchIO}\ (\texttt{throwIO}\ e_1)\ e_2] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[e_2\ e_1] \rangle\}}$$

IOGetChar

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{getChar}] \rangle\} \xrightarrow{?c} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{unitIO}\ c] \rangle\}}$$

IOPutChar

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{putChar}\ c] \rangle\} \xrightarrow{!c} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{unitIO}\ ()] \rangle\}}$$

IOFork

$$\frac{\theta' \text{ fresh}}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{forkIO}\ e] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{unitIO}\ \theta'] \rangle, \langle \theta', e \rangle\}}$$

IOMyThreadId

$$\frac{}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{myThreadId}] \rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{unitIO}\ \theta] \rangle\}}$$

SyncInit

$$\frac{\mathbb{b}_\theta \text{ fresh}}{\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{sync}\ e]\rangle\} \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B}[\mathbb{b}_\theta \mapsto \mathit{false}];\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \bullet, e, M^{IO}\rangle\}}$$

EvtFizzle

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{true}}{\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{IO}\rangle\} \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T}}$$

EvtEval

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{false} \qquad e \hookrightarrow e'}{\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[e], M^{IO}\rangle\} \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[e'], M^{IO}\rangle\}}$$

EvtThenAlways

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{false}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{thenEvt}\ (\texttt{alwaysEvt}\ e_1)\ e_2], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[e_2\ e_1], M^{IO}\rangle\}\end{array}}$$

EvtThenThrow

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{false}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{thenEvt}\ (\texttt{throwEvt}\ e_1)\ e_2], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{throwEvt}\ e_1], M^{IO}\rangle\}\end{array}}$$

EvtCatchAlways

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{false}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{catchEvt}\ (\texttt{alwaysEvt}\ e_1)\ e_2], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{alwaysEvt}\ e_1], M^{IO}\rangle\}\end{array}}$$

EvtCatchThrow

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{false}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{catchEvt}\ (\texttt{throwEvt}\ e_1)\ e_2], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[e_2\ e_1], M^{IO}\rangle\}\end{array}}$$

EvtChoose

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \mathit{false}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{chooseEvt}\ e_1\ e_2], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \texttt{Left}{:}\rho, M^{Evt}[e_1], M^{IO}\rangle, \langle \theta, \mathbb{b}_\theta, \texttt{Right}{:}\rho, M^{Evt}[e_1], M^{IO}\rangle\}\end{array}}$$

EvtMyThreadId

$$\frac{}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{myThreadIdEvt}], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{alwaysEvt}\ \theta], M^{IO}\rangle\}\end{array}}$$

NewChan

$$\frac{\kappa' \text{ fresh}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{newChan}], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K}[\kappa' \mapsto \langle\{\},\{\}\rangle];\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{alwaysEvt}\ \kappa'], M^{IO}\rangle\}\end{array}}$$

EvtSend

$$\frac{\begin{array}{c}\mathbb{B}(\mathbb{b}_\theta) = \mathit{false} \qquad \mathbb{K}(\kappa) = \langle s_{\mathsf{S}}, s_{\mathsf{R}}\rangle \\ (\mathbb{L}', \mathcal{T}') = F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, s_{\mathsf{R}})\end{array}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{sendEvt}\ \kappa\ e], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K}[\kappa \mapsto \langle s_{\mathsf{S}} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO}\rangle\}, s_{\mathsf{R}}\rangle];\mathbb{L}';\mathbb{B};\mathcal{T}'\end{array}}$$

$$F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, \{\}) \quad = \quad (\mathbb{L}, \mathcal{T})$$

$$F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, s_{\mathsf{R}} \uplus \langle \theta', \mathbb{b}_{\theta'}, \rho', M^{Evt'}, M^{IO'}\rangle) \quad =$$

$$\begin{cases} F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO}\rangle}\left(\mathbb{L}\begin{bmatrix}\mathbb{l} \mapsto \{\}, \\ \mathbb{l}' \mapsto \{\}\end{bmatrix}, \mathcal{T} \uplus \begin{Bmatrix}\langle \theta, \mathbb{b}_\theta, \mathsf{Send}(\theta', \mathbb{b}_{\theta'}, \rho', \mathbb{l}'; \mathbb{l}){:}\rho, M^{Evt}[\texttt{alwaysEvt}\ ()], M^{IO}\rangle \\ \langle \theta', \mathbb{b}_{\theta'}, \mathsf{Recv}(\theta, \mathbb{b}_\theta, \rho, \mathbb{l}; \mathbb{l}'){:}\rho', M^{Evt'}[\texttt{alwaysEvt}\ e], M^{IO'}\rangle\end{Bmatrix}, s_{\mathsf{R}}\right) \\ \qquad \text{if } \mathbb{B}(\mathbb{b}_{\theta'}) = \mathit{false} \text{ and } \mathsf{Coherent}(\langle \theta, \mathbb{b}_\theta, \rho\rangle, \langle \theta', \mathbb{b}'_\theta, \rho'\rangle), \text{ where } \mathbb{l} \text{ fresh and } \mathbb{l}' \text{ fresh} \\ F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, e, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, s_{\mathsf{R}}) \\ \qquad \text{otherwise}\end{cases}$$

EvtRecv

$$\frac{\begin{array}{c}\mathbb{B}(\mathbb{b}_\theta) = \mathit{false} \qquad \mathbb{K}(\kappa) = \langle s_{\mathsf{S}}, s_{\mathsf{R}}\rangle \\ (\mathbb{L}', \mathcal{T}') = F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, s_{\mathsf{R}})\end{array}}{\begin{array}{l}\mathbb{K};\mathbb{L};\mathbb{B};\mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}[\texttt{recvEvt}\ \kappa], M^{IO}\rangle\} \\ \quad \xrightarrow{\epsilon} \mathbb{K}[\kappa \mapsto \langle s_{\mathsf{S}}, s_{\mathsf{R}} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO}\rangle\}\rangle];\mathbb{L}';\mathbb{B};\mathcal{T}'\end{array}}$$

$$F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, \{\}) \quad = \quad (\mathbb{L}, \mathcal{T})$$

$$F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, s_{\mathsf{S}} \uplus \langle \theta', \mathbb{b}_{\theta'}, \rho', e', M^{Evt'}, M^{IO'}\rangle) \quad =$$

$$\begin{cases} F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO}\rangle}\left(\mathbb{L}\begin{bmatrix}\mathbb{l} \mapsto \{\}, \\ \mathbb{l}' \mapsto \{\}\end{bmatrix}, \mathcal{T} \uplus \begin{Bmatrix}\langle \theta, \mathbb{b}_\theta, \mathsf{Recv}(\theta', \mathbb{b}_{\theta'}, \rho', \mathbb{l}'; \mathbb{l}){:}\rho, M^{Evt}[\texttt{alwaysEvt}\ e'], M^{IO}\rangle \\ \langle \theta', \mathbb{b}_{\theta'}, \mathsf{Send}(\theta, \mathbb{b}_\theta, \rho, \mathbb{l}; \mathbb{l}'){:}\rho', M^{Evt'}[\texttt{alwaysEvt}\ ()], M^{IO'}\rangle\end{Bmatrix}, s_{\mathsf{S}}\right) \\ \qquad \text{if } \mathbb{B}(\mathbb{b}_{\theta'}) = \mathit{false} \text{ and } \mathsf{Coherent}(\langle \theta, \rho\rangle, \langle \theta', \rho'\rangle), \text{ where } \mathbb{l} \text{ fresh and } \mathbb{l}' \text{ fresh} \\ F_{\mathbb{B}}^{\langle \theta, \mathbb{b}_\theta, \rho, M^{Evt}, M^{IO}\rangle}(\mathbb{L}, \mathcal{T}, s_{\mathsf{S}}) \\ \qquad \text{otherwise}\end{cases}$$

FinishThrow

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \textit{false}}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \texttt{throwEvt}\ e, M^{IO}\rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T}}$$

FinishAlways

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \textit{false} \qquad \mathbb{b}_\rho \text{ fresh} \qquad \mathbb{L}' = L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \rho)}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \texttt{alwaysEvt}\ e, M^{IO}\rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}'; \mathbb{B} \uplus \{\mathbb{b}_\rho \mapsto \textit{false}\}; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO}\rangle^?\}}$$

$$\begin{array}{rcl}
L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \bullet) & = & \mathbb{L} \\
L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \mathsf{Left}{:}\rho') & = & L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \rho') \\
L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \mathsf{Right}{:}\rho') & = & L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \rho') \\
L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \mathsf{Send}(_; \mathbb{l}){:}\rho') & = & L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}[\mathbb{l} \mapsto \mathbb{L}(\mathbb{l}) \uplus \{\langle \rho, \mathbb{b}_\rho\rangle\}], \rho') \\
L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}, \mathsf{Recv}(_; \mathbb{l}){:}\rho') & = & L^{\langle \rho, \mathbb{b}_\rho\rangle}(\mathbb{L}[\mathbb{l} \mapsto \mathbb{L}(\mathbb{l}) \uplus \{\langle \rho, \mathbb{b}_\rho\rangle\}], \rho')
\end{array}$$

CommitSearch

$$\frac{\mathbb{B}' = \begin{cases} B(\mathbb{B}, \mathcal{M}) & \text{if } S_{\mathbb{L}}(\theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, \{\}) = \{\mathcal{M}, \ldots\} \\ \mathbb{B} & \text{if } S_{\mathbb{L}}(\theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, \{\}) = \{\} \end{cases}}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO}\rangle^?\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}'; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO}\rangle\}}$$

$$S_{\mathbb{L}}(\theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, \mathcal{M}) \quad = \quad \begin{cases} \{\mathcal{M}\} & \text{if } \mathcal{M}(\theta) = \langle \mathbb{b}_\theta, \mathbb{b}_\rho\rangle \\ \{\} & \text{if } \mathcal{M}(\theta) = \langle \mathbb{b}'_\theta, \mathbb{b}'_\rho\rangle \wedge (\mathbb{b}_\theta \neq \mathbb{b}'_\theta \vee \mathbb{b}_\rho \neq \mathbb{b}_\rho) \\ \{\} & \text{if } \theta \notin \mathit{dom}(\mathcal{M}) \wedge \mathbb{B}(\mathbb{b}_\theta) = \textit{true} \\ \overline{S}_{\mathbb{L}}(\rho, \mathcal{M} \uplus \{\theta \mapsto (\mathbb{b}_\theta, \mathbb{b}_\rho)\}) & \text{if } \theta \notin \mathit{dom}(\mathcal{M}) \wedge \mathbb{B}(\mathbb{b}_\theta) = \textit{false} \end{cases}$$

$$\begin{array}{rcl}
\overline{S}_{\mathbb{L}}(\bullet, \mathcal{M}) & = & \{\mathcal{M}\} \\
\overline{S}_{\mathbb{L}}(\mathsf{Left}{:}\rho, \mathcal{M}) & = & \overline{S}(\rho, \mathcal{M}) \\
\overline{S}_{\mathbb{L}}(\mathsf{Right}{:}\rho, \mathcal{M}) & = & \overline{S}(\rho, \mathcal{M}) \\
\overline{S}_{\mathbb{L}}(\mathsf{Send}(\theta', \mathbb{b}_{\theta'}, _, \mathbb{l}'; _){:}\rho, \mathcal{M}) & = & \bigcup\{\ S_{\mathbb{L}}(\theta', \mathbb{b}_{\theta'}, \rho', \mathbb{b}_{\rho'}, \mathcal{M}') \mid \mathcal{M}' \in \overline{S}_{\mathbb{L}}(\rho, \mathcal{M}) \wedge \langle \rho', \mathbb{b}_{\rho'}\rangle \in \mathbb{L}(\mathbb{l}')\ \} \\
\overline{S}_{\mathbb{L}}(\mathsf{Recv}(\theta', \mathbb{b}_{\theta'}, _, \mathbb{l}'; _){:}\rho, \mathcal{M}) & = & \bigcup\{\ S_{\mathbb{L}}(\theta', \mathbb{b}_{\theta'}, \rho', \mathbb{b}_{\rho'}, \mathcal{M}') \mid \mathcal{M}' \in \overline{S}_{\mathbb{L}}(\rho, \mathcal{M}) \wedge \langle \rho', \mathbb{b}_{\rho'}\rangle \in \mathbb{L}(\mathbb{l}')\ \}
\end{array}$$

$$\begin{array}{rcl}
B(\mathbb{B}, \{\}) & = & \mathbb{B} \\
B(\mathbb{B}, \mathcal{M} \uplus \{\theta \mapsto \langle \mathbb{b}_\theta, \mathbb{b}_\rho\rangle\}) & = & B(\mathbb{B}[\mathbb{b}_\theta \mapsto \textit{true}, \mathbb{b}_\rho \mapsto \textit{true}], \mathcal{M})
\end{array}$$

CommitFizzle

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \textit{true} \qquad \mathbb{B}(\mathbb{b}_\rho) = \textit{false}}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO}\rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T}}$$

CommitCommit

$$\frac{\mathbb{B}(\mathbb{b}_\theta) = \textit{true} \qquad \mathbb{B}(\mathbb{b}_\rho) = \textit{true}}{\mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, \mathbb{b}_\theta, \rho, \mathbb{b}_\rho, e, M^{IO}\rangle\} \xrightarrow{\epsilon} \mathbb{K}; \mathbb{L}; \mathbb{B}; \mathcal{T} \uplus \{\langle \theta, M^{IO}[\texttt{unitIO}\ e]\rangle\}}$$