Friot: A Functional Reactive Language for IoT Programs with Dependent Type-and-Effect System (Report)

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I. TYPE CHECKING TREES FOR FUNCTION DELAY

Table I

delay

$$\dfrac{\dfrac{\Phi = \underline{\mathbf{LightUp}}}{\Gamma' \vdash \mathtt{ev\ (LightUp)} : \mathtt{Unit}\ \&\ \underline{\mathbf{LightUp}}}\,(\texttt{T-Event}) \qquad \dfrac{\dfrac{\Phi = \underline{\mathbf{Tick}}}{\Gamma' \vdash \mathtt{ev\ (Tick)} : \mathtt{Unit}\ \&\ \underline{\mathbf{Tick}}}\,(\texttt{T-Event}) \qquad \mathbf{A}}{\Gamma' \vdash (\mathtt{ev\ (Tick);\ delay\ (t\ \text{-}\ 1);}) : \mathtt{Unit}\ \&\ (\underline{\mathbf{Tick}} \cdot \Phi^{(\mathtt{t}-1)}_{\mathtt{delay}})}\,(\texttt{T-Let})}{\Gamma' \vdash (\mathtt{if\ t == 0\ then\ ev\ (LightUp)\ else\ ev\ (Tick);\ delay\ (t\ \text{-}\ 1);}) : \mathtt{Unit}\ \&\ (\mathtt{t} == 0 \wedge \underline{\mathbf{LightUp}}) \vee (\mathtt{t} \neq 0 \wedge \underline{\mathbf{Tick}} \cdot \Phi^{(\mathtt{t}-1)}_{\mathtt{delay}})}\,(\texttt{T-If})$$

$$\dfrac{\textit{... (Effects Computation } \boldsymbol{I}\textit{) ...}}{\Gamma \vdash (\mathtt{delay\ t\ =\ if\ ...\ then\ ...\ else\ ...}) : (\mathtt{t} : \mathtt{Int}) \rightarrow (\mathtt{Unit}\ \&\ (\mathtt{t} \geq 0 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 0 \wedge \underline{\mathbf{Tick}}^{\omega}))}\,(\texttt{T-Fun})$$

$\Gamma' = \Gamma,\ \mathtt{delay} : \tau_{\mathtt{delay}}$

$\Phi^{(\mathtt{t}-1)}_{\mathtt{delay}} = (\mathtt{t} \geq 1 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}\text{-}1} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 1 \wedge \underline{\mathbf{Tick}}^{\omega})$

A:

$$\dfrac{\dfrac{\mathtt{sty}(\Gamma'(\mathtt{delay})) \in \rightarrow}{\Gamma' \vdash \mathtt{delay} : (\mathtt{t} : \mathtt{Int}) \rightarrow (\mathtt{Unit}\ \&\ (\mathtt{t} \geq 0 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 0 \wedge \underline{\mathbf{Tick}}^{\omega}))}\,(\texttt{T-VaF}) \qquad \dfrac{\mathtt{sty}(\Gamma'(\mathtt{t})) = \mathtt{Int}}{\Gamma' \vdash (\mathtt{t\ \text{-}\ 1}) : \mathtt{int}}\,(\texttt{T-Var, T-Op})}{\Gamma' \vdash \mathtt{delay\ (t\ \text{-}\ 1)} : (\mathtt{t\ \text{-}\ 1} : \mathtt{int}) \rightarrow (\mathtt{Unit}\ \&\ (\mathtt{t} \geq 1 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}\ \text{-}\ 1} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 1 \wedge \underline{\mathbf{Tick}}^{\omega})))}\,(\texttt{T-App, S-Base})$$

I:

$$\begin{aligned}
& (\mathtt{t} == 0 \wedge \underline{\mathbf{LightUp}}) \vee (\mathtt{t} \neq 0 \wedge \underline{\mathbf{Tick}} \cdot \Phi^{(\mathtt{t}-1)}_{\mathtt{delay}}) \\
\equiv\quad & (\mathtt{t} == 0 \wedge \underline{\mathbf{LightUp}}) \vee (\mathtt{t} \neq 0 \wedge \underline{\mathbf{Tick}} \cdot ((\mathtt{t} \geq 1 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}\text{-}1} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 1 \wedge \underline{\mathbf{Tick}}^{\omega}))) \\
\equiv\quad & (\mathtt{t} == 0 \wedge \underline{\mathbf{LightUp}}) \vee ((\mathtt{t} \neq 0 \wedge \mathtt{t} \geq 1) \wedge \underline{\mathbf{Tick}} \cdot \underline{\mathbf{Tick}}^{\mathtt{t}\text{-}1} \cdot \underline{\mathbf{LightUp}}) \vee ((\mathtt{t} \neq 0 \wedge \mathtt{t} < 1) \wedge (\underline{\mathbf{Tick}} \cdot \underline{\mathbf{Tick}}^{\omega})) \\
\equiv\quad & (\mathtt{t} == 0 \wedge \underline{\mathbf{LightUp}}) \vee (\mathtt{t} \geq 1 \wedge \underline{\mathbf{Tick}} \cdot \underline{\mathbf{Tick}}^{\mathtt{t}\text{-}1} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 0 \wedge (\underline{\mathbf{Tick}} \cdot \underline{\mathbf{Tick}}^{\omega})) \\
\equiv\quad & (\mathtt{t} == 0 \wedge \underline{\mathbf{LightUp}}) \vee (\mathtt{t} \geq 1 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 0 \wedge \underline{\mathbf{Tick}}^{\omega}) \\
\equiv\quad & (\mathtt{t} \geq 0 \wedge \underline{\mathbf{Tick}}^{\mathtt{t}} \cdot \underline{\mathbf{LightUp}}) \vee (\mathtt{t} < 0 \wedge \underline{\mathbf{Tick}}^{\omega}) \\
\equiv\quad & \Phi_{\mathtt{delay}}
\end{aligned}$$

$$\dfrac{\mathtt{c} \in \mathtt{B}}{\Gamma \vdash \mathtt{c} : (\{\mathtt{u} : \mathtt{B} \mid \mathtt{u} = \mathtt{c}\})}\,(\texttt{T-Const}) \qquad \dfrac{\mathtt{sty}(\Gamma(\mathtt{x})) = \mathtt{B}}{\Gamma \vdash \mathtt{x} : (\{\mathtt{u} : \mathtt{B} \mid \mathtt{u} = \mathtt{x}\})}\,(\texttt{T-Var}) \qquad \dfrac{\mathtt{sty}(\Gamma(\mathtt{x})) \in \rightarrow}{\Gamma \vdash \mathtt{x} : (\Gamma(\mathtt{x}))}\,(\texttt{T-VaF}) \qquad \dfrac{\Phi = \underline{\mathbf{a}}}{\Gamma \vdash \mathtt{ev}(\mathtt{a}) : (\mathtt{Unit}\ \&\ \Phi)}\,(\texttt{T-Event})$$

$$\dfrac{\Gamma \vdash \mathtt{e}_1 : \tau_1 \quad \Gamma \vdash \mathtt{e}_2 : \tau_2 \quad \Gamma(\oplus) \vdash \mathtt{x}_1 : \tau_1 \rightarrow \mathtt{x}_2 : \tau_2 \rightarrow \tau_3}{\Gamma \vdash \mathtt{e}_1 \oplus \mathtt{e}_2 : \tau_3[\mathtt{e}_1/\mathtt{x}_1][\mathtt{e}_2/\mathtt{x}_2]}\,(\texttt{T-Op}) \qquad \dfrac{\tau_{\mathtt{F}} = (\overline{\mathtt{x}} : \overline{\tau}) \rightarrow (\tau\ \&\ \Phi_{\mathtt{F}}) \quad \Gamma,\ \mathtt{F} : \tau_{\mathtt{F}},\ \overline{\mathtt{x}} : \overline{\tau} \vdash \mathtt{e} : \tau\ \&\ \Phi_{\mathtt{F}}}{\Gamma \vdash (\mathtt{F}\ \overline{\mathtt{x}}\ =\ \mathtt{e}) : \tau_{\mathtt{F}}\ \&\ \Phi_{\mathtt{F}}}\,(\texttt{T-Fun})$$

$$\dfrac{\Gamma, \mathtt{p} : \tau_{\mathtt{p}} \vdash \mathtt{e} : (\tau\ \&\ \Phi)}{\Gamma \vdash \lambda \mathtt{p}.\mathtt{e} : (\mathtt{p} : \tau_{\mathtt{p}}) \rightarrow \tau}\,(\texttt{T-Lam}) \qquad \dfrac{\Gamma \vdash \mathtt{e} : \mathtt{x}_1 : \tau_1 \rightarrow \tau\ \&\ \Phi \quad \Gamma \vdash \mathtt{e}_1 : \tau_1\ \&\ \Phi_1}{\Gamma \vdash \mathtt{e}\ \mathtt{e}_1 : \tau[\mathtt{e}_1/\mathtt{x}_1]\ \&\ \Phi_1 \cdot \Phi}\,(\texttt{T-App}) \qquad \dfrac{\Gamma \vdash \mathtt{e}_1 : \tau_1\ \&\ \Phi_1 \quad \Gamma, \mathtt{x} : \tau_1 \vdash \mathtt{e}_2 : \tau_2\ \&\ \Phi_2}{\Gamma \vdash \mathbf{let}\ (\mathtt{e}_1; \mathtt{x}.\mathtt{e}_2) : \tau_2\ \&\ \Phi_1 \cdot \Phi_2}\,(\texttt{T-Let})$$

$$\dfrac{\Gamma,\ \mathtt{e} \Downarrow \mathtt{true} \vdash \mathtt{e}_1 : \tau\ \&\ \Phi_1 \quad \Gamma,\ \mathtt{e} \Downarrow \mathtt{false} \vdash \mathtt{e}_2 : \tau\ \&\ \Phi_2}{\Gamma \vdash \mathbf{if}\ (\mathtt{e}; \mathtt{e}_1; \mathtt{e}_2) : \tau\ \&\ \Phi_1 \vee \Phi_2}\,(\texttt{T-If}) \qquad \dfrac{\Gamma \vdash \mathtt{e} : \tau_{\mathtt{e}} \quad \Gamma,\ \mathtt{ty}(\mathtt{D}_{\mathtt{i}}) = \overline{\mathtt{p}_{\mathtt{j}} : \tau_{\mathtt{j}}} \rightarrow \tau_{\mathtt{e}},\ \mathtt{x} : \tau_{\mathtt{e}} \vdash \mathtt{e}_{\mathtt{i}} : \tau\ \&\ \Phi_{\mathtt{i}}}{\Gamma \vdash \mathbf{case}\ \mathtt{x} = \mathtt{e}\ \mathbf{of}\ \{\mathtt{D}_{\mathtt{i}}\ \overline{\mathtt{p}_{\mathtt{j}}} \rightarrow \mathtt{e}_{\mathtt{i}}\} : \tau\ \&\ (\vee_{\mathtt{i} \in \mathtt{I}}\ \Phi_{\mathtt{i}})}\,(\texttt{T-Case})$$

$$\dfrac{\mathtt{T} \in \mathtt{B} \quad \models \Gamma \vdash \pi_1 \Rightarrow \pi_2}{\Gamma \vdash \{\mathtt{u} : \mathtt{T} \mid \pi_1\} <: \{\mathtt{u} : \mathtt{T} \mid \pi_2\}}\,(\texttt{S-Base}) \qquad \dfrac{\Gamma \vdash \tau_2 <: \tau_1 \quad \Gamma, \mathtt{x} : \tau_2 \vdash \sigma_1 <: \sigma_2}{\Gamma \vdash (\mathtt{x} : \tau_1) \rightarrow \sigma_1 <: (\mathtt{x} : \tau_2) \rightarrow \sigma_2}\,(\texttt{S-Fun}) \qquad \dfrac{\Gamma \vdash \tau_1 <: \tau_2 \quad \Phi_1 \preceq \Phi_2}{\Gamma \vdash (\tau_1\ \&\ \Phi_1) <: (\tau_2\ \&\ \Phi_2)}\,(\texttt{S-Qual})$$

Figure 1. Type Judgements.

$$\frac{\mathtt{S} = \{\ \}}{\vdash\ \{\Delta\}\ \mathtt{c}\ \{\mathtt{S}\}}(\texttt{FV-Const}) \qquad \frac{\mathtt{sty}(\Gamma(\mathtt{x})) = \mathtt{B}}{\Gamma \vdash \mathtt{x} : (\{\mathtt{u} : \mathtt{B} \mid \mathtt{u} = \mathtt{x}\})}(\texttt{T-Var}) \qquad \frac{\mathtt{sty}(\Gamma(\mathtt{x})) \in \rightarrow}{\Gamma \vdash \mathtt{x} : (\Gamma(\mathtt{x}))}(\texttt{T-VaF}) \qquad \frac{\Phi = \underline{\mathbf{a}}}{\Gamma \vdash \mathtt{ev}(\mathtt{a}) : (\mathtt{Unit}\ \&\ \Phi)}(\texttt{T-Event})$$

$$\frac{\Gamma \vdash \mathtt{e}_1 : \tau_1 \quad \Gamma \vdash \mathtt{e}_2 : \tau_2 \quad \Gamma(\oplus) \vdash \mathtt{x}_1 : \tau_1 \rightarrow \mathtt{x}_2 : \tau_2 \rightarrow \tau_3}{\Gamma \vdash \mathtt{e}_1 \oplus \mathtt{e}_2 : \tau_3[\mathtt{e}_1/\mathtt{x}_1][\mathtt{e}_2/\mathtt{x}_2]}(\texttt{T-Op}) \qquad \frac{\tau_{\mathtt{F}} = (\overline{\mathtt{x}} : \overline{\tau}) \rightarrow (\tau\ \&\ \Phi_{\mathtt{F}}) \quad \Gamma,\ \mathtt{F} : \tau_{\mathtt{F}},\ \overline{\mathtt{x}} : \overline{\tau} \vdash \mathtt{e} : \tau\ \&\ \Phi_{\mathtt{F}}}{\Gamma \vdash (\mathtt{F}\ \overline{\mathtt{x}}\ =\ \mathtt{e}) : \tau_{\mathtt{F}}\ \&\ \Phi_{\mathtt{F}}}(\texttt{T-Fun})$$

$$\frac{\Gamma, \mathtt{p} : \tau_{\mathtt{p}} \vdash \mathtt{e} : (\tau\ \&\ \Phi)}{\Gamma \vdash \lambda \mathtt{p}.\mathtt{e} : (\mathtt{p} : \tau_{\mathtt{p}}) \rightarrow \tau}(\texttt{T-Lam}) \qquad \frac{\Gamma \vdash \mathtt{e} : \mathtt{x}_1 : \tau_1 \rightarrow \tau\ \&\ \Phi \quad \Gamma \vdash \mathtt{e}_1 : \tau_1\ \&\ \Phi_1}{\Gamma \vdash \mathtt{e}\ \mathtt{e}_1 : \tau[\mathtt{e}_1/\mathtt{x}_1]\ \&\ \Phi_1 \cdot \Phi}(\texttt{T-App}) \qquad \frac{\Gamma \vdash \mathtt{e}_1 : \tau_1\ \&\ \Phi_1 \quad \Gamma, \mathtt{x} : \tau_1 \vdash \mathtt{e}_2 : \tau_2\ \&\ \Phi_2}{\Gamma \vdash \mathbf{let}\ (\mathtt{e}_1; \mathtt{x}.\mathtt{e}_2) : \tau_2\ \&\ \Phi_1 \cdot \Phi_2}(\texttt{T-Let})$$

$$\frac{\Gamma,\ \mathtt{e} \Downarrow \mathtt{true} \vdash \mathtt{e}_1 : \tau\ \&\ \Phi_1 \quad \Gamma,\ \mathtt{e} \Downarrow \mathtt{false} \vdash \mathtt{e}_2 : \tau\ \&\ \Phi_2}{\Gamma \vdash \mathbf{if}\ (\mathtt{e}; \mathtt{e}_1; \mathtt{e}_2) : \tau\ \&\ \Phi_1 \vee \Phi_2}(\texttt{T-If}) \qquad \frac{\Gamma \vdash \mathtt{e} : \tau_{\mathtt{e}} \quad \Gamma,\ \mathtt{ty}(\mathtt{D}_{\mathtt{i}}) = \overline{\mathtt{p}_{\mathtt{j}} : \tau_{\mathtt{j}}} \rightarrow \tau_{\mathtt{e}},\ \mathtt{x} : \tau_{\mathtt{e}} \vdash \mathtt{e}_{\mathtt{i}} : \tau\ \&\ \Phi_{\mathtt{i}}}{\Gamma \vdash \mathbf{case}\ \mathtt{x} = \mathtt{e}\ \mathbf{of}\ \{\mathtt{D}_{\mathtt{i}}\ \overline{\mathtt{p}_{\mathtt{j}}} \rightarrow \mathtt{e}_{\mathtt{i}}\} : \tau\ \&\ (\vee_{\mathtt{i} \in \mathtt{I}}\ \Phi_{\mathtt{i}})}(\texttt{T-Case})$$

$$\frac{\mathtt{T} \in \mathtt{B} \quad \models \Gamma \vdash \pi_1 \Rightarrow \pi_2}{\Gamma \vdash \{\mathtt{u} : \mathtt{T} \mid \pi_1\} <: \{\mathtt{u} : \mathtt{T} \mid \pi_2\}}(\texttt{S-Base}) \qquad \frac{\Gamma \vdash \tau_2 <: \tau_1 \quad \Gamma, \mathtt{x} : \tau_2 \vdash \sigma_1 <: \sigma_2}{\Gamma \vdash (\mathtt{x} : \tau_1) \rightarrow \sigma_1 <: (\mathtt{x} : \tau_2) \rightarrow \sigma_2}(\texttt{S-Fun}) \qquad \frac{\Gamma \vdash \tau_1 <: \tau_2 \quad \Phi_1 \preceq \Phi_2}{\Gamma \vdash (\tau_1\ \&\ \Phi_1) <: (\tau_2\ \&\ \Phi_2)}\ (\texttt{S-Qual})$$

Figure 2. Forward Verification Rules with Non-Determinism