Transient and undefined extraction

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Before the transient semantics of Vitousek et al. [1] reports a blame error, it collects relevant types from a blame map and extracts relevant parts of the types. The extraction metafunction is partial; this document shows an example program that ends up invoking the extraction function on arguments outside its domain.

The goal is to give a well-typed expression e_s and an untyped context C_0 such that the evaluation of $C_0[e_s]$:

1. adds the type $\mathsf{int} \to \mathsf{int}$ to the blame map,
2. evaluates to a runtime error dereferencing the argument to a function,
3. and asks for $\mathit{extract}(\textsc{Arg} : \textsc{Deref}, \mathsf{int} \to \mathsf{int})$.

Since $\mathit{extract}(\textsc{Deref}, \mathsf{int})$ is undefined, the example program has undefined behavior.

Source expression

See figure 2 [1] for the grammar.

$$e_s = f_0\ (f_1\ f_2)$$

where:

$$\begin{aligned} f_0 &= \mathtt{fun}\ f_0\ (x_0 : (\star \to \star)) \to (\mathsf{int} \to \mathsf{int}).\ x_0 \\ f_1 &= \mathtt{fun}\ f_1\ (x_1 : (\mathsf{ref}\ \mathsf{int} \to \mathsf{int})) \to (\star \to \star).\ x_1 \\ f_2 &= \mathtt{fun}\ f_2\ (x_2 : \mathsf{ref}\ \mathsf{int}) \to \mathsf{int}.\ !\,x_2 \end{aligned}$$

$$C_0 = \Box\ v_0$$

where:

$$\begin{aligned} v_0 &= \mathtt{ref}\ v_1 \\ v_1 &= \mathtt{ref}\ 4 \end{aligned}$$

Source-to-target translation

Translation of e_s to the target language $(\cdot \vdash e_s \rightsquigarrow e : \mathsf{int})$. See figure 3 [1] for the definition.

Let: $T_0 = \star \to \star$ and $T_1 = \mathsf{int} \to \mathsf{int}$ and $T_2 = \mathsf{ref}\ \mathsf{int} \to \mathsf{int}$

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$$\frac{\dfrac{\dfrac{}{(f_0 : T_0 \to T_1), (x_0 : T_0) \vdash x_0 \rightsquigarrow x_0 : T_0} \qquad \dfrac{\dfrac{}{\mathsf{int} \sim \star} \quad \dfrac{}{\mathsf{int} \sim \star}}{T_1 \sim T_0}}{\cdot \vdash \mathsf{fun}\ f_0\ (x_0 : (\star \to \star)) \to (\mathsf{int} \to \mathsf{int}).\ x_0 \rightsquigarrow \mathsf{fun}\ f_0\ x_0.\ (\mathsf{let}\ x_0 = x_0 \Downarrow \langle \to; f_0; \textsc{Arg} \rangle\ \mathsf{in}\ x_0) : T_0 \to T_1}}{\vdots_0}$$

$$\frac{\dfrac{(f_1 : T_2 \to T_0), (x_1 : T_2) \vdash x_1 \rightsquigarrow x_1 : T_2 \qquad \dfrac{\dfrac{}{\mathsf{ref\ int} \sim \star} \quad \dfrac{}{\mathsf{int} \sim \star}}{T_2 \sim T_0}}{\cdot \vdash \mathsf{fun}\ f_1\ (x_1 : (\mathsf{ref\ int} \to \mathsf{int})) \to (\star \to \star).\ x_1 \rightsquigarrow \mathsf{fun}\ f_1\ x_1.\ (\mathsf{let}\ x_1 = x_1 \Downarrow \langle \to; f_1; \textsc{Arg} \rangle\ \mathsf{in}\ x_1) : T_2 \to T_0}}{\vdots_2}$$

$$\frac{\dfrac{\dfrac{}{(f_2 : T_2), (x_2 : \mathsf{ref\ int}) \vdash x_2 \rightsquigarrow x_2 : \mathsf{ref\ int}} \qquad \mathsf{ref\ int} \triangleright \mathsf{ref\ int} \qquad \mathsf{fresh}(x_3) \qquad \mathsf{fresh}(\ell_2)}{(f_2 : T_2), (x_2 : \mathsf{ref\ int}) \vdash !\, x_2 \rightsquigarrow \mathsf{let}\ x_3 = (x_2 :: \mathsf{ref\ int} \Rightarrow^{\ell_2} \mathsf{ref\ int})\ \mathsf{in}\ !\, x_3 \Downarrow \langle \mathsf{int}; x_3; \textsc{Deref} \rangle : \mathsf{int}}}{\vdots_4}$$

$$\frac{\dfrac{\dfrac{\vdots_4}{(f_2 : T_2), (x_2 : \mathsf{ref\ int}) \vdash !\, x_2 \rightsquigarrow e_3 : \mathsf{int}}}{\cdot \vdash \mathsf{fun}\ f_2\ (x_2 : \mathsf{ref\ int}) \to \mathsf{int}.\ !\, x_2 \rightsquigarrow \mathsf{fun}\ f_2\ x_2.\ (\mathsf{let}\ x_2 = (x_2 \Downarrow \langle \mathsf{ref}; f_2; \textsc{Arg} \rangle)\ \mathsf{in}\ e_3) : T_2}}{\vdots_3}$$

$$\frac{\dfrac{\dfrac{\vdots_2}{\cdot \vdash f_1 \rightsquigarrow e_1 : T_2 \to T_0} \qquad \dfrac{\vdots_3}{\cdot \vdash f_2 \rightsquigarrow e_2 : T_2} \qquad T_2 \to T_0 \triangleright T_2 \to T_0 \qquad T_2 [\sim T_2 \qquad \mathsf{fresh}(f_1) \qquad \mathsf{fresh}(\ell_1)}{\cdot \vdash f_1\ f_2 \rightsquigarrow \mathsf{let}\ f_1 = e_1 :: (T_2 \to T_0) \Rightarrow^{\ell_1} (T_2 \to T_0)\ \mathsf{in}\ (f_1\ e_2) \Downarrow \langle \to; f_1; \textsc{Res} \rangle : T_0}}{\vdots_1}$$

$$\frac{\dfrac{\vdots_0}{\cdot \vdash f_0 \rightsquigarrow e_0 : T_0 \to T_1} \qquad \dfrac{\vdots_1}{\cdot \vdash f_1\ f_2 \rightsquigarrow e_1 : T_0} \qquad T_0 \to T_1 \triangleright T_0 \to T_1 \qquad T_0 \sim T_0 \qquad \mathsf{fresh}(f_0) \qquad \mathsf{fresh}(\ell_0)}{\cdot \vdash f_0\ (f_1\ f_2) \rightsquigarrow \mathsf{let}\ f_0 = e_0 :: (T_0 \to T_1) \Rightarrow^{\ell_0} (T_0 \to T_1)\ \mathsf{in}\ (f_0\ (e_1 :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \to; f_0; \textsc{Res} \rangle : T_1}$$

Reduction

See figure 4 for the reduction rules, figure 5 for casts-to-types ($[\![\,]\!]$), and figure 6 for blame [1].

Claim 1. *$C_0[e]$ steps to a state for which $\longmapsto$ is undefined*

Proof. Let: $\sigma_0 := \emptyset$ and $\mathcal{B}_0 := \emptyset$

$\quad\langle C_0[\texttt{let}\ f_0 = e_0 :: (T_0 \to T_1) \Rightarrow^{\ell_0} (T_0 \to T_1)\ \texttt{in}\ (f_0\ (e_1 :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \to; f_0; \textsc{Res}\rangle], \sigma_0, \mathcal{B}_0\rangle$

$\longmapsto \langle C_0[\texttt{let}\ f_0 = a_0 :: (T_0 \to T_1) \Rightarrow^{\ell_0} (T_0 \to T_1)\ \texttt{in}\ (f_0\ (e_1 :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \to; f_0; \textsc{Res}\rangle], \sigma_1, \mathcal{B}_0\rangle$

by:

- $e_0 = \texttt{fun}\ f_0\ x_0. (\texttt{let}\ x_0 = x_0 \Downarrow \langle \to; f_0; \textsc{Arg}\rangle\ \texttt{in}\ x_0)$
- $\sigma_1 := \sigma_0[a_0 \mapsto \lambda x_0.\texttt{let}\ x_0 = x_0 \Downarrow \langle \to; a_0; \textsc{Arg}\rangle\ \texttt{in}\ x_0]$

$\longmapsto \langle C_0[\texttt{let}\ f_0 = a_0\ \texttt{in}\ (f_0\ (e_1 :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \to; f_0; \textsc{Res}\rangle], \sigma_1, \mathcal{B}_1\rangle$

by:

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$$\frac{\sigma_1(a_0) = (\lambda x_0.\texttt{let}\ x_0 = x_0 \Downarrow \langle \star; a_0; \textsc{Arg}\rangle\ \texttt{in}\ x_0)}{hastype(\sigma_1, a_0, \to)}$$

- $\llbracket \star \to \star \Rightarrow^{\ell_0} \mathsf{int} \to \mathsf{int} \rrbracket = \llbracket \mathsf{int} \Rightarrow^{\ell_0} \star \rrbracket \to^{\epsilon} \llbracket \star \Rightarrow^{\mathsf{int}} \rrbracket = \mathsf{int}^{\epsilon} \to^{\epsilon} \mathsf{int}^{\ell_0}$
- $\varrho(\mathcal{B}_0, a_0, \mathsf{int}^{\epsilon} \to^{\epsilon} \mathsf{int}^{\ell_0}) = \mathcal{B}_0[a_0 \mapsto \{\mathsf{int}^{\epsilon} \to^{\epsilon} \mathsf{int}^{\ell_0}\}] = \mathcal{B}_1$

$\longmapsto \langle C_0[(a_0\ (e_1 :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \to; a_0; \textsc{Res}\rangle], \sigma_1, \mathcal{B}_1\rangle$

by:

- $\langle (\texttt{let}\ f_0 = a_0\ \texttt{in}\ e_4), \sigma_1, \mathcal{B}_1\rangle \longrightarrow \langle (e_4[a_0/f_0]), \sigma_1, \mathcal{B}_1\rangle$

$= \langle C_1[\texttt{let}\ f_1 = e_1 :: (T_2 \to T_0) \Rightarrow^{\ell_1} (T_2 \to T_0)\ \texttt{in}\ (f_1\ e_2) \Downarrow \langle \to; f_1; \textsc{Res}\rangle], \sigma_1, \mathcal{B}_1\rangle$

by:

- $e_1 = \texttt{fun}\ f_1\ x_1. (\texttt{let}\ x_1 = x_1 \Downarrow \langle \to; f_1; \textsc{Arg}\rangle\ \texttt{in}\ x_1)$
- $C_1 = C_0[(a_0\ (\square :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \to; a_0; \textsc{Res}\rangle]$

$\longmapsto \langle C_1[\texttt{let}\ f_1 = a_1 :: (T_2 \to T_0) \Rightarrow^{\ell_1} (T_2 \to T_0)\ \texttt{in}\ (f_1\ e_2) \Downarrow \langle \to; f_1; \textsc{Res}\rangle], \sigma_2, \mathcal{B}_1\rangle$

by:

- $e_1 = \texttt{fun}\ f_1\ x_1. (\texttt{let}\ x_1 = x_1 \Downarrow \langle \to; f_1; \textsc{Arg}\rangle\ \texttt{in}\ x_1)$
- $\sigma_2 := \sigma_1[a_1 \mapsto \lambda x_1.\texttt{let}\ x_1 = x_1 \Downarrow \langle \to; a_1; \textsc{Arg}\rangle\ \texttt{in}\ x_1]$

$\longmapsto \langle C_1[\texttt{let}\ f_1 = a_1\ \texttt{in}\ (f_1\ e_2) \Downarrow \langle \to; f_1; \textsc{Res}\rangle], \sigma_2, \mathcal{B}_2\rangle$

by:

- $\dfrac{\sigma_2(a_1) \in \lambda x.e}{hastype(\sigma_2, a_1, \to)}$
- $\llbracket \mathsf{ref\ int} \to \mathsf{int} \Rightarrow^{\ell_1} \star \to \star \rrbracket = \llbracket \star \Rightarrow^{\ell_1} \mathsf{ref\ int} \rrbracket \to^{\epsilon} \llbracket \mathsf{int} \Rightarrow^{\star} \rrbracket = \mathsf{ref}^{\mathsf{int}^{\ell_1}}\ \ell_1 \to^{\epsilon} \mathsf{int}^{\epsilon}$
- $\varrho(\mathcal{B}_1, a_1, \mathsf{ref}^{\mathsf{int}^{\ell_1}}\ \ell_1 \to^{\epsilon} \mathsf{int}^{\epsilon}) = \mathcal{B}_1[a_1 \mapsto \{\mathsf{ref}^{\mathsf{int}^{\ell_1}}\ \ell_1 \to^{\epsilon} \mathsf{int}^{\epsilon}\}] = \mathcal{B}_2$

$\longmapsto \langle C_1[(a_1\ e_2) \Downarrow \langle \to; a_1; \textsc{Res}\rangle], \sigma_2, \mathcal{B}_2\rangle$

$\longmapsto \langle C_1[(a_1\ a_2) \Downarrow \langle \to; a_1; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_2\rangle$

by:

- $e_2 = \texttt{fun}\ f_2\ x_2. (\texttt{let}\ x_2 = (x_2 \Downarrow \langle \mathsf{ref}; f_2; \textsc{Arg}\rangle)\ \texttt{in}\ e_3)$
- $\sigma_3 := \sigma_2[a_2 \mapsto \lambda x_2.(\texttt{let}\ x_2 = (x_2 \Downarrow \langle \mathsf{ref}; a_2; \textsc{Arg}\rangle)\ \texttt{in}\ e_3)]$
- $f_2 \notin fvs(e_3)$

$\longmapsto \langle C_1[(\texttt{let}\ x_1 = a_2 \Downarrow \langle \to; a_1; \textsc{Arg}\rangle\ \texttt{in}\ x_1) \Downarrow \langle \to; a_1; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_2\rangle$

by:

- $\sigma_3(a_1) = \lambda x_1.\texttt{let}\ x_1 = x_1 \Downarrow \langle \to; a_1; \textsc{Arg}\rangle\ \texttt{in}\ x_1$

$\longmapsto \langle C_1[(\texttt{let}\,x_1 = a_2\ \texttt{in}\ x_1) \Downarrow \langle \rightarrow; a_1; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_3\rangle$

by:

- $\dfrac{\sigma_3(a_2) \in \lambda x.e}{\mathit{hastype}(\sigma_3, a_2, \rightarrow)}$
- $\varrho(\mathcal{B}_2, a_2, \langle a_1, \textsc{Arg}\rangle) = \mathcal{B}_2[a_2 \mapsto \{\langle a_1, \textsc{Arg}\rangle\} = \mathcal{B}_3$

$\longmapsto \langle C_1[a_2 \Downarrow \langle \rightarrow; a_1; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_3\rangle$

$\longmapsto \langle C_1[a_2], \sigma_3, \mathcal{B}_4\rangle$

by:

- $\dfrac{\sigma_3(a_2) \in \lambda x.e}{\mathit{hastype}(\sigma_3, a_2, \rightarrow)}$
- $\varrho(\mathcal{B}_3, a_2, \langle a_1, \textsc{Res}\rangle) = \mathcal{B}_3[a_2 \mapsto \{\langle a_1, \textsc{Arg}\rangle, \langle a_1, \textsc{Res}\rangle\} = \mathcal{B}_4$

$= \langle C_0[(a_0\ (a_2 :: T_0 \Rightarrow^{\ell_0} T_0)) \Downarrow \langle \rightarrow; a_0; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_4\rangle$

$\longmapsto \langle C_0[(a_0\ a_2) \Downarrow \langle \rightarrow; a_0; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_5\rangle$

by:

- $\dfrac{\sigma_3(a_2) \in \lambda x.e}{\mathit{hastype}(\sigma_3, a_2, \rightarrow)}$
- $T_0 = \mathsf{int} \rightarrow \mathsf{int}$
- $[\![\mathsf{int} \rightarrow \mathsf{int} \Rightarrow^{\ell_0} \mathsf{int} \rightarrow \mathsf{int}]\!] = [\![\mathsf{int} \Rightarrow^{\mathsf{int}} \ell_0]\!] \rightarrow^{\epsilon} [\![\mathsf{int} \Rightarrow^{\mathsf{int}} \ell_0]\!] = \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0}$
- $\varrho(\mathcal{B}_4, a_2, \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0}) = \mathcal{B}_4[a_2 \mapsto \{\langle a_1, \textsc{Arg}\rangle, \langle a_1, \textsc{Res}\rangle, \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0}\}] = \mathcal{B}_5$

$\longmapsto \langle C_0[(\texttt{let}\,x_0 = a_2 \Downarrow \langle \rightarrow; a_0; \textsc{Arg}\rangle\ \texttt{in}\ x_0) \Downarrow \langle \rightarrow; a_0; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_5\rangle$

by:

- $\sigma_3(a_0) = \lambda x_0.(\texttt{let}\,x_0 = x_0 \Downarrow \langle \rightarrow; a_0; \textsc{Arg}\rangle\ \texttt{in}\ x_0)$

$\longmapsto \langle C_0[(\texttt{let}\,x_0 = a_2\ \texttt{in}\ x_0) \Downarrow \langle \rightarrow; a_0; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_6\rangle$

by:

- $\dfrac{\sigma_3(a_2) \in \lambda x.e}{\mathit{hastype}(\sigma_3, a_2, \rightarrow)}$
- $\varrho(\mathcal{B}_5, a_2, \langle a_0, \textsc{Arg}\rangle) = \mathcal{B}_5[a_2 \mapsto \{\langle a_1, \textsc{Arg}\rangle, \langle a_1, \textsc{Res}\rangle, \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0}, \langle a_0, \textsc{Arg}\rangle\}] = \mathcal{B}_6$

$\longmapsto \langle C_0[a_2 \Downarrow \langle \rightarrow; a_0; \textsc{Res}\rangle], \sigma_3, \mathcal{B}_6\rangle$

$\longmapsto \langle C_0[a_2], \sigma_3, \mathcal{B}_7\rangle$

by:

- $\dfrac{\sigma_3(a_2) \in \lambda x.e}{\mathit{hastype}(\sigma_3, a_2, \rightarrow)}$
- $\varrho(\mathcal{B}_6, a_2, \langle a_0, \textsc{Res}\rangle) = \mathcal{B}_6[a_2 \mapsto \{\langle a_1, \textsc{Arg}\rangle, \langle a_1, \textsc{Res}\rangle, \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0}, \langle a_0, \textsc{Arg}\rangle, \langle a_0, \textsc{Res}\rangle\}] = \mathcal{B}_7$

$\longmapsto \langle (a_2\ (\texttt{ref}\ a_3)), \sigma_4, \mathcal{B}_7\rangle$

by:

- $\sigma_4 = \sigma_3[a_3 \mapsto 4]$

$\longmapsto \langle (a_2\ a_4), \sigma_5, \mathcal{B}_7\rangle$

by:

- $\sigma_5 = \sigma_4[a_4 \mapsto a_3]$

$\longmapsto$ $\langle \mathtt{let}\ x_2 = (a_4 \Downarrow \langle \text{ref}; a_2; \textsc{Arg}\rangle)\ \mathtt{in}\ \mathtt{let}\ x_3 = (x_2 :: \text{ref int} \Rightarrow^{\ell_2} \text{ref int})\ \mathtt{in}\ !\, x_3 \Downarrow \langle \text{int}; x_3; \textsc{Deref}\rangle, \sigma_5, \mathcal{B}_7\rangle$

by:

- $\sigma_5(a_2) = \lambda x_2.(\mathtt{let}\ x_2 = (x_2 \Downarrow \langle \text{ref}; a_2; \textsc{Arg}\rangle)\ \mathtt{in}\ e_3)$
- $e_3 = \mathtt{let}\ x_3 = (x_2 :: \text{ref int} \Rightarrow^{\ell_2} \text{ref int})\ \mathtt{in}\ !\, x_3 \Downarrow \langle \text{int}; x_3; \textsc{Deref}\rangle$

$\longmapsto$ $\langle \mathtt{let}\ x_2 = a_4\ \mathtt{in}\ \mathtt{let}\ x_3 = (x_2 :: \text{ref int} \Rightarrow^{\ell_2} \text{ref int})\ \mathtt{in}\ !\, x_3 \Downarrow \langle \text{int}; x_3; \textsc{Deref}\rangle, \sigma_5, \mathcal{B}_8\rangle$

by:

- $\dfrac{\sigma(a_4) = a_3}{\mathit{hastype}(\sigma_6, a_4, \text{ref})}$
- $\varrho(\mathcal{B}_7, a_4, \langle a_2, \textsc{Arg}\rangle) = \mathcal{B}_7[a_4 \mapsto \{\langle a_2, \textsc{Arg}\rangle\} = \mathcal{B}_8$

$\longmapsto$ $\langle \mathtt{let}\ x_3 = (a_4 :: \text{ref int} \Rightarrow^{\ell_2} \text{ref int})\ \mathtt{in}\ !\, x_3 \Downarrow \langle \text{int}; x_3; \textsc{Deref}\rangle, \sigma_5, \mathcal{B}_8\rangle$

$\longmapsto$ $\langle \mathtt{let}\ x_3 = a_4\ \mathtt{in}\ !\, x_3 \Downarrow \langle \text{int}; x_3; \textsc{Deref}\rangle, \sigma_5, \mathcal{B}_9\rangle$

by:

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$$\dfrac{\sigma(a_4) = a_3}{\mathit{hastype}(\sigma_5, a_4, \text{ref})}$$
- $[\![\text{ref int} \Rightarrow^{\ell_2} \text{ref int}]\!] = \text{ref}^{[\![\text{int} \Leftrightarrow^{\ell_2} \text{int}]\!]}\ \epsilon = \text{ref}^{\text{int}^{\epsilon}}\ \epsilon$
- $\varrho(\mathcal{B}_8, a_4, \text{ref}^{\text{int}^{\epsilon}}\ \epsilon) = \mathcal{B}_8[a_4 \mapsto \{\langle a_2, \textsc{Arg}\rangle, \text{ref}^{\text{int}^{\epsilon}}\ \epsilon\} = \mathcal{B}_9$

$\longmapsto$ $\langle !\, a_4 \Downarrow \langle \text{int}; a_4; \textsc{Deref}\rangle, \sigma_5, \mathcal{B}_9\rangle$

$\longmapsto$ $\langle a_3 \Downarrow \langle \text{int}; a_4; \textsc{Deref}\rangle, \sigma_5, \mathcal{B}_9\rangle$

$\longmapsto$ UNDEFINED

because:

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$$\dfrac{\sigma_5(a_3) = 4}{\neg \mathit{hastype}(\sigma_5, a_3, \text{int})}$$
-
$$\dfrac{\begin{array}{c}\mathcal{B}_9(a_4) = \{\langle a_2, \textsc{Arg}\rangle, \text{ref}^{\text{int}^{\epsilon}}\ \epsilon\} \\ \dfrac{\vdots_0}{\mathit{collectblame}(\textsc{Deref}, \mathcal{B}_9, \langle a_2, \textsc{Arg}\rangle)} \qquad \dfrac{\mathit{extract}(\textsc{Deref}, \text{ref}^{\text{int}^{\epsilon}}\ \epsilon) = \text{int}^{\epsilon} \qquad \mathit{label}(\text{int}^{\epsilon}) = \epsilon}{\mathit{collectblame}(\textsc{Deref}, \mathcal{B}_9, \text{ref}^{\text{int}^{\epsilon}}\ \epsilon) = \emptyset}\end{array}}{\mathit{blame}(\sigma_5, a_3, a_4, \textsc{Deref}, \mathcal{B}_9)}$$
-
$$\begin{array}{c}\dfrac{\begin{array}{c}\mathcal{B}_9(a_2) = \{\langle a_1, \textsc{Arg}\rangle, \langle a_1, \textsc{Res}\rangle, \text{int}^{\epsilon_0} \rightarrow^{\epsilon} \text{int}^{\epsilon_0}, \langle a_0, \textsc{Arg}\rangle, \langle a_0, \textsc{Res}\rangle\} \\ \dfrac{\vdots_1}{\mathit{collectblame}(\textsc{Arg}; \textsc{Deref}, \mathcal{B}_9, \text{int}^{\epsilon_0} \rightarrow^{\epsilon} \text{int}^{\epsilon_0})} \qquad \cdots\end{array}}{\dfrac{\mathit{collectblame}(\textsc{Deref}, \mathcal{B}_9, \langle a_2, \textsc{Arg}\rangle)}{\vdots_0}}\end{array}$$

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$$\cfrac{\cfrac{\mathit{extract}\,(\textsc{Arg};\textsc{Deref}, \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0}) = \mathit{extract}\,(\textsc{Deref}, \mathsf{int}^{\epsilon_0}) = \mathrm{UNDEFINED}}{\mathit{collectblame}\,(\textsc{Arg};\textsc{Deref}, \mathcal{B}_9, \mathsf{int}^{\epsilon_0} \rightarrow^{\epsilon} \mathsf{int}^{\epsilon_0})}}{\vdots_1}$$

□

REFERENCES

[1] Michael M. Vitousek, Cameron Swords, and Jeremy G. Siek. 2017. Big Types in Little Runtime: Open-World Soundness and Collaborative Blame for Gradual Type Systems. In *POPL*. 762–774.