| | |
|---|---|
| $\rho$ ::= | エスケープの有無 (束を構成) |
| $\quad$ *true* | エスケープするかもしれない ($\top$) |
| $\quad$ *false* | 決してエスケープしない ($\bot$) |
| $G$ ::= | 現在のフレームよりもグローバルな array か否か (束を構成) |
| $\quad$ *true* | グローバルな array かもしれない ($\top$) |
| $\quad$ *false* | 決してグローバルな array ではない ($\bot$) |
| $\tau$ ::= | 型 |
| $\quad \pi$ | プリミティブ型 |
| $\quad (\overline{\tau} \rightarrow \tau)_\rho$ | 関数型 |
| $\quad (\tau_1 \times \ldots \times \tau_n)_\rho$ | 組型 |
| $\quad (\tau\ \texttt{array})_{\rho,G}$ | 配列型 |
| $e$ ::= | 式 |
| $\quad c$ | 定数 |
| $\quad op(e_1, \ldots, e_n)$ | プリミティブ演算 |
| $\quad \texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3$ | 条件分岐 |
| $\quad \texttt{let}\ x = e_1\ \texttt{in}\ e_2$ | 変数定義 |
| $\quad x$ | 変数の読み出し |
| $\quad \texttt{let rec}\ _\rho\ x\ \overline{y} = e_1\ \texttt{in}\ e_2$ | 再帰関数定義 |
| $\quad e_1\ \overline{e_2}$ | 関数呼び出し |
| $\quad (e_1, \ldots, e_n)_\rho$ | 組の作成 |
| $\quad \texttt{let}\ (x_1, \ldots, x_n) = e_1\ \texttt{in}\ e_2$ | 組の読み出し |
| $\quad \texttt{Array.create}_\rho\ e_1\ e_2$ | 配列の作成 |
| $\quad e_1.(e_2)$ | 配列の読み出し |
| $\quad e_1.(e_2) \leftarrow e_3$ | 配列への書き込み |

図 1: エスケープ解析用に拡張された Min-Caml の構文。$\overline{x}$ 等は $x_1, \ldots, x_n$ 等の略。$\rho$ はコンパイラがエスケープ解析により補う

$$
\begin{array}{lcl}
\mathit{Globalize}(x_1 : \tau_1, \ldots, x_n : \tau_n) & = & x_1 : \mathit{Globalize}(\tau_1), \ldots, x_n : \mathit{Globalize}(\tau_n) \\
\\
\mathit{Globalize}((\overline{\tau} \to \tau)_\rho) & = & (\mathit{Globalize}(\overline{\tau}) \to \mathit{Globalize}(\tau))_\rho \\
\mathit{Globalize}((\tau_1 \times \ldots \times \tau_n)_\rho) & = & (\mathit{Globalize}(\tau_1) \times \ldots \times \mathit{Globalize}(\tau_n))_\rho \\
\mathit{Globalize}((\tau\ \texttt{array})_{\rho,G}) & = & (\mathit{Globalize}(\tau)\ \texttt{array})_{\rho,\mathit{true}} \\
\mathit{Globalize}(\tau) & = & \tau \quad \text{(上記以外)} \\
\\
\mathit{Escapes}((\overline{\tau} \to \tau)_\rho) & = & \rho \\
\mathit{Escapes}((\tau_1 \times \ldots \times \tau_n)_\rho) & = & \rho \\
\mathit{Escapes}((\tau\ \texttt{array})_{\rho,G}) & = & \rho \\
\mathit{Escapes}(\tau) & = & \mathit{true} \quad \text{(上記以外)}
\end{array}
$$

図 2: エスケープ解析用の補助関数

$$
\frac{c\ \text{は}\ \pi\ \text{型の定数}}{\Gamma \vdash c : \pi}
\qquad
\frac{\Gamma \vdash e_1 : \pi_1 \quad \ldots \quad \Gamma \vdash e_n : \pi_n \qquad \mathit{op}\ \text{は}\ \pi_1, \ldots, \pi_n\ \text{型の値を受け取って}\ \pi\ \text{型の値を返すプリミティブ演算}}{\Gamma \vdash \mathit{op}(e_1, \ldots, e_n) : \pi}
$$

$$
\frac{\Gamma \vdash e_1 : \texttt{bool} \quad \Gamma \vdash e_2 : \tau \quad \Gamma \vdash e_3 : \tau}{\Gamma \vdash \texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3 : \tau}
\qquad
\frac{\Gamma \vdash e_1 : \tau_1 \quad \Gamma, x : \tau_1 \vdash e_2 : \tau_2}{\Gamma \vdash \texttt{let}\ x = e_1\ \texttt{in}\ e_2 : \tau_2}
$$

$$
\frac{\Gamma(x) = \tau}{\Gamma \vdash x : \tau}
\qquad
\frac{\begin{array}{c}\mathit{Globalize}(\Gamma, x : (\overline{\tau} \to \tau)_\rho, \overline{y} : \overline{\tau}) \vdash e_1 : \tau \\ \Gamma, x : (\overline{\tau} \to \tau)_\rho \vdash e_2 : \tau' \\ \mathit{true} \sqsubseteq \mathit{Escapes}(\tau) \\ \forall z \in \mathcal{FV}(e_1) \setminus \{x, \overline{y}\}.\ \rho \sqsubseteq \mathit{Escapes}(\Gamma(z))\end{array}}{\Gamma \vdash \texttt{let rec}_{\ \rho}\ x\ \overline{y} = e_1\ \texttt{in}\ e_2 : \tau'}
\qquad
\frac{\Gamma \vdash e_1 : (\overline{\tau} \to \tau)_\rho \quad \Gamma \vdash \overline{e_2} : \overline{\tau}}{\Gamma \vdash e_1\ \overline{e_2} : \tau}
$$

$$
\frac{\begin{array}{c}\Gamma \vdash e_1 : \tau_1 \quad \ldots \quad \Gamma \vdash e_n : \tau_n \\ \rho \sqsubseteq \mathit{Escapes}(\tau_1) \quad \ldots \quad \rho \sqsubseteq \mathit{Escapes}(\tau_n)\end{array}}{\Gamma \vdash (e_1, \ldots, e_n)_\rho : (\tau_1 \times \ldots \times \tau_n)_\rho}
\qquad
\frac{\begin{array}{c}\Gamma \vdash e_1 : (\tau_1 \times \ldots \times \tau_n)_\rho \\ \Gamma, x_1 : \tau_1, \ldots, x_n : \tau_n \vdash e_2 : \tau\end{array}}{\Gamma \vdash \texttt{let}\ (x_1, \ldots, x_n) = e_1\ \texttt{in}\ e_2 : \tau}
$$

$$
\frac{\begin{array}{c}\Gamma \vdash e_1 : \mathbf{int} \quad \Gamma \vdash e_2 : \tau \\ \rho \sqsubseteq \mathit{Escapes}(\tau)\end{array}}{\Gamma \vdash \texttt{Array.create}_\rho\ e_1\ e_2 : (\tau\ \texttt{array})_{\rho,G}}
\qquad
\frac{\Gamma \vdash e_1 : (\tau\ \texttt{array})_{\rho,G} \quad \Gamma \vdash e_2 : \mathbf{int}}{\Gamma \vdash e_1.(e_2) : \tau}
$$

$$
\frac{\begin{array}{c}\Gamma \vdash e_1 : (\tau\ \texttt{array})_{\rho,G} \quad \Gamma \vdash e_2 : \mathbf{int} \quad \Gamma \vdash e_3 : \tau \\ G \sqsubseteq \mathit{Escapes}(\tau)\end{array}}{\Gamma \vdash e_1.(e_2) \leftarrow e_3 : \texttt{unit}}
$$

図 3: エスケープ解析用の型付け規則

プログラム:

$$\texttt{let rec}\ \ f\ x = (\texttt{let}\ p = (x, x)\ \texttt{in let}\ q = (p, x)\ \texttt{in}\ q)\ \texttt{in}\ f\ 3$$

型付け:

$$\frac{\dfrac{\dfrac{}{f:\tau_f,\, x:\mathbf{int} \vdash x:\mathbf{int}} \quad \dfrac{}{f:\tau_f,\, x:\mathbf{int} \vdash x:\mathbf{int}}}{f:\tau_f,\, x:\mathbf{int} \vdash (x,x)_{\rho_p}:\tau_p} \qquad \dfrac{\dfrac{\dfrac{}{f:\tau_f,\, x:\mathbf{int},\, p:\tau_p \vdash p:\tau_p} \quad \dfrac{}{f:\tau_f,\, x:\mathbf{int},\, p:\tau_p \vdash x:\mathbf{int}}}{f:\tau_f,\, x:\mathbf{int},\, p:\tau_p \vdash (p,x)_{\rho_q}:\tau_q} \quad \cdots}{f:\tau_f,\, x:\mathbf{int},\, p:\tau_p \vdash \texttt{let}\ q = (p,x)_{\rho_q}\ \texttt{in}\ q:\tau_q}}{\dfrac{f:\tau_f,\, x:\mathbf{int} \vdash \texttt{let}\ p = (x,x)_{\rho_p}\ \texttt{in let}\ q = (p,x)_{\rho_q}\ \texttt{in}\ q:\tau_q \qquad \cdots}{\emptyset \vdash \texttt{let rec}\ _{\rho_f}\ f\ x = (\texttt{let}\ p = (x,x)_{\rho_p}\ \texttt{in let}\ q = (p,x)_{\rho_q}\ \texttt{in}\ q)\ \texttt{in}\ f\ 3:\tau_q}}$$

ただし $\tau_p$ は $(\mathbf{int} \times \mathbf{int})_{\rho_p}$、$\tau_q$ は $(\tau_p \times \mathbf{int})_{\rho_q}$、$\tau_f$ は $(\mathbf{int} \to \tau_q)_{\rho_f}$、の略記

制約:

$$\begin{array}{lll} \rho_p \sqsubseteq \mathit{Escapes}(\pi) \quad \rho_p \sqsubseteq \mathit{Escapes}(\pi) & & (\text{組 p}) \\ \rho_q \sqsubseteq \mathit{Escapes}(\tau_p) \quad \rho_q \sqsubseteq \mathit{Escapes}(\pi) & & (\text{組 q}) \\ \mathit{true} \sqsubseteq \mathit{Escapes}(\tau_q) & & (\text{返り値}) \end{array}$$

Simplify された制約:

$$\begin{array}{l} \rho_q \sqsubseteq \rho_p \\ \mathit{true} \sqsubseteq \rho_q \end{array}$$

反復アルゴリズムによって求まる解:

$$\begin{array}{l} \rho_p = \mathit{true} \\ \rho_q = \mathit{true} \\ \rho_f = \mathit{false} \end{array}$$

図 4: エスケープ解析の例 1

プログラム:

$$\mathtt{let}\ a = \mathtt{ref}\ (1,2)\ \mathtt{in}\ \mathtt{let}\ \mathtt{rec}\ \ f\ () = \mathtt{let}\ b = \mathtt{ref}\ (3,4)\ \mathtt{in}\ a := (5,6);\ b := (7,8)\ \mathtt{in}\ f\ ()$$

ただし $\mathtt{ref}\ e$ は $\mathtt{Array.create}\ 1\ e$、$e_1 := e_2$ は $e_1.(0) \leftarrow e_2$、$e_1; e_2$ は $\mathtt{let}\ \_ = e_1\ \mathtt{in}\ e_2$、の略記

型付け:

$$\dfrac{\dfrac{\dfrac{\vdots}{\emptyset \vdash (1,2)_{\rho_{12}} : \tau_{12}}}{\emptyset \vdash \mathtt{ref}_{\rho_a}(1,2)_{\rho_{12}} : \tau_{a\_f}} \quad \dfrac{\dfrac{\dfrac{\dfrac{\vdots}{AT \vdash (3,4)_{\rho_{34}} : \tau_{34}}}{AT \vdash \mathtt{ref}_{\rho_b}(3,4)_{\rho_{34}} : \tau_{b\_f}} \quad \dfrac{\dfrac{\ldots \quad \dfrac{\vdots}{AT, B \vdash (5,6)_{\rho_{12}} : \tau_{12}}}{AT, B \vdash a := (5,6)_{\rho_{12}} : \mathtt{unit}} \quad \dfrac{\ldots \quad \dfrac{\vdots}{AT, B \vdash (7,8)_{\rho_{34}} : \tau_{34}}}{AT, B \vdash b := (7,8)_{\rho_{34}} : \mathtt{unit}}}{AT, B \vdash a := (5,6)_{\rho_{12}}; b := (7,8)_{\rho_{34}} : \mathtt{unit}}}{AT \vdash \mathtt{let}\ b = \mathtt{ref}_{\rho_b}(3,4)_{\rho_{34}}\ \mathtt{in}\ a := (5,6)_{\rho_{12}}; b := (7,8)_{\rho_{34}} : \mathtt{unit}} \quad \ldots}{A \vdash \mathtt{let}\ \mathtt{rec}\ {}_{\rho_f}\ f\ () = \mathtt{let}\ b = \mathtt{ref}_{\rho_b}(3,4)_{\rho_{34}}\ \mathtt{in}\ a := (5,6)_{\rho_{12}}; b := (7,8)_{\rho_{34}}\ \mathtt{in}\ f\ () : \mathtt{unit}}}{\emptyset \vdash \mathtt{let}\ a = \mathtt{ref}_{\rho_a}(1,2)_{\rho_{12}}\ \mathtt{in}\ \mathtt{let}\ \mathtt{rec}\ {}_{\rho_f}\ f\ () = \mathtt{let}\ b = \mathtt{ref}_{\rho_b}(3,4)_{\rho_{34}}\ \mathtt{in}\ a := (5,6)_{\rho_{12}}; b := (7,8)_{\rho_{34}}\ \mathtt{in}\ f\ () : \mathtt{unit}}$$

ただし $\tau_{12}$ は $(\mathbf{int} \times \mathbf{int})_{\rho_{12}}$、$\tau_{34}$ は $(\mathbf{int} \times \mathbf{int})_{\rho_{34}}$、
$\tau_a$ は $(\tau_{12}\ \mathtt{ref})_{\rho_a, G_a}$、$\tau_{a\_t}$ は $(\tau_{12}\ \mathtt{ref})_{\rho_a, true}$、$\tau_b$ は $(\tau_{34}\ \mathtt{ref})_{\rho_b, G_b}$、$\tau_{b\_t}$ は $(\tau_{34}\ \mathtt{ref})_{\rho_b, true}$、
$A$ は $a : \tau_a$、$AT$ は $a : \tau_{a\_t}$、$B$ は $b : \tau_b$、$BT$ は $b : \tau_{b\_t}$、の略記

制約:

| | | |
|---|---|---|
| $\rho_{12} \sqsubseteq Escapes(\pi)$ | $\rho_{12} \sqsubseteq Escapes(\pi)$ | (組 (1, 2)) |
| $\rho_{34} \sqsubseteq Escapes(\pi)$ | $\rho_{34} \sqsubseteq Escapes(\pi)$ | (組 (3, 4)) |
| $\rho_{12} \sqsubseteq Escapes(\pi)$ | $\rho_{12} \sqsubseteq Escapes(\pi)$ | (組 (5, 6)) |
| $\rho_{34} \sqsubseteq Escapes(\pi)$ | $\rho_{34} \sqsubseteq Escapes(\pi)$ | (組 (7, 8)) |
| $\rho_a \sqsubseteq Escapes(\tau_{12})$ | | (参照 a) |
| $\rho_b \sqsubseteq Escapes(\tau_{34})$ | | (参照 b) |
| $true \sqsubseteq Escapes(\tau_{12})$ | | (参照 a への代入) |
| $G_b \sqsubseteq Escapes(\tau_{34})$ | | (参照 b への代入) |
| $\rho_f \sqsubseteq Escapes(\tau_{a\_f})$ | | (関数 f の自由変数) |
| $true \sqsubseteq Escapes(\pi)$ | | (関数 f の返り値) |

Simplify された制約:

$$\rho_a \sqsubseteq \rho_{12}$$
$$\rho_b \sqsubseteq \rho_{34}$$
$$true \sqsubseteq \rho_{12}$$
$$G_b \sqsubseteq \rho_{34}$$
$$\rho_f \sqsubseteq \rho_a$$

反復アルゴリズムによって求まる解:

$$\rho_{12} = true$$
$$\rho_{34} = false$$
$$\rho_a = false$$
$$\rho_b = false$$
$$\rho_f = false$$

図 5: エスケープ解析の例 2