e ::=	式
c	定数
$op(e_1, \ldots, e_n)$	プリミティブ演算
$\texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3$	条件分岐
$\texttt{let}\ x = e_1\ \texttt{in}\ e_2$	変数定義
x	変数の読み出し
$\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2$	再帰関数定義
$e\ e_1\ \ldots\ e_n$	関数呼び出し
$(e_1, \ldots, e_n)$	組の作成
$\texttt{let}\ (x_1, \ldots, x_n) = e_1\ \texttt{in}\ e_2$	組の読み出し
$\texttt{Array.create}\ e_1\ e_2$	配列の作成
$e_1.(e_2)$	配列の読み出し
$e_1.(e_2) \leftarrow e_3$	配列への書き込み

図 1: MinCaml の抽象構文（型は省略）

τ ::=	型
π	プリミティブ型
$\tau_1 \rightarrow \ldots \rightarrow \tau_n \rightarrow \tau$	関数型
$\tau_1 \times \ldots \times \tau_n$	組型
$\tau\ \texttt{array}$	配列型
α	型変数（型推論用）

図 2: MinCaml の型

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

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

$$\frac{\Gamma, x : \tau_1 \to \ldots \to \tau_n \to \tau, y_1 : \tau_1, \ldots, y_n : \tau_n \vdash e_1 : \tau \qquad \Gamma, x : \tau_1 \to \ldots \to \tau_n \to \tau \vdash e_2 : \tau'}{\Gamma \vdash \texttt{let rec } x\ y_1\ \ldots\ y_n = e_1 \texttt{ in } e_2 : \tau'} \qquad \frac{\Gamma \vdash e : \tau_1 \to \ldots \to \tau_n \to \tau \qquad \Gamma \vdash e_1 : \tau_1 \quad \ldots \quad \Gamma \vdash e_n : \tau_n}{\Gamma \vdash e\ e_1\ \ldots\ e_n : \tau}$$

$$\frac{\Gamma \vdash e_1 : \tau_1 \quad \ldots \quad \Gamma \vdash e_n : \tau_n}{\Gamma \vdash (e_1, \ldots, e_n) : \tau_1 \times \ldots \times \tau_n} \qquad \frac{\Gamma \vdash e_1 : \tau_1 \times \ldots \times \tau_n \quad \Gamma, x_1 : \tau_1, \ldots, x_n : \tau_n \vdash e_2 : \tau}{\Gamma \vdash \texttt{let } (x_1, \ldots, x_n) = e_1 \texttt{ in } e_2 : \tau}$$

$$\frac{\Gamma \vdash e_1 : \texttt{int} \quad \Gamma \vdash e_2 : \tau}{\Gamma \vdash \texttt{Array.create } e_1\ e_2 : \tau \texttt{ array}}$$

$$\frac{\Gamma \vdash e_1 : \tau \texttt{ array} \quad \Gamma \vdash e_2 : \texttt{int}}{\Gamma \vdash e_1.(e_2) : \tau} \qquad \frac{\Gamma \vdash e_1 : \tau \texttt{ array} \quad \Gamma \vdash e_2 : \texttt{int} \quad \Gamma \vdash e_3 : \tau}{\Gamma \vdash e_1.(e_2) \leftarrow e_3 : \texttt{unit}}$$

図 3: MinCaml の型つけ規則

e ::=
- c
- $op(x_1, \ldots, x_n)$
- $\texttt{if } x = y \texttt{ then } e_1 \texttt{ else } e_2$
- $\texttt{if } x \leq y \texttt{ then } e_1 \texttt{ else } e_2$
- $\texttt{let } x = e_1 \texttt{ in } e_2$
- x
- $\texttt{let rec } x\ y_1\ \ldots\ y_n = e_1 \texttt{ in } e_2$
- $x\ y_1\ \ldots\ y_n$
- $(x_1, \ldots, x_n)$
- $\texttt{let } (x_1, \ldots, x_n) = y \texttt{ in } e$
- $x.(y)$
- $x.(y) \leftarrow z$

図 4: MinCaml の K 正規形（外部配列・外部関数適用は省略）

$\mathcal{K}$: `Syntax.t` $\rightarrow$ `KNormal.t`

$$
\begin{array}{lcl}
\mathcal{K}(c) & = & c \\
\mathcal{K}(\texttt{not}(e)) & = & \mathcal{K}(\texttt{if}\ e\ \texttt{then false else true}) \\
\mathcal{K}(e_1 = e_2) & = & \mathcal{K}(\texttt{if}\ e_1 = e_2\ \texttt{then true else false}) \\
\mathcal{K}(e_1 \leq e_2) & = & \mathcal{K}(\texttt{if}\ e_1 \leq e_2\ \texttt{then true else false}) \\
\mathcal{K}(op(e_1, \ldots, e_n)) & = & \texttt{let}\ x_1 = \mathcal{K}(e_1)\ \texttt{in}\ \ldots\ \texttt{let}\ x_n = \mathcal{K}(e_n)\ \texttt{in}\ op(x_1, \ldots, x_n) \\
 & & \hfill op\ \text{が論理演算・比較以外の場合} \\
\mathcal{K}(\texttt{if not}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3) & = & \mathcal{K}(\texttt{if}\ e_1\ \texttt{then}\ e_3\ \texttt{else}\ e_2) \\
\mathcal{K}(\texttt{if}\ e_1 = e_2\ \texttt{then}\ e_3\ \texttt{else}\ e_4) & = & \texttt{let}\ x = \mathcal{K}(e_1)\ \texttt{in let}\ y = \mathcal{K}(e_2)\ \texttt{in} \\
 & & \texttt{if}\ x = y\ \texttt{then}\ \mathcal{K}(e_3)\ \texttt{else}\ \mathcal{K}(e_4) \\
\mathcal{K}(\texttt{if}\ e_1 \leq e_2\ \texttt{then}\ e_3\ \texttt{else}\ e_4) & = & \texttt{let}\ x = \mathcal{K}(e_1)\ \texttt{in let}\ y = \mathcal{K}(e_2)\ \texttt{in} \\
 & & \texttt{if}\ x \leq y\ \texttt{then}\ \mathcal{K}(e_3)\ \texttt{else}\ \mathcal{K}(e_4) \\
\mathcal{K}(\texttt{if}\ e_1\ \texttt{then}\ e_2\ \texttt{else}\ e_3) & = & \mathcal{K}(\texttt{if}\ e_1 = \texttt{false then}\ e_3\ \texttt{else}\ e_2) \\
 & & \hfill e_1\ \text{が論理演算・比較以外の場合} \\
\mathcal{K}(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & \texttt{let}\ x = \mathcal{K}(e_1)\ \texttt{in}\ \mathcal{K}(e_2) \\
\mathcal{K}(x) & = & x \\
\mathcal{K}(\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2) & = & \texttt{let rec}\ x\ y_1\ \ldots\ y_n = \mathcal{K}(e_1)\ \texttt{in}\ \mathcal{K}(e_2) \\
\mathcal{K}(e\ e_1\ \ldots\ e_n) & = & \texttt{let}\ x = \mathcal{K}(e)\ \texttt{in let}\ y_1 = \mathcal{K}(e_1)\ \texttt{in}\ \ldots\ \texttt{let}\ y_n = \mathcal{K}(e_n)\ \texttt{in} \\
 & & x\ y_1\ \ldots\ y_n \\
\mathcal{K}(e_1, \ldots, e_n) & = & \texttt{let}\ x_1 = \mathcal{K}(e_1)\ \texttt{in}\ \ldots\ \texttt{let}\ x_n = \mathcal{K}(e_n)\ \texttt{in}\ (x_1, \ldots, x_n) \\
\mathcal{K}(\texttt{let}\ (x_1, \ldots, x_n) = e_1\ \texttt{in}\ e_2) & = & \texttt{let}\ y = \mathcal{K}(e_1)\ \texttt{in let}\ (x_1, \ldots, x_n) = y\ \texttt{in}\ \mathcal{K}(e_2) \\
\mathcal{K}(\texttt{Array.create}\ e_1\ e_2) & = & \texttt{let}\ x = \mathcal{K}(e_1)\ \texttt{in let}\ y = \mathcal{K}(e_2)\ \texttt{in create\_array}\ x\ y \\
\mathcal{K}(e_1.(e_2)) & = & \texttt{let}\ x = \mathcal{K}(e_1)\ \texttt{in let}\ y = \mathcal{K}(e_2)\ \texttt{in}\ x.(y) \\
\mathcal{K}(e_1.(e_2) \leftarrow e_3) & = & \texttt{let}\ x = \mathcal{K}(e_1)\ \texttt{in let}\ y = \mathcal{K}(e_2)\ \texttt{in let}\ z = \mathcal{K}(e_3)\ \texttt{in} \\
 & & x.(y) \leftarrow z
\end{array}
$$

図 5: K 正規化（論理値の整数化と、insert_let による最適化は省略）。右辺に出現していて左辺に出現していない変数は、すべて新しい (fresh) とする。

$\alpha : \texttt{Id.t M.t} \to \texttt{KNormal.t} \to \texttt{KNormal.t}$

$$
\begin{array}{lcl}
\alpha_\varepsilon(c) & = & c \\
\alpha_\varepsilon(op(x_1, \ldots, x_n)) & = & op(\varepsilon(x_1), \ldots, \varepsilon(x_n)) \\
\alpha_\varepsilon(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ \varepsilon(x) = \varepsilon(y)\ \texttt{then}\ \alpha_\varepsilon(e_1)\ \texttt{else}\ \alpha_\varepsilon(e_2) \\
\alpha_\varepsilon(\texttt{if}\ x \le y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ \varepsilon(x) \le \varepsilon(y)\ \texttt{then}\ \alpha_\varepsilon(e_1)\ \texttt{else}\ \alpha_\varepsilon(e_2) \\
\alpha_\varepsilon(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & \texttt{let}\ x' = \alpha_\varepsilon(e_1)\ \texttt{in}\ \alpha_{\varepsilon, x \mapsto x'}(e_2) \\
\alpha_\varepsilon(x) & = & \varepsilon(x) \\
\alpha_\varepsilon(\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2) & = & \texttt{let rec}\ x'\ y'_1\ \ldots\ y'_n = \alpha_{\varepsilon, x \mapsto x', y_1 \mapsto y'_1, \ldots, y_n \mapsto y'_n}(e_1)\ \texttt{in} \\
 & & \alpha_{\varepsilon, x \mapsto x'}(e_2) \\
\alpha_\varepsilon(x\ y_1\ \ldots\ y_n) & = & \varepsilon(x)\ \varepsilon(y_1)\ \ldots\ \varepsilon(y_n) \\
\alpha_\varepsilon((x_1, \ldots, x_n)) & = & (\varepsilon(x_1), \ldots, \varepsilon(x_n)) \\
\alpha_\varepsilon(\texttt{let}\ (x_1, \ldots, x_n) = y\ \texttt{in}\ e) & = & \texttt{let}\ (x'_1, \ldots, x'_n) = \varepsilon(y)\ \texttt{in}\ \alpha_{\varepsilon, x_1 \mapsto x'_1, \ldots, x_n \mapsto x'_n}(e) \\
\alpha_\varepsilon(x.(y)) & = & \varepsilon(x).(\varepsilon(y)) \\
\alpha_\varepsilon(x.(y) \leftarrow z) & = & \varepsilon(x).(\varepsilon(y)) \leftarrow \varepsilon(z)
\end{array}
$$

図 6: α 変換。ε は α 変換前の変数を受け取って、α 変換後の変数を返す写像。右辺に出現していて左辺に出現していない変数（x' など）は、すべて fresh とする。

$\beta : \texttt{Id.t M.t} \to \texttt{KNormal.t} \to \texttt{KNormal.t}$

$$
\begin{array}{lcll}
\beta_\varepsilon(c) & = & c & \\
\beta_\varepsilon(op(x_1, \ldots, x_n)) & = & op(\varepsilon(x_1), \ldots, \varepsilon(x_n)) & \\
\beta_\varepsilon(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ \varepsilon(x) = \varepsilon(y)\ \texttt{then}\ \beta_\varepsilon(e_1)\ \texttt{else}\ \beta_\varepsilon(e_2) & \\
\beta_\varepsilon(\texttt{if}\ x \le y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ \varepsilon(x) \le \varepsilon(y)\ \texttt{then}\ \beta_\varepsilon(e_1)\ \texttt{else}\ \beta_\varepsilon(e_2) & \\
\beta_\varepsilon(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & \beta_{\varepsilon, x \mapsto y}(e_2) & \beta_\varepsilon(e_1)\ \text{が変数}\ y\ \text{の場合} \\
\beta_\varepsilon(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & \texttt{let}\ x = \beta_\varepsilon(e_1)\ \texttt{in}\ \beta_\varepsilon(e_2) & \beta_\varepsilon(e_1)\ \text{が変数でない場合} \\
\beta_\varepsilon(x) & = & \varepsilon(x) & \\
\beta_\varepsilon(\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2) & = & \texttt{let rec}\ x\ y_1\ \ldots\ y_n = \beta_\varepsilon(e_1)\ \texttt{in}\ \beta_\varepsilon(e_2) & \\
\beta_\varepsilon(x\ y_1\ \ldots\ y_n) & = & \varepsilon(x)\ \varepsilon(y_1)\ \ldots\ \varepsilon(y_n) & \\
\beta_\varepsilon((x_1, \ldots, x_n)) & = & (\varepsilon(x_1), \ldots, \varepsilon(x_n)) & \\
\beta_\varepsilon(\texttt{let}\ (x_1, \ldots, x_n) = y\ \texttt{in}\ e) & = & \texttt{let}\ (x_1, \ldots, x_n) = \varepsilon(y)\ \texttt{in}\ \beta_\varepsilon(e) & \\
\beta_\varepsilon(x.(y)) & = & \varepsilon(x).(\varepsilon(y)) & \\
\beta_\varepsilon(x.(y) \leftarrow z) & = & \varepsilon(x).(\varepsilon(y)) \leftarrow \varepsilon(z) &
\end{array}
$$

図 7: β 簡約。ε は β 簡約前の変数を受け取って、β 簡約後の変数を返す写像。$\varepsilon(x)$ が定義されていない場合は、$\varepsilon(x) = x$ とみなす。

$\mathcal{A}$: `KNormal.t` $\rightarrow$ `KNormal.t`

$$
\begin{array}{lcl}
\mathcal{A}(c) & = & c \\
\mathcal{A}(op(x_1,\ldots,x_n)) & = & op(x_1,\ldots,x_n) \\
\mathcal{A}(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ x = y\ \texttt{then}\ \mathcal{A}(e_1)\ \texttt{else}\ \mathcal{A}(e_2) \\
\mathcal{A}(\texttt{if}\ x \le y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ x \le y\ \texttt{then}\ \mathcal{A}(e_1)\ \texttt{else}\ \mathcal{A}(e_2) \\
\mathcal{A}(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & \texttt{let}\ \ldots\ \texttt{in}\ \texttt{let}\ x = e_1'\ \texttt{in}\ \mathcal{A}(e_2) \\
 & & \quad \mathcal{A}(e_1) = \texttt{let}\ \ldots\ \texttt{in}\ e_1'\ \text{という形で} \\
 & & \quad (\texttt{let}\ \ldots\ \texttt{in}\ \text{は}\ 0\ \text{個以上の}\ \texttt{let}\ \text{の列})\text{、} \\
 & & \quad e_1'\ \text{は}\ \texttt{let}\ \text{でない} \\
\mathcal{A}(x) & = & x \\
\mathcal{A}(\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2) & = & \texttt{let rec}\ x\ y_1\ \ldots\ y_n = \mathcal{A}(e_1)\ \texttt{in}\ \mathcal{A}(e_2) \\
\mathcal{A}(x\ y_1\ \ldots\ y_n) & = & x\ y_1\ \ldots\ y_n \\
\mathcal{A}((x_1,\ldots,x_n)) & = & (x_1,\ldots,x_n) \\
\mathcal{A}(\texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ e) & = & \texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ \mathcal{A}(e) \\
\mathcal{A}(x.(y)) & = & x.(y) \\
\mathcal{A}(x.(y) \leftarrow z) & = & x.(y) \leftarrow z
\end{array}
$$

図 8: ネストした `let` の簡約

$\mathcal{I} : (\mathtt{Id.t\ list} \times \mathtt{KNormal.t})\ \mathtt{M.t} \to \mathtt{KNormal.t} \to \mathtt{KNormal.t}$

$$
\begin{array}{lcll}
\mathcal{I}_\varepsilon(c) & = & c & \\
\mathcal{I}_\varepsilon(op(x_1,\ldots,x_n)) & = & op(x_1,\ldots,x_n) & \\
\mathcal{I}_\varepsilon(\mathtt{if}\ x=y\ \mathtt{then}\ e_1\ \mathtt{else}\ e_2) & = & \mathtt{if}\ x=y\ \mathtt{then}\ \mathcal{I}_\varepsilon(e_1)\ \mathtt{else}\ \mathcal{I}_\varepsilon(e_2) & \\
\mathcal{I}_\varepsilon(\mathtt{if}\ x\le y\ \mathtt{then}\ e_1\ \mathtt{else}\ e_2) & = & \mathtt{if}\ x\le y\ \mathtt{then}\ \mathcal{I}_\varepsilon(e_1)\ \mathtt{else}\ \mathcal{I}_\varepsilon(e_2) & \\
\mathcal{I}_\varepsilon(\mathtt{let}\ x=e_1\ \mathtt{in}\ e_2) & = & \mathtt{let}\ x=\mathcal{I}_\varepsilon(e_1)\ \mathtt{in}\ \mathcal{I}_\varepsilon(e_2) & \\
\mathcal{I}_\varepsilon(x) & = & x & \\
\mathcal{I}_\varepsilon(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n=e_1\ \mathtt{in}\ e_2) & = & \varepsilon'=\varepsilon, x\mapsto((y_1,\ldots,y_n),e_1)\ \text{として} & \\
 & & \mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n=\mathcal{I}_{\varepsilon'}(e_1)\ \mathtt{in}\ \mathcal{I}_{\varepsilon'}(e_2) & \\
 & & & \mathit{size}(e_1)\le \mathit{th}\ \text{の場合} \\
\mathcal{I}_\varepsilon(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n=e_1\ \mathtt{in}\ e_2) & = & \mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n=\mathcal{I}_\varepsilon(e_1)\ \mathtt{in}\ \mathcal{I}_\varepsilon(e_2) & \\
 & & & \mathit{size}(e_1)> \mathit{th}\ \text{の場合} \\
\mathcal{I}_\varepsilon(x\ y_1\ \ldots\ y_n) & = & \alpha_{y_1\mapsto z_1,\ldots,y_n\mapsto z_n}(e) & \varepsilon(x)=((z_1,\ldots,z_n),e)\ \text{の場合} \\
\mathcal{I}_\varepsilon(x\ y_1\ \ldots\ y_n) & = & x\ y_1\ \ldots\ y_n & \varepsilon(x)\ \text{が定義されていない場合} \\
\mathcal{I}_\varepsilon((x_1,\ldots,x_n)) & = & (x_1,\ldots,x_n) & \\
\mathcal{I}_\varepsilon(\mathtt{let}\ (x_1,\ldots,x_n)=y\ \mathtt{in}\ e) & = & \mathtt{let}\ (x_1,\ldots,x_n)=y\ \mathtt{in}\ \mathcal{I}_\varepsilon(e) & \\
\mathcal{I}_\varepsilon(x.(y)) & = & x.(y) & \\
\mathcal{I}_\varepsilon(x.(y)\leftarrow z) & = & x.(y)\leftarrow z &
\end{array}
$$

$$
\begin{array}{lcl}
\mathit{size}(c) & = & 1 \\
\mathit{size}(op(x_1,\ldots,x_n)) & = & 1 \\
\mathit{size}(\mathtt{if}\ x=y\ \mathtt{then}\ e_1\ \mathtt{else}\ e_2) & = & 1+\mathit{size}(e_1)+\mathit{size}(e_2) \\
\mathit{size}(\mathtt{if}\ x\le y\ \mathtt{then}\ e_1\ \mathtt{else}\ e_2) & = & 1+\mathit{size}(e_1)+\mathit{size}(e_2) \\
\mathit{size}(\mathtt{let}\ x=e_1\ \mathtt{in}\ e_2) & = & 1+\mathit{size}(e_1)+\mathit{size}(e_2) \\
\mathit{size}(x) & = & 1 \\
\mathit{size}(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n=e_1\ \mathtt{in}\ e_2) & = & 1+\mathit{size}(e_1)+\mathit{size}(e_2) \\
\mathit{size}(x\ y_1\ \ldots\ y_n) & = & 1 \\
\mathit{size}((x_1,\ldots,x_n)) & = & 1 \\
\mathit{size}(\mathtt{let}\ (x_1,\ldots,x_n)=y\ \mathtt{in}\ e) & = & 1+\mathit{size}(e) \\
\mathit{size}(x.(y)) & = & 1 \\
\mathit{size}(x.(y)\leftarrow z) & = & 1
\end{array}
$$

図 9: インライン展開。ε はサイズの小さい関数名を受け取って、仮引数と本体を返す写像。th はインライン展開する関数の最大サイズ（ユーザ指定）。

$\mathcal{F}$: `KNormal.t M.t` $\to$ `KNormal.t` $\to$ `KNormal.t`

$$
\begin{array}{lcll}
\mathcal{F}_\varepsilon(c) & = & c & \\
\mathcal{F}_\varepsilon(op(x_1,\ldots,x_n)) & = & c & op(\varepsilon(x_1),\ldots,\varepsilon(x_n)) = c \text{ の場合} \\
\mathcal{F}_\varepsilon(op(x_1,\ldots,x_n)) & = & op(x_1,\ldots,x_n) & \text{それ以外の場合} \\
\mathcal{F}_\varepsilon(\texttt{if } x = y \texttt{ then } e_1 \texttt{ else } e_2) & = & \mathcal{F}_\varepsilon(e_1) & \varepsilon(x) \text{ と } \varepsilon(y) \text{ が等しい定数の場合} \\
\mathcal{F}_\varepsilon(\texttt{if } x = y \texttt{ then } e_1 \texttt{ else } e_2) & = & \mathcal{F}_\varepsilon(e_2) & \varepsilon(x) \text{ と } \varepsilon(y) \text{ が異なる定数の場合} \\
\mathcal{F}_\varepsilon(\texttt{if } x = y \texttt{ then } e_1 \texttt{ else } e_2) & = & \texttt{if } x = y \texttt{ then } \mathcal{F}_\varepsilon(e_1) \texttt{ else } \mathcal{F}_\varepsilon(e_2) & \text{それ以外の場合} \\
\mathcal{F}_\varepsilon(\texttt{if } x \le y \texttt{ then } e_1 \texttt{ else } e_2) & = & \mathcal{F}_\varepsilon(e_1) & \varepsilon(x) \text{ と } \varepsilon(y) \text{ が定数で、} \varepsilon(x) \le \varepsilon(y) \text{ の場合} \\
\mathcal{F}_\varepsilon(\texttt{if } x \le y \texttt{ then } e_1 \texttt{ else } e_2) & = & \mathcal{F}_\varepsilon(e_2) & \varepsilon(x) \text{ と } \varepsilon(y) \text{ が定数で、} \varepsilon(x) > \varepsilon(y) \text{ の場合} \\
\mathcal{F}_\varepsilon(\texttt{if } x \le y \texttt{ then } e_1 \texttt{ else } e_2) & = & \texttt{if } x \le y \texttt{ then } \mathcal{F}_\varepsilon(e_1) \texttt{ else } \mathcal{F}_\varepsilon(e_2) & \text{それ以外の場合} \\
\mathcal{F}_\varepsilon(\texttt{let } x = e_1 \texttt{ in } e_2) & = & e_1' = \mathcal{F}_\varepsilon(e_1) \text{ として} & \\
 & & \texttt{let } x = e_1' \texttt{ in } \mathcal{F}_{\varepsilon, x \mapsto e_1'}(e_2) & \\
\mathcal{F}_\varepsilon(x) & = & x & \\
\mathcal{F}_\varepsilon(\texttt{let rec } x\ y_1\ \ldots\ y_n = e_1 \texttt{ in } e_2) & = & \texttt{let rec } x\ y_1\ \ldots\ y_n = \mathcal{F}_\varepsilon(e_1) \texttt{ in } \mathcal{F}_\varepsilon(e_2) & \\
\mathcal{F}_\varepsilon(x\ y_1\ \ldots\ y_n) & = & x\ y_1\ \ldots\ y_n & \\
\mathcal{F}_\varepsilon((x_1,\ldots,x_n)) & = & (x_1,\ldots,x_n) & \\
\mathcal{F}_\varepsilon(\texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } e) & = & \texttt{let } x_1 = y_1 \texttt{ in } \ldots \texttt{ let } x_n = y_n \texttt{ in } \mathcal{F}_\varepsilon(e) & \\
 & & & \varepsilon(y) = (y_1,\ldots,y_n) \text{ の場合} \\
\mathcal{F}_\varepsilon(\texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } e) & = & \texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } \mathcal{F}_\varepsilon(e) & \\
\mathcal{F}_\varepsilon(x.(y)) & = & x.(y) & \\
\mathcal{F}_\varepsilon(x.(y) \leftarrow z) & = & x.(y) \leftarrow z &
\end{array}
$$

図 10: 定数畳み込み。ε は変数を受け取って、定数を返す写像。

$\mathcal{E}$: KNormal.t $\rightarrow$ KNormal.t

$$
\begin{array}{lcll}
\mathcal{E}(c) & = & c & \\
\mathcal{E}(op(x_1,\ldots,x_n)) & = & op(x_1,\ldots,x_n) & \\
\mathcal{E}(\texttt{if } x = y \texttt{ then } e_1 \texttt{ else } e_2) & = & \texttt{if } x = y \texttt{ then } \mathcal{E}(e_1) \texttt{ else } \mathcal{E}(e_2) & \\
\mathcal{E}(\texttt{if } x \leq y \texttt{ then } e_1 \texttt{ else } e_2) & = & \texttt{if } x \leq y \texttt{ then } \mathcal{E}(e_1) \texttt{ else } \mathcal{E}(e_2) & \\
\mathcal{E}(\texttt{let } x = e_1 \texttt{ in } e_2) & = & \mathcal{E}(e_2) & \mathit{effect}(\mathcal{E}(e_1)) = \mathit{false} \text{ かつ } x \notin FV(\mathcal{E}(e_2)) \text{ の場合} \\
\mathcal{E}(\texttt{let } x = e_1 \texttt{ in } e_2) & = & \texttt{let } x = \mathcal{E}(e_1) \texttt{ in } \mathcal{E}(e_2) & \text{それ以外の場合} \\
\mathcal{E}(x) & = & x & \\
\mathcal{E}(\texttt{let rec } x\ y_1\ \ldots\ y_n = e_1 \texttt{ in } e_2) & = & \mathcal{E}(e_2) & x \notin FV(\mathcal{E}(e_2)) \text{ の場合} \\
\mathcal{E}(\texttt{let rec } x\ y_1\ \ldots\ y_n = e_1 \texttt{ in } e_2) & = & \texttt{let rec } x\ y_1\ \ldots\ y_n = \mathcal{E}(e_1) \texttt{ in } \mathcal{E}(e_2) & \text{それ以外の場合} \\
\mathcal{E}(x\ y_1\ \ldots\ y_n) & = & x\ y_1\ \ldots\ y_n & \\
\mathcal{E}((x_1,\ldots,x_n)) & = & (x_1,\ldots,x_n) & \\
\mathcal{E}(\texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } e) & = & \mathcal{E}(e) & \{x_1,\ldots,x_n\} \cap FV(\mathcal{E}(e)) = \emptyset \text{ の場合} \\
\mathcal{E}(\texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } e) & = & \texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } \mathcal{E}(e) & \text{それ以外の場合} \\
\mathcal{E}(x.(y)) & = & x.(y) & \\
\mathcal{E}(x.(y) \leftarrow z) & = & x.(y) \leftarrow z &
\end{array}
$$

effect : KNormal.t $\rightarrow$ bool

$$
\begin{array}{lcl}
\mathit{effect}(c) & = & \mathit{false} \\
\mathit{effect}(op(x_1,\ldots,x_n)) & = & \mathit{false} \\
\mathit{effect}(\texttt{if } x = y \texttt{ then } e_1 \texttt{ else } e_2) & = & \mathit{effect}(e_1) \vee \mathit{effect}(e_2) \\
\mathit{effect}(\texttt{if } x \leq y \texttt{ then } e_1 \texttt{ else } e_2) & = & \mathit{effect}(e_1) \vee \mathit{effect}(e_2) \\
\mathit{effect}(\texttt{let } x = e_1 \texttt{ in } e_2) & = & \mathit{effect}(e_1) \vee \mathit{effect}(e_2) \\
\mathit{effect}(x) & = & \mathit{false} \\
\mathit{effect}(\texttt{let rec } x\ y_1\ \ldots\ y_n = e_1 \texttt{ in } e_2) & = & \mathit{effect}(e_2) \\
\mathit{effect}(x\ y_1\ \ldots\ y_n) & = & \mathit{true} \\
\mathit{effect}((x_1,\ldots,x_n)) & = & \mathit{false} \\
\mathit{effect}(\texttt{let } (x_1,\ldots,x_n) = y \texttt{ in } e) & = & \mathit{effect}(e) \\
\mathit{effect}(x.(y)) & = & \mathit{false} \\
\mathit{effect}(x.(y) \leftarrow z) & = & \mathit{true}
\end{array}
$$

図 11: 不要定義削除 (1/2)

FV : `KNormal.t` $\rightarrow$ `S.t`

$$
\begin{array}{lcl}
FV(c) & = & \emptyset \\
FV(op(x_1,\ldots,x_n)) & = & \{x_1,\ldots,x_n\} \\
FV(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \{x,y\} \cup FV(e_1) \cup FV(e_2) \\
FV(\texttt{if}\ x \leq y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \{x,y\} \cup FV(e_1) \cup FV(e_2) \\
FV(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & FV(e_1) \cup (FV(e_2) \setminus \{x\}) \\
FV(x) & = & \{x\} \\
FV(\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2) & = & ((FV(e_1) \setminus \{y_1,\ldots,y_n\}) \cup FV(e_2)) \setminus \{x\} \\
FV(x\ y_1\ \ldots\ y_n) & = & \{x,y_1,\ldots,y_n\} \\
FV((x_1,\ldots,x_n)) & = & \{x_1,\ldots,x_n\} \\
FV(\texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ e) & = & \{y\} \cup (FV(e) \setminus \{x_1,\ldots,x_n\}) \\
FV(x.(y)) & = & \{x,y\} \\
FV(x.(y) \leftarrow z) & = & \{x,y,z\}
\end{array}
$$

図 12: 不要定義削除 (2/2)

P ::=	プログラム全体
$(\{D_1,\ldots,D_n\},e)$	トップレベル関数定義の集合とメインルーチンの式
D ::=	トップレベル関数定義
$\mathtt{L}_x(y_1,\ldots,y_m)(z_1,\ldots,z_n) = e$	関数のラベルと仮引数、自由変数、および本体
e ::=	
c	
$op(x_1,\ldots,x_n)$	
$\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2$	
$\texttt{if}\ x \leq y\ \texttt{then}\ e_1\ \texttt{else}\ e_2$	
$\texttt{let}\ x = e_1\ \texttt{in}\ e_2$	
x	
$\mathit{make\_closure}\ x = (\mathtt{L}_x,(y_1,\ldots,y_n))\ \texttt{in}\ e$	クロージャ生成
$\mathit{apply\_closure}(x,y_1,\ldots,y_n)$	クロージャを用いた関数呼び出し
$\mathit{apply\_direct}(\mathtt{L}_x,y_1,\ldots,y_n)$	クロージャを用いない関数呼び出し (known function call)
$(x_1,\ldots,x_n)$	
$\texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ e$	
$x.(y)$	
$x.(y) \leftarrow z$	

図 13: クロージャ変換後の構文

$\mathcal{C}$: `KNormal.t` $\rightarrow$ `Closure.t`

$$
\begin{array}{lcl}
\mathcal{C}(c) & = & c \\
\mathcal{C}(op(x_1,\ldots,x_n)) & = & op(x_1,\ldots,x_n) \\
\mathcal{C}(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ x = y\ \texttt{then}\ \mathcal{C}(e_1)\ \texttt{else}\ \mathcal{C}(e_2) \\
\mathcal{C}(\texttt{if}\ x \le y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ x \le y\ \texttt{then}\ \mathcal{C}(e_1)\ \texttt{else}\ \mathcal{C}(e_2) \\
\mathcal{C}(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & \texttt{let}\ x = \mathcal{C}(e_1)\ \texttt{in}\ \mathcal{C}(e_2) \\
\mathcal{C}(x) & = & x \\
\mathcal{C}(\texttt{let rec}\ x\ y_1\ \ldots\ y_n = e_1\ \texttt{in}\ e_2) & = & \mathcal{D}\ \text{に}\ \texttt{L}_x(y_1,\ldots,y_n)(z_1,\ldots,z_m) = e_1'\ \text{を加え、} \\
 & & \mathit{make\_closure}\ x = (\texttt{L}_x,(z_1,\ldots,z_m))\ \texttt{in}\ e_2'\text{を返す} \\
 & & \quad\text{ただし}\ e_1' = \mathcal{C}(e_1),\ e_2' = \mathcal{C}(e_2), \\
 & & \quad FV(e_1') \setminus \{x, y_1,\ldots,y_n\} = \{z_1,\ldots,z_m\} \\
\mathcal{C}(x\ y_1\ \ldots\ y_n) & = & \mathit{apply\_closure}(x, y_1,\ldots,y_n) \\
\mathcal{C}((x_1,\ldots,x_n)) & = & (x_1,\ldots,x_n) \\
\mathcal{C}(\texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ e) & = & \texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ \mathcal{C}(e) \\
\mathcal{C}(x.(y)) & = & x.(y) \\
\mathcal{C}(x.(y) \leftarrow z) & = & x.(y) \leftarrow z
\end{array}
$$

FV : `Closure.t` $\rightarrow$ `S.t`

$$
\begin{array}{lcl}
FV(c) & = & \emptyset \\
FV(op(x_1,\ldots,x_n)) & = & \{x_1,\ldots,x_n\} \\
FV(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \{x,y\} \cup FV(e_1) \cup FV(e_2) \\
FV(\texttt{if}\ x \le y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \{x,y\} \cup FV(e_1) \cup FV(e_2) \\
FV(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & FV(e_1) \cup (FV(e_2) \setminus \{x\}) \\
FV(x) & = & \{x\} \\
FV(\mathit{make\_closure}\ x = (\texttt{L}_x,(y_1,\ldots,y_n))\ \texttt{in}\ e) & = & \{y_1,\ldots,y_n\} \cup (FV(e) \setminus \{x\}) \\
FV(\mathit{apply\_closure}(x, y_1,\ldots,y_n)) & = & \{x, y_1,\ldots,y_n\} \\
FV(\mathit{apply\_direct}(\texttt{L}_x, y_1,\ldots,y_n)) & = & \{y_1,\ldots,y_n\} \\
FV((x_1,\ldots,x_n)) & = & \{x_1,\ldots,x_n\} \\
FV(\texttt{let}\ (x_1,\ldots,x_n) = y\ \texttt{in}\ e) & = & \{y\} \cup (FV(e) \setminus \{x_1,\ldots,x_n\}) \\
FV(x.(y)) & = & \{x,y\} \\
FV(x.(y) \leftarrow z) & = & \{x,y,z\}
\end{array}
$$

図 14: 賢くない Closure 変換 $\mathcal{C}(e)$。$\mathcal{D}$ はトップレベル関数定義の集合を記憶しておくためのグローバル変数。

$\mathcal{C} : \mathtt{S.t} \to \mathtt{KNormal.t} \to \mathtt{Closure.t}$

$$
\begin{array}{lcll}
\mathcal{C}_s(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n = e_1\ \mathtt{in}\ e_2) & = & \mathcal{D}\ \text{に}\ \mathtt{L}_x(y_1,\ldots,y_n)() = e_1'\ \text{を加え、} & \\
 & & \mathit{make\_closure}\ x = (\mathtt{L}_x, ())\ \mathtt{in}\ e_2'\text{を返す} & \\
 & & \quad\text{ただし}\ e_1' = \mathcal{C}_{s'}(e_1),\ e_2' = \mathcal{C}_{s'}(e_2),\ s' = s \cup \{x\}, & \\
 & & \quad FV(e_1') \setminus \{y_1,\ldots,y_n\} = \emptyset\ \text{の場合} & \\
\mathcal{C}_s(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n = e_1\ \mathtt{in}\ e_2) & = & \mathcal{D}\ \text{に}\ \mathtt{L}_x(y_1,\ldots,y_n)(z_1,\ldots,z_m) = e_1'\ \text{を加え、} & \\
 & & \mathit{make\_closure}\ x = (\mathtt{L}_x, (z_1,\ldots,z_m))\ \mathtt{in}\ e_2'\text{を返す} & \\
 & & \quad\text{ただし}\ e_1' = \mathcal{C}_s(e_1),\ e_2' = \mathcal{C}_s(e_2), & \\
 & & \quad FV(e_1') \setminus \{y_1,\ldots,y_n\} \neq \emptyset, & \\
 & & \quad FV(e_1') \setminus \{x, y_1,\ldots,y_n\} = \{z_1,\ldots,z_m\}\ \text{の場合} & \\
\mathcal{C}_s(x\ y_1\ \ldots\ y_n) & = & \mathit{apply\_closure}(x, y_1,\ldots,y_n) & x \notin s\ \text{の場合} \\
\mathcal{C}_s(x\ y_1\ \ldots\ y_n) & = & \mathit{apply\_direct}(\mathtt{L}_x, y_1,\ldots,y_n) & x \in s\ \text{の場合}
\end{array}
$$

図 15: やや賢い Closure 変換 $\mathcal{C}_s(e)$。s は自由変数がないとわかっている関数の名前の集合。

$\mathcal{C} : \mathtt{S.t} \to \mathtt{KNormal.t} \to \mathtt{Closure.t}$

$$
\begin{array}{lcll}
\mathcal{C}_s(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n = e_1\ \mathtt{in}\ e_2) & = & \mathcal{D}\ \text{に}\ \mathtt{L}_x(y_1,\ldots,y_n)() = e_1'\ \text{を加え、} & \\
 & & \mathit{make\_closure}\ x = (\mathtt{L}_x, ())\ \mathtt{in}\ e_2'\text{を返す} & \\
 & & \quad\text{ただし}\ e_1' = \mathcal{C}_{s'}(e_1),\ e_2' = \mathcal{C}_{s'}(e_2),\ s' = s \cup \{x\}, & \\
 & & \quad FV(e_1') \setminus \{y_1,\ldots,y_n\} = \emptyset\ \text{かつ}\ x \in FV(e_2')\ \text{の場合} & \\
\mathcal{C}_s(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n = e_1\ \mathtt{in}\ e_2) & = & \mathcal{D}\ \text{に}\ \mathtt{L}_x(y_1,\ldots,y_n)() = e_1'\ \text{を加え、}e_2'\text{を返す} & \\
 & & \quad\text{ただし}\ e_1' = \mathcal{C}_{s'}(e_1),\ e_2' = \mathcal{C}_{s'}(e_2),\ s' = s \cup \{x\}, & \\
 & & \quad FV(e_1') \setminus \{y_1,\ldots,y_n\} = \emptyset\ \text{かつ}\ x \notin FV(e_2')\ \text{の場合} & \\
\mathcal{C}_s(\mathtt{let\ rec}\ x\ y_1\ \ldots\ y_n = e_1\ \mathtt{in}\ e_2) & = & \mathcal{D}\ \text{に}\ \mathtt{L}_x(y_1,\ldots,y_n)(z_1,\ldots,z_m) = e_1'\ \text{を加え、} & \\
 & & \mathit{make\_closure}\ x = (\mathtt{L}_x, (z_1,\ldots,z_m))\ \mathtt{in}\ e_2'\text{を返す} & \\
 & & \quad\text{ただし}\ e_1' = \mathcal{C}_s(e_1),\ e_2' = \mathcal{C}_s(e_2), & \\
 & & \quad FV(e_1') \setminus \{y_1,\ldots,y_n\} \neq \emptyset, & \\
 & & \quad FV(e_1') \setminus \{x, y_1,\ldots,y_n\} = \{z_1,\ldots,z_m\}\ \text{の場合} & \\
\mathcal{C}_s(x\ y_1\ \ldots\ y_n) & = & \mathit{apply\_closure}(x, y_1,\ldots,y_n) & x \notin s\ \text{の場合} \\
\mathcal{C}_s(x\ y_1\ \ldots\ y_n) & = & \mathit{apply\_direct}(\mathtt{L}_x, y_1,\ldots,y_n) & x \in s\ \text{の場合}
\end{array}
$$

図 16: もっと賢い Closure 変換 $\mathcal{C}_s(e)$

P ::=	
$(\{D_1, \ldots, D_n\}, E)$	
D ::=	
$\mathtt{L}_x(y_1, \ldots, y_n) = E$	
E ::=	命令の列
$x \leftarrow e; E$	代入
e	返値
e ::=	式
c	即値
$\mathtt{L}_x$	ラベル
$op(x_1, \ldots, x_n)$	算術演算
$\mathtt{if}\ x = y\ \mathtt{then}\ E_1\ \mathtt{else}\ E_2$	比較＆分岐
$\mathtt{if}\ x \leq y\ \mathtt{then}\ E_1\ \mathtt{else}\ E_2$	比較＆分岐
x	`mov` 命令
$apply\_closure(x, y_1, \ldots, y_n)$	クロージャを用いた関数呼び出し
$apply\_direct(\mathtt{L}_x, y_1, \ldots, y_n)$	クロージャを用いない関数呼び出し
$x.(y)$	ロード
$x.(y) \leftarrow z$	ストア
$\mathtt{save}(x, y)$	変数 x の値をスタック位置 y に退避する
$\mathtt{restore}(y)$	スタック位置 y から値を復元する

図 17: 仮想マシンコードの構文

$$
\begin{array}{lcl}
\mathcal{V} : \texttt{Closure.prog} \rightarrow \texttt{SparcAsm.prog} & & \\
\mathcal{V}((\{D_1, \ldots, D_n\}, e)) & = & (\{\mathcal{V}(D_1), \ldots, \mathcal{V}(D_n)\}, \mathcal{V}(e)) \\
 & & \\
\mathcal{V} : \texttt{Closure.fundef} \rightarrow \texttt{SparcAsm.fundef} & & \\
\mathcal{V}(\texttt{L}_x(y_1, \ldots, y_n)(z_1, \ldots, z_n) = e) & = & \texttt{L}_x(y_1, \ldots, y_n) = z_1 \leftarrow \texttt{R}_0.(4); \ldots; z_n \leftarrow \texttt{R}_0.(4n); \mathcal{V}(e) \\
 & & \\
\mathcal{V} : \texttt{Closure.t} \rightarrow \texttt{SparcAsm.t} & & \\
\mathcal{V}(c) & = & c \\
\mathcal{V}(op(x_1, \ldots, x_n)) & = & op(x_1, \ldots, x_n) \\
\mathcal{V}(\texttt{if}\ x = y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ x = y\ \texttt{then}\ \mathcal{V}(e_1)\ \texttt{else}\ \mathcal{V}(e_2) \\
\mathcal{V}(\texttt{if}\ x \leq y\ \texttt{then}\ e_1\ \texttt{else}\ e_2) & = & \texttt{if}\ x \leq y\ \texttt{then}\ \mathcal{V}(e_1)\ \texttt{else}\ \mathcal{V}(e_2) \\
\mathcal{V}(\texttt{let}\ x = e_1\ \texttt{in}\ e_2) & = & x \leftarrow \mathcal{V}(e_1); \mathcal{V}(e_2) \\
\mathcal{V}(x) & = & x \\
\mathcal{V}(\mathit{make\_closure}\ x = (\texttt{L}_x, (y_1, \ldots, y_n))\ \texttt{in}\ e) & = & x \leftarrow \texttt{R}_{\texttt{hp}}; \texttt{R}_{\texttt{hp}} \leftarrow \texttt{R}_{\texttt{hp}} + 4(n+1); z \leftarrow \texttt{L}_x; x.(0) \leftarrow z; \\
 & & x.(4) \leftarrow y_1; \ldots; x.(4n) \leftarrow y_n; \mathcal{V}(e) \\
\mathcal{V}(\mathit{apply\_closure}(x, y_1, \ldots, y_n)) & = & \mathit{apply\_closure}(x, y_1, \ldots, y_n) \\
\mathcal{V}(\mathit{apply\_direct}(\texttt{L}_x, y_1, \ldots, y_n)) & = & \mathit{apply\_direct}(\texttt{L}_x, y_1, \ldots, y_n) \\
\mathcal{V}((x_1, \ldots, x_n)) & = & y \leftarrow \texttt{R}_{\texttt{hp}}; \texttt{R}_{\texttt{hp}} \leftarrow \texttt{R}_{\texttt{hp}} + 4n; \\
 & & y.(0) \leftarrow x_1; \ldots; y.(4(n-1)) \leftarrow x_n; y \\
\mathcal{V}(\texttt{let}\ (x_1, \ldots, x_n) = y\ \texttt{in}\ e) & = & \{x_1, \ldots, x_n\} \cap FV(e) = \{x_{i_1}, \ldots, x_{i_m}\}\ \text{として} \\
 & & x_{i_1} \leftarrow y.(4(i_1 - 1)); \ldots; x_{i_m} \leftarrow y.(4(i_m - 1)); \mathcal{V}(e) \\
\mathcal{V}(x.(y)) & = & y' \leftarrow 4 \times y; x.(y') \\
\mathcal{V}(x.(y) \leftarrow z) & = & y' \leftarrow 4 \times y; x.(y') \leftarrow z
\end{array}
$$

図 18: 仮想マシンコード生成 $\mathcal{V}(P)$, $\mathcal{V}(D)$ および $\mathcal{V}(e)$。右辺に出現して左辺に出現しない変数は fresh とする。$\texttt{R}_{\texttt{hp}}$ はヒープポインタ（専用レジスタ）。$e_1; e_2$ はダミーの変数 x について $x \leftarrow e_1; e_2$ の略記。$x \leftarrow E_1; E_2$ は、$E_1 = (x_1 \leftarrow e_1; \ldots; x_n \leftarrow e_n; e)$ として、$x_1 \leftarrow e_1; \ldots; x_n \leftarrow e_n; x \leftarrow e; E_2$ の略記。

$$
\begin{array}{lcl}
FV : \texttt{S.t} \rightarrow \texttt{SparcAsm.t} \rightarrow \texttt{S.t} & & \\
FV_s(x \leftarrow e; E) & = & s' = FV_s(E) \setminus \{x\} \text{ として } FV_{s'}(e) \\
FV_s(e) & = & FV_s(e) \\
 & & \\
FV : \texttt{S.t} \rightarrow \texttt{SparcAsm.exp} \rightarrow \texttt{S.t} & & \\
FV_s(c) & = & s \\
FV_s(\texttt{L}_x) & = & s \\
FV_s(op(x_1, \ldots, x_n)) & = & \{x_1, \ldots, x_n\} \cup s \\
FV_s(\texttt{if } x = y \texttt{ then } E_1 \texttt{ else } E_2) & = & \{x, y\} \cup FV_s(E_1) \cup FV_s(E_2) \\
FV_s(\texttt{if } x \leq y \texttt{ then } E_1 \texttt{ else } E_2) & = & \{x, y\} \cup FV_s(E_1) \cup FV_s(E_2) \\
FV_s(x) & = & \{x\} \cup s \\
FV_s(\mathit{apply\_closure}(x, y_1, \ldots, y_n)) & = & \{x, y_1, \ldots, y_n\} \cup s \\
FV_s(\mathit{apply\_direct}(\texttt{L}_x, y_1, \ldots, y_n)) & = & \{y_1, \ldots, y_n\} \cup s \\
FV_s(x.(y)) & = & \{x, y\} \cup s \\
FV_s(x.(y) \leftarrow z) & = & \{x, y, z\} \cup s \\
FV_s(\texttt{save}(x, y)) & = & \{x\} \cup s \\
FV_s(\texttt{restore}(y)) & = & s
\end{array}
$$

図 19: 命令の列 E および式 e において生きている変数の集合 $FV_s(E)$ および $FV_s(e)$。s は E や e の後で使われる変数の集合。以後の $FV(E)$ は $FV_\emptyset(E)$ の略記。

$$
\begin{array}{lcll}
\multicolumn{4}{l}{\mathcal{R} : \texttt{SparcAsm.prog} \to \texttt{SparcAsm.prog}} \\
\mathcal{R}((\{D_1,\ldots,D_n\},E)) & = & (\{\mathcal{R}(D_1),\ldots,\mathcal{R}(D_n)\},\mathcal{R}_\emptyset(E,x,())) & x\ \text{はダミーの fresh な変数} \\
\\
\multicolumn{4}{l}{\mathcal{R} : \texttt{SparcAsm.fundef} \to \texttt{SparcAsm.fundef}} \\
\mathcal{R}(\texttt{L}_x(y_1,\ldots,y_n)=E) & = & \texttt{L}_x(\texttt{R}_1,\ldots,\texttt{R}_n)=\mathcal{R}_{x\mapsto\texttt{R}_0,y_1\mapsto\texttt{R}_1,\ldots,y_n\mapsto\texttt{R}_n}(E,\texttt{R}_0,\texttt{R}_0) & \\
\\
\multicolumn{4}{l}{\mathcal{R} : \texttt{Id.t M.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t} \times \texttt{SparcAsm.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t M.t}} \\
\mathcal{R}_\varepsilon((x\leftarrow e;E),z_{\texttt{dest}},E_{\texttt{cont}}) & = & E'_{\texttt{cont}}=(z_{\texttt{dest}}\leftarrow E;E_{\texttt{cont}}), & \\
 & & \mathcal{R}_\varepsilon(e,x,E'_{\texttt{cont}})=(E',\varepsilon'), & \\
 & & r\notin\{\varepsilon'(y)\mid y\in FV(E'_{\texttt{cont}})\}, & \\
 & & \mathcal{R}_{\varepsilon',x\mapsto r}(E,z_{\texttt{dest}},E_{\texttt{cont}})=(E'',\varepsilon'')\ \text{として} & \\
 & & ((r\leftarrow E';E''),\varepsilon'') & x\ \text{がレジスタでない場合} \\
\mathcal{R}_\varepsilon((r\leftarrow e;E),z_{\texttt{dest}},E_{\texttt{cont}}) & = & E'_{\texttt{cont}}=(z_{\texttt{dest}}\leftarrow E;E_{\texttt{cont}}), & \\
 & & \mathcal{R}_\varepsilon(e,r,E'_{\texttt{cont}})=(E',\varepsilon'), & \\
 & & \mathcal{R}_{\varepsilon'}(E,z_{\texttt{dest}},E_{\texttt{cont}})=(E'',\varepsilon'')\ \text{として} & \\
 & & ((r\leftarrow E';E''),\varepsilon'') & \\
\mathcal{R}_\varepsilon(e,x,E_{\texttt{cont}}) & = & \mathcal{R}_\varepsilon(e,x,E_{\texttt{cont}}) & \text{（次図参照）}
\end{array}
$$

図 20: 単純なレジスタ割り当て $\mathcal{R}(P)$, $\mathcal{R}(D)$ および $\mathcal{R}_\varepsilon(E,z_{\texttt{dest}},E_{\texttt{cont}})$。$\varepsilon$ は変数からレジスタへの写像、$z_{\texttt{dest}}$ は E の結果をセットする変数、$E_{\texttt{cont}}$ は E の後に実行される命令の列。$\mathcal{R}_\varepsilon(E,x,E_{\texttt{cont}})$ の返り値はレジスタ割り当てされた命令の列 E' と、E の後のレジスタ割り当てを表す写像 ε' の組。[ファイル `regAlloc.notarget-nospill.ml` 参照]

$$
\begin{array}{lcl}
\multicolumn{3}{l}{\mathcal{R} : \texttt{Id.t M.t} \to \texttt{SparcAsm.exp} \times \texttt{Id.t} \times \texttt{SparcAsm.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t M.t}} \\
\mathcal{R}_\varepsilon(c, z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (c, \varepsilon) \\
\mathcal{R}_\varepsilon(\texttt{L}_x, z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\texttt{L}_x, \varepsilon) \\
\mathcal{R}_\varepsilon(\mathit{op}(x_1, \ldots, x_n), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\mathit{op}(\varepsilon(x_1), \ldots, \varepsilon(x_n)), \varepsilon) \\
\mathcal{R}_\varepsilon(\texttt{if } x = y \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}, E_{\texttt{cont}}) & = & \mathcal{R}_\varepsilon(E_1, z_{\texttt{dest}}, E_{\texttt{cont}}) = (E'_1, \varepsilon_1), \\
& & \mathcal{R}_\varepsilon(E_2, z_{\texttt{dest}}, E_{\texttt{cont}}) = (E'_2, \varepsilon_2), \\
& & \varepsilon' = \{z \mapsto r \mid \varepsilon_1(z) = \varepsilon_2(z) = r\}, \\
& & \{z_1, \ldots, z_n\} = \\
& & \quad (FV(E_{\texttt{cont}}) \setminus \{z_{\texttt{dest}}\} \setminus \mathit{dom}(\varepsilon')) \cap \mathit{dom}(\varepsilon) \text{ として} \\
& & ((\texttt{save}(\varepsilon(z_1), z_1); \ldots; \texttt{save}(\varepsilon(z_n), z_n); \\
& & \;\; \texttt{if } \varepsilon(x) \le \varepsilon(y) \texttt{ then } E'_1 \texttt{ else } E'_2), \varepsilon') \\
\mathcal{R}_\varepsilon(\texttt{if } x \le y \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}, E_{\texttt{cont}}) & = & \text{同様} \\
\mathcal{R}_\varepsilon(x, z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\varepsilon(x), \varepsilon) \\
\mathcal{R}_\varepsilon(\mathit{apply\_closure}(x, y_1, \ldots, y_n), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & \{z_1, \ldots, z_n\} = (FV(E_{\texttt{cont}}) \setminus \{z_{\texttt{dest}}\}) \cap \mathit{dom}(\varepsilon) \text{ として} \\
& & ((\texttt{save}(\varepsilon(z_1), z_1); \ldots; \texttt{save}(\varepsilon(z_n), z_n); \\
& & \;\; \mathit{apply\_closure}(\varepsilon(x), \varepsilon(y_1), \ldots, \varepsilon(y_n))), \emptyset) \\
\mathcal{R}_\varepsilon(\mathit{apply\_direct}(\texttt{L}_x, y_1, \ldots, y_n), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & \text{同様} \\
\mathcal{R}_\varepsilon(x.(y), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\varepsilon(x).(\varepsilon(y)), \varepsilon) \\
\mathcal{R}_\varepsilon(x.(y) \leftarrow z, z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\varepsilon(x).(\varepsilon(y)) \leftarrow \varepsilon(z), \varepsilon) \\
\mathcal{R}_\varepsilon(\texttt{save}(x, y), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\texttt{save}(\varepsilon(x), y), \varepsilon) \\
\mathcal{R}_\varepsilon(\texttt{restore}(y), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & (\texttt{restore}(y), \varepsilon)
\end{array}
$$

図 21: 単純なレジスタ割り当て $\mathcal{R}_\varepsilon(e, z_{\texttt{dest}}, E_{\texttt{cont}})$。$\mathcal{R}_\varepsilon(e)$ の右辺で変数 x のレジスタ $\varepsilon(x)$ が定義されていない場合は、$\mathcal{R}_\varepsilon(e) = \mathcal{R}_\varepsilon(x \leftarrow \texttt{restore}(x); e)$ とする。ただしレジスタ r については $\varepsilon(r) = r$ とする。[ファイル `regAlloc.notarget-nospill.ml` 参照]

$$
\begin{array}{lcl}
\mathcal{T} : \texttt{Id.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t} \to \texttt{bool} \times \texttt{S.t} & & \\
\mathcal{T}_x((y \leftarrow e; E), z_{\texttt{dest}}) & = & \mathcal{T}_x(e, y) = (c_1, s_1) \text{ として、もし } c_1 \text{ ならば } (\mathit{true}, s_1) \\
 & & \text{そうでなければ } \mathcal{T}_x(E, z_{\texttt{dest}}) = (c_2, s_2) \text{ として } (c_2, s_1 \cup s_2) \\
\mathcal{T}_x(e, z_{\texttt{dest}}) & = & \mathcal{T}_x(e, z_{\texttt{dest}}) \\
 & & \\
\mathcal{T} : \texttt{Id.t} \to \texttt{SparcAsm.exp} \times \texttt{Id.t} \to \texttt{bool} \times \texttt{S.t} & & \\
\mathcal{T}_x(x, z_{\texttt{dest}}) & = & (\mathit{false}, \{z_{\texttt{dest}}\}) \\
\mathcal{T}_x(\texttt{if } y = z \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}) & = & \mathcal{T}_x(E_1, z_{\texttt{dest}}) = (c_1, s_1), \\
 & & \mathcal{T}_x(E_2, z_{\texttt{dest}}) = (c_2, s_2) \text{ として} \\
 & & (c_1 \wedge c_2, s_1 \cup s_2) \\
\mathcal{T}_x(\texttt{if } y \le z \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}) & = & \text{同上} \\
\mathcal{T}_x(\mathit{apply\_closure}(y_0, y_1, \ldots, y_n), z_{\texttt{dest}}) & = & (\mathit{true}, \{\texttt{R}_i \mid x = y_i\}) \\
\mathcal{T}_x(\mathit{apply\_direct}(\texttt{L}_y, y_1, \ldots, y_n), z_{\texttt{dest}}) & = & \text{同上} \\
\mathcal{T}_x(e, z_{\texttt{dest}}) & = & (\mathit{false}, \emptyset) \qquad \text{それ以外の場合}
\end{array}
$$

図 22: 変数 x に割り当てるレジスタ r を選ぶときに使う targeting $\mathcal{T}_x(E, z_{\texttt{dest}})$ および $\mathcal{T}_x(e, z_{\texttt{dest}})$。$E$ や e で関数呼び出しがあったかどうかを表す論理値 c と、x を割り当てると良いレジスタの集合 s の組を返す。前々図の「x がレジスタでない場合」において、$\mathcal{T}_x(E'_{\texttt{cont}}, z_{\texttt{dest}}) = (c, s)$ として、できれば $r \in s$ とする。[ファイル `regAlloc.target-nospill.ml` 参照]

$$
\begin{array}{lcl}
\mathcal{R} : \texttt{Id.t M.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t} \times \texttt{SparcAsm.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t M.t} & & \\
\mathcal{R}_\varepsilon((x \leftarrow e; E), z_{\texttt{dest}}, E_{\texttt{cont}}) & = & E'_{\texttt{cont}} = (z_{\texttt{dest}} \leftarrow E; E_{\texttt{cont}}), \\
 & & \mathcal{R}_\varepsilon(e, x, E'_{\texttt{cont}}) = (E', \varepsilon'), \\
 & & y \in FV(E'_{\texttt{cont}}), \\
 & & \mathcal{R}_{\varepsilon' \setminus \{y \mapsto \varepsilon'(y)\}, x \mapsto \varepsilon'(y)}(E, z_{\texttt{dest}}, E_{\texttt{cont}}) = (E'', \varepsilon'') \text{ として} \\
 & & \begin{cases} ((\texttt{save}(\varepsilon(y), y); \varepsilon'(y) \leftarrow E'; E''), \varepsilon'') & y \in \mathit{dom}(\varepsilon) \text{ のとき} \\ ((\varepsilon'(y) \leftarrow E'; E''), \varepsilon'') & y \notin \mathit{dom}(\varepsilon) \text{ のとき} \end{cases} \\
 & & \qquad x \text{ がレジスタでなく、} \\
 & & \qquad r \notin \{\varepsilon'(y) \mid y \in FV(E'_{\texttt{cont}})\} \text{ なる } r \text{ がない場合}
\end{array}
$$

図 23: spilling をするレジスタ割り当て $\mathcal{R}_\varepsilon(E, z_{\texttt{dest}}, E_{\texttt{cont}})$ [ファイル `regAlloc.target-latespill.ml` 参照]

$$
\begin{array}{lcl}
\multicolumn{3}{l}{\mathcal{S} : \texttt{SparcAsm.prog} \rightarrow \texttt{string}} \\
\mathcal{S}((\{D_1, \ldots, D_n\}, E)) & = & \texttt{.section ".text"} \\
 & & \mathcal{S}(D_1) \\
 & & \ldots \\
 & & \mathcal{S}(D_n) \\
 & & \texttt{.global min\_caml\_start} \\
 & & \texttt{min\_caml\_start:} \\
 & & \texttt{save \%sp, -112, \%sp} \\
 & & \mathcal{S}(E, \texttt{\%g0}) \\
 & & \texttt{ret} \\
 & & \texttt{restore} \\
 & & \\
\multicolumn{3}{l}{\mathcal{S} : \texttt{SparcAsm.fundef} \rightarrow \texttt{string}} \\
\mathcal{S}(\texttt{L}_x(y_1, \ldots, y_n) = E) & = & x\texttt{:} \\
 & & \mathcal{S}(E, \texttt{R}_0) \\
 & & \texttt{retl} \\
 & & \texttt{nop} \\
 & & \\
\multicolumn{3}{l}{\mathcal{S} : \texttt{SparcAsm.t} \times \texttt{Id.t} \rightarrow \texttt{string}} \\
\mathcal{S}((x \leftarrow e; E), z_{\texttt{dest}}) & = & \mathcal{S}(e, x) \\
 & & \mathcal{S}(E, z_{\texttt{dest}}) \\
\mathcal{S}(e, z_{\texttt{dest}}) & = & \mathcal{S}(e, z_{\texttt{dest}})
\end{array}
$$

図 24: 単純なアセンブリ生成 $\mathcal{S}(P)$, $\mathcal{S}(D)$ および $\mathcal{S}(E, z_{\texttt{dest}})$

$$
\begin{array}{lcl}
\mathcal{S} : \texttt{SparcAsm.exp} \times \texttt{Id.t} \to \texttt{string} & & \\
\mathcal{S}(c, z_{\texttt{dest}}) & = & \texttt{set } c, z_{\texttt{dest}} \\
\mathcal{S}(\texttt{L}_x, z_{\texttt{dest}}) & = & \texttt{set L}_x, z_{\texttt{dest}} \\
\mathcal{S}(op(x_1, \ldots, x_n), z_{\texttt{dest}}) & = & op\ x_1, \ldots, x_n, z_{\texttt{dest}} \\
\mathcal{S}(\texttt{if } x = y \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}) & = & \texttt{cmp } x, y \\
 & & \texttt{bne } b_1 \\
 & & \texttt{nop} \\
 & & \mathcal{S}(E_1, z_{\texttt{dest}}) \\
 & & \texttt{b } b_2 \\
 & & \texttt{nop} \\
 & & b_1\texttt{:} \\
 & & \mathcal{S}(E_2, z_{\texttt{dest}}) \\
 & & b_2\texttt{:} \\
\mathcal{S}(\texttt{if } x \le y \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}) & = & \text{同様} \\
\mathcal{S}(x, z_{\texttt{dest}}) & = & \texttt{mov } x, z_{\texttt{dest}} \\
\mathcal{S}(apply\_closure(x, y_1, \ldots, y_n), z_{\texttt{dest}}) & = & shuffle((x, y_1, \ldots, y_n), (\texttt{R}_0, \texttt{R}_1, \ldots, \texttt{R}_n)) \\
 & & \texttt{st R}_{\texttt{ra}}, [\texttt{R}_{\texttt{st}} + 4\#\varepsilon] \\
 & & \texttt{ld } [\texttt{R}_0], \texttt{R}_{n+1} \\
 & & \texttt{call R}_{n+1} \\
 & & \texttt{add R}_{\texttt{st}}, 4(\#\varepsilon + 1), \texttt{R}_{\texttt{st}} \texttt{ ! } \textit{delay slot} \\
 & & \texttt{sub R}_{\texttt{st}}, 4(\#\varepsilon + 1), \texttt{R}_{\texttt{st}} \\
 & & \texttt{ld } [\texttt{R}_{\texttt{st}} + 4\#\varepsilon], \texttt{R}_{\texttt{ra}} \\
 & & \texttt{mov R}_0, z_{\texttt{dest}} \\
\mathcal{S}(apply\_direct(\texttt{L}_x, y_1, \ldots, y_n), z_{\texttt{dest}}) & = & shuffle((y_1, \ldots, y_n), (\texttt{R}_1, \ldots, \texttt{R}_n)) \\
 & & \texttt{st R}_{\texttt{ra}}, [\texttt{R}_{\texttt{st}} + 4\#\varepsilon] \\
 & & \texttt{call } x \\
 & & \texttt{add R}_{\texttt{st}}, 4(\#\varepsilon + 1), \texttt{R}_{\texttt{st}} \texttt{ ! } \textit{delay slot} \\
 & & \texttt{sub R}_{\texttt{st}}, 4(\#\varepsilon + 1), \texttt{R}_{\texttt{st}} \\
 & & \texttt{ld } [\texttt{R}_{\texttt{st}} + 4\#\varepsilon], \texttt{R}_{\texttt{ra}} \\
 & & \texttt{mov R}_0, z_{\texttt{dest}} \\
\mathcal{S}(x.(y), z_{\texttt{dest}}) & = & \texttt{ld } [x + y], z_{\texttt{dest}} \\
\mathcal{S}(x.(y) \leftarrow z, z_{\texttt{dest}}) & = & \texttt{st } z, [x + y] \\
\mathcal{S}(\texttt{save}(x, y), z_{\texttt{dest}}) & = & \text{もし } y \notin dom(\varepsilon) \text{ なら } \varepsilon \text{ に } y \mapsto 4\#\varepsilon \text{ を加えて} \\
 & & \texttt{st } x, [\texttt{R}_{\texttt{st}} + \varepsilon(y)] \\
\mathcal{S}(\texttt{restore}(y), z_{\texttt{dest}}) & = & \texttt{ld } [\texttt{R}_{\texttt{st}} + \varepsilon(y)], z_{\texttt{dest}}
\end{array}
$$

図 25: 単純なアセンブリ生成 $\mathcal{S}(e, z_{\texttt{dest}})$。$\varepsilon$ はスタック位置を記憶するグローバル変数。$\#\varepsilon$ は ε の要素の個数。$shuffle((x_1, \ldots, x_n), (r_1, \ldots, r_n))$ は $x_1, \ldots, x_n$ を $r_1, \ldots, r_n$ に適切な順序で移動する命令。

$$
\begin{array}{lcl}
\mathcal{S} : \texttt{S.t} \to \texttt{SparcAsm.t} \times \texttt{Id.t} \to \texttt{S.t} \times \texttt{string} & & \\
\mathcal{S}_s((x \leftarrow e; E), z_{\texttt{dest}}) & = & \mathcal{S}_s(e, x) = (s', S), \\
 & & \mathcal{S}_{s'}(E, z_{\texttt{dest}}) = (s'', S') \text{ として} \\
 & & (s'', SS') \\
\mathcal{S}_s(e, z_{\texttt{dest}}) & = & \mathcal{S}_s(e, z_{\texttt{dest}}) \\
 & & \\
\mathcal{S} : \texttt{S.t} \to \texttt{SparcAsm.exp} \times \texttt{Id.t} \to \texttt{S.t} \times \texttt{string} & & \\
\mathcal{S}_s(\texttt{if } x = y \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}) & = & \mathcal{S}_s(E_1, z_{\texttt{dest}}) = (s_1, S_1), \\
 & & \mathcal{S}_s(E_2, z_{\texttt{dest}}) = (s_2, S_2) \text{ として} \\
 & & (s_1 \cap s_2, \\
 & & \;\texttt{cmp } x, y \\
 & & \;\texttt{bne } b_1 \\
 & & \;\texttt{nop} \\
 & & \;S_1 \\
 & & \;\texttt{b } b_2 \\
 & & \;\texttt{nop} \\
 & & \;b_1\texttt{:} \\
 & & \;S_2 \\
 & & \;b_2\texttt{:}) \\
\mathcal{S}_s(\texttt{if } x \le y \texttt{ then } E_1 \texttt{ else } E_2, z_{\texttt{dest}}) & = & \text{同様} \\
\mathcal{S}_s(\texttt{save}(x, y), z_{\texttt{dest}}) & = & (s, \texttt{nop}) \qquad\qquad\qquad\qquad y \in s \text{ の場合} \\
\mathcal{S}_s(\texttt{save}(x, y), z_{\texttt{dest}}) & = & \text{もし } y \notin dom(\varepsilon) \text{ なら } \varepsilon \text{ に } y \mapsto 4\#\varepsilon \text{ を加えて} \\
 & & (s \cup \{y\}, \texttt{st } x, [\texttt{R}_{\texttt{st}} + \varepsilon(y)]) \qquad y \notin s \text{ の場合} \\
\mathcal{S}_s(e, z_{\texttt{dest}}) & = & (s, \text{以前と同様}) \qquad\qquad\qquad \text{上述以外の場合}
\end{array}
$$

図 26: 無駄な save を省略するアセンブリ生成 $\mathcal{S}_s(E, z_{\texttt{dest}})$ および $\mathcal{S}_s(e, z_{\texttt{dest}})$。$s$ はすでに save された変数の名前の集合。以前の $\mathcal{S}(E, z_{\texttt{dest}})$ は $\mathcal{S}_\emptyset(E, z_{\texttt{dest}}) = (s, S)$ として S の略記とする。

$$
\begin{array}{lcl}
\mathcal{S} : \texttt{SparcAsm.fundef} \to \texttt{string} & & \\
\mathcal{S}(\texttt{L}_x(y_1, \ldots, y_n) = E) & = & \mathcal{S}_\emptyset(E, \texttt{tail}) = (s, S) \text{ として} \\
 & & x\texttt{:} \\
 & & S \\
 & & \\
\mathcal{S} : \texttt{S.t} \to \texttt{SparcAsm.exp} \times \texttt{Id.t} \to \texttt{S.t} \times \texttt{string} & & \\
\mathcal{S}_s(\texttt{if } x = y \texttt{ then } E_1 \texttt{ else } E_2, \texttt{tail}) & = & \mathcal{S}_s(E_1, \texttt{tail}) = (s_1, S_1), \\
 & & \mathcal{S}_s(E_2, \texttt{tail}) = (s_2, S_2) \text{ として} \\
 & & (\emptyset, \\
 & & \ \texttt{cmp } x, y \\
 & & \ \texttt{bne } b \\
 & & \ \texttt{nop} \\
 & & \ S_1 \\
 & & \ b\texttt{:} \\
 & & \ S_2) \\
\mathcal{S}_s(\texttt{if } x \leq y \texttt{ then } E_1 \texttt{ else } E_2, \texttt{tail}) & = & \text{同様} \\
\mathcal{S}_s(\mathit{apply\_closure}(x, y_1, \ldots, y_n), \texttt{tail}) & = & (\emptyset, \\
 & & \ \mathit{shuffle}((x, y_1, \ldots, y_n), (\texttt{R}_0, \texttt{R}_1, \ldots, \texttt{R}_n)) \\
 & & \ \texttt{ld } [\texttt{R}_0], \texttt{R}_{n+1} \\
 & & \ \texttt{jmp } \texttt{R}_{n+1} \\
 & & \ \texttt{nop}) \\
\mathcal{S}_s(\mathit{apply\_direct}(\texttt{L}_x, y_1, \ldots, y_n), \texttt{tail}) & = & (\emptyset, \\
 & & \ \mathit{shuffle}((y_1, \ldots, y_n), (\texttt{R}_1, \ldots, \texttt{R}_n)) \\
 & & \ \texttt{b } x \\
 & & \ \texttt{nop}) \\
\mathcal{S}_s(e, \texttt{tail}) & = & \mathcal{S}_s(e, \texttt{R}_0) = (s', S) \text{ として} \\
 & & (\emptyset, \\
 & & \ S \\
 & & \ \texttt{retl} \\
 & & \ \texttt{nop}) \qquad\qquad \text{上述以外の場合}
\end{array}
$$

図 27: 末尾呼び出し最適化をするアセンブリ生成 $\mathcal{S}_s(D)$ および $\mathcal{S}_s(e, z_{\texttt{dest}})$。$z_{\texttt{dest}} = \texttt{tail}$ の場合が末尾。