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1 Grammar

$$
\begin{array}{lll}
e & ::= x & \textit{expressions} \\
& \mid\ r & \\
& \mid\ \texttt{new}\ x \Rightarrow \overline{\sigma = e} & \\
& \mid\ e.m(e) & \\
& \mid\ e.\pi(e) & \\
& \mid\ l & (\textit{runtimeform}) \\
\\
v & ::= r & \textit{values} \\
& \mid\ l & \\
\\
d & ::= \texttt{def}\ m(x : \tau) : \tau & \textit{unlabeled decls.} \\
\\
\sigma & ::= d\ \texttt{with}\ \varepsilon & \textit{labeled decls.}
\end{array}
\qquad
\begin{array}{lll}
\tau & ::= \{\bar{\sigma}\} & \textit{types} \\
& \mid\ \{\bar{r}\} & \\
\\
\Gamma & ::= \varnothing & \textit{contexts} \\
& \mid\ \Gamma,\ x : \tau & \\
\\
\mu & ::= \varnothing & \textit{store} \\
& \mid\ \mu,\ l \mapsto \{x \Rightarrow \overline{\sigma = e}\} & \\
& \mid\ \mu,\ l \mapsto \{x \Rightarrow \bar{r}\} &
\end{array}
$$

- The contents of μ have the form $l \mapsto \{x \Rightarrow \overline{\sigma = e}\}$, which means the memory address l points to an object with the type $\{\bar{\sigma}\}$. x is the 'this' variable.
- For an expression e, $e[e_1/x_1, ..., e_n/x_n]$ is a new expression with the structure of e, where every free occurrence of x_i is replaced with e_i.
- $\varnothing$ refers to the empty set. The empty type, consisting of zero method declarations, is denoted `Unit`.
- A configuration is a pair $\langle \mu\ ;\ e \rangle$.
- $\langle \mu\ ;\ e \rangle \longrightarrow \langle \mu'\ ;\ e' \rangle$ if, after one reduction step on e in heap μ, the program ends in heap μ' and ready to execute e'.
- To execute a program e is to perform reduction steps starting from the configuration $\langle \varnothing, e \rangle$.
- $\langle \mu_1\ ;\ e_1 \rangle \longrightarrow_* \langle \mu_2\ ;\ e_2 \rangle$ if the configuration $\langle \mu_2\ ;\ e_2 \rangle$ can be reached from the configuration $\langle \mu_1, e_1 \rangle$ by the application of one or more reduction rules.
- If $\langle \mu_1\ ;\ e_1 \rangle \longrightarrow_* \langle \mu_2\ ;\ v \rangle$, for some value v, then we say that $\langle \mu_1\ ;\ e_1 \rangle$ terminates.

2 Dynamic Semantics

This first section introduces a basic dynamic semantics that has no notion of an effect.

$\boxed{\langle \mu, e \rangle \longrightarrow \langle \mu, e \rangle}$

$$\frac{\langle \mu \ ; \ e_1 \rangle \longrightarrow \langle \mu \ ; \ e_1' \rangle}{\langle \mu \ ; \ e_1.m(e_2) \rangle \longrightarrow \langle \mu' \ ; \ e_1'.m(e_2) \rangle} \ (\text{E-MethCall1}) \qquad \frac{\langle \mu \ ; \ e_2 \rangle \longrightarrow \langle \mu' \ ; \ e_2' \rangle}{\langle \mu \ ; \ l.m(e_2) \rangle \longrightarrow \langle \mu' \ ; \ l.m(e_2') \rangle} \ (\text{E-MethCall2})$$

$$\frac{l \mapsto \{x \Rightarrow \overline{\sigma = e}\} \in \mu \quad \texttt{def m}(y : \tau_1) : \tau_2 \ \texttt{with} \ \varepsilon = e' \in \overline{\sigma = e}}{\langle \mu \ ; \ l.m(v) \rangle \longrightarrow \langle \mu \ ; \ e'[l/x, v/y] \rangle} \ (\text{E-MethCall3})$$

$$\frac{\langle \mu \ ; \ e_1 \rangle \longrightarrow \langle \mu' \ ; \ e_1' \rangle}{\langle \mu \ ; \ e_1.\pi(e_2) \rangle \longrightarrow \langle \mu' \ ; \ e_1'.\pi(e_2) \rangle} \ (\text{E-OperCall1}) \qquad \frac{\langle \mu \ ; \ e_2 \rangle \longrightarrow \langle \mu' \ ; \ e_2' \rangle}{\langle \mu \ ; \ r.\pi(e_2) \rangle \longrightarrow \langle \mu' \ ; \ r.\pi(e_2') \rangle} \ (\text{E-OperCall2})$$

$$\frac{r \in R \quad \pi \in \Pi}{\langle \mu \ ; \ r.\pi(v) \rangle \longrightarrow \langle \mu' \ ; \ \texttt{Unit} \rangle} \ (\text{E-OperCall3})$$

$$\frac{l \notin dom(\mu)}{\langle \mu \ ; \ \texttt{new x} \Rightarrow \overline{\sigma = e} \rangle \longrightarrow \langle \mu, l \mapsto \texttt{new x} \Rightarrow \overline{\sigma = e} \ ; \ l \rangle} \ (\text{E-New}_\sigma)$$

3 Dynamic Semantics With Effects

We amend the definition of configuration. A configuration is a triple $\langle \mu, e, \varepsilon \rangle$, where ε is an accumulated set of effects (i.e. pairs from $R \times \Pi$) from the computation so far. A program e has the effect (r, π) if $\langle \varnothing \ ; \ e \ ; \ \varnothing \rangle \longrightarrow_* \langle \mu \ ; \ e' \ ; \ \varepsilon \rangle$, where $(r, \pi) \in \varepsilon$.

$$\boxed{\langle \mu, e, \varepsilon \rangle \longrightarrow \langle \mu, e, \varepsilon \rangle}$$

$$\frac{\langle \mu \ ; \ e_1 \ ; \ \varepsilon \rangle \longrightarrow \langle \mu \ ; \ e_1' \ ; \ \varepsilon' \rangle}{\langle \mu \ ; \ e_1.m(e_2) \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ e_1'.m(e_2) \ ; \ \varepsilon' \rangle} \ (\text{E-MethCall1}) \qquad \frac{\langle \mu \ ; \ e_2 \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ e_2' \ ; \ \varepsilon' \rangle}{\langle \mu \ ; \ l.m(e_2) \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ l.m(e_2') \ ; \ \varepsilon' \rangle} \ (\text{E-MethCall2})$$

$$\frac{l \mapsto \{x \Rightarrow \overline{\sigma = e}\} \in \mu \quad \texttt{def m}(y : \tau_1) : \tau_2 \ \texttt{with} \ \varepsilon_2 = e' \in \overline{\sigma = e}}{\langle \mu \ ; \ l.m(v) \ ; \ \varepsilon \rangle \longrightarrow \langle \mu \ ; \ e'[l/x, v/y] \ ; \ \varepsilon \rangle} \ (\text{E-MethCall3})$$

$$\frac{\langle \mu \ ; \ e_1 \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ e_1' \ ; \ \varepsilon' \rangle}{\langle \mu \ ; \ e_1.\pi(e_2) \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ e_1'.\pi(e_2) \ ; \ \varepsilon' \rangle} \ (\text{E-OperCall1}) \qquad \frac{\langle \mu \ ; \ e_2 \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ e_2' \ ; \ \varepsilon' \rangle}{\langle \mu \ ; \ r.\pi(e_2) \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ r.\pi(e_2') \ ; \ \varepsilon' \rangle} \ (\text{E-OperCall2})$$

$$\frac{r \in R \quad \pi \in \Pi}{\langle \mu \ ; \ r.\pi(v) \ ; \ \varepsilon \rangle \longrightarrow \langle \mu' \ ; \ \texttt{Unit} \ ; \ \varepsilon \cup \{(r, m)\} \rangle} \ (\text{E-OperCall3})$$

$$\frac{l \notin dom(\mu)}{\langle \mu \ ; \ \texttt{new x} \Rightarrow \overline{\sigma = e} \ ; \ \varepsilon \rangle \longrightarrow \langle \mu, l \mapsto \texttt{new x} \Rightarrow \overline{\sigma = e} \ ; \ l \ ; \ \varepsilon \rangle} \ (\text{E-New}_\sigma)$$