x	::=	ALPHANUMERIC $\mid \star$ALPHANUMERIC	*variables*
$\overset{\star}{\ell}$	::=	$\ell \mid *$	*general labels*
ℓ			*labels*
T	::=	$[t, \ldots]$	*stack*
t	::=	$\langle \eta, \overset{\star}{\ell}, S \rangle$	*stack frames*
S	::=	$[s, \ldots]$	*programs*
s	::=	$\ell : \overset{\star}{\ell} : d$	*clauses*
d	::=	$x = e \mid$ `return` $x \mid$ `goto` $\ell \mid$ `goto` ℓ `if not` x	*directives*
		$\mid$ `raise` $x \mid$ `catch` $x \mid$ `pass`	
B	::=	$\{x \mapsto m, \ldots\}$	*bindings*
H	::=	$\{m \mapsto v, \ldots\}$	*heap*
v	::=	$\mathbb{Z} \mid [m, \ldots] \mid (m, \ldots) \mid B \mid F \mid M \mid *$	*values*
e	::=	$v \mid x \mid$ `def` $x(x, \ldots) = \{S\} \mid x(x, \ldots) \mid x.x \mid [x, \ldots] \mid (x, \ldots)$	*expressions*
Y	::=	$[y, \ldots]$	*microcode stack*
Z	::=	$[z, \ldots]$	*microcode literal stack*
y	::=	STORE $\mid$ WRAP $\mid$ BIND $\mid$ LOOKUP $\mid$ LIST $n \mid$ TUPLE n	*microcode commands*
		$\mid$ ADVANCE $\mid$ POP $\mid$ PUSH $S \mid$ RAISE $\mid$ GOTO $\ell \mid$ GOTOIFN ℓ	
		$\mid$ CALL $n \mid$ RETRIEVE $\mid$ ALLOCNAMEERROR $\mid$ ALLOCTYPEERROR $\mid$ ALLOCATTRERROR	
z	::=	$x \mid m \mid v$	*microcode literals*
P	::=	$m \mapsto m$	*parental map*
$\overset{\star}{m}$	::=	$m \mid \eta \mid *$	*general memory locations*
η, m	::=	<ADDRESS>	*memory locations*
F	::=	$\langle \eta,$ `def` $(x) \rightarrow S \rangle \mid \mathfrak{F}$	*general functions*
M	::=	$\langle \eta, \eta,$ `def` $(x) \rightarrow S \rangle \mid \langle \eta, \mathfrak{M} \rangle$	*general methods*
$\mathfrak{F}$			*magic functions*
$\mathfrak{M}$			*magic methods*
n			*integers*

Figure 1: Expression Grammar

STORE v

$$\frac{m \notin H \qquad H' = H[m \mapsto v]}{P, Z \,||[v, \textsc{Store}]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[m]\,||\, Y, T, H'}$$

WRAP m

$$\frac{v = \textsc{GetObj}(H, m)}{P, Z \,||[m, \textsc{Wrap}]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[v]\,||\, Y, T, H}$$

BIND m TO x

$$\frac{B = H[\eta] \qquad B' = B[x \mapsto m] \qquad H' = H[\eta \mapsto B']}{P, Z \,||[m, x, \textsc{Bind}]\,||\, Y, T, H \longrightarrow^1 P, Z \,||\, Y, T, H'}$$

ADVANCE

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : d \qquad \ell \overset{s}{\blacktriangleleft} \overset{\star''}{\ell}}{P, Z \,||[\textsc{Advance}]\,||\, Y, [\langle \eta, \ell, S \rangle]\,||\, T, H \longrightarrow^1 P, Z \,||\, Y, [\langle \eta, \overset{\star''}{\ell}, S \rangle]\,||\, T, H}$$

POP

$$\frac{}{P, Z \,||[\textsc{Pop}]\,||\, Y, t\,||\, T, H \longrightarrow^1 P, Z \,||\, Y, T, H}$$

PUSH S

$$\frac{P' = P[\eta' \mapsto \eta], \eta' \notin P \qquad S = [\ell : \overset{\star'}{\ell} : d, \ldots]}{P, Z \,||[\eta, \textsc{Push}\ S]\,||\, Y, T, H \longrightarrow^1 P', Z \,||\, Y, [\langle \eta', \ell, S \rangle]\,||\, T, H}$$

LOOK UP x (BOUND)

$$\frac{\textsc{Lookup}(P, H, \eta, x) = m}{P, Z \,||[x, \textsc{LookUp}]\,||\, Y, [\langle \eta, \ell, S \rangle]\,||\, T, H \longrightarrow^1 P, Z \,||[m]\,||\, Y, [\langle \eta, \ell, S \rangle]\,||\, T, H}$$

LOOK UP x (NAMEERROR)

$$\frac{\textsc{Lookup}(P, H, \eta, x) = *}{P, Z \,||[x, \textsc{LookUp}]\,||\, Y, [\langle \eta, \ell, S \rangle]\,||\, T, H \longrightarrow^1 P, [\textsc{AllocNameError}, \textsc{Raise}], [\langle \eta, \ell, S \rangle]\,||\, T, H}$$

MAKE LIST

$$\frac{v = [m_1, \ldots, m_n]}{P, Z \,||[m_1, \ldots, m_n, \textsc{List}\ n]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[v]\,||\, Y, T, H}$$

MAKE TUPLE

$$\frac{v = (m_1, \ldots, m_n)}{P, Z \,||[m_1, \ldots, m_n, \textsc{Tuple}\ n]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[v]\,||\, Y, T, H}$$

Figure 2: Microcommands

RAISE (NO EXCEPTION LABEL)

$$\frac{S(\ell) = \ell : * : d}{P, Z \,||[\textsc{Raise}]\,||\, Y, [\langle \eta, \ell, S\rangle]\,||\, T, H \longrightarrow^1 P, Z \,||[\textsc{Pop}, \textsc{Raise}]\,||\, Y, [\langle \eta, \ell, S\rangle]\,||\, T, H}$$

RAISE (CAUGHT)

$$\frac{S(\ell) = \ell : \ell_0 : d \qquad S(\ell_0) = \ell_0 : \ell_1 : \texttt{ catch } x \qquad Y' = [x, \textsc{Bind}, \textsc{Advance}]}{P, Z \,||[\textsc{Raise}]\,||\, Y, [\langle \eta, \ell, S\rangle]\,||\, T, H \longrightarrow^1 P, Z \,||\, Y' \,||\, Y, [\langle \eta, \ell_0, S\rangle]\,||\, T, H}$$

GOTO ℓ

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : d}{P, Z \,||[\textsc{Goto}\ \ell]\,||\, Y, [\langle \eta, \ell', S\rangle]\,||\, T, H \longrightarrow^1 P, Z \,||\, Y, [\langle \eta, \ell, S\rangle]\,||\, T, H}$$

GOTOIFN ℓ (SUCCESS)

$$\frac{H[m] = \textsc{False} \qquad S(\ell) = \ell : \overset{\star'}{\ell} : d}{P, Z \,||[m, \textsc{Gotoifn}\ \ell]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[\textsc{Goto}]\,||\, Y, T, H}$$

GOTOIFN ℓ (FAILURE)

$$\frac{H[m] = \textsc{True}}{P, Z \,||[m, \textsc{Gotoifn}\ \ell]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[\textsc{Advance}]\,||\, Y, T, H}$$

CALL FUNCTION m

$$\frac{\begin{array}{c} H[m_0] = \langle \eta,\ \texttt{def}\ (x_1, \ldots, x_n) \to S\rangle \\ Y' = [\eta, \textsc{Push}\ S, m_1, x_1, \textsc{Bind}, \ldots, m_n, x_n, \textsc{Bind}] \end{array}}{P, Z \,||[m_0, \ldots, m_n, \textsc{Call}\ n]\,||\, Y, T, H \longrightarrow^1 P, Z \,||\, Y' \,||\, Y, T, H}$$

CALL FUNCTION (WRONG ARGS)

$$\frac{H[m_0] = \langle \eta,\ \texttt{def}\ (x_1, \ldots, x_q) \to S\rangle, q \neq n}{P, Z \,||[m_0, \ldots, m_n, \textsc{Call}\ n]\,||\, Y, T, H \longrightarrow^1 P, [\textsc{AllocTypeError}, \textsc{Raise}], T, H}$$

CALL METHOD m

$$\frac{\begin{array}{c} H[m_0] = \langle m_1, \eta,\ \texttt{def}\ (x_1, \ldots, x_n) \to S\rangle \\ Y' = [\eta, \textsc{Push}\ S, m, \textsc{Bind}, m_1, x_1, \textsc{Bind}, \ldots, m_n, x_n, \textsc{Bind}] \end{array}}{P, Z \,||[m_0, m_2, \ldots, m_n, \textsc{Call}\ n]\,||\, Y, T, H \longrightarrow^1 P, Z \,||\, Y' \,||\, Y, T, H}$$

CALL METHOD (WRONG ARGS)

$$\frac{H[m_0] = \langle m_1, \eta,\ \texttt{def}\ (x_1, \ldots, x_q) \to S\rangle, q \neq n}{P, Z \,||[m_0, m_2, \ldots, m_n, \textsc{Call}\ n]\,||\, Y, T, H \longrightarrow^1 P, [\textsc{AllocTypeError}, \textsc{Raise}], T, H}$$

RETRIEVE x

$$\frac{\textsc{LookupObj}(P, H, m, x) = m'}{P, Z \,||[m, x, \textsc{Retrieve}]\,||\, Y, T, H \longrightarrow^1 P, Z \,||[m']\,||\, Y, T, H}$$

RETRIEVE x (ATTRIBUTEERROR)

$$\frac{\textsc{LookupObj}(P, H, m, x) = *}{P, Z \,||[m, x, \textsc{Retrieve}]\,||\, Y, T, H \longrightarrow^1 P, [\textsc{AllocAttrError}, \textsc{Raise}], T, H}$$

Figure 3: Microcommands (cont.)

Literal Assignment

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : x = \mathbb{Z} \qquad Y = [v, \textsc{Store}, \textsc{Wrap}, \textsc{Store}, x, \textsc{Bind}, \textsc{Advance}]}{P, [\,], [\langle \eta, \ell, S \rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S \rangle] \,||\, T, H}$$

(TODO: make literal category (ints, str, bool, None) – TC)

Name Assignment

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : x_1 = x_2 \qquad Y = [x_2, \textsc{Lookup}, x_1, \textsc{Bind}, \textsc{Advance}]}{P, [\,], [\langle \eta, \ell, S \rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S \rangle] \,||\, T, H}$$

List Assignment

$$\frac{\begin{array}{c} S(\ell) = \ell : \overset{\star'}{\ell} : x = [x_1, \ldots, x_n] \\ Y = [(x_1, \textsc{Lookup}), \ldots, (x_n, \textsc{Lookup}), \textsc{List}\ n, \textsc{Store}, \textsc{Wrap}, \textsc{Store}, x, \textsc{Bind}, \textsc{Advance}] \end{array}}{P, [\,], [\langle \eta, \ell, S \rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S \rangle] \,||\, T, H}$$

(Parentheses in Y group instructions together for convenience of reading. – TC)

Tuple Assignment

$$\frac{\begin{array}{c} S(\ell) = \ell : \overset{\star'}{\ell} : x = [x_1, \ldots, x_n] \\ Y = [(x_1, \textsc{Lookup}), \ldots, (x_n, \textsc{Lookup}), \textsc{Tuple}\ n, \textsc{Store}, \textsc{Wrap}, \textsc{Store}, x, \textsc{Bind}, \textsc{Advance}] \end{array}}{P, [\,], [\langle \eta, \ell, S \rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S \rangle] \,||\, T, H}$$

FunctionDef Assignment

$$\frac{\begin{array}{c} S(\ell) = \ell : \ell' : x = \texttt{def}\ (x_1, \ldots, x_n) = \{S'\} \qquad v = \langle \eta, \texttt{def}\ (x_1, \ldots, x_n) \to S' \rangle \\ Y = [v, \textsc{Store}, \textsc{Wrap}, \textsc{Store}, x, \textsc{Bind}, \textsc{Advance}] \end{array}}{P, [\,], [\langle \eta, \ell, S \rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S \rangle] \,||\, T, H}$$

Attribute Assignment

$$\frac{S(\ell) = \ell : \ell' : x = x_1.x_2 \qquad Y = [x_1, \textsc{Lookup}, x_2, \textsc{Retrieve}, \textsc{Wrap}, \textsc{Store}, x, \textsc{Bind}]}{P, [\,], [\langle \eta, \ell, S \rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S \rangle] \,||\, T, H}$$

Figure 4: Operational Semantics: Assignment

FUNCTION CALL

$$\frac{S(\ell) = \ell : \ell' : x = x_0(x_1, \ldots, x_n) \qquad Y = [x_0, \textsc{Lookup}, \ldots, x_n, \textsc{Lookup}, \textsc{Call}\ n+1]}{P, [\,], [\langle \eta, \ell, S\rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S\rangle] \,||\, T, H}$$

METHOD CALL

$$\frac{S(\ell) = \ell : \ell' : x = x_1.x_0(x_2, \ldots, x_n) \qquad Y = [x_1, \textsc{Lookup}, x_0, \textsc{Retrieve}, x_2, \textsc{Lookup}, \ldots, x_n, \textsc{Lookup}, \textsc{Call}\ n]}{P, [\,], [\langle \eta, \ell, S\rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S\rangle] \,||\, T, H}$$

Figure 5: Operational Semantics: Call

PASS

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : \texttt{pass} \qquad Y = [\textsc{Advance}]}{P, [\,], [\langle \eta, \ell, S\rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S\rangle] \,||\, T, H}$$

RETURN

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : \texttt{return}\ x \qquad T = [\langle \eta', \ell'', S'\rangle] \,||\, T' \qquad S(\ell'') = \ell'' : \overset{\star'''}{\ell} : x' = e \qquad Y = [x, \textsc{LookUp}, \textsc{Pop}, x', \textsc{Bind}, \textsc{Advance}]}{P, [\,], [\langle \eta, \ell, S\rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S\rangle] \,||\, T, H}$$

GOTO

$$\frac{S(\ell) = \ell : \overset{\star'}{\ell} : \texttt{goto}\ \ell'' \qquad Y = [\textsc{Goto}\ \ell'']}{P, [\,], [\langle \eta, \ell, S\rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S\rangle] \,||\, T, H}$$

GOTOIFNOT

$$\frac{S(\ell) = \ell : \ell' : \texttt{goto}\ \ell''\ \texttt{if not}\ x \qquad Y = [x, \textsc{Lookup}, \textsc{GotoIfN}\ \ell'']}{P, [\,], [\langle \eta, \ell, S\rangle] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, \ell, S\rangle] \,||\, T, H}$$

END OF FUNCTION

$$\frac{t = \langle \ell, S'\rangle \qquad S(\ell) = \ell : \overset{\star'}{\ell} : x = e \qquad Y = [m_{\texttt{None}}, x, \textsc{Bind}, \textsc{Pop}, \textsc{Advance}]}{P, [\,], [\langle \eta, *, S\rangle, t] \,||\, T, H \longrightarrow^1 P, Y, [\langle \eta, *, S\rangle, t] \,||\, T, H}$$

($m_{\texttt{None}}$ is a memory location reserved for `None`*. – TC)*

END OF PROGRAM

$$\frac{}{P, [\,], [\langle \eta, *, S\rangle], H \longrightarrow^1 P, [\,], [\,], H}$$

Figure 6: Operational Semantics: Flow

Definition 0.1.

$$\textsc{Lookup}(m_0, P, H, x_2) =$$

Definition 0.2.

$$\textsc{GetObj}(H, m) = \begin{cases} B, & \textit{if } v = B \\ B = \star x_{value} \mapsto v, & \textit{otherwise} \end{cases}, H[m] = v \tag{1}$$

Definition 0.3. $H[m][\_\_call\_\_] = m', H[m'] = v$

$$\textsc{GetCall}(H, m) = \begin{cases} \textsc{GetCall}(H, m'), & \textit{if } \ v = B \\ m', & \textit{if } v = F \mid M \end{cases} \tag{2}$$

Figure 7: Helper Functions