metavariable, $x$, $xs$, $y$, $uf$, $f$, $d$

| | | | | |
|---|---|---|---|---|
| term, t, u | ::= | | | term |
| | \| | $x$ | | variable |
| | \| | $v$ | | value |
| | \| | $t\ u$ | | application |
| | \| | $t\ ;\ u$ | | effect execution |
| | \| | $\mathsf{case}\ t\ \mathsf{of}\ \{() \mapsto u\}$ | | pattern-matching on unit |
| | \| | $\mathsf{case}\ t\ \mathsf{of}\ \{\mathsf{Ur}\ x \mapsto u\}$ | | pattern-matching on exponentiated value |
| | \| | $\mathsf{case}\ t\ \mathsf{of}\ \{1.x_1 \mapsto u_1, 2.x_2 \mapsto u_2\}$ | | pattern-matching on sum |
| | \| | $\mathsf{case}\ t\ \mathsf{of}\ \{\langle x_1, x_2\rangle \mapsto u\}$ | | pattern-matching on product |
| | \| | $\mathsf{case}\ t\ \mathsf{of}\ \{\underset{R}{\mathsf{roll}}\ x \mapsto u\}$ | | unroll for recursive types |
| | \| | $\underset{A}{\mathsf{alloc}}\ d\ .\ t$ | | allocate data |
| | \| | $t \triangleleft ()$ | | fill destination with unit |
| | \| | $t \triangleleft u$ | | fill terminal-type destination |
| | \| | $t \triangleleft \mathsf{Ur}\ u$ | | fill destination with exponential |
| | \| | $t \triangleleft 1.d\ .\ u$ | | fill sum-type destination with variant 1 |
| | \| | $t \triangleleft 2.d\ .\ u$ | | fill sum-type destination with variant 2 |
| | \| | $t \triangleleft \langle d_1, d_2\rangle\ .\ u$ | | fill product-type destination |
| | \| | $t \triangleleft \underset{R}{\mathsf{roll}}\ d\ .\ u$ | | fill destination with recursive type |
| | \| | $(t)$ | S | |
| | \| | $t[var\_subs]$ | M | |
| var_sub, vs | ::= | | | variable substitution |
| | \| | $x := t$ | | |
| var_subs | ::= | | | variable substitutions |
| | \| | $vs$ | | |
| | \| | $vs, var\_subs$ | | |
| heap_val, h | ::= | | | |
| | \| | $()$ | | |
| | \| | $\mathsf{Ur}\ l$ | | |
| | \| | $1.l$ | | |
| | \| | $2.l$ | | |
| | \| | $\langle l_1, l_2\rangle$ | | |
| | \| | $\underset{R}{\mathsf{roll}}\ l$ | | |
| | \| | $C\overline{l}$ | M | generic for all the cases above |
| val, v | ::= | | | unreducible value |
| | \| | $\bullet$ | | no-effect effect |
| | \| | $\lfloor l \rfloor$ | | address of an allocated memory area |
| | \| | $\lambda x{:}A\ .\ t$ | | lambda abstraction |
| | \| | $h$ | | heap value |
| *label*, $l$ | ::= | | | memory address |
| labels | ::= | | | |
| | \| | $l$ | | |
| | \| | $l$, labels | | |
| | \| | $\overline{l}$ | M | |

| | | | | |
|---|---|---|---|---|
| | \| | $\bar{l}$, labels | M | |
| $label\_set$, $L$ | ::= | | | set of used labels |
| | \| | $\emptyset$ | | |
| | \| | {labels} | | |
| | \| | $L_1 \sqcup L_2$ | | |
| | \| | $(L)$ | S | |
| heap_affect, ha | ::= | | | heap cell |
| | \| | $l \triangleleft \mathsf{v}$ | | |
| | \| | $\bar{l} \triangleleft \bar{\mathsf{v}}$ | M | generic for multiple occurences |
| heap_affects | ::= | | | heap cells |
| | \| | ha | | |
| | \| | ha, heap_affects | | |
| heap_context, $\mathbb{H}$ | ::= | | | heap contents |
| | \| | $\emptyset$ | | |
| | \| | {heap_affects} | | |
| | \| | $\mathbb{H}_1 \sqcup \mathbb{H}_2$ | | |
| type, A, B | ::= | | | |
| | \| | $\perp$ | | bottom type |
| | \| | 1 | | unit type |
| | \| | R | | recursive type bound to a name |
| | \| | $\mathsf{A} \otimes \mathsf{B}$ | | product type |
| | \| | $\mathsf{A} \oplus \mathsf{B}$ | | sum type |
| | \| | $\mathsf{A} \multimap \mathsf{B}$ | | linear function type |
| | \| | $\lfloor \mathsf{A} \rfloor$ | | destination type |
| | \| | !A | | exponential |
| | \| | (A) | S | |
| | \| | $\mathsf{W}[\mathsf{r} := \mathsf{A}]$ | M | |
| type_with_hole, W | ::= | | | |
| | \| | $\perp$ | | bottom type |
| | \| | r | | type hole in recursive definition |
| | \| | 1 | | unit type |
| | \| | R | | recursive type bound to a name |
| | \| | $\mathsf{W}_1 \otimes \mathsf{W}_2$ | | product type |
| | \| | $\mathsf{W}_1 \oplus \mathsf{W}_2$ | | sum type |
| | \| | $\mathsf{W}_1 \multimap \mathsf{W}_2$ | | linear function type |
| | \| | $\lfloor \mathsf{W} \rfloor$ | | destination type |
| | \| | !W | | exponential |
| | \| | (W) | S | |
| rec_type_bound, R | ::= | | | recursive type bound to a name |
| rec_type_def | ::= | | | |
| | \| | $\mu\, \mathsf{r}\, .\, \mathsf{W}$ | | |

| | | | |
|---|---|---|---|
| type_affect, ta | $::=$ | | type affectation |
| | $\|$ | $x : A$ | var |
| | $\|$ | $l : A$ | label |
| | $\|$ | $\bar{l} : \bar{A}$ | generic for multiple occurences |
| type_affects | $::=$ | | type affectations |
| | $\|$ | ta | |
| | $\|$ | ta, type_affects | |
| typing_context, $\Gamma$, $\mho$, $\Phi$, $\Psi$ | $::=$ | | typing context |
| | $\|$ | $\emptyset$ | |
| | $\|$ | $\{$type_affects$\}$ | |
| | $\|$ | $\Gamma_1 \sqcup \Gamma_2$ | |
| types, $\bar{A}$ | $::=$ | | |
| | $\|$ | $\cdot$ | empty type list |
| | $\|$ | $A$ | |
| | $\|$ | $A$ types | |
| command | $::=$ | | |
| | $\|$ | $\mathbb{H} \underset{L}{\diamondsuit}\ t$ | |
| heap_constructor, C | $::=$ | | |
| | $\|$ | $\{()\}$ | |
| | $\|$ | $\{\ \mathsf{Ur}\ \}$ | |
| | $\|$ | $\{1.\}$ | |
| | $\|$ | $\{2.\}$ | |
| | $\|$ | $\{\langle,\rangle\}$ | |
| | $\|$ | $\{\ \mathsf{roll}\ R\}$ | |
| judg | $::=$ | | |
| | $\|$ | $l \in \mathsf{names}\,(\Phi)$ | |
| | $\|$ | $l \notin \mathsf{names}\,(\Phi)$ | |
| | $\|$ | type_affect $\in \Gamma$ | |
| | $\|$ | $\mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset$ | |
| | $\|$ | $\mathsf{names}\,(\Phi) \sqcup \mathsf{names}\,(\Psi) \subset L$ | |
| | $\|$ | $l \in L$ | |
| | $\|$ | $l \notin L$ | |
| | $\|$ | heap_affect $\in \mathbb{H}$ | |
| | $\|$ | $A = B$ | |
| | $\|$ | $t = u$ | |
| | $\|$ | $\Gamma = D$ | |
| | $\|$ | $R \overset{\mathsf{fix}}{=}$ rec_type_def | |
| | $\|$ | $C : \bar{A} \overset{c}{\rightharpoonup} A$ | |
| | $\|$ | $\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash$ command $: A$ | |
| | $\|$ | $\Phi\ ;\ \Psi \vdash \mathbb{H}$ | |
| | $\|$ | $\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash t : A$ | |
| | $\|$ | command $\Downarrow$ command$'$ | |

terminals ::=

| $()$
| $\mapsto$
| $\star$
| $\circledast$
| $\oplus$
| $\multimap$
| $:=$
| $\vdash$
| $\sqcup$
| $;$
| $\cap$
| $\emptyset$
| $\longrightarrow$
| $\triangleright$
| $\neq$
| $\in$
| $\notin$
| \n
| $\langle$
| $\rangle$
| 1.
| 2.
| Ur
| $\triangleleft$
| $|$
| $\oslash$
| $\overset{\mathsf{c}}{\lrcorner}$
| $=$
| $\Downarrow$
| $\ldots$
| $\overset{\mathsf{fix}}{\equiv}$
| $\bot$
| $\bullet$
| $\subset$

formula ::=

| judgement

Ctx ::=

| $l \in \mathsf{names}\,(\Phi)$
| $l \notin \mathsf{names}\,(\Phi)$
| type_affect $\in \Gamma$
| $\mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset$ $\quad$ $\Gamma_1$ and $\Gamma_2$ are disjoint typing contexts with no clashi

LabelSet ::=

| $\mathsf{names}\,(\Phi) \sqcup \mathsf{names}\,(\Psi) \subset L$
| $l \in L$
| $l = \mathsf{fresh}(\mathbb{L} \setminus L)$

| | | | |
|---|---|---|---|
| Heap | ::= | | |
| | \| | heap_affect $\in \mathbb{H}$ | |
| Eq | ::= | | |
| | \| | $A = B$ | |
| | \| | $t = u$ | |
| | \| | $\Gamma = D$ | |
| Ty | ::= | | |
| | \| | $R \overset{\text{fix}}{=}$ rec_type_def | |
| | \| | $C : \bar{A} \xrightharpoonup{c} A$ | Heap constructor C builds a value of type A given a |
| | \| | $\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash$ command : $A$ | |
| | \| | $\Phi\ ;\ \Psi \vdash \mathbb{H}$ | $\mathbb{H}$ is a well-typed heap given heap typing context $\Phi$ |
| | \| | $\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash t : A$ | t is a well-typed term of type A given heap typing c |
| Sem | ::= | | |
| | \| | command $\Downarrow$ command′ | |
| judgement | ::= | | |
| | \| | Ctx | |
| | \| | LabelSet | |
| | \| | Heap | |
| | \| | Eq | |
| | \| | Ty | |
| | \| | Sem | |
| user_syntax | ::= | | |
| | \| | metavariable | |
| | \| | term | |
| | \| | var_sub | |
| | \| | var_subs | |
| | \| | heap_val | |
| | \| | val | |
| | \| | *label* | |
| | \| | labels | |
| | \| | *label_set* | |
| | \| | heap_affect | |
| | \| | heap_affects | |
| | \| | heap_context | |
| | \| | type | |
| | \| | type_with_hole | |
| | \| | rec_type_bound | |
| | \| | rec_type_def | |
| | \| | type_affect | |
| | \| | type_affects | |
| | \| | typing_context | |
| | \| | types | |
| | \| | command | |
| | \| | heap_constructor | |
| | \| | judg | |

| terminals

$\boxed{l \in \mathsf{names}(\Phi)}$

$\boxed{l \notin \mathsf{names}(\Phi)}$

$\boxed{\mathsf{type\_affect} \in \Gamma}$

$\boxed{\mathsf{names}(\Gamma_1) \cap \mathsf{names}(\Gamma_2) = \emptyset}$ $\Gamma_1$ and $\Gamma_2$ are disjoint typing contexts with no clashing variable names or lab

$\boxed{\mathsf{names}(\Phi) \sqcup \mathsf{names}(\Psi) \subset L}$

$\boxed{l \in L}$

$\boxed{l = \mathsf{fresh}(\mathbb{L} \setminus L)}$

$\boxed{\mathsf{heap\_affect} \in \mathbb{H}}$

$\boxed{\mathsf{A} = \mathsf{B}}$

$\boxed{\mathsf{t} = \mathsf{u}}$

$\boxed{\Gamma = \mathsf{D}}$

$\boxed{\mathsf{R} \overset{\mathsf{fix}}{=} \mathsf{rec\_type\_def}}$

$\boxed{\mathsf{C} : \bar{\mathsf{A}} \overset{\mathsf{c}}{\multimap} \mathsf{A}}$ Heap constructor C builds a value of type A given arguments of type $\bar{\mathsf{A}}$

$$\frac{}{\{()\} : \cdot \overset{\mathsf{c}}{\multimap} \mathsf{1}} \quad \textsc{TyCtor\_U}$$

$$\frac{}{\{1.\} : \mathsf{A} \overset{\mathsf{c}}{\multimap} \mathsf{A} \oplus \mathsf{B}} \quad \textsc{TyCtor\_V1}$$

$$\frac{}{\{2.\} : \mathsf{B} \overset{\mathsf{c}}{\multimap} \mathsf{A} \oplus \mathsf{B}} \quad \textsc{TyCtor\_V2}$$

$$\frac{}{\{\langle,\rangle\} : \mathsf{A}\ \ \mathsf{B} \overset{\mathsf{c}}{\multimap} \mathsf{A} \otimes \mathsf{B}} \quad \textsc{TyCtor\_P}$$

$$\frac{}{\{\mathsf{Ur}\} : \mathsf{A} \overset{\mathsf{c}}{\multimap} !\mathsf{A}} \quad \textsc{TyCtor\_E}$$

$$\frac{\mathsf{R} \overset{\mathsf{fix}}{=} \mu\, \mathsf{r} \,.\, \mathsf{W}}{\{\mathsf{roll}\, \mathsf{R}\} : \mathsf{W}[\mathsf{r} := \mathsf{R}] \overset{\mathsf{c}}{\multimap} \mathsf{R}} \quad \textsc{TyCtor\_R}$$

$\boxed{\Phi ; \Psi ; \mho ; \Gamma \vdash \mathsf{command} : \mathsf{A}}$

$$\frac{\begin{array}{l}\mathsf{names}(\Phi) \sqcup \mathsf{names}(\Psi) \subset L \\ \Phi ; \Psi \vdash \mathbb{H} \\ \Phi ; \Psi ; \mho ; \Gamma \vdash \mathsf{t} : \mathsf{A}\end{array}}{\Phi ; \Psi ; \mho ; \Gamma \vdash \mathbb{H} \underset{L}{\Diamond} \mathsf{t} : \mathsf{A}} \quad \textsc{TyCommand\_Def}$$

$\boxed{\Phi ; \Psi \vdash \mathbb{H}}$ $\mathbb{H}$ is a well-typed heap given heap typing context $\Phi$

$$\frac{}{\emptyset ; \Psi \vdash \emptyset} \quad \textsc{TyHeap\_Empty}$$

$$\frac{\begin{array}{l}\Phi ; \Psi \vdash \mathbb{H} \\ \Phi ; \Psi ; \emptyset ; \emptyset \vdash \mathsf{v} : \mathsf{A}\end{array}}{\Phi \sqcup \{l : \mathsf{A}\} ; \Psi \vdash \mathbb{H} \sqcup \{l \triangleleft \mathsf{v}\}} \quad \textsc{TyHeap\_Val}$$

$\boxed{\Phi ; \Psi ; \mho ; \Gamma \vdash \mathsf{t} : \mathsf{A}}$ t is a well-typed term of type A given heap typing context $\Phi$, unrestricted typing cont

$$\frac{}{\Phi ; \emptyset ; \mho ; \emptyset \vdash \bullet : \bot} \quad \textsc{TyTerm\_NoEff}$$

$$\frac{l \notin \mathsf{names}\,(\Phi)}{\Phi\ ;\ \{l : A\}\ ;\ \mho\ ;\ \emptyset \vdash \lfloor l \rfloor : \lfloor A \rfloor}\ \textsc{TyTerm\_LDest}$$

$$\frac{\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \sqcup \{x : A\} \vdash t : B}{\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash \lambda x{:}A\,.\,t : A \multimap B}\ \textsc{TyTerm\_Lam}$$

$$\frac{C : \bar{A} \overset{c}{\rightharpoonup} A}{\Phi \sqcup \{\bar{l} : \bar{A}\}\ ;\ \emptyset\ ;\ \mho\ ;\ \emptyset \vdash C\,\bar{l} : A}\ \textsc{TyTerm\_HeapVal}$$

$$\frac{}{\Phi\ ;\ \emptyset\ ;\ \mho\ ;\ \{x : A\} \vdash x : A}\ \textsc{TyTerm\_Id}$$

$$\frac{}{\Phi\ ;\ \emptyset\ ;\ \mho \sqcup \{x : A\}\ ;\ \emptyset \vdash x : A}\ \textsc{TyTerm\_Id'}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : A \multimap B\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \vdash u : A\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash t\,u : B}\ \textsc{TyTerm\_App}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : \bot\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash t\ ;\ u : B}\ \textsc{TyTerm\_WithEff}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : 1\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \vdash u : A\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash \mathsf{case}\, t\, \mathsf{of}\, \{() \mapsto u\} : A}\ \textsc{TyTerm\_PatU}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : !A\\ \Phi\ ;\ \Psi_2\ ;\ \mho \sqcup \{x : A\}\ ;\ \Gamma_2 \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash \mathsf{case}\, t\, \mathsf{of}\, \{\,\mathsf{Ur}\ x \mapsto u\} : B}\ \textsc{TyTerm\_PatE}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : A_1 \oplus A_2\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{x_1 : A_1\} \vdash u_1 : B\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{x_2 : A_2\} \vdash u_2 : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash \mathsf{case}\, t\, \mathsf{of}\, \{1.x_1 \mapsto u_1, 2.x_2 \mapsto u_2\} : B}\ \textsc{TyTerm\_PatS}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : A_1 \otimes A_2\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{x_1 : A_1, x_2 : A_2\} \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash \mathsf{case}\, t\, \mathsf{of}\, \{\langle x_1, x_2 \rangle \mapsto u\} : B}\ \textsc{TyTerm\_PatP}$$

$$\frac{\begin{array}{l}R \overset{\mathsf{fix}}{=} \mu\, r\,.\, W\\ \Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : R\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{x : W[r := R]\} \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash \mathsf{case}\ t\ \mathsf{of}\ \{\mathsf{roll}_{R}\ x \mapsto u\} : B}\ \textsc{TyTerm\_PatR}$$

$$\frac{\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \sqcup \{d : \lfloor A \rfloor\} \vdash t : \bot}{\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash \mathsf{alloc}_{A}\ d\,.\,t : A}\ \textsc{TyTerm\_Alloc}$$

$$\frac{\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash t : \lfloor 1 \rfloor}{\Phi\ ;\ \Psi\ ;\ \mho\ ;\ \Gamma \vdash t \lhd () : \bot}\ \textsc{TyTerm\_FillU}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : \lfloor A \rfloor\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \vdash u : A\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash t \lhd u : \bot}\ \textsc{TyTerm\_FillL}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma \vdash t : \lfloor !A \rfloor\\ \Phi\ ;\ \emptyset\ ;\ \mho\ ;\ \emptyset \vdash u : A\end{array}}{\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma \vdash t \lhd \mathsf{Ur}\ u : \bot}\ \textsc{TyTerm\_FillE}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : \lfloor A_1 \oplus A_2 \rfloor\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{d' : \lfloor A_1 \rfloor\} \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash t \lhd 1.d'\,.\,u : B}\ \textsc{TyTerm\_FillV1}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : \lfloor A_1 \oplus A_2 \rfloor\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{d' : \lfloor A_2 \rfloor\} \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma \vdash t \lhd 2.d'\,.\,u : B}\ \textsc{TyTerm\_FillV2}$$

$$\frac{\begin{array}{l}\Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : \lfloor A_1 \otimes A_2 \rfloor\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{d_1 : \lfloor A_1 \rfloor, d_2 : \lfloor A_2 \rfloor\} \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash t \lhd \langle d_1, d_2 \rangle\,.\,u : B}\ \textsc{TyTerm\_FillP}$$

$$\frac{\begin{array}{l}R \overset{\mathsf{fix}}{=} \mu\, r\,.\,W\\ \Phi\ ;\ \Psi_1\ ;\ \mho\ ;\ \Gamma_1 \vdash t : \lfloor R \rfloor\\ \Phi\ ;\ \Psi_2\ ;\ \mho\ ;\ \Gamma_2 \sqcup \{d : \lfloor W[r := R] \rfloor\} \vdash u : B\\ \mathsf{names}\,(\Gamma_1) \cap \mathsf{names}\,(\Gamma_2) = \emptyset\\ \mathsf{names}\,(\Psi_1) \cap \mathsf{names}\,(\Psi_2) = \emptyset\end{array}}{\Phi\ ;\ \Psi_1 \sqcup \Psi_2\ ;\ \mho\ ;\ \Gamma_1 \sqcup \Gamma_2 \vdash t \lhd \mathsf{roll}_{R}\ d\,.\,u : B}\ \textsc{TyTerm\_FillR}$$

$\boxed{\mathsf{command} \Downarrow \mathsf{command}'}$

$$\frac{}{\mathbb{H} \underset{L}{\diamond} \bullet \ \Downarrow\ \mathbb{H} \underset{L}{\diamond} \bullet}\ \textsc{SemOp\_NoEff}\ \textit{(value)}$$

$$\frac{}{\mathbb{H} \underset{L}{\diamond} \lfloor l \rfloor \ \Downarrow\ \mathbb{H} \underset{L}{\diamond} \lfloor l \rfloor}\ \textsc{SemOp\_LDest}\ \textit{(value)}$$

$$\frac{}{\mathbb{H} \underset{L}{\diamond} \lambda x{:}A\,.\,t \ \Downarrow\ \mathbb{H} \underset{L}{\diamond} \lambda x{:}A\,.\,t}\ \textsc{SemOp\_Lam}\ \textit{(value)}$$

$$\frac{}{\mathbb{H} \underset{L}{\diamond} C\bar{l} \ \Downarrow\ \mathbb{H} \underset{L}{\diamond} C\bar{l}}\ \textsc{SemOp\_HeapVal}\ \textit{(value)}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \underset{L_1}{\diamondsuit} \lambda x{:}A\,.\,\mathsf{t}' \\ \mathbb{H}_1 \underset{L_1}{\diamondsuit} \mathsf{u} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2 \\ \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{t}'[x := \mathsf{v}_2] \Downarrow \mathbb{H}_3 \underset{L_3}{\diamondsuit} \mathsf{v}_3\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t}\ \mathsf{u} \Downarrow \mathbb{H}_3 \underset{L_3}{\diamondsuit} \mathsf{v}_3}\ \textsc{SemOp\_App}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \underset{L_1}{\diamondsuit} () \\ \mathbb{H}_1 \underset{L_1}{\diamondsuit} \mathsf{u} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{case}\ \mathsf{t}\ \mathsf{of}\ \{() \mapsto \mathsf{u}\} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_PatU}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \mathsf{Ur}\ l \\ \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \mathsf{u}[x := \mathsf{v}_1] \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{case}\ \mathsf{t}\ \mathsf{of}\ \{\mathsf{Ur}\ x \mapsto \mathsf{u}\} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_PatE}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} 1.l \\ \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \mathsf{u}_1[x_1 := \mathsf{v}] \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{case}\ \mathsf{t}\ \mathsf{of}\ \{1.x_1 \mapsto \mathsf{u}_1, 2.x_2 \mapsto \mathsf{u}_2\} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_PatV1}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} 2.l \\ \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \mathsf{u}_2[x_2 := \mathsf{v}] \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{case}\ \mathsf{t}\ \mathsf{of}\ \{1.x_1 \mapsto \mathsf{u}_1, 2.x_2 \mapsto \mathsf{u}_2\} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_PatV2}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \sqcup \{l_1 \triangleleft \mathsf{v}_{11}, l_2 \triangleleft \mathsf{v}_{12}\} \underset{L_1}{\diamondsuit} \langle l_1, l_2\rangle \\ \mathbb{H}_1 \sqcup \{l_1 \triangleleft \mathsf{v}_{11}, l_2 \triangleleft \mathsf{v}_{12}\} \underset{L_1}{\diamondsuit} \mathsf{u}[x_1 := \mathsf{v}_1, x_2 := \mathsf{v}_2] \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{case}\ \mathsf{t}\ \mathsf{of}\ \{\langle x_1, x_2\rangle \mapsto \mathsf{u}\} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_PatP}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \underset{R}{\mathsf{roll}}\ l \\ \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \mathsf{u}[x := \mathsf{v}_1] \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{case}\ \mathsf{t}\ \mathsf{of}\ \{\underset{R}{\mathsf{roll}}\ x \mapsto \mathsf{u}\} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_PatR}$$

$$\frac{\begin{array}{c}\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \underset{L_1}{\diamondsuit} \bullet \\ \mathbb{H}_1 \underset{L_1}{\diamondsuit} \mathsf{u} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t}\ ;\ \mathsf{u} \Downarrow \mathbb{H}_2 \underset{L_2}{\diamondsuit} \mathsf{v}_2}\ \textsc{SemOp\_WithEff}$$

$$\frac{\begin{array}{l}l = \mathsf{fresh}(\mathbb{L} \setminus L_0) \\ \mathbb{H}_0 \underset{L_0 \sqcup \{l\}}{\diamondsuit} \mathsf{t}[d := \lfloor l \rfloor] \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \bullet\end{array}}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \underset{A}{\mathsf{alloc}}\ d\,.\,\mathsf{t} \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft \mathsf{v}_1\} \underset{L_1}{\diamondsuit} \mathsf{v}_1}\ \textsc{SemOp\_Alloc}$$

$$\frac{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \Downarrow \mathbb{H}_1 \underset{L_1}{\diamondsuit} \lfloor l \rfloor}{\mathbb{H}_0 \underset{L_0}{\diamondsuit} \mathsf{t} \triangleleft () \Downarrow \mathbb{H}_1 \sqcup \{l \triangleleft ()\} \underset{L_1}{\diamondsuit} \bullet}\ \textsc{SemOp\_FillU}$$

$$\frac{\begin{array}{l}\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \;\Downarrow\; \mathbb{H}_1 \underset{L_1}{\Diamond} \lfloor l \rfloor \\ \mathbb{H}_1 \underset{L_1}{\Diamond} \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \underset{L_2}{\Diamond} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \triangleleft \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \sqcup \{l \triangleleft \mathsf{v}_2\} \underset{L_2}{\Diamond} \bullet}\quad \textsc{SemOp\_FillL}$$

$$\frac{\begin{array}{l}\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \;\Downarrow\; \mathbb{H}_1 \underset{L_1}{\Diamond} \lfloor l \rfloor \\ \mathbb{H}_1 \underset{L_1}{\Diamond} \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \underset{L_2}{\Diamond} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \triangleleft \mathsf{Ur}\ \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \sqcup \{l \triangleleft \mathsf{Ur}\ l', l' \triangleleft \mathsf{v}_2\} \underset{L_2}{\Diamond} \bullet}\quad \textsc{SemOp\_FillE}$$

$$\frac{\begin{array}{l}l' = \mathsf{fresh}(\mathbb{L} \setminus L_1) \\ \mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \;\Downarrow\; \mathbb{H}_1 \underset{L_1}{\Diamond} \lfloor l \rfloor \\ \mathbb{H}_1 \underset{L_1 \sqcup \{l'\}}{\Diamond} \mathsf{u}[\mathsf{d} := \lfloor l' \rfloor] \;\Downarrow\; \mathbb{H}_2 \sqcup \{l' \triangleleft \mathsf{v}_1\} \underset{L_2}{\Diamond} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \triangleleft 1.\mathsf{d} \,.\, \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \sqcup \{l \triangleleft 1.l', l' \triangleleft \mathsf{v}_1\} \underset{L_2}{\Diamond} \mathsf{v}_2}\quad \textsc{SemOp\_FillV1}$$

$$\frac{\begin{array}{l}l' = \mathsf{fresh}(\mathbb{L} \setminus L_1) \\ \mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \;\Downarrow\; \mathbb{H}_1 \underset{L_1}{\Diamond} \lfloor l \rfloor \\ \mathbb{H}_1 \underset{L_1 \sqcup \{l'\}}{\Diamond} \mathsf{u}[\mathsf{d} := \lfloor l' \rfloor] \;\Downarrow\; \mathbb{H}_2 \sqcup \{l' \triangleleft \mathsf{v}_1\} \underset{L_2}{\Diamond} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \triangleleft 2.\mathsf{d} \,.\, \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \sqcup \{l \triangleleft 2.l', l' \triangleleft \mathsf{v}_1\} \underset{L_2}{\Diamond} \mathsf{v}_2}\quad \textsc{SemOp\_FillV2}$$

$$\frac{\begin{array}{l}l_1 = \mathsf{fresh}(\mathbb{L} \setminus L_1) \\ l_2 = \mathsf{fresh}(\mathbb{L} \setminus (L_1 \sqcup \{l_1\})) \\ \mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \;\Downarrow\; \mathbb{H}_1 \underset{L_1}{\Diamond} \lfloor l \rfloor \\ \mathbb{H}_1 \underset{L_1 \sqcup \{l_1, l_2\}}{\Diamond} \mathsf{u}[\mathsf{d}_1 := \lfloor l_1 \rfloor, \mathsf{d}_2 := \lfloor l_2 \rfloor] \;\Downarrow\; \mathbb{H}_2 \sqcup \{l_1 \triangleleft \mathsf{v}_{11}, l_2 \triangleleft \mathsf{v}_{12}\} \underset{L_2}{\Diamond} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \triangleleft \langle \mathsf{d}_1, \mathsf{d}_2 \rangle \,.\, \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \sqcup \{l \triangleleft \langle l_1, l_2 \rangle, l_1 \triangleleft \mathsf{v}_{11}, l_2 \triangleleft \mathsf{v}_{12}\} \underset{L_2}{\Diamond} \mathsf{v}_2}\quad \textsc{SemOp\_FillP}$$

$$\frac{\begin{array}{l}l' = \mathsf{fresh}(\mathbb{L} \setminus L_1) \\ \mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \;\Downarrow\; \mathbb{H}_1 \underset{L_1}{\Diamond} \lfloor l \rfloor \\ \mathbb{H}_1 \underset{L_1 \sqcup \{l'\}}{\Diamond} \mathsf{u}[\mathsf{d} := \lfloor l' \rfloor] \;\Downarrow\; \mathbb{H}_2 \sqcup \{l' \triangleleft \mathsf{v}_1\} \underset{L_2}{\Diamond} \mathsf{v}_2\end{array}}{\mathbb{H}_0 \underset{L_0}{\Diamond} \mathsf{t} \triangleleft \underset{\mathsf{R}}{\mathsf{roll}}\ \mathsf{d} \,.\, \mathsf{u} \;\Downarrow\; \mathbb{H}_2 \sqcup \{l \triangleleft \underset{\mathsf{R}}{\mathsf{roll}}\ l', l' \triangleleft \mathsf{v}_1\} \underset{L_2}{\Diamond} \mathsf{v}_2}\quad \textsc{SemOp\_FillR}$$

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Definition rules:         50 good    0 bad
Definition rule clauses: 151 good    0 bad
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