Semantic Type Soundness for System Capless

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This document drafts semantic type soundness for System Capless. We first formally define System Capless, then sketch logical type soundness proof for it.

1 Definitions of System Capless

The following sections define System Capless.

1.1 Syntax

x, y, z			**Term Variable**
T, U			**Type Variable**
c			**Capture Variable**
S, R	$:=$		**Shape Type**
		$\top$	Top
		X	Type Variable
		$(x : T) \to E$	Function
		$[X <: S] \to E$	Type Function
		$[c <: B] \to E$	Capture Function
		Unit	Unit
		Capability	Capability
S, R	$:=$	$S^\wedge C$	**Shape Type**
E, F	$:=$		**Existential Type**
		$\exists c.T$	existential type
		T	capturing type
θ	$:=$		**Capture**
		x	variable
		c	capability
C	$:=$	$\{\theta_1, ..., \theta_n\}$	**Capture Set**
B	$:=$	$* \mid C$	**Capture Bound**

s, t, u	$:=$		**Term**
		a	answer
		$x\, y$	application
		$x[S]$	type application
		$x[C]$	capture application
		$\text{let } x = t \text{ in } u$	let
		$\text{unpack } t \text{ as } \langle c, x \rangle \text{ in } u$	unpack
a	$:=$		**Answer**
		x	variable
		v	value
v	$:=$		**Value**
		$()$	Unit
		$\lambda(x : T).t$	Function
		$\lambda[X <: S].t$	Type Function
		$\lambda[c <: B].t$	Capture Function
		$\langle C, x \rangle$	Packing
Γ	$:=$		**Type Context**
		$[]$	
		$\Gamma, x : T$	
		$\Gamma, X <: S$	
		$\Gamma, c <: B$	
Σ	$:=$	$\cdot \mid \Sigma, x \mapsto v \mid \Sigma, x \mapsto \mathbf{cap}$	**Store**

Figure 1: Syntax of System Capless.

Figure 1 defines the syntax of System Capless. It is an extension of System $\mathsf{CC}_{<:\square}$.

1.2 Type System

Figure 2 defines the type system of System Capless.

1.3 Operational Semantics

Figure 3 defines the small-step evaluation relation, $\Sigma \mid s \xrightarrow{C} \Sigma' \mid s'$, for System Capless. This evaluation relation is indexed by a capability set C representing an *upper bound* on the capabilities that may be invoked during evaluation. The semantics is *monotonic*: if $\Sigma \mid s \xrightarrow{C} \Sigma' \mid s'$ holds, then $\Sigma \mid s \xrightarrow{C \cup C'} \Sigma' \mid s'$ holds for any C'. Only the (e-invoke) rule actually uses capabilities from C; all other rules are parametric in C.

We write $\Sigma \mid s \xrightarrow[*]{C} \Sigma' \mid s'$ for the reflexive, transitive closure of $\Sigma \mid s \xrightarrow{C} \Sigma' \mid s'$.

Figure 4 defines a big-step evaluation relation. $\Sigma \mid t \overset{C}{\twoheadrightarrow} Q$ means that for any possible evaluation $\Sigma \mid t \xrightarrow[*]{C} \Sigma' \mid a$, the resulting configuration satisfies the postcondition Q.

Typing $C; \Gamma \vdash t : E$

$$\frac{x : S \wedge C \in \Gamma}{\{x\}; \Gamma \vdash x : S \wedge \{x\}} \quad \text{(var)}$$

$$\frac{C_1; \Gamma \vdash e : T_1 \quad \Gamma \vdash C_2, T_2 \text{ wf} \quad \Gamma \vdash T_1 <: T_2 \quad \Gamma \vdash C_1 <: C_2}{C_2; \Gamma \vdash e : T_2} \quad \text{(sub)}$$

$$\frac{}{\{\}; \Gamma \vdash () : \mathsf{Unit}} \quad \text{(var)}$$

$$\frac{C; (\Gamma, x : T) \vdash t : E}{\{\}; \Gamma \vdash \lambda(x : T)t : ((x : T) \to E) \wedge (C \setminus \{x\})} \quad \text{(abs)}$$

$$\frac{C; (\Gamma, X <: S) \vdash t : E}{\{\}; \Gamma \vdash \lambda[X <: S]t : ([X <: S] \to E) \wedge C} \quad \text{(tabs)}$$

$$\frac{C; (\Gamma, c <: B) \vdash t : E \quad \Gamma \vdash C \text{ wf}}{\{\}; \Gamma \vdash \lambda[c <: B]t : ([X <: S] \to E) \wedge C} \quad \text{(cabs)}$$

$$\frac{C; \Gamma \vdash x : ((z : T) \to E) \wedge C_f \quad C; \Gamma \vdash y : T}{C; \Gamma \vdash x\, y : [z := x]E} \quad \text{(app)}$$

$$\frac{C; \Gamma \vdash x : ([X <: S] \to E) \wedge C_f}{C; \Gamma \vdash x[S] : [X := S]E} \quad \text{(tapp)}$$

$$\frac{C; \Gamma \vdash x : ([c <: B] \to E) \wedge C_f \quad \Gamma \vdash C <: B}{C; \Gamma \vdash x[C] : [c := C]E} \quad \text{(capp)}$$

$$\frac{C; \Gamma \vdash x : [c := C]T}{C; \Gamma \vdash \langle C, x \rangle : \exists c.T} \quad \text{(pack)}$$

$$\frac{C; \Gamma \vdash t : T \quad C; (\Gamma, x : T) \vdash u : U \quad \Gamma \vdash C, U \text{ wf}}{C; \Gamma \vdash \text{let } x = t \text{ in } u : U} \quad \text{(let)}$$

$$\frac{C; \Gamma \vdash t : \exists c.T \quad C; (\Gamma, c <: *, x : T) \vdash u : U \quad \Gamma \vdash (C \setminus \{x\}), U \text{ wf}}{C \setminus \{x\}; \Gamma \vdash \text{unpack } t \text{ as } \langle c, x \rangle \text{ in } u : U} \quad \text{(unpack)}$$

Subcapturing $\Gamma \vdash C_1 <: C_2, \Gamma \vdash C <: B$

$$\frac{C_1 \subseteq C_2}{\Gamma \vdash C_1 <: C_2} \quad \text{(sc-subset)}$$

$$\frac{\Gamma \vdash C_1 <: C_2 \quad \Gamma \vdash C_2 <: C_3}{\Gamma \vdash C_1 <: C_3} \quad \text{(sc-trans)}$$

$$\frac{\Gamma \vdash C_1 <: C \quad \Gamma \vdash C_2 <: C}{\Gamma \vdash C_1 \cup C_2 <: C} \quad \text{(sc-union)}$$

$$\frac{x : S \wedge C \in \Gamma}{\Gamma \vdash \{x\} <: C} \quad \text{(sc-var)}$$

$$\frac{c <: C \in \Gamma}{\Gamma \vdash \{c\} <: C} \quad \text{(sc-cvar)}$$

$$\frac{}{\Gamma \vdash C <: *} \quad \text{(sc-bound)}$$

Subtyping $\Gamma \vdash E_1 <: E_2$

$$\frac{}{\Gamma \vdash S <: \top} \quad \text{(top)}$$

$$\frac{}{\Gamma \vdash S <: S} \quad \text{(refl)}$$

$$\frac{\Gamma \vdash S_1 <: S_2 \quad \Gamma \vdash S_2 <: S_3}{\Gamma \vdash S_1 <: S_3} \quad \text{(trans)}$$

$$\frac{X <: S \in \Gamma}{\Gamma \vdash X <: S} \quad \text{(tvar)}$$

$$\frac{(\Gamma, c <: *) \vdash T_1 <: T_2}{\Gamma \vdash \exists c.T_1 <: \exists c.T_2} \quad \text{(exists)}$$

$$\frac{\Gamma \vdash T_2 <: T_1 \quad (\Gamma, x : T_2) \vdash E_1 <: E_2}{\Gamma \vdash (x : T_1) \to E_1 <: (x : T_2) \to E_2} \quad \text{(fun)}$$

$$\frac{\Gamma \vdash S_2 <: S_1 \quad (\Gamma, X <: S_2) \vdash E_1 <: E_2}{\Gamma \vdash [X <: S_1] \to E_1 <: [X <: S_2] \to E_2} \quad \text{(tfun)}$$

$$\frac{\Gamma \vdash B_2 <: B_1 \quad (\Gamma, c <: B_2) \vdash E_1 <: E_2}{\Gamma \vdash [c <: B_1] \to E_1 <: [c <: B_2] \to E_2} \quad \text{(cfun)}$$

Figure 2: Type System of System Capless.

Proposition 1.3.1: Given $\Sigma \mid t \overset{C}{\twoheadrightarrow} Q$, there exist Σ' and a such that $\Sigma \sqsubset \Sigma' \wedge Q(a)(\Sigma')$.

Proposition 1.3.2: Given $\Sigma \mid t \overset{C}{\twoheadrightarrow} Q$, for any Σ' and a such that $\Sigma \mid t \xrightarrow[*]{C} \Sigma' \mid a$, we have $Q(a)(\Sigma')$.

$$
\begin{array}{rlr}
\Sigma \mid x\,y \xrightarrow{C} \Sigma \mid [z := y]t & \text{if } \ \Sigma(x) = \lambda(z : T)t & \text{(e-apply)} \\
\Sigma \mid x\,y \xrightarrow{C} \Sigma \mid () & \text{if } \ x \in C \text{ and } \Sigma(x) = \mathbf{cap} \text{ and } \Sigma(y) = () & \text{(e-invoke)} \\
\Sigma \mid x[S] \xrightarrow{C} \Sigma \mid [X := \top]t & \text{if } \ \Sigma(x) = \lambda[X <: S']t & \text{(e-tapply)} \\
\Sigma \mid x[C'] \xrightarrow{C} \Sigma \mid [c := \{\}]t & \text{if } \ \Sigma(x) = \lambda[c <: B]t & \text{(e-capply)} \\
\Sigma \mid \text{let } x = t \text{ in } u \xrightarrow{C} \Sigma' \mid \text{let } x = t' \text{ in } u & \text{if } \ \Sigma \mid t \xrightarrow{C} \Sigma' \mid t' & \text{(e-ctx1)} \\
\Sigma \mid \text{unpack } t \text{ as } \langle c, x \rangle \text{ in } u \xrightarrow{C} \Sigma' \mid \text{unpack } t' \text{ as } \langle c, x \rangle \text{ in } u & \text{if } \ \Sigma \mid t \xrightarrow{C} \Sigma' \mid t' & \text{(e-ctx2)} \\
\Sigma \mid \text{let } x = y \text{ in } t \xrightarrow{C} \Sigma \mid [x := y]t & & \text{(e-rename)} \\
\Sigma \mid \text{let } x = v \text{ in } t \xrightarrow{C} (\Sigma, x \mapsto v) \mid t & & \text{(e-lift)} \\
\Sigma \mid \text{unpack } \langle c', x' \rangle \text{ as } \langle c, x \rangle \text{ in } u \xrightarrow{C} \Sigma \mid [c := c'][x := x']u & & \text{(e-unpack)}
\end{array}
$$

Figure 3: Operational Semantics of System Capless.

Proposition 1.3.3: If $\forall \Sigma' \forall a, \left(\Sigma \mid t \xrightarrow[*]{C} \Sigma' \mid a\right) \to Q(a)(\Sigma')$, then $\Sigma \mid t \overset{C}{\twoheadrightarrow} Q$.

Proposition 1.3.1, Proposition 1.3.2, and Proposition 1.3.3 establish the equivalence between small-step evaluation and big-step evaluation.

2 Semantic Type Soundness

2.1 Type Denotation

The types are interpreted into predicates. The interpretation is done under a type environment ρ, which maps type variables to predicates of the type $\text{CaptureSet} \to \text{Term} \to \text{Heap} \to \text{Prop}$ (representing the denotation function for shape types parameterized by capability sets); term variables to capability sets; and capture variables to capability sets.

$$\frac{Q(a)(\Sigma)}{\Sigma \mid a \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-ans)} \qquad \frac{\Sigma(x) = \lambda(z : T)t \quad \Sigma \mid [z := y]t \overset{C}{\twoheadrightarrow} Q}{\Sigma \mid x\,y \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-apply)}$$

$$\frac{\Sigma(x) = \lambda[X <: S]t \quad \Sigma \mid [X := \top]t \overset{C}{\twoheadrightarrow} Q}{\Sigma \mid x[S'] \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-tapply)} \qquad \frac{\Sigma(x) = \lambda[c <: B]t \quad \Sigma \mid [c := \{\}]t \overset{C}{\twoheadrightarrow} Q}{\Sigma \mid x[C'] \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-capply)}$$

$$\frac{\Sigma(x) = \mathbf{cap} \quad \Sigma(y) = () \quad Q(())(\Sigma) \quad x \in C}{\Sigma \mid x\,y \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-invoke)}$$

$$\frac{\Sigma \mid t \overset{C}{\twoheadrightarrow} Q' \quad \left(\forall v \forall \Sigma', \Sigma \sqsubset \Sigma' \to Q'(v)(\Sigma') \to (\Sigma', x \mapsto v) \mid u \overset{C}{\twoheadrightarrow} Q\right) \quad \left(\forall z \forall \Sigma', \Sigma \sqsubset \Sigma' \to Q'(z)(\Sigma') \to \Sigma' \mid [x := z]u \overset{C}{\twoheadrightarrow} Q\right)}{\Sigma \mid \text{let } x = t \text{ in } u \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-let)}$$

$$\frac{\Sigma \mid t \overset{C}{\twoheadrightarrow} Q' \quad \left(\forall C' \forall z \forall \Sigma', \Sigma \sqsubset \Sigma' \to Q'(\langle C', z \rangle)(\Sigma') \to \Sigma \mid [x := z][c := \{\}]u \overset{C}{\twoheadrightarrow} Q\right)}{\Sigma \mid \text{unpack } t \text{ as } \langle c, x \rangle \text{ in } u \overset{C}{\twoheadrightarrow} Q}\ \text{(bs-unpack)}$$

Figure 4: Big-Step Evaluation for System Capless.

Given predicates P and Q of type $\text{CaptureSet} \to \text{Term} \to \text{Heap} \to \text{Prop}$, we write $P \Rightarrow Q$ for the logical implication between them: $P \Rightarrow Q$ iff $\forall C \forall t \forall \Sigma, P(C)(t)(\Sigma) \to Q(C)(t)(\Sigma)$.

We write $\Sigma_1 \sqsubset \Sigma_2$ for subsumption between stores: $\Sigma_1 \sqsubset \Sigma_2$ iff $\forall x, \Sigma_1(x) = e \to \Sigma_2(x) = e$. Here e can be either a value v or a capability $\mathbf{cap}$.

We write $\mathcal{C}$ for a capture set that contains only capabilities in the store Σ, i.e. $\mathcal{C} = \{x_1, ..., x_n\}$ and $\forall i, \Sigma(x_i) = \mathbf{cap}$. The store is inferred from the context in which $\mathcal{C}$ is used.

We write $\Sigma(t)$ for resolving a term t in the store Σ. Basically, if t is a variable x, then $\Sigma(t) = \Sigma(x)$; otherwise, $\Sigma(t) = t$.

We write $[\![S]\!]_{\rho,\cdot}$ as a shorthand for $\lambda\mathcal{C}.[\![S]\!]_{\rho,\mathcal{C}}$.

We first define the denotation of capture sets and capture bounds, which maps them to sets of capabilities.

$$
\begin{aligned}
[\![\{\}]\!]_\rho &= \{\} \\
[\![\{x\}]\!]_\rho &= \rho(x) \\
[\![\{c\}]\!]_\rho &= \rho(c) \\
[\![C_1 \cup C_2]\!]_\rho &= [\![C_1]\!] \cup [\![C_2]\!] \\
[\![*]\!]_\rho &= \mathbb{N}
\end{aligned}
$$

Type denotations are defined as follows. The denotation function now acts on shape types and takes a capability set as an additional parameter.

$$
\begin{aligned}
[\![\top]\!]_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\ \mathsf{True} \\
[\![\mathsf{Unit}]\!]_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\ t = () \\
[\![\mathsf{Capability}]\!]_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\exists z. z \in [\![C]\!]_\rho \wedge \Sigma(z) = \mathbf{cap} \\
[\![X]\!]_{\rho,\mathcal{C}} &= \rho(X)([\![C]\!]_\rho) \\
[\![(x:T) \to E]\!]_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\exists T_0 t_0, \Sigma(t) = \lambda(z:T_0)t_0 \wedge \\
&\qquad \forall z \forall \Sigma', \Sigma \sqsubset \Sigma' \to [\![T]\!]_\rho(z)(\Sigma') \to [\![E]\!]^e_{\left(\left[x := [\![C_T]\!]_\rho\right]\rho\right),\mathcal{C}}([x := z]t_0)(\Sigma') \\
&\qquad \text{where } T = S_T{}^\wedge C_T \\
[\![[X <: S] \to E]\!]_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\exists S_0 t_0, \Sigma(t) = \lambda[X <: S_0]t_0 \wedge \\
&\qquad \forall P \forall \Sigma', \Sigma \sqsubset \Sigma' \to \left(P \Rightarrow [\![S]\!]_{\rho,\cdot}\right) \to [\![E]\!]^e_{([X:=P]\rho),\mathcal{C}}([x := \top]t_0)(\Sigma') \\
[\![[c <: B] \to E]\!]_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\exists B_0 t_0, \Sigma(t) = \lambda[c <: B_0]t_0 \wedge \\
&\qquad \forall C_0 \forall \Sigma', \Sigma \sqsubset \Sigma' \to \left(C_0 \subseteq [\![B]\!]_\rho\right) \to [\![E]\!]^e_{([c:=C_0]\rho),\mathcal{C}}([x := \{\}]t_0)(\Sigma') \\
[\![S^\wedge C]\!]_\rho &= [\![S]\!]_{\rho,[\![C]\!]_\rho} \\
[\![\exists c.T]\!]_\rho &= \lambda t.\lambda\Sigma.\exists\mathcal{C}, [\![T]\!]_{[c:=\mathcal{C}]\rho}(t)(\Sigma) \\
[\![E]\!]^e_{\rho,\mathcal{C}} &= \lambda t.\lambda\Sigma.\Sigma \mid t \overset{\mathcal{C}}{\twoheadrightarrow} [\![E]\!]_\rho
\end{aligned}
$$

Then, we need to define semantic typing for contexts $(\Gamma, \rho) \vDash \Sigma$.

$$
\begin{aligned}
([], \rho) \vDash \Sigma &:= \mathsf{True} \\
((\Gamma, x : S^\wedge C), \rho) \vDash \Sigma &:= [\![S]\!]_{\rho,[\![C]\!]_\rho}(x)(\Sigma) \wedge \rho(x) = [\![C]\!]_\rho \wedge (\Gamma, \rho) \vDash \Sigma \\
((\Gamma, X <: S), \rho) \vDash \Sigma &:= \left(\rho(X) \Rightarrow [\![S]\!]_{\rho,\cdot}\right) \wedge (\Gamma, \rho) \vDash \Sigma \\
((\Gamma, c <: B), \rho) \vDash \Sigma &:= \left(\rho(c) \subseteq [\![B]\!]_\rho\right) \wedge (\Gamma, \rho) \vDash \Sigma
\end{aligned}
$$

Finally, we can define semantic typing:

$$
C; \Gamma \vDash t : T := \forall\rho\forall\Sigma, (\Gamma, \rho) \vDash \Sigma \to [\![T]\!]^e_\rho(t)(\Sigma)
$$

Theorem 2.1.1 (Fundamental Theorem of Semantic Type Soundness): If $C; \Gamma \vdash t : T$ then $C; \Gamma \vDash t : T$. That is, syntactic typing implies semantic typing.