CIS 500

Software Foundations

Fall 2005

7 November

Announcements

- Midterm II is one week from Wednesday (November 16).
  - It will cover TAPL chapters 8-14 (except 12).
  - Recitations this week will be review for midterm.
  - No in class review.
- Homework 6 due today.
- Homework 7 out today, due November 14.

References

Another example

```
BoolArray = Ref (Nat→Bool);

newarray = λ_:Unit. ref (λn:Nat.false);
         : Unit → BoolArray

lookup = λa:BoolArray. λn:Nat. (!a) n;
       : BoolArray → Nat → Bool

update = λa:BoolArray. λm:Nat. λv:Bool.
           let oldf = !a in
           a := (λn:Nat. if equal m n then v else oldf n);
       : BoolArray → Nat → Bool → Unit


 let a = newarray () in
 print (lookup a 3);
 update a 3 true;
 lookup a 3
```

Syntax

t ::=		*terms*
	`unit`	*unit constant*
	`x`	*variable*
	`λx:T.t`	*abstraction*
	`t t`	*application*
	`ref t`	*reference creation*
	`!t`	*dereference*
	`t:=t`	*assignment*
	`l`	*store location*
v ::=		*values*
	`unit`	*unit constant*
	`λx:T.t`	*abstraction value*
	`l`	*store location*

Evaluation

An assignment $t_1 := t_2$ first evaluates t_1 and t_2 until they become values...

$$\frac{t_1 \mid \mu \longrightarrow t_1' \mid \mu'}{t_1 := t_2 \mid \mu \longrightarrow t_1' := t_2 \mid \mu'} \qquad \text{(E-Assign1)}$$

$$\frac{t_2 \mid \mu \longrightarrow t_2' \mid \mu'}{v_1 := t_2 \mid \mu \longrightarrow v_1 := t_2' \mid \mu'} \qquad \text{(E-Assign2)}$$

... and then returns `unit` and updates the store:

$$l := v_2 \mid \mu \longrightarrow \mathtt{unit} \mid [l \mapsto v_2]\mu \qquad \text{(E-Assign)}$$

A term of the form $\texttt{ref}\ \texttt{t}_1$ first evaluates inside $\texttt{t}_1$ until it becomes a value...

$$\frac{\texttt{t}_1 \mid \mu \longrightarrow \texttt{t}_1' \mid \mu'}{\texttt{ref}\ \texttt{t}_1 \mid \mu \longrightarrow \texttt{ref}\ \texttt{t}_1' \mid \mu'} \qquad \text{(E-Ref)}$$

... and then chooses (allocates) a fresh location $\texttt{l}$, augments the store with a binding from $\texttt{l}$ to $\texttt{v}_1$, and returns $\texttt{l}$:

$$\frac{\texttt{l} \notin \mathit{dom}(\mu)}{\texttt{ref}\ \texttt{v}_1 \mid \mu \longrightarrow \texttt{l} \mid (\mu, \texttt{l} \mapsto \texttt{v}_1)} \qquad \text{(E-RefV)}$$

A term $!t_1$ first evaluates in t_1 until it becomes a value...

$$\frac{t_1 \mid \mu \longrightarrow t_1' \mid \mu'}{!t_1 \mid \mu \longrightarrow !t_1' \mid \mu'} \qquad \text{(E-Deref)}$$

... and then looks up this value (which must be a location, if the original term was well typed) and returns its contents in the current store:

$$\frac{\mu(l) = v}{!l \mid \mu \longrightarrow v \mid \mu} \qquad \text{(E-DerefLoc)}$$

Evaluation rules for function abstraction and application are augmented with stores, but don't do anything with them directly.

$$\frac{t_1 \mid \mu \longrightarrow t_1' \mid \mu'}{t_1\ t_2 \mid \mu \longrightarrow t_1'\ t_2 \mid \mu'} \qquad \text{(E-App1)}$$

$$\frac{t_2 \mid \mu \longrightarrow t_2' \mid \mu'}{v_1\ t_2 \mid \mu \longrightarrow v_1\ t_2' \mid \mu'} \qquad \text{(E-App2)}$$

$$(\lambda x{:}T_{11}.t_{12})\ v_2 \mid \mu \longrightarrow [x \mapsto v_2]t_{12} \mid \mu \qquad \text{(E-AppAbs)}$$

Store Typings

Typing Locations

Q: What is the type of a location?

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A: It depends on the store!

E.g., in the store $(\mathtt{l}_1 \mapsto \mathtt{unit}, \mathtt{l}_2 \mapsto \mathtt{unit})$, the term $!\mathtt{l}_2$ has type $\mathtt{Unit}$.

But in the store $(\mathtt{l}_1 \mapsto \mathtt{unit}, \mathtt{l}_2 \mapsto \lambda \mathtt{x{:}Unit.x})$, the term $!\mathtt{l}_2$ has type $\mathtt{Unit} \to \mathtt{Unit}$.

Typing Locations — first try

Roughly:

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$$\frac{\Gamma \vdash \mu(l) : T_1}{\Gamma \vdash l : \texttt{Ref}\ T_1}$$

More precisely:

$$\frac{\Gamma \mid \mu \vdash \mu(l) : T_1}{\Gamma \mid \mu \vdash l : \texttt{Ref}\ T_1}$$

I.e., typing is now a four-place relation (between contexts, stores, terms, and types).

Problem

However, this rule is not completely satisfactory. For one thing, it can make typing derivations very large!

E.g., if

$$
\begin{aligned}
(\mu = {} & \mathtt{l}_1 \mapsto \mathtt{\lambda x{:}Nat.\ 999}, \\
& \mathtt{l}_2 \mapsto \mathtt{\lambda x{:}Nat.\ !l_1\ (!l_1\ x)}, \\
& \mathtt{l}_3 \mapsto \mathtt{\lambda x{:}Nat.\ !l_2\ (!l_2\ x)}, \\
& \mathtt{l}_4 \mapsto \mathtt{\lambda x{:}Nat.\ !l_3\ (!l_3\ x)}, \\
& \mathtt{l}_5 \mapsto \mathtt{\lambda x{:}Nat.\ !l_4\ (!l_4\ x)}),
\end{aligned}
$$

then how big is the typing derivation for $\mathtt{!l_5}$?

Problem!

But wait... it gets worse. Suppose

$$(\mu = l_1 \mapsto \lambda x{:}\mathtt{Nat}.\ !l_2\ x,$$
$$l_2 \mapsto \lambda x{:}\mathtt{Nat}.\ !l_1\ x),$$

Now how big is the typing derivation for $!l_2$?

Store Typings

Observation: The typing rules we have chosen for references guarantee that a given location in the store is always used to hold values of the same type.

These intended types can be collected into a store typing — a partial function from locations to types.

E.g., for

$$\begin{aligned}\mu = (&l_1 \mapsto \lambda x{:}\mathtt{Nat}.\ 999,\\ &l_2 \mapsto \lambda x{:}\mathtt{Nat}.\ !l_1\ (!l_1\ x),\\ &l_3 \mapsto \lambda x{:}\mathtt{Nat}.\ !l_2\ (!l_2\ x),\\ &l_4 \mapsto \lambda x{:}\mathtt{Nat}.\ !l_3\ (!l_3\ x),\\ &l_5 \mapsto \lambda x{:}\mathtt{Nat}.\ !l_4\ (!l_4\ x)),\end{aligned}$$

A reasonable store typing would be

$$\begin{aligned}\Sigma = (&l_1 \mapsto \mathtt{Nat}\to\mathtt{Nat},\\ &l_2 \mapsto \mathtt{Nat}\to\mathtt{Nat},\\ &l_3 \mapsto \mathtt{Nat}\to\mathtt{Nat},\\ &l_4 \mapsto \mathtt{Nat}\to\mathtt{Nat},\\ &l_5 \mapsto \mathtt{Nat}\to\mathtt{Nat})\end{aligned}$$

Now, suppose we are given a store typing Σ describing the store μ in which we intend to evaluate some term t. Then we can use Σ to look up the types of locations in t instead of calculating them from the values in μ.

$$\frac{\Sigma(l) = T_1}{\Gamma \mid \Sigma \vdash l : \text{Ref } T_1} \qquad \text{(T-Loc)}$$

I.e., typing is now a four-place relation between between contexts, store typings, terms, and types.

Final typing rules

$$\frac{\Sigma(l) = T_1}{\Gamma \mid \Sigma \vdash l : \mathtt{Ref}\ T_1} \qquad \text{(T-Loc)}$$

$$\frac{\Gamma \mid \Sigma \vdash t_1 : T_1}{\Gamma \mid \Sigma \vdash \mathtt{ref}\ t_1 : \mathtt{Ref}\ T_1} \qquad \text{(T-Ref)}$$

$$\frac{\Gamma \mid \Sigma \vdash t_1 : \mathtt{Ref}\ T_{11}}{\Gamma \mid \Sigma \vdash !t_1 : T_{11}} \qquad \text{(T-Deref)}$$

$$\frac{\Gamma \mid \Sigma \vdash t_1 : \mathtt{Ref}\ T_{11} \qquad \Gamma \mid \Sigma \vdash t_2 : T_{11}}{\Gamma \mid \Sigma \vdash t_1 := t_2 : \mathtt{Unit}} \qquad \text{(T-Assign)}$$

Q: Where do these store typings come from?

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A: When we first typecheck a program, there will be no explicit locations, so we can use an empty store typing.

So, when a new location is created during evaluation,

$$\frac{\mathbf{l} \notin \mathit{dom}(\boldsymbol{\mu})}{\texttt{ref}\ \texttt{v}_1 \mid \boldsymbol{\mu} \longrightarrow \mathbf{l} \mid (\boldsymbol{\mu}, \mathbf{l} \mapsto \texttt{v}_1)} \qquad \text{(E-RefV)}$$

we can observe the type of $\texttt{v}_1$ and extend the "current store typing" appropriately.

Proving type safety

Stating the presevation theorem is a little trickier now. What is wrong with this statement of preservation?

If $\Gamma \mid \Sigma \vdash t : T$ and $t \mid \mu \longrightarrow t' \mid \mu'$ then $\Gamma \mid \Sigma \vdash t' : T$.

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We need to talk about how stores can be typed! There is no connection between Σ and μ.

Store typing

A store μ is said to be well-typed with respect to a typing context Γ and a store typing Σ, written $\Gamma \mid \Sigma \vdash \mu$, if

$$dom(\mu) = dom(\Sigma) \text{ and } \Gamma \mid \Sigma \vdash \mu(l) : \Sigma(l) \text{ for every } l \in dom(\mu)$$

Preservation theorem, second try

What is wrong with this statement of the preservation theorem?

If $\Gamma \mid \Sigma \vdash t : T$ and $\Gamma \mid \Sigma \vdash \mu$ and $t \mid \mu \longrightarrow t' \mid \mu'$ then

$$\Gamma \mid \Sigma \vdash t' : T$$

Preservation theorem

If $\Gamma \mid \Sigma \vdash \mathtt{t} : \mathtt{T}$ and $\Gamma \mid \Sigma \vdash \mu$ and $\mathtt{t} \mid \mu \longrightarrow \mathtt{t}' \mid \mu'$ then,

for some $\Sigma' \supseteq \Sigma, \Gamma \mid \Sigma' \vdash \mathtt{t}' : \mathtt{T}$

New lemmas for preservation

Substitution for stores:

If $\Gamma \mid \Sigma \vdash \mu$ and $\Sigma(l) = T$ and $\Gamma \mid \Sigma \vdash v : T$ then

$$\Gamma \mid \Sigma \vdash [l \mapsto v]\mu$$

New lemmas for preservation

Substitution for stores:

If $\Gamma \mid \Sigma \vdash \mu$ and $\Sigma(l) = T$ and $\Gamma \mid \Sigma \vdash v : T$ then

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Weakening for stores:

If $\Gamma \mid \Sigma \vdash t : T$ and $\Sigma' \supseteq \Sigma$, then

$$\Gamma \mid \Sigma' \vdash t : T$$

Progress theorem

Suppose that $\emptyset \mid \Sigma \vdash \mathtt{t} : \mathtt{T}$ then either

1. $\mathtt{t}$ is a value, or else
2. for any store μ such that $\emptyset \mid \Sigma \vdash \mu$, there is some $\mathtt{t}'$ and store μ' with $\mathtt{t} \mid \mu \longrightarrow \mathtt{t}' \mid \mu'$.

Progress theorem

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1. $\mathtt{t}$ is a value, or else
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Why isn't Σ required to be empty?

Safety

If $\emptyset \mid \emptyset \vdash \mathtt{t} : \mathtt{T}$ and $\mathtt{t} \mid \emptyset \longrightarrow^* \mathtt{t'} \mid \mu$ and $\mathtt{t'} \mid \mu \not\longrightarrow$ then $\mathtt{t}$ is a value.