Design Principles of Programming Languages

Practices in Class

Chap 13-19

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Code packages

- “fullref”
- “fullerror”
- “rcdsub”
- “fullsub”
- “joinsub”
Syntax

We added to \( \lambda \rightarrow \) (with Unit) syntactic forms for creating, dereferencing, and assigning reference cells, plus a new type constructor \texttt{Ref}.

\[
\begin{align*}
t & ::= \\
& \text{unit} \\
x \\
\lambda x:T.t \\
t t \\
\text{ref } t \\
!t \\
t := t \\
\end{align*}
\]

\[
\begin{align*}
\text{terms} \\
& \text{unit constant} \\
& \text{variable} \\
& \text{abstraction} \\
& \text{application} \\
& \text{reference creation} \\
& \text{dereference} \\
& \text{assignment} \\
& \text{store location}
\end{align*}
\]
Evaluation becomes a **four-place** relation: \( t | \mu \rightarrow t' | \mu' \)

\[
\frac{l \notin \text{dom}(\mu)}{\text{ref } v_1 | \mu \rightarrow l | (\mu, l \mapsto v_1)} \quad \text{(E-RefV)}
\]

\[
\frac{\mu(l) = v}{!l | \mu \rightarrow v | \mu} \quad \text{(E-DerefLoc)}
\]

\[
l := v_2 | \mu \rightarrow \text{unit} | [l \mapsto v_2] \mu \quad \text{(E-Assgin)}
\]
Typing becomes a *three-place* relation:\[ \Gamma \mid \Sigma \vdash t : T \]

\[
\begin{align*}
\Sigma(l) &= T_1 \\
\Gamma \mid \Sigma \vdash l : \text{Ref} \ T_1
\end{align*}
\]

(T-Loc)

\[
\begin{align*}
\Gamma \mid \Sigma \vdash t_1 : T_1 \\
\Gamma \mid \Sigma \vdash \text{ref} \ t_1 : \text{Ref} \ T_1
\end{align*}
\]

(T-Ref)

\[
\begin{align*}
\Gamma \mid \Sigma \vdash t_1 : \text{Ref} \ T_{11} \\
\Gamma \mid \Sigma \vdash !t_1 : T_{11}
\end{align*}
\]

(T-Deref)

\[
\begin{align*}
\Gamma \mid \Sigma \vdash t_1 : \text{Ref} \ T_{11} \\
\Gamma \mid \Sigma \vdash t_2 : T_{11} \\
\Gamma \mid \Sigma \vdash t_1 := t_2 : \text{Unit}
\end{align*}
\]

(T-Assign)
Subtype Relation

\[ \text{S} \subseteq \text{S} \quad \text{(S-REFL)} \]

\[ \text{S} \subseteq \text{U} \quad \text{U} \subseteq \text{T} \quad \frac{\text{S} \subseteq \text{U} \quad \text{U} \subseteq \text{T}}{\text{S} \subseteq \text{T}} \quad \text{(S-TRANS)} \]

\[ \{l_i : T_i \; | \; i \in 1 \ldots n+k\} \subseteq \{l_i : T_i \; | \; i \in 1 \ldots n\} \quad \text{(S-RCD WIDTH)} \]

\[ \text{for each } i \quad S_i \subseteq T_i \quad \frac{\{l_i : S_i \; | \; i \in 1 \ldots n\} \subseteq \{l_i : T_i \; | \; i \in 1 \ldots n\}}{\text{(S-RCD DEPTH)}} \]

\[ \{k_j : S_j \; | \; j \in 1 \ldots n\} \text{ is a permutation of } \{l_i : T_i \; | \; i \in 1 \ldots n\} \quad \text{(S-RCD PERM)} \]

\[ T_1 \subseteq S_1 \quad S_2 \subseteq T_2 \quad \frac{T_1 \subseteq S_1 \quad S_2 \subseteq T_2}{S_1 \rightarrow S_2 \subseteq T_1 \rightarrow T_2} \quad \text{(S-ARROW)} \]

\[ \text{S} \subseteq \text{Top} \quad \text{(S-TOP)} \]
Syntax
\[ t ::= \]
\[ x \]
\[ \lambda x:T . t \]
\[ t \, t \]

\[ v ::= \]
\[ \lambda x:T . t \]

\[ T ::= \]
\[ \text{Top} \]
\[ T \rightarrow T \]

\[ \Gamma ::= \]
\[ \emptyset \]
\[ \Gamma, x:T \]

Subtyping
\[ S <: T \]
(S-REFL)
\[ S <: U \quad U <: T \]
\[ S <: T \]
(S-TRANS)
\[ S <: \text{Top} \]
(S-TOP)
\[ T_1 <: S_1 \quad S_2 <: T_2 \]
\[ S_1 \rightarrow S_2 <: T_1 \rightarrow T_2 \]
(S-ARROW)

Typing
\[ \Gamma \vdash t : T \]
(T-VAR)
\[ \Gamma, x:T_1 \vdash t_2 : T_2 \]
\[ \Gamma \vdash \lambda x:T_1 . t_2 : T_1 \rightarrow T_2 \]
(T-ABS)
\[ \Gamma \vdash t_1 : T_1 \rightarrow T_2 \quad \Gamma \vdash t_2 : T_1 \]
\[ \Gamma \vdash t_1 \, t_2 : T_1 \rightarrow T_2 \]
(T-APP)
\[ \Gamma \vdash t : S \quad S <: T \]
\[ \Gamma \vdash t : T \]
(T-SUB)

Evaluation
\[ t_1 \rightarrow t'_1 \]
(E-APP1)
\[ t_1 \, t_2 \rightarrow t'_1 \, t_2 \]
\[ t_2 \rightarrow t'_2 \]
(E-APP2)
\[ v_1 \, t_2 \rightarrow v_1 \, t'_2 \]
\[ (\lambda x:T_1 \rightarrow T_2) \, v_2 \rightarrow [x \rightarrow v_2] \, t_2 \]
(E-APPABS)
Records

\[
\begin{align*}
\Gamma \vdash t : T & \quad \text{(T-RCD)} \\
\Gamma \vdash \{l_i=t_i \; | \; i \in 1..n\} : \{l_i:T_i \; | \; i \in 1..n\} & \quad \text{(T-PROJ)} \\
\Gamma \vdash t_1 : \{l_i:T_i \; | \; i \in 1..n\} & \quad \text{(T-PROJ)} \\
\Gamma \vdash t_1 . l_j : T_j & \quad \text{(T-PROJ)}
\end{align*}
\]
“Algorithmic” subtype relation

\[\mathcal{S} <: \text{Top}\]

\[
\begin{align*}
\vdash & T_1 <: S_1 & \vdash & S_2 <: T_2 \\
\hline \\
\vdash & S_1 \rightarrow S_2 <: T_1 \rightarrow T_2 \\
\end{align*}
\]

\[\text{(SA-ARROW)}\]

\[
\begin{align*}
\{l_i, i \in 1..n\} \subseteq \{k_j, j \in 1..m\} & \quad \text{for each } k_j = l_i, \quad \vdash S_j <: T_j \\
\hline \\
\vdash \{k_j : S_j, j \in 1..m\} <: \{l_i : T_i, i \in 1..n\} \\
\end{align*}
\]

\[\text{(SA-RCD)}\]
Subtyping Algorithm

This *recursively defined total function* is a decision procedure for the subtype relation:

\[
\text{subtype}(S, T) = \\
\quad \text{if } T = \text{Top}, \text{ then } \text{true} \\
\quad \text{else if } S = S_1 \rightarrow S_2 \text{ and } T = T_1 \rightarrow T_2 \\
\quad \quad \text{then } \text{subtype}(T_1, S_1) \land \text{subtype}(S_2, T_2) \\
\quad \text{else if } S = \{k_j: S_j \in \{1, \ldots, m\}\} \text{ and } T = \{l_i: T_i \in \{1, \ldots, n\}\} \\
\quad \quad \text{then } \{\{l_i \in \{1, \ldots, n\}\} \subseteq \{k_j \in \{1, \ldots, m\}\} \\
\quad \quad \quad \land \text{ for all } i \in \{1, \ldots, n\} \text{ there is some } j \in \{1, \ldots, m\} \text{ with } k_j = l_i \\
\quad \quad \text{and } \text{subtype}(S_j, T_i) \\
\quad \text{else } \text{false.}
\]
Algorithmic Typing

The next step is to “build in” the use of subsumption in application rules, by changing the T-App rule to incorporate a subtyping premise.

\[
\Gamma \vdash t_1 : T_{11} \rightarrow T_{12} \quad \Gamma \vdash t_2 : T_2 \quad \vdash T_2 <: T_{11} \\
\Gamma \vdash t_1 \ t_2 : T_{12}
\]

Given any typing derivation, we can now

1. **normalize** it, to move all uses of subsumption to either just before applications (in the right-hand premise) or at the very end

2. **replace** uses of T-App with T-SUB in the right-hand premise by uses of the extended rule above

This yields a derivation in which there is just **one** use of subsumption, at the very end!
What learnt in Chap 18-19

1. Identify some characteristic “core features” of object-oriented programming

2. Develop two different analysis of these features:
   2.1 A translation into a lower-level language
   2.2 A direct, high-level formalization of a simple object-oriented language (“Featherweight Java”)

Object-oriented languages

Most OO languages treats each object as
A *data structure*
  - encapsulating some internal states
  - offering access to these states
via a *collection of methods*.

*Basic features* of object-oriented languages

* encapsulation
* Inheritance

.......
Modeling features of OO with \( \lambda \)-calculus

*How* the *basic features* of object-oriented languages

*encapsulation of state*

*Inheritance*

......

can be understood as “*derived forms*” in a lower-level language with a rich collection of *primitive features*:

*(higher-order) functions*

*records*

*references*

*recursion*

*subtyping*
Encapsulation

An object is a record of functions, which maintain *common internal state via a shared reference to a record* of mutable instance variables.

This state is inaccessible *outside of the object* because there is no way to name it.

– lexical scoping ensures that instance variables can only be named from inside the methods.
Inheritance

Objects that *share parts of their interfaces* will typically (though not always) *share parts of their behaviors*.

To avoid duplication of code, the way is to write the implementations of these behaviors in *just one place*.

⇒ *inheritance*

Basic mechanism of inheritance: *classes*

A class is a *data structure* that can be

– *instantiated* to create new objects (“instances”)
– *refined* to create new classes (“subclasses”)
The essence of objects

- Encapsulation of state with behavior
- Behavior-based subtyping
- Inheritance (incremental definition of behaviors)
- Access of super class
- Open recursion through this
Featherweight Java

A concrete language with core OO features

FJ models “core OO features” and their types and *nothing else*.

History:

— Originally proposed by a Penn visiting student (Atsushi Igarashi) as a tool for analyzing GJ (“Java plus generics”), which later became Java 1.5

— Since then used by many others for studying a wide variety of Java features and proposed extensions
Practice #1

• Do exercise 18.6.1
  – Write a subclass of `resetCounterClass` with an additional method `dec` that subtracts one from the current value stored in the counter.
  – Use the `fullref` checker to test your new class.
Practice #2

• Do exercise 18.7.1
  – Define a subclass of backupCounterClass with two new methods, reset2 and backup2, controlling a second “backup register.” This register should be completely separate from the one added by backupCounterClass: calling reset should restore the counter to its value at the time of the last call to backup (as it does now) and calling reset2 should restore the counter to its value at the time of the last call to backup2.
  – Use the fullref checker to test your new class
Practice #3

- Do exercise 17.3.1
  - The *joinexercise* typechecker is an incomplete implementation of the simply typed lambda-calculus with subtyping, records, and conditionals: basic parsing and printing functions are provided, but the clause for TmIf is missing from the typeof function, as is the join function on which it depends. Add *booleans and conditionals* (and joins and meets) to this implementation.
  - Refer to: § 16.3 showed how adding booleans and conditionals to a language with subtyping required extra support functions for calculating the least upper bounds of a given pair of types. The proof of Proposition 16.3.2 (see page 522) gave mathematical descriptions of the necessary algorithms.
Practice #4

• Do exercise 17.3.3
  – If the subtype check in the application rule fails, the error message that our typechecker prints may not be very helpful to the user. We can improve it by including the expected parameter type and the actual argument type in the error message, but even this may be hard to understand.
  – Reimplement the typeof and subtype functions to make all of the error messages as informative as possible.