1 Abstract Binding Trees

The abstract syntax trees we saw previously contained the concept of variables, but not the ability to give variables meaning. To do that, we need the concept of binding, which is provided by the abstract binding tree, or abt. Like ast’s, abt’s are characterized by variables and operators, but operators have notion of binding.

In an abt, every operator may specify a number of variables that are bound within the scope of the operator. Operators accordingly have arities that reflect the number and sorts of variables they bind. For example, an operator let of arity

\((\text{Exp}, \text{Exp}.\text{Exp})\text{Exp}\)

takes a first abt argument that has no bound variables of sort Exp and a second argument with one bound variable of sort Exp and which is also of sort Exp. The notation \(x.e\) is used to indicate a binder, or an expression coupled with a named bound variable. We might use such an operator to represent a let-expression in ML:

\(\text{let}(1, x.x + 2)\) for \(\text{let } x = 1 \text{ in } x + 2 \text{ end}\)

Inside an operator that binds some variable \(x\), \(x\) is considered bound, and a variable that is not inside a binding of its own name is considered free. The distinction between bound and free variables is significant when we consider the semantics of substitution.

Binders themselves are not valid abt’s but for convenience we often use notation that pretends they are.

2 Statics

The statics of a language is the system of rules that govern the meaning of the language at expression-level before the expression is evaluated (updated) according to a different set of rules known as the dynamics. It usually consists of typing judgments that determine whether an expression is well-formed.

Given a language, we introduce two sorts, Typ and Exp, corresponding to the types and expressions of the language respectively. When parsing of the program completes, we will have an abt that can be decomposed into subtrees falling into these sorts.
Example of the syntax of a language:

<table>
<thead>
<tr>
<th>Typ</th>
<th>Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau ) ::= num</td>
<td>( e ) ::= x</td>
</tr>
<tr>
<td></td>
<td>num([n])</td>
</tr>
<tr>
<td></td>
<td>plus(e₁; e₂)</td>
</tr>
<tr>
<td></td>
<td>times(e₁; e₂)</td>
</tr>
<tr>
<td></td>
<td>let(e₁; x.e₂)</td>
</tr>
</tbody>
</table>

We then define a judgment, **typing**, which relates an expression \( e \) with its type \( \tau \) using the **typing context** \( \Gamma \):

\[
\Gamma \vdash e : \tau
\]

**Example** of our language’s typing judgment definition:

\[
\begin{align*}
\Gamma, x : \tau & \vdash x : \tau \\
\Gamma \vdash num[n] : num \\
\Gamma \vdash e₁ : num & \quad \Gamma \vdash e₂ : num \\
\Gamma \vdash plus(e₁; e₂) : num \\
\Gamma \vdash e₁ : num & \quad \Gamma \vdash e₂ : num \\
\Gamma \vdash times(e₁; e₂) : num \\
\Gamma \vdash e₁ : \tau₁ & \quad \Gamma, x : \tau₁ \vdash e₂ : \tau₂ \\
\Gamma \vdash let(e₁; x.e₂) : \tau₂ \\
\end{align*}
\]

The rules state the following:

- Variables are given types by the context.
- Numeric literals are of type `num`.
- Sums and products of two expressions of type `num` are of type `num`.
- Given that \( e₁ \) has some type \( \tau₁ \), if substituting \( e₁ \) for \( x \) with type \( \tau₁ \) in \( e₂ \) would give it type \( \tau₂ \), then \( \text{let } x = e₁ \text{ in } e₂ \) has type \( \tau₂ \).

A **unicity of typing** theorem ensures the consistency of a type system. It says:

For all \( \Gamma \) and \( e \), there is at most one \( \tau \) such that \( \Gamma \vdash e : \tau \).

### 3 Dynamics

The **dynamics** of a language describe how expressions evaluate. In this class we mainly focus on **structural dynamics**, which is given by a system of **transitions** from one expression to another, until final states called **values** are reached.

The judgment \( e \text{ val} \) states that \( e \) is a value. The judgment \( e \mapsto e' \) states that expression \( e \) steps to expression \( e' \).

**Example** of our language’s value and step judgment definitions:

\[
\begin{align*}
\text{num[n] val} \\
n₁ + n₂ = n \\
\text{plus(num[n₁]; num[n₂])} & \mapsto \text{num[n]}
\end{align*}
\]
The rules state the following:

- Numeric literals are values.
- Sums and products evaluate their first argument, then their second, then evaluate to the arithmetic result. Note that this constitutes an **eager, left-to-right** dynamics, meaning that arguments are evaluated immediately from left to right. Most languages we study in this course will share this property.
- Let-expressions evaluate their substitute argument, then perform substitution to yield a new expression. This is eager as before, though there is discussion in Section 5.2 of PFPL as to how it might be lazy instead.

Note what the dynamics does not do: account for free variables, or likewise ill-typed expressions. The intention is for the statics check to have already occurred, and for dynamics to purely describe evaluation. Here we also did not account for runtime errors, but you will do so in Assignment 1.

A **canonical forms lemma** says that if we know the type of an expression, we already know what the values of the expression look like. It looks like this:

If $e \text{ val}$, then [for each type $\tau$ in the language,]

if $\Gamma \vdash e : \tau$ then $e = V$ [where $V$ is the form of the value].

**Example** of our language’s canonical forms lemma:

If $e \text{ val}$, then if $\Gamma \vdash e : \text{num}$, then $e = \text{num}[n]$ for some $n$.

Not all languages have canonical forms, as it depends on the definition of values.

There are two other useful notions for a dynamics: finality, which says that a well-typed expression is either a value or can step (never both); and determinacy, which says that an expression always steps to a unique expression if it can step at all. Finality is usually assumed to hold in this course, and so is determinacy (until much later in the course!).
4 Type Safety

A progress theorem guarantees our language does not get stuck during execution:

If \( \cdot \vdash e : \tau \), then either \( e \textsf{ val} \), or there exists \( e' \) such that \( e \rightarrow e' \).

A preservation theorem guarantees our language never violates the type of an expression:

If \( \cdot \vdash e : \tau \) and \( e \rightarrow e' \), then \( \cdot \vdash e' : \tau \).

Notice that the progress and preservation theorems only apply to typing judgments where the context is empty. This means that they only apply to closed terms: there can be no free variables in \( e \).

Together, progress and preservation constitute the central property of a language: type safety.

Progress and preservation can be proven about a language using rule induction.

4.1 Progress Proof

A proof of progress proceeds by rule induction on the typing derivation. We can specialize the principle of rule induction for a proof of progress on the example language like so:

Let \( P(e) \) be the property that either \( e \textsf{ val} \) or there exists an \( e' \) such that \( e \rightarrow e' \).

To prove that if \( \cdot \vdash e : \tau \), then either \( e \textsf{ val} \), or there exists \( e' \) such that \( e \rightarrow e' \), it is sufficient to prove the following:

- \( P(\text{num}[n]) \)
- If \( P(e_1), P(e_2), \cdot \vdash e_1 : \text{num} \), and \( \cdot \vdash e_2 : \text{num} \), then \( P(\text{plus}(e_1; e_2)) \)
- If \( P(e_1), P(e_2), \cdot \vdash e_1 : \text{num} \), and \( \cdot \vdash e_2 : \text{num} \), then \( P(\text{times}(e_1; e_2)) \)
- If \( P(e_1), \cdot \vdash e_1 : \tau_1 \), and \( x : \tau_1 \vdash e_2 : \tau_2 \), then \( P(\text{let}(e_1; x.e_2)) \)

The proof itself is left as an exercise.

4.2 Preservation Proof

A proof of preservation proceeds by rule induction on the transition judgment, because it hinges on examining all possible transitions from a given expression. A proof of preservation for the example language is given below.

In the below proof, we make use of the following lemmas:

1. Inversion on Typing:
   - If \( \Gamma \vdash \text{plus}(e_1; e_2) : \tau \) then \( \tau = \text{num}, \Gamma \vdash e_1 : \text{num} \), and \( \Gamma \vdash e_2 : \text{num} \).
   - If \( \Gamma \vdash \text{times}(e_1; e_2) : \tau \) then \( \tau = \text{num}, \Gamma \vdash e_1 : \text{num} \), and \( \Gamma \vdash e_2 : \text{num} \).
   - If \( \Gamma \vdash \text{let}(e_1; x.e_2) : \tau \) then \( \Gamma \vdash e_1 : \tau_1 \) s.t. \( \Gamma, x : \tau_1 \vdash e_2 : \tau \).

2. Substitution Lemma: If \( \Gamma, x : \tau \vdash e' : \tau' \) and \( \Gamma \vdash e : \tau \) then \( \Gamma \vdash [e/x]e' : \tau' \).

**PROOF:**

Let \( P(e, e') \) be the property that if \( \cdot \vdash e : \tau \), then \( \cdot \vdash e' : \tau \). Proceed by rule induction on judgment \( e \rightarrow e' \).
4.2 Preservation Proof

Case: If \( n_1 + n_2 = n \), then \( \mathcal{P}(\text{plus}(\text{num}[n_1]; \text{num}[n_2]), \text{num}[n]) \)

I.H.: \( n_1 + n_2 = n \)
Assume \( \vdash \text{plus}(\text{num}[n_1]; \text{num}[n_2]) : \tau \)
WTS: \( \vdash \text{num}[n] : \tau \)
  \[ \vdash \text{plus}(\text{num}[n_1]; \text{num}[n_2]) : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash \text{num}[n] : \text{num} \quad \text{[Typing rule for \text{num}]} \]
  \[ \vdash \text{num}[n] : \tau \quad \text{[Take \( \tau = \text{num} \)]} \]

Case: If \( \mathcal{P}(e_1, e'_1) \) and \( e_1 \rightarrow e'_1 \), then \( \mathcal{P}(\text{plus}(e_1; e_2), \text{plus}(e'_1; e_2)) \)

I.H.: \( \mathcal{P}(e_1, e'_1) \) and \( e_1 \rightarrow e'_1 \)
Assume \( \vdash \text{plus}(e_1; e_2) : \tau \)
WTS: \( \vdash \text{plus}(e'_1; e_2) : \tau \)
  \[ \vdash \text{plus}(e_1; e_2) : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash e_1 : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash e'_1 : \text{num} \quad \text{[I.H.]} \]
  \[ \vdash e_2 : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash \text{plus}(e'_1; e_2) : \text{num} \quad \text{[Typing rule for \text{plus}]} \]
  \[ \vdash \text{plus}(e'_1; e_2) : \tau \quad \text{[Take \( \tau = \text{num} \)]} \]

Case: If \( \mathcal{P}(e_2, e'_2) \) and \( e_2 \val \) and \( e_2 \rightarrow e'_2 \), then \( \mathcal{P}(\text{plus}(e_1; e_2), \text{plus}(e_1; e'_2)) \)

I.H.: \( \mathcal{P}(e_2, e'_2) \) and \( e_2 \val \) and \( e_2 \rightarrow e'_2 \)
Assume \( \vdash \text{plus}(e_1; e_2) : \tau \)
WTS: \( \vdash \text{plus}(e_1; e'_2) : \tau \)
  \[ \vdash \text{plus}(e_1; e_2) : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash e_2 : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash e'_2 : \text{num} \quad \text{[I.H.]} \]
  \[ \vdash e_1 : \text{num} \quad \text{[Inversion on Typing]} \]
  \[ \vdash \text{plus}(e_1; e'_2) : \text{num} \quad \text{[Typing rule for \text{plus}]} \]
  \[ \vdash \text{plus}(e_1; e'_2) : \tau \quad \text{[Take \( \tau = \text{num} \)]} \]

Case: If \( n_1 \times n_2 = n \), then \( \mathcal{P}(\text{times}(\text{num}[n_1]; \text{num}[n_2]), \text{num}[n]) \)

[Identical to the proof for \text{plus}. Left as exercise.]

Case: If \( \mathcal{P}(e_1, e'_1) \) and \( e_1 \rightarrow e'_1 \), then \( \mathcal{P}(\text{times}(e_1; e_2), \text{times}(e'_1; e_2)) \)

[Identical to the proof for \text{plus}. Left as exercise.]

Case: If \( \mathcal{P}(e_2, e'_2) \) and \( e_2 \val \) and \( e_2 \rightarrow e'_2 \), then \( \mathcal{P}(\text{times}(e_1; e_2), \text{times}(e_1; e'_2)) \)

[Identical to the proof for \text{plus}. Left as exercise.]

Case: If \( \mathcal{P}(e_1, e'_1) \) and \( e_1 \rightarrow e'_1 \), then \( \mathcal{P}(\text{let}(e_1; x.e_2), \text{let}(e'_1; x.e_2)) \)

I.H.: \( \mathcal{P}(e_1, e'_1) \) and \( e_1 \rightarrow e'_1 \)
Assume \( \vdash \text{let}(e_1; x.e_2) : \tau \)
4.2 Preservation Proof

WTS: \( \vdash \text{let}(e'_1; x.e_2) : \tau \)

\[
\begin{align*}
\vdash e_1 : \tau_1 \text{ s.t. } x : \tau_1 \vdash e_2 : \tau & \quad \text{[Inversion on Typing]} \\
\vdash e'_1 : \tau_1 \text{ s.t. } x : \tau_1 \vdash e_2 : \tau & \quad \text{[I.H.]} \\
\vdash \text{let}(e'_1; x.e_2) : \tau & \quad \text{[Typing rule for let]}
\end{align*}
\]

- **Case:** If \( e_1 \) val, then \( P(\text{let}(e_1; x.e_2), [e_1/x]e_2) \)

  I.H.: \( e_1 \) val
  Assume: \( \vdash \text{let}(e_1; x.e_2) : \tau \)
  WTS: \( \vdash [e_1/x]e_2 : \tau \)

\[
\begin{align*}
\vdash e_1 : \tau_1 \text{ s.t. } x : \tau_1 \vdash e_2 : \tau & \quad \text{[Inversion on Typing]} \\
\vdash [e_1/x]e_2 : \tau & \quad \text{[Substitution Lemma]}
\end{align*}
\]

This completes the proof of preservation for the example language.

\[\blacksquare\]