The simply-typed λ-calculus: functions

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Reading: PFPL §8.2

The term $z : \mathsf{Num} \vdash \mathsf{plus}(z; z) : \mathsf{Num}$ expresses the idea of doubling a number. Should we wish to use this term, we must first substitute a number—e.g. $\mathsf{num}[57]$—for the free variable z. Instead, we would like our programming language to be able express doubling as a concept itself. That will be achieved by adding **functions**.

1 Statics

We extend the syntax chart with the following constructs:

$$
\begin{array}{llcll}
\text{types} & \tau & ::= & \dots & \\
 & & & \tau_1 \to \tau_2 & \text{function type} \\
\text{pre-terms} & e & ::= & \dots & \\
 & & & \lambda x : \tau .\, e & \text{abstraction} \\
 & & & e_1(e_2) & \text{application}
\end{array}
$$

The typing is given by the following two rules.

$$
\textsc{Lam}\ \frac{\Gamma, x : \sigma \vdash e : \tau}{\Gamma \vdash \lambda x : \sigma .\, e : \sigma \to \tau}
\qquad\qquad
\textsc{App}\ \frac{\Gamma \vdash e_1 : \sigma \to \tau \qquad \Gamma \vdash e_2 : \sigma}{\Gamma \vdash e_1(e_2) : \tau}
$$

The first rule creates λ-**abstractions**: it discharges a free variable $x : \sigma$, thereby creating a function which accepts an argument of type σ and returns a result of type τ. Hence, we may express the concept of doubling by

$$\vdash \lambda z : \mathsf{Num}.\, \mathsf{plus}(z; z) : \mathsf{Num} \to \mathsf{Num}$$

which is a term of **function type**.

The second rule is known as **application**, and allows the application of a function to a compatible argument.

2 Dynamics

The dynamics of function types are given by the following rules.

$$
\textsc{Val-Lam}\ \frac{}{\lambda x : \tau .\, e\ \mathsf{val}}
\qquad
\textsc{D-App-1}\ \frac{e_1 \longmapsto e_1'}{e_1(e_2) \longmapsto e_1'(e_2)}
\qquad
\textsc{D-Beta}\ \frac{}{(\lambda x : \tau .\, e_1)(e_2) \longmapsto e_1[e_2/x]}
$$

The definition of substitution is the same as before, but extended with the clauses

$$
(\lambda y : \tau .\, u)[e/x] \stackrel{\text{def}}{=} \lambda y : \tau .\, u[e/x]
\qquad\qquad
(e_1(e_2))[e/x] \stackrel{\text{def}}{=} (e_1[e/x])(e_2[e/x])
$$

Every λ-abstraction is a value: its body is 'frozen' until an argument is provided.

The rule D-Beta encapsulates the meaning of functions. If we have a function $\lambda x.\, e_1$ is applied to an argument e_2, then we must evaluate the **body** e_1 of the function with the **argument** e_2 substituted for the variable x. This accords with our mathematical experience: if $f(x) \stackrel{\text{def}}{=} x^2$ then $f(5) = (x^2)[5/x] = 5^2$. However, we shall now write the definition using λ-notation, viz. as $f \stackrel{\text{def}}{=} \lambda x.\, x^2$.

3 Examples

Our typing rule is the most obvious solution to adding functions. However, it is worth noting that we have perhaps obtained more than we asked: our language now has **higher-order functions**.

For example, we have the following typing derivation.

$$\cfrac{\cfrac{\cfrac{\cfrac{}{x : \mathsf{Num}, y : \mathsf{Num} \vdash x : \mathsf{Num}}\,\textsc{Var} \qquad \cfrac{}{x : \mathsf{Num}, y : \mathsf{Num} \vdash y : \mathsf{Num}}\,\textsc{Var}}{x : \mathsf{Num}, y : \mathsf{Num} \vdash \mathsf{plus}(x; y) : \mathsf{Num}}\,\textsc{Plus}}{x : \mathsf{Num} \vdash \lambda y : \mathsf{Num}.\, \mathsf{plus}(x; y) : \mathsf{Num} \to \mathsf{Num}}\,\textsc{Lam}}{\vdash \underbrace{\lambda x : \mathsf{Num}.\, \lambda y : \mathsf{Num}.\, \mathsf{plus}(x; y)}_{\mathsf{add}} : \mathsf{Num} \to (\mathsf{Num} \to \mathsf{Num})}\,\textsc{Lam}$$

This is a function that returns a function. It corresponds to the Haskell definition

```
add :: Integer → Integer → Integer
add x y = x + y
```

which can also be written as

```
add :: Integer → Integer → Integer
add = \x → \y → x + y
```

This definition gives rise to the following transition sequence.

$$\begin{aligned} \mathsf{add}(\mathsf{num}[1])(\mathsf{num}[2]) &\longmapsto (\lambda y : \mathsf{Num}.\, \mathsf{plus}(\mathsf{num}[1]; y))(\mathsf{num}[2]) \\ &\longmapsto \mathsf{plus}(\mathsf{num}[1]; \mathsf{num}[2]) \\ &\longmapsto \mathsf{num}[3] \end{aligned}$$

The following is also a valid derivation, where $\Gamma \overset{\text{def}}{=} f : \mathsf{Num} \to \mathsf{Num}, x : \mathsf{Num}$.

$$\cfrac{\cfrac{\cfrac{\cfrac{}{\Gamma \vdash f : \mathsf{Num} \to \mathsf{Num}} \qquad \cfrac{\cfrac{}{\Gamma \vdash f : \mathsf{Num} \to \mathsf{Num}}\,\textsc{Var} \qquad \cfrac{}{\Gamma \vdash x : \mathsf{Num}}\,\textsc{Var}}{\Gamma \vdash f(x) : \mathsf{Num}}\,\textsc{App}}{f : \mathsf{Num} \to \mathsf{Num}, x : \mathsf{Num} \vdash f(f(x)) : \mathsf{Num}}\,\textsc{App}}{f : \mathsf{Num} \to \mathsf{Num} \vdash \lambda x : \mathsf{Num}.\, f(f(x)) : \mathsf{Num} \to \mathsf{Num}}\,\textsc{Lam}}{\vdash \underbrace{\lambda f : \mathsf{Num} \to \mathsf{Num}.\, \lambda x : \mathsf{Num}.\, f(f(x))}_{\mathsf{twice}} : (\mathsf{Num} \to \mathsf{Num}) \to (\mathsf{Num} \to \mathsf{Num})}\,\textsc{Lam}$$

This is a function that both takes in and returns a function. It corresponds to the Haskell definition

```
twice :: (Num → Num) → Num → Num
twice f x = f (f x)
```

This gives rise to the multi-step transition: $\mathsf{twice}(\mathsf{add}(\mathsf{num}[2]))(\mathsf{num}[0]) \longmapsto^* \mathsf{num}[4]$.

It is possible to obtain only first-order functions, but it requires additional effort: see PFPL §8.1.

4 Properties

We have completed a presentation of

the simply-typed λ-calculus (STLC) = product types + sum types + function types (+ constants)

The optional constants referred to above amount to the the basic language of numbers and strings, which consists of some **base types**—e.g. Num and Str—as well as some **primitive functions**, e.g. $\mathsf{plus}(-;-)$ and $\mathsf{cat}(-;-)$.

The STLC satisfies the usual properties of type safety, namely progress and preservation.