Encodings

CS 152 (Spring 2020)

Harvard University

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Today, we will learn about

- Lambda calculus encodings
- Church numerals
- Recursion and fixed point-combinators

Lambda calculus encodings

- The pure lambda calculus contains only functions as values.
- It is not exactly easy to write large or interesting programs in the pure lambda calculus.
- We can however encode objects, such as booleans, and integers.

Booleans

Booleans

We want to define functions *TRUE*, *FALSE*, *AND*, *IF*, and other operators such that the expected behavior holds, for example:

$$\mathit{AND}\ \mathit{TRUE}\ \mathit{FALSE} = \mathit{FALSE}$$
$$\mathit{IF}\ \mathit{TRUE}\ e_1\ e_2 = e_1$$
$$\mathit{IF}\ \mathit{FALSE}\ e_1\ e_2 = e_2$$

TRUE and FALSE

$$TRUE \triangleq \lambda x.\, \lambda y.\, x$$
$$FALSE \triangleq \lambda x.\, \lambda y.\, y$$

IF

The function *IF* should behave like

$$\lambda b.\, \lambda t.\, \lambda f.\, \text{if } b = \mathit{TRUE} \text{ then } t \text{ else } f.$$

The definitions for *TRUE* and *FALSE* make this very easy.

$$\mathit{IF} \triangleq \lambda b.\, \lambda t.\, \lambda f.\, b\ t\ f$$

NOT, AND, OR

$$\begin{aligned}
NOT &\triangleq \lambda b.\, b\ FALSE\ \ TRUE \\
AND &\triangleq \lambda b_1.\, \lambda b_2.\, b_1\ \ b_2\ FALSE \\
OR &\triangleq \lambda b_1.\, \lambda b_2.\, b_1\ \ TRUE\ \ b_2
\end{aligned}$$

Church numerals

Church numerals encode the natural number n as a function that takes f and x, and applies f to x n times.

$$
\begin{aligned}
\overline{0} &\triangleq \lambda f.\, \lambda x.\, x \\
\overline{1} &= \lambda f.\, \lambda x.\, f\ x \\
\overline{2} &= \lambda f.\, \lambda x.\, f\ (f\ x) \\
\mathsf{SUCC} &\triangleq \lambda n.\, \lambda f.\, \lambda x.\, f\ (n\ f\ x)
\end{aligned}
$$

Addition

Let us define addition now. Intuitively, the natural number $n_1 + n_2$ is the result of apply the successor function n_1 times to n_2.

$$ADD \triangleq \lambda n_1.\, \lambda n_2.\, n_1 \ SUCC \ n_2$$

Recursion and the fixed-point combinators

Recursion and the fixed-point combinators

We would like to define a function that computes factorials.

$$FACT \triangleq \lambda n.\, \textbf{if } n = 0 \textbf{ then } 1 \textbf{ else } n \times FACT\ (n - 1)$$

Recursion and the fixed-point combinators

$$FACT \triangleq \lambda n.\, IF\ (ISZERO\ n)\ 1\ (TIMES\ n\ (FACT\ (PRED\ n)))$$

Recursion and the fixed-point combinators

Note that this is not a definition, it's a recursive equation.

Recursion Removal Trick

- We can perform a "trick" to define a function $FACT$ that satisfies the recursive equation above.

- First, let's define a new function $FACT'$ that looks like $FACT$, but takes an additional argument f.

- We assume that the function f will be instantiated with an actual parameter of... $FACT'$.

$$FACT' \triangleq \lambda f.\, \lambda n.\, \textbf{if } n = 0 \textbf{ then } 1 \textbf{ else } n \times (f\ f\ (n-1))$$

Now we can define the factorial function $FACT$ in terms of $FACT'$.

$$FACT \triangleq FACT' \; FACT'$$

Let's try evaluating $FACT\ 3 = m$.

$$
\begin{aligned}
m &= (FACT'\ FACT')\ 3 \\
&= ((\lambda f.\,\lambda n.\,\textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times (f\ f\ (n-1)))\ FACT')\ 3 \\
&\longrightarrow (\lambda n.\,\textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times (FACT'\ FACT'\ (n-1)))\ 3 \\
&\longrightarrow \textbf{if}\ 3 = 0\ \textbf{then}\ 1\ \textbf{else}\ 3 \times (FACT'\ FACT'\ (3-1)) \\
&\longrightarrow 3 \times (FACT'\ FACT'\ (3-1)) \\
&\longrightarrow \ldots \\
&\longrightarrow 3 \times 2 \times 1 \times 1 \\
&\longrightarrow^{*} 6
\end{aligned}
$$

So we now have a technique for writing a recursive function f: write a function f' that explicitly takes a copy of itself as an argument, and then define

$$f \triangleq f' \ f'.$$

Fixed point combinators

Alternatively, we can express a recursive function as the fixed point of some other, higher-order function, and then find that fixed point.

Fixed point combinator

Thus *FACT* is a fixed point of the following function.

$$G \triangleq \lambda f.\, \lambda n.\, \textbf{if } n = 0 \textbf{ then } 1 \textbf{ else } n \times (f\ (n-1))$$

Fixed point combinator

Recall that if g if a fixed point of G, then we have $G\ g = g$.

Fixed point combinator

- A *combinator* is simply a closed lambda term
- Our functions *SUCC* and *ADD* are examples of combinators.
- It is possible to define programs using only combinators, thus avoiding the use of variables completely.

The Y combinator

The Y combinator is defined as

$$Y \triangleq \lambda f.\,(\lambda x.\, f\ (x\ x))\ (\lambda x.\, f\ (x\ x)).$$

It was discovered by Haskell Curry, and is one of the simplest fixed-point combinators.

The fixed point of the higher order function G is equal to $G\ (G\ (G\ (G\ (G\ \ldots))))$. Intuitively, the Y combinator unrolls this equality, as needed.

Let's see it in action, on our function G, where

$$G = \lambda f.\, \lambda n.\, \textbf{if } n = 0 \textbf{ then } 1 \textbf{ else } n \times (f\ (n-1))$$

and the factorial function is the fixed point of G.
(We will use CBN semantics.)

$$
\begin{aligned}
FACT &= Y\ G \\
&= (\lambda f.\, (\lambda x.\, f\ (x\ x))\ (\lambda x.\, f\ (x\ x)))\ G \\
&\longrightarrow (\lambda x.\, G\ (x\ x))\ (\lambda x.\, G\ (x\ x)) \\
&\longrightarrow G\ ((\lambda x.\, G\ (x\ x))\ (\lambda x.\, G\ (x\ x))) \\
&=_\beta G\ (FACT) \\
&= (\lambda f.\, \lambda n.\, \textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times (f\ (n-1)))\ FACT \\
&\longrightarrow \lambda n.\, \textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times (FACT\ (n-1))
\end{aligned}
$$

Note that the Y combinator works under CBN semantics, but not CBV. (What happens when we evaluate $Y\ G$ under CBV?)

There is a variant of the Y combinator, Z, that works under CBV semantics. It is defined as

$$Z \triangleq \lambda f.\,(\lambda x.\, f\ (\lambda y.\, x\ x\ y))\ (\lambda x.\, f\ (\lambda y.\, x\ x\ y)).$$

The Turing fixed-point combinator

The Turing fixed-point combinator, denoted Θ, was discovered by Alan Turing.

The Turing fixed-point combinator

Suppose we have a higher order function f, and want the fixed point of f. We know that $\Theta\ f$ is a fixed point of f, so we have

$$\Theta\ f = f\ (\Theta\ f).$$

This means, that we can write the following recursive equation for Θ.

$$\Theta = \lambda f.\, f\ (\Theta\ f)$$

Now we can use the recursion removal trick we described earlier! Let's define $\Theta' = \lambda t.\, \lambda f.\, f\ (t\ t\ f)$, and define

$$\begin{aligned} \Theta &\triangleq \Theta'\ \Theta' \\ &= (\lambda t.\, \lambda f.\, f\ (t\ t\ f))\ (\lambda t.\, \lambda f.\, f\ (t\ t\ f)) \end{aligned}$$

Let's try out the Turing combinator on our higher order function G that we used to define $FACT$. Again, we will use CBN semantics.

$$
\begin{aligned}
FACT &= \Theta\ G \\
&= ((\lambda t.\, \lambda f.\, f\ (t\ t\ f))\ (\lambda t.\, \lambda f.\, f\ (t\ t\ f)))\ G \\
&\longrightarrow (\lambda f.\, f\ ((\lambda t.\, \lambda f.\, f\ (t\ t\ f))\ (\lambda t.\, \lambda f.\, f\ (t\ t\ f))\ f))\ G \\
&\longrightarrow G\ ((\lambda t.\, \lambda f.\, f\ (t\ t\ f))\ (\lambda t.\, \lambda f.\, f\ (t\ t\ f))\ G) \\
&= G\ (\Theta\ G) \\
&= (\lambda f.\, \lambda n.\, \textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times (f\ (n-1)))\ (\Theta\ G) \\
&\longrightarrow \lambda n.\, \textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times ((\Theta\ G)\ (n-1)) \\
&= \lambda n.\, \textbf{if}\ n = 0\ \textbf{then}\ 1\ \textbf{else}\ n \times (FACT\ (n-1))
\end{aligned}
$$