ARITHMETIC ON CHURCH NUMERALS USING A NOTATIONAL TRICK

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Church numerals allow us to represent numbers in pure lambda calculus. In this short note we'll see how to define addition, multiplication, and exponentiation on Church numerals using a cute notational trick. As a bonus, we'll see how to define predecessor and fast growing functions.

1 ADDITION, MULTIPLICATION, AND EXPONENTIATION

Church repesents a natural number n as a higher order function, which I'll denote $\mathbf{n}$. The function $\mathbf{n}$ takes another function f and composes f with itself n times:

$$\mathbf{n}\ f = \underbrace{f \circ f \cdots \circ f}_{n \text{ times}} = f^n$$

We can convert a Church numeral $\mathbf{n}$ back to an ordinary nat by applying it to the ordinary successor function $S : \mathbb{N} \to \mathbb{N}$ given by $S\ n = n + 1$: then $\mathbf{n}\ S\ 0$ gives us back an ordinary natural number n because $\mathbf{n}\ S\ 0$ is the n-fold application of the successor function to the number 0, which just increments it n times.

The first few Church numerals are:

$$\begin{aligned}
\mathbf{0} &\triangleq \lambda f.\lambda z.z \\
\mathbf{1} &\triangleq \lambda f.\lambda z.fz \\
\mathbf{2} &\triangleq \lambda f.\lambda z.f(fz) \\
\mathbf{3} &\triangleq \lambda f.\lambda z.f(f(fz))
\end{aligned}$$

Many descriptions of Church numerals will view them in that way: as a function that takes *two* arguments f and z that computes $f(f(\ldots(fz)\ldots))$, but this point of view gets incredibly confusing when you try to define arithmetic on them, particularly multiplication and exponentiation. So think about $\mathbf{n}\ f = f^n$ as performing n-fold function composition.

If will be helpful to introduce an alternative notation for function application:

$$x^f \equiv f(x)$$

This may seem strange, but using this notation we can *define* the first few Church numerals as:

$$\begin{aligned}
f^{\mathbf{0}} &\triangleq \mathsf{id} \\
f^{\mathbf{1}} &\triangleq f \\
f^{\mathbf{2}} &\triangleq f \circ f \\
f^{\mathbf{3}} &\triangleq f \circ f \circ f
\end{aligned}$$

Note that on the left hand side, we are really defining $\mathbf{3}$ as the function $\mathbf{3}(f) \triangleq f \circ f \circ f$.

The advantage of this notation is apparent when defining addition and multiplication on Church numerals:

$$f^{\mathbf{n}+\mathbf{m}} \triangleq f^{\mathbf{n}} \circ f^{\mathbf{m}} \qquad\qquad f^{\mathbf{n}\cdot\mathbf{m}} \triangleq (f^{\mathbf{n}})^{\mathbf{m}}$$

Exponentiation of Church numerals is even better: our notation already makes $\mathbf{n}^{\mathbf{m}}$ do the right thing:

$$\mathbf{n}^{\mathbf{m}} \equiv \mathbf{m}(\mathbf{n}) \qquad \text{(already does the right thing!)}$$

The proofs that this does arithmetic correctly look like a triviality when using our notation: if $[n]$ is the Church numeral corresponding to an ordinary natural number $n \in \mathbb{N}$, *i.e.*, satisfying $f^{[n]} = f^n$, where $f^{[m]} \equiv [m](f)$ according to our notation, and f^n for ordinary natural number $n \in \mathbb{N}$ is n-fold function composition, then

$$f^{[n]+[m]} = f^{[n]} \circ f^{[m]} = f^n \circ f^m = f^{n+m} = f^{[n+m]}$$

The proofs for multiplication and exponentiation are similar.

2 PREDECESSOR

Surprisingly, defining the predecessor on Church numerals is the most difficult. I think this solution is due to Curry.

We define the function $f : \mathbb{N} \times \mathbb{N} \to \mathbb{N} \times \mathbb{N}$:

$$f((a, b)) = (s(a), a)$$

If we start with $(0, x)$ and keep applying f we get the following sequence:

$$(0, x) \to (1, 0) \to (2, 1) \to (3, 2) \to (4, 3) \to \cdots$$

So

$$f^n((0, x))_1 = n$$
$$f^n((0, x))_2 = \begin{cases} x & \text{if } n = 0 \\ n - 1 & \text{if } n > 0 \end{cases}$$

So we can define the predecessor function:

$$p = \lambda \mathbf{n}. f^{\mathbf{n}}(0, 0)$$

So that $p(0) = 0$ and $p(n) = n - 1$ for $n > 0$.

2.1 PAIRS

We made use of pairs to define the predecessor, so to use pure lambda calculus we need to define pairs in terms of lambda. We represent a pair (a, b) as:

$$(a, b) = \lambda f. f\ a\ b$$

We can extract the components by passing in the function f:

$$\mathsf{fst} = \lambda x. x\ (\lambda a. \lambda b. a)$$
$$\mathsf{snd} = \lambda x. x\ (\lambda a. \lambda b. b)$$

2.2 Disjoint union

Another way to define the predecessor is with disjoint unions. We take:

$$\mathsf{inl}(a) = \lambda f.\lambda g.fa$$
$$\mathsf{inr}(a) = \lambda f.\lambda g.ga$$

Then we can define:

$$f(\mathsf{inl}(a)) = \mathsf{inr}(a)$$
$$f(\mathsf{inr}(a)) = \mathsf{inr}(s(a))$$

We can do this pattern match on an inl/inr by calling it with the two branches as arguments:

$$f(x) = x\ (\lambda a.\mathsf{inr}(a))\ (\lambda a.\mathsf{inr}(s(a)))$$

And we can define:

$$p(\mathbf{n}) = f^{\mathbf{n}}\ \mathsf{inl}(0)\ (\lambda x.x)\ (\lambda x.x)$$

3 Fast growing functions

Given any function $g : \mathrm{N} \to \mathrm{N}$ we can define a series of ever faster growing functions as follows:

$$f_0(n) = g(n)$$
$$f_{k+1}(n) = f_k^n(n)$$

We can define this function using Church numerals:

$$f_{\mathbf{k}} = (\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ g$$

If we take $g = S$ the successor function, then,

$$f_0(n) = n + 1$$
$$f_1(n) = 2n$$
$$f_2(n) = 2^n \cdot n$$

The function $A(n) = f_n(n)$ grows pretty quickly. We can play the same game again, by putting $g = A$, obtaining a sequence:

$$h_0(n) = A(n)$$
$$h_{k+1}(n) = h_k^n(n)$$

To get a feeling for how fast this grows, consider h_1:

$$\begin{aligned} h_1(n) &= h_0^n(n) \\ &= A(A(A(\ldots A(A(n))))) \\ &= A(A(A(\ldots A(f_n(n))))) \\ &= A(A(A(\ldots f_{f_n(n)}(f_n(n))))) \end{aligned}$$

An expression like $h_3(3)$ gives us a relatively short lambda term that will normalise to a huge term. We might as well start with $g(n) = n^n$ since that's even easier to write using Church numerals:

$$\begin{aligned}
g &= \lambda \mathbf{a}.\mathbf{a}^{\mathbf{a}} \\
A &= \lambda \mathbf{k}.(\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ g\ \mathbf{k} \\
h &= \lambda \mathbf{k}.(\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ A\ \mathbf{k} \\
\mathbf{3} &= \lambda f.\lambda z.f(f(f\ z)) \\
X &= h\ \mathbf{3}
\end{aligned}$$

You can't write down anything close to the number X even if you were to write a hundred pages of towers of exponentials. Of course, we can continue this game, and define a sequence

$$\begin{aligned}
g_0 &= \lambda \mathbf{a}.\mathbf{a}^{\mathbf{a}} \\
g_1 &= \lambda \mathbf{k}.(\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ g_0\ \mathbf{k} \\
g_2 &= \lambda \mathbf{k}.(\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ g_1\ \mathbf{k} \\
&\dots
\end{aligned}$$

Which can be generalised as:

$$\begin{aligned}
f(g) &= \lambda \mathbf{k}.(\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ g\ \mathbf{k} \\
g_n &= f^n(g_0)
\end{aligned}$$

So we get an even more compact, yet much larger number with:

$$\begin{aligned}
f &= \lambda g.\lambda \mathbf{k}.(\lambda f.\lambda \mathbf{n}.f^{\mathbf{n}}\ \mathbf{n})^{\mathbf{k}}\ g\ \mathbf{k} \\
Y &= f^3\ (\lambda \mathbf{a}.\mathbf{a}^{\mathbf{a}})\ \mathbf{3}
\end{aligned}$$

Of course, you can easily define much faster growing functions. But here's a challenge: what's the shortest lambda term that normalises, but takes more than the age of the universe to normalise? Or: what's the largest Church numeral you can write down in less than 30 symbols?

Please let me know of any mistakes. I haven't checked for them :)

— Jules