

λ -Calculus

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λ-Calculus

The term language we defined for Higher Order Abstract Syntax is almost a full featured programming language.

Just enrich the syntax slightly:

$$\begin{array}{lll} t & ::= & \text{Symbol} \\ & | & x \quad \text{(variables)} \\ & | & t_1 \ t_2 \quad \text{(application)} \\ & | & \lambda x. t \quad (\lambda\text{-abstraction}) \end{array}$$

There is just one rule to evaluate terms, called *β-reduction*:

$$(\lambda x. t) \ u \quad \mapsto_{\beta} \quad t[x := u]$$

Just as in Haskell, $(\lambda x. t)$ denotes a **function** that, given an argument for x , returns t .

Syntax Concerns

Function application is **left associative**:

$$f\ a\ b\ c \quad = \quad ((f\ a)\ b)\ c$$

λ -abstraction extends **as far as possible**:

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

All functions are unary, like Haskell. Multiple argument functions are modelled with nested λ -abstractions:

$$\lambda x. \lambda y. x + y$$

β-reduction

β-reduction is a *congruence*:

$$\frac{}{(\lambda x. t) u \mapsto_{\beta} t[x := u]}$$

$$\frac{t \mapsto_{\beta} t'}{s t \mapsto_{\beta} s t'} \quad \frac{s \mapsto_{\beta} s'}{s t \mapsto_{\beta} s' t} \quad \frac{t \mapsto_{\beta} t'}{\lambda x. t \mapsto_{\beta} \lambda x. t'}$$

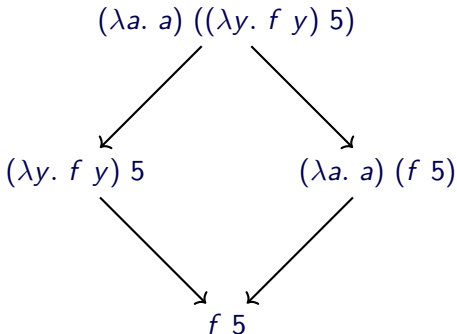
This means we can pick any reducible subexpression (called a *redex*) and perform β-reduction.

Example:

$$\begin{aligned} (\lambda x. \lambda y. f (y x)) \text{ 5 } (\lambda x. x) &\mapsto_{\beta} (\lambda y. f (y \text{ 5})) (\lambda x. x) \\ &\mapsto_{\beta} f ((\lambda x. x) \text{ 5}) \\ &\mapsto_{\beta} f \text{ 5} \end{aligned}$$

Confluence

Suppose we arrive via one reduction path to an expression that cannot be reduced further (called a *normal form*). Then any other reduction path will result in the *same normal form*.



Equivalence

Confluence means we can define another notion of *equivalence*, which equates more than α -equivalence. Two terms are $\alpha\beta$ -equivalent, written $s \equiv_{\alpha\beta} t$ if they β -reduce to α -equivalent normal forms.

η

There is also another equation that cannot be proven from β -equivalence alone, called η -reduction:

$$(\lambda x. f \ x) \mapsto_{\eta} f$$

Adding this reduction to the system preserves confluence and uniqueness of normal forms, so we have a notion of $\alpha\beta\eta$ -equivalence also.

Normal Forms

Does every term in λ -calculus have a normal form?

$$(\lambda x. x x)(\lambda x. x x)$$

Try to β -reduce this! (the answer is that it doesn't have a normal form)

Why learn this stuff?

- λ -calculus is a *Turing-complete* programming language.
- λ -calculus is the foundation for every functional programming language and some non-functional ones.
- λ -calculus is the foundation of *Higher Order Logic* and *Type Theory*, the two main foundations used for mathematics in interactive proof assistants.
- λ -calculus is the smallest example of a usable programming language, so it's good for research and teaching about programming languages.

Making λ -Calculus Usable

In order to demonstrate that λ calculus is actually a usable (in theory) programming language, we will demonstrate how to encode booleans and natural numbers as λ -terms, along with their operations.

General Idea

We transform a data type into the type of its *eliminator*. In other words, we make a function that can serve the same purpose as the data type at its use sites.

Booleans

How do we **use** booleans? **To choose between two results!**

So, a boolean will be a function that, given two arguments, returns the first one if it is true and the second one if it is false:

$$\text{TRUE} \equiv \lambda a. \lambda b. a$$

$$\text{FALSE} \equiv \lambda a. \lambda b. b$$

How do we write conjunction? to “board”

$$\text{AND} \equiv \lambda p. \lambda q. p \ q \ p$$

Example (Test it out!)

Try β -normalising AND TRUE FALSE .

What about **IMPLIES**?

Natural Numbers

How do we **use** natural numbers? **To do something n times!**

So, a natural number will be a function that takes a function f and a value x , and applies the function f to x that number of times:

$$\begin{aligned}\text{ZERO} &\equiv \lambda f. \lambda x. x \\ \text{ONE} &\equiv \lambda f. \lambda x. f\ x \\ \text{TWO} &\equiv \lambda f. \lambda x. f\ (f\ x) \\ &\dots\end{aligned}$$

How do we write SUC?

$$\text{SUC} \equiv \lambda n. \lambda f. \lambda x. f\ (n\ f\ x)$$

How do we write ADD?

$$\text{ADD} \equiv \lambda m. \lambda n. \lambda f. \lambda x. m\ f\ (n\ f\ x)$$

Natural Number Practice

Example

Try β -normalising `SUC ONE`.

Example

Try writing a different λ -term for defining `SUC`.

Example

Try writing a λ -term for defining `MULTIPLY`.