Lambda Calculus

Haskell and Cryptocurrencies

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Goals

- Untyped Lambda Calculus
- α-Equivalence
- β-Equivalence
- Reduction Strategies
- Church Encodings
- General Recursion & Y-Combinator

Untyped Lambda Calculus

High-level properties

- Provides simple semantics and a formal model for *computation*.
- Turing complete.
- Makes two simplifications:
    - only *anonymous* functions
    - only functions of one argument (*curried* functions)
- *Haskell* is based upon and compiles to a (typed!) version of the Lambda Calculus (as first intermediate compiler target, *Core*).

History

- Based upon work by *Frege* from 1893 and Schönfinkel from the 1920s.
- Introduced by *Alonzo Church* in the 1930s.
- Shown to be logically inconsistent in 1935 by *Stephen Kleene* and *J. B. Rosser*.
- Fixed by Church in 1936 – *Untyped Lambda Calculus*.
- Relation to programming languages clarified in the 1960s.

Lambda expressions

Lambda expressions (or lambda terms) are composed of

- *variables* $v_1, v_2, \ldots, v_n, \ldots$,
- the *abstraction symbols* λ and `.`,
- parentheses `( )`.

The *set of lambda expressions* Λ is inductively defined as:

- If x is a variable, then $x \in \Lambda$. (variable)
- If x is a variable and $M \in \Lambda$, then $(\lambda x.M) \in \Lambda$. (lambda abstraction)
- If $M, N \in \Lambda$, then $(MN) \in \Lambda$. (application)

Notation

To keep the notation of lambda expressions uncluttered, the following conventions are normally applied:

- Outermost parentheses are dropped: MN instead of (MN).
- Applications are assumed to be left associative: MNP instead of $(MN)P$.
- The body of an abstraction extends as far right as possible: $\lambda x.MN$ means $\lambda x.(MN)$, *not* $(\lambda x.M)N$.
- A sequence of abstracttions is contracted: $\lambda x.\lambda y.\lambda z.M$ is abbreviated as $\lambda xyz.M$.

Notation (contd.)

This is just as in Haskell:

- `f x = (f x)`
- `f x y = (f x) y`
- `\ x -> \ y -> \ z -> f = \ x y z -> f`

Let

- As "syntactic sugar", we can also introduce let bindings:
- For a variable x and lambda expressions M and N, we can define $\textbf{let}\ x = N\ \textbf{in}\ M$ as $(\lambda x.M)\ N$.
- Later, once we learn about β-reduction, we will see that this "means" substituting N for x in M, which coincides with the intuitive idea we have of how **let** "should" behave.
- This technique is actually used frequently in JavaScript ...

Free variables

- Let V be the set of variables. For each lambda expression $M \in \Lambda$, we define the set of free variables $FV(M) \subset V$ as follows:
  - For a variable $x \in V$, $FV(x) = \{x\}$.
  - For an abstraction, $FV(\lambda x.M) = FV(M) \setminus \{x\}$.
  - For an application, $FV(MN) = FV(M) \cup FV(N)$.
- Given a lambda expression $M \in \Lambda$, we call a variable $x \in V$ free (in M) if $x \in FV(M)$.
- In an abstraction $\lambda x.M$, we call the variable x bound.

Subexpressions

We define the notion of subexpression of a lambda expression inductively as follows:

- Each term is a subexpression of itself. Sub-expressions other than the term itself are called proper subexpressions.
- A variable has no proper subexpressions.
- The proper subexpressions of an application MN are the subexpressions of M and the subexpressions of N.
- The proper subexpression of an abstraction $\lambda x.M$ are the subexpressions of the body M.

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- $x[x := N] = N$.
- For a variable $y \neq x$, $y[x := N] = y$.

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- $x[x := N] \;=\; N$.
- For a variable $y \neq x$, $y[x := N] \;=\; y$.
- $(P\,Q)[x := N] \;=\; P[x := N]\, Q[x := N]$

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- For a variable $y \neq x$, $y[x := N] \ = \ y$.
- $(P\ Q)[x := N] \ = \ P[x := N]\ Q[x := N]$
- $(\lambda x.P)[x := N] \ := \ \lambda x.P$.
- For a variable $y \neq x$ with $y \notin FV(N)$, $(\lambda y.P)[x := N] \ := \ \lambda y.(P[x := N])$.
- For an abstraction $\lambda y.P$ with $y \neq x$ and $y \in FV(N)$, pick a variable $z \notin FV(N) \cup FV(P)$, then $(\lambda y.P)[x := N] \ := \ \lambda z.(P[y := z][x := N])$.

Substitution (contd.)

- It looks as if substitution was not well defined, because the result depends on a *choice* of variable in the last case.
- In the next section, we will define an equivalence relation on lambda expressions, α-*equivalence*, which will make the choice of variable name irrelevant.

Example substitutions

- $(\lambda x.x)[x := z\,(\lambda u.u)] = \lambda x.x$

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- $(\lambda y.x)[x := z\,(\lambda u.u)] = \lambda y.z\,(\lambda u.u)$
- $$\begin{aligned} &(\lambda z.x)[x := z\,(\lambda u.u)] \\ &\qquad = \lambda z'.\big(x[z := z'][x := z\,(\lambda u.u)]\big) \\ &\qquad = \lambda z'.\big(x[x := z\,(\lambda u.u)]\big) \\ &\qquad = \lambda z'.z\,(\lambda u.u) \end{aligned}$$

α-Equivalence

α-Equivalence

We define the notion $M \sim_\alpha N$ of α-equivalence between two lambda expressions M and N inductively as follows:

- For two variables x and y, $x \sim_\alpha y$ iff $x = y$.
- $(MN) \sim_\alpha (PQ)$ iff $M \sim_\alpha P$ and $N \sim_\alpha Q$.
- For abstractions $\lambda x.M$ and $\lambda y.N$, choose a variable z with $z \notin FV(m) \cup FV(N)$. Then $\lambda x.M \sim_\alpha \lambda y.N$ iff $M[x := z] \sim_\alpha N]y := z]$.
- All other expressions are *not* α-equivalent.

Intuitively, α-equivalence means that two expressions are equal except for the naming of bound variables.

α-Equivalence (contd.)

Equality

From now on, we will always consider $\Lambda / \sim_\alpha$ instead of Λ, i.e. we will consider two α-equivalent lambda expressions as *equal*.

Substitution

As soon as α-equivalence becomes equality, the problem in our definition of substitution goes away, because different "picks" of variable name in the last case clearly lead to α-equivalent results.

α-Equivalence (contd.)

- The necessity to deal with α-equivalence makes implementation of substitution and equality checking quite tricky.
- There are ways (for example *De Bruijn indices*) of handling variable names differently in the definition of lambda expressions that lead to *syntactically identical* terms for α-equivalent expressions.
- However, the presentation we chose seems to be the most "human readable".

β-Equivalence

β-Equivalence captures "computation"

- As explained above, α-equivalence is more of a technical nuisance, capturing the intuitive idea that the names of bound variables should not matter.
- β-equivalence, on the other hand, lies at the very heart of Lambda Calculus and captures the notion of computation.
- Intuitively, the *act of computation* preserves β-equivalence.
- So what does *computation* mean in the context of Lambda Calculus?

β-Reduction

- Consider a lambda expression of the form $(\lambda x.M)\ N$, i.e. an application where the first argument is an abstraction.
- By definition, this term β-reduces to $M[x := N]$.
- This act of “plugging in” an expression for the bound variable in an abstraction is what constitutes the idea of computation in Lambda Calculus.

Redex, β-equivalence & normal form

- A redex of a lambda expression P is a subexpression of P of the form $(\lambda x.M)\ N$.
- Let P' denote the lambda expression obtained by replacing a redex $(\lambda x.M)\ N$ with $M[x := N]$. We say that P β-reduces to P' (in one step).
- We say that P β-reduces to P' (or that P' is a β-reduct of P) if reducing zero or more redexes transforms P into P'.
- Two lambda expressions P and P' are β-equivalent ($P \sim_\beta P'$) if one can be transformed into the other by a chain of β-reductions (or their inverses).
- A lambda expression without redex is said to be in normal form.
- We say a lambda expression P has normal form P' if P β-reduces to P' and P' is in normal form.

Questions

- Can lambda expression have more than one normal form?
- Does any lambda expression have a normal form?
- If a lambda expression *does* have a normal form, how can I find it/one?

The Church-Rosser theorem

Theorem

Let P be a lambda expression, and let P' and P'' be two β-reducts of P. Then there is a lambda expression Q such that both P' and P'' β-reduce to Q.

$$\begin{tikzcd}
& P \arrow[dl, twoheadrightarrow] \arrow[dr, twoheadrightarrow] & \\
P' \arrow[dr, twoheadrightarrow] & & P'' \arrow[dl, twoheadrightarrow] \\
& Q &
\end{tikzcd}$$

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$$\begin{tikzcd} & P \arrow[dl] \arrow[dr] & \\ P' \arrow[dr] & & P'' \arrow[dl] \\ & Q & \end{tikzcd}$$

At most one

Church-Rosser immediately(!) implies that a lambda expression has *at most one* normal form.

No normal form ...

- Consider the lambda expression $\omega := (\lambda x.xx)(\lambda x.xx)$.

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No normal form ...

- Consider the lambda expression $\omega := (\lambda x.xx)(\lambda x.xx)$.
- There is only one redex, ω itself.
- Let's reduce it!
- $(xx)[x := \lambda x.xx] = (\lambda x.xx)(\lambda x.xx) = \omega$.
- ω only has one redex, and β-reducing that one redex gives ω as a reduct!
- By definition, ω is not(!) in normal form. So ω has no normal form!

Open question

- So we know from Church-Rosser that a lambda expression's normal form is unique if it exists.
- We have seen an example of a lambda expression that does *not* have a normal form.
- Open question: How to find the normal form if it exists?
- To be more precise: If there is more than one redex, which one do we reduce first?

Reduction Strategies

Reduction strategies

Reduction Strategy

A reduction strategy is an algorithm that, given a lambda expression, decides which redex to reduce (if at least one exists).

Call by value

- Consider the strategy of always reducing the *leftmost innermost* redex first.
- This strategy is called call by value or eager evaluation.
- Intuitively, it means evaluating the arguments to a function first, then applying the function.
- Example:

$$
\begin{aligned}
& ((\lambda xy.x)\ (\lambda x.x))\ ((\lambda x.x)\ y) \\
\rightsquigarrow_\beta\ & (\lambda yx.x)\ ((\lambda x.x)\ y) \\
\rightsquigarrow_\beta\ & (\lambda yx.x)\ y \\
\rightsquigarrow_\beta\ & \lambda x.x
\end{aligned}
$$

Call by name

- Now consider the strategy of always reducing the *leftmost outermost* redex first.
- This strategy is called call by name.
- Intuitively, it means applying a function before evaluating its arguments.
- Example:

$$
\begin{aligned}
& ((\lambda xy.x)\ (\lambda x.x))\ ((\lambda x.x)\ y) \\
\rightsquigarrow_\beta\ & (\lambda yx.x)\ ((\lambda x.x)\ y) \\
\rightsquigarrow_\beta\ & \lambda x.x
\end{aligned}
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Comparison

With both strategies, we arrive at the same normal form (Church-Rosser!). But call by name needs one step less.

Call by need

- There is an optimization of *call by name*, called call by need (or lazy evaluation).
- The problem with call by name is that when substituting, we may duplicate function arguments and then maybe will have to evaluate them several times.
- In call by need, instead of substituting arguments by copying them, a pointer to the argument is substituted,
- If an argument needs to be evaluated once, all copies of it profit from the evaluation.

Theorem

Let P be a lambda expression which has a normal form. Then the *call by name/need* strategy will reduce to this normal form.

Counterexample

- Consider the lambda expression $(\lambda xy.x)\ (\lambda x.x)\ \omega$.
- It has a normal form, which call by name/need reduces to in two steps:

$$\begin{aligned} & (\lambda xy.x)\ (\lambda x.x)\ \omega \\ \rightsquigarrow_\beta\ & (\lambda yx.x)\ \omega \\ \rightsquigarrow_\beta\ & (\lambda x.x) \end{aligned}$$

- Call by value, on the other hand, enters an infinite loop, because it tries to reduce ω in the second step.
- So we see that call by name finds strictly more normal forms than call by value.
- This example corresponds to the Haskell expression `const id undefined`.

The reduction strategy of Haskell

- The Haskell standard does not dictate the use of one particular reduction strategy.
- Instead, it prescribes that Haskell has non-strict semantics, which essentially means that reduction must lead to the same results as via call by name.
- In practice, lazy evaluation (call by need) is mostly used by the Haskell compiler, with semantics-preserving optimisations in many places.

Church Encodings

Church encoding

- It is possible to encode an amazing range of datatypes in the Untyped Lambda Calculus.
- Examples are natural numbers, booleans, pairs, lists and sums.

Church encoding of booleans

- Booleans are encoded as functions that take two arguments.
- If the boolean is `True`, the first argument is returned, if it is `False`, the second is returned.
- `true` $:= \lambda xy.x$
- `false` $:= \lambda xy.y$.
- With this, we can define `ifThenElse`:
  `ifThenElse` $:= \lambda bxy.bxy$
- And logical functions like `not`:
  `not` $:= \lambda b.$`ifThenElse` b `false` `true`.

Church encoding of natural numbers

- Natural numbers are also encoded as functions taking two arguments, where the result of applying f and x to a natural number is applying f n-times to x:
- `zero` $:= \lambda fx.x$.
- `succ` $:= \lambda nfx.f\,(nfx)$.
- We can define addition: `add` $:= \lambda mnfx.mf(nfx)$
- and multiplication: `mul` $:= \lambda mnfx.m(nf)x$
- and test for zero: `isZero` $:= \lambda n.n(\lambda xzy.y)(\lambda xy.x)$
- and predecessor (more complicated!):
  `pred` $:= \lambda nfx.n(\lambda gh.h(gf))(\lambda u.x)(\lambda u.u)$.
- and many more...

Church encoding of pairs

- Pairs are encoded as functions that take a function of two arguments. The idea is to supply the argument function with the two components of the pair as arguments:
- `pair` $:= \lambda xyf.fxy$.
- `fst` $:= \lambda p.p(\lambda xy.x)$.
- `snd` $:= \lambda p.p(\lambda xy.y)$.

General Recursion & Y-Combinator

Fixpoint operators

- A fixpoint operator F is a lambda expression F with the property that for all lambda expressions g, we have $g(Fg) \sim_\beta Fg$.
- In Haskell, we have the function `fix` in `Control.Monad.Fix`:

```
fix :: (a -> a) -> a
fix f = let x = f x in x
```

- `fix` can be used to implement recursive functions:

```
factorial :: Int -> Int
factorial = fix $ \ f n ->
  if n == 0 then 1 else n * f (n - 1)
```

The Y-combinator

- Consider the lambda expression $Y := \lambda f.(\lambda x.f(xx))(\lambda x.f(xx))$.
- We claim that Y is a fixpoint operator:

$$\begin{aligned} & Yg \\ = \; & \big(\lambda f.(\lambda x.f(xx))(\lambda x.f(xx))\big)\; g \\ \sim_\beta \; & (\lambda x.g(xx))(\lambda x.g(xx)) \\ \sim_\beta \; & g((\lambda x.g(xx))(\lambda x.g(xx))) \\ \sim_\beta \; & g(Yg) \end{aligned}$$

- Using call by name, we can use Y to define recursive functions. For call by value, this won't work, but there are (more complicated) fixpoint operators that work for call by value as well.

Factorial with Y

$$
\begin{aligned}
\texttt{factorial} := Y\, \lambda f n.\texttt{ifThenElse}&(\texttt{isZero}\ n)\\
&(\texttt{succ}\ \texttt{zero})\\
&(\texttt{mul}\ n\ (f\ (\texttt{pred}\ n)))
\end{aligned}
$$