CS618: Program Analysis
2016-17 Ist Semester

The Untyped Lambda Calculus

Amey Karkare

karkare@cse.iitk.ac.in

karkare@cse.iitb.ac.in

Department of CSE, IIT Kanpur/Bombay

Reference Book

Types and Programming Languages by Benjamin C. Pierce

The Abstract Syntax

t := x – Variable

The Abstract Syntax

$$
\begin{array}{lll}
\mathrm{t} & := & x \qquad\qquad\qquad \text{– Variable} \\
 & & \mid \lambda x.\mathrm{t} \qquad \text{– Abstraction}
\end{array}
$$

The Abstract Syntax

$$
\begin{array}{lcll}
t & := & x & \text{– Variable} \\
 & & \mid \lambda x.t & \text{– Abstraction} \\
 & & \mid t\ t & \text{– Application}
\end{array}
$$

The Abstract Syntax

$$
\begin{array}{lcll}
\text{t} & := & x & \text{– Variable} \\
 & & \mid \lambda x.\text{t} & \text{– Abstraction} \\
 & & \mid \text{t t} & \text{– Application}
\end{array}
$$

Parenthesis, (...), can be used for grouping and scoping.

Conventions

- $\lambda x.t_1 t_2 t_3$ is an abbreviation for $\lambda x.(t_1 t_2 t_3)$, i.e., the scope of x is as far to the right as possible until it is

Conventions

- $\lambda x.t_1 t_2 t_3$ is an abbreviation for $\lambda x.(t_1 t_2 t_3)$, i.e., the scope of x is as far to the right as possible until it is
  - terminated by a **)** whose matching **(** occurs to the left pf λ, OR

Conventions

- $\lambda x.t_1 t_2 t_3$ is an abbreviation for $\lambda x.(t_1 t_2 t_3)$, i.e., the scope of x is as far to the right as possible until it is
  - terminated by a **)** whose matching **(** occurs to the left pf λ, OR
  - terminated by the end of the term.

Conventions

- $\lambda x.t_1t_2t_3$ is an abbreviation for $\lambda x.(t_1t_2t_3)$, i.e., the scope of x is as far to the right as possible until it is
  - terminated by a **)** whose matching **(** occurs to the left pf λ, OR
  - terminated by the end of the term.
- Applications associate to the left: $t_1t_2t_3$ to be read as $(t_1t_2)t_3$ and not as $t_1(t_2t_3)$

Conventions

- $\lambda x.t_1t_2t_3$ is an abbreviation for $\lambda x.(t_1t_2t_3)$, i.e., the scope of x is as far to the right as possible until it is
  - terminated by a **)** whose matching **(** occurs to the left pf λ, OR
  - terminated by the end of the term.
- Applications associate to the left: $t_1t_2t_3$ to be read as $(t_1t_2)t_3$ and not as $t_1(t_2t_3)$
- $\lambda xyz.t$ is an abbreviation for $\lambda x \lambda y \lambda z.t$ which in turn is abbreviation for $\lambda x.(\lambda y.(\lambda z.t))$.

α-renaming

- The name of a bound variable has no meaning except for its use to identify the bounding λ.

α-renaming

- The name of a bound variable has no meaning except for its use to identify the bounding λ.
- Renaming a λ variable, including all its bound occurrences, does not change the meaning of an expression. For example, $\lambda x.x\ x\ y$ is equivalent to $\lambda u.u\ u\ y$

α-*renaming*

- The name of a bound variable has no meaning except for its use to identify the bounding λ.
- Renaming a λ variable, including all its bound occurrences, does not change the meaning of an expression. For example, $\lambda x.x\ x\ y$ is equivalent to $\lambda u.u\ u\ y$
  - But it is not same as $\lambda x.x\ x\ w$

α-renaming

- The name of a bound variable has no meaning except for its use to identify the bounding λ.
- Renaming a λ variable, including all its bound occurrences, does not change the meaning of an expression. For example, $\lambda x.x\ x\ y$ is equivalent to $\lambda u.u\ u\ y$
  - But it is not same as $\lambda x.x\ x\ w$
  - Can not change free variables!

β-reduction (Execution Semantics)

- if an abstraction $\lambda x.\mathrm{t}_1$ is applied to a term t_2 then the result of the application is

β-reduction (Execution Semantics)

- if an abstraction $\lambda x.t_1$ is applied to a term t_2 then the result of the application is
  - the body of the abstraction t_1 with all free occurrences of the formal parameter x replaced with t_2.

β-reduction (Execution Semantics)

- if an abstraction $\lambda x.\mathrm{t}_1$ is applied to a term t_2 then the result of the application is
  - the body of the abstraction t_1 with all free occurrences of the formal parameter x replaced with t_2.
- For example,

$$(\lambda f \lambda x.f\ (f\ x))\ g \xrightarrow{\beta} \lambda x.g\ (g\ x)$$

Caution

- During β-reduction, make sure a free variable is not captured inadvertently.

Caution

- During β-reduction, make sure a free variable is not captured inadvertently.
- The following reduction is **WRONG**

$$(\lambda x \lambda y.x)(\lambda x.y) \xrightarrow{\beta} \lambda y.\lambda x.y$$

Caution

- During β-reduction, make sure a free variable is not captured inadvertently.
- The following reduction is **WRONG**

$$(\lambda x \lambda y.x)(\lambda x.y) \xrightarrow{\beta} \lambda y.\lambda x.y$$

- Use α-renaming to avoid variable capture

$$(\lambda x \lambda y.x)(\lambda x.y) \xrightarrow{\alpha} (\lambda u \lambda v.u)(\lambda x.y) \xrightarrow{\beta} \lambda v.\lambda x.y$$

Exercise

- Apply β-reduction as far as possible

1. $(\lambda x\ y\ z.\ x\ z\ (y\ z))\ (\lambda x\ y.\ x)\ (\lambda y.y)$
2. $(\lambda x.\ x\ x)(\lambda x.\ x\ x)$
3. $(\lambda x\ y\ z.\ x\ z\ (y\ z))\ (\lambda x\ y.\ x)\ ((\lambda x.\ x\ x)(\lambda x.\ x\ x))$

Church-Rosser Theorem

- Multiple ways to apply β-reduction

Church-Rosser Theorem

- Multiple ways to apply β-reduction
- Some may not terminate

Church-Rosser Theorem

- Multiple ways to apply β-reduction
- Some may not terminate
- However, if two different reduction sequences terminate then they always terminate in the same term

Church-Rosser Theorem

- Multiple ways to apply β-reduction
- Some may not terminate
- However, if two different reduction sequences terminate then they always terminate in the same term
  - Also called the *Diamond Property*

Church-Rosser Theorem

- Multiple ways to apply β-reduction
- Some may not terminate
- However, if two different reduction sequences terminate then they always terminate in the same term
  - Also called the *Diamond Property*
- Leftmost, outermost reduction will find the normal form if it exists

Programming in λ Calculus

- Where is the other stuff?

Programming in λ Calculus

- Where is the other stuff?
- Constants?

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans
- Complex Types?

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans
- Complex Types?
  - Lists

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans
- Complex Types?
  - Lists
  - Arrays

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans
- Complex Types?
  - Lists
  - Arrays
- Don't we need data?

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans
- Complex Types?
  - Lists
  - Arrays
- Don't we need data?

Programming in λ Calculus

- Where is the other stuff?
- Constants?
  - Numbers
  - Booleans
- Complex Types?
  - Lists
  - Arrays
- Don't we need data?

Abstractions act as functions as well as data!

Numbers: Church Numerals

- We need a “Zero”

Numbers: Church Numerals

- We need a “Zero”
  - “Absence of item”

Numbers: Church Numerals

- We need a “Zero”
  - “Absence of item”
- And something to count

Numbers: Church Numerals

- We need a “Zero”
  - “Absence of item”
- And something to count
  - “Presence of item”

Numbers: Church Numerals

- We need a “Zero”
  - “Absence of item”
- And something to count
  - “Presence of item”
- Intuition: Whiteboard and Marker

Numbers: Church Numerals

- We need a “Zero”
  - “Absence of item”
- And something to count
  - “Presence of item”
- Intuition: Whiteboard and Marker
  - Blank board represents Zero

Numbers: Church Numerals

- We need a "Zero"
  - "Absence of item"
- And something to count
  - "Presence of item"
- Intuition: Whiteboard and Marker
  - Blank board represents Zero
  - Each mark by marker represents a count.

Numbers: Church Numerals

- We need a “Zero”
  - “Absence of item”
- And something to count
  - “Presence of item”
- Intuition: Whiteboard and Marker
  - Blank board represents Zero
  - Each mark by marker represents a count.
  - However, other pairs of objects will work as well

Numbers: Church Numerals

- We need a "Zero"
  - "Absence of item"
- And something to count
  - "Presence of item"
- Intuition: Whiteboard and Marker
  - Blank board represents Zero
  - Each mark by marker represents a count.
  - However, other pairs of objects will work as well
- Lets translate this intuition into λ-expressions

Numbers

- Zero = $\lambda m\ w.\ w$

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard
- One = $\lambda m\ w.\ m\ w$

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard
- One = $\lambda m\ w.\ m\ w$
  - One mark on the whiteboard

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard
- One = $\lambda m\ w.\ m\ w$
  - One mark on the whiteboard
- Two = $\lambda m\ w.\ m\ (m\ w)$

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard
- One = $\lambda m\ w.\ m\ w$
  - One mark on the whiteboard
- Two = $\lambda m\ w.\ m\ (m\ w)$
- ...

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard
- One = $\lambda m\ w.\ m\ w$
  - One mark on the whiteboard
- Two = $\lambda m\ w.\ m\ (m\ w)$
- ...
- What about operations?

Numbers

- Zero = $\lambda m\ w.\ w$
  - No mark on the whiteboard
- One = $\lambda m\ w.\ m\ w$
  - One mark on the whiteboard
- Two = $\lambda m\ w.\ m\ (m\ w)$
- ...
- What about operations?
  - add, multiply, subtract, divide, ...?

Operations on Numbers

- succ = $\lambda x\ m\ w.\ m\ (x\ m\ w)$

Operations on Numbers

- succ = $\lambda x\ m\ w.\ m\ (x\ m\ w)$
  - Verify: succ N = N + 1

Operations on Numbers

- succ = $\lambda x\ m\ w.\ m\ (x\ m\ w)$
  - Verify: succ N = N + 1
- add = $\lambda x\ y\ m\ w.\ x\ m\ (y\ m\ w)$

Operations on Numbers

- succ = $\lambda x\ m\ w.\ m\ (x\ m\ w)$
  - Verify: succ N = N + 1
- add = $\lambda x\ y\ m\ w.\ x\ m\ (y\ m\ w)$
  - Verify: add M N = M + N

Operations on Numbers

- succ = $\lambda x\ m\ w.\ m\ (x\ m\ w)$
  - Verify: succ N = N + 1
- add = $\lambda x\ y\ m\ w.\ x\ m\ (y\ m\ w)$
  - Verify: add M N = M + N
- mult = $\lambda x\ y\ m\ w.\ x\ (y\ m)\ w$

Operations on Numbers

- succ = $\lambda x\ m\ w.\ m\ (x\ m\ w)$
  - Verify: succ N = N + 1
- add = $\lambda x\ y\ m\ w.\ x\ m\ (y\ m\ w)$
  - Verify: add M N = M + N
- mult = $\lambda x\ y\ m\ w.\ x\ (y\ m)\ w$
  - Verify: mult M N = M * N

More Operations

- pred = $\lambda x\ m\ w.\ x\ (\lambda g\ h.\ h\ (g\ m))(\lambda u.\ w)(\lambda u.\ u)$

More Operations

- pred = $\lambda x\ m\ w.\ x\ (\lambda g\ h.\ h\ (g\ m))(\lambda u.\ w)(\lambda u.\ u)$
  - Verify: pred N = N - 1

More Operations

- pred = $\lambda x\ m\ w.\ x\ (\lambda g\ h.\ h\ (g\ m))(\lambda u.\ w)(\lambda u.\ u)$
  - Verify: pred N = N - 1
- nminus = $\lambda x\ y.\ y$ pred x

More Operations

- pred = $\lambda x\ m\ w.\ x\ (\lambda g\ h.\ h\ (g\ m))(\lambda u.\ w)(\lambda u.\ u)$
  - Verify: pred N = N - 1
- nminus = $\lambda x\ y.\ y$ pred x
  - Verify: nminus M N = max(0, M - N) – natural subtraction

Church Booleans

- True and False

Church Booleans

- True and False
- Intuition: Selection of one out of two (complementary) choices

Church Booleans

- True and False
- Intuition: Selection of one out of two (complementary) choices
- True = $\lambda x\ y.\ x$

Church Booleans

- True and False
- Intuition: Selection of one out of two (complementary) choices
- True = $\lambda x\ y.\ x$
- False = $\lambda x\ y.\ y$

Church Booleans

- True and False
- Intuition: Selection of one out of two (complementary) choices
- True = $\lambda x\ y.\ x$
- False = $\lambda x\ y.\ y$
- Predicate:

Church Booleans

- True and False
- Intuition: Selection of one out of two (complementary) choices
- True = $\lambda x\ y.\ x$
- False = $\lambda x\ y.\ y$
- Predicate:
  - isZero = $\lambda x.\ x\ (\lambda u.\text{False})\ \text{True}$

Operations on Booleans

- Logical operations

$$\begin{aligned} \mathit{and} &= \lambda p\, q.\ p\ q\ p \\ \mathit{or} &= \lambda p\, q.\ p\ p\ q \\ \mathit{not} &= \lambda p\ t\ f.p\ f\ t \end{aligned}$$

Operations on Booleans

- Logical operations

$$\begin{aligned} \mathit{and} &= \lambda p\, q.\ p\, q\, p \\ \mathit{or} &= \lambda p\, q.\ p\, p\, q \\ \mathit{not} &= \lambda p\, t\, f. p\, f\, t \end{aligned}$$

- The conditional operator *if*

$$\mathit{if} = \lambda c\, e_t\, e_f.\ (c\, e_t\, e_f)$$

Operations on Booleans

- Logical operations

$$\begin{aligned} and &= \lambda p\, q.\, p\, q\, p \\ or &= \lambda p\, q.\, p\, p\, q \\ not &= \lambda p\, t\, f. p\, f\, t \end{aligned}$$

- The conditional operator *if*
  - $if\ c\ e_t\ e_f$ reduces to e_t if c is True, and to e_f if c is False

$$if = \lambda c\, e_t\, e_f.\, (c\, e_t\, e_f)$$

More...

- More such types can be found at
  `https://en.wikipedia.org/wiki/Church_encoding`

More. . .

- More such types can be found at
  `https://en.wikipedia.org/wiki/Church_encoding`
- It is fun to come up with your own definitions for constants and operations over different types

More. . .

- More such types can be found at
  `https://en.wikipedia.org/wiki/Church_encoding`
- It is fun to come up with your own definitions for constants and operations over different types
- or to develop understanding for existing definitions.

We are missing something!!

- The machinery described so far does not allow us to define Recursive functions
  - Factorial, Fibonacci, ...
- There is no concept of "named" functions
  - So no way to refer to a function "recursively"!
- Fix-point computation comes to rescue

Fix-point and Y-combinator

- A fix-point of a function f is a value p such that $f\ p = p$

Fix-point and Y-combinator

- A fix-point of a function f is a value p such that $f\ p = p$
- Assume existence of a magic expression, called Y-combinator, that when applied to a λ-expression, gives its fixed point

$$Y\ f = f\ (Y\ f)$$

Fix-point and Y-combinator

- A fix-point of a function f is a value p such that $f\ p = p$
- Assume existence of a magic expression, called Y-combinator, that when applied to a λ-expression, gives its fixed point
$$Y\ f = f\ (Y\ f)$$
- Y-combinator gives us a way to apply a function recursively

Recursion Example: Factorial

$$\begin{aligned}\text{fact} &= \lambda n.\ \mathit{if}\ (\text{isZero}\ n)\ \text{One}\ (\text{mult}\ n\ (\text{fact}\ (\text{pred}\ n))) \\ &= (\lambda f\ n.\ \mathit{if}\ (\text{isZero}\ n)\ \text{One}\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))\ \text{fact}\end{aligned}$$

Recursion Example: Factorial

$$\begin{aligned} \text{fact} &= \lambda n.\ \textit{if}\ (\text{isZero}\ n)\ \text{One}\ (\text{mult}\ n\ (\text{fact}\ (\text{pred}\ n))) \\ &= (\lambda f\ n.\ \textit{if}\ (\text{isZero}\ n)\ \text{One}\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))\ \text{fact} \end{aligned}$$

$$\text{fact} = g\ \text{fact}$$

- fact is a fixed point of the function

$$g = (\lambda f\ n.\ \textit{if}\ (\text{isZero}\ n)\text{One}\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))$$

Recursion Example: Factorial

$$\begin{aligned}\text{fact} &= \lambda n.\ \mathit{if}\ (\text{isZero}\ n)\ \text{One}\ (\text{mult}\ n\ (\text{fact}\ (\text{pred}\ n)))\\ &= (\lambda f\ n.\ \mathit{if}\ (\text{isZero}\ n)\ \text{One}\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))\ \text{fact}\end{aligned}$$

$$\text{fact} = g\ \text{fact}$$

- fact is a fixed point of the function

$$g = (\lambda f\ n.\ \mathit{if}\ (\text{isZero}\ n)\text{One}\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))$$

- Using Y-combinator,

$$\text{fact} = Y\ g$$

Factorial: Verify

$$\text{fact } 2 = (Y\ g)\ 2$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator}
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda fn.\ if\ (\text{isZero } n)\ 1\ (\text{mult } n\ (f\ (\text{pred } n))))\ (Y\ g)\ 2
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda f n.\ \mathit{if}\ (\text{isZero}\ n)\ 1\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))\ (Y\ g)\ 2 \\
&= (\lambda n.\ \mathit{if}\ (\text{isZero}\ n)\ 1\ (\text{mult}\ n\ ((Y\ g)\ (\text{pred}\ n))))\ 2
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda fn.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ (f\ (\text{pred } n))))\ (Y\ g)\ 2 \\
&= (\lambda n.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ ((Y\ g)\ (\text{pred } n))))\ 2 \\
&= \mathit{if}\ (\text{isZero } 2)\ 1\ (\text{mult } 2\ ((Y\ g)(\text{pred} 2)))
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda fn.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ (f\ (\text{pred } n))))\ (Y\ g)\ 2 \\
&= (\lambda n.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ ((Y\ g)\ (\text{pred } n))))\ 2 \\
&= \mathit{if}\ (\text{isZero } 2)\ 1\ (\text{mult } 2\ ((Y\ g)(\text{pred2}))) \\
&= (\text{mult } 2\ ((Y\ g)\ 1))
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda f n.\ \mathit{if}\ (\text{isZero}\ n)\ 1\ (\text{mult}\ n\ (f\ (\text{pred}\ n))))\ (Y\ g)\ 2 \\
&= (\lambda n.\ \mathit{if}\ (\text{isZero}\ n)\ 1\ (\text{mult}\ n\ ((Y\ g)\ (\text{pred}\ n))))\ 2 \\
&= \mathit{if}\ (\text{isZero}\ 2)\ 1\ (\text{mult}\ 2\ ((Y\ g)(\text{pred2}))) \\
&= (\text{mult}\ 2\ ((Y\ g)\ 1)) \\
&\quad \ldots \\
&= (\text{mult}\ 2\ (\text{mult}\ 1\ (\mathit{if}\ (\text{isZero}\ 0)\ 1\ (\ldots))))
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda fn.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ (f\ (\text{pred } n))))\ (Y\ g)\ 2 \\
&= (\lambda n.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ ((Y\ g)\ (\text{pred } n))))\ 2 \\
&= \mathit{if}\ (\text{isZero } 2)\ 1\ (\text{mult } 2\ ((Y\ g)(\text{pred} 2))) \\
&= (\text{mult } 2\ ((Y\ g)\ 1)) \\
&\ \ \ \ldots \\
&= (\text{mult } 2\ (\text{mult } 1\ (\mathit{if}\ (\text{isZero } 0)\ 1\ (\ldots)))) \\
&= (\text{mult } 2\ (\text{mult } 1\ 1))
\end{aligned}
$$

Factorial: Verify

$$
\begin{aligned}
\text{fact } 2 &= (Y\ g)\ 2 \\
&= g\ (Y\ g)\ 2 \quad \text{– by definition of Y-combinator} \\
&= (\lambda fn.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ (f\ (\text{pred } n))))\ (Y\ g)\ 2 \\
&= (\lambda n.\ \mathit{if}\ (\text{isZero } n)\ 1\ (\text{mult } n\ ((Y\ g)\ (\text{pred } n))))\ 2 \\
&= \mathit{if}\ (\text{isZero } 2)\ 1\ (\text{mult } 2\ ((Y\ g)(\text{pred2}))) \\
&= (\text{mult } 2\ ((Y\ g)\ 1)) \\
&\quad \ldots \\
&= (\text{mult } 2\ (\text{mult } 1\ (\mathit{if}\ (\text{isZero } 0)\ 1\ (\ldots)))) \\
&= (\text{mult } 2\ (\text{mult } 1\ 1)) \\
&= 2
\end{aligned}
$$

Recursion and Y-combinator

- Y-combinator allows to unroll the body of loop once—similar to one unfolding of recursive call

Recursion and Y-combinator

- Y-combinator allows to unroll the body of loop once—similar to one unfolding of recursive call
- Sequence of Y-combinator applications allow complete unfolding of recursive calls

Recursion and Y-combinator

- Y-combinator allows to unroll the body of loop once—similar to one unfolding of recursive call
- Sequence of Y-combinator applications allow complete unfolding of recursive calls

Recursion and Y-combinator

- Y-combinator allows to unroll the body of loop once—similar to one unfolding of recursive call
- Sequence of Y-combinator applications allow complete unfolding of recursive calls

BUT, what about the existence of Y-combinator?

Y-combinators

- Many candidates exist

$$Y_1 = \lambda f.\ (\lambda x.\ f\ (x\ x))\ (\lambda x.\ f\ (x\ x))$$

Y-combinators

- Many candidates exist

$$Y_1 = \lambda f.\ (\lambda x.\ f\ (x\ x))\ (\lambda x.\ f\ (x\ x))$$

$$Y = \lambda abcdefghijklmnopqstuvwxwzr.r(thisisafixedpointcombinator)$$

Y-combinators

- Many candidates exist

$$Y_1 = \lambda f.\ (\lambda x.\ f\ (x\ x))\ (\lambda x.\ f\ (x\ x))$$

$$Y = \lambda abcdefghijklmnopqstuvwxwzr.r(thisisafixedpointcombinator)$$

$$Y_{\text{funny}} = TTTTT\ TTTTT\ TTTTT\ TTTTT\ TTTTT\ T$$

Y-combinators

- Many candidates exist

$$Y_1 = \lambda f.\ (\lambda x.\ f\ (x\ x))\ (\lambda x.\ f\ (x\ x))$$

$$Y = \lambda abcdefghijklmnopqstuvwxwzr.r(thisisafixedpointcombinator)$$

$$Y_{\text{funny}} = TTTTT\ TTTTT\ TTTTT\ TTTTT\ TTTTT\ T$$

- Verify that $(Y\ f)\ =\ f\ (Y\ f)$ for each

Summary

- A cursory look at λ-calculus

Summary

- A cursory look at λ-calculus
- Functions are data, and Data are functions!

Summary

- A cursory look at λ-calculus
- Functions are data, and Data are functions!
- Not covered but important to know: The power of λ calculus is equivalent to that of Turing Machine ("Church Turing Thesis")