CSE 114A

Introduction to Functional Programming

Lambda Calculus

Based on course materials developed by Ranjit Jhala and Owen Arden

1930s

What is computable?

Princeton, NJ

Alonzo Church

C-T thesis

Cambridge, UK

Alan Turing

Lambda Calculus

Turing machine

$$
\begin{aligned}
e ::= \; & \lambda x.\, e \\
\mid \; & e_1 \, (e_2) \\
\mid \; & x
\end{aligned}
$$

Machine

low level

machine code

Fn prog lang

Lisp (mem safe)

Scheme

Racket

Haskell

ML

Ocaml

~~Scala~~

memory safe lang

GC

asm lang

C

~~Fa~~Fortran Cobol

Pascal

C++

Java

C#

Python

Scala F#

Imperative

Your favorite language

- Probably has lots of features:
  - [?]Assignment (x = x + 1)
  - [?]Booleans, integers, characters, strings,... [?]
  - Conditionals
  - [?]Loops,[?] return, break, continue
  - [?]Functions
  - [?]Recursion
  - [?]References / pointers
  - [?]Objects and classes
  - [?]Inheritance
  - … and more

The Lambda Calculus

- Features
  - ?Functions
  - (that's it)

The Lambda Calculus

- Seriously…
  - ~~⍰Assignment (x = x + 1)~~
  - ~~⍰Booleans, integers, characters, strings,… ⍰~~
  - ~~Conditionals~~
  - ~~⍰Loops,⍰ return, break, continue~~
  - **⍰Functions**
  - ~~⍰Recursion~~
  - ~~⍰References / pointers~~
  - ~~⍰Objects and classes~~
  - ~~⍰Inheritance~~
  - ~~… and more~~

The only thing you can do is:

Define a function

Call a function

Describing a Programming Language

- **Syntax**
  - What do programs ***look like***?
- **Semantics**
  - What do programs ***mean***?
  - **Operational semantics:**
    - How do programs ***execute step-by-step?***

Syntax: What programs look like

```
e ::= x
    | \x -> e
    | e1 e2
```

- A set of *expressions* **e** (aka *programs* or λ-*terms*)
- There are three kinds of expressions
  - **Variables**: eg x, y, z
  - **Function definitions** (aka abstractions) \x -> e
    - x is the *formal parameter*, e is the *body*
  - **Function calls** (aka application) e1 e2
    - e1 is the *function*, e2 is the *argument*

Examples

```
-- The identity function ("for any x compute x")
\x -> x

-- A function that returns the identity function
\x -> (\y -> y)

-- A function that applies its argument to
-- the identity function
\f -> f (\x -> x)
```

QUIZ: Lambda syntax

Which of the following terms are syntactically incorrect? *

- A. \(\x -> x) -> y
- B. \x -> x x
- C. \x -> x (y x)
- A and C
- All of the above

http://tiny.cc/cse116-lambda-ind

QUIZ: Lambda syntax

Which of the following terms are syntactically incorrect? *

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- A and C
- All of the above

http://tiny.cc/cse116-lambda-grp

Semantics: Scope of a Variable

- The part of a program where a **variable is visible**
- In the expression \x -> e
  - x is the newly introduced variable
  - e **is the scope** of x
  - any **occurrence** of x in \x -> e is **bound** (by the **binder** \x)

Semantics: Scope of a Variable

- For example, x is **bound** in:

```
\x -> x
\x -> (\y -> x)
```

- An occurrence of x in e is **free** if it's *not bound* by an enclosing abstraction

- For example, x is **free** in:

```
x y                 -- no binders at all!
\y -> x y           -- no \x binder
(\x -> \y -> y) x   -- x is outside the scope
                    --  of the \x binder;
                    -- intuition: it's not "the same" x
```

QUIZ: Variable scope

In the expression (\x -> x) x, is x bound or free? *

- A. bound
- B. free
- C. first occurrence is bound, second is free
- D. first occurrence is bound, second and third are free
- E. first two occurrences are bound, third is free

http://tiny.cc/cse116-scope-ind

QUIZ: Variable scope

In the expression (\x -> x) x, is x bound or free? *

- A. bound
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- C. first occurrence is bound, second is free
- D. first occurrence is bound, second and third are free
- E. first two occurrences are bound, third is free

http://tiny.cc/cse116-scope-grp

Free Variables

- An variable x is **free** in **e** if there exists a free occurrence of **x** in **e**
- We can formally define the set of all free variables in a term like so:

```
FV(x)         = ???
FV(\x -> e)   = ???
FV(e1 e2)     = ???
```

Free Variables

- An variable x is **free** in **e** if there exists a free occurrence of **x** in **e**

- We can formally define the set of all free variables in a term like so:

```
FV(x)          = {x}
FV(\x -> e)    = FV(e) - {x}
FV(e1 e2)      = FV(e1) U FV(e2)
```

Closed Expressions

- If e has no free variables it is said to be closed
- Closed expressions are also called **combinators**
  - **Q:** What is the *shortest* closed expression?

Closed Expressions

- If e has no free variables it is said to be closed
- Closed expressions are also called **combinators**
  - **Q:** What is the *shortest* closed expression?
  - **A:** \x -> x

Semantics: What programs mean

- How do I “run” or “execute” a λ-term?

- Think of middle-school algebra:

```
-- Simplify expression:
  (x + 2)*(3*x - 1)
 =
  ???
```

- **Execute** = rewrite step-by-step following simple rules until no more rules apply

Rewrite rules of lambda calculus

1. α-step (aka renaming formals)
2. β-step (aka function call)

Semantics: β-Reduction

```
(\x -> e1) e2   =b>   e1[x := e2]
```

where e1[x := e2] means "e1 with all free occurrences of x replaced with e2"

- Computation by *search-and-replace*:
  - If you see an *abstraction* applied to an argument, take the *body* of the abstraction and replace all free occurrences of the *formal* by that argument
  - We say that `(\x -> e1) e2` *β-steps* to `e1[x := e2]`

Examples

```
(\x -> x) apple
=b> apple
```

Is this right? Ask Elsa!

```
(\f -> f (\x -> x)) (give apple)
=b> ???
```

Examples

```
(\x -> x) apple
=b> apple
```

Is this right? Ask Elsa!

```
(\f -> f (\x -> x)) (give apple)
=b> give apple (\x -> x)
```

QUIZ: β-Reduction 1

(\x -> (\y -> y)) apple =b> ??? *

- A. apple
- B. \y -> apple
- C. \x -> apple
- D. \y -> y
- E. \x -> y

http://tiny.cc/cse116-beta1-ind

QUIZ: β-Reduction 1

(\x -> (\y -> y)) apple =b> ??? *

- A. apple
- B. \y -> apple
- C. \x -> apple
- D. \y -> y
- E. \x -> y

http://tiny.cc/cse116-beta1-grp

QUIZ: β-Reduction 2

(\x -> x (\x -> x)) apple =b> ??? *

- A. apple (\x -> x)
- B. apple (\apple -> apple)
- C. apple (\x -> apple)
- D. apple
- E. \x -> x

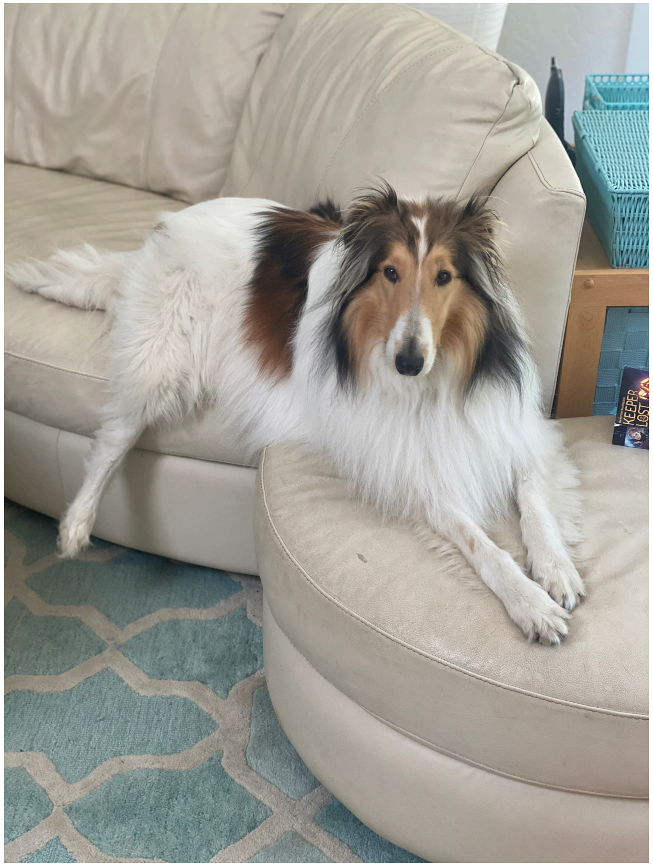
http://tiny.cc/cse116-beta2-ind

QUIZ: β-Reduction 2

(\x -> x (\x -> x)) apple =b> ??? *

- A. apple (\x -> x)
- B. apple (\apple -> apple)
- C. apple (\x -> apple)
- D. apple
- E. \x -> x

http://tiny.cc/cse116-beta2-grp


KEEPER
LOST

A Tricky One

```
    (\x -> (\y -> x)) y
=b> (\y -> y)
```

Is this right?

Problem: the free y in the argument has been *captured* by \y!

Solution: make sure that all *free variables* of the argument are different from the *binders* in the body.

Capture-Avoiding Substitution

- We have to fix our definition of *β*-reduction:

```
(\x -> e1) e2  =b>  e1[x := e2]
```

where e1[x := e2] means ~~“e1 with all free occurrences of x replaced with e2”~~

- e1 with all *free* occurrences of x replaced with e2, **as long as** no free variables of e2 get captured
- undefined otherwise

Capture-Avoiding Substitution

Formally:

```
x[x := e]             = e
y[x := e]             = y     -- assuming x /= y
(e1 e2)[x := e]       = (e1[x := e]) (e2[x := e])
(\x -> e1)[x := e]    = \x -> e1 -- why just `e1`?

(\y -> e1)[x := e]
   | not (y in FV(e)) = \y -> e1[x := e]
   | otherwise         = undefined -- but what then???
```

Semantics: α-Reduction

Semantics: α-Reduction

```
\x -> e    =a>   \y -> e[x := y]
                 where y not in FV(e)
```

- We can rename a formal parameter and replace all its occurrences in the body
- We say that `(\x -> e)` *a-steps* to `(\y -> e[x := y])`

Semantics: α-Reduction

```
\x -> e    =a>   \y -> e[x := y]
                 where y not in FV(e)
```

- Example:

```
       \x -> x
  =a>  \y -> y
  =a>  \z -> z
```

  - All these expressions are α-equivalent

Example

What's wrong with these?

```
-- (A)
\f -> f x    =a>  \x -> x x

-- (B)
(\x -> \y -> y) y    =a>  (\x -> \z -> z) z

-- (C)
\x -> \y -> x y  =a>  \apple -> \orange -> apple orange
```

The Tricky One

```
    (\x -> (\y -> x)) y
=a> ???
```

To avoid getting confused, you can always rename formals, so that different variables have different names!

The Tricky One

```
    (\x -> (\y -> x)) y
=a> (\x -> (\z -> x)) y
=b> \z -> y
```

To avoid getting confused, you can always rename formals, so that different variables have different names!

Normal Forms

A **redex** is a λ-term of the form

```
(\x -> e1) e2
```

A λ-term is in **normal form** if it contains no redexes.

QUIZ: Normal form

Which of the following terms are not in normal form ? *

- A. x
- B. x y
- C. (\x -> x) y
- D. x (\y -> y)
- E. C and D

http://tiny.cc/cse116-norm-ind

QUIZ: Normal form

Which of the following terms are not in normal form ? *

- A. x
- B. x y
- C. (\x -> x) y
- D. x (\y -> y)
- E. C and D

http://tiny.cc/cse116-norm-grp

Semantics: Evaluation

- A λ-term e evaluates to e' if

1. There is a sequence of steps

```
e =?> e_1 =?> ... =?> e_N =?> e’
```

where each =?> is either =a> or =b>

2. e’ is in *normal form*

Example of evaluation

```
(\x -> x) apple
  =b> apple
```

```
(\f -> f (\x -> x)) (\x -> x)
  =?> ???
```

```
(\x -> x x) (\x -> x)
  =?> ???
```

Example of evaluation

```
(\x -> x) apple
  =b> apple


(\f -> f (\x -> x)) (\x -> x)
  =b> (\x -> x) (\x -> x)
  =b> \x -> x


(\x -> x x) (\x -> x)
  =?> ???
```

Example of evaluation

```
(\x -> x) apple
  =b> apple


(\f -> f (\x -> x)) (\x -> x)
  =b> (\x -> x) (\x -> x)
  =b> \x -> x


(\x -> x x) (\x -> x)
  =b> (\x -> x) (\x -> x)
  =b> \x -> x
```

Elsa shortcuts

- Named λ-terms

```
let ID = \x -> x  -- abbreviation for \x -> x
```

- To substitute a name with its definition, use a =d> step:

```
ID apple
  =d> (\x -> x) apple  -- expand definition
  =b> apple            -- beta-reduce
```

Elsa shortcuts

- Evaluation
  - e1 =*> e2: e1 reduces to e2 in 0 or more steps
    - where each step is =a>, =b>, or =d>
  - e1 =~> e2: e1 evaluates to e2
- *What is the difference?*

Non-Terminating Evaluation

```
(\x -> x x) (\x -> x x)

=b> ???
```

Non-Terminating Evaluation

```
    (\x -> x x) (\x -> x x)

=b> (\x -> x x) (\x -> x x)
```

- Oh no… we can write programs that loop back to themselves
- And never reduce to normal form!
- This combinator is called Ω

Non-Terminating Evaluation

- What if we pass Ω as an argument to another function?

```
let OMEGA = (\x -> x x) (\x -> x x)

(\x -> \y -> y) OMEGA
```

- Does this reduce to a normal form? Try it at home!

Programming in λ-calculus

- Real languages have lots of features
  - Multi-argument functions
  - Booleans
  - Records (structs, tuples)
  - Numbers
  - Recursion
- Let's see how to encode all of these features with the λ-calculus.

Multi-Argument Functions

```haskell
-- The identity function ("for any x compute x")
\x -> x

-- A function that returns the identity function
\x -> (\y -> y)

-- A function that applies its argument to
-- the identity function
\f -> f (\x -> x)
```

- How do I define a function with two arguments?
  - e.g. a function that takes x and y and returns y

Multi-Argument Functions

```
-- A function that returns the identity function
\x -> (\y -> y)
```

OR: a function that takes two arguments
and returns the second one!

- How do I define a function with two arguments?
    - e.g. a function that takes x and y and returns y

Multi-Argument Functions

- How do I apply a function to two arguments?
  - e.g. apply \x -> (\y -> y) to apple and banana?

```
-- first apply to apple, then apply the result to banana

(((\x -> (\y -> y)) apple) banana)
```

Syntactic Sugar

- Convenient notation used as a shorthand for valid syntax

instead of	**we write**
`\x -> (\y -> (\z -> e))`	`\x -> \y -> \z -> e`
`\x -> \y -> \z -> e`	`\x y z -> e`
`(((e1 e2) e3) e4)`	`e1 e2 e3 e4`

```
\x y -> y      -- A function that that takes two arguments
               -- and returns the second one...

(\x y -> y) apple banana -- ... applied to two arguments
```

Programming in λ-calculus

- Real languages have lots of features
  - Multi-argument functions
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λ-calculus: Booleans

- How can we encode Boolean values (TRUE and FALSE) as functions?

- Well, what do we **do** with a Boolean **b**?

  - We make a ***binary choice***

```
if b then e1 else e2
```

Booleans: API

- We need to define three functions

```
let TRUE  = ???
let FALSE = ???
let ITE   = \b x y -> ???  -- if b then x else y
```

such that

```
ITE TRUE apple banana =~> apple
ITE FALSE apple banana =~> banana
```

(Here, `let NAME = e` means NAME is an *abbreviation* for e)

Booleans: Implementation

```
let TRUE  = \x y -> x       -- Returns first argument
let FALSE = \x y -> y       -- Returns second argument
let ITE   = \b x y -> b x y -- Applies cond. to branches
                            -- (redundant, but
                            --  improves readability)
```

Example: Branches step-by-step

```
eval ite_true:
  ITE TRUE e1 e2
  =d> (\b x y -> b    x  y) TRUE e1 e2  -- expand def ITE
  =b>   (\x y -> TRUE x  y)      e1 e2  -- beta-step
  =b>     (\y -> TRUE e1 y)         e2  -- beta-step
  =b>            TRUE e1 e2             -- expand def TRUE
  =d>     (\x y -> x) e1 e2             -- beta-step
  =b>       (\y -> e1)   e2             -- beta-step
  =b> e1
```

Example: Branches step-by-step

- Now you try it!
- Can you fill in the blanks to make it happen?
  - http://goto.ucsd.edu/elsa

```
eval ite_false:
  ITE FALSE e1 e2

  -- fill the steps in!

  =b> e2
```

Example: Branches step-by-step

```
eval ite_false:
  ITE FALSE e1 e2
  =d> (\b x y -> b    x  y) FALSE e1 e2  -- expand def ITE
  =b>   (\x y -> FALSE x  y)      e1 e2  -- beta-step
  =b>     (\y -> FALSE e1 y)         e2  -- beta-step
  =b>            FALSE e1 e2             -- expand def TRUE
  =d>     (\x y -> y) e1 e2              -- beta-step
  =b>       (\y -> y)    e2              -- beta-step
  =b> e2
```

Boolean operators

- Now that we have ITE it’s easy to define other Boolean operators:

```
let NOT = \b     -> ???

let AND = \b1 b2 -> ???

let OR  = \b1 b2 -> ???
```

Boolean operators

- Now that we have ITE it's easy to define other Boolean operators:

```
let NOT = \b      -> ITE b FALSE TRUE

let AND = \b1 b2 -> ITE b1 b2 FALSE

let OR  = \b1 b2 -> ITE b1 TRUE b2
```

Boolean operators

- Now that we have ITE it's easy to define other Boolean operators:

```
let NOT = \b     -> b FALSE TRUE

let AND = \b1 b2 -> b1 b2 FALSE

let OR  = \b1 b2 -> b1 TRUE b2
```

  - (since ITE is redundant)
  - *Which definition to do you prefer and why?*

Programming in λ-calculus

- Real languages have lots of features
  - **Booleans** [done]
  - Records (structs, tuples)
  - Numbers
  - **Functions** [we got those]
  - Recursion

λ-calculus: Records

- Let’s start with records with two fields (aka pairs)?
- Well, what do we **do** with a pair?

1. **Pack two** items into a pair, then
2. **Get first** item, or
3. **Get second** item.

Pairs: API

- We need to define three functions

```
let PAIR = \x y -> ???     -- Make a pair with x and y
                           -- { fst : x, snd : y }
let FST  = \p -> ???       -- Return first element
                           -- p.fst
let SND  = \p -> ???       -- Return second element
                           -- p.snd
```

such that

```
FST (PAIR apple banana) =~> apple
SND (PAIR apple banana) =~> banana
```

Pairs: Implementation

- A pair of x and y is just something that lets you pick between x and y! (I.e. a function that takes a boolean and returns either x or y)

```
let PAIR = \x y -> (\b -> ITE b x y)
let FST  = \p -> p TRUE    -- call w/ TRUE, get 1st value
let SND  = \p -> p FALSE   -- call w/ FALSE, get 2nd value
```

Exercise: Triples?

- How can we implement a record that contains **three** values?

```
let TRIPLE = \x y z -> ???
let FST3  = \t -> ???
let SND3  = \t -> ???
let TRD3  = \t -> ???
```

Exercise: Triples?

- How can we implement a record that contains **three** values?

```
let TRIPLE = \x y z -> PAIR x (PAIR y z)
let FST3  = \t -> FST t
let SND3  = \t -> FST (SND t)
let TRD3  = \t -> SND (SND t)
```

Programming in λ-calculus

- Real languages have lots of features
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λ-calculus: Numbers

- Let's start with **natural numbers** (0, 1, 2, …)
- What do we do with natural numbers?

1. **Count**: 0, inc
2. **Arithmetic**: dec, +, -, *
3. **Comparisons**: ==, <=, etc

Natural Numbers: API

- We need to define:
  - A family of **numerals**: ZERO, ONE, TWO, THREE, …
  - Arithmetic functions: INC, DEC, ADD, SUB, MULT
  - Comparisons: IS_ZERO, EQ

Such that they respect all regular laws of arithmetic, e.g.

```
IS_ZERO ZERO          =~> TRUE
IS_ZERO (INC ZERO)    =~> FALSE
INC ONE               =~> TWO
...
```

Pairs: Implementation

- **Church numerals**: a *number* N is encoded as a combinator that *calls a function on an argument* N *times*

```
let ONE   = \f x -> f x
let TWO   = \f x -> f (f x)
let THREE = \f x -> f (f (f x))
let FOUR  = \f x -> f (f (f (f x)))
let FIVE  = \f x -> f (f (f (f (f x))))
let SIX   = \f x -> f (f (f (f (f (f x)))))
...
```

QUIZ: Church Numerals

Which of these is a valid encoding of ZERO ? *

- A: let ZERO = \f x -> x
- B: let ZERO = \f x -> f
- C: let ZERO = \f x -> f x
- D: let ZERO = \x -> x
- E: None of the above

http://tiny.cc/cse116-church-ind

QUIZ: Church Numerals

Which of these is a valid encoding of ZERO ? *

- A: let ZERO = \f x -> x
- B: let ZERO = \f x -> f
- C: let ZERO = \f x -> f x
- D: let ZERO = \x -> x
- E: None of the above

http://tiny.cc/cse116-church-grp

λ-calculus: Increment

```
-- Call `f` on `x` one more time than `n` does
let INC   = \n -> (\f x -> ???)
```

- Example

```
eval inc_zero :
  INC ZERO
  =d> (\n f x -> f (n f x)) ZERO
  =b> \f x -> f (ZERO f x)
  =*> \f x -> f x
  =d> ONE
```

QUIZ: ADD

How shall we implement ADD? *

- A. let ADD = \n m -> n INC m
- B. let ADD = \n m -> INC n m
- C. let ADD = \n m -> n m INC
- D. let ADD = \n m -> n (m INC)
- E. let ADD = \n m -> n (INC m)

http://tiny.cc/cse116-add-ind

QUIZ: ADD

How shall we implement ADD? *

- A. let ADD = \n m -> n INC m
- B. let ADD = \n m -> INC n m
- C. let ADD = \n m -> n m INC
- D. let ADD = \n m -> n (m INC)
- E. let ADD = \n m -> n (INC m)

http://tiny.cc/cse116-add-grp

λ-calculus: Addition

```
--  Call `f` on `x` exactly `n + m` times
let ADD = \n m -> n INC m
```

- Example

```
eval add_one_zero :
  ADD ONE ZERO
  =~> ONE
```

QUIZ: MULT

How shall we implement MULT? *

- A. let MULT = \n m -> n ADD m
- B. let MULT = \n m -> n (ADD m) ZERO
- C. let MULT = \n m -> m (ADD n) ZERO
- D. let MULT = \n m -> n (ADD m ZERO)
- E. let MULT = \n m -> (n ADD m) ZERO

http://tiny.cc/cse116-mult-ind

QUIZ: MULT

How shall we implement MULT? *

- A. let MULT = \n m -> n ADD m
- B. let MULT = \n m -> n (ADD m) ZERO
- C. let MULT = \n m -> m (ADD n) ZERO
- D. let MULT = \n m -> n (ADD m ZERO)
- E. let MULT = \n m -> (n ADD m) ZERO

http://tiny.cc/cse116-mult-grp

λ-calculus: Multiplication

```
--  Call `f` on `x` exactly `n * m` times
let MULT = \n m -> n (ADD m) ZERO
```

- Example

```
eval two_times_one :
  MULT TWO ONE
  =~> TWO
```

Programming in λ-calculus

- Real languages have lots of features
  - Multi-argument functions
  - Booleans
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  - Numbers
  - Recursion

λ-calculus: Recursion

- I want to write a function that sums up natural numbers up to n:

```
\n -> ...            -- 1 + 2 + ... + n
```

QUIZ: SUM

Is this a correct implementation of SUM? *

```
let SUM = \n -> ITE (ISZ n)
                  ZERO
                  (ADD n (SUM (DEC n)))
```

- A. Yes
- B. No

http://tiny.cc/cse116-sum-ind

QUIZ: SUM

Is this a correct implementation of SUM? *

```
let SUM = \n -> ITE (ISZ n)
            ZERO
            (ADD n (SUM (DEC n)))
```

- A. Yes
- B. No

http://tiny.cc/cse116-sum-grp

λ-calculus: Recursion

- No! Named terms in Elsa are just syntactic sugar
- To translate an Elsa term to λ-calculus: replace each name with its definition

```
\n -> ITE (ISZ n)
        ZERO
        (ADD n (SUM (DEC n))) -- But SUM is
                              -- not a thing!
```

- **Recursion**: Inside this function I want to call the same function on DEC n
- Looks like we can't do recursion, because it requires being able to refer to functions *by name*, but in λ-calculus functions are *anonymous*.
- ***Right?***

λ-calculus: Recursion

- Think again!
- Recursion: ~~Inside this function I want to call the same function on DEC n~~
  - Inside this function I want to call a function on DEC n
  - And BTW, I want it to be the same function
- Step 1: Pass in the function to call "recursively"

```
let STEP =
  \rec ->
   \n -> ITE (ISZ n)
           ZERO
           (ADD n (rec (DEC n))) -- Call some rec
```

λ-calculus: Recursion

- Step 1: Pass in the function to call "recursively"

```
let STEP =
  \rec ->
   \n -> ITE (ISZ n)
           ZERO
           (ADD n (rec (DEC n))) -- Call some rec
```

- Step 2: Do something clever to `STEP`, so that the function passed as `rec` itself becomes

```
\n -> ITE (ISZ n) ZERO (ADD n (rec (DEC n)))
```

λ-calculus: Fixpoint Combinator

- **Wanted**: a combinator `FIX` such that `FIX STEP` calls `STEP` with itself as the first argument:

```
FIX STEP
=*> STEP (FIX STEP)
```

(In math: a *fixpoint* of a function $f(x)$ is a point x, such that $f(x) = x$)

- Once we have it, we can define:

```
let SUM = FIX STEP
```

- Then by property of `FIX` we have:

```
SUM =*> STEP SUM -- (1)
```

λ-calculus: Fixpoint Combinator

```
eval sum_one:
  SUM ONE
  =*> STEP SUM ONE                            -- (1)
  =d> (\rec n -> ITE (ISZ n) ZERO (ADD n (rec (DEC n)))) SUM ONE
  =b>     (\n -> ITE (ISZ n) ZERO (ADD n (SUM (DEC n))))     ONE
                                                  -- ^^^ the magic happened!
  =b>             ITE (ISZ ONE) ZERO (ADD ONE (SUM (DEC ONE)))
  =*> ADD ONE (SUM ZERO)                      -- def of ISZ, ITE, DEC, ...
  =*> ADD ONE (STEP SUM ZERO)                 -- (1)
  =d> ADD ONE
        ((\rec n -> ITE (ISZ n) ZERO (ADD n (rec (DEC n)))) SUM ZERO)
  =b> ADD ONE ((\n -> ITE (ISZ n) ZERO (ADD n (SUM (DEC n)))) ZERO)
  =b> ADD ONE (ITE (ISZ ZERO) ZERO (ADD ZERO (SUM (DEC ZERO))))
  =b> ADD ONE ZERO
  =~> ONE
```

λ-calculus: Fixpoint Combinator

- So how do we define `FIX`?

- Remember Ω? It *replicates itself!*

```
(\x -> x x) (\x -> x x)
=b> (\x -> x x) (\x -> x x)
```

- We need something similar but more involved.

λ-calculus: Fixpoint Combinator

- The Y combinator discovered by Haskell Curry:

```
let FIX = \stp -> (\x -> stp (x x)) (\x -> stp (x x))
```

- How does it work?

```
eval fix_step:
     FIX STEP
  =d> (\stp -> (\x -> stp (x x)) (\x -> stp (x x))) STEP
  =b>         (\x -> STEP (x x)) (\x -> STEP (x x))
  =b> STEP   ((\x -> STEP (x x)) (\x -> STEP (x x)))
  --       ^^^^^^^^^^ this is FIX STEP ^^^^^^^^^^^
```

Programming in λ-calculus

- Real languages have lots of features
  - Multi-argument functions
  - Booleans
  - Records (structs, tuples)
  - Numbers
  - Recursion

Next time: Intro to Haskell