# CSE341: Programming Languages

## Structs, Implementing Languages, Implementing Higher-Order Functions

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(slides “borrowed” from Dan Grossman)
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## An aside - Parenthesis bias

- If you look at the HTML for a web page, it takes the same approach:
  - `(foo` written `<foo>`
  - `)` written `</foo>`
- But for some reason, LISP/Scheme/Racket is the target of subjective parenthesis-bashing
  - Curiously, often by people who have no problem with HTML
  - You are entitled to your opinion about syntax, but a good historian wouldn’t refuse to study a country where he/she didn’t like people’s accents

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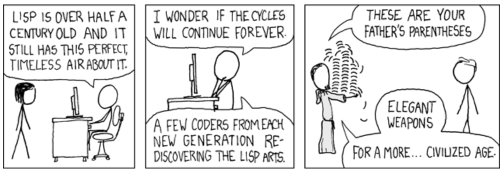

**http://xkcd.com/297/**

LISP invented around 1959 by
John McCarthy (9/4/27-10/23/2011)

- Invented garbage collection

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## Review

- Given pairs and dynamic typing, you can code up “one-of types” by using first list-element like a constructor name:

```
(define (const i)    (list 'const i))
(define (add e1 e2)  (list 'add e1 e2))
(define (negate e)   (list 'negate e))
```

- But much better and more convenient is Racket’s structs
  - Makes a new dynamic type (`pair?` answers false)
  - Provides constructor, predicate, accessors

```
(struct const  (i)     #:transparent)
(struct add  (e1 e2)   #:transparent)
(struct negate  (e)    #:transparent)
```

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## Defines trees

- Either lists or structs (we’ll use structs) can then let us build trees to represent compound data such as expressions

```
(add (const 4)
     (negate (add (const 1)
                  (negate (const 7)))))
```

- Since Racket is dynamically typed, the idea that a set of constructors are variants for “an expression datatype” is in our heads / comments

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## Haskell’s view of Racket’s “type system”

One way to describe Racket is that it has “one big datatype”
- All values have this same one type

- Constructors are applied implicitly (values are *tagged*)
  - `42` is implicitly “int constructor with `42`”

| inttag | 42 |
|---|---|

- Primitives implicitly *check tags and extract data*, raising errors for wrong constructors
  - `+` is implicitly “check for int constructors and extract data”
  - [Actually Racket has a *numeric tower* that `+` works on]
- Built-in: numbers, strings, booleans, pairs, symbols, procedures, etc.
  - Each struct creates a *new constructor*, a feature many dynamic languages do not have
  - `(struct …)` can be neither a function nor a macro

## Implementing PLs

Most of the course is learning fundamental concepts for *using* PLs
  - Syntax vs. semantics vs. idioms
  - Powerful constructs like pattern-matching, closures, dynamically typed pairs, macros, …

An educated computer scientist should also know some things about *implementing* PLs
  - Implementing something requires fully understanding its semantics
  - Things like closures and objects are not "magic"
  - Many programming tasks are like implementing PLs
    - Example: rendering a document ("program" is the [structured] document and "pixels" is the output)

## Ways to implement a language

Two fundamental ways to implement a PL *A*

- Write an interpreter in another language *B*
  - Better names: evaluator, executor
  - Take a program in *A* and produce an answer (in *A*)

- Write a compiler in another language *B* to a third language *C*
  - Better name: translator
  - Translation must *preserve meaning* (equivalence)

We call *B* the metalanguage; crucial to keep *A* and *B* straight

Very first language needed a hardware implementation

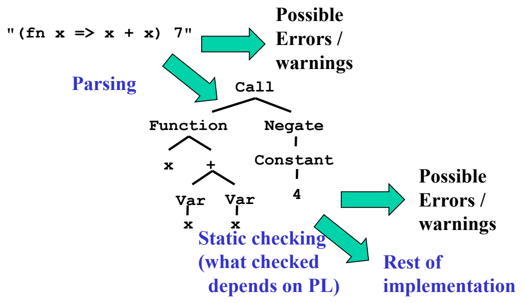
## Reality more complicated

Evaluation (interpreter) and translation (compiler) are your options
  - But in modern practice have both and multiple layers

A plausible example:
  - Java compiler to bytecode intermediate language
  - Have an interpreter for bytecode (itself in binary), but compile frequent functions to binary at run-time
  - The chip is itself an interpreter for binary
    - Well, except these days the x86 has a translator in hardware to more primitive micro-operations that it then executes

Racket uses a similar mix

## Implementing a language



`"(fn x => x + x) 7"`

**Possible Errors / warnings**

**Parsing**

`Call`

`Function` `Negate`

`x` `+` `Constant`

`Var` `Var` `4`

`x` `x`

**Static checking (what checked depends on PL)**

**Possible Errors / warnings**

**Rest of implementation**

## Skipping those steps

Alternately, we can *embed* our language inside (data structures) in the metalanguage
  - Skip parsing: Use constructors instead of just strings
  - These abstract syntax trees (ASTs) are already ideal structures for passing to an interpreter

We can also, for simplicity, skip static checking
  - Assume subexpressions are actually subexpressions
    - *Do not* worry about `(add #f "hi")`
  - For dynamic errors in the embedded language, interpreter can give an error message
    - *Do* worry about `(add (fun …) (int 14))`

## The arith-exp example

This embedding approach is exactly what we did for the PL of arithmetic expressions:

```
(struct const (i)    #:transparent)
(struct add (e1 e2) #:transparent)
(struct negate (e)   #:transparent)
```

```
(add (const 4)
     (negate (add (const 1)
                  (negate (const 7)))))
```

```
(define (eval-exp e) … )
```

Note: So simple there are no dynamic type errors in the interpreter

## *The interpreter*

An interpreter takes programs in the language and produces values (answers) in the language

- Typically via recursive helper functions with cases
- This example is so simple we don't need a helper and can assume all recursive results are constants

```
(define (eval-exp e)
   (cond
     [(const? e) e]
     [(add? e)
      (const (+ (const-i (eval-exp (add-e1 e)))
                (const-i (eval-exp (add-e2 e)))))]
     [(negate? e)
      (const (- (const-i (eval-exp (negate-e e)))))]
     [#t (error “eval-exp expected an expression”)]))
```

## *“Macros”*

Another advantage of the embedding approach is we can use the metalanguage to define helper functions that create programs in our language

- They generate the (abstract) syntax
- Result can *then* be put in a larger program or evaluated
- This is a lot like a macro, using the metalanguage as our macro system

Example:

All this does is create a program that has four constant expressions:

```
(define (triple x) (add x (add x x)))

(define p (add (const 1) (triple (const 2))))
```

## *What's missing*

Two very interesting features missing from our arithmetic-expression language:

- Local variables
- Higher-order functions with lexical scope

How to support local variables:

- Interpreter helper function(s) need to take an *environment*
- As we have said since lecture 1, the environment maps variable names to values
  - A Racket association list works well enough
- Evaluate a variable expression by looking up the name
- A let-body is evaluated in a larger environment

## *Higher-order functions*

The “magic”: How is the “right environment” around for lexical scope when functions may return other functions, store them in data structures, etc.?

Lack of magic: The interpreter uses a closure data structure (with two parts) to keep the environment it will need to use later

Evaluate a function expression:

- A function is not a value; a closure is a value
- Create a closure out of (a) the function and (b) the current environment

Evaluate a function call:

- …

## *Function calls*

- Evaluate 1st subexpression to a closure with current environment
- Evaluate 2nd subexpression to a value with current environment
- Evaluate closure's function's body in the closure's environment, extended to map the function's argument-name to the argument-value
  - And for recursion, function's name to the whole closure

This is the same semantics we learned a few weeks ago “coded up”

Given a closure, the code part is only ever evaluated using the environment part (extended), not the environment at the call-site

## *Is that expensive?*

- *Time* to build a closure is tiny: a struct with two fields

- *Space* to store closures *might* be large if environment is large
  - But environments are immutable, so natural and correct to have lots of sharing, e.g., of list tails (cf. earlier lectures)

- Alternative: Homework 5 challenge problem is to, when creating a closure, store a possibly-smaller environment holding only the variables that are free variables in the function body
  - Free variables: Variables that occur, not counting shadowed uses of the same variable name
  - A function body would never need anything else from the environment

## *Free variables examples*

```
(lambda () (+ x y z))

(lambda (x) (+ x y z))

(lambda (x) (if x y z))

(lambda (x) (let ([y 0]) (+ x y z)))

(lambda (x y z) (+ x y z))

(lambda (x) (+ y (let ([y z]) (+ y y))))
```

## *Free variables examples*

```
(lambda () (+ x y z))   ; x y z

(lambda (x) (+ x y z))  ; y z

(lambda (x) (if x y z)) ; y z

(lambda (x) (let ([y 0]) (+ x y z))) ; z

(lambda (x y z) (+ x y z)) ; {}

(lambda (x) (+ y (let ([y z]) (+ y y)))) ; y z
```

## *Free variables examples – mini-exercises*

```
(lambda () (+ j 3))

((lambda (j) (+ j k 3))

(lambda (j) (let ([k 0]) (+ j k 3)))
```

## *Compiling higher-order functions*

- Key to the interpreter approach: Interpreter helper function takes an environment argument
  - Recursive calls can use a different environment
- Can also compile higher-order functions by having the translation produce “regular” functions (like in C or assembly) that *all* take an extra *explicit* argument called “environment”
- And compiler replaces all uses of free variables with code that looks up the variable using the environment argument
  - Can make these fast operations with some tricks
- Running program still creates closures and every function call passes the closure’s environment to the closure’s code