# CSE 413
# Languages & Implementation

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Structs, Implementing Languages

(credits: Dan Grossman, CSE 341)

## Goals

- Representing programs as data
- Racket structs as a better way to represent abstract programs (& other data)
- Writing interpreters to execute programs represented as data
- Using closures to implement higher-order functions

- This stuff is crucial for the next assignment
  - Without it you will be totally lost
  - With it, it's challenging but straightforward

## Data structures in Racket

We’ve been using functions to abstract from lists

```
(make-expr left op right) =>
             (list left op right)
(operator expr) => (cadr expr)
```

etc.

We could also build “weakly typed” or self-describing data by tagging each list:

```
(define (Const i)    (list ‘Const i))
(define (Add e1 e2) (list ‘Add e1 e2))
(define (Negate e)  (list ‘Negate e))
```

See sample code for more examples + evaluator

## Comments on what we did

Using lists where the car of the list encodes “what kind of expression”

Key points

- Defined our own constructor, test, extract-data functions
  - Much better style than car, cadr, etc.
- Elegant recursive evaluator with big cond
- With no type system, no notion of “what is an expression” other than documentation
  - But if we use the helper functions correctly, we’re ok
  - Could add more explicit error checking if desired

## Racket structs

New Racket feature

```
(struct foo (bar baz bam)   #:transparent)
```

Defines a new kind of thing (type) and introduces several associate functions:

- Constructor: **`(foo e1 e2 e3)`**
  - Returns a new "**`foo`**" with bar, baz, and bam fields initialized to e1, e2, e3
- Predicate: **`(foo? e)`**
  - Evaluate e and return #t if it is something made with the **`foo`** (constructor) function
- Extractors: **`(foo-bar e)`**
  - Evaluate e. If result was made with the **`foo`** constructor, return the **`bar`** field, else an error
  - Similar extractors for other fields (foo-baz, foo-bam)

## An idiom

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

For "types" like expressions, create one struct for each "kind of" expression

- Conveniently definies constructors, tester, and extractor functions, e.g., **`add add? add-e1`**
- There's nothing that ties **`add`**, **`negate`**, **`const`** together as the "expression type" other than the convention we have in our heads and in comments
- Also nothing that restricts "types" of fields – also just convention in code and in comments

## Representing program as trees

Can use either lists or structs (we'll use structs) to build trees to represent compound data & programs

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

See code for more extensive set of struct defintions and associated evaluator for a small integer language

## Attributes

- #:transparent
  - Optional; makes struct fields visible & for us prints them in the interactions window

Also available (and optional):

- #:mutable
  - Can decide if each struct type supports mutation
    - (we will avoid this; guarantees no mutation)
  - mcons is just a predefined mutable struct

## Contrasting approaches

```
(struct add (e1 e2)   #:transparent)
```

vs

```
(define (add e1 e2) (list 'add e1 e2)
(define (add? e) (eq? (car e) 'add))
(define (add-e1) (car (cdr e)))
(define (add-e2) (car (cdr (cdr e))))
```

- This is *not* just “syntactic sugar”
  - i.e., not just convenient syntax for writing something already in the language

## The key difference

```
(struct add (e1 e2) #:transparent)
```

- The result of evaluating **`(add x y)`** is *not* a list
  - And there is no list for which **`add?`** returns #t

- **`struct`** makes a new kind of thing – a new type

- So using an “add” as an argument to car, cdr, etc. is a runtime error – not true for the version with lists

## Now

Step back to look at approaches to implementing programming languages…

## Implementing languages

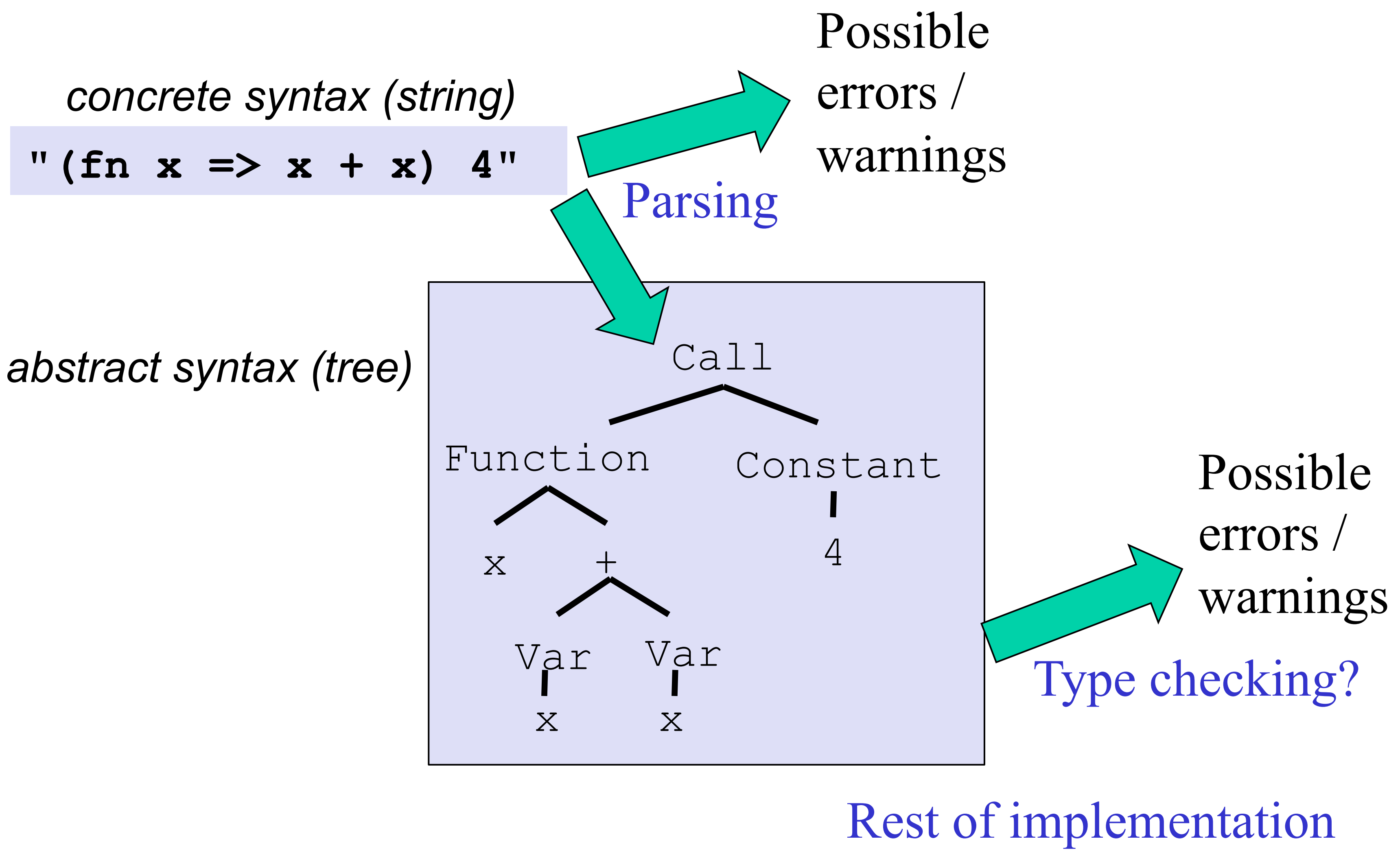
Much of the course so far has been about fundamental concepts for *using* PLs

- Syntax, semantics, idioms
- Important concepts like closures, delayed evaluation, …

But we also want to learn basics of *implementing* PLs

- Requires fully understanding semantics
- Things like closures and objects are not "magic"
- Many programming techniques are related/similar
  - Ex: rendering a document ("program" is the structured document, "pixels" is the output)

# Typical workflow



## Interpreters or Compilers

The “rest of implementation” takes the abstract syntax tree (AST) as data and “runs the program” to produce a result

Two fundamental ways to implement a prog. lang. A

- Write an *interpreter* in another language B
  - (Better names: evaluator, executor)
  - Read program in A and produce an answer (in A)
- Write a *compiler* in another language B
  - (Better name: translator)
  - Read program in A, produce an equivalent program in another language C
  - Translation must *preserve meaning* (equivalence)
- We call B the “metalanguage”
  - Crucial to keep A and B straight

## It’s really more complicated

Evaluation (interpreter) and translation (compiler) are the options, but many languages are implemented with both and have multiple layers

Example: Java

- Compiler to bytecode intermediate language (.class)
- Can interpret the bytecode directly, but also…
- Can compile frequently executed code to binary
- The processor chip is an interpreter for binary
  - Except these days the chip translates x86 binary to a more primitive code that it executes

Racket uses a similar mix

## Sermon (er, rant)

Interpreter vs compiler vs combinations is about language implementation, not language definition

There is no such thing as a “compiled language” or “interpreted language”

- Program cannot see how the implementation works

Unfortunately you hear things like this all the time:

- “C is faster because it’s compiled and LISP is interpreted”
- Nonsense: You can write a C interpreter or a LISP compiler
- Please politely correct your managers, friends, and other professors. ☺

## OK, they do have a point

A traditional compiler does not need the language implementation to run the program

- Can "ship the binary" without the compiler

But Racket, Scheme, Javascript, Ruby, … have **`eval`**

- At runtime can create data and treat it as a program
- Then run that program
- So we need an implementation (compiler, interpreter, combination) at runtime

It is also true that some languages are designed with a particular implementation strategy in mind, but it doesn't mean they couldn't be implemented differently.

## Embedding one language in another

How is **`(negate (add (const 2) (const 2)))`**
a "program" compared to "-(2+2)" ?

A traditional implementation includes a *parser* to read the string "-(2+2)" and turn it into a tree-like data structure called an *abstract syntax tree (AST)*.

- Ideal representation for either interpreting or as an intermediate stage in compiling
- Our **`(negate ...)`** data structure is an AST
- For now we'll create trees directly and interpret them
  - Will cover parsing later in the course
- We'll also assume perfect programmers and not worry about syntax errors – parser would normally guarantee legal AST
  - Interpreter still needs to worry about semantic (type) errors

## The arith-exp example

This embedding approach is exactly what we did to represent the language of arithmetic expressions using Racket structs

```
(struct const (i)    #:transparent)
(struct add (e1 e2) #:transparent)
(struct negate (e)  #:transparent)
(add (const 4)
     (negate (add (const 1)
                  (negate (const 7)))))
```

The missing piece is to define the interpreter

```
(define (eval-exp e) … )
```

## 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 helpers 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"))))
```

See example code – two versions, one with just ints, one with a second boolean type

## “Macros”

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

- They generate the (abstract) syntax
- Result can *then* be put in a larger program or evaluated

Example – Racket functions that produce abstract code:

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

(all this does in create a program with 4 constant expressions)

## What's missing

- Two major things missing from this language
  - Variables: let bindings, function arguments
  - Higher-order functions with lexical scope (closures)

- To support local variables:
  - Interpreter function(s) need an *environment* as an additional argument
    - Environment maps names to values
    - A Racket association list works fine for us
  - Evaluate a variable expression by looking up the name
  - A let-body is evaluated in an augmented environment with the local binding(s)

## Higher-order functions

The “magic”: How is the “right environment” found 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 when the closure function is executed

To evaluate a function expression:

- A function is not a value, a closure is a value
  - Evaluation of a function returns a closure
- Create a closure out of (i) the function and (ii) the current environment

To evaluate a function call…

## Function calls

To evaluate `(call exp1 exp2)`

- Evaluate `exp1` in the current environment to get a closure
- Evaluate `exp2` in the current environment to get a value
- Evaluate the closure's function's body *in the closure's environment* extended to map the function's argument name to the argument value
  - We only will implement single-argument functions
  - For recursion, a function name will evaluate to its entire closure

This is the same semantics we've been learning

Given a closure, the code part is always evaluated using the closure's environment part (extended with the argument binding), *not* the current environment at the call site.

## Sounds expensive!

It isn't!!

- *Time* to build a closure is tiny: struct with two fields
- *Space* to store closures *might* be large if the environment is large
  - But environments are immutable, so lots of sharing is natural and correct

Possible HW challenge problem (extra credit): when creating a closure store a possibly smaller environment holding only function *free variables*, i.e., "global" variables used in a function but not bound in it

- Function body would never need anything else from the environment

## What's next?

- Specific details of MUPL (interpreter assignment)
  - Demo/questions now

- Then we're mostly done with functional programming…

…but need to take out the garbage later

(and fit in a midterm exam when MUPL is done)

- After that: Ruby and object-oriented programming, grammars, scanners, parsers, more implementation