CSE413: Programming Languages and Implementation

Racket structs
Implementing languages with interpreters
Implementing closures

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Hi!

- I’m not Hal ☺
- I love this stuff and have taught this stuff many times
  - But not in CSE413
  - So stop me if I use jargon you don’t know, etc.
- This stuff is *crucial* for your next homework
  - Without it you will be totally lost
  - With it, it’s challenging but straightforward
- This material hopefully takes just about two class periods
  - See also code

Announcements from Hal

- Reminder: HW4 due Thursday night, 11PM
- HW5 Posted, due a week from Thursday, 11PM
- Midterm the following Monday, November 3, in class

Goals

1. Learn how to *write* interpreters for implementing programming languages

2. In particular, use closures to implement higher-order functions

3. Represent the *code* of one language as *data* in another language

4. Learn Racket's *structs* as a better way than lists to represent the code of another language

Goals will overlap, but very roughly will go 3-and-4, then 1, then 2

Dynamic typing + lists = everything

We know:

- Racket has lists
- Racket is dynamically typed

So: (nested) lists can hold any kind of tree-shaped data

- Can just mix values of different types and use primitives like **`number?`**, **`string?`**, **`pair?`**, etc. to “see what you have”
- Can use cons cells to build up any kind of data

“This works” – see code for a little language of arithmetic expressions

Comments on what we did

Using lists where car of list encodes "what kind of expression"

Key points:

- Define our own constructor, test-variant, extract-data functions
  - Just better style than hard-to-read uses of **`car`**, **`cdr`**
- Elegant recursive structure with a "big cond"
- With no type system, no notion of "what is an expression" except in documentation
  - But if we use the helper functions correctly, then okay
  - Could add more explicit error-checking if desired

Note: Use of symbols and **`eq?`** is idiomatic Racket, but not necessary

New feature

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

Defines a new kind of thing and introduces several new functions:

- **`(foo e1 e2 e3)`** returns “a foo” with **`bar`**, **`baz`**, **`quux`** fields holding results of evaluating **`e1`**, **`e2`**, and **`e3`**
- **`(foo? e)`** evaluates **`e`** and returns **`#t`** if and only if the result is something that was made with the **`foo`** function
- **`(foo-bar e)`** evaluates **`e`**. If result was made with the **`foo`** function, return the contents of the **`bar`** field, else an error
- **`(foo-baz e)`** evaluates **`e`**. If result was made with the **`foo`** function, return the contents of the **`baz`** field, else an error
- **`(foo-quux e)`** evaluates **`e`**. If result was made with the **`foo`** function, return the contents of the **`quux`** field, else an error

An idiom

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

For “types” like expression, create one struct for each “kind of exp”

- Conveniently defines constructor, tester, and extractor functions
    - E.g., **`const`**, **`const?`**, **`const-int`**
- Dynamic typing means “these are the kinds of expression” is “still [just] in comments”
- Dynamic typing means “types” of fields are also “just in comments”

All we need

These structs are all we need to:

- Build trees representing expressions, e.g.,

```
(multiply (negate (add (const 2) (const 2)))
          (const 7))
```

- Build our **`eval-exp`** function (see code):

```
(define (eval-exp e)
  (cond [(const? e) e]
        [(negate? e)
         (const (- (const-int
                     (eval-exp (negate-e e)))))]
        [(add? e) …]
        [(multiply? e) …]…
```

Attributes

- **`#:transparent`** is an optional attribute on struct definitions
  - For us, prints struct values in the REPL (interactions window)rather than hiding them, which is convenient for debugging homework

- **`#:mutable`** is another optional attribute on struct definitions

```
(struct card (suit rank) #:transparent #:mutable)
; also defines set-card-suit!, set-card-rank!
```

  - Can decide if each struct supports mutation, with usual advantages and disadvantages
    - We will avoid this attribute; guarantees no mutation
  - mcons is just a predefined mutable struct

Contrasting Approaches

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

Versus

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

This is *not* a case of “syntactic sugar”

– Syntactic sugar: More convenient syntax for writing something already in the language

The key difference

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

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

- **`struct`** makes a new kind of thing: extending Racket with a new kind of data

- So calling **`car`**, **`cdr`**, or **`mult-e1`** on “an add” is a run-time error
  - Not true for the version with lists (!)

List approach is error-prone

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

- Can break abstraction by using **`car`**, **`cdr`**, and list-library functions directly on “add expressions”
  - Silent likely error:

```
(define xs (list (add (const 1)(const 4)) …))
(car (car xs))
```

- Can make data that **`add?`** wrongly answers **`#t`** to

```
(cons 'add "I am not an add")
```

Summary of advantages

Struct approach:

- Is better style and more concise for *defining* data types
- Is about equally convenient for *using* data types
- But much better at timely errors when *misusing* data types
  - Cannot use accessor functions on wrong kind of data
  - Cannot confuse tester functions

But: Still doesn't enforce that fields "have the right type"

- Not covering: Could use Racket's *modules* or *contracts* to do that

Struct is special

Often we end up learning that some convenient feature could be coded up with other features

Not so with struct definitions:

- A function cannot introduce multiple bindings
- Creating a new kind of data has to be a "built-in primitive"
  - Result of constructor function returns **`#f`** for *every* other tester function: **`number?`**, **`pair?`**, other structs' tester functions, etc.

Now…

A step back to talk about general approaches to implementing programming languages…

Implementing languages

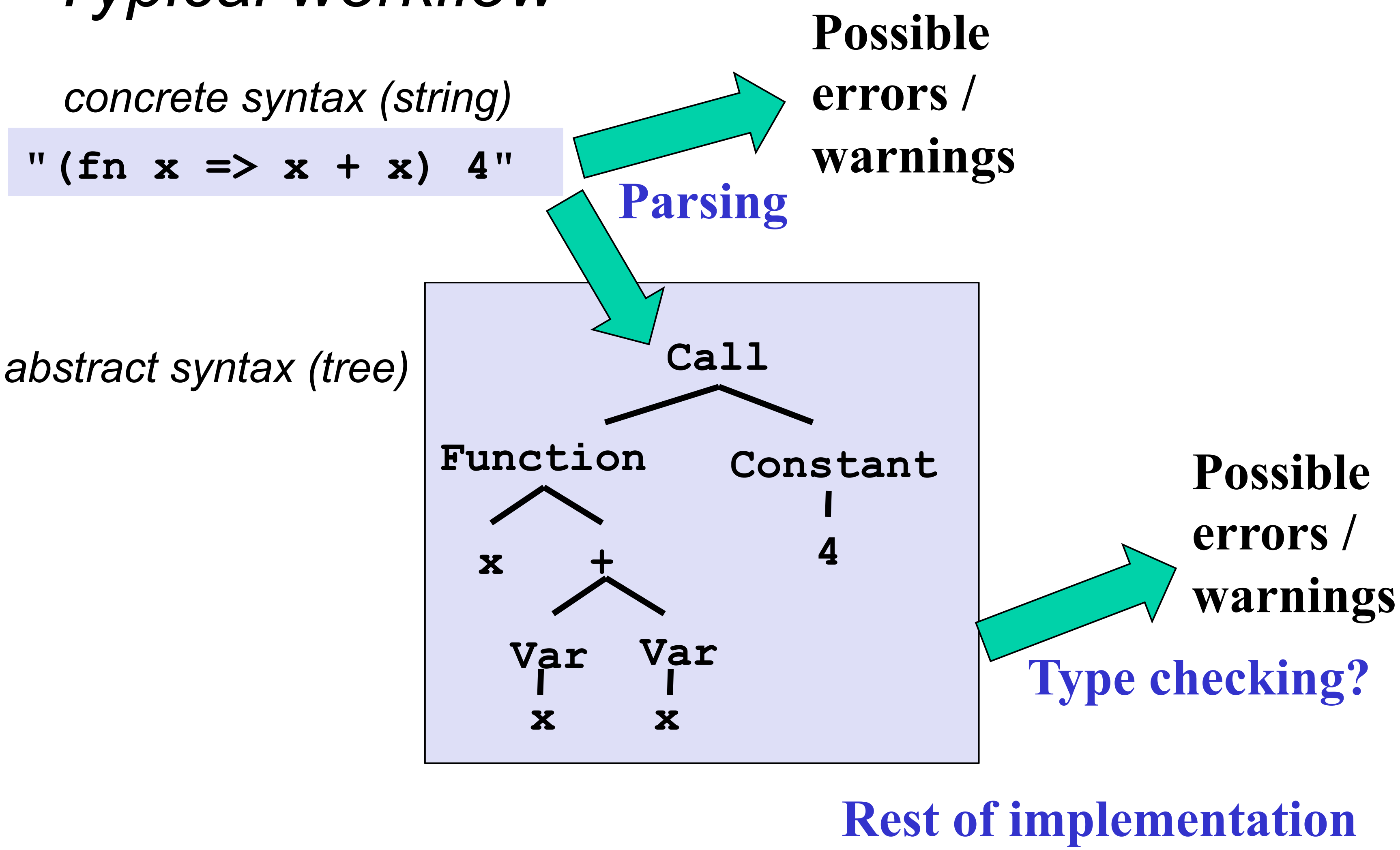
Much of course has been fundamental concepts for *using* PLs

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

But also valuable (and fun!) to learn basics of *implementing* PLs

- Requires fully understanding semantics
- Things like closures and objects are not "magic"
- Many programming techniques are related/similar
  - Example: rendering a document ("program" is the structured document, "pixels" is the output)
- Substantial part of CSE413 course description

Typical workflow



Interpreter or compiler

So "rest of implementation" takes the abstract syntax tree (AST) and "runs the program" to produce a result

Fundamentally, two approaches to implement a PL *B*:

- Write an interpreter in another language *A*
  - Better names: evaluator, executor
  - Take a program in *B* and produce an answer (in *B*)
- Write a compiler in another language *A* to a third language *C*
  - Better name: translator
  - Translation must *preserve meaning* (equivalence)

We call *A* the metalanguage

- Crucial to keep *A* and *B* straight

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 it then executes

Racket implementation itself uses a similar mix

Sermon

Interpreter versus compiler versus combinations is about a particular language **implementation**, not the language **definition**

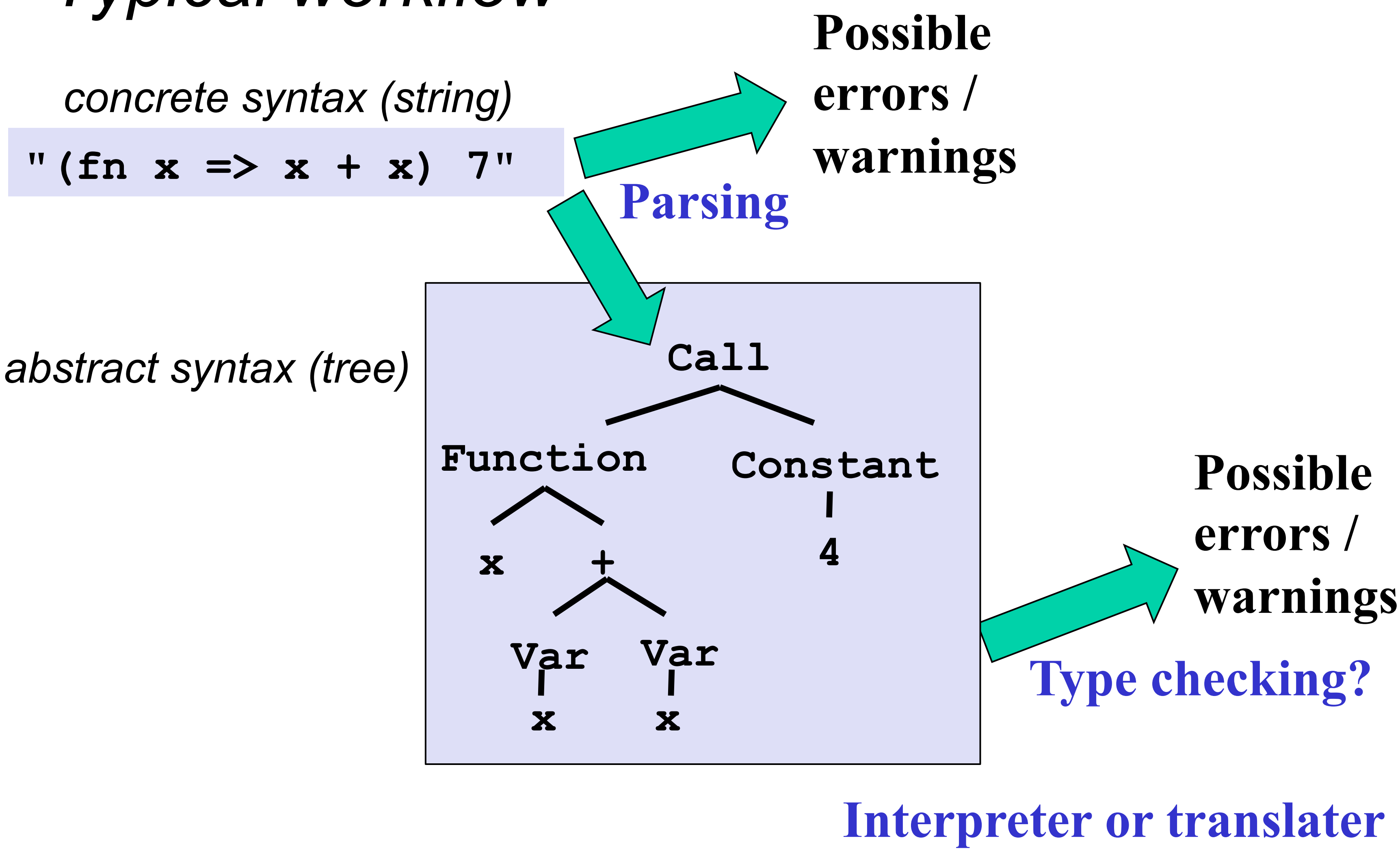
So there is no such thing as a "compiled language" or an "interpreted language"

- Programs cannot "see" how the implementation works

Unfortunately, you often hear such phrases

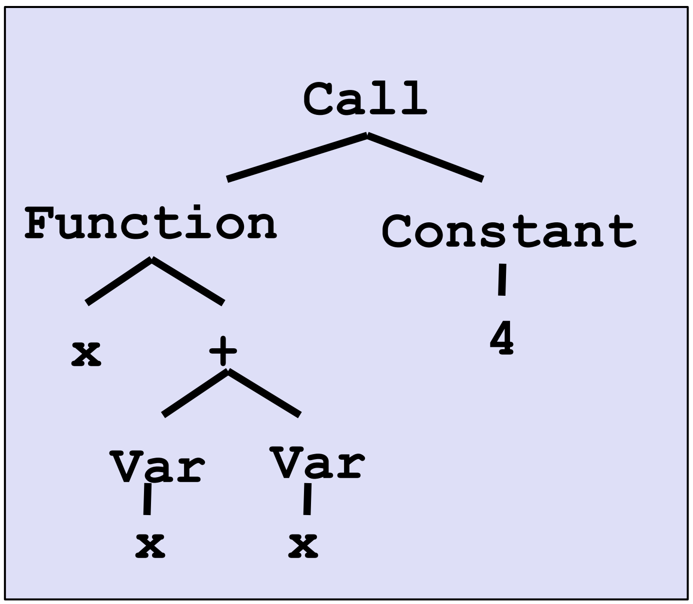
- "C is faster because it's compiled and LISP is interpreted"
- This is nonsense; politely correct people
- (Admittedly, languages with "eval" must "ship with some implementation of the language" in each program)

Typical workflow



Skipping parsing [until later in quarter]

- If implementing PL *B* in PL *A*, we can skip parsing
  - Have *B* programmers write ASTs directly in PL *A*
  - Not so bad with Racket structs
  - Embeds *B* programs as trees in *A*




```
; define B's abstract syntax
(struct call …)
(struct function …)
(struct var …)
…
```

```
; example B program
(call (function (list "x")
                (add (var "x")
                     (var "x")))
      (const 4))
```

Already did an example!

- Let the metalanguage *A* = Racket
- Let the language-implemented *B* = "*Arithmetic Language*"
- Arithmetic programs written with calls to Racket constructors
- The interpreter is **`eval-exp`**

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

```
(define (eval-exp e)
  (cond [(const? e) e]
        [(negate? e)
         (const (- (const-int
                    (eval-exp (negate-e e)))))]
        [(add? e) …]
        [(multiply? e) …]…
```

Racket data structure is *Arithmetic Language* program, which **`eval-exp`** runs

What we know

- Define (abstract) syntax of language *B* with Racket structs
  - *B* called MUPL in homework
- Write *B* programs directly in Racket via constructors
- Implement interpreter for *B* as a (recursive) Racket function

Now, a subtle-but-important distinction:

- Interpreter can *assume* input is a "legal AST for B"
  - Okay to give wrong answer or inscrutable error otherwise
- Interpreter *must check* that recursive results are the right kind of *value*
  - Give a good error message otherwise

Legal ASTs

- "Trees the interpreter must handle" are a subset of all the trees Racket allows as a dynamically typed language

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

- Can assume "right types" for struct fields
  - **`const`** holds a number
  - **`negate`** holds a legal AST
  - **`add`** and **`multiply`** hold 2 legal ASTs

- Illegal ASTs can "crash the interpreter" – *this is fine*

```
(multiply (add (const 3) "uh-oh") (const 4))
(negate -7)
```

Interpreter results

- Our interpreters return expressions, but not any expressions
  - Result should always be a *value-in-language-being-interpreted*, a kind of expression that evaluates to itself
  - If not, the interpreter has a bug
- So far, only values are from **`const`**, e.g., **`(const 17)`**
- But a larger language has more values than just numbers
  - Booleans, strings, etc.
  - Pairs of values (definition of value recursive)
  - Closures
  - …

Example

See code for language that adds booleans, number-comparison, and conditionals:

```
(struct bool (b) #:transparent)
(struct eq-num (e1 e2) #:transparent)
(struct if-then-else (e1 e2 e3) #:transparent)
```

What if the program is a legal AST, but evaluation of it tries to use the wrong kind of value?

- For example, “add a boolean”
- You should detect this and give an error message not in terms of the interpreter implementation
- Means checking a recursive result whenever a particular kind of value is needed
  - No need to check if any kind of value is okay

Dealing with variables

- Interpreters so far have been for languages without variables
  - No let-expressions, functions-with-arguments, etc.
  - Language in homework has all these things

- This segment describes in English what to do
  - Up to you to translate this to code

- Fortunately, what you have to implement is what you have been using conceptually throughout course

Dealing with variables

- An environment is a mapping from variables (Racket strings) to values (as defined by the language)
  - Only ever put pairs of strings and values in the environment

- Evaluation takes place in an environment
  - Environment passed as argument to interpreter helper function
  - A variable expression looks up the variable in the environment
  - Most subexpressions use same environment as outer expression
  - A let-expression evaluates its body in a larger environment

The Set-up

So now a recursive helper function has all the interesting stuff:

```
(define (eval-under-env e env)
   (cond … ; case for each kind of
    ))     ; expression
```

- Recursive calls must "pass down" correct environment

Then **`eval-exp`** just calls **`eval-under-env`** with same expression and the *empty environment*

On homework, environments themselves are just Racket lists containing Racket pairs of a string (the MUPL variable name, e.g., **`"x"`**) and a MUPL value (e.g., **`(int 17)`**)

A grading detail

- Stylistically **`eval-under-env`** would be a helper function one could define locally inside **`eval-exp`**

- But homework has you not do this
  - Helps with grading tests to call **`eval-under-env`** directly, so we need it at top-level

The best part

- The most interesting and mind-bending part of the homework is that the language being implemented has first-class closures
  – With lexical scope of course

- Fortunately, what you have to implement is what you have previously learned about closures…

Higher-order functions

The "magic": How do we use the "right environment" 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

```
(struct closure (env fun) #:transparent)
```

Evaluate a function expression:

- A function is *not* a value; a closure *is* a value
  - Evaluating a function returns a closure
- Create a closure out of (a) the function and (b) the current environment when the function was evaluated

Evaluate a function call:

- …

Function calls

```
(call e1 e2)
```

- Use current environment to evaluate **`e1`** to a closure
  - Error if result is a value that is not a closure
- Use current environment to evaluate **`e2`** to a value
- 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, map the function's name to the whole closure

This is the same semantics you learned already "coded up"

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

Optional: 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
  - Still, end up keeping around bindings that are not needed
- Alternative used in practice: 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

Optional: 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}
```

Optional: Computing free variables

- So does the interpreter have to analyze the code body every time it creates a closure?

- No: Before evaluation begins, compute free variables of every function in program and store this information with the function

- Compared to naïve store-entire-environment approach, building a closure now takes more time but less space
  – And time proportional to number of free variables
  – And various optimizations are possible

- [Also use a much better data structure for looking up variables than a list]

Optional: compiling higher-order functions

- If we are compiling to a language without closures (like assembly), cannot rely on there being a "current environment"
- So compile functions by having the translation produce "regular" functions 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

Recall…

Our approach to language implementation:

- Implementing language *B* in language *A*
- Skipping parsing by writing language *B* programs directly in terms of language *A* constructors
- An interpreter written in *A* recursively evaluates

Now: The idea of using *A* functions like *B* macros

- “Feels like” extending the syntax of B
- Use of a “macro” expands into language syntax before the program is run, i.e., before calling the main interpreter function

Put it together

With our set-up, we can use language *A* (i.e., Racket) *functions* that produce language *B* abstract syntax as language *B* "macros"

- Language *B* programs can use the "macros" as though they are part of language *B*
- No change to the interpreter or struct definitions
- Just a programming idiom enabled by our set-up
  - Helps teach what macros are
- See code for example "macro" definitions and "macro" uses
  - "macro expansion" happens before calling **`eval-exp`**