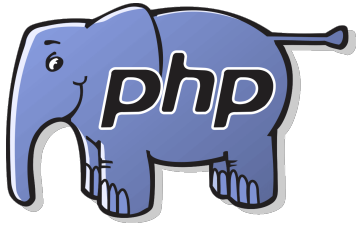
CS 360
Programming Languages
Interpreters



Swift

JavaScript

Dart

Implementing PLs

Most of the course is learning fundamental concepts for *using* and *understanding* PLs.

- Syntax vs. semantics vs. idioms.
- Powerful constructs like closures, first-class objects, iterators (streams), multithreading, …

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 small PLs.
  - Example: "connect-the-dots programming language" from 141.

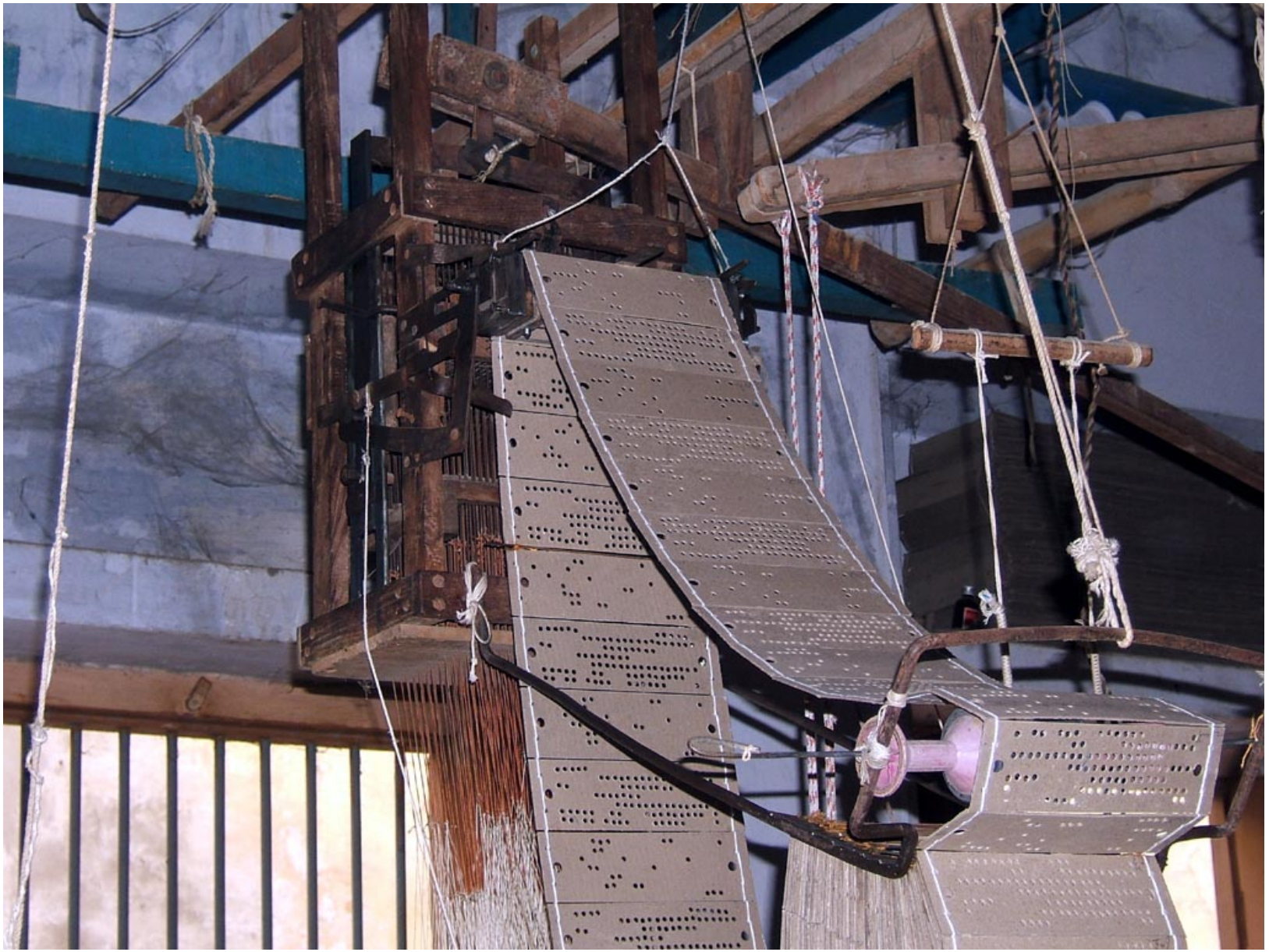
Ways to implement a language

Two fundamental ways to implement a programming language *X.*

- Write an **interpreter** in another language *Y.*
  - Better names: ***evaluator, executor.***
  - Immediately executes the input program as it's read.

- Write a **compiler** in another language *Y* that compiles to a third language *Z.*
  - Better name: ***translator***
  - Takes a program in *X* and produce an equivalent program in *Z*.

First programming language?



First programming language?

Interpreters vs compilers

- Interpreters
  - Takes one "statement" of code at a time and executes it in the language of the interpreter.
  - Like having a human interpreter with you in a foreign country.
- Compilers
  - Translate code in language X into code in language Z and save it for later. (Typically to a file on disk.)
  - Like having a person translate a document into a foreign language for you.

Reality is more complicated

Evaluation (interpreter) and translation (compiler) are your options.

- But in modern practice we can have multiple layers of both.

A example with Java:

- Java was designed to be platform independent.
  - Any program written in Java should be able to run on any computer.
- Achieved with the "Java Virtual Machine."
  - An idealized computer for which people have written interpreters that run on "real" computers.

Example: Java

- Java programs are compiled to an "intermediate representation" called ***bytecode***.
  - Think of bytecode as an instruction set for the JVM.
- Bytecode is then interpreted by a (software) interpreter in machine-code.
- Complication: Bytecode interpreter can compile frequently-used functions to machine code if it desires (*just-in-time compilation*).
- CPU itself is an interpreter for machine code.

Sermon

*Interpreter vs compiler vs 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 hear these phrases all the time:

- “C is faster because it’s compiled and LISP is interpreted.”
- I can write a C interpreter or a LISP compiler, regardless of what most implementations happen to do.

One complication

In a traditional implementation via compiler, you do not need the language implementation (the compiler) to run the program.

- Only to compile it.
- To let other people run your program, you give them the compiled binary code.

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

- Allows a program, while it is running, to create a string (or in Racket, a list) with arbitrary code and execute it.
- Since we don't know ahead of time what the code will be, we need a language implementation at run-time to support **`eval`**
- Usually you see this in languages that are traditionally interpreted, because then implementing **`eval`** is easy: the interpreter is already available.

`eval` / `apply`

- These functions are built into Racket, and are a traditional part of LISP/Scheme implementations.

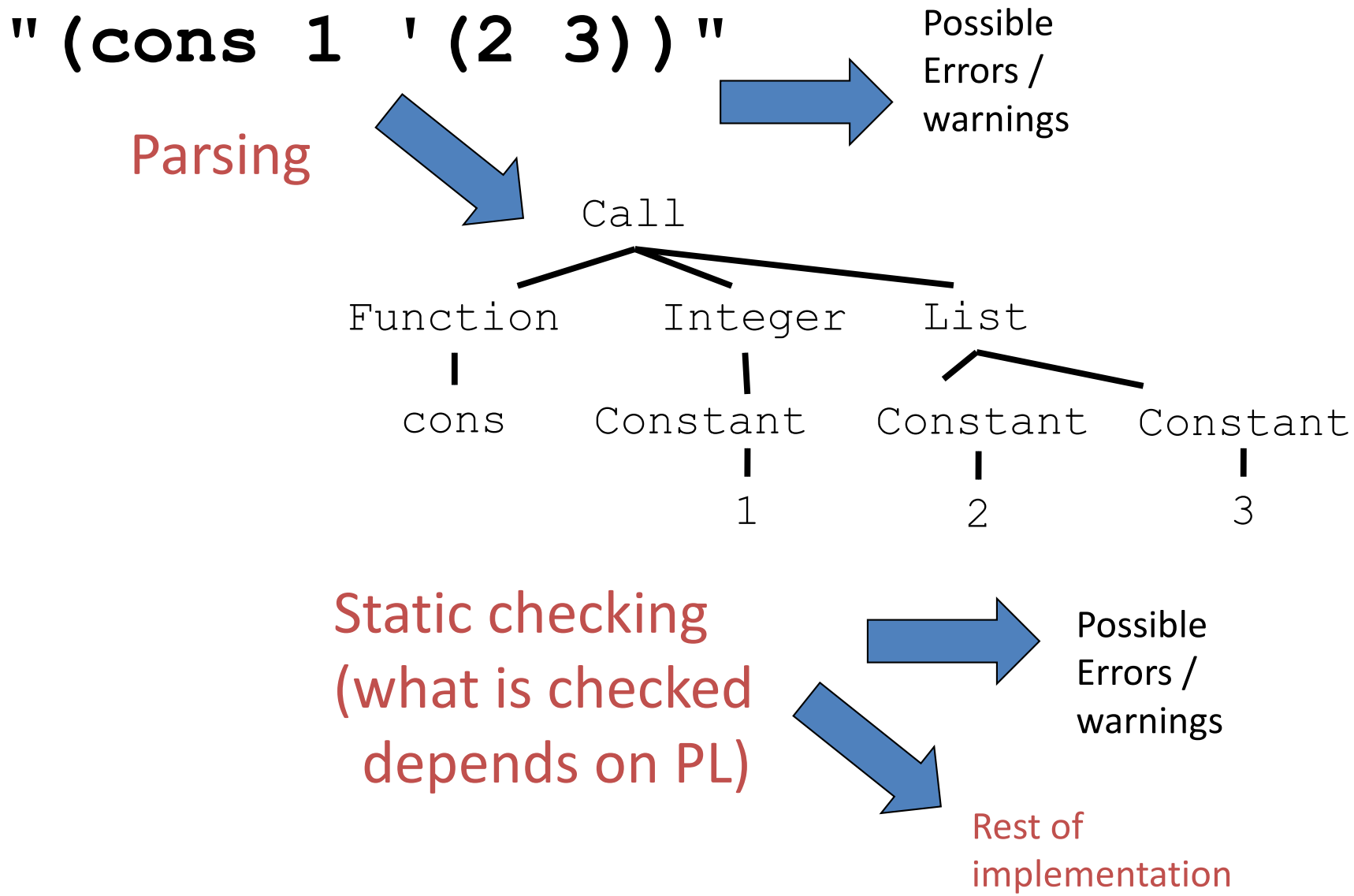
- `eval`: takes a list argument and treats it like program code, executing it and returning the result.

- `apply`: takes a function and a list, and calls the function on the arguments in the list.

quote

- Also built-in, but we don't notice it because it's called automatically whenever we use a single quote.
- **`(quote …)`** or **`'(…)`** is a special form that makes "everything underneath" into plain symbols and lists, instead of interpreting them as variables or function calls.
- **`eval`** and **`quote`** are inverses:
  - **`quote`** stops evaluation of something.
  - **`eval`** forces evaluation of something.

Back to implementing a language



Skipping those steps

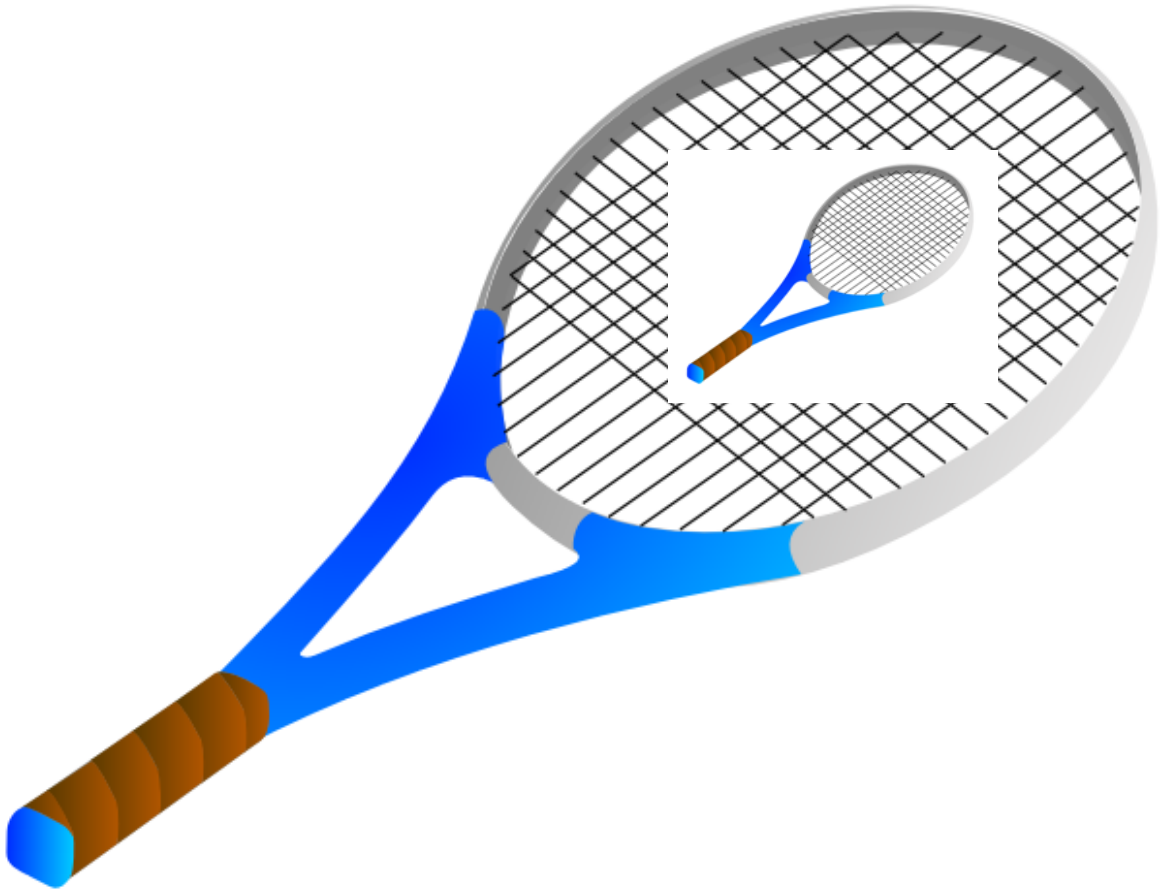
LISP/Scheme-like languages have an interesting property:

- The format in which we write a the program code (a list) is identical to the main data structure the language itself uses to represent data (a list).
- Because these lists are always fully parenthesized, we get parsing essentially for free!
- Not so in Python, C++, Java, etc.

We can also, for simplicity, skip static checking.

- Assume subexpressions have correct types.
  - We will not worry about **`(add #f "hi").`**
- Interpreter will just crash.

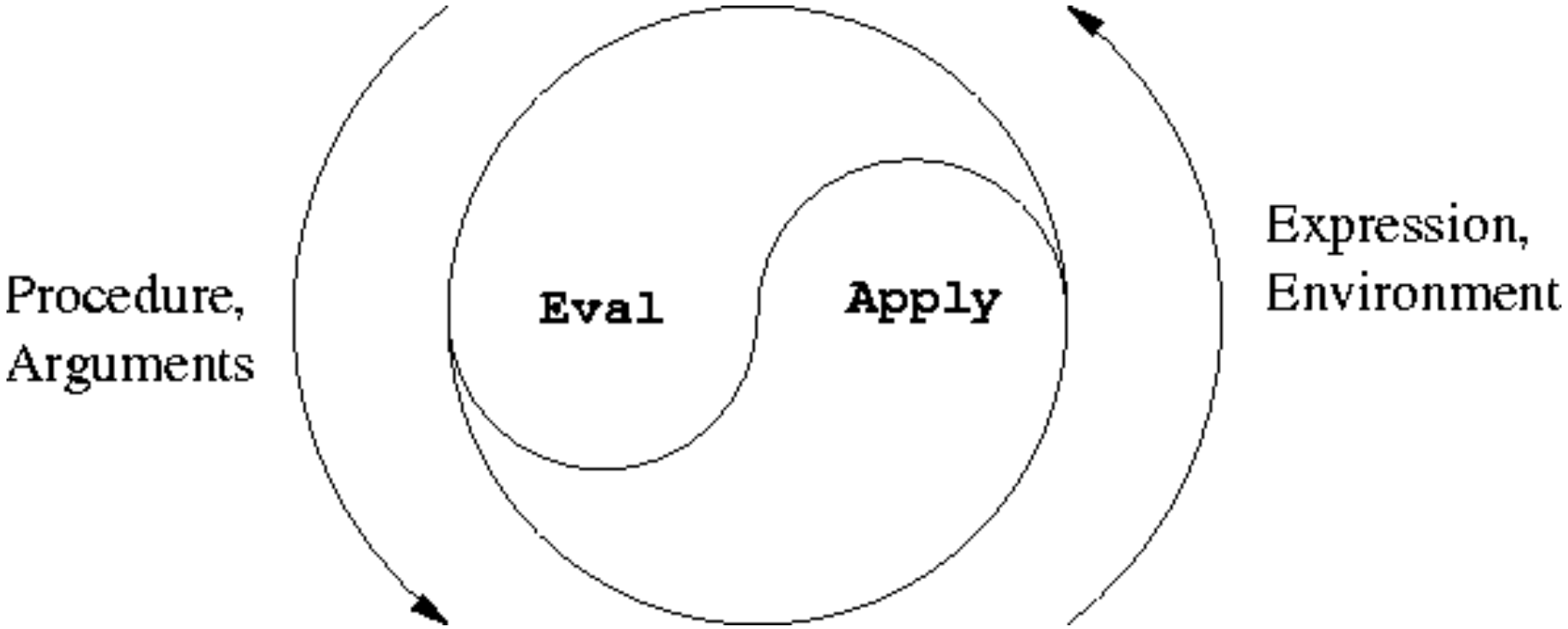
Write (Mini-)Racket in Racket



Mini-Racket

- Only one data type: numbers.
  - No booleans, lists, etc.
- Mini-Racket will use *names* for all functions rather than symbols.
  - `add`, `sub`, `mul`, etc.
- Simplified mechanisms for conditionals, function definitions, and function calls.

Heart of the interpreter



- **`mini-eval`**: Evaluates an expression and returns a value (will call **`mini-apply`** to handle functions)
- **`mini-apply`**: Takes a function and argument values and evaluate its body (calls **`mini-eval`**).

```
(define (mini-eval expr env)
```
    is this a _____ expression?
    if so, then call our special handler
        for that type of expression.
```
)
```
What kind of expressions will we have?

- numbers
- variables (symbols)
- math function calls
- others as we need them

- How do we evaluate a (literal) number?
  - That is, when the interpreter sees a number, what value should it return?

- Just return it!

- Psuedocode for first line of **`mini-eval`**:
  - If this expression is a number, then return it.

- How do we handle `(add 3 4)`?

- Need two functions:
  - One to detect that an expression is an addition expression.
  - One to evaluate the expression.

`(add 3 4)`

- Is this an expression an addition expression?

```
(equal? 'add (car expr))
```

- Evaluate an addition expression:

```
(+ (cadr expr) (caddr expr))
```

You try (lab, part 1)

- Add subtraction (e.g., sub)
- Add multiplication (mul)
- Add division (div)
- Add exponentiation (exp)
- Optional:
  - Add other primitives, like sqrt, abs, etc.
  - Make sub work with single arguments (returns the negation).

(add 3 (add 4 5))

- Why doesn't this work?

(add 3 (add 4 5))

- How *should* our language evaluate this sort of expression?
- We could forbid this kind of expression.
  - Insist things to be added always be numbers.
- Or, we could allow the things to be added to be expressions themselves.
  - Need a recursive call to `mini-eval` inside `eval-add`.

You try (lab, part 2)

- Fix your math commands so that they will recursively evaluate their arguments.

Adding Variables

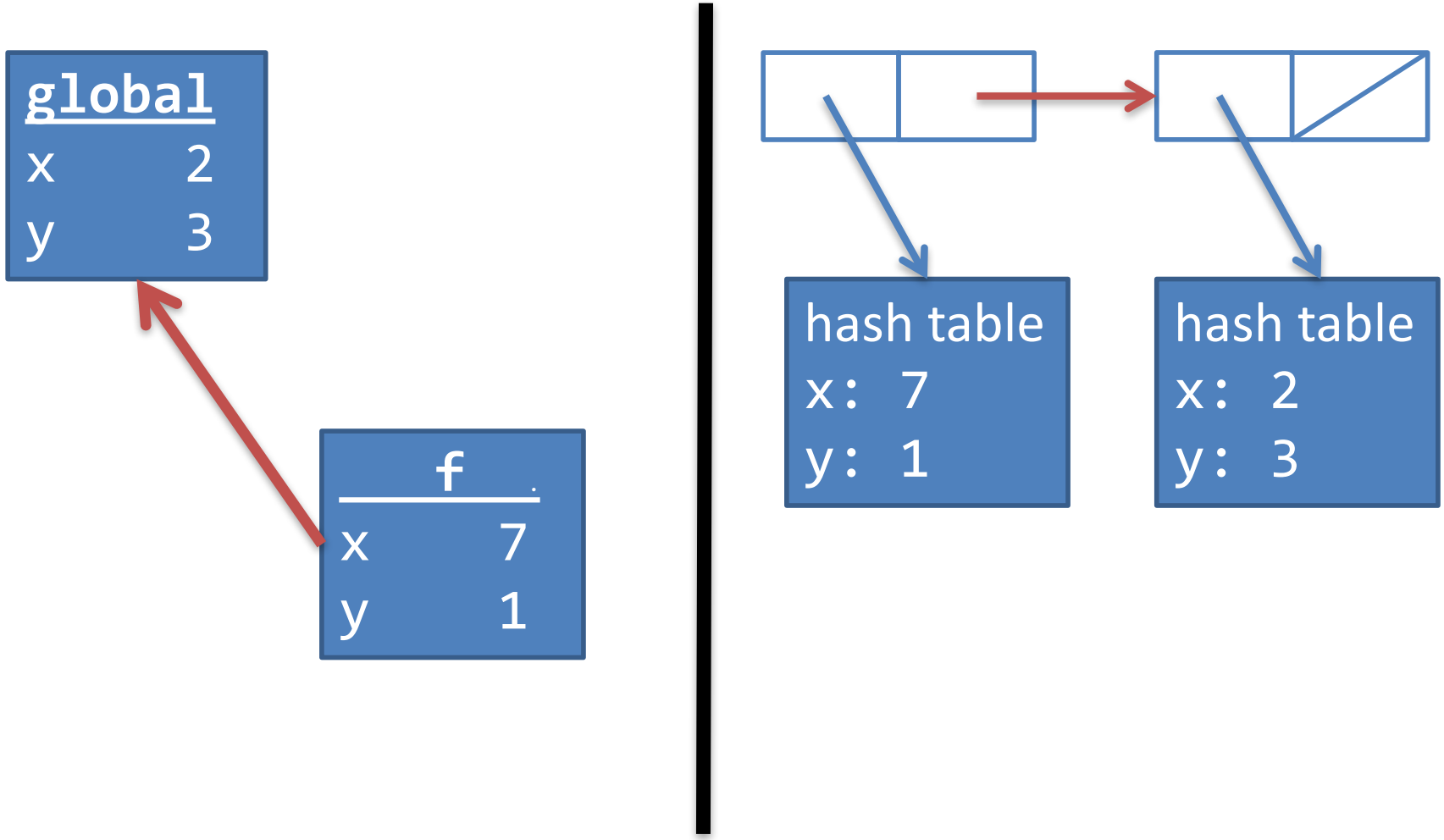
Implementing variables

- Represent a *frame* as a hash table.
- Racket's hash tables:

```
(define ht (make-hash))
(hash-set! ht key value)
(hash-has-key? ht key)
(hash-ref ht key)
```

Implementing variables

- Represent an environment as a list of frames.



Implementing variables

- Two things we can do with a variable in our programming language:
  - Define a variable
  - Get the value of a variable

- Pretty much the same two things we can do with a variable in regular Racket (except for `set!`)

Getting the value of a variable

- New type of expression: a ***symbol***.
- Whenever `mini-eval` sees a symbol, it should look up the value of the variable corresponding to that symbol.

Getting the value of a variable

Follow the rules of lexical scoping:

```
(define (lookup-variable-value var env)
  ; Pseudocode:
  ; If our current frame has a value for the
  ;   variable, then get its value and return it.
  ; Otherwise, if our current frame has a frame
  ;   pointer, then follow it and try the lookup
  ;   there.
  ; Otherwise, (if we are out of frames), throw an
  ;   error.
```

Getting the value of a variable

Follow the rules of lexical scoping:

```
(define (lookup-variable-value var env)
  (cond ((hash-has-key? (car env) var)
         (hash-ref (car env) var))
        ((not (null? env))
         (lookup-variable-value var (cdr env)))
        ((null? env)
         (error "unbound variable" var))))
```

Defining a variable (lab, part 3)

- `mini-eval` needs to handle expressions that look like `(define variable expr)`
  - `expr` can contain sub-expressions.
- Add two functions to the evaluator:
  - `definition?`: tests if an expression fits the form of a definition.
  - `eval-definition`: extract the variable, recursively evaluate the expression that holds the value, and add a binding to the current frame.

Implementing conditionals

- We will have one conditional in Mini-Racket: `ifzero`
- Syntax: `(ifzero expr1 expr2 expr3)`
- Semantics:
  - Evaluate `expr1`, test if it's equal to zero.
  - If yes, evaluate and return `expr2`.
  - If no, evaluate and return `expr3`.

Implementing conditionals (lab, part 4)

- Add functions `ifzero?` and `eval-ifzero`.

- If time, try challenges on the back of the lab.

- Designing our interpreter around **`mini-eval`**.
- **`(define (mini-eval expr env) …`**
- Determines what type of expression **`expr`** is
- Dispatch the evaluation of the expression to the appropriate function
  - **`number?`** -> evaluate in place
  - **`symbol?`** -> **`lookup-variable-value`**
  - **`add?/subtract?/multiply?`** -> appropriate math func
  - **`definition?`** -> **`eval-define`**
  - **`ifzero?`** -> **`eval-ifzero`**

Today

- Two more pieces to add:
  - Closures (`lambda?` / `eval-lambda`)
  - Function calls (`call?` / `eval-call`)

Mini-Racket will have some simplifications from normal Racket.

- All functions will have exactly one argument.
- Removes the need for lambda expressions to have parentheses.

- Normal Racket: `(lambda (x) (+ x 1))`

- Mini-Racket: `(lambda x (add x 1))`

Mini-Racket will have some simplifications from normal Racket.

- Normal Racket has two versions of define, one for variables and one for functions:
```
(define x 3)
(define (add1 x) (+ x 1)).
```

- The 2nd version is just a shortcut for
```
(define add1 (lambda (x) (+ x 1))
```

Mini-Racket will have some simplifications from normal Racket.

- Mini-Racket will not have the "shortcut" define; we must use an explicit lambda.

- Normal Racket:

```
(define (add1 x) (+ x 1))
(define add1 (lambda (x) (+ x 1)))
```

- Mini-Racket:

```
(define add1 (lambda x (add x 1))
```

Mini-Racket will have some simplifications from normal Racket.

- Normal Racket recognizes a function call as any list that starts with a function name (or anything that evaluates to a closure).

- Mini-Racket will recognize function calls as lists that starts with the symbol `call`.
  - This makes the Mini-Racket syntax more complicated, but simplifies the interpreter code.

Mini-Racket will have some simplifications from normal Racket.

- Normal Racket: `(add1 5)`
- Mini-Racket: `(call add1 5)`

Implementing closures

- In Mini-Racket, all (user-defined) functions and closures will have a single argument.
- Syntax: **`(lambda var expr)`**
  - Note the different syntax from "real" Racket.
- Semantics: Creates a new closure (anonymous function) of the single argument `var`, whose body is `expr`.

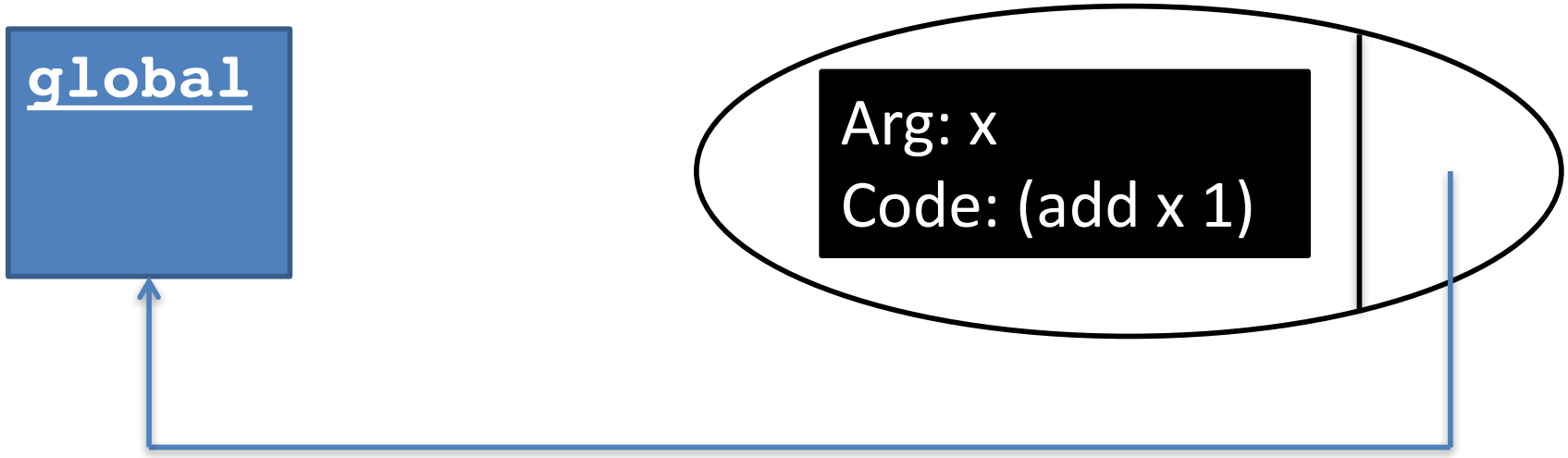
(lambda var expr)

- Need a new data structure to represent a closure.
- Why can't we just represent them as the list (lambda var closure) above?
  - Hint: What is missing? Think of environment diagrams.

`(lambda var expr)`

- We will represent closures internally in Mini-Racket using a list of four components:
  - The symbol `'closure`
  - The argument variable (`var`)
  - The body (`expr`)
  - The environment in which this closure was defined.

Evaluate at top level: `(lambda x (add x 1))`



Our evaluator should return

```
'(closure x (add x 1) (#hash(…)))
```

Write `lambda?` and `eval-lambda`

- `lambda?` is easy.
- `eval-lambda` should:
  - Extract the variable name and the body, but ***don't evaluate the body*** (not until we call the function)
  - Return a list of the symbol `'closure`, the variable, the body, and the current environment.

```
(define (eval-lambda expr env)
  (list 'closure
        (cadr expr)        ; the variable
        (caddr expr)       ; the body
        env))
```

Function calls

- First we need the other half of the `eval/apply` paradigm.

- Remember from environment diagrams:

- To evaluate a function call, make a new frame with the function's arguments bound to their values, then run the body of the function using the new environment for variable lookups.

Mini-Apply

```
(define (mini-apply closure argval)
```

Pseudocode:

- Make a new frame mapping the closure's argument (i.e., the variable name) to `argval`.
- Make a new environment consisting of the new frame pointing to the closure's environment.
- Evaluate the closure's body in the new environment (and return the result).

Mini-Apply

```
(define (mini-apply closure argval)
  (let ((new-frame (make-hash)))
    (hash-set! new-frame <arg-name> argval)
    (let ((new-env
           <construct new environment>))
      <eval body of closure in new-env>
    )))
```

Mini-Apply

```
(define (mini-apply closure argval)
  (let ((new-frame (make-hash)))
    (hash-set! new-frame (cadr closure) argval)
    (let ((new-env
           (cons new-frame (cadddr closure))))
      (mini-eval (caddr closure) new-env))))
```

Function calls

- Syntax: `(call expr1 expr2)`
- Semantics:
  - Evaluate `expr1` (must evaluate to a closure)
  - Evaluate `expr2` to a value (the argument value)
  - Apply closure to value (and return result)

You try it

- Write `call?` (easy)
- Write `eval-call` (a little harder)
  - Evaluate `expr1` (must evaluate to a closure)
  - Evaluate `expr2` to a value (the argument value)
  - Apply closure to value (and return result)
- When done, you now have a Turing-complete language!

```
; expr looks like
; (call expr1 expr2)
(define (eval-call expr env)
  (mini-apply
    <eval the function>
    <eval the argument>)
```

```
; expr looks like
; (call expr1 expr2)
(define (eval-call expr env)
  (mini-apply
    (mini-eval (cadr expr) env)
    (mini-eval (caddr expr) env)))
```

Magic in 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 to keep the environment it will need to use later

Is this expensive?

- *Time* to build a closure is tiny: make a list with four items.

- *Space* to store closures *might* be large if environment is large.

Interpreter steps

- Parser
  - Takes code and produces an intermediate representation (IR), e.g., abstract syntax tree.
- Static checking
  - Typically includes syntactical analysis and type checking.
- Interpreter directly runs code in the IR.

Compiler steps

- Parser
- Static checking
- Code optimizer
  - Take AST and alter it to make the code execute faster.
- Code generator
  - Produce code in output language (and save it, as opposed to running it).

Code optimization

```
// Test if n is prime
boolean isPrime(int n) {
 for (int x = 2; x < sqrt(n); x++) {
   if (n % x == 0) return false;
 }
 return true;
}
```

Code optimization

```
// Test if n is prime
boolean isPrime(int n) {
 double temp = sqrt(n);
 for (int x = 2; x < temp; x++) {
   if (n % x == 0) return false;
 }
 return true;
}
```

Common code optimizations

- Replacing constant expressions with their evaluations.
- Ex: Game that displays an 8 by 8 grid. Each cell will be 50 pixels by 50 pixels on the screen.
  - `int CELL_WIDTH = 50;`
  - `int BOARD_WIDTH = 8 * CELL_WIDTH;`

Common code optimizations

- Replacing constant expressions with their evaluations.
- Ex: Game that displays an 8 by 8 grid. Each cell will be 50 pixels by 50 pixels on the screen.
  - `int CELL_WIDTH = 50;`
  - `int BOARD_WIDTH = 400;`
- References to these variables would probably replaced with constants as well.

Common code optimizations

- Reordering code to improve cache performance.

```
for (int x = 0; x < HUGE_NUMBER; x++) {
  huge_array[x] = f(x)
  another_huge_array[x] = g(x)
}
```

Common code optimizations

- Reordering code to improve cache performance.

```
for (int x = 0; x < HUGE_NUMBER; x++) {
  huge_array[x] = f(x)
}
for (int x = 0; x < HUGE_NUMBER; x++) {
  another_huge_array[x] = g(x)
}
```

Common code optimizations

- Loops: unrolling, combining/distribution, change nesting
- Finding common subexpressions and replacing with a reference to a temporary variable.
  - `(a + b)/4 + (a + b)/3`
- Recursion: replace with iteration if possible.
  - That's what tail-recursion optimization does!

- Why don't interpreters do these optimizations?

- Usually, there's not enough time.
  - We need the code to run ***NOW***!
  - Sometimes, can optimize a little (e.g., tail-recursion).

Code generation

- Last phase of compilation.
- Choose what operations to use in the output language and what order to put them in *(instruction selection, instruction scheduling).*
- If output in a low-level language:
  - Pick what variables are stored in which registers (register allocation).
  - Include debugging code? (store "true" function/variable names and line numbers?)

Java

- Uses both interpretation and compilation!
- Step 1: Compile Java source to bytecode.
  - Bytecode is "machine code" for a made-up computer, the Java Virtual Machine (JVM).
- Step 2: An interpreter interprets the bytecode.

- Historically, the bytecode interpreter made Java code execute very slowly (1990s).

Just-in-time compilation

- Bytecode interpreters historically would translate each bytecode command into machine code and immediately execute it.
- A just-in-time compiler has two optimizations:
  - Caches bytecode -> machine code translations so it can re-use them later.
  - Dynamically compiles sections of bytecode into machine code "when it thinks it should."

JIT: a classic trade-off

- Startup is slightly slower
  - Need time to do some initial dynamic compilation.
- Once the program starts, it runs faster than a regular interpreter.
  - Because some sections are now compiled.