Set!

- Unlike ML, Racket really has assignment statements
  - But used *only-when-really-appropriate!*

```
(set! x e)
```

- For the **`x`** in the current environment, subsequent lookups of **`x`** get the result of evaluating expression **`e`**
  - Any code using this **`x`** will be affected
  - Like **`x = e`** in Java, C, Python, etc.

- Once you have side-effects, sequences are useful:

```
(begin e1 e2 … en)
```

Example

Example uses **`set!`** at top-level; mutating local variables is similar

```
(define b 3)
(define f (lambda (x) (* 1 (+ x b))))
(define c (+ b 4)) ; 7
(set! b 5)
(define z (f 4))   ; 9
(define w c)       ; 7
```

Not much new here:

- Environment for closure determined when function is defined, but body is evaluated when function is called
- Once an expression produces a value, it is irrelevant how the value was produced

Top-level

- Mutating top-level definitions is particularly problematic
  - What if any code could do **`set!`** on anything?
  - How could we defend against this?

- A general principle: If something you need not to change might change, make a local copy of it. Example:

```
(define b 3)
(define f
  (let ([b b])
    (lambda (x) (* 1 (+ x b)))))
```

Could use a different name for local copy but do not need to

But wait…

- Simple elegant language design:
  - Primitives like **+** and ***** are just predefined variables bound to functions
  - But maybe that means they are mutable
  - Example continued:

```
(define f
  (let ([b b]
        [+ +]
        [* *])
    (lambda (x) (* 1 (+ x b)))))
```

  - Even that won't work if **f** uses other functions that use things that might get mutated – all functions would need to copy everything mutable they used

No such madness

In Racket, *you do not have to program like this*

- Each file is a module
- *If* a module does not use **`set!`** on a top-level variable, then Racket makes it constant and forbids **`set!`** outside the module
- Primitives like **`+`**, **`*`**, and **`cons`** are in a module that does not mutate them

Showed you this for the *concept* of copying to defend against mutation

- Easier defense: Do not allow mutation
- Mutable top-level bindings a highly dubious idea

The truth about **`cons`**

`cons` just makes a pair

- Often called a *cons cell*
- By convention and standard library, lists are nested pairs that eventually end with **`null`**

```
(define pr (cons 1 (cons #t "hi"))) ; '(1 #t . "hi")
(define lst (cons 1 (cons #t (cons "hi" null))))
(define hi (cdr (cdr pr)))
(define hi-again (car (cdr (cdr lst))))
(define hi-another (caddr lst))
(define no (list? pr))
(define yes (pair? pr))
(define of-course (and (list? lst) (pair? lst)))
```

Passing an *improper list* to functions like **`length`** is a run-time error

The truth about `cons`

So why allow improper lists?

- Pairs are useful
- Without static types, why distinguish `(e1,e2)` and `e1::e2`

Style:

- Use proper lists for collections of unknown size
- But feel free to use `cons` to build a pair
  - Though structs (like records) may be better

Built-in primitives:

- `list?` returns true for proper lists, including the empty list
- `pair?` returns true for things made by cons
  - All improper and proper lists except the empty list

cons cells are immutable

What if you wanted to mutate the *contents* of a cons cell?

- In Racket you cannot (major change from Scheme)
- This is good
  - List-aliasing irrelevant
  - Implementation can make **`list?`** fast since listness is determined when cons cell is created

Set! does not change list contents

This does *not* mutate the contents of a cons cell:

```
(define x (cons 14 null))
(define y x)
(set! x (cons 42 null))
(define fourteen (car y))
```

– Like Java's **`x = new Cons(42,null)`**, *not* **`x.car = 42`**

mcons cells are mutable

Since mutable pairs are sometimes useful (will use them soon), Racket provides them too:

- **`mcons`**
- **`mcar`**
- **`mcdr`**
- **`mpair?`**
- **`set-mcar!`**
- **`set-mcdr!`**

Run-time error to use **`mcar`** on a cons cell or **`car`** on an mcons cell

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 “datatypes” like exp, create one struct for each “kind of exp”

- structs are like ML constructors!
- But provide constructor, tester, and extractor functions
  - Instead of patterns
  - E.g., **`const`**, **`const?`**, **`const-int`**
- Dynamic typing means “these are the kinds of exp” is “in comments” rather than a *type system*
- Dynamic typing means “types” of fields are also “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 rather than hiding them, which is convenient for debugging homework

- **`#:mutable`** is another optional attribute on struct definitions
  - Provides more functions, for example:

```
(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
    - As expected, we will avoid this attribute
  - mcons is just a predefined mutable struct

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

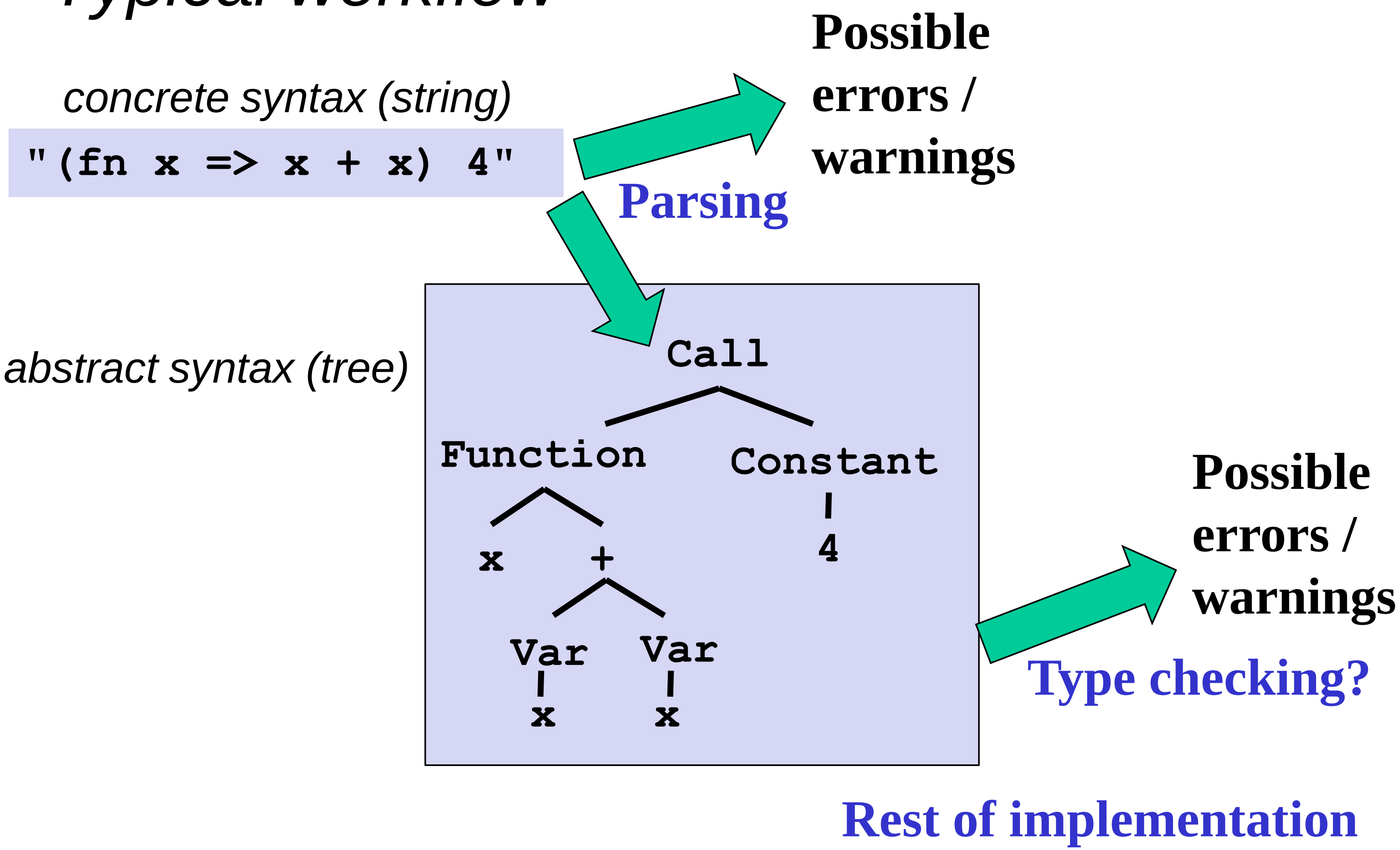
Struct is special

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
- Neither functions nor macros can create a new kind of data
  - Result of constructor function returns **`#f`** for *every* other tester function: **`number?`**, **`pair?`**, other structs' tester functions, etc.

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 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

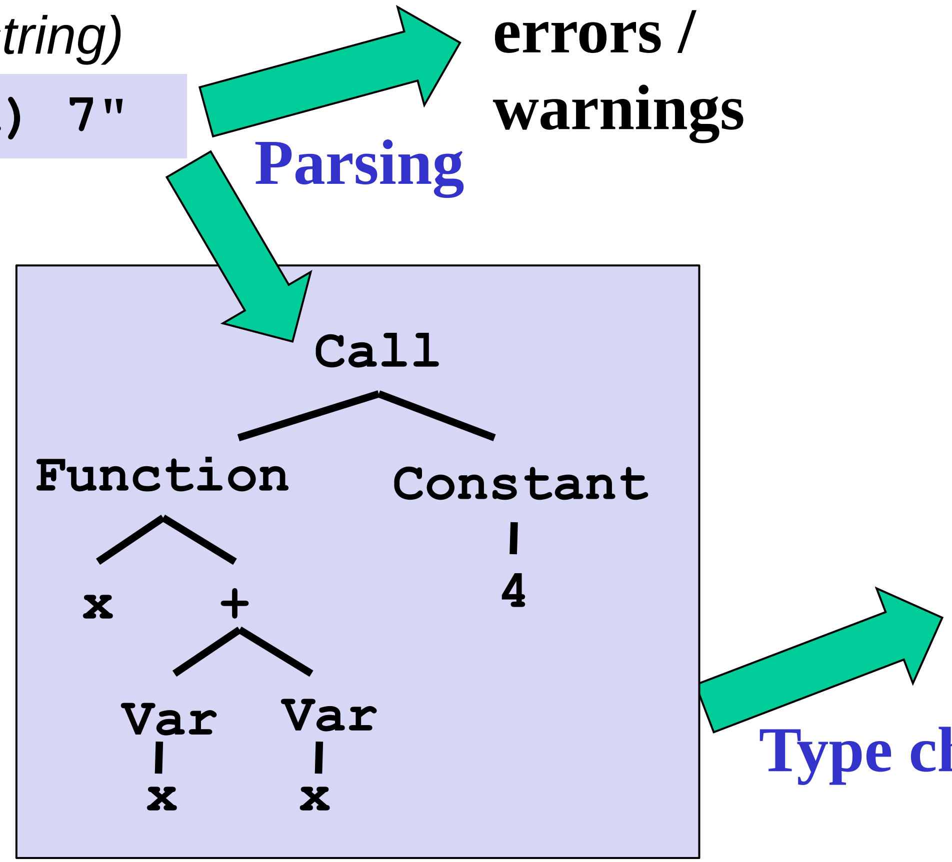
concrete syntax (string)

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

Possible errors / warnings

Parsing

abstract syntax (tree)



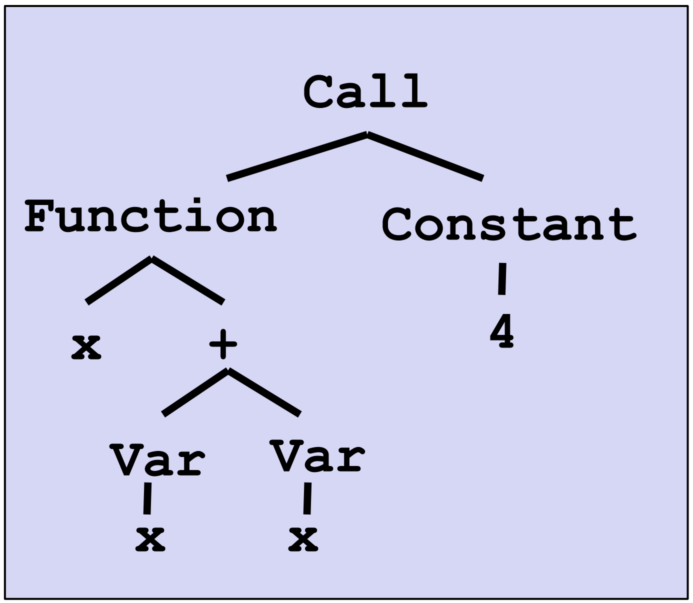
Possible errors / warnings

Type checking?

Interpreter or translater

Skipping parsing

- If implementing PL *B* in PL *A*, we can skip parsing
  - Have *B* programmers write ASTs directly in PL *A*
  - Not so bad with ML constructors or 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