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

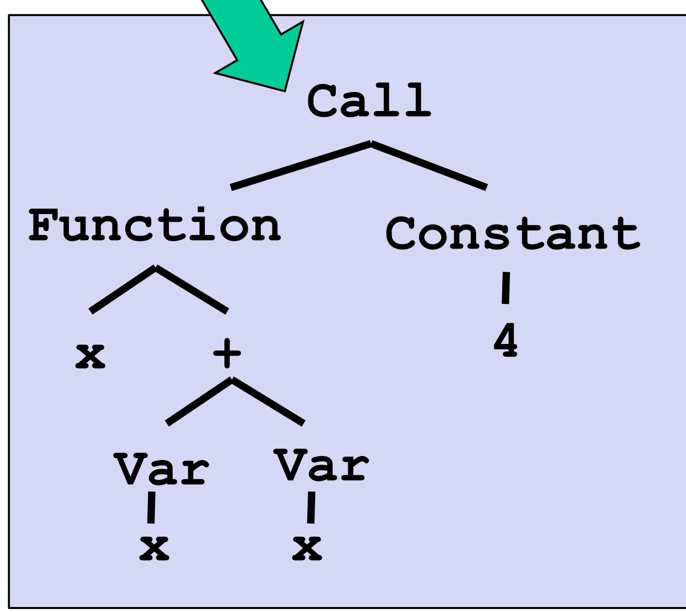
concrete syntax (string)

`"(fn x => x + x) 4"`

Parsing

Possible errors / warnings

abstract syntax (tree)



Type checking?

Possible errors / warnings

Rest of implementation

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

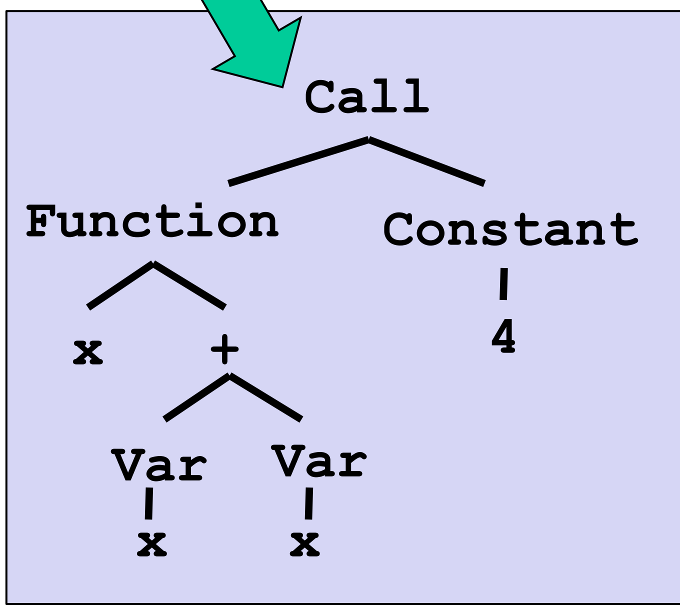
concrete syntax (string)

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

Possible errors / warnings

Parsing

abstract syntax (tree)



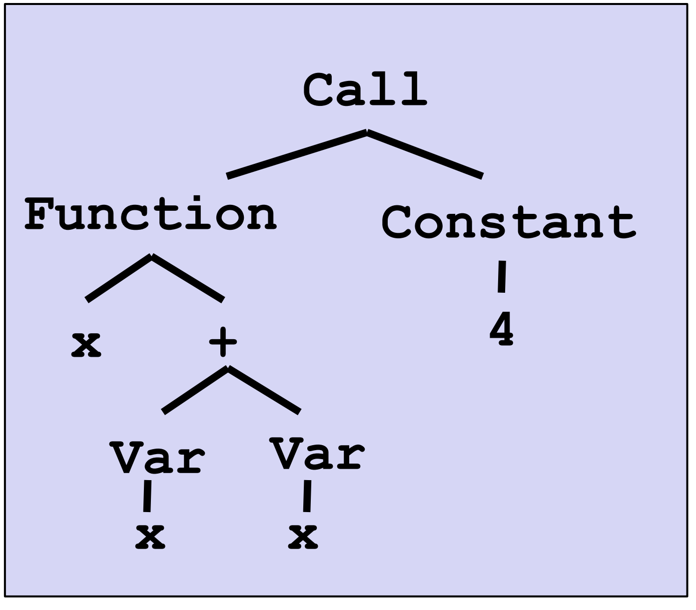
Possible errors / warnings

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

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"

```
(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*, 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

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

What we know about macros:

- Extend the syntax of a language
- 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`**