Typical workflow

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

**Parsing**

- Concrete syntax (string)
- Abstract syntax (tree)

**Possible errors / warnings**

```
Call
Function
Constant 1
+ 1
Var x
Var x
```

```
Type checking?
```

```
Rest of implementation
```

**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)
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))

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 (el e2) #:transparent)
(struct multiply (el 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

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 we have been stressing since the very, very beginning of the course

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 do not do this on your homework
  - We have grading tests that 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 we have been stressing since we first 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

\texttt{(call e1 e2)}

- Use current environment to evaluate \texttt{e1} to a closure
  - Error if result is a value that is not a closure
- Use current environment to evaluate \texttt{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 we learned a few weeks ago "coded up"

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

Is that expensive?

- \textit{Time} to build a closure is tiny: a struct with two fields
- \textit{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 (cf. lecture 3)
  - 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

Free variables examples

\begin{verbatim}
(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}
\end{verbatim}

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 \textit{B} in language \textit{A}
- Skipping parsing by writing language \textit{B} programs directly in terms of language \textit{A} constructors
- An interpreter written in \textit{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`

**Hygiene issues**

- Earlier we had material on hygiene issues with macros
- (Among other things), problems with shadowing variables when using local variables to avoid evaluating expressions more than once
- The “macro” approach described here does not deal well with this