Typical workflow

concrete syntax (string)
"(fn x => x + x) 4"

abstract syntax (tree)

Call
Function  Constant
x +     4
Var  Var
x     x

Parsing

Possible errors / warnings

Type checking?

Possible errors / warnings

Rest of implementation

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**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
Interpretation 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
```

**Abstract syntax (tree):**

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

**Possible errors / warnings**

**Parser**

**Possible errors / warnings**

**Type checking?**

**Interpreter or translator**
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 $A = \text{Racket}$
- Let the language-implemented $B = \text{"Arithmetic Language"}$
- Arithmetic programs written with calls to Racket constructors
- The interpreter is $\text{eval-exp}$

\begin{verbatim}
(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) ...]...)
\end{verbatim}

$\text{Racket}$ data structure is $\text{Arithmetic Language}$ program, which $\text{eval-exp}$ 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*, 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:

```plaintext
(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
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:

```scheme
(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)`)

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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

(\texttt{struct closure (env fun) #:transparent})

Evaluate a function expression:

– A function is \textit{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

\[(\text{call } e_1 \ e_2)\]

- Use current environment to evaluate \(e_1\) to a closure
  - Error if result is a value that is not a closure
- Use current environment to evaluate \(e_2\) 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 \textit{only} ever evaluated using the environment part (extended), \textit{not} the environment at the call-site
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 (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

\[
(\text{lambda} (\ ) (\ + \ x \ y \ z)) \ ; \ \{x, \ y, \ z\}
\]

\[
(\text{lambda} (x) (\ + \ x \ y \ z)) \ ; \ \{y, \ z\}
\]

\[
(\text{lambda} (x) (\text{if} \ x \ y \ z)) \ ; \ \{y, \ z\}
\]

\[
(\text{lambda} (x) (\text{let} (\ [y \ 0]) (\ + \ x \ y \ z))) \ ; \ \{z\}
\]

\[
(\text{lambda} (x \ y \ z) (\ + \ x \ y \ z)) \ ; \ \{\}
\]

\[
(\text{lambda} (x) (\ + \ y (\text{let} (\ [y \ z]) (\ + \ y \ y)))) \ ; \ \{y, \ z\}
\]
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

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