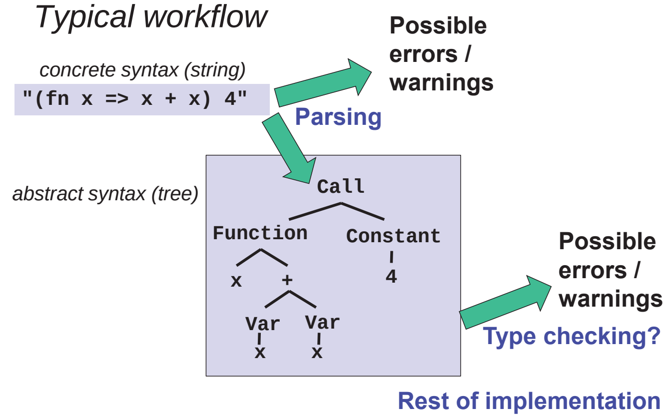
PAUL G. ALLEN SCHOOL OF COMPUTER SCIENCE & ENGINEERING

CSE341: Programming Languages

Lecture 17 Implementing Languages Including Closures

Dan Grossman
Autumn 2018

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

DrRacket uses a similar mix

Sermon

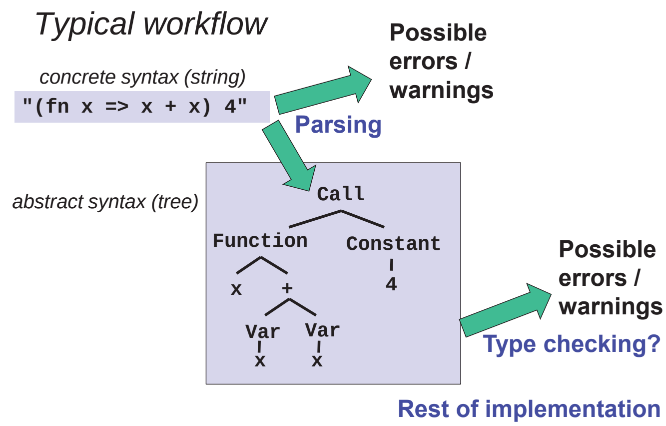
Interpreter versus compiler versus combinations is about a particular language **implementation**, not the language **definition**

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

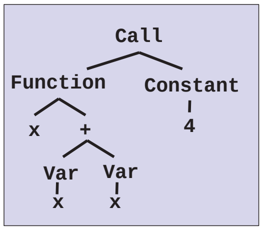
  - (Admittedly, languages with "eval" must "ship with some implementation of the language" in each program)

Typical workflow



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" – *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:

```
(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:

```
(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

`(call e1 e2)`

- Use current environment to evaluate **e1** to a closure
  - Error if result is a value that is not a closure
- Use current environment to evaluate **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), *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

```
(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}
```


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