Lecture #24: Programming Languages and Programs

- A *programming language* is a notation for describing computations or processes.
- These range from *low-level* notations, such as machine language or simple hardware description languages, where the subject matter is typically finite bit sequences and primitive operations on them that correspond directly to machine instructions or gates, ...
- ... To *high-level* notations, such as Python, in which the subject matter can be objects and operations of arbitrary complexity.
- They may be *general-purpose*, such as Python or Java, or *domain-specific*, specialized to particular purposes, such as CSS or XAML.
- Their implementations may stand alone (as for most implementations of Python or C), or be *embedded* as a component of a larger system.
- The universe of implementations of these languages is layered: Python can be implemented in C, which in turn can be implemented in assembly language, which in turn is implemented in machine language, which in turn is implemented with gates.

Metalinguistic Abstraction

- We've created abstractions of actions—functions—and of things—classes.
- *Metalinguistic abstraction* refers to the creation of languages—abstracting *description*. Programming languages are one example.
- Programming languages are *effective:* they can be implemented.
- These implementations *interpret* utterances in that language, performing the described computation or controlling the described process.
- The interpreter may be hardware (interpreting machine-language programs) or software (a program called an *interpreter*), or (increasingly common) both.
- To be implemented, though, the grammar and meaning of utterances in the programming language must be defined precisely.

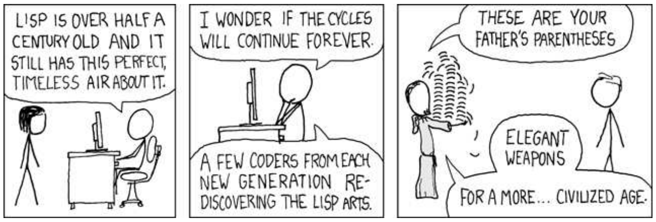
Review (from Lecture 1): What's In A Programming Language?

- Values: the things programs fiddle with;
- Primitive operations (on values);
- Combining mechanisms: glue operations together;
- Predefined names (the "library");
- Definitional mechanisms: which allow one to introduce symbolic names and (in effect) to extend the library.

The Scheme Language

Scheme is a dialect of Lisp:

- "The only programming language that is beautiful."
  —Neal Stephenson
- "The greatest single programming language ever designed"
  —Alan Kay



Scheme Background

- Invented in the 1970s by Guy Steele ("The Great Quux"), who has also participated in the development of Emacs, Java, and Common Lisp.
- Designed to simplify and clean up certain irregularities in Lisp dialects at the time.
- Used in a fast Lisp compiler (Rabbit).
- Still maintained by a standards committee (although both Brian Harvey and I agree that recent versions have accumulated an unfortunate layer of cruft).

Values

- We divide Scheme data into *atoms* and *pairs*.
- The classical atoms:
  - Numbers: integer, floating-point, complex, rational.
  - Symbols.
  - Booleans: #t, #f.
  - The empty list: ().
  - Procedures (functions).
- Some newer-fangled, mutable atoms:
  - Vectors: Python lists.
  - Strings.
  - Characters: Like Python 1-element strings.
- Pairs are two-element tuples, where the elements are (recursively) Scheme values.

Symbols

- Lisp was originally designed to manipulate *symbolic data:* e.g., formulae as opposed merely to numbers.
- Such data is typically recursively defined (e.g., "an expression consists of an operator and subexpressions").
- The "base cases" had to include numbers, but also variables or words.
- For this purpose, Lisp introduced the notion of a *symbol:*
  - Essentially a constant string.
  - Two symbols with the same "spelling" (string) are always the same object.
  - Confusingly, the reader (the program that reads in Scheme programs and data) converts symbols it reads into lower-case first.
- The main operation on symbols, therefore, is *equality.*

Pairs and Lists

- As we've seen, one can build practically any data structure out of pairs.
- The Scheme notation for the pair of values V_1 and V_2 is

  $(V_1 \;.\; V_2)$

- In Scheme, the main use of pairs is to build *lists*, defined recursively like an rlist:
  - The empty list, written "()", is a list.
  - The pair consisting of a value V and a list L is a list that starts with V, and whose tail is L.
- Lists are so prevalent that there is a standard abbreviation: You can write (V . ()) as (V), and (. . . . (V . R)) as $(\ldots V \;.\; R\,)$.
- By repeated application of these rules, the typical list: $(V_1 \;.\; (V_2 \;.\; (\ldots (V_n \;.\; ())\ldots)))$ becomes just $(V_1\; V_2\; \ldots\; V_n)$.

Programs

- Scheme expressions programs are instances of Lisp data structures ("Scheme is written in Scheme").
- At the bottom, numerals, booleans, characters, and strings are expressions that stand for themselves.
- Most lists stand for function calls:

  (OP E_1 $\cdots$ E_n)

  as a Scheme expression means "evaluate *OP* and the E_1 (recursively), and then apply the value of *OP*, which must be a function, to the values of the arguments E_i."
- A few lists, identified by their *OP*, are *special forms*, which each have different meanings.

Quotation

- Since programs are data, we have a problem: suppose you want your program to create a piece of data that happens to look like a program?
- How do we say, for example, "Set the variable x to the three-element list (+ 1 2)" without it meaning "Set the variable x to the value 3?"
- The "quote" special form does this: evaluating (quote E) yields E itself as the value, without treating it like a Scheme expression to be evaluated.

```
>>> (+ 1 2)
3
>>> (quote (+ 1 2))
(+ 1 2)
>>> '(+ 1 2)      ; Shorthand. Converted to (quote (+ 1 2))
(+ 1 2)
```

- How about

```
>>> (quote (1 2 '(3 4)))      ;?
(1 2 (quote (3 4)))
```


Symbols

- When evaluated as a program, a symbol acts like a variable name.
- Variables are bound in environments, just as in Python, although the syntax differs.
- To define a new symbol, either use it as a parameter name (later), or use the "define" special form:

```
(define pi 3.1415926)
(define pi**2 (* pi pi))
```

- This (re)defines the symbols in the current environment. The second expression is evaluated first.
- To assign a new value to an existing binding, use the `set!` special form:

```
(set! pi 3)
```

- Here, pi must be defined, and it is that definition that is changed (not like Python).

Function Evaluation

- Function evaluation is just like Python: same environment frames, same rules for what it means to call a user-defined function.
- To create a new function, we use the `lambda` special form:

```
>>> ( (lambda (x y) (+ (* x x) (* y y))) 3 4)
25
>>> (define fib
          (lambda (n) (if (< n 2) n (+ (fib (- n 2) (- n 1))))))
>>> (fib 5)
5
```

- The last is so common, there's an abbreviation:

```
>>> (define (fib n)
          (if (< n 2) n (+ (fib (- n 2) (- n 1)))))
```

Numbers

- All the usual numeric operations and comparisons:

```
>>> (- (quotient (* (+ 3 7 10) (- 1000 8)) 992) 17)
3
>>> (> 7 2)
#t
>>> (< 2 4 8)
#t
>>> (= 3 (+ 1 2) (- 4 1))
#t
>>> (integer? 5)
#t
>>> (integer? 'a)
#f
```


Lists and Pairs

- Pairs (and therefore lists) have a basic constructor and accessors:

```
>>> (cons 1 2)
(1 . 2)
>>> (cons 'a (cons 'b '()))
(1 2)
>>> (define L (a b c))
>>> (car L)
a
>>> (cdr L)
(b c)
>>> (cadr L)    ; (car (cdr L))
b
>>> (cdddr L)   ; (cdr (cdr (cdr L)))
()
```

- And one that is especially for lists:

```
>>> (list (+ 1 2) 'a 4)
(3 a 4)
>>> ; Why not just write ((+ 1 2) a 4)?
```


Conditionals

- The basic control structures are the conditionals, which are special forms:

```
>>> (define x 14)
>>> (define n 2)
>>> (if (not (zero? n))     ; Condition
...     (quotient x n)      ; If condition is not #f
...     x)                  ; If condition is #f
7
>>> (and (< 2 3) (> 3 4))
#f
>>> (and (< 2 3) '())
()
>>> (or (< 2 3) (> 3 4))
#t
>>> (or (< 3 2) '())
()
```


Traditional Conditionals

Traditional Lisp had a more elaborate special form, which Scheme inherited:

```
>>> (define x 5)
>>> (cond ((< x 1) 'small)
...       ((< x 3) 'medium)
...       ((< x 5) 'large)
...       (else    'big))
big
```


Binding Constructs: Let

- Sometimes, you'd like to introduce local variables or named constants.
- The let special form does this:

```
>>> (define x 17)
>>> (let ((x 5)
...        (y (+ x 2)))
...       (+ x y))
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```

- This is a *derived form*, equivalent to:

```
>>> ((lambda (x y)
          (+ x y))
     5 (+ x 2))
```


Tail recursion

- With just the functions and special forms so far, can write anything.
- But there is one problem: how to get an arbitrary iteration that doesn't overflow the execution stack because recursion gets too deep?
- Scheme requires *tail-recursive functions to work like iterations.*
- This means that in this program:

```
(define (fib n)
     (define (fib1 n1 n2 n)
            (if (< n 2)
                n2
                (fib1 n2 (+ n1 n2) (- n 1))))
     (if (= n 0) 0
         (fib1 0 1 n)))
```

- Instead of calling `fib1` recursively, we *replace* the call on `fib1` with the recursive call.
- Result: *don't need* **while** *loops.*

Examples

- Length of a list:

```
(define (length L)
   (if (null? L) 0 (+ 1 (length (cdr L)))))
```

- Tail-recursive length:

```
(define (length L)
   (define (add-length prev L)
      (if (null? L) prev (add-length (+ prev 1) (cdr L))))
   (add-length 0 L))
```

- Scheme version of __getitem__:

```
(define (nth k L)
    (if (= k 0) (car L) (nth (- k 1) (cdr L))))
```


Example: Operating on Scheme

Evaluate a Scheme expression containing only numbers and binary +, -, and *:

```
(define (eval E)
    (if (number? E) E
        (let ((left (eval (nth 1 E)))
              (right (eval (nth 2 E)))
              (op (nth 0 E)))
          (let ((func (cond ((eq? op '+) +)
                            ((eq? op '-) -)
                            (#t *))))
              (func left right)))))
```

- E is an expression, represented as a Scheme value.
- If it's a number, it "evaluates to itself."
- Otherwise, it must have the form (op left right), where op is one of the symbols +, - or *. We evaluate left and right, find the function that corresponds to op, and apply it.
- Since this is Scheme we are evaluating (in Scheme), the function associated with the symbol +, e.g., is bound to the symbol +.