"The trouble with programmers is that you can never tell what a programmer is doing until it's too late."

- Seymour Cray

CSE341
Programming Languages

Lecture 10 – December 2019

Functional Programming

Slides are taken from C. Li & W. He

History

Lambda Calculus (Church, 1932-33)	formal model of computation
Lisp (McCarthy, 1960) ***Scheme***, 70s	symbolic computations with lists
APL (Iverson, 1962)	algebraic programming with arrays
ISWIM (Landin, 1966)	let and where clauses equational reasoning; birth of "pure" functional programming ...
ML (Edinburgh, 1979) ***Caml*** 1985, ***Ocaml***	originally meta language for theorem proving
SASL, KRC, Miranda (Turner, 1976-85)	lazy evaluation
Haskell (Hudak, Wadler, et al., 1988)	"Grand Unification" of functional languages ...

Functional Programming

- Functional programming is a style of programming:

  Imperative Programming:
  - Program = Data + Algorithms

  OO Programming:
  - Program = Object. message (object)

  Functional Programming:
  - Program = Functions Functions

- Computation is done by application of functions

Functional Programming Languages

- Functional language support and advocate for the style of FP
- Important Features:
  - Everything is function (input → function → output)
  - No variables or assignments (only constant values, arguments, and returned values → no notion of state, memory location)
  - No loops (only recursive functions)
  - No side-effect (Referential Transparency)
    - The value of a function depends only on the values of its parameters
    - Evaluating a function with the same parameters gets the same results
    - There is no state
    - Evaluation order or execution path do not matter
    - `random()` and `getchar()` are not referentially transparent
  - Functions are first-class values: functions are values, can be parameters and return values, can be composed

FP in Imperative Languages

- Imperative style

```
int sumto(int n){
   int i, sum = 0;
   for(i = 1; i <= n; i++) sum += i;
   return sum;
}
```

- Functional style:

```
int sumto(int n){
   if (n <= 0) return 0;
   else return sumto(n-1) + n;
}
```


Why does it matter, anyway?

- The advantages of functional programming languages:
  - Simple semantics, concise, flexible
  - ``No'' side effect
  - Less bugs
- It does have drawbacks:
  - Execution efficiency
  - More abstract and mathematical, thus more difficult to learn and use
- Even if we do not use FP languages:
  - Features of recursion and higher-order functions have gotten into most programming languages

Functional Programming Languages in Use

- Popular in prototyping, mathematical proof systems, AI and logic applications, research and education
- Scheme:
  - Document Style Semantics and Specification Language (SGML stylesheets)
  - GIMP
  - Guile (GNU's official scripting language)
  - Emacs
- Haskell
  - Linspire (commerical Debian-based Linux distribution)
  - xmonad (X Window Manager)

Scheme

Scheme: Lisp dialect

- Syntax (slightly simplified):

  expression → *atom* | *list*
  atom → *number* | *string* | *identifier* | *character* | *boolean*
  list → '(' *expression-sequence* ')'
  expression-sequence → *expression* *expression-sequence* | *expression*

- Everything is an expression: programs, data, …

  Thus programs are executed by evaluating expressions

- Only 2 basic kinds of expressions:
  - atoms: unstructured
  - lists: the only structure (a slight simplification)

Expressions

`42`	—a number
`"hello"`	—a string
`#T`	—the Boolean value "true"
`#\a`	—the character 'a'
`(2.1 2.2 3.1)`	—a list of numbers
`hello`	—a identifier
`(+ 2 3)`	—a list (identifier "+" and two numbers)
`(* (+ 2 3) (/ 6 2))`	—a list (identifier "*" and two lists)

Evaluation of Expressions

Programs are executed by evaluating expressions. Thus semantics are defined by evaluation rules of expressions.

Evaluation Rules:

- number | string: evaluate to itself
- Identifier: looked up in the environment, i.e., dynamically maintained symbol table
- List: recursively evaluate the elements

Eager Evaluation

- A list is evaluated by recursively evaluating each element:
  - unspecified order
  - first element must evaluate to a function

    This function is then applied to the evaluated values of the rest of the list (*prefix form*)

```
E.g.
3 + 4 * 5                 (+ 3 (* 4 5))
(a == b)&&(a != 0)        (and (= a b) (not (= a 0)))
gcd(10,35)                (gcd 10 35)
```

- Most expressions use applicative order evaluation (eager evaluation): subexpressions are first evaluated, then the expression is evaluated

  (correspondingly in imperative language: arguments are evaluated at a call site before they are passed to the called function)

Lazy Evaluation: Special Forms

- `if` function `(if a b c)`:
  - `a` is always evaluated
  - Either `b` or `c` (but not both) is evaluated and returned as result.
  - `c` is optional. (if `a` is false and `c` is missing, the value of the expression is undefined.)

  e.g., `(if (= a 0) 0 (/ 1 a))`
- `cond`: `(cond (e1 v1) (e2 v2) ... (else vn))`
  - The `(ei vi)` are considered in order
  - `ei` is evaluated. If it is true, `vi` is then evaluated, and the value is the result of the `cond` expression.
  - If no `ei` is evaluated to true, `vn` is then evaluated, and the value is the result of the `cond` expression.
  - If no `ei` is evaluated to true, and `vn` is missing, the value of the expression is undefined.

```
(cond ((= a 0) 0) ((= a 1) 1) (else (/ 1 a)))
```


Lazy Evaluation: Special Forms

- `define` function:
  declare identifiers for constants and function, and thus put them into symbol table.

  `(define a b)`: define a name
  `(define (a p1 p2 …) b1 b2 …)`: define a function `a` with parameters `p1 p2 ….`

  the first expression after define is never evaluated.
  e.g.,
  - `(define x (+ 2 3))`
  - ```
    (define (gcd u v)
       (if (= v 0) u (gcd v (remainder u v))))
    ```
    ```

Lazy Evaluation: Special Forms

- `Quote`, or `'` for short, has as its whole purpose to *not* evaluate its argument:
  `(quote (2 3 4))` or `'(2 3 4)` returns just `(2 3 4)`.

  (we need a list of numbers as a data structure)

- `eval` function: get evaluation back
  `(eval '(+ 2 3))` returns 5

Other Special Forms

- `let` function:
  create a binding list (a list of name-value associations), then evaluate an expression (based on the values of the names)

  `(let ((n1 e1) (n2 e2) …) v1 v2 …)`

  `e.g., (let ((a 2) (b 3)) (+ a b))`

- Is this assignment?

Lists

List

- Only data structure
- Used to construct other data structures
- Thus we must have functions to manipulate lists

- `cons:` construct a list
  `(1 2 3) = (cons 1 (cons 2 (cons 3 '())))`
  `(1 2 3) = (cons 1 '(2 3))`
- `car`: the first element (head), which is an expression
  `(car '(1 2 3)) = 1`
- `cdr:` the tail, which is a list
  `(cdr '(1 2 3)) = (2 3)`

Data structures

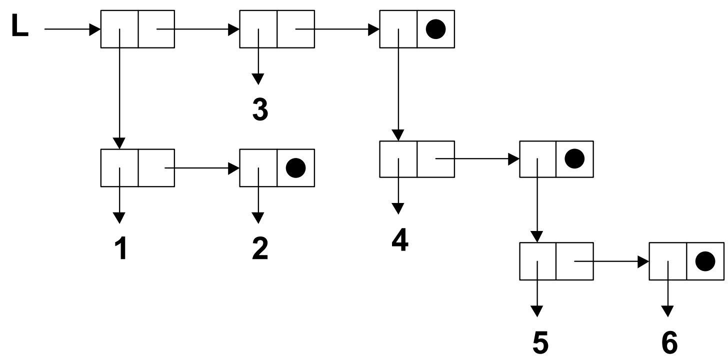
```
(define L '((1 2) 3 (4 (5 6))))
(car (car L))
(cdr (car L))
(car (car (cdr (cdr L))))
```

Note:
```
car(car = caar
cdr(car = cdar
car(car(cdr(cdr = caaddr
```

Box diagrams

a List = (head expression, tail list)

L = ((1 2) 3 (4 (5 6))) looks as follows in memory



Other list manipulations: based on car, cdr, cons

- ```
  (define (append L M)
             (if (null? L)
                   M
                   (cons (car L) (append (cdr L) M))
              )
  )
  ```

- ```
  (define (reverse L)
     (if (null? L)
           M
          (append (reverse (cdr L)) (list (car L)))
      )
  )
  ```

Lambda expressions/function values

- A function can be created dynamically using a `lambda` expression, which returns a value that is a function:
  `(lambda (x) (* x x))`

- The syntax of a `lambda` expression:
  (lambda *list-of-parameters* *exp1* *exp2* …)

- Indeed, the "function" form of `define` is just syntactic sugar for a `lambda`:
  `(define (f x) (* x x))`
  is equivalent to:
  `(define f (lambda (x) (* x x)))`

Function values as data

- The result of a `lambda` can be manipulated as ordinary data:

```
> ((lambda (x) (* x x)) 5)
25

> (define (add-x x) (lambda(y)(+ x y)))
> (define add-2 (add-x 2))
> (add-2 15)
17
```

Higher-order functions

- higher-order function:

  a function that returns a function as its value

  or takes a function as a parameter

  or both
- E.g.:
  - `add-x`
  - compose (next slide)

Higher-order functions

```
(define (compose f g)
  (lambda (x) (f (g x))))

(define (map f L)
  (if (null? L) L
      (cons (f (car L))(map f (cdr L)))))

(define (filter p L)
  (cond
    ((null? L) L)
    ((p (car L)) (cons (car L)
                       (filter p (cdr L))))
    (else (filter p (cdr L)))))
```

`let` expressions as lambdas:

- A `let` expression is really just a lambda applied immediately:
  `(let ((x 2) (y 3)) (+ x y))`
  is the same as
  `((lambda (x y) (+ x y)) 2 3)`

- This is why the following `let` expression is an error if we want x = 2 throughout:
  `(let ((x 2) (y (+ x 1))) (+ x y))`
- Nested `let` (lexical scoping)

  `(let ((x 2)) (let ((y (+ x 1))) (+ x y)))`

Lazy Evaluation

```python
def generator():
        i = 1
        while True:
                yield i
                i += 1
```