COP4020 Programming Languages

Functional Programming

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Overview

- What is functional programming?
- Historical origins of functional programming
- Functional programming today
- Concepts of functional programming
- Functional programming with Scheme
- Learn (more) by example

What is Functional Programming?

- Functional programming is a declarative programming style (programming paradigm)
  - Pro: flow of computation is declarative, i.e. more implicit
  - Pro: promotes building more complex functions from other functions that serve as building blocks (component reuse)
  - Pro: behavior of functions defined by the values of input arguments only (no side-effects via global/static variables)
  - Cons: function composition is (considered to be) stateless
  - Cons: programmers prefer imperative programming constructs such as statement composition, while functional languages emphasize function composition

Concepts of Functional Programming

- Functional programming defines the outputs of a program purely as a mathematical function of the inputs with no notion of internal state (no side effects)
  - A *pure function* can be counted on to return the same output each time we invoke it with the same input parameter values
  - No global (statically allocated) variables
  - No explicit (pointer) assignments
    - Dangling pointers and un-initialized variables cannot occur
  - Example pure functional programming languages: Miranda, Haskell, and Sisal
- Non-pure functional programming languages include “imperative features” that cause side effects (e.g. destructive assignments to global variables or assignments/changes to lists and data structures)
  - Example: Lisp, Scheme, and ML

Functional Language Constructs

- Building blocks are functions
- No statement composition
  - Function composition
- No variable assignments
  - But: can use local "variables" to hold a value assigned once
- No loops
  - Recursion
  - List comprehensions in Miranda and Haskell
  - But: "do-loops" in Scheme
- Conditional flow with if-then-else or argument patterns
- Functional languages can be typed (Haskell) or untyped (Lisp)

- Haskell examples:

```
gcd a b
  | a == b = a
  | a >  b = gcd (a-b) b
  | a <  b = gcd a (b-a)

fac 0 = 1
fac n = n * fac (n-1)

member x []    = false
member x (y:xs)
     | x == y = true
     | x <> y = member x xs
```

Theory and Origin of Functional Languages

- Church's thesis:
  - All models of computation are equally powerful
  - Turing's model of computation: Turing machine
    - Reading/writing of values on an infinite tape by a finite state machine
  - Church's model of computation: Lambda Calculus
  - Functional programming languages implement Lambda Calculus
- Computability theory
  - A program can be viewed as a constructive proof that some mathematical object with a desired property exists
  - A function is a mapping from inputs to output objects and computes output objects from appropriate inputs
    - For example, the proposition that every pair of nonnegative integers (the inputs) has a greatest common divisor (the output object) has a constructive proof implemented by Euclid's algorithm written as a "function"

Impact of Functional Languages on Language Design

- Useful features are found in functional languages that are often missing in procedural languages or have been adopted by modern programming languages:
  - *First-class function values*: the ability of functions to return newly constructed functions
  - *Higher-order functions*: functions that take other functions as input parameters or return functions
  - *Polymorphism*: the ability to write functions that operate on more than one type of data
  - *Aggregate constructs* for constructing structured objects: the ability to specify a structured object in-line such as a complete list or record value
  - *Garbage collection*

Functional Programming Today

- Significant improvements in theory and practice of functional programming have been made in recent years
  - Strongly typed (with type inference)
  - Modular
  - Sugaring: imperative language features that are automatically translated to functional constructs (e.g. loops by recursion)
  - Improved efficiency
- Remaining obstacles to functional programming:
  - Social: most programmers are trained in imperative programming and aren't used to think in terms of function composition
  - Commercial: not many libraries, not very portable, and no IDEs

Applications

- Many (commercial) applications are built with functional programming languages based on the ability to manipulate symbolic data more easily

- Examples:
  - Computer algebra (e.g. Reduce system)
  - Natural language processing
  - Artificial intelligence
  - Automatic theorem proving
  - Algorithmic optimization of functional programs

LISP and Scheme

- The original functional language and implementation of Lambda Calculus
- Lisp and dialects (Scheme, common Lisp) are still the most widely used functional languages
- Simple and elegant design of Lisp:
  - Homogeneity of programs and data: a Lisp program is a list and can be manipulated in Lisp as a list
  - Self-definition: a Lisp interpreter can be written in Lisp
  - Interactive: user interaction via "read-eval-print" loop

Scheme

- Scheme is a popular Lisp dialect
- Lisp and Scheme adopt a form of prefix notation called *Cambridge Polish* notation
- Scheme is case insensitive
- A Scheme expression is composed of
  - Atoms, e.g. a literal number, string, or identifier name,
  - Lists, e.g. '(a b c)
  - Function invocations written in list notation: the first list element is the *function* (or operator) followed by the arguments to which it is applied:

    ($function\ arg_1\ arg_2\ arg_3\ ...\ arg_n$)

  - For example, *sin*(*x***x*+1) is written as (sin (+ (* x x) 1))

Read-Eval-Print

- The "Read-eval-print" loop provides user interaction in Scheme
- An expression is read, evaluated, and the result printed
  - Input: 9
  - Output: 9
  - Input: (+ 3 4)
  - Output: 7
  - Input: (+ (* 2 3) 1)
  - Output: 7
- User can load a program from a file with the load function

  (load "my_scheme_program")

  Note: a file should use the .scm extension

Working with Data Structures

- An expression operates on values and compound data structures built from atoms and lists
- A value is either an atom or a compound list
- Atoms are
  - Numbers, e.g. 7 and 3.14
  - Strings, e.g. "abc"
  - Boolean values #t (true) and #f (false)
  - Symbols, which are identifiers escaped with a single quote, e.g. 'y
  - The empty list ()
- When entering a list as a literal value, escape it with a single quote
  - Without the quote it is a function invocation!
  - For example, '(a b c) is a list while (a b c) is a function application
  - Lists can be nested and may contain any value, e.g. '(1 (a b) "s")

Checking the Type of a Value

- The type of a value can be checked with
  - (boolean? *x*) ; is *x* a Boolean?
  - (char? *x*) ; is *x* a character?
  - (string? *x*) ; is *x* a string?
  - (symbol? *x*) ; is *x* a symbol?
  - (number? *x*) ; is *x* a number?
  - (list? *x*) ; is *x* a list?
  - (pair? *x*) ; is *x* a non-empty list?
  - (null? *x*) ; is *x* an empty list?
- Examples
  - (list? '(2)) $\Rightarrow$ #t
  - (number? "abc") $\Rightarrow$ #f
- Portability note: on some systems false (#f) is replaced with ()

Working with Lists

- (car *xs*) returns the head (first element) of list *xs*
- (cdr *xs*) (pronounced "coulder") returns the tail of list *xs*
- (cons *x* *xs*) joins an element *x* and a list *xs* to construct a new list
- (list x_1 x_2 … x_n) generates a list from its arguments
- Examples:
  - (car '(2 3 4)) ⇒ 2
  - (car '(2)) ⇒ 2
  - (car '()) ⇒ Error
  - (cdr '(2 3)) ⇒ (3)
  - (car (cdr '(2 3 4))) ⇒ 3 ; also abbreviated as (cadr '(2 3 4))
  - (cdr (cdr '(2 3 4))) ⇒ (4) ; also abbreviated as (cddr '(2 3 4))
  - (cdr '(2)) ⇒ ()
  - (cons 2 '(3)) ⇒ (2 3)
  - (cons 2 '(3 4)) ⇒ (2 3 4)
  - (list 1 2 3) ⇒ (1 2 3)

The “if” Special Form

- Special forms resemble functions but have special evaluation rules
  - Evaluation of arguments depends on the special construct
- The “if” special form returns the value of *thenexpr* or *elseexpr* depending on a *condition*

  (if *condition thenexpr elseexpr*)

- Examples
  - (if #t 1 2) ⇒ 1
  - (if #f 1 "a") ⇒ "a"
  - (if (string? "s") (+ 1 2) 4) ⇒ 3
  - (if (> 1 2) "yes" "no") ⇒ "no"

The "cond" Special Form

- A more general if-then-else can be written using the "cond" special form that takes a sequence of (*condition value*) pairs and returns the first *value* x_i for which *condition* c_i is true:

  (cond (c_1 x_1) (c_2 x_2) … (else x_n))

- Examples
  - (cond (#f 1) (#t 2) (#t 3)) ⇒ 2
  - (cond ((< 1 2) "one") ((>= 1 2) "two")) ⇒ "one"
  - (cond ((< 2 1) 1) ((= 2 1) 2) (else 3)) ⇒ 3
- Note: "else" is used to return a default value

Logical Expressions

- Relations
  - Numeric comparison operators <, <=, =, >, <=, and <>
- Boolean operators
  - (and x_1 x_2 … x_n), (or x_1 x_2 … x_n)
- Other test operators
  - (zero? x), (odd? x), (even? x)
  - (eq? x_1 x_2) tests whether x_1 and x_2 refer to the same object
    (eq? 'a 'a) ⇒ #t
    (eq? '(a b) '(a b)) ⇒ #f
  - (equal? x_1 x_2) tests whether x_1 and x_2 are structurally equivalent
    (equal? 'a 'a) ⇒ #t
    (equal? '(a b) '(a b)) ⇒ #t
  - (member *x* *xs*) returns the sublist of *xs* that starts with *x*, or returns ()
    (member 5 '(a b)) ⇒ ()
    (member 5 '(1 2 3 4 5 6)) ⇒ (5 6)

Lambda Calculus: Functions = Lambda Abstractions

- A *lambda abstraction* is a nameless function (a mapping) specified with the lambda special form:

  (lambda *args body*)

  where *args* is a list of formal arguments and *body* is an expression that returns the result of the function evaluation when applied to actual arguments
- A lambda expression is an unevaluated function
- Examples:
  - (lambda (x) (+ x 1))
  - (lambda (x) (* x x))
  - (lambda (a b) (sqrt (+ (* a a) (* b b))))

Lambda Calculus: Invocation = Beta Reduction

- A lambda abstraction is *applied* to actual arguments using the familiar list notation

  $(\textit{function}\ \textit{arg}_1\ \textit{arg}_2\ ...\ \textit{arg}_n)$

  where *function* is the name of a function or a lambda abstraction
- *Beta reduction* is the process of replacing formal arguments in the lambda abstraction's body with actuals
- Examples
  - ((lambda (x) (* x x)) 3) ⇒ (* 3 3) ⇒ 9
  - ((lambda (f a) (f (f a))) (lambda (x) (* x x)) 3)
⇒ (f (f 3)) where f = (lambda (x) (* x x))
⇒ (f ((lambda (x) (* x x)) 3)) where f = (lambda (x) (* x x))
⇒ (f 9) where f = (lambda (x) (* x x))
⇒ ((lambda (x) (* x x)) 9)
⇒ (* 9 9)
⇒ 81

Defining Global Names

- A global name is defined with the “define” special form

  (define *name value*)

- Usually the values are functions (lambda abstractions)
- Examples:
  - (define my-name "foo")
  - (define determiners '("a" "an" "the"))
  - (define sqr (lambda (x) (* x x)))
  - (define twice (lambda (f a) (f (f a))))
  - (twice sqr 3) ⇒ ((lambda (f a) (f (f a))) (lambda (x) (* x x)) 3) ⇒ … ⇒ 81

Using Local Names

- The "let" special form (let-expression) provides a scope construct for local name-to-value bindings

  (let (($name_1$ x_1) ($name_2$ x_2) … ($name_n$ x_n)) *expression*)

  where $name_1$, $name_2$, …, $name_n$ in *expression* are substituted by x_1, x_2, …, x_n
- Examples
  - (let ((plus +) (two 2)) (plus two two)) ⇒ 4
  - (let ((a 3) (b 4)) (sqrt (+ (* a a) (* b b)))) ⇒ 5
  - (let ((sqr (lambda (x) (* x x))) (sqrt (+ (sqr 3) (sqr 4))) ⇒ 5

Local Bindings with Self References

- A global name can simply refer to itself (for recursion)
  - (define fac (lambda (n) (if (zero? n) 1 (* n (fac (- n 1))))))
- A let-expression cannot refer to its own definitions
  - Its definitions are not in scope, only outer definitions are visible
- Use the letrec special form for recursive local definitions

  (letrec (($name_1$ x_1) ($name_2$ x_2) … ($name_n$ x_n)) *expr*)

  where $name_i$ in *expr* refers to x_i
- Examples
  - (letrec ((fac (lambda (n) (if (zero? n) 1 (* n (fac (- n 1)))))))
    (fac 5)) $\Rightarrow$ 120

I/O

- (display *x*) prints value of *x* and returns an unspecified value
  - (display "Hello World!")
    Displays: "Hello World!"
  - (display (+ 2 3))
    Displays: 5
- (newline) advances to a new line
- (read) returns a value from standard input
  - (if (member (read) '(6 3 5 9)) "You guessed it!" "No luck")
    Enter: 5
    Displays: You guessed it!

Blocks

- (begin x_1 x_2 … x_n) sequences a series of expressions x_i, evaluates them, and returns the value of the last one x_n
- Examples:
  - ```
    (begin
      (display "Hello World!")
      (newline)
    )
    ```
  - ```
    (let ( (x 1)
            (y (read))
            (plus +)
          )
          (begin
             (display (plus x y))
             (newline)
          )
    )
    ```

Do-loops

- The “do” special form takes a list of triples and a tuple with a terminating condition and return value, and multiple expressions x_i to be evaluated in the loop

  (do (*triples*) (*condition ret-expr*) x_1 x_2 … x_n)

- Each triple contains the name of an iterator, its initial value, and the update value of the iterator
- Example (displays values 0 to 9)
  - ```
    (do ( (i 0 (+ i 1)) )
          ( (>= i 10) "done" )
          (display i)
          (newline)
    )
    ```
    ```

Higher-Order Functions

- A function is a *higher-order function* (also called a functional form) if
  - It takes a function as an argument, or
  - It returns a newly constructed function as a result
- For example, a function that applies a function to an argument twice is a higher-order function
  - (define twice (lambda (f a) (f (f a))))
- Scheme has several built-in higher-order functions
  - (apply *f xs*) takes a function *f* and a list *xs* and applies *f* to the elements of the list as its arguments
  - (apply '+ '(3 4)) ⇒ 7
  - (apply (lambda (x) (* x x)) '(3))
  - (map *f xs*) takes a function *f* and a list *xs* and returns a list with the function applied to each element of *xs*
  - (map odd? '(1 2 3 4)) ⇒ (#t #f #t #f)
  - (map (lambda (x) (* x x)) '(1 2 3 4)) ⇒ (1 4 9 16)

Non-Pure Constructs

- Assignments are considered non-pure in functional programming because they can change the global state of the program and possibly influence function outcomes
- The value of a *pure function* only depends on its arguments
- (set! *name x*) re-assigns *x* to local or global *name*
  - ```
    (define a 0)
    (set! a 1) ; overwrite with 1
    ```
  - ```
    (let ( (a 0) )
         (begin
           (set! a (+ a 1)) ; increment a by 1
           (display a)      ; shows 1
         )
    )
    ```
- (set-car! *x xs*) overwrites the head of a list *xs* with *x*
- (set-cdr! *xs ys*) overwrites the tail of a list *xs* with *ys*

Example 1

- Recursive factorial:

```
(define fact
  (lambda (n)
    (if (zero? n) 1 (* n (fact (- n 1))))
  )
)
```

- (fact 2) $\Rightarrow$ (if (zero? 2) 1 (* 2 (fact (- 2 1))))
  $\Rightarrow$ (* 2 (fact 1))
  $\Rightarrow$ (* 2 (if (zero? 1) 1 (* 1 (fact (- 1 1)))))
  $\Rightarrow$ (* 2 (* 1 (fact 0)))
  $\Rightarrow$ (* 2 (* 1 (if (zero? 0) 1 (* 0 (fact (- 0 1))))
  $\Rightarrow$ (* 2 (* 1 1))
  $\Rightarrow$ 2

Example 2

- Iterative factorial

```
(define iterfact
  (lambda (n)
    (do ( (i 1 (+ i 1))          ; i runs from 1 updated by 1
            (f 1 (* f i))        ; f from 1, multiplied by i
          )
          ( (> i n) f )          ; until i > n, return f
                                 ; loop body is omitted
    )
  )
)
```

Example 3

- Sum the elements of a list

```
(define sum
  (lambda (lst)
    (if (null? lst)
      0
      (+ (car lst) (sum (cdr lst)))
    )
  )
)
```

- (sum '(1 2 3)) $\Rightarrow$ (+ 1 (sum (2 3)))
  $\Rightarrow$ (+ 1 (+ 2 (sum (3))))
  $\Rightarrow$ (+ 1 (+ 2 (+ 3 (sum ()))))
  $\Rightarrow$ (+ 1 (+ 2 (+ 3 0)))

Example 4

- Generate a list of *n* copies of *x*

```
(define fill
  (lambda (n x)
    (if (= n 0)
      ()
      (cons x (fill (- n 1) x)))
  )
)
```

- (fill 2 'a) ⇒ (cons a (fill 1 a))
  ⇒ (cons a (cons a (fill 0 a)))
  ⇒ (cons a (cons a ()))
  ⇒ (a a)

Example 5

- Replace *x* with *y* in list *xs*

```
(define subst
  (lambda (x y xs)
    (cond
      ((null? xs)            ())
      ((eq? (car xs) x)   (cons y (subst x y (cdr xs))))
      (else                      (cons (car xs) (subst x y (cdr xs))))
    )
  )
)
```

- (subst 3 0 '(8 2 3 4 3 5)) $\Rightarrow$ '(8 2 0 4 0 5)

Example 6

- Higher-order reductions

```
(define reduce
  (lambda (op xs)
    (if (null? (cdr xs))
      (car xs)
      (op (car xs) (reduce op (cdr xs)))
    )
  )
)
```

- (reduce and '(#t #t #f)) ⇒ (and #t (and #t #f)) ⇒ #f
- (reduce * '(1 2 3)) ⇒ (* 1 (* 2 3)) ⇒ 6
- (reduce + '(1 2 3)) ⇒ (+ 1 (+ 2 3)) ⇒ 6

Example 7

- Higher-order filter operation: keep elements of a list for which a condition is true

```
(define filter
  (lambda (op xs)
    (cond
      ((null? xs)      ())
      ((op (car xs))  (cons (car xs) (filter op (cdr xs))))
      (else            (filter op (cdr xs)))
    )
  )
)
```

- (filter odd? '(1 2 3 4 5)) ⇒ (1 3 5)
- (filter (lambda (n) (<> n 0)) '(0 1 2 3 4)) ⇒ (1 2 3 4)

Example 8

- Binary tree insertion, where () are leaves and (*val left right*) is a node

```
(define insert
  (lambda (n T)
    (cond
      ((null? T)          (list n () ()))
      ((= (car T) n)      T)
      ((> (car T) n)      (list (car T) (insert n (cadr T)) (caddr T)))
      ((< (car T) n)      (list (car T) (cadr T) (insert n (caddr T))))
    )
  )
)
```

- (insert 1 '(3 () (4 () ()))) ⇒ (3 (1 () ()) (4 () ()))