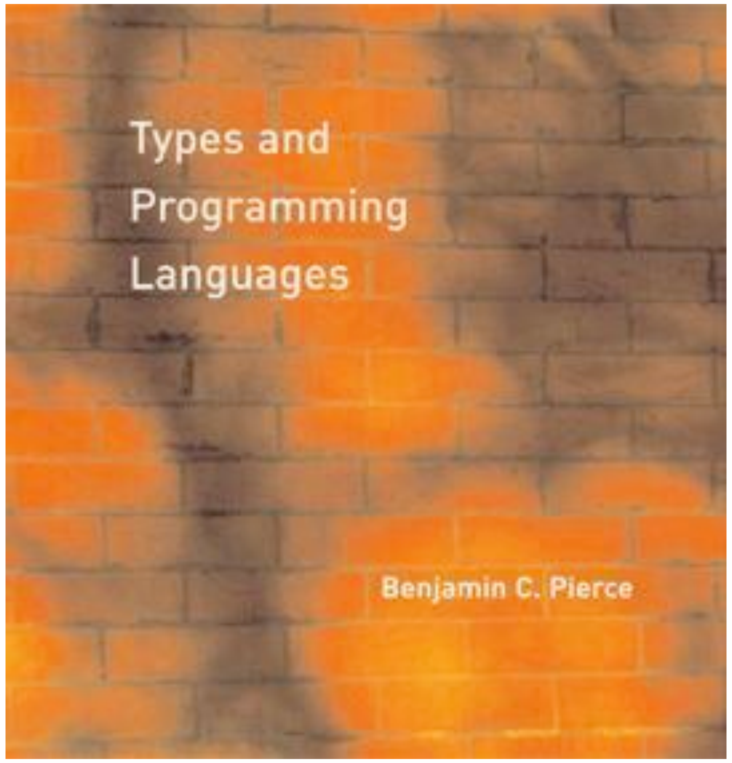
Programming Languages
Fall 2014



Prof. Liang Huang

huang@qc.cs.cuny.edu

Computer Science is no more about computers than astronomy is about telescopes.

— (Mis)attributed to Edsger Dijkstra, 1970.

Computer science is not really about computers -- and it's not about computers in the same sense that physics is not really about particle accelerators, and biology is not about microscopes and Petri dishes... and geometry isn't really about using surveying instruments... when some field is just getting started and you don't really understand it very well, it's very easy to confuse the essence of what you're doing with the tools that you use.

— Harry Abelson (1986), Intro to Computer Science Course, MIT

Computer Science

- CS is not a science -- it does not require experimental tests
- CS is not engineering -- it does not have physical constraints and it cares more about abstraction than reality
- CS is
    - a “magical” branch of pure and abstract mathematics
    - an “abstract” version of engineering w/o physical constraints
    - CS focuses on abstraction and mathematical rigor
        - abstraction is even more important than rigor
            - definitions are important than (mostly boring) proofs

What is PL all about?

- a formal perspective on programs and programming
  - the *linguistics* of programming languages; "*comparative literature*"
  - view programs and whole languages as mathematical objects
  - make and prove rigorous claims about them
    - important in some domains (safety-critical systems, hardware design, security protocols, inner loops of key algorithms, ...)
  - detailed study of a range of language features

- our approaches: abstraction and rigorous proofs
  - geometry: abstract and precise description of space/shape
  - CS: abstract and precise description of "processes"

What this course is *not*...

- an introduction to programming
  - you should be fluent in at least two mainstream languages
- a comparative survey of different programming languages
  - this course is the "linguistics" of programming languages
  - "comparative literature" rather than English/Russian/Chinese...
- a course on functional programming (FP)
  - though we'll teach Haskell and FP is everywhere in this course
- a course on compilers
  - you should know lexical analysis, regular grammar, automata, context-free grammars, parsing, and abstract syntax

Syllabus

- Part 0: Background
  - Functional Programming with Haskell
  - Inductive Proofs
- Part I: Basics
  - Operational Semantics
  - λ-calculus
- Part II: Type Systems
  - Simply Typed λ-calculus
  - Type Safety
  - Subtyping

Functional Programming and Haskell Tutorial

(with a comparison to Python,
the best imperative language)

Functional Programming

- functional languages (Lisp/Scheme, Haskell, SML/Ocaml, Scala, ...)
  - persistent data structures (immutable once built)
  - recursion as the primary control structure
  - heavy use of higher-order functions (functions that take functions as arguments and return functions as results)
- imperative languages (C/C++, Java, Python, ...)
  - mutable data structures
  - looping rather than recursion
  - first-order rather than higher-order programming
  - Python incorporated many functional programming features!

First Impression: Quicksort

```java
public void sort(int low, int high)
{
    if (low >= high) return;
    int p = partition(low, high);
    sort(low, p);
    sort(p + 1, high);
}

void swap(int i, int j)
{
    int temp = a[i];
    a[i] = a[j];
    a[j] = temp;
}
```

```java
int partition(int low, int high)
{
    int pivot = a[low];
    int i = low - 1;
    int j = high + 1;
    while (i < j)
    {
        i++; while (a[i] < pivot) i++;
        j--; while (a[j] > pivot) j--;
        if (i < j) swap(i, j);
    }
    return j;
}
```

Java

```haskell
qsort [] = []
qsort (p:xs) = qsort left ++ [p] ++ qsort right
    where
        left = [x|x<-xs, x<p]
        right = [x|x<-xs, x>=p]
```

Haskell

```python
def sort(a):
    if a == []:
        return []
    else:
        p = a[0]
        left  = [x for x in a if x < p]
        right = [x for x in a[1:] if x >= p]
        return sort(left) + [p] + sort(right)
```

```haskell
or:
left = filter (< p) xs
right = filter (>= p) xs
```

Python

do **not** use C/C++ or Java anymore!

The GHC Interpreter

```
[<lhuang@Mac OS X:~>] ghci
GHCi, version 7.6.3:
Prelude> 3 + 5
8
Prelude> 3 / 5
0.6
Prelude> 3 /= 5
True
Prelude> [1, 2] ++ [3]
[1,2,3]
Prelude> let a = [1,2] ++ [3]
Prelude> a
[1,2,3]
Prelude> length a
3
Prelude> reverse a
[3,2,1]
Prelude> min 3 5
3
Prelude> [3, "a"]
    No instance for (Num Char) ...
```

float div

not !=

not +

function application

```
[<lhuang@Mac OS X:~>] python
Python 2.7.3
>>> 3 + 5
8
>>> 3 / 5
0
>>> 3 != 5
True
>>> [1, 2] + [3]
[1, 2, 3]
>>> a = [1, 2] + [3]
>>> a
[1, 2, 3]
>>> len(a)
3
>>> list(reversed(a))
[3, 2, 1]
>>> min(3, 5)
3
>>> [3, "a"]
[3, 'a']
```

Lists (and Strings)

- Haskell lists are homogenous (Python: heterogenous)
- Haskell strings are list of chars (Python: string is not list, and no distinction b/w str and char)

```
Prelude> "hello" ++ " " ++ "world"
"hello world"
Prelude> ["h", "e"]
["h","e"]
Prelude> ['h', 'e']
"he"
Prelude> "3" + [3]
  Error
```

```
>>> "hello" + " " + "world"
"hello world"
>>> ["h", "e"]
["h", "e"]
>>> ['h', 'e']
["h", "e"]
>>> "3" + [3]
["3", 3]
```

Lists are LinkedLists

- Haskell lists are linked lists (Python: array of pointers)
  - cons operator : , head and tail
- but Haskell also support random-access features

```
Prelude> 'A':" SMALL CAT"
"A SMALL CAT"
Prelude> "A":" SMALL CAT"
  Error
Prelude> "A":[" SMALL CAT"]
["A"," SMALL CAT"]
Prelude> head [1,2,3]
1
Prelude> tail [1,2,3]
[2,3]
Prelude> null [1]
False
Prelude> [1,2,3] !! 1
2
```

```
>>> [1,2,3][0]
1
>>> [1,2,3][1:]
[2,3]
>>> [1] == []
False
>>> [1,2,3][1]
2
```

Function Definition and Application

```
Prelude> let f x = x+1
Prelude> f 5
6
Prelude> map f [1..10]
[2,3,4,5,6,7,8,9,10,11]

Prelude> let g x y = x+y
Prelude> g 2 3
5
Prelude> (g 2) 3
5
Prelude> let g2 = g 2
Prelude> g2 3
5
Prelude> map g2 [1..10]
[3,4,5,6,7,8,9,10,11,12]
```

Conditionals

```
Prelude> if 3 < 5 then [] else [3]
[]
Prelude> let min' x y = if x < y then x else y
Prelude> min' 3 5
3
Prelude> let f = min' 3
Prelude> f 5
3
Prelude> f 2
2
```

partial application

```
>>> [] if 3 < 5 else [3]
[]
>>> def min1(x, y): return x if x < y else y
>>> min1(3, 5)
3
>>> f = lambda x: min1(3, x)
>>> f(5)
3
>>> f(2)
2
```

```
from functools import partial
f = partial(min1, 3)
```

List Comprehensions

```
Prelude> [x*2 | x <- [1..10]]
[2,4,6,8,10,12,14,16,18,20]
Prelude> let f x = x*2
Prelude> [f x | x <- [1..10]]
[2,4,6,8,10,12,14,16,18,20]
Prelude> map f [1..10]
[2,4,6,8,10,12,14,16,18,20]

Prelude> [x*y | x <- [2,5,10], y <- [8,10,11], x*y > 50]
[55,80,100,110]

Prelude> let a = [2..20]
Prelude> [x | x <- a, null [y | y<-a, y<x, x `mod` y == 0]]
[2,3,5,7,11,13,17,19]

Prelude> let nouns = ["hobo", "frog", "pope"]
Prelude> let adjs = ["lazy", "grouchy"]
Prelude> [adj ++ " " ++ noun | adj <- adjs, noun <- nouns]
["lazy hobo","lazy frog","lazy pope","grouchy hobo","grouchy
frog","grouchy pope"]
```

Recursive Functions: fact and fib

- recursion is the essence of functional programming
  - also essence of whole computer science, and the human species

```
Prelude> let fact n = if n == 0 then 1 else n * fact (n-1)
Prelude> fact 5
120
Prelude> let fib n = if n < 3 then 1 else fib (n-1) + fib (n-2)
Prelude> fib 10
55
Prelude> let s a = if null a then 0 else head a + s (tail a)
Prelude> s [1,2,3]
6
Prelude> sum [1,2,3]
6
Prelude> let rev a = if null a then [] else rev (tail a) ++ [head a]
Prelude> rev [1,2,3]
[3,2,1]
Prelude> reverse [1,2,3]
[3,2,1]
```

```
def rev(a): return [] if a==[] else rev(a[1:])+[a[0]]
```

Quicksort (and load)

```
Prelude> let qsort a = if null a then [] else qsort [x | x<-a, x<head a] ++ [head a]
++ qsort [x | x <- tail a, x >= (head a)]
Prelude> qsort [2,1,3]
[1,2,3]
```

```
[<lhuang@Mac OS X:~/teaching/PL>] cat qsort.hs
qsort a =
    if null a then []
    else qsort [x | x <- a, x<head a]
             ++ [head a]
             ++ qsort [x | x <- tail a, x >= (head a)]
[<lhuang@Mac OS X:~/teaching/PL>] ghci
Prelude> :l qsort.hs
[1 of 1] Compiling Main             ( qsort.hs, interpreted )
Ok, modules loaded: Main.
*Main> qsort [1,2,-1]
[-1,1,2]
```

$$\{x \mid x \in a,\ x < pivot\}$$

```
def qsort(a):
    if a == []:
        return []
    else:
        pivot = a[0]
        left  = [x for x in a if x < pivot ]
        right = [x for x in a[1:] if x >= pivot]
        return qsort(left) + [pivot] + qsort(right)
```

Pattern Matching

```
fact n = if n == 0 then 1 else n * fact (n-1)
```

```
fact 0 = 1
fact n = n * fact (n-1)
```

```
fib n = if n < 3 then 1 else fib (n-1) + fib (n-2)
```

```
fib 1 = 1
fib 2 = 1
fib n = fib (n-1) + fib (n-2)
```

```
rev a = if null a then [] else rev (tail a) ++ [head a]
```

```
rev [] = []
rev (x:xs) = (rev xs) ++ [x]
```

Quicksort Revisited

```
qsort a =
    if null a then []
    else qsort [x | x <- a, x<head a]
             ++ [head a]
             ++ qsort [x | x <- tail a, x >= (head a)]
```

```
qsort [] = []
qsort (x:xs) =
    let left =  [a | a <- xs, a <  x]
        right = [a | a <- xs, a >= x]
    in  qsort left ++ [x] ++ qsort right
```

```
def qsort(a):
    if a == []:
        return []
    else:
        pivot = a[0]
        left  = [x for x in a if x < pivot ]
        right = [x for x in a[1:] if x >= pivot]
        return qsort(left) + [pivot] + qsort(right)
```

$$\{x \mid x \in a,\ x < pivot\}$$

```
public void sort(int low, int high)
{
    if (low >= high) return;
    int p = partition(low, high);
    sort(low, p);
    sort(p + 1, high);
}
```

```
void swap(int i, int j)
{
    int temp = a[i];
    a[i] = a[j];
    a[j] = temp;
}
```

```
int partition(int low, int high)
{
    int pivot = a[low];
    int i = low - 1;
    int j = high + 1;
    while (i < j)
    {
        i++; while (a[i] < pivot) i++;
        j--; while (a[j] > pivot) j--;
        if (i < j) swap(i, j);
    }
    return j;
}
```

where ... vs. let ... in

```
qsort a =
    if null a then []
    else qsort [x | x <- a, x<head a]
             ++ [head a]
             ++ qsort [x | x <- tail a, x >= (head a)]
```

```
qsort [] = []
qsort (x:xs) =
    let left =  [a | a <- xs, a <  x]
        right = [a | a <- xs, a >= x]
    in  qsort left ++ [x] ++ qsort right
```

```
let ... in ...        <=>       ... where ...
```

```
qsort [] = []
qsort (x:xs) = qsort left ++ [x] ++ qsort right
 where left  = [a | a <- xs, a <  x]
       right = [a | a <- xs, a >= x]
```