Data Structures and Functional Programming

Course Overview

http://www.flickr.com/photos/rofi/2097239111/

Nate Foster
Cornell University
Spring 2012

Course staff

Instructor: Nate Foster

- Joined Cornell last year from UPenn
- Research area: programming languages
- Functional programmer since 1998

TAs: Shrutarshi Basu (coordinator), Ashir Amer, Stuart Davis, Gautam Kamath, Katie Meusling, Greg Zecchinni

Consultants: *many*

You have a large and veteran staff. Make use of them!

Office hours in Upson 360 Sunday-Thursday from 7-9pm
Additional office hours Thursday from 5-7pm

Course meetings

Lectures: Tuesday and Thursday 10:10-11am

Recitations: Monday and Wednesday, 2:30 and 3:30

- A third section will be added, at a time that helps out students with conflicts (probably in the evening)
- We'll pick the time at the end of class today

New material in lecture *and* recitation

- You are expected to attend both

Class participation counts

- Please stick to the same section

Course web site

http://www.cs.cornell.edu/Courses/cs3110

- Course material
- Homework
- Announcements

Includes a complete set of course notes

- Nearest equivalent to a textbook
- But the lectures and sections are definitive

Links to lecture notes will go live shortly after lecture

Goal is to help, not replace attendance!

Piazza and CMS

piazza Ask. Answer. Explore. Whenever.

- Online discussion forum
- Monitored by TAs/consultants
- Ask for help, but don’t post solutions

CMS

- “Course Management System”
- Built by Andrew Myers (with help from lots of students)
- Assignments and grades posted here

Coursework

6 problem sets

- Due Thursdays at 11:59pm
- PS #1 (out today) is due Thurday 2/2
- Electronic submission via CMS

4 x individual assignments

2 x two-person assignments

- 3 weeks for the big assignments
- There will be intermediate checkpoints

6 (small) quizzes in lecture

2 preliminary exams and a final

Grading

Breakdown:

- 45% - Problem sets
- 5% - Quizzes (lowest dropped)
- 30% - Preliminary exams (lower exam weighted less)
- 20% - Final exam

Will follow the usual CS3110 curve

- Centered around a B/B+

Late policy

You can hand it in until we start grading

- 15% penalty / day
- After we start grading, no credit

Save your code and submit early and often

- CMS is your friend
- Be certain you have submitted something, even if it isn't perfect and you are improving it

If you have a emergency (e.g., medical, family) talk to Nate before the last second

Academic integrity

Strictly enforced

Easier to check than you might think

- We compare submissions using automated tools

Unpleasant and painful for everyone involved

To avoid pressure, start early

- We try hard to encourage this
- Take advantage of the large veteran staff
- Let Nate know if you run into difficulty

What this course is about

Programming isn’t hard

Programming **well** is **very** hard

- Programmers vary greatly
- 10X or more difference in skills

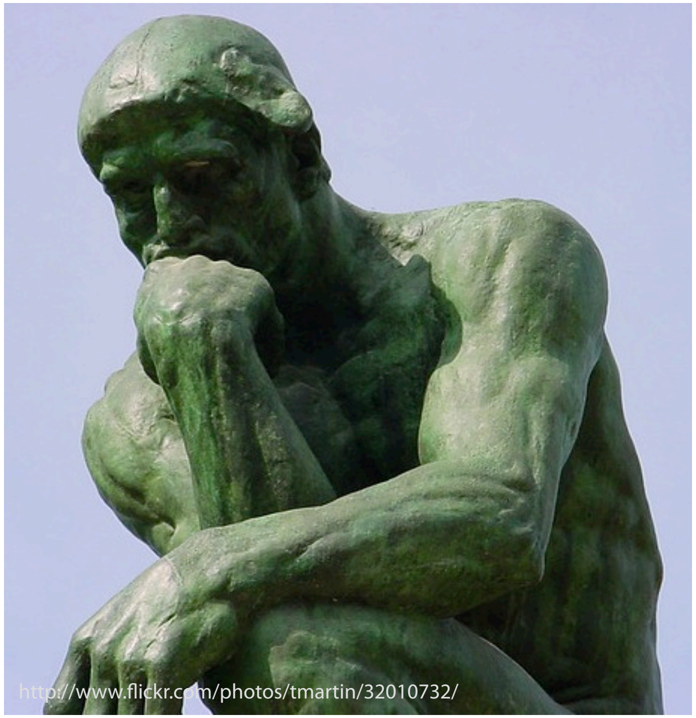
We want you to write code that is:

- Reliable, efficient, readable, testable, provable, maintainable… **beautiful**!

Expand your problem-solving skills

- Recognize problems and map them onto the right abstractions and algorithms

Thinking versus typing



http://www.flickr.com/photos/tmartin/32010732/

"A year at the lab bench saves an hour at the library"

Fact: there are an infinite number of incorrect programs

Corollary: making random tweaks to your code is unlikely to help

- If you find yourself changing "<" to "<=" in the hopes that your code will work, you're in trouble

Lesson: think before you type!

CS 3110 Challenges

In early courses smart students can get away with bad habits

- "Just hack until it works"
- Solve everything by yourself
- Write first, test later

CS 3110 ≈ Tour de France

- Professionals need good work habits and the right approach

Will need to think *rigorously* about programs and their models

- Think for a few minutes, instead of typing for days!

http://www.flickr.com/photos/franklintello/4349205547/

Rule #1

Good programmers are lazy

- Never write the same code twice (why?)
- Reuse libraries (why?)
- Keep interfaces small and simple (why?)

Pick a language that makes it easy to write the code you need

- Early emphasis on speed is a disaster (why?)

Rapid prototyping!

Main goal of CS3110

Master key linguistic abstractions:

- Procedural abstraction
- Control: iteration, recursion, pattern matching, laziness, exceptions, events
- Encapsulation: closures, ADTs
- Parameterization: higher-order procedures, modules

Mostly in service to rule #1

Transcends individual programming languages

Other goals

Exposure to software engineering techniques:

- Modular design
- Integrated testing
- Code reviews

Exposure to abstract models:

- Models for design & communication
- Models & techniques for proving correctness
- Models for analyzing space & time

Rigorous thinking about programs!

- Proofs, like in high school geometry

Choice of language

This matters less than you suspect

Must be able to learn new languages

- This is relatively easy if you understand programming models and paradigms

We will be using OCaml, a dialect of ML

Why use yet another language?

- Not to mention an obscure one?

Main answer: OCaml programs are easy to reason about

Why Caml ?

Awesome OCaml feature: many common errors simply impossible

- More precisely, they are caught at compile time
- Early failure is very important (why?)

Functional language

- Programs have a clear semantics
- Heavy use of recursion
- Lots of higher-order functions
- Few side effects

Statically typed and type safe

- Many bugs caught by compiler

Imperative Programming

Program uses **commands** (a.k.a **statements**) that *do* things to the **state** of the system:

- `x = x + 1;`
- `a[i] = 42;`
- `p.next = p.next.next;`

Functions and methods can have **side effects**

- `int wheels(Vehicle v) { v.size++; return v.numw; }`

Functional Style

Idea: program without side effects

- Effect of a function is *only* to return a result value

Program is an **expression** that can be evaluated to produce a **value**

- For example, evaluating 2+2 yields 4
- Just like mathematical expressions

Enables **equational reasoning** about programs:

- if x equals y, replacing y with x has no effect:
- `let x=f(0) in x+x` equivalent to `f(0)+f(0)`

Functional Style

Bind variables to values, don't mutate existing variables

No concept of **x=x+1** or **x++**

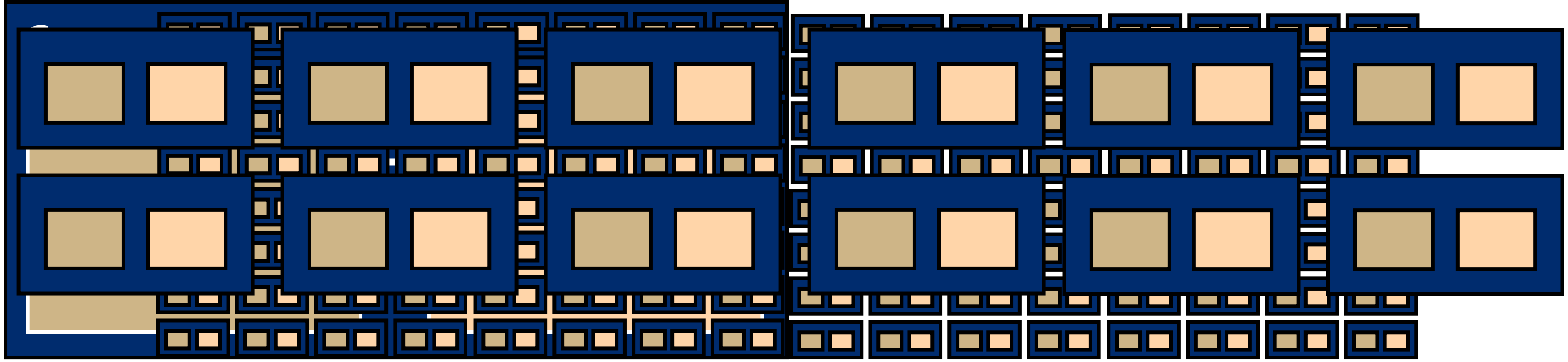
These do nothing remotely like **x++**

- **let x = x+1 in x**
- **let rec x = x+1 in x**

The former assumes an existing binding for **x** and creates a new one (no modification of **x**)

The latter is an invalid expression

Trends against imperative style



Fantasy: program interacts with a single system state

- Interactions are reads from and writes to variables or fields.
- Reads and writes are very fast
- Side effects are instantly seen by all parts of a program

Reality : there is no single state

- Multicores have own caches with inconsistent copies of state
- Programs are spread across different cores and computers (PS5 & PS6)
- Side effects in one thread may not be immediately visible in another
- **Imperative languages are a bad match to modern hardware**

Imperative vs. functional

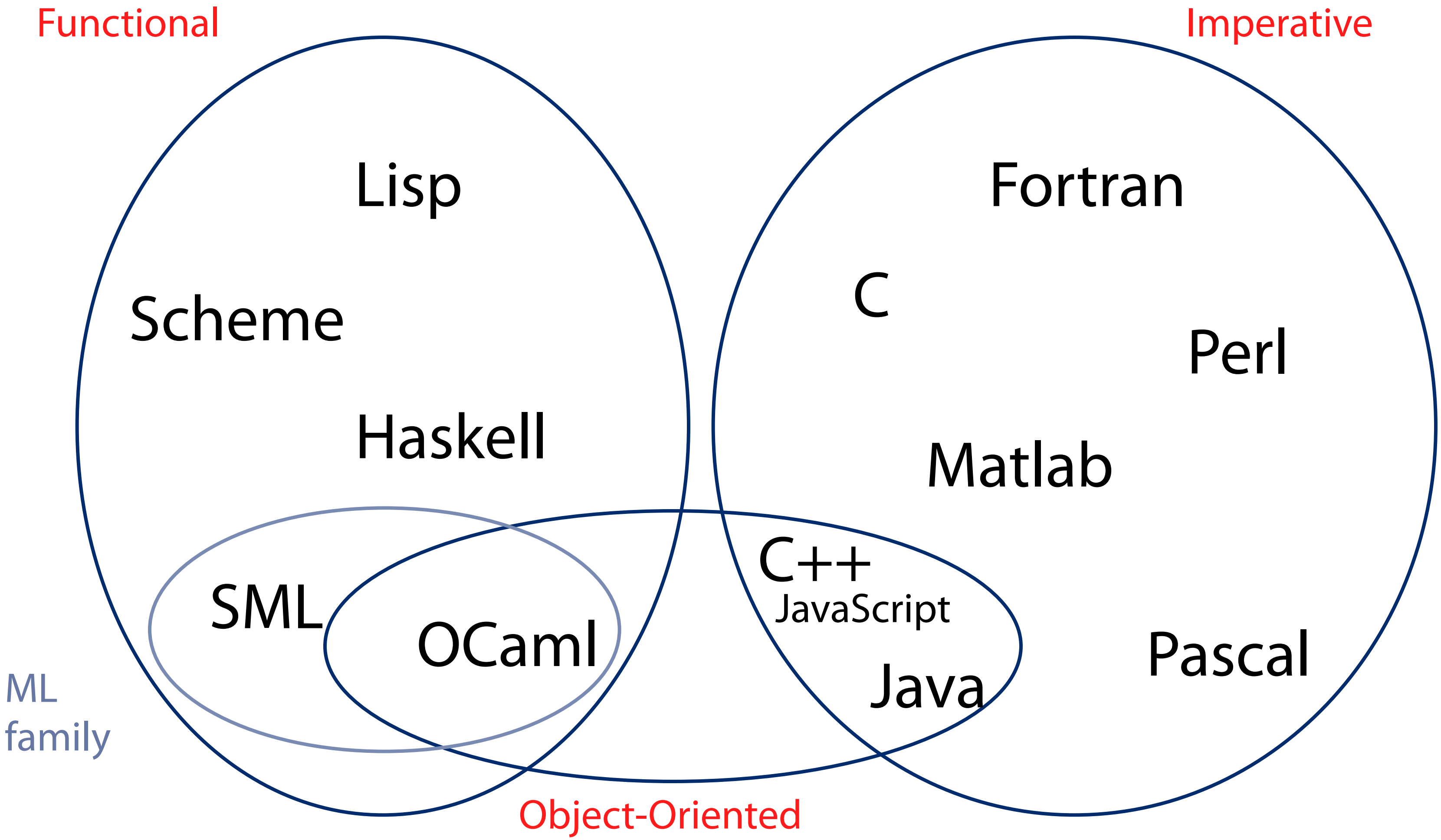
Functional programming languages

- Encourages building code out of functions
- f(x) always gives same result
- No side effects: easier to reason about what happens
- Better fit to modern hardware, distributed systems

Functional style usable in Java, C, Python…

- Becoming more important with interactive UI's and multiple cores
- Provides a form of encapsulation – hide the state and side effects inside a functional abstraction

Programming Languages Map



Functional

Imperative

Lisp

Scheme

Haskell

SML

OCaml

ML family

Fortran

C

Perl

Matlab

C++

JavaScript

Java

Pascal

Object-Oriented

Imperative “vs.” functional

Functional languages:

- Higher level of abstraction
- Closer to specification
- Easier to develop robust software

Imperative languages:

- Lower level of abstraction
- Often more efficient
- More difficult to maintain, debug
- More error-prone

Example 1: Sum Squares

```
y = 0;
for (x = 1; x <= n; x++) {
 y = y + x*x;
}
```

Example 1: Sum Squares

```
int sumsq(int n) {
    y = 0;
    for (x = 1; x <= n; x++) {
        y += x*x;
    }
    return n;
}
let rec sumsq (n:int):int =
  if n=0 then 0
  else n*n + sumsq(n-1)
```

Example 1: Sum Squares Revisited

Types can be left implicit and then inferred.

For example, in following, typechecker determines that **`n`** is an integer, and **`sumsq`** returns an integer

```
let rec sumsq n =
  if n=0 then 0
  else n*n + sumsq(n-1)
```

Example 1a: Sum f's

Functions are first-class objects

Can be used as arguments and returned as values

```
let rec sumop f n =
  if n=0 then 0
  else f n + sumop f (n-1)

sumop cube 5
sumop (function x -> x*x*x) 5
```

Example 2: Reverse List

```
List reverse(List x) {
   List y = null;
   while (x != null) {
     List t = x.next;
     x.next = y;
     y = x;
     x = t;
  }
  return y;
}
```

Example 2: Reverse List

```
let rec reverse lst =
  match lst with
      [] -> []
    | h :: t -> reverse t  @ [h]
```

Pattern matching simplifies working with data structures, being sure to handle all cases

Example 3: Pythagoras

```
let pythagoras x y z =
  let square n = n*n in
    square z = square x + square y
```

Every expression returns a value, when this function is applied it returns a Boolean value

Why OCaml?

Objective Caml is one of the most robust and general functional languages available

- Used in financial industry
- Lightweight and good for rapid prototyping

Embodies important ideas better than Java, C++

- Many of these ideas work in Java, C++, and you should use them…

Learning a different language paradigms will make you a more flexible programmer down the road

- Likely that Java and C++ will be replaced
- Principles and concepts beat syntax
- Ideas in ML will likely be in next-generation languages

Rough schedule

Introduction to functional programming (6)

Functional data structures (5)

Verification and Testing (5)

Preliminary Exam #1

Concurrency (1)

Data structures and analysis of algorithms (5)

Preliminary Exam #2

Topics: streams, λ-calculus, garbage collection

Final exam