CS 4110

Programming Languages & Logics

Lecture 1
Course Overview

26 August 2014

Programming Languages

One of the oldest fields in Computer Science…

- λ-calculus – Church (1936)
- FORTRAN – Backus (1957)
- LISP – McCarthy (1958)
- ALGOL 60 – Backus, Naur, Perlis, & others (1960)
- Pascal – Wirth (1970)
- C – Ritchie (1972)
- Smalltalk – Kay & others (1972)
- ML – Milner and others (1978)
- C++ – Stroustrup (1982)
- Haskell – Hudak, Peyton Jones, Wadler, & others (1989)
- Java – Gosling (1995)
- C# – Microsoft (2001)
- Scala – Odersky (2003)
- F# – Syme (2005)

Programming Languages

...and one of the most vibrant areas today!

PL intersects with many other areas of computing

Current trends

- Domain-specific languages
- Static analysis and types
- Language-based security
- Verification and model checking
- Concurrency

Both theoretically and practically “meaty”

Syllabus

Course Staff

Instructor

Nate Foster
Office: Gates 432
Hours: Mon 4-5pm and Friday 11am-12pm

Teaching Assistant

Fran Mota
Office: Hours: TBA

Web Page

`http://www.cs.cornell.edu/Courses/cs4110/2014fa`

Discussion

`http://www.piazza.com`

Course Goals

- Techniques for modeling programs* mathematically
  - Operational, axiomatic, and denotational semantics
  - Examples with advanced features
  - Reasoning principles (induction, co-induction)
- Explore applications of these techniques
  - Optimization
  - Type systems
  - Verification
- Gain experience implementing languages
  - Interpreters
  - Program transformations
  - Analysis tools
- PhD students: cover material for PL qualifying exam
- Have fun :-)

*and whole languages!

Prerequisites

Mathematical Maturity

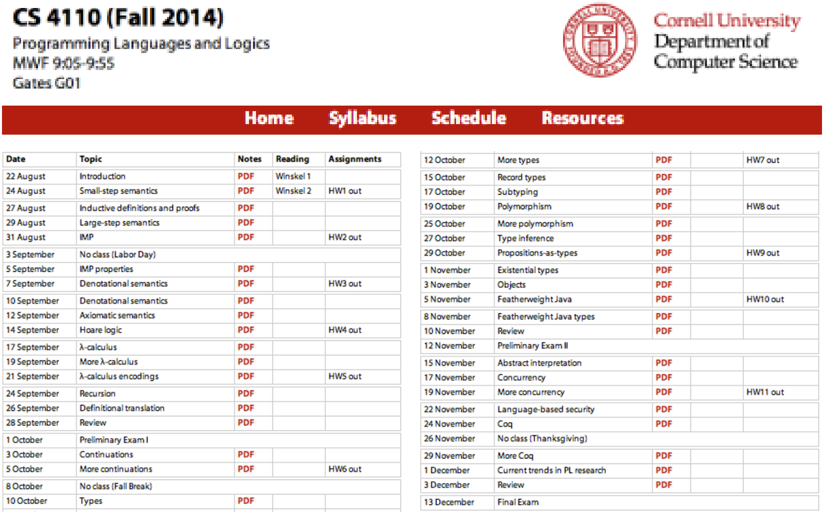
- Much of this class will involve formal reasoning
- Set theory, formal proofs, induction
- Most challenging topic: denotational semantics

Programming Experience

- Comfortable using a functional language
- For undergrads: CS 3110 or equivalent

Interest (having fun is a goal! :-)

If you don’t meet these prerequisites, get in touch



CS 4110 (Fall 2014)

Programming Languages and Logics
MWF 9:05-9:55
Gates G01

Cornell University
Department of
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Mathematical Preliminaries & Operational Semantics

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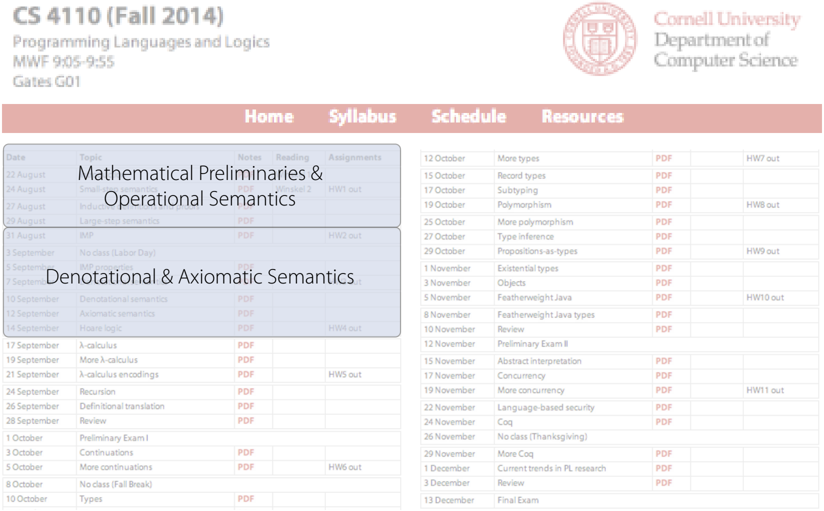

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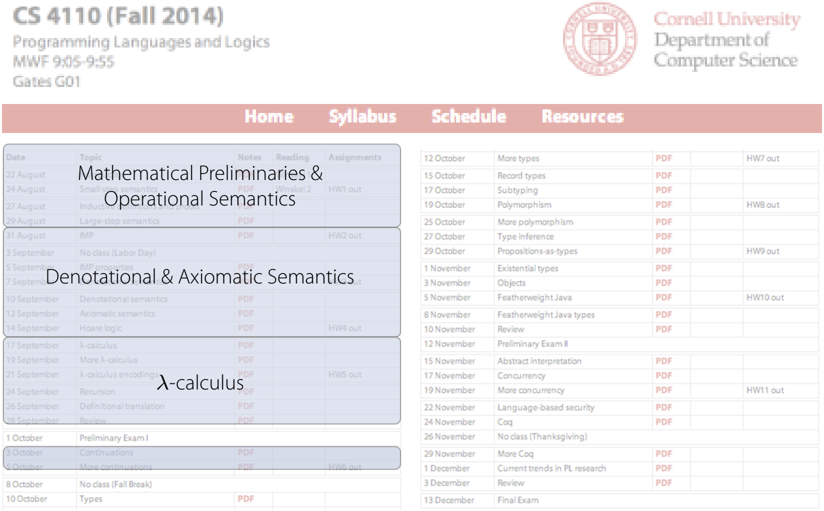

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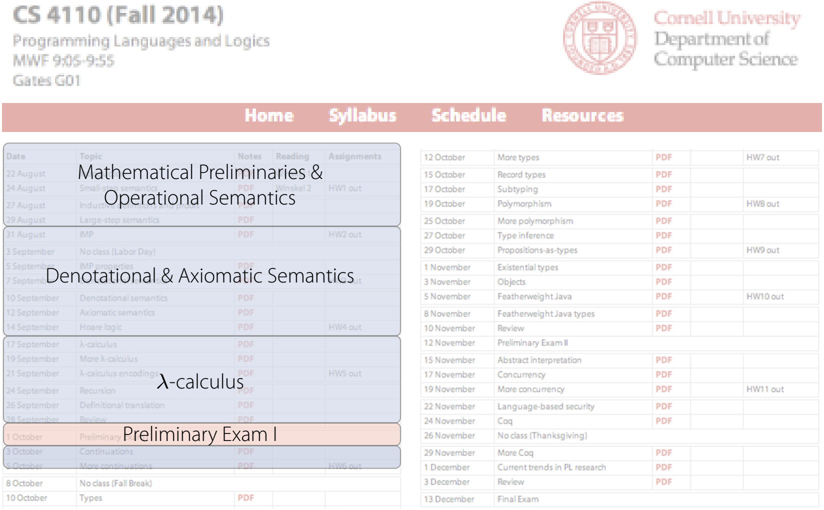
Mathematical Preliminaries & Operational Semantics

Denotational & Axiomatic Semantics

λ-calculus



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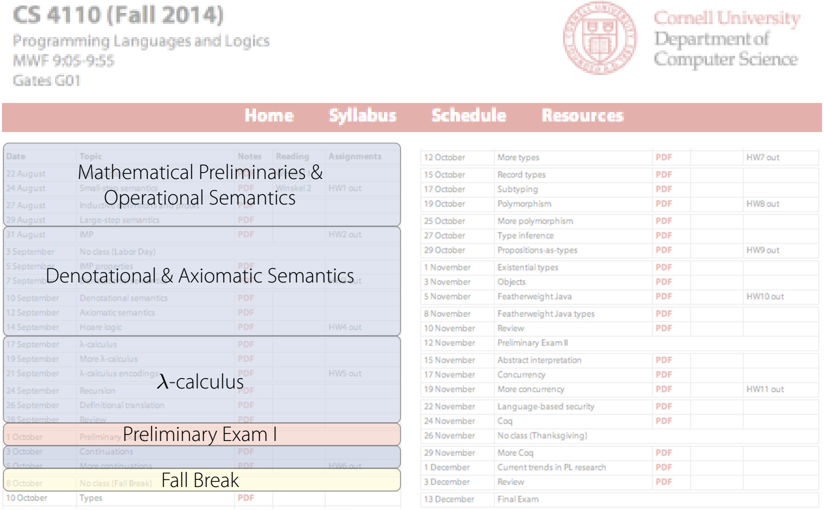

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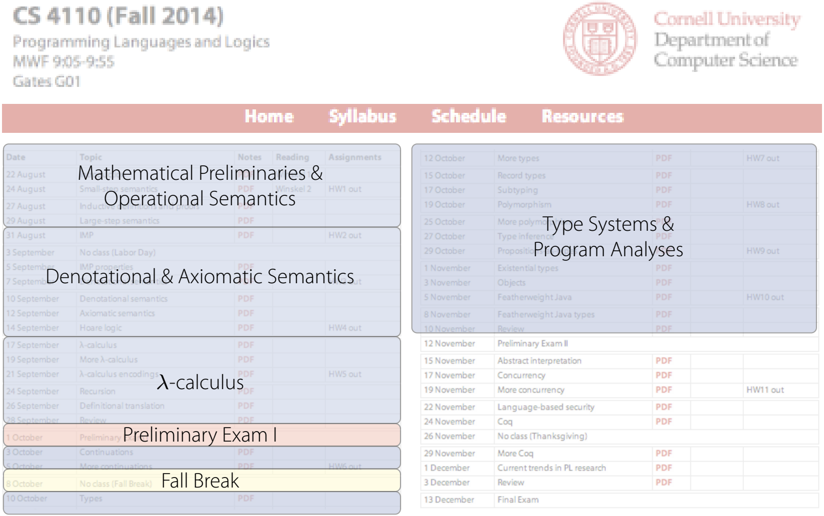

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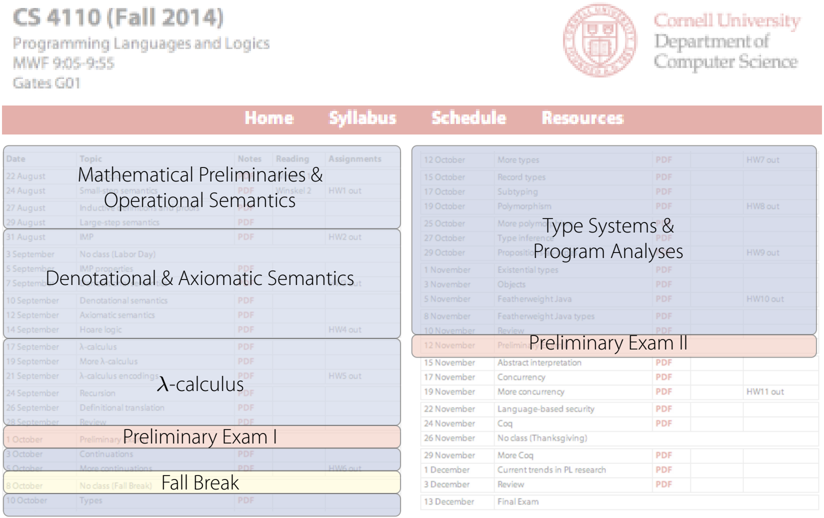
Denotational & Axiomatic Semantics

λ-calculus

Preliminary Exam I

Fall Break

Type Systems & Program Analyses



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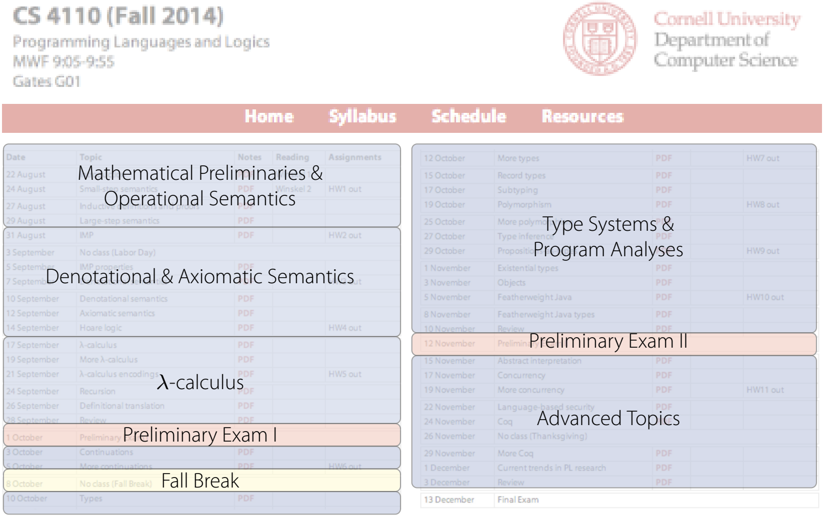

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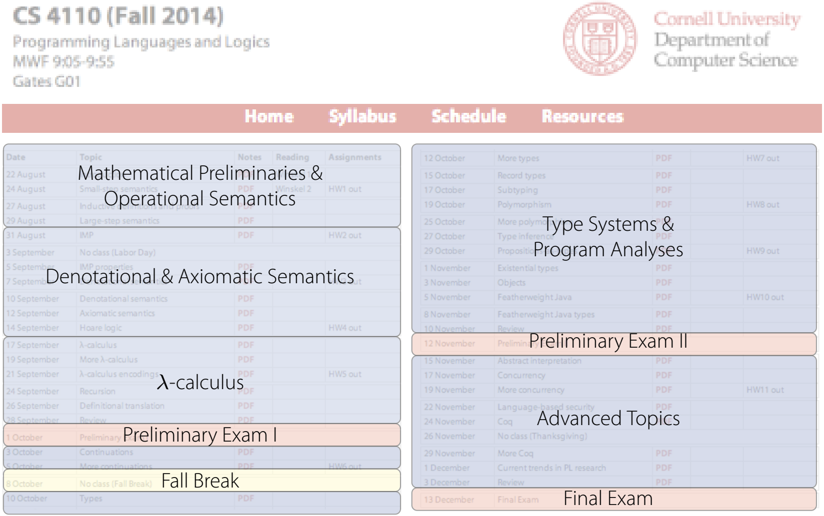
Advanced Topics



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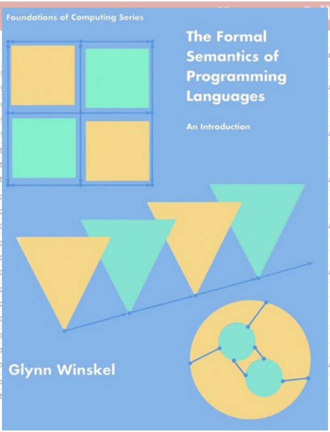
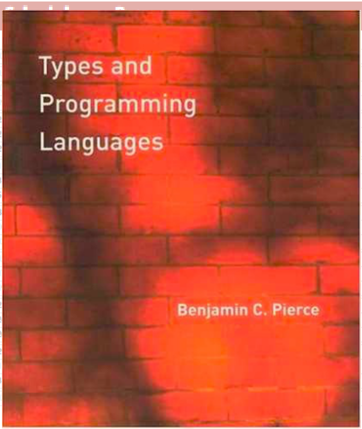
Cornell University
Department of Computer Science





Course Work

Participation (5%)

- Lectures
- Office hours
- Online discussions

Homework (40%)

- 10 assignments, roughly one per week
- Mix of theory and practice
- Can work with *one* partner
- No late submissions
- Two slip days and lowest score discarded

Preliminary Exams (15% each)

- October 6th
- November 14th

Final Exam (25%)

- Date TBD

Academic Integrity

Some simple requests:

1. You are here as members of an academic community. Conduct yourself with integrity.

2. Problem sets must be completed with your partner, and only your partner. You must *not* consult other students, alums, friends, Google, GitHub, StackExchange, Course Hero, etc.!

3. If you aren’t sure what is allowed and what isn’t, please ask.

Special Needs and Wellness

- I will provide reasonable accommodations to students with documented disabilities (e.g., physical, learning, psychiatric, vision, hearing, or systemic).

- If you are experiencing undue personal or academic stress at any time during the semester (or if you notice that a fellow student is), contact me, Engineering Advising, or Gannett.

Language Specification

Language Specification

Formal Semantics: what do programs mean?

Three Approaches

- Operational
  - Models program by its execution on abstract machine
  - Useful for implementing compilers and interpreters
- Axiomatic
  - Models program by the logical formulas it obeys
  - Useful for proving program correctness
- Denotational
  - Models program literally as mathematical objects
  - Useful for theoretical foundations

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Question: few languages have a formal semantics. Why?

Formal Semantics

Too Hard?

- Modeling a real-world language is hard
- Notation can gets very dense
- Sometimes requires developing new mathematics
- Not yet cost-effective for everyday use

Overly General?

- Explains the behavior of a program on *every* input
- Most programmers are content knowing the behavior of their program on *this* input (or these inputs)

Okay, so who needs semantics?

A Tricky Example

Question #1: is the following Java program legal?

Question #2: if yes, what does it do?

```
class A { static int a = B.b + 1; }
class B { static int b = A.a + 1; }
```

Who Needs Semantics?

Unambiguous Description

- Anyone who wants to design a new feature
- Basis for most formal arguments
- Standard tool in PL research

Exhaustive Reasoning

- Sometimes have to know behavior on all inputs
- Compilers and interpreters
- Static analysis tools
- Program transformation tools
- Critical software

Language Design

Design Desiderata

Question: What makes a good programming language?

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Wrong! Are COBOL and JavaScript the best languages?

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Wrong! Are COBOL and JavaScript the best languages?

Some good features:

- Simplicity (clean, orthogonal constructs)
- Readability (elegant syntax)
- Safety (guarantees that programs won’t “go wrong”)
- Support for programming in the large (modularity)
- Efficiency (good execution model and tools)

Design Challenges

Unfortunately these goals almost always conflict.

- Types provide strong guarantees but restrict expressiveness.
- Safety checks eliminate errors but have a cost—either at compile time or run time.
- Some verification tools are so complicated, you essentially need a PhD to use them!

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A lot of research in programming languages is about discovering ways to gain without (too much) pain.

Story: Unexpected Interactions

A real story illustrating the perils of language design

Cast of characters includes famous computer scientists

Timeline:

- 1982: ML is a functional language with type inference, polymorphism (generics), and monomorphic references (pointers)
- 1985: Standard ML innovates by adding polymorphic references → unsoundness
- 1995: The "innovation" fixed

ML Type System

Polymorphism: allows code to be used at different types

Examples:

- List.length : $\forall\alpha.\ \alpha$ list $\rightarrow$ int
- List.hd : $\forall\alpha.\ \alpha$ list $\rightarrow \alpha$

Type Inference: $e \leadsto \tau$

- e.g., let $id\ (x) = x \leadsto \forall\alpha.\ \alpha \rightarrow \alpha$
- Generalize types not constrainted by the program
- Instantiate types at use id (true) $\leadsto$ bool

ML References

By default, values in ML are immutable.

But we can easily extend the language with imperative features.

Add reference types of the form τ ref

Add expressions of the form

ref $e : \tau$ ref	where $e : \tau$	(allocate)
$!e : \tau$	where $e : \tau$ ref	(dereference)
$e_1 := e_2$: unit	where $e_1 : \tau$ *ref* and $e_2 : \tau$	(assign)

Works as you'd expect (like pointers in C).

Polymorphism + References

Consider the following program

Code	Type Analysis
`let id = (fun x -> x)`	

Polymorphism + References

Consider the following program

Code	Type Analysis
`let id = (fun x -> x)`	
`let p = ref id`	

Polymorphism + References

Consider the following program

Code	Type Analysis

`let id = (fun x -> x)`
`let p = ref id`
`let inc = (fun n -> n+1)`	

Polymorphism + References

Consider the following program

Code	Type Analysis
let id = (fun x -> x)	
let p = ref id	
let inc = (fun n -> n+1)	
p := inc;	
(!p) true	

Polymorphism + References

Consider the following program

Code	Type Analysis
let id = (fun x -> x)	id : $\alpha \to \alpha$
let p = ref id	
let inc = (fun n -> n+1)	
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Polymorphism + References

Consider the following program

Code	Type Analysis
`let id = (fun x -> x)`	id : $\alpha \to \alpha$
`let p = ref id`	p : $(\alpha \to \alpha)$ ref
`let inc = (fun n -> n+1)`	
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Code	Type Analysis
`let id = (fun x -> x)`	id : $\alpha \to \alpha$
`let p = ref id`	p : $(\alpha \to \alpha)$ ref
`let inc = (fun n -> n+1)`	inc : int $\to$ int
`p := inc;`	OK since p : (int $\to$ int) ref
`(!p) true`	OK since p : (bool $\to$ bool) ref

Polymorphism + References

Problem

- Type system is not sound
- Well-typed program $\rightarrow^*$ type error!

Polymorphism + References

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Proposed Solutions

1. "Weak" type variables
    - Can only be instantiated in restricted ways
    - But type exposes functional vs. imperative
    - Difficult to use

Polymorphism + References

Problem

- Type system is not sound
- Well-typed program $\rightarrow^*$ type error!

Proposed Solutions

1. “Weak” type variables
    - Can only be instantiated in restricted ways
    - But type exposes functional vs. imperative
    - Difficult to use
2. Value restriction
    - Only generalize types of values
    - Most ML programs already obey it
    - Simple proof of type soundness

Lessons Learned

- Features often interact in unexpected ways
- The design space is huge
- Good designs are sparse and don't happen by accident
- Simplicity is rare: n features → n^2 interactions
- Most PL researchers work with small languages (e.g., λ-calculus) to study core issues in isolation
- But must pay attention to whole languages too