CS 4110

Programming Languages & Logics

Lecture 1
Course Overview

22 August 2012

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: Upson 4137
Hours: Mon 4-5pm and Wed 11am-12pm

Teaching Assistants

TBA

Web Page

`http://www.cs.cornell.edu/Courses/cs4110/2012fa`

`http://bit.ly/CS4110`

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

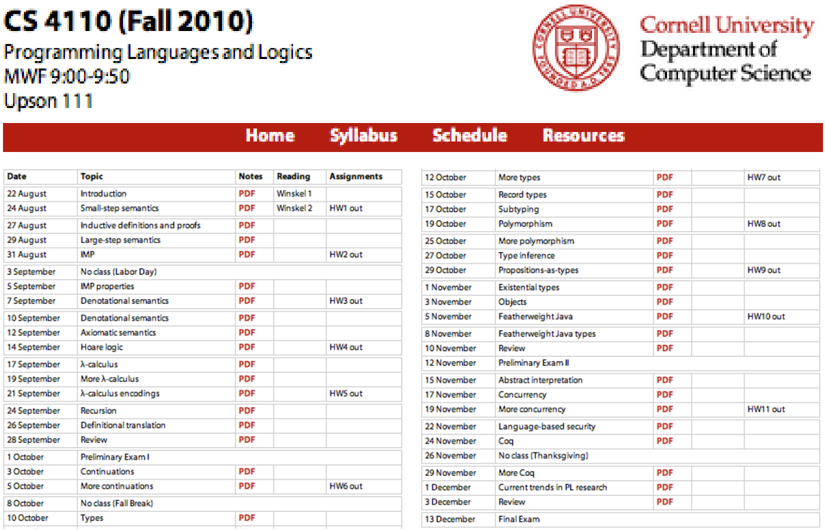
- Much of this class will involve formal reasoning
- Set theory, formal proofs, induction
- Most challenging topic: denotational semantics

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



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Programming Languages and Logics
MWF 9:00-9:50
Upson 111

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Computer Science

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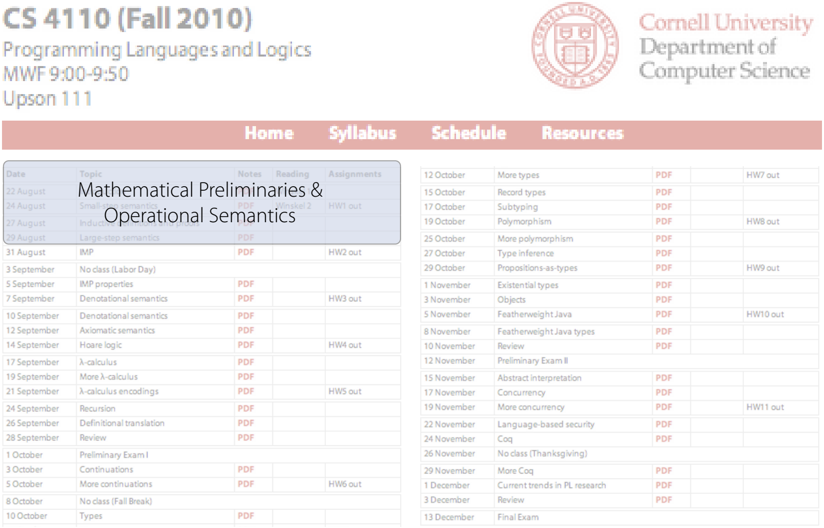
Mathematical Preliminaries & Operational Semantics



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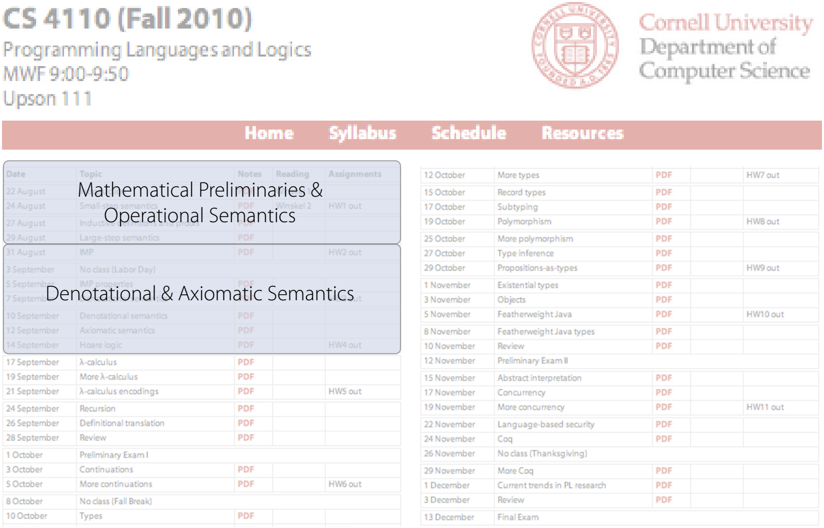

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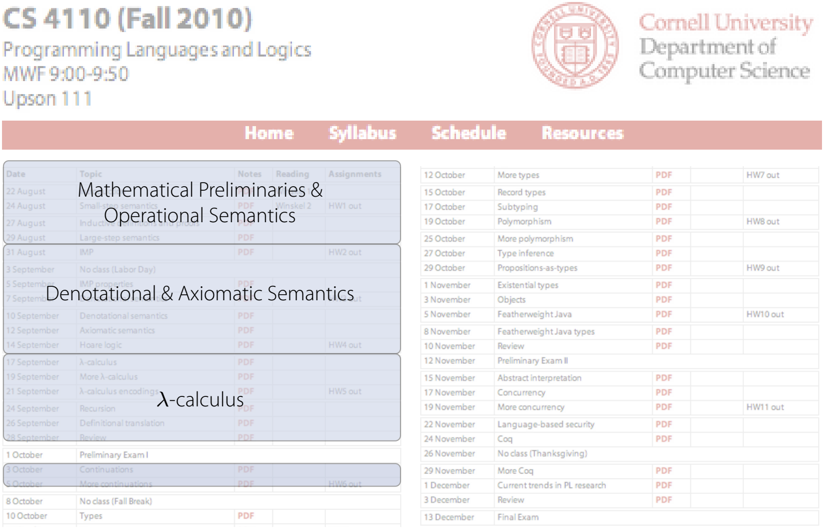

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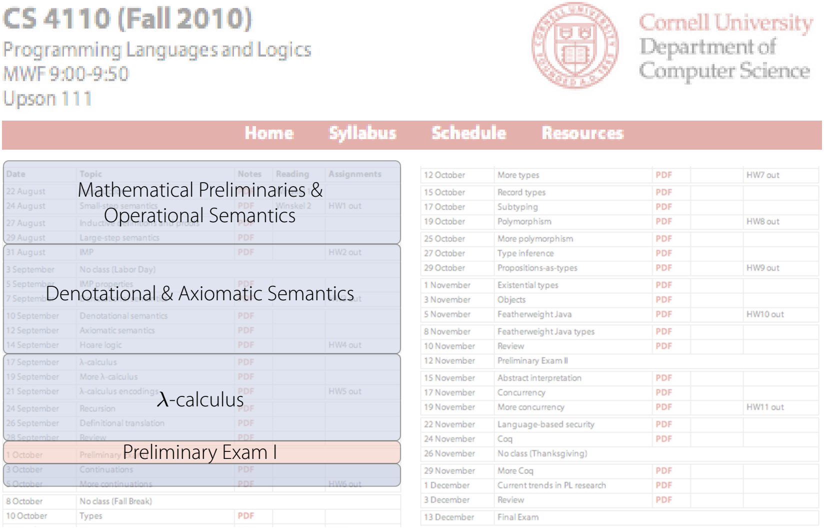
Mathematical Preliminaries & Operational Semantics

Denotational & Axiomatic Semantics

λ-calculus



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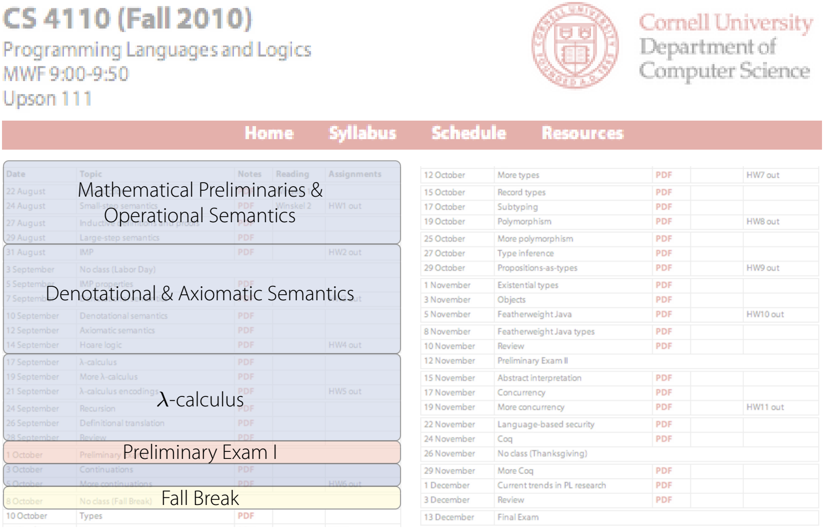

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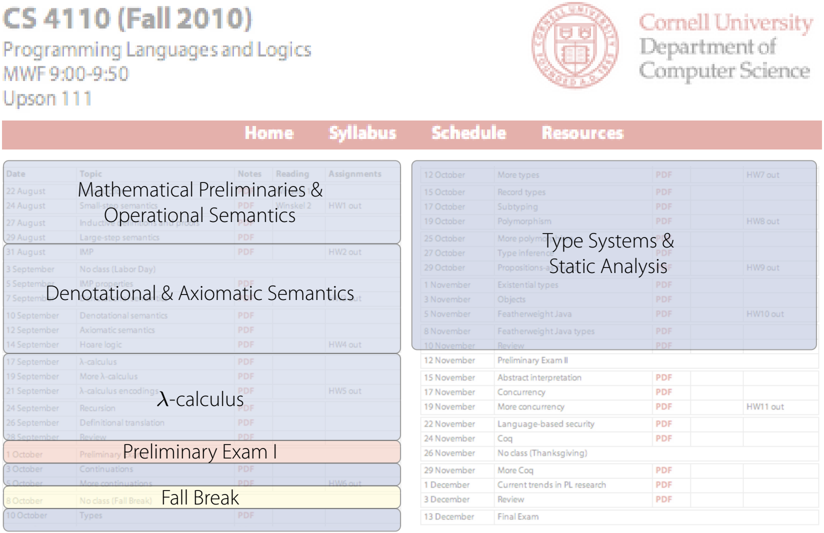

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Type Systems & Static Analysis

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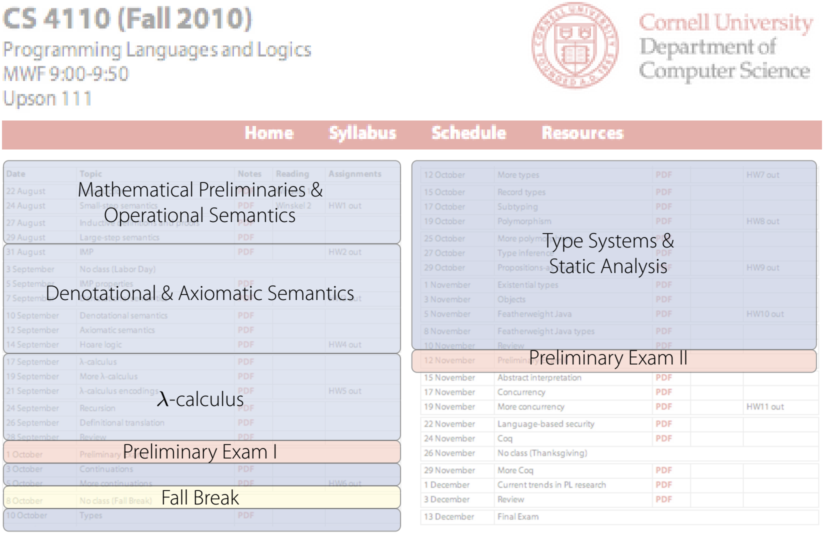

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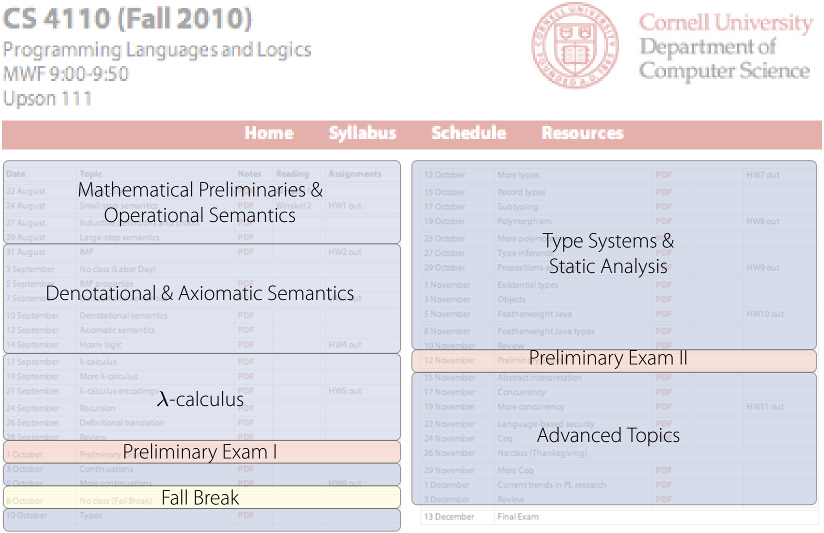
Preliminary Exam I

Fall Break

Type Systems & Static Analysis

Preliminary Exam II



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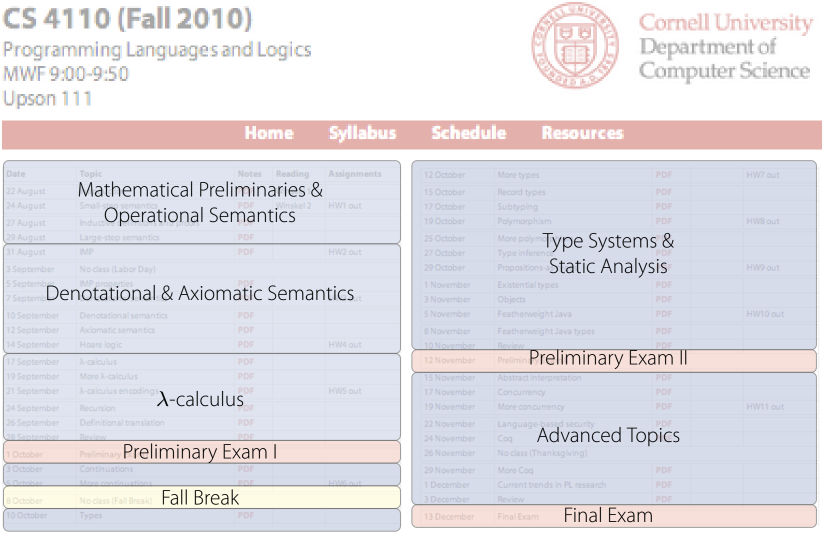
Type Systems & Static Analysis

Preliminary Exam II

Advanced Topics



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29 November	More Coq	PDF		
1 December	Current trends in PL research	PDF		
3 December	Review	PDF		
13 December	Final Exam			

CS 4110 (Fall 2010)

Programming Languages and Logics
MWF 9:00-9:50
Upson 111

Cornell University
Department of
Computer Science

labus

Date	ments
22 Au	
24 Au	ut
27 Au	
29 Au	
31 Au	ut
3 Sept	
5 Sept	
7 Sept	ut
10 Sep	
12 Sep	
14 Sep	ut
17 Sep	
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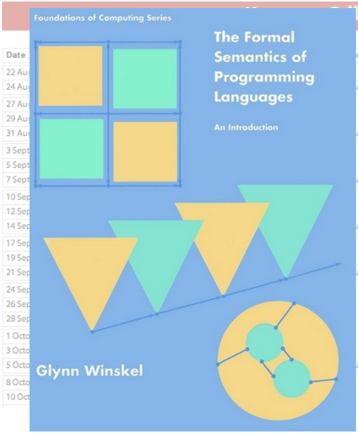
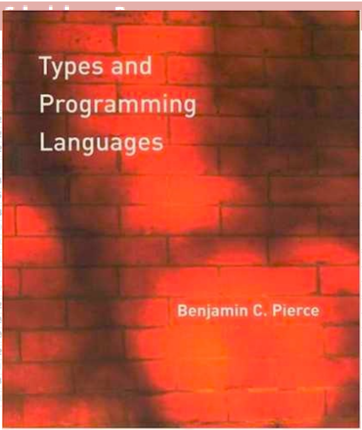


Foundations of Computing Series

The Formal Semantics of Programming Languages

An Introduction

Glynn Winskel



Types and Programming Languages

Benjamin C. Pierce

Course Work

Participation (5%)

- Lectures
- Office hours
- Coffee
- Piazza discussions

Homework (40%)

- 11 assignments, roughly one per week
- Mix of theory and practice

Preliminary Exams (15% each)

- October 1st
- November 14th

Final Exam (25%)

- December 12th

Academic Integrity

Two simple requests:

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

2. 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 who have a documented disability (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

Language Specification

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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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One answer: “a good language is one people use”

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Wrong! Are COBOL and JavaScript the best languages?

Design Desiderata

Question: What makes a good programming language?

One answer: “a good language is one people use”

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!

Design Challenges

Unfortunately these goals almost always conflict.

- Types provide strong guarantees but restrict expressiveness.
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- Some verification tools are so complicated, you essentially need a PhD to use them!

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: $e \rightsquigarrow \tau$

- e.g., let $id\,(x) = x \rightsquigarrow \forall\alpha.\ \alpha \rightarrow \alpha$
- Generalize types not constrainted by the program
- Instantiate types at use id (true) $\rightsquigarrow$ 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 : τ ref	where e : τ	(allocate)
!e : τ	where e : τ ref	(dereference)
$e_1 := e_2$: unit	where e_1 : τ *ref* and e_2 : τ	(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)	
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	p : $(\alpha \to \alpha)$ ref
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	p : $(\alpha \to \alpha)$ ref
let inc = (fun n -> n+1)	inc : int $\to$ int
p := inc;	
(!p) true	

Polymorphism + References

Consider the following program

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

Polymorphism + References

Problem

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

Polymorphism + References

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- 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

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 $\rightarrow$ n^2 interactions
- Most PL researchers work with really small languages (e.g., λ-calculus) to study core issues in isolation
- But must pay attention to whole languages too