Lecture 1

CIS 500: SOFTWARE FOUNDATIONS

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Fall 2016

How do we **build** software?
^
that works
^
(and be confident
that it does)

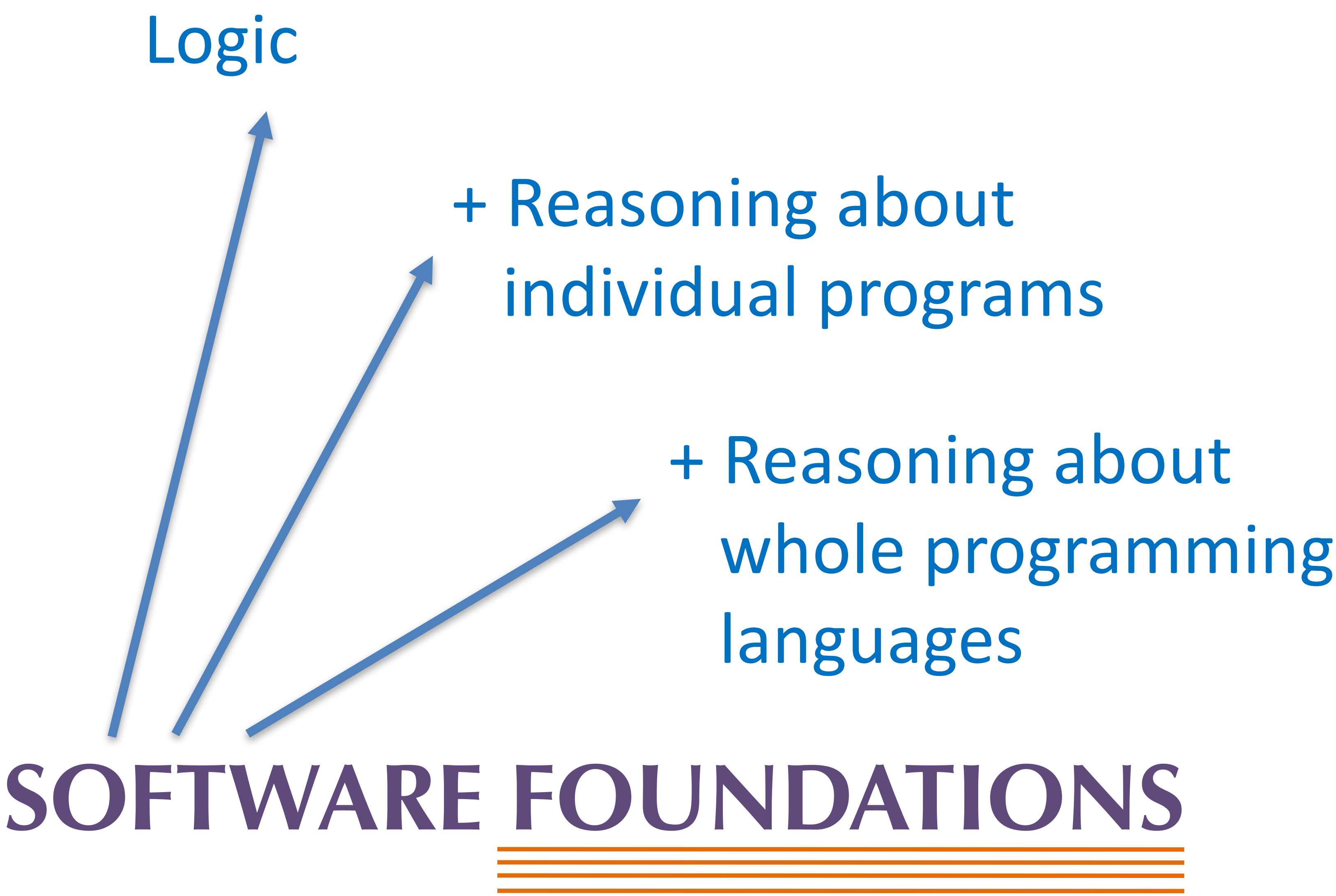
Critical Software

Individual programs

- Operating systems
- Network stacks
- Crypto
- Medical devices
- Flight control systems
- Power plants
- Home security
- …

Programming languages

- Static type systems
- Data abstraction and modularity
- Security controls
- Compiler correctness


Logic
+ Reasoning about individual programs
+ Reasoning about whole programming languages
SOFTWARE FOUNDATIONS

LOGICAL FOUNDATIONS

Q: How do we know something is true?

A: We test it out

Q: But that isn't truth; testing can only give us evidence. How do we know something is **true**?

A: We prove it

Q: How do we know that we have a proof?

A: We need to define what it means to be a proof. A proof is a logical sequence of arguments, starting from some initial assumptions

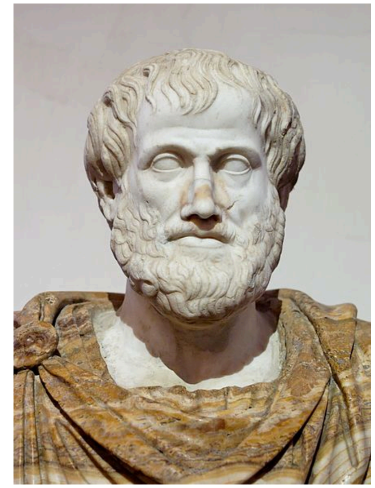
Q: How do we know that we have a valid sequence of arguments? Can any list be a proof?

All humans are mortal

All Greeks are human

Therefore I am a Greek!

A: No, no, no! We need to think about how we *think*….



Aristotle
384 – 322 BC

Euclid
~300 BC

First we need a language…

- Gottlob Frege: a German mathematician who started in geometry but became interested in logic and foundations of arithmetic.

- 1879 Published "*Begriffsschrift, eine der arithmetischen nachgebildete Formelsprache des reinen Denkens*" (Concept-Script: A Formal Language for Pure Thought Modeled on that of Arithmetic)
  - First rigorous treatment of functions and quantified variables
  - $\vdash A$, $\neg A$, $\forall x.F(x)$
  - First notation able to express arbitrarily complicated logical statements

Gottlob Frege
1848-1925


BEGRIFFSSCHRIFT,

EINE DER ARITHMETISCHEN NACHGEBILDETE

FORMELSPRACHE

DES REINEN DENKENS.

VON

Dr. GOTTLOB FREGE.

HALLE a/S.

VERLAG VON LOUIS NEBERT.

1879.

Images in this & following slides taken from Wikipedia.

Formalization of Arithmetic

- 1884: *Die Grundlagen der Arithmetik* (The Foundations of Arithmetic)
- 1893: *Grundgesetze der Arithmetik* (Basic Laws of Arithmetic, Vol. 1)
- 1903: *Grundgesetze der Arithmetik* (Basic Laws of Arithmetic, Vol. 2)
- Frege's Goals:
  - isolate logical principles of inference
  - derive laws of arithmetic from first principles
  - set mathematics on a solid foundation of logic

- David Hilbert: a German recognized as one of the most influential mathematicians ever.
  - algebra, axiomatization of geometry, physics,…
  - 1900: published his "23 Problems"
    - Problem #2: Prove
      are consistent

ilbert
1943

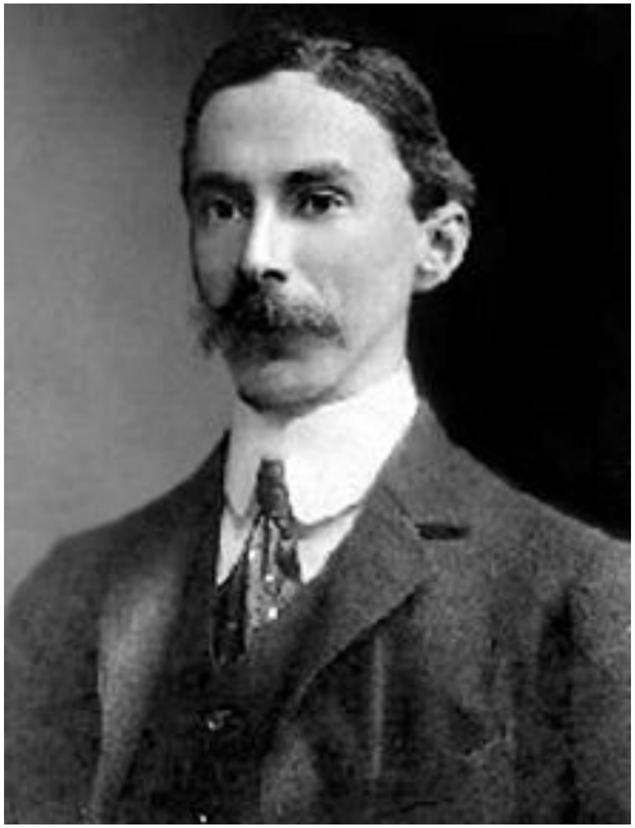
The plot thickens…

Just as Volume 2 was going to print in 1903, Frege received a letter…

Bertrand Russell

- *Russell's paradox:*

> 1. Set comprehension notation:
>   { x | P(x) }   "The set of x such that P(x)"
>
> 2. Let X be the set { Y | Y $\notin$ X }.
>
> 3. Ask the logical question:
>   Does X $\in$ X hold?
>
> 4. Paradox!   If X $\in$ X then X $\notin$ X.
>   If X $\notin$ X then X $\in$ X.



Bertrand Russell
1872 - 1970

- Frege's language could derive Russell's paradox $\Rightarrow$ it was *inconsistent*.
- Frege's logical system could derive anything. Oops(!!)

Addendum to Frege's 1903 Book

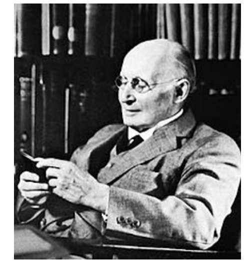
"Hardly anything more unfortunate can befall a scientific writer than to have one of the foundations of his edifice shaken after the work is finished. This was the position I was placed in by a letter of Mr. Bertrand Russell, just when the printing of this volume was nearing its completion."

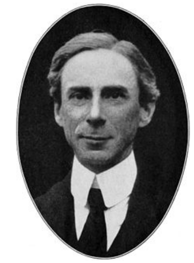
– Frege, 1903

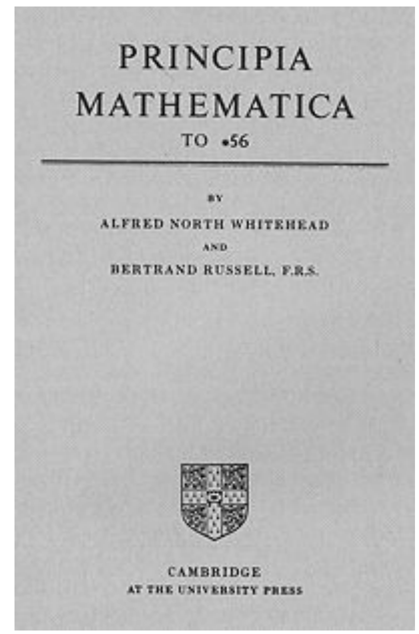
Aftermath of Frege and Russell

- Frege came up with a fix, but it made his logic trivial…
- 1908: Russell fixed the inconsistency of Frege's logic by developing a *theory of types*.
- 1910, 1912, 1913, (revised 1927): *Principia Mathematica* (Whitehead & Russell)
  - Goal: axioms and rules from which *all* mathematical truths could be derived.
  - It was a bit unwieldy…

> "From this proposition it will follow,
> when arithmetical addition has been defined,
> that 1+1=2."
> —Volume I, 1st edition, *page 379*


Whitehead


Russell


PRINCIPIA
MATHEMATICA
TO *56

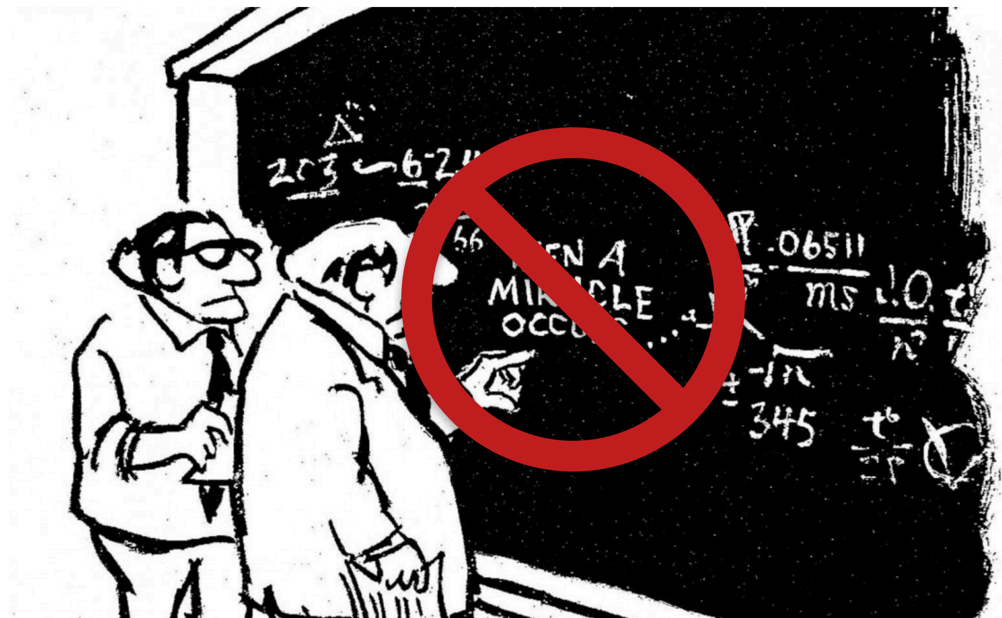
BY
ALFRED NORTH WHITEHEAD
AND
BERTRAND RUSSELL, F.R.S.

CAMBRIDGE
AT THE UNIVERSITY PRESS

1920's: Hilbert's Program

A plan to secure the foundations of mathematics:

- Develop a *formal system* of all mathematics.
  - Mathematical statements should be written in a precise formal language
  - Mathematical proofs should proceed by well-specified rules
- Prove *completeness*
  - i.e. that all true mathematical statements can be proved
- Prove *consistency*
  - i.e. that no contradictory conclusions can be proved
- Prove *decidability*
  - i.e. there should be an algorithm for determining whether a given statement has a proof



Things were going well, following Russell & Whitehead, until…

Logic in the 1930s and 1940s

- 1931: Kurt Gödel's first and second incompleteness theorems.
  - Demonstrated that any consistent formal theory capable of expressing arithmetic cannot be complete.
  - Write down: "This statement is not provable." as an arithmetic statement.

- 1936: Genzen proves consistency of arithmetic.
- 1936: Church introduces the λ-calculus.
- 1936: Turing introduces Turing machines
  - Is there a decision procedure for arithmetic?
  - Answer: no, it's undecidable
  - The famous "halting problem"
    - only in 1938 did Turing get his Ph.D.

- 1940: Church introduces the *simple theory of types*

Kurt Gödel
1906 - 1978

Gerhard Gentzen
1909 - 1945

Alonzo Church
1903 - 1995

Alan Turing
1912 - 1954

Fast Forward…

- 1958 (Haskell Curry) and 1969 (William Howard) observe a remarkable correspondence:

Haskell Curry
1900 – 1982

William Howard
1926 –

types	~	propositions
programs	~	proofs
computation	~	simplification

N.G. de Bruijn
1918 - 2012

- 1967 – 1980's: N.G. de Bruijn runs Automath project
  - uses the Curry-Howard correspondence for computer-verified mathematics

- 1971: Jean-Yves Girard introduces System F
- 1972: Girard introduces Fω
- 1972: Per Marin-Löf introduces intuitionistic type theory
- 1974: John Reynolds independently discovers System F

Basis for modern type systems: OCaml, Haskell, Scala, Java, C#, …

… to the Present

- 1984: Coquand and Huet first begin implementing a new theorem prover "Coq"
- 1985: Coquand introduces the calculus of constructions
  - combines features from intuitionistic type theory and Fω
- 1989: Coquand and Paulin extend CoC to the calculus of inductive constructions
  - adds "inductive types" as a primitive
- 1992: Coq ported to Xavier Leroy's OCaml
- 1990's: up to Coq version 6.2
- 2000-2015: up to Coq version 8.4
- 2016: Coq version 8.5 ← CIS 500

Too many contributors to list here…

- 2013: Coq receives ACM Software System Award

Thiery Coquand
1961 –

Gérard Huet
1947 –

http://coq.inria.fr/refman/Reference-Manual002.html

So much for foundations… what about the “software” part?

PROGRAMMING FOUNDATIONS

Building Reliable Software

- Suppose you work at (or run) a software company.

- Suppose, like Frege, you've sunk 30+ person-years into developing the "next big thing":
  - Boeing Dreamliner2 flight controller
  - Autonomous vehicle control software for Nissan
  - Gene therapy DNA tailoring algorithms
  - Super-efficient green-energy power grid controller

- Suppose, like Frege, your company has invested a lot of material resources that are also at stake.

- How do you avoid getting a letter like the one from Russell?

Or, worse yet, *not* getting the letter,
with disastrous consequences down the road?

Approaches to Software Reliability

- Social
  - Code reviews
  - Extreme/Pair programming
- Methodological
  - Design patterns
  - Test-driven development
  - Version control
  - Bug tracking
- Technological
  - "lint" tools, static analysis
  - Fuzzers, random testing
- Mathematical
  - Sound type systems
  - "Formal" verification

Less "formal": Techniques may miss problems in programs

This isn't a tradeoff… all of these methods should be used.

Even the most "formal" argument can still have holes:

- Did you prove the right thing?
- Do your assumptions match reality?
- Knuth: "Beware of bugs in the above code; I have only proved it correct, not tried it."

More "formal": eliminate *with certainty* as many problems as possible.

Five Interwoven Threads

1. basic tools from logic for making and justifying precise claims about programs
2. the use of proof assistants to construct rigorous, machine checkable, logical arguments
3. the idea of functional programming, both as a method of programming and as a bridge between programming and logic
4. techniques for formal verification of properties of specific programs
5. the use of type systems for establishing well-behavedness guarantees for all programs in a given language

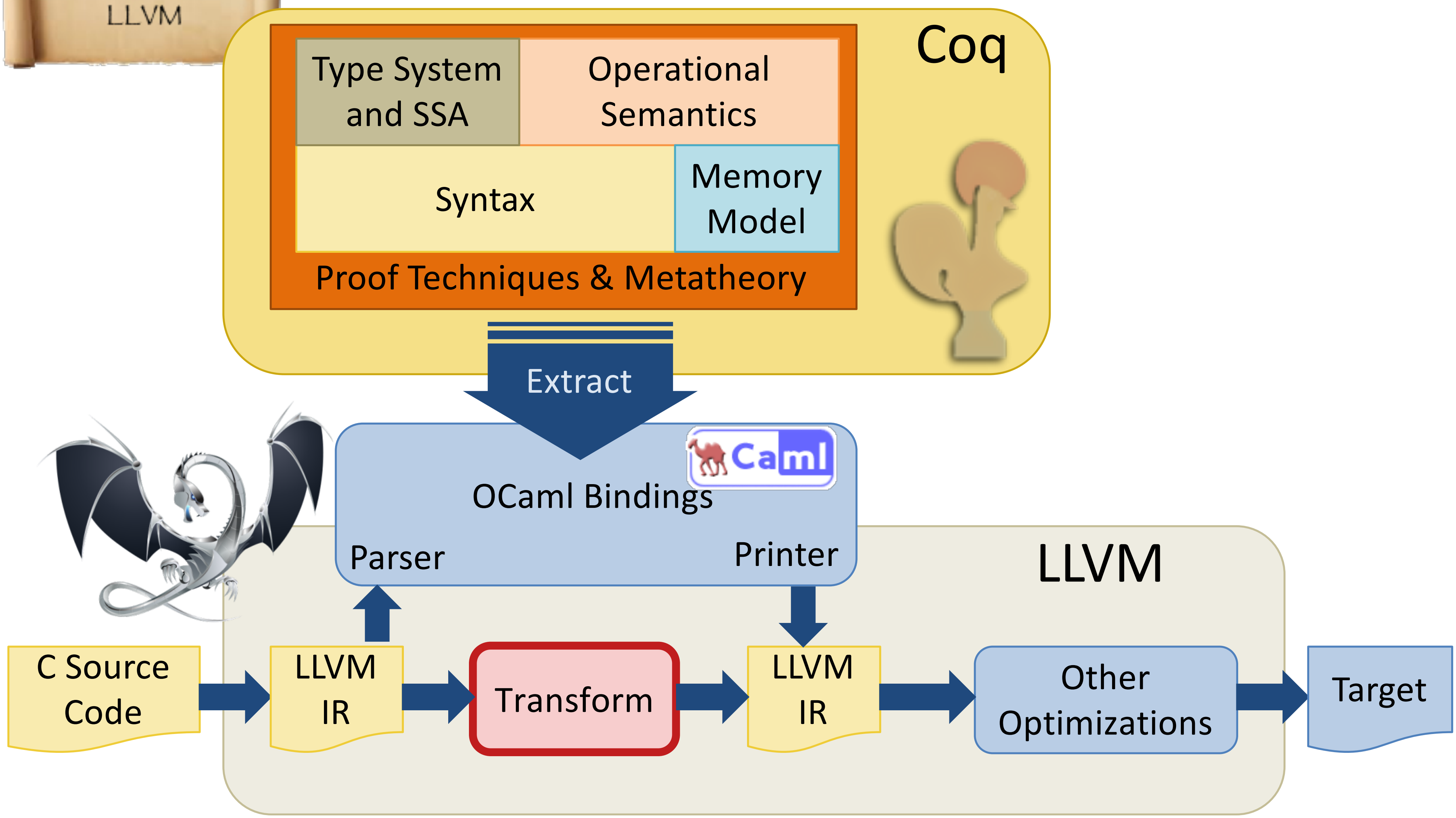
Can it Scale?

Use of formal methods to verify full-scale software systems is a hot research topic!

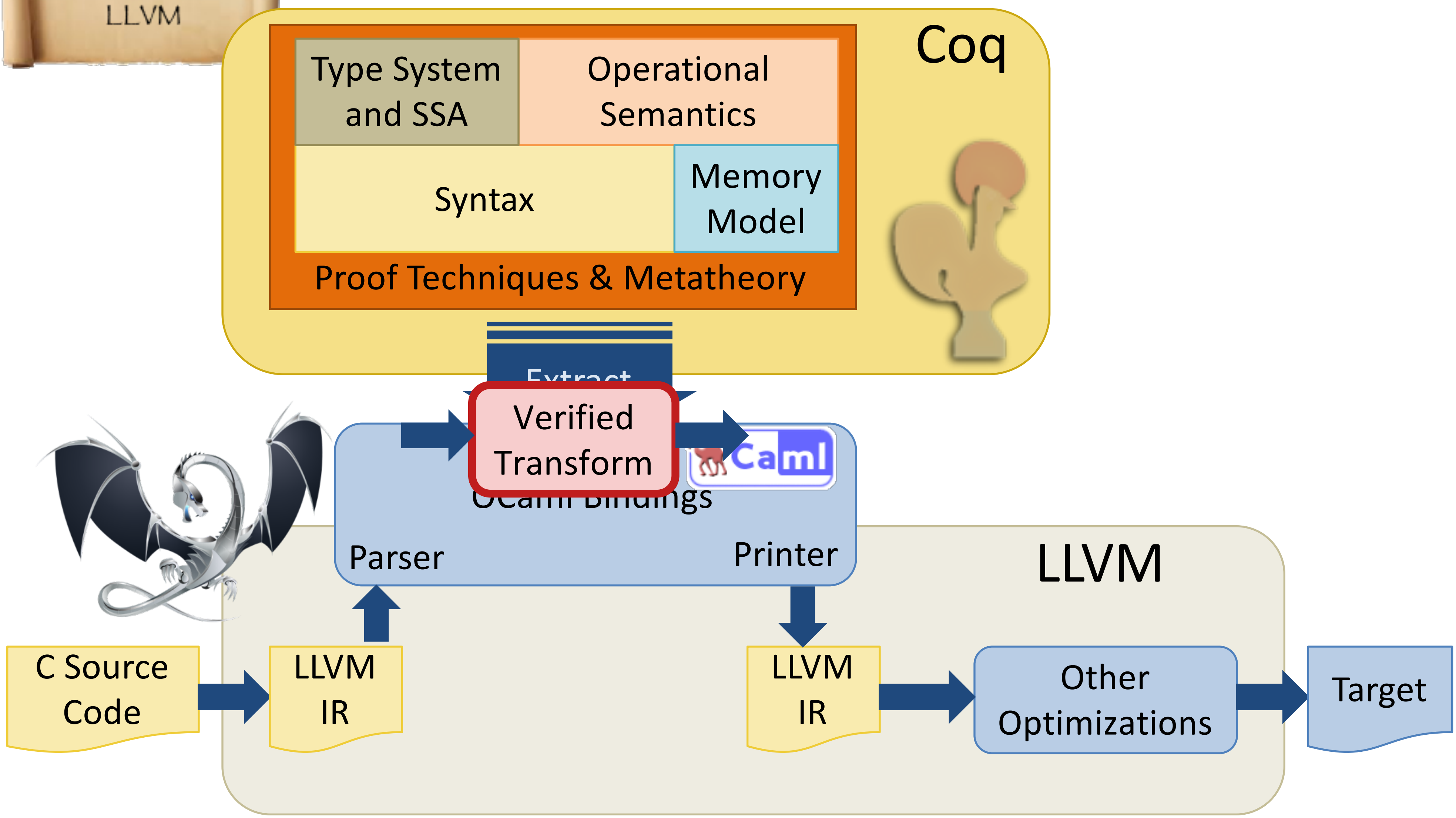
- CompCert – fully verified C compiler
  Leroy, INRIA

- Vellvm – formalized LLVM IR
  Zdancewic, Penn
- Ynot – verified DBMS, web services
  Morrisett, Harvard
- Verified Software Toolchain
  Appel, Princeton
- Bedrock – web programming, packet filters
  Chlipala, MIT
- CertiKOS – certified OS kernel
  Shao & Ford, Yale

Vellvm Framework

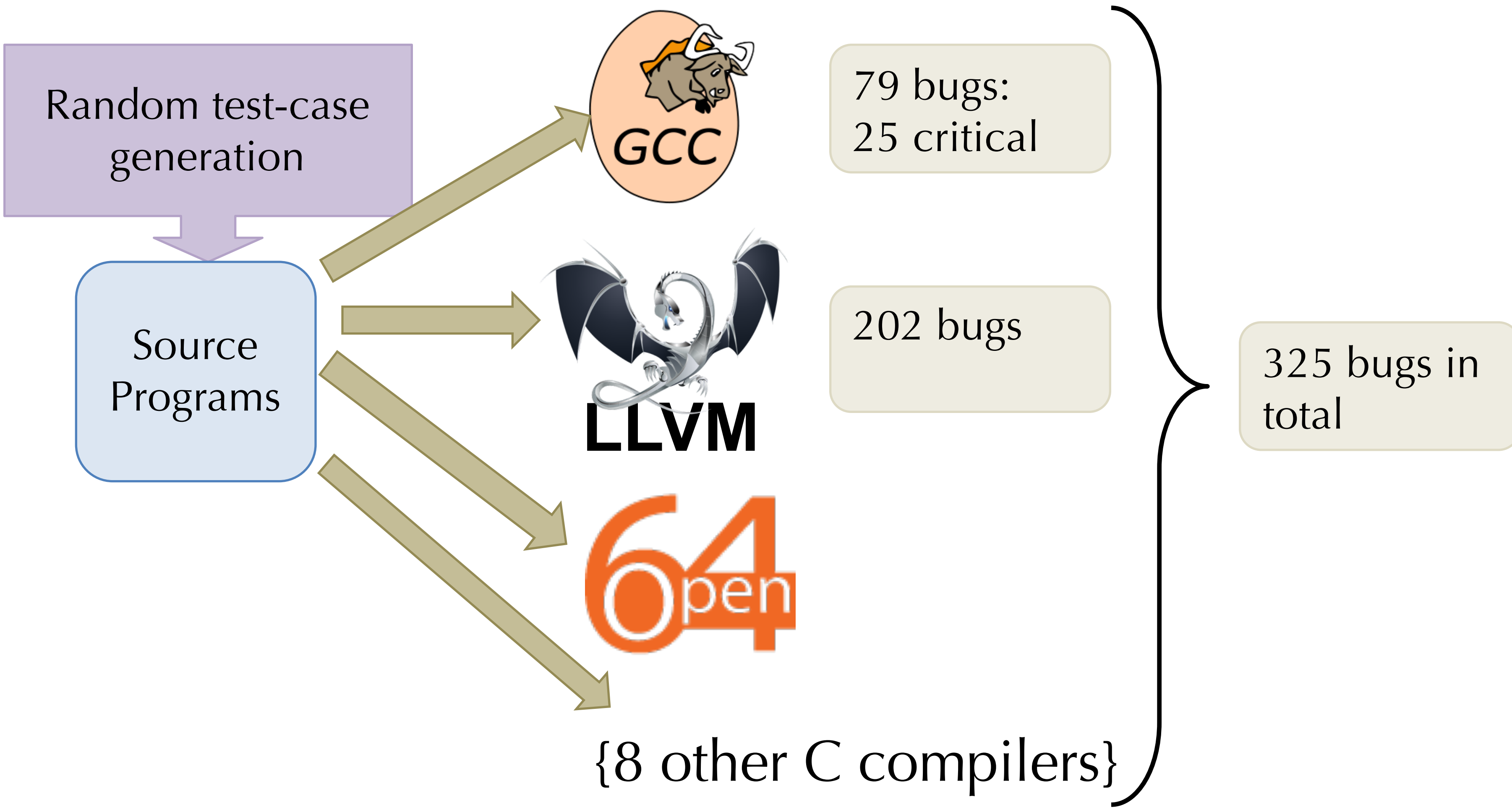


Vellvm Framework



Does it work?

Finding and Understanding Bugs in C Compilers [Yang et al. PLDI 2011]



Verified Compiler: CompCert [Leroy et al.]
<10 bugs found in *unverified* front-end component

Regehr's Group Concludes

The striking thing about our CompCert results is that the *middle-end bugs* we found in all other compilers are *absent*. As of early 2011, the under-development version of *CompCert is the only compiler we have tested for which Csmith cannot find wrong-code errors*. This is not for lack of trying: we have devoted about six CPU-years to the task. *The apparent unbreakability of CompCert supports a strong argument that developing compiler optimizations within a proof framework, where safety checks are explicit and machine-checked, has tangible benefits for compiler users.*

deep spec the science of deep specification

- National Science Foundation "Expedition" Project
  - $10M over five years
  - Penn: Pierce / Weirich / Zdancewic
  - Princeton: Appel
  - Yale: Shao
  - MIT: Chlipala

- Many ways to get involved (especially after CIS 500!)
- See www.deepspec.org

CIS 500

- Foundations
  - Functional programming
  - Constructive logic
  - Logical foundations
  - Proof techniques for inductive definitions
- Semantics
  - Operational semantics
  - Modeling imperative "While" programs
  - Hoare logic for reasoning about program correctness
- Type Systems
  - Simply typed λ-calculus
  - Type safety
  - Subtyping
  - Dependently-typed programming
- Coq interactive theorem prover
  - turns doing proofs & logic into programming → fun!

COURSE MECHANICS

Administrivia

- Instructor: Benjamin Pierce
  Office hours: Tuesdays, 4-5:30
  Levine 562

- TAs:
  - Kenny Foner
    Office hours: Fridays 10-noon
  - Antoine Voizard
    Office hours: Monday afternoons

- Location: Berger Auditorium
- E-mail: cis500@seas.upenn.edu (goes to all course staff)
- Web site: http://www.seas.upenn.edu/~cis500
- Canvas: https://upenn.instructure.com
- PiazzQ: http://piazza.com/upenn/spring2016/cis500

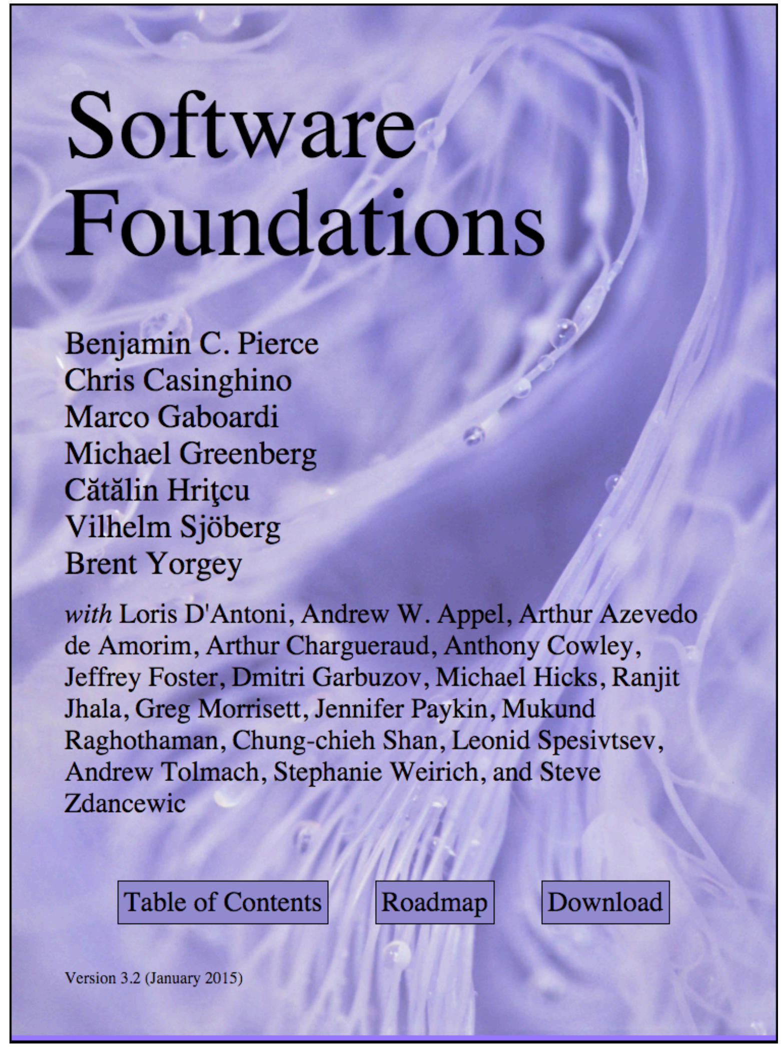
Resources

- Course textbook: *Software Foundations*
  - Electronic edition tailor-made for this class

Use the version available from the cis500 course web pages!!

(A new version of each chapter will generally go live just before class. :-)

- Additional resources:
  - *Types and Programming Languages* (Pierce, 2002 MIT Press)
  - *Interactive Theorem Proving and Program Development* (Bertot and Castéran, 2004 Springer)
  - *Certified Programming with Dependent Types* (Chlipala, electronic edition)



Course Policies

- Prerequisites:
  - Significant programming experience
  - Mathematical sophistication
  - Undergraduate functional programming or compilers class helpful

Grading:

• 24% Homework	(~12 weekly assignments)
• 18% Midterm I	(in class, probably Oct 4^{th})
• 18% Midterm 2	(in class, probably Nov. 8^{th})
• 36% Final	(Tuesday, Dec. 20, noon-2PM)
• 4% Class participation	

⇒ Lecture attendance is crucial!

"Regular" and "Advanced" tracks are graded separately

“Regular” vs. “Advanced” Tracks

- “Advanced” track:
  - More and harder exercises
  - More challenging exams
  - Covering a superset of the “regular” material

- Everybody starts in the advanced track by default.
- Students who wish to take CIS 500 for WPE I credit (Ph.D.) *must* complete the advanced track.
- Students may switch from advanced to regular track at any time.
  - Notify the course staff in writing (by e-mail).
  - The change is *permanent* after the first midterm.
- Students wishing to switch (back) to the advanced track:
  - Must do so *before* the first midterm exam.
  - Must make up all the advanced exercises (or accept the grade penalty).
- Only students taking the advanced track are eligible for an A+.

Class Participation

- Class attendance is mandatory.
- We will be using "clickers" for
  - in-class mini quizzes
  - Real-time "polls" during lectures
- TurningPoint clicker use will also be your attendance record.
- For next time: *buy a clicker.*
- *Any TurningPoint RF clicker will work; see note on course website.*

Homework Policies

- Homework is to be done *individually*
- Homework must be *submitted via Canvas*
- Homework that is late is subject to:
  - 25% penalty for 1 day late (up to 24 hours after deadline)
  - 50% penalty for 2 days late
  - 75% penalty for 3 days late

- Homework is due at *11:00am* on the due date
- Advanced track students must complete (or try to complete) all non-optional exercises.
  - Missing "advanced" exercises will count against your score.
- Regular track students must complete (or try to complete) all non-optional exercises except those marked "advanced".
  - Missing "advanced" exercises will not count against your score.
  - (But you are welcome to try them!)

TODO for you

- Before next class:
  - Register for Piazza (if you are not already registered)
  - Try to log in to Canvas
  - Install Coq (version 8.5pl2, not 8.4 or 8.6)
  - Obtain a clicker
  - Start reading: Preface and Basics

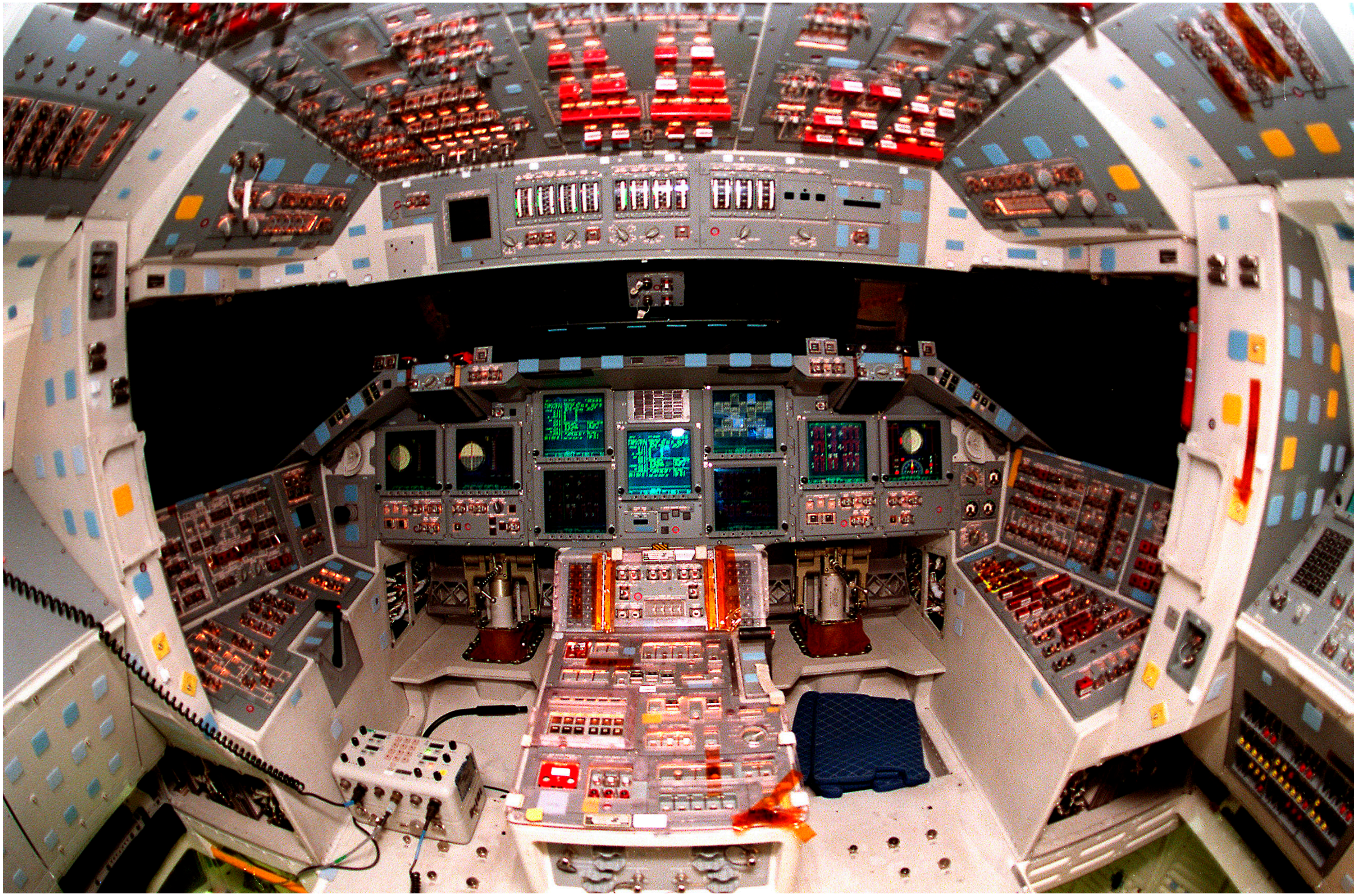
- HW1: Exercises in Basics.v
  - Due: Tuesday, September 6th at 11:00am
  - Available from course web page
  - Complete all non-optional exercises
    - There are no "advanced" problems for this HW
  - Submit to Canvas

COQ

Coq in CIS 500

- We'll use Coq version 8.5
  - Available on CETS systems
  - Easy to install on your own machine
- See the web pages at: coq.inria.fr
- Two different user interfaces
  - CoqIDE – a standalone GUI / editor
  - ProofGeneral – an Emacs-based editing environment
- Course web pages have more information.

Coq's Full System



Subset Used in CIS 500

To start.

By the end of the semester.

Getting acquainted with Coq…

BASICS.V