Conclusions

CS 6371: Advanced Programming Languages

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Final Exam Content

- Pre-midterm material
  - functional programming (OCaml)
    - parametric polymorphism
    - partial evaluation, currying
    - tail-recursion
  - operational semantics (large-step and small-step)
  - denotational semantics
  - structural induction
  - fixpoint induction
  - semantic equivalence
- Post-midterm material (emphasized)
  - logic programming (Prolog)
    - backtracking search
    - reversible programming
    - order-sensitivity, confluence, Church-Rosser
  - untyped, simply-typed, and polymorphic λ-calculus (System F)
    - type-checking vs. type-inference
    - shallow vs. non-shallow types
    - Curry-Howard isomorphism and type-inhabitation
    - λ-cube
  - axiomatic semantics
    - partial vs. total correctness
    - Hoare Logic
    - loop invariants
    - weakest precondition, strongest postcondition

Summary

APL: The Big Picture

Language Families

- Programming Language Semantics
  - **Operational:** defines program behavior
  - **Denotational:** defines program mathematical equivalent
  - **Static:** defines program safety
  - **Axiomatic:** verifies program correctness
- Three styles of programming:
  - **Imperative:** programs are sequences of instructions
  - **Functional:** programs are functions from inputs to outputs
  - **Logic:** programs are declarative input-output relations

Language Popularity

- Which languages are most popularly used in the "real world" (e.g., industry)?
  - unquestionably the imperative ones (C/C++/Java)
- Why?
  - easy to compile (no longer a compelling reason)
  - momentum (large labor pool, well-developed tools)
  - easy to write code that almost works
- The "software crisis"
  - Microsoft spends over half of its budget on testing.
  - Programs still regularly buggy, exploited, etc.
  - "Find better programmers" is not the answer.

Better Programming Languages

What makes a language "advanced"?

- Correctness/reliability over efficiency (within reason)
  - "If I want it to run faster, I'll buy more processors."
  - Compilers as proof-assistants
- Small-gap translation from mathematical spec to code
- Separation of concerns (the "what" vs. the "how")
- Succinctness
  - less code = fewer bugs
  - code-reuse (parametric polymorphism)
- Modularity
  - object-oriented programming
  - See also: OCaml module system, aspect-oriented programming
- *Programmer efficiency* vs. program efficiency

Language Choice

Should we bury C/C++/Java?

- No! C/C++ is the right solution for many things:
  - writing the inner loop of a matrix multiplier
  - writing device drivers (but use formal verification)
  - implementing some runtime libraries (e.g., fast string libs)
- But unsafe languages are overused/misused due to lack of programmer awareness of alternatives and trade-offs.
- Java/Rust was/is a great step forward...
  - brought type-safe programming to the masses
  - popularized automated garbage-collection
  - extended (limited) forms of safety to low-level code
- But such languages still have major weaknesses:
  - uncaught exceptions are only slightly better than crashes
  - Java language definition defies optimization
  - foundation on untyped, unsafe runtime leads to many compromises
  - lack of dependent typing means no correctness-checking

Grand Challenges

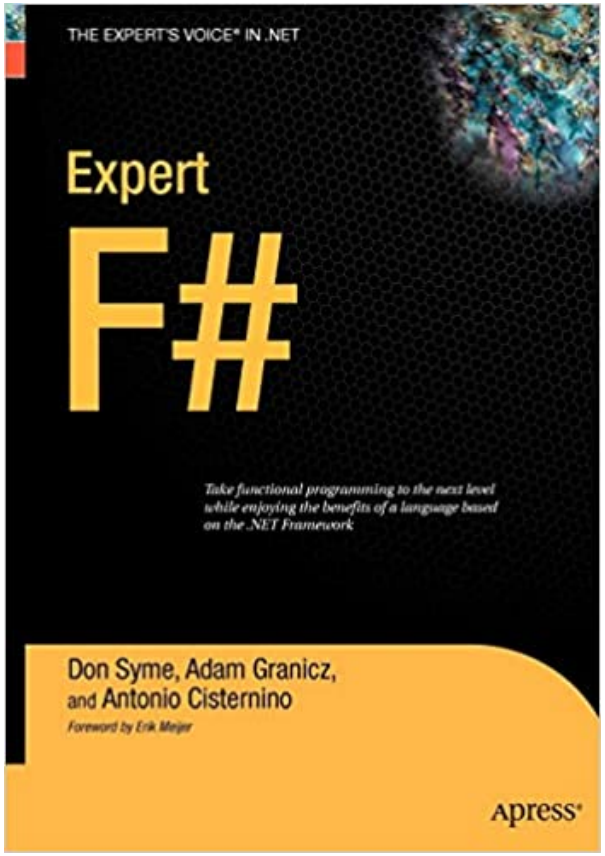
- How can we make it "easy" (or easier) to construct iron-clad, fully machine-validated software?
  - Example: *Compositional CompCert* [Stewart et al., POPL 2015]
- What kind of languages might segue the imperative world toward strongly typed, functional/declarative programming?
  - Example: F# [Syme et al., 2001]
- Can we use modern PL theory to debug/correct/analyze legacy codes?
  - Example: Compiler-instrumented Dynamic Secret Redaction for C [Araujo & Hamlen, USENIX Security 2015]
- Can we use PL theory to solve security problems like data confidentiality enforcement?
  - Example: Java Information Flow [Myers, POPL 1999]
- How can we create verified, highly parallelized software?
  - Example: n-Variant Framework of Verification for Java Source Code on CPU$\times$GPU Hybrid Platform [Duan et al., HPDC 2019]

Relevance/Usefulness

- Practical right now
  - functional and logic programming
  - operational/denotational semantics for compiler design and analysis
  - static semantics for program safety verification
- Fundamental for understanding real-world software verification
  - λ-calculus
  - Hoare Logic
  - structural/fixpoint induction
- Learning to write formal, rigorous proofs
  - essential if you want to do science, not just programming
  - infrequently taught at the undergraduate level
  - If you can't prove easy things, you can't program hard things.
    - every program is a constructive proof (Curry-Howard)
    - Example: If you can't reason inductively, you can't program recursively.

Functional Programming at Microsoft

Microsoft's Functional Language:
F# (OCaml for Visual Studio .NET)

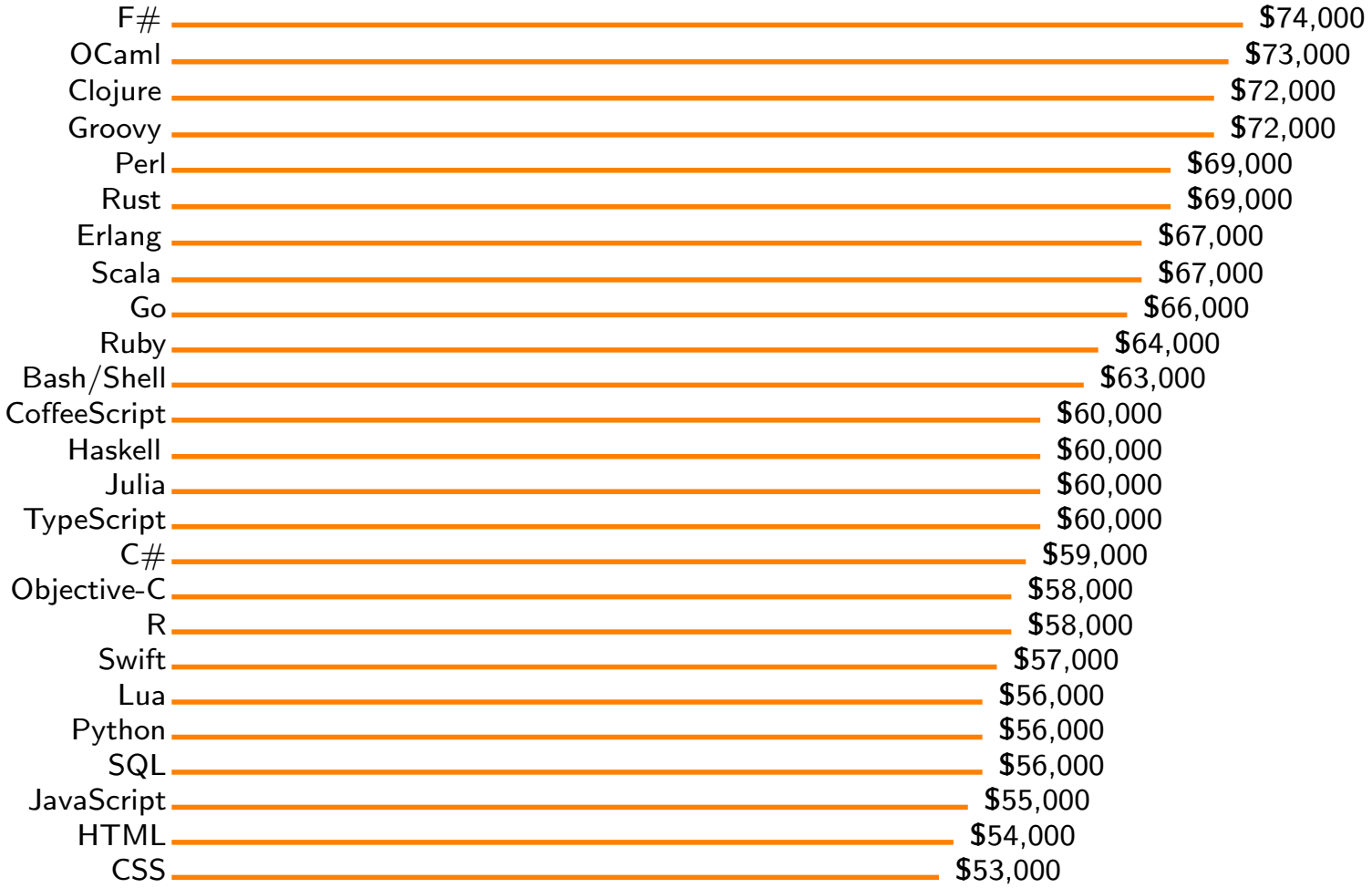


Functional Programming at Facebook

Facebook's Polymorphic, Statically-typed Web Dev Language

Stack Overflow Developer Survey

What Languages Are Associated with the Highest Salaries Worldwide?



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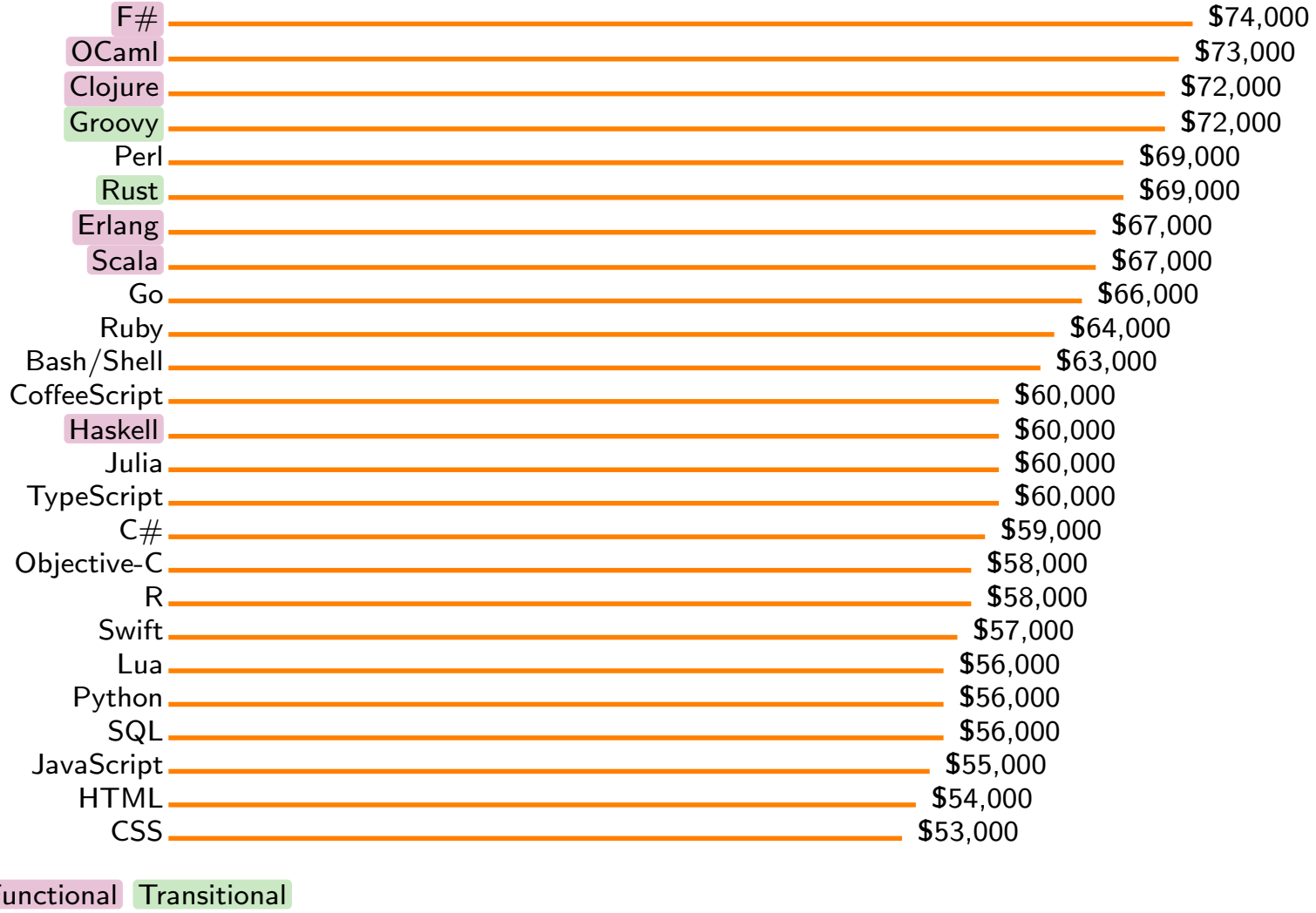
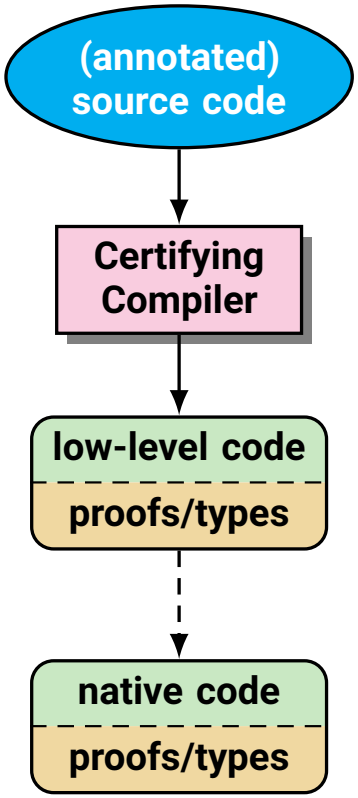


Next Steps

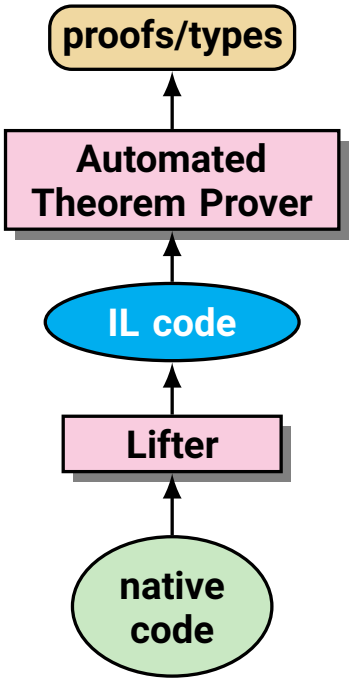
- CS 6353: Compiler Construction
  - We learned how to design and analyze a language.
  - CC teaches how to build a compiler for a language.
- CS 6374: Computational Logic
  - learn about automated theorem proving
  - tools for doing formal software verification
- CS 6301.nnn: Language-based Security (shameless plug)
  - type theory for security analysis & enforcement
  - information flow, access control, etc.
- Independent study research
  - Dr. Gupta: logic programming
  - Me: language-based security

Bottom-up Formal Methods



Top-down FM:

- build high-assurance software from sources
- proofs/types driven by source-level info
- certifying, type-preserving compilation
- Example: Coq/Gallina



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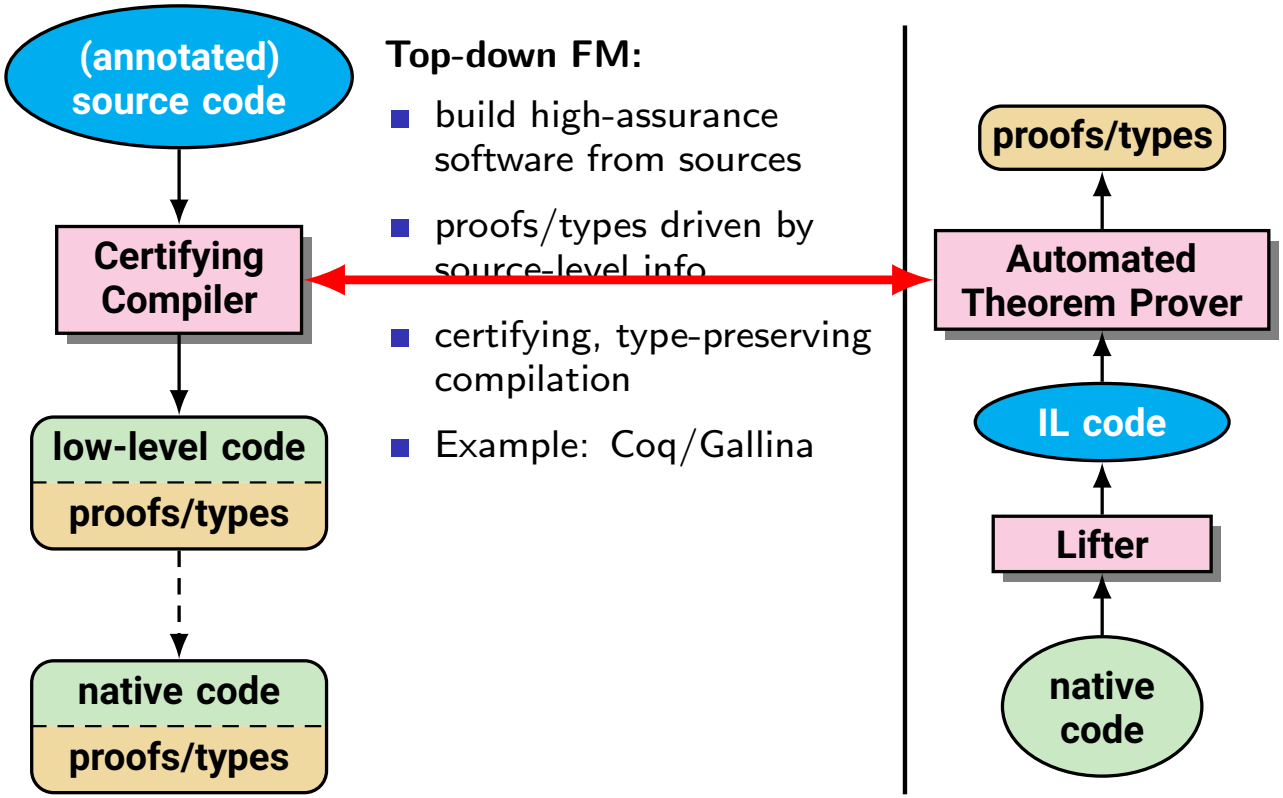

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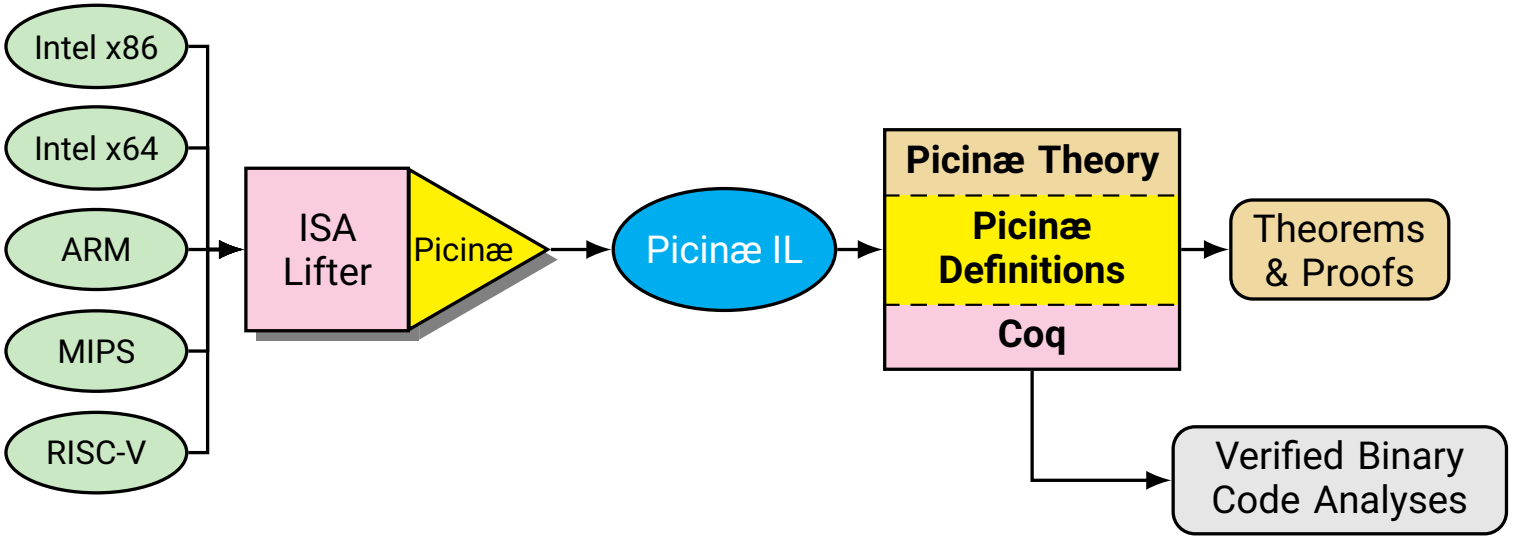
Picinæ: Platform in Coq for INstruction-level Analysis of Executables

Bridging two technologies:

- ISA Operational Semantics: Ghidra P-Code (NSA), Binary Analysis Platform (CMU)
- Program-proof Co-development: INRIA Coq



Soft(ware) Targets

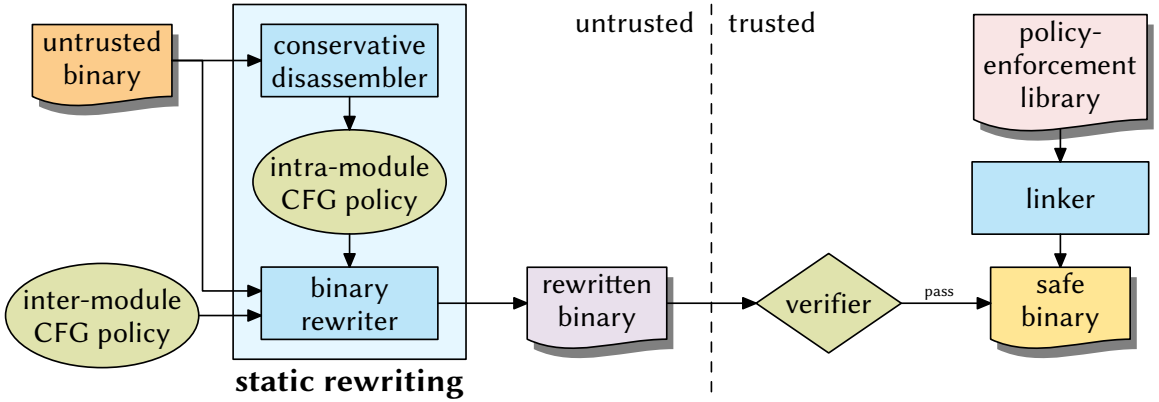
Windows / MacOS in mission-critical environments:

- "$\approx 75\%$ of control systems are on **Windows XP** or other **nonsupported** OSes" [Daryl Haegley, Office of Assistant Secretary of Defense for Energy, Installations and Environment]
- $> 25\%$ of all government computers currently run an **outdated Windows** or **MacOS** operating system [BitSight, 2017]
- DHS, Coast Guard and Secret Service currently store top secret information on **outdated Windows 2003** servers [OIG-18-56, 2018]
- Hundreds of satellites run **Windows 95** and/or are contreolled by **Windows Mobile** devices.

Object Flow Integrity

Securing Large, Component-driven Software Products:

- denotational semantics of C++ object hierarchies
- reflective programming for C++
- automated code synthesis from security specifications
- median 0.34% overhead on COTS Windows applications



W. Wang, X. Xu, K.W. Hamlen, "Object Flow Integrity." In *Proceedings of the 24th ACM Conference on Computer and Communications Security (CCS)*, pp. 1909–1924, November 2017. [tier-1]

Course Feedback

Feedback is welcome!

- Topics you wish had been included but weren't?
- Homework/exam difficulty level
- Style of instruction, lecture format
- Course resources (no textbook...)

Reminder: Please take time to submit course evals!