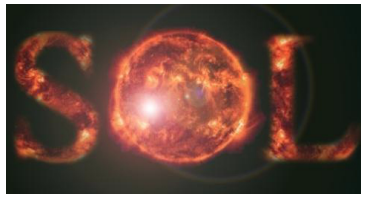
Why Information-flow is Different From – and harder than – Verifying other kinds of Properties

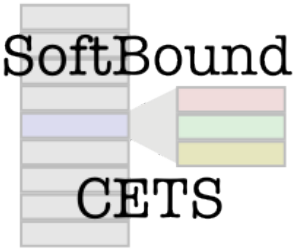
Steve Zdancewic
University *of* Pennsylvania

Where I am Coming From

- Security-Oriented Languages
  - Information-flow specification/verification
  - Authorization policies



- Low-level memory safety in legacy C code: SoftBound / CETS
  - Instrumenting LLVM code against buffer overflows

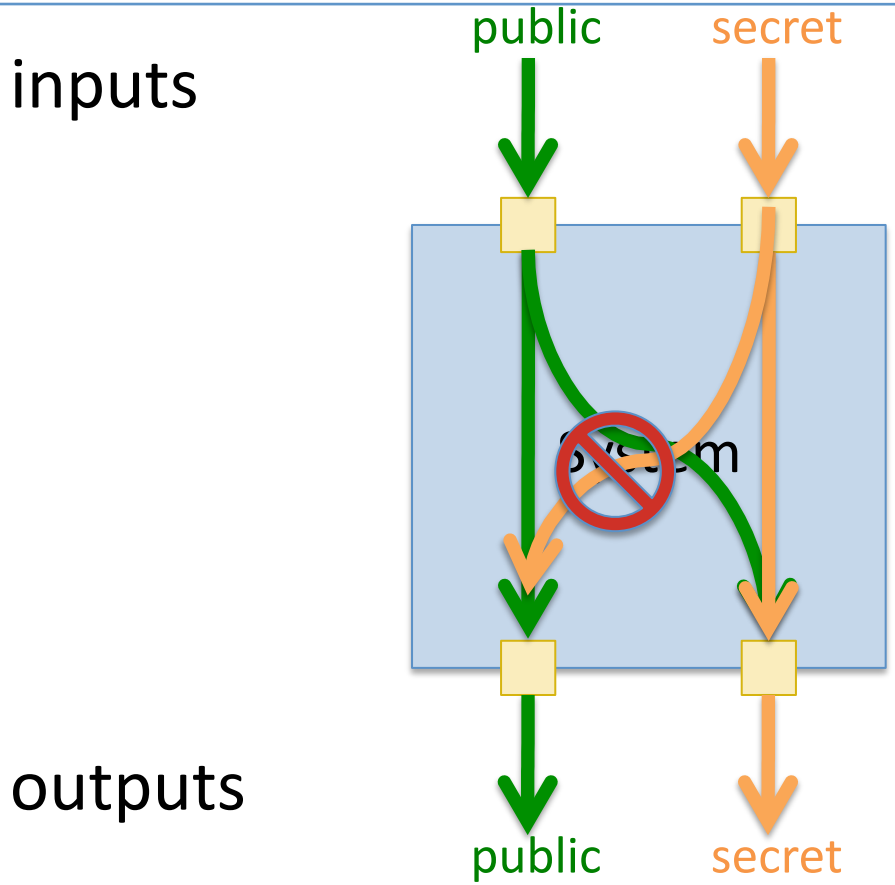


- Verified LLVM project
  - Coq model of the LLVM IR for verified program transformations / optimizations

Plan

- What do I mean by “information flow”
- Why it is different than usual “properties”
  - For a technical meaning of properties
- Ramifications?
- High-level overview of PL techniques that might apply to hardware

Information-flow Policies



- Protecting against leakage of confidential information
  - *Noninterference* (& many variants in the literature)

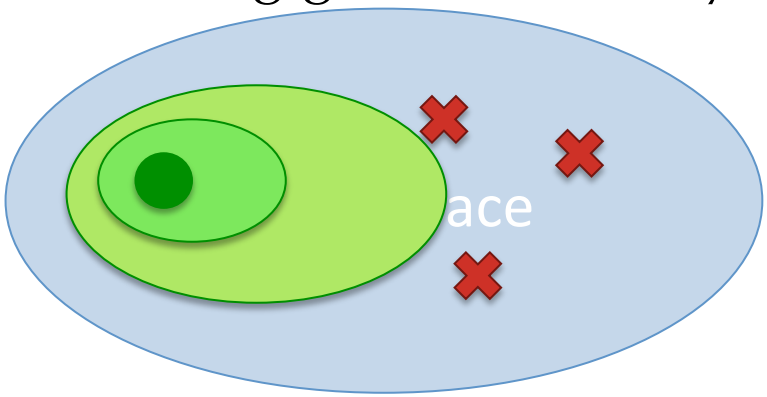
[Goguen & Meseguer; Lamport; Manna & Pnueli; etc.]

Information-Flow Policies in Hardware?

- Useful to prevent design mistakes?
  - Ensure that testing infrastructure doesn't impact consumer-observable behavior?
  - Check properties of hardware that manipulates secrets (e.g. crypto hardware does not leak private keys)
- Useful in the context of untrusted components
  - 3rd party IP?

Program Properties

- Often, verification is concerned with:
  - Safety: something bad *does not* happen
  - Liveness: something good *eventually does* happen



- A property can be specified by a predicate on a *single trace* of the system's execution.
  - Model checking as a validation mechanism
  - Refinement/simulation as translation correctness

[Alpern & Schneider; Lamport; Manna & Pnueli; etc.]

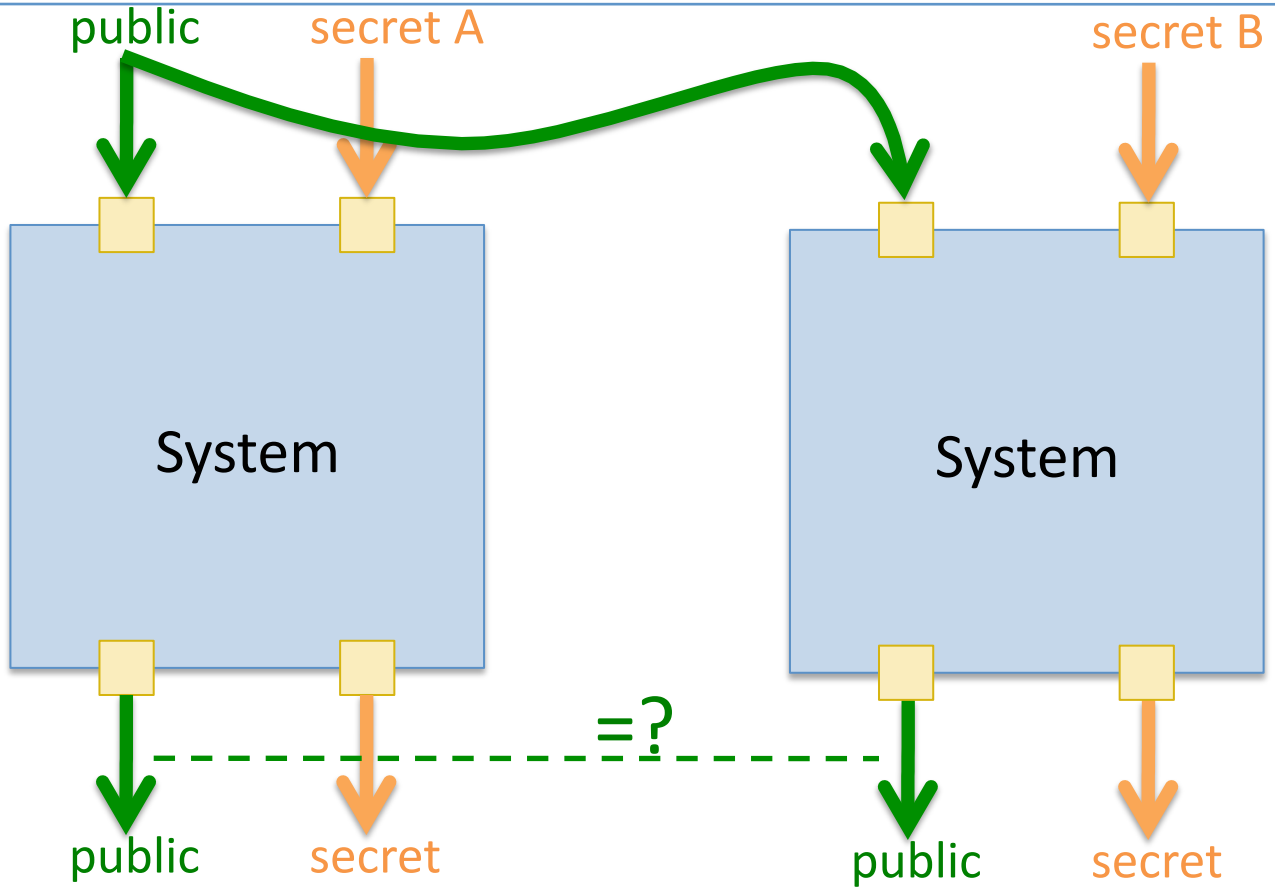
Information-flow is *not* a Trace Property

- Information-flow security constraints are usually specified by correlating *two* executions of the system.
- Intuitively: Information can leaked by observing that some event *didn't* happen.

```
secret = read_secret_input();
public = 0;
if (secret > 10) {
  public = 1;
}
// public = 1 iff secret > 10
```

- Information-flow is a property about a *set* of possible traces.

Specifying Information Flow



- Given the same public input and different secret inputs, does the system produce the same public outputs?

(Somewhat) More Formally

- A system P is information-flow secure, if, for all attack contexts C_1 and C_2 :

$$C_1[P] \approx C_2[P]$$

- Here $\approx$ is any notion of "system equivalence"
  - It characterizes the "level of abstraction" (i.e. the observational power of the attacker/system)
- *Attack context*: tests P by supplying different secrets
  - More generally: what influence does the attacker have on P?
- Related techniques from the PL world: relational parametricity and logical relations
  - Used to reason about modularity and abstraction in programs

Verifying Software Information Flow Policies

- Static analysis:
  - post-hoc verification of existing code
  - difficult, but possible in practice
- Type systems:
  - programming language support for creating software that is secure by construction
  - type safety implies information-flow security
  - conservative: rules out some good programs

- (Also a growing literature on dynamic enforcement mechanisms)

What about Refinement?

- Corollary: Information-flow properties are *not* preserved by refinement.
- Trivial Example:

```
secret = read_secret_input();
public = ???;          // (unspecified, i.e. nondeterministic)
```

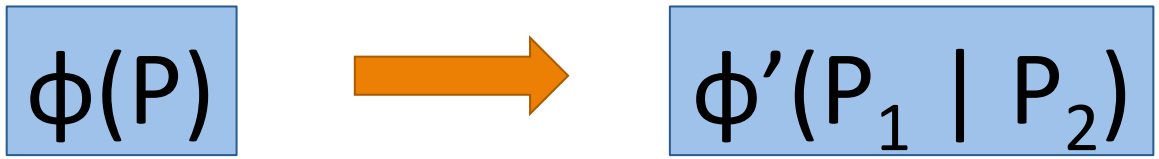
```
secret = read_secret_input();
public = secret;   // (refinement allowed by resolving nondeterminism)
```

- Solution(?): Include information-flow properties in the specification property to be preserved by refinement.

Model Checking?

- Desirable information-flow policies are *not* expressible in mu calculus.
  - mu-calculus is the specification logic supported by many standard model checkers.

- One possibility:
  - Model-checking a "doubled" version of the system



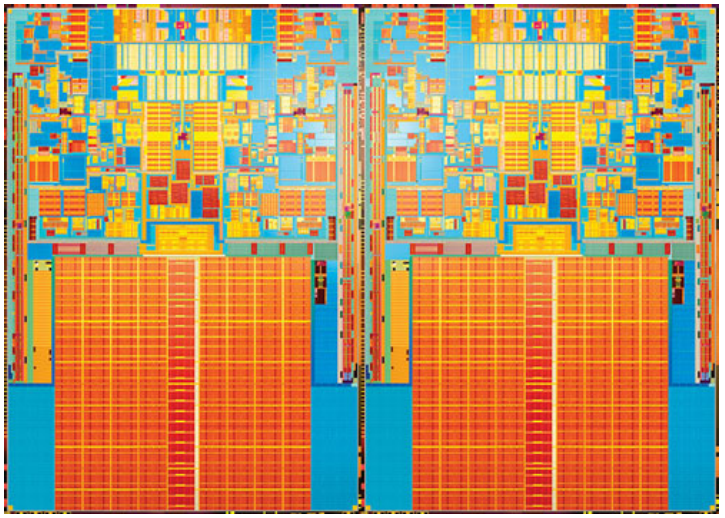
  - State-space blowup?

Challenges (at the Software Level)

- Information-flow specification is relative to some level of abstraction.
  - Detail of the model impacts the "observations" that the attacker can make. What is the choice of $\approx$?
  - Choice affects the strength of the result & difficulty of verification
- Policy is hard:
  - What information is confidential?
  - Typically, noninterference (and its relatives) are not the desired policy.
  - Need more precise specifications of permissible information flows

Hardware Introduces More Problems

- Parallelism / Concurrency
  - notoriously tricky in software
- Speculation, out-of-order execution
- Relaxed memory consistency models
- Caching / Timing Effects
- Power channels
- …



- How do these interact with information flow?
  - Even specifying the desired property might be hard.

Conclusions

- Information-flow is *not* a safety (or liveness) property
  - not directly amenable to model checking
  - must be careful with refinement

- Programming languages and security communities have made significant advances in formalizing information-flow properties at the software level.
  - Can these techniques be useful for hardware too?