Manifest Safety and Security

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Collaborators

- This work is, in part, joint with Lujo Bauer, Karl Crary, Peter Lee, Mike Reiter, and Frank Pfenning at Carnegie Mellon.
- Work on manifest security is partly in collaboration with Benjamin Pierce, Stephanie Weirich, and Steve Zdancewic at UPenn.
- Thanks especially to our students!

Safe and Secure Extensible Systems

- Extensible systems are prevalent:
  - Volunteer networks.
  - Browsers, operating systems.
  - Virtual communities (eg, Second Life)
- Provides adaptability through customization, but threatens safety and security.

Safe and Secure Extensible Platforms

- How can we build extensible systems without compromising integrity?
- Using manifest security, which means:
  - Rigorously specified policies.
  - Guaranteed compliance with policy.
  - Direct relationship to running code.

Current Approaches

- Extensible systems rely on two main methods for ensuring safety and security:
  - Restriction: limit potential damage by limiting capabilities of extensions.
  - Detection: monitor execution to detect violations.
- These are means … but to what ends?

Current Approaches

- Restriction limits both good and bad behavior.
  - In the limit, extensibility is disallowed.
  - In practice, extensions have very limited capabilities.
- Tension between expressiveness and safety & security of extensions.

Current Approaches

- Detection requires run-time monitoring, and provides only a post-mortem analysis.
  - Overhead can be significant.
  - Little help with ensuring good behavior.
- Applies only to conditions that can be checked at run-time!
  - eg, information flow vs access control

What's Really At Stake?

- Current methods attempt to address a high-level problem using low-level methods.
  - Violates the "end-to-end" principle.
  - Cannot define "security" at the level of bits, bytes, packets, address spaces, ...
- Safety and security are governed by principals and policies, not bits and bytes.

A Logical View

- Fundamentally, we wish to prove a theorem about a program.
  - Does not violate API restrictions.
  - Does not leak sensitive information.
  - Complies with access control policies.
- How can we state and prove such theorems about practical systems?

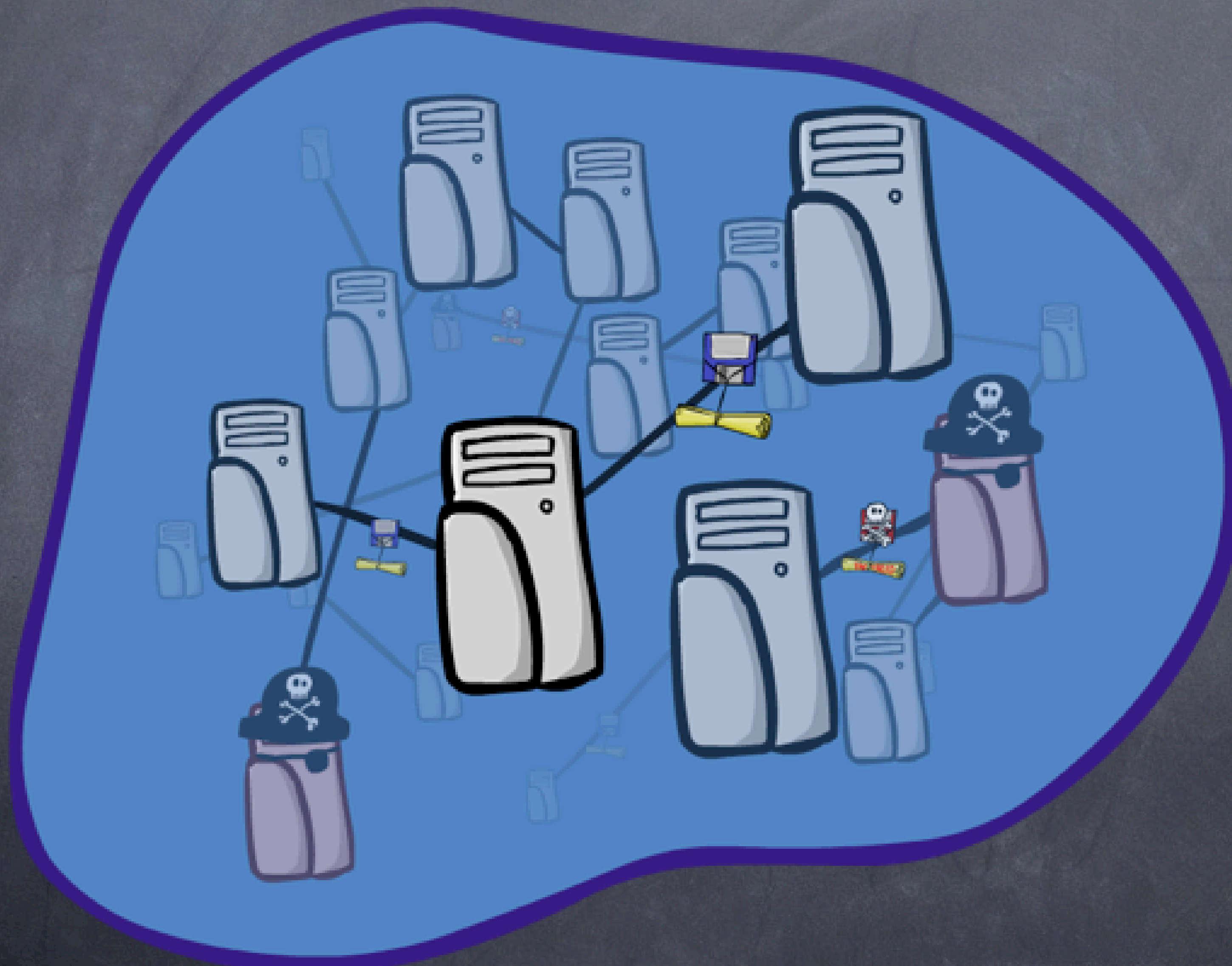
Implementing Manifest Safety and Security

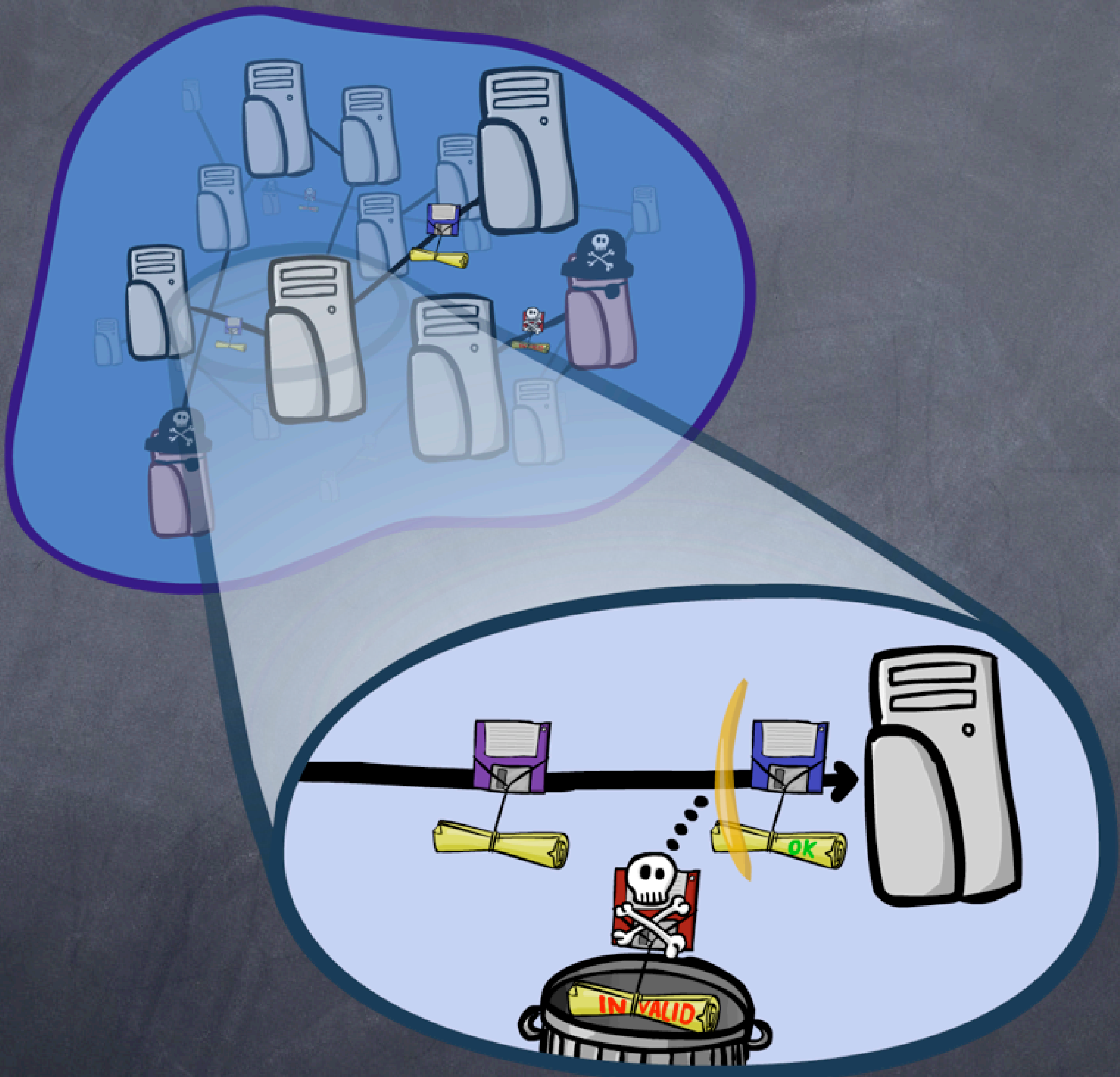
- ConCert Project: Trustless Grid Computing
  - Manifest safety for mobile code.
- Grey Project: Proof-Carrying Authorization.
  - Manifest security for access control.
- A New Project (TM): Secure Extensibility.
  - Manifestly secure extensible systems.

Trustless Grid Computing in ConCert

- A general framework for grid computing.
  - Loosely coupled volunteer network.
  - Work-stealing scheduler.
- Manifest safety: verification, not trust.
  - Hosts specify safety policy.
  - Clients must prove compliance.

The ConCert Grid

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Manifest Safety

- Logical specification of safety properties.
  - Execution safety: no illegal instructions, no branches to unsafe code.
  - Memory safety: no out-of-bounds array accesses, no stack violations.
- Logics include assembly-level type systems and Hoare-like annotations.

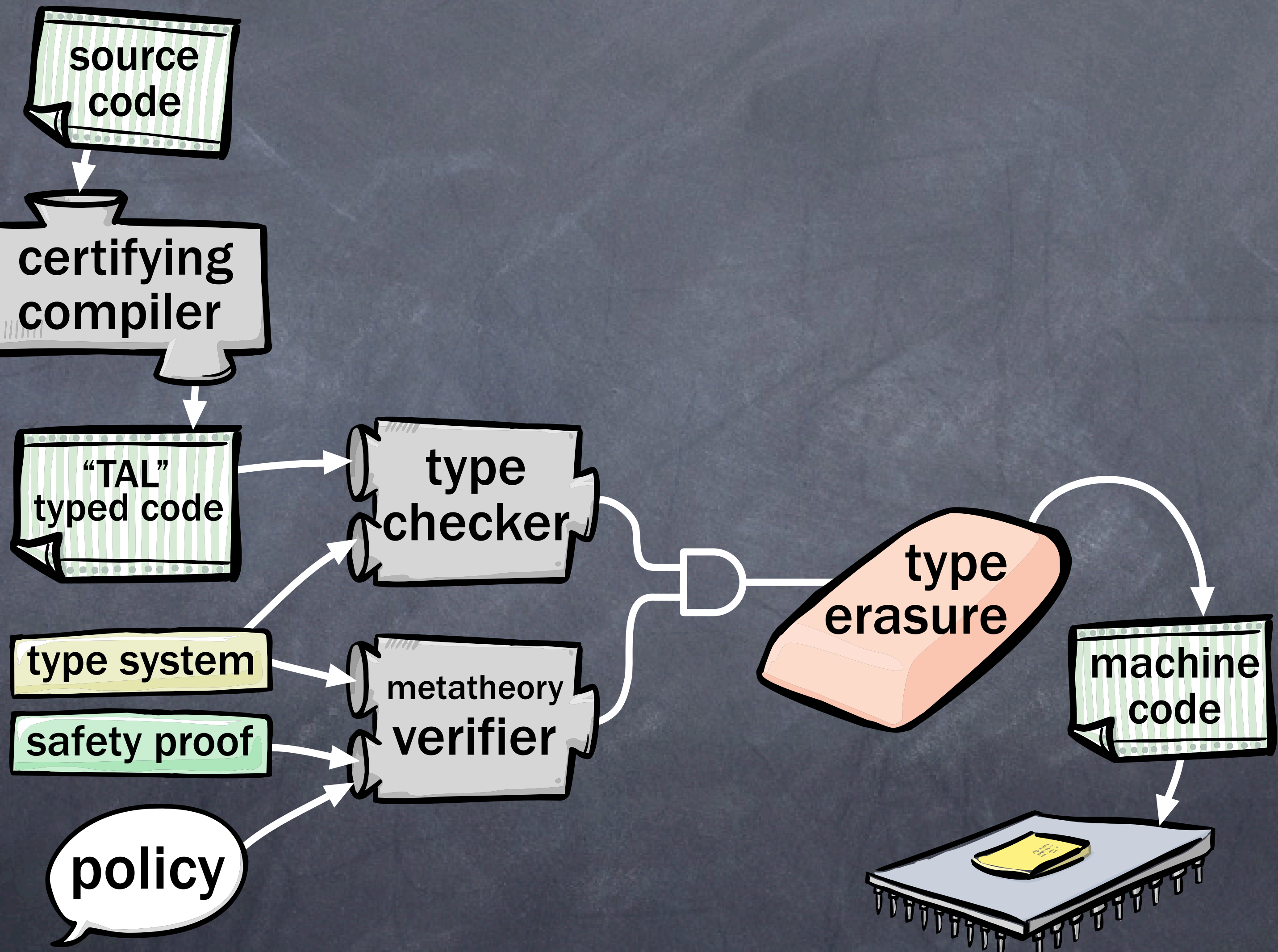
Manifest Safety

- Enforcement by proof- and type checking.
  - Reject programs that do not pass checks.
- Compliance ensured by certifying compilers.
  - Transfer source-level safety properties to object-level code.
  - Produce formal certificates of compliance with host policy.

Certification and Verification Methods

- Proof-Carrying Code.
  - VCGen + Theorem Proving for certification.
  - LF representation of proofs.
- Typed Assembly Language.
  - Typed compilation and type checking.
  - Type annotations on object code.

TAL Certification



A TAL-R Snippet

```
;; stack is described by S
;; sp  : S
;;
;; virtual clock reads N+k+1
;; vck : N+k+1
;;
;; ebx contains an int->int that runs in at most k steps
;; ebx : ALL i:Nat. ALL r:ST.
;;          { eax:int,
;;            sp:{ eax:int, sp:r, vck:i }->0 * r
;;            vck:i+k }->0

add eax, eax, edx ;; consume one clock tick

;; vck : N+k

call ebx [N'] [S] ;; instantiate i=N and r=S,
                  ;; place retaddr on stack, jump

;; vck : N
```

How TAL Defends Against Safety Attacks

- Malicious source code.
  - `loadFile "accounts.qdf"` is rejected.
- Malicious hand-written assembly code.
  - `call loadFile` is ill-typed.
  - `mov sp[0],0xfe00b0c4; ret`
    is also ill-typed

How TAL Defends Against Attacks

- One can think up more and more “tricks” ...
  - Indirect jumps, stack over-runs, etc.
- But it is a theorem that no well-typed assembly program can violate the safety policy.
  - No attack will pass type checker!

How TAL Defends Against Attacks

- Aha! What if we change the type system?
  - Nope, must supply a proof of soundness with respect to the safety policy!
- Rats! Is there no way to defeat it?
  - No! Not within the confines of the policy.
  - But the policy may be "wrong" (more on this later).

What Can Be Certified?

- How far can we take this? What sort of properties can we certify?
- Short answer: anything for which one can devise a type system!
  - eg, TAL-R precludes certain DoS attacks
- Long answer: limited by how hard it is to generate and check proofs.

From Safety to Security

- Code safety is necessary for security.
  - Precludes violation of language semantics.
  - Source-level reasoning, not object-level enforcement.
- Can we extend manifest safety to manifest security?

Manifest Security

- Security policies are stated in a formal logical system.
  - Augmented by certificates to identify principals and sign assertions.
  - Assertions involve accessibility, ownership, delegation, etc.
- No fundamental limits on expressive power!

Manifest Security

- Compliance is demonstrated by a proof.
  - eg, principal must prove that his/her access to a resource is entailed by the policy.
  - Compose rules of deduction, starting with policy axioms and external certificates.
- Unforgeable, mechanically checkable.

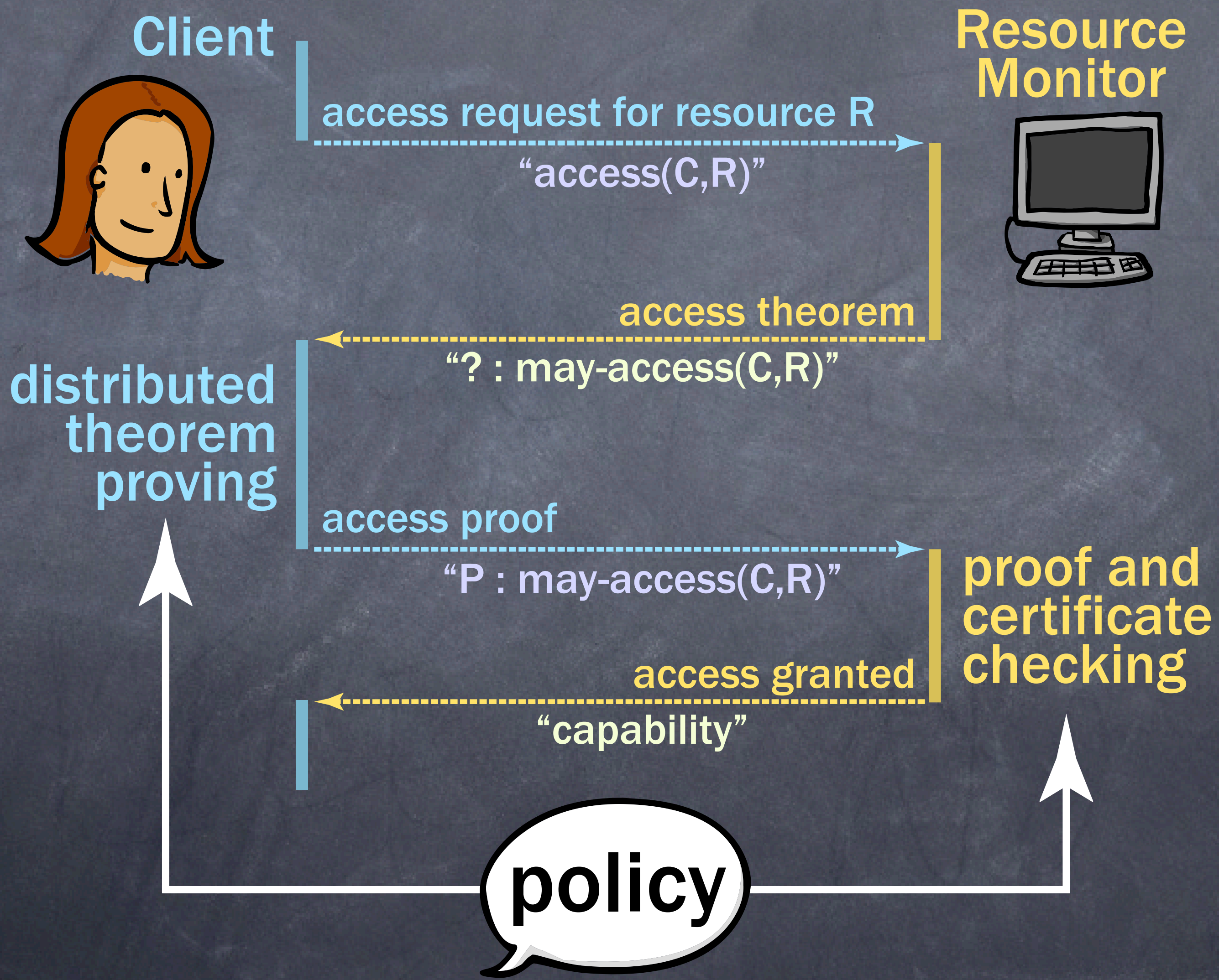
Manifest Security

- Enforcement is by proof checking and cryptography.
  - Present proof to reference monitor.
  - Proof checker verifies evidence.
  - Proof provides an "audit trail".
- Direct expression and enforcement of intended security constraint!

Manifest Security

- Policies are formally analyzable.
  - eg, using cut elimination to investigate existence of proofs of certain assertions
  - provides a mathematical foundation for understanding consequences of a policy.
- Security policies can be very hard to understand!

Proof-Carrying Authorization Logic



Proof-Carrying Authorization Logic

- A simple policy (all axioms are signed):

```
reg says class (s, c) ...
prof says
  if reg says class(s, c), then
    mayacc (s, r)
```

- A proof of `mayacc (s, r)` involves:
  - Certificate acquisition to est. identity.
  - Logical inference from axioms.

How PCA Defends Against Attacks

- Replay attacks: client attempts to re-use previous authorization.
  - Access control theorem and capability are time-stamped.
- Fraudulent assertions by principals.
  - Requires breaking digital signatures.

How PCA Defends Against Attacks

- Misapplication of policy rules.
  - Prevented by proof checker, which ensures validity of all proofs.
- Fraudulent policies.
  - All axioms are signed, so must break cryptographic framework.

How PCA Defends Against Mistakes

- A principal may sign an assertion with unexpected consequences.
  - eg, a quantifier rotation $\forall\exists$ vs $\exists\forall$
- Requires policy analysis to validate.
  - Instance of mechanized meta-reasoning.

How PCA Defends Against Mistakes

- Proofs provide an audit trail for analyzing attacks.
  - Reveals who said what and why this was sufficient for access.
  - Facilitates tracking errors in policy.
- Meaningful at the level of the policy, not at the level of some enforcement mechanism!

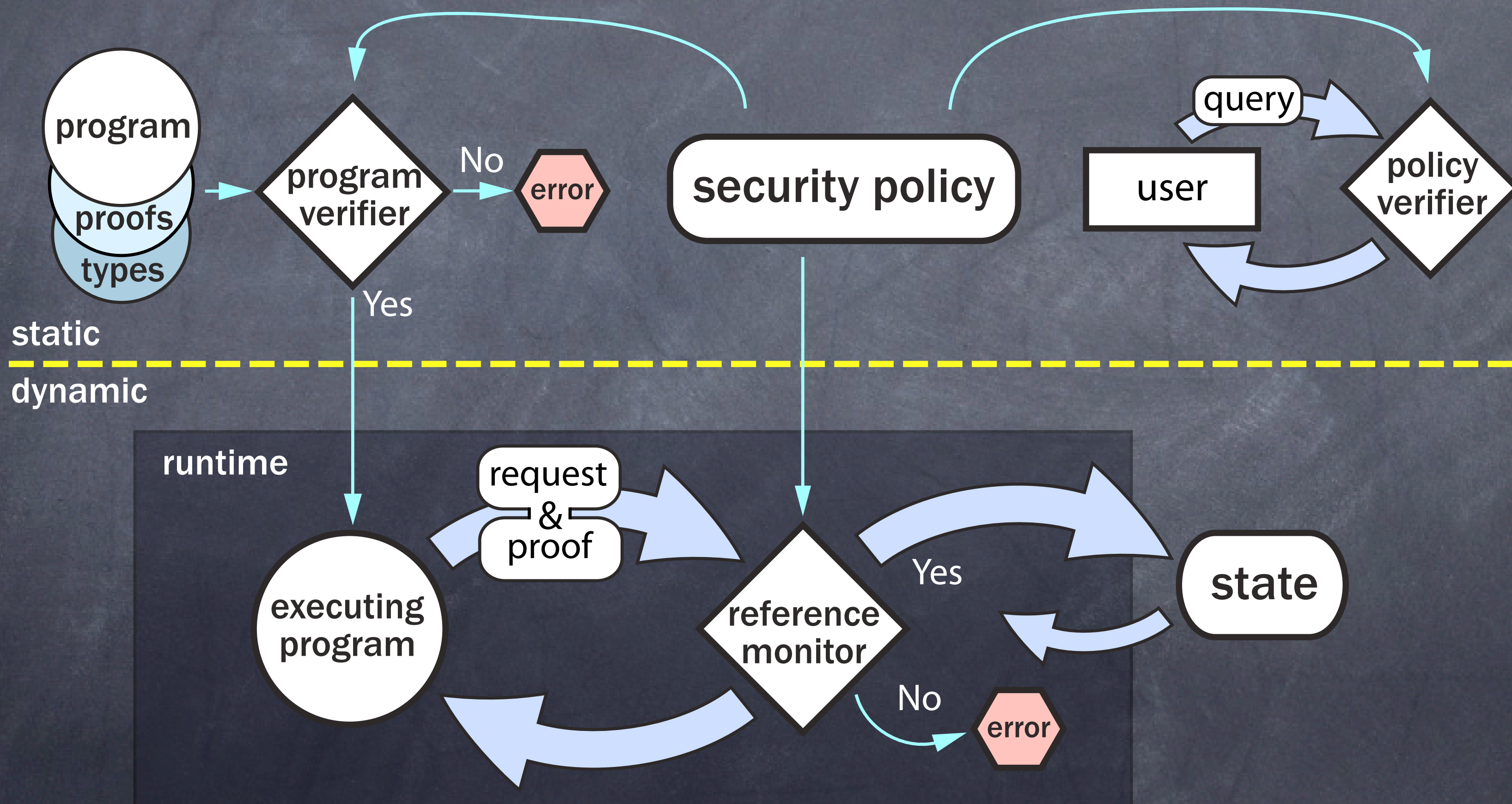
Secure Extensibility

- How can we use manifest safety and security to implement safe extensibility?
- Testbed: extensible browser architecture.
  - Safety against low-level attacks.
  - Security against unauthorized access and insecure information flows.

Manifestly Secure Extensibility

- Extend logics beyond safety and access control.
  - privacy and integrity
  - epistemic logic for info flow?
- Integrate security obligations into the programming language.
  - track proofs in the type system

Manifestly Secure Extension Architecture



Manifest Security Infrastructure

- Logical frameworks.
  - Specifying and analyzing security logics and programming languages.
  - Representing and checking proofs.
- Certifying theorem provers.
  - Finding proofs of logical assertions.

Manifest Security Infrastructure

- Theoretical investigations.
  - Logics to express security policies.
  - Analysis of logics and languages.
  - Algorithms for proof checking and proof search.
- Informed by and informing practice!

Manifest Safety and Security

- Make safety and security policies explicit.
  - Rigorously specified in a suitable logic.
  - Analyzable and mechanizable.
- Enforce compliance of extensions with policy.
  - Require explicit proofs of compliance.
  - Verify using proof- and type checking.

Manifest Safety and Security

- Validate policies by meta-theoretic analysis.
    - Ensure that policies capture intentions.
    - eg, not too restrictive, not too permissive
- Validate languages by semantic analysis.
    - Ensure that accepted programs are indeed well-behaved.