AURA:
A language with authorization and audit

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SOL

Security-oriented Languages

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- Manifest Security Project (NSF-0714649)
  - Penn: Benjamin Pierce, Stephanie Weirich
  - CMU: Karl Crary, Bob Harper, Frank Pfenning
- CAREER: Language-based Distributed System Security (NSF-0311204)

Goal of the AURA project:

- Develop a security-oriented programming language that supports:
  - Proof-carrying Authorization
    [Appel & Felton] [Bauer et al.]
  - Strong information-flow properties
    (as in Jif [Myers et al.] , FlowCaml [Pottier & Simonet])

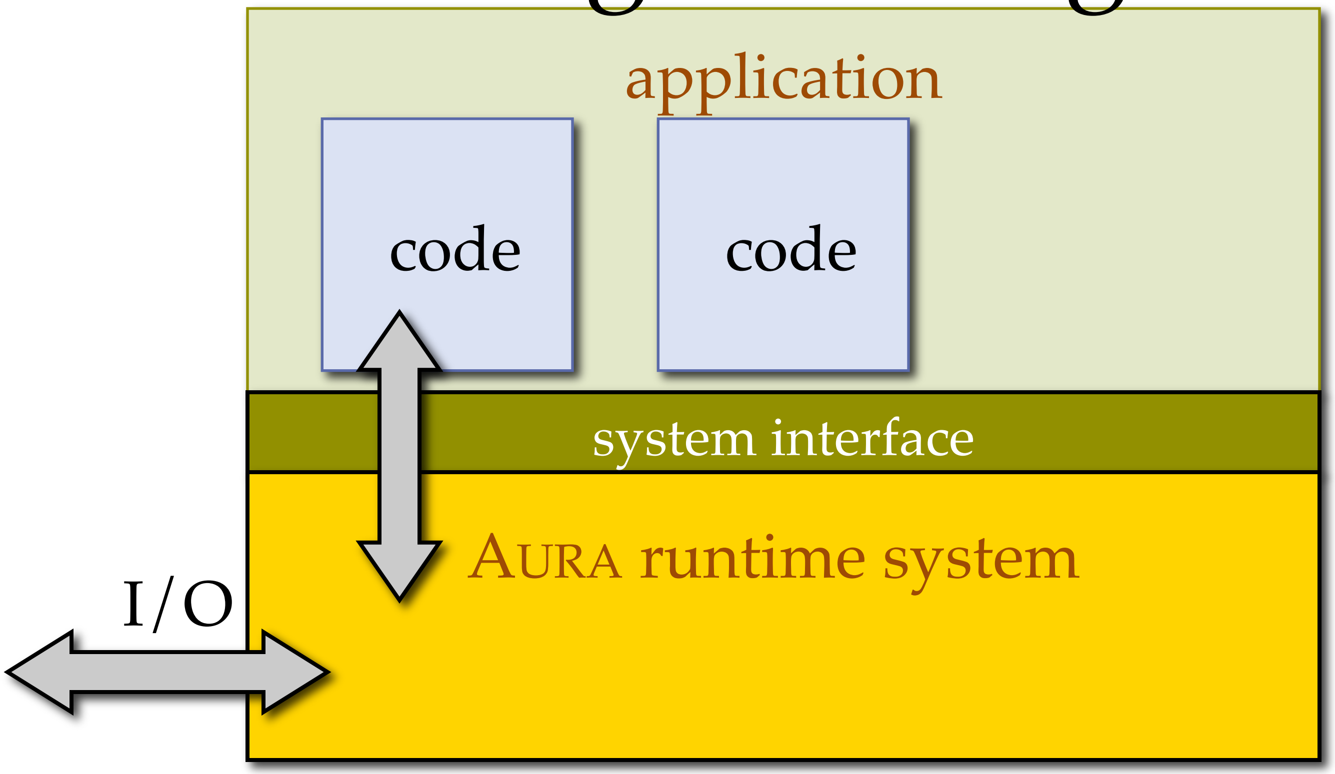
- Why?
  - Declarative policies (for access control & information flow)
  - Auditing & logging: proofs of authorization are informative
  - Good theoretical foundations

- In this talk: tour of AURA's
  - Focus on the authorization and audit components

Outline

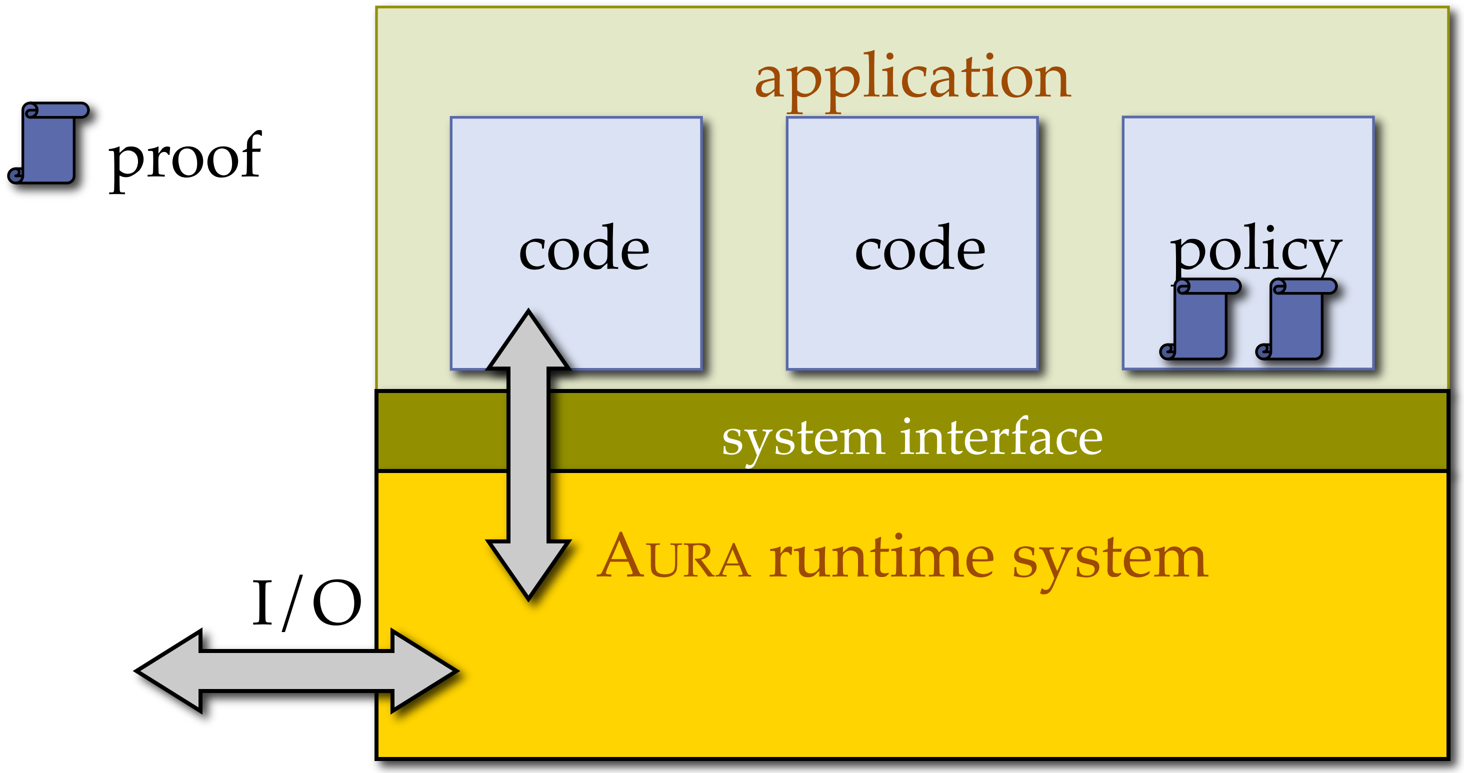
- AURA's programming model
- Authorization logic
  - Examples
- Programming in AURA
  - (Restricted) Dependent types
- Status, future directions, conclusions

AURA: Programming Model



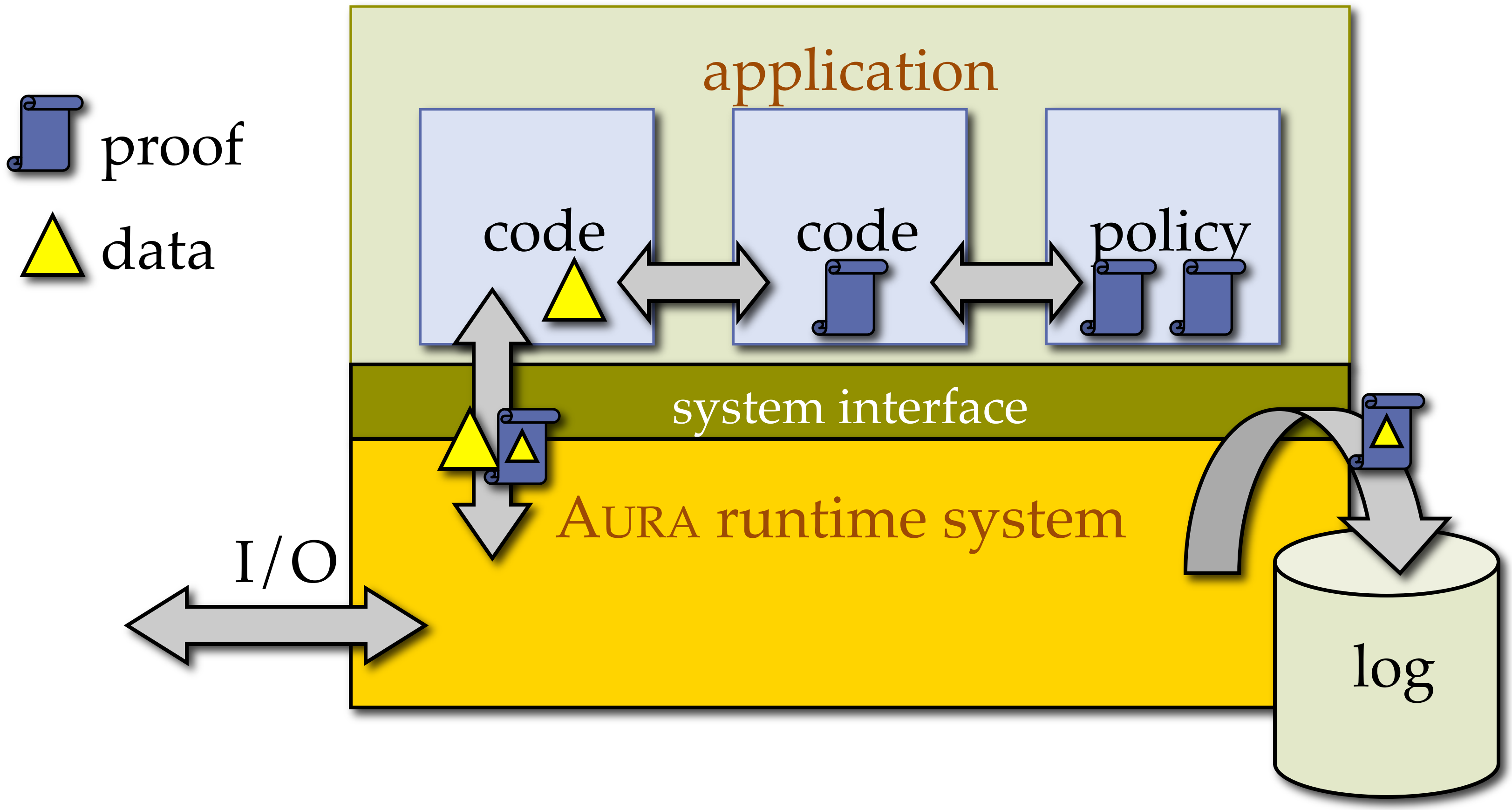
- AURA is a call-by-value type-safe functional programming language
- As in Java, C#, etc. AURA provides an interface to the OS resources
  - disk, network, memory, …
- AURA is intended to be used for writing security-critical components

AURA: Authorization Policies



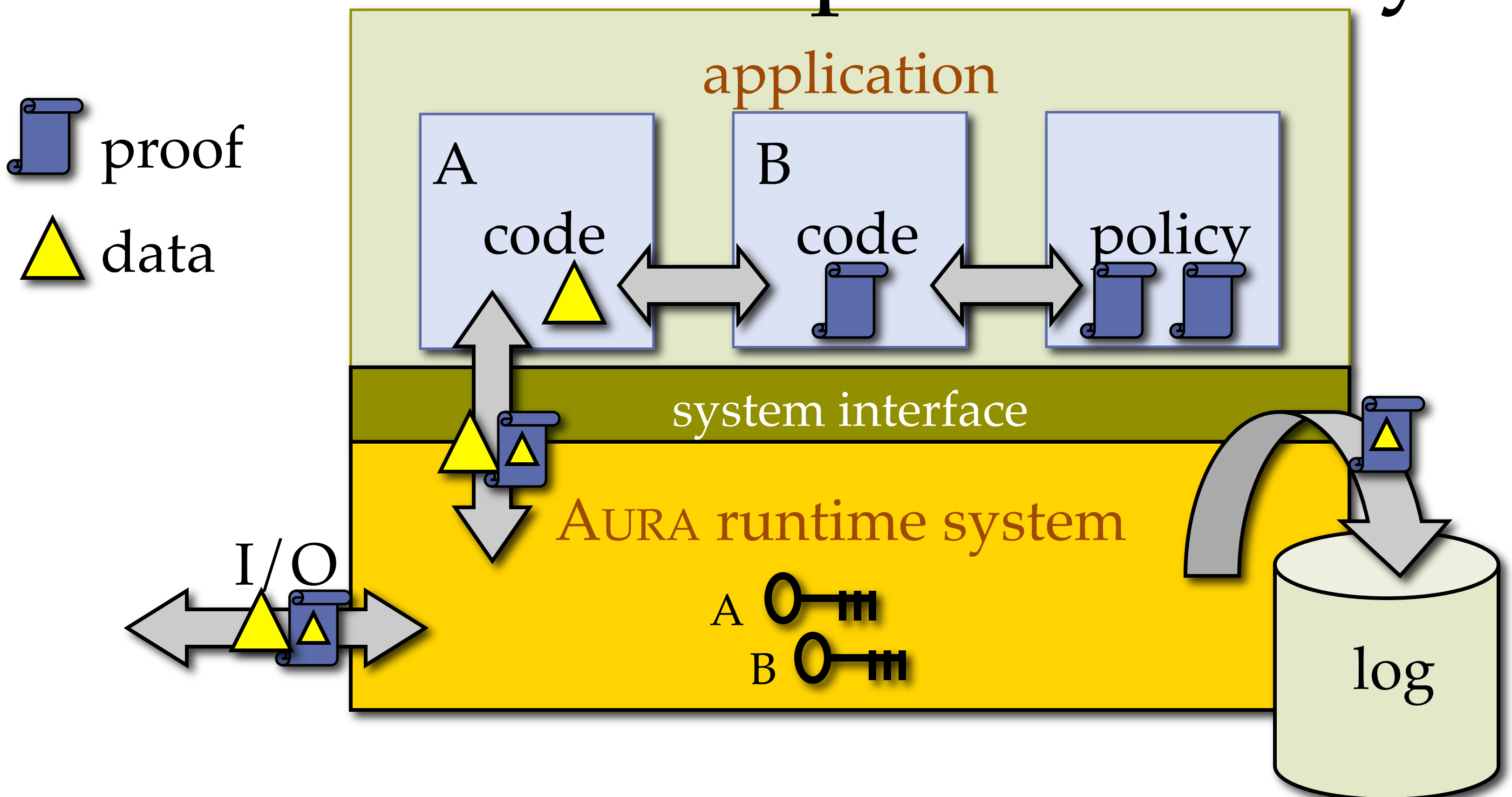
- AURA security policies are expressed in an authorization logic
- Applications can define their own policies
- Language provides features for creating/manipulating proofs

AURA: Authorization Policies



- Proofs are first class and they can depend on data
- Proof objects are capabilities needed to access resources protected by the runtime: AURA's type system ensures compliance
- The runtime logs the proofs for later audit

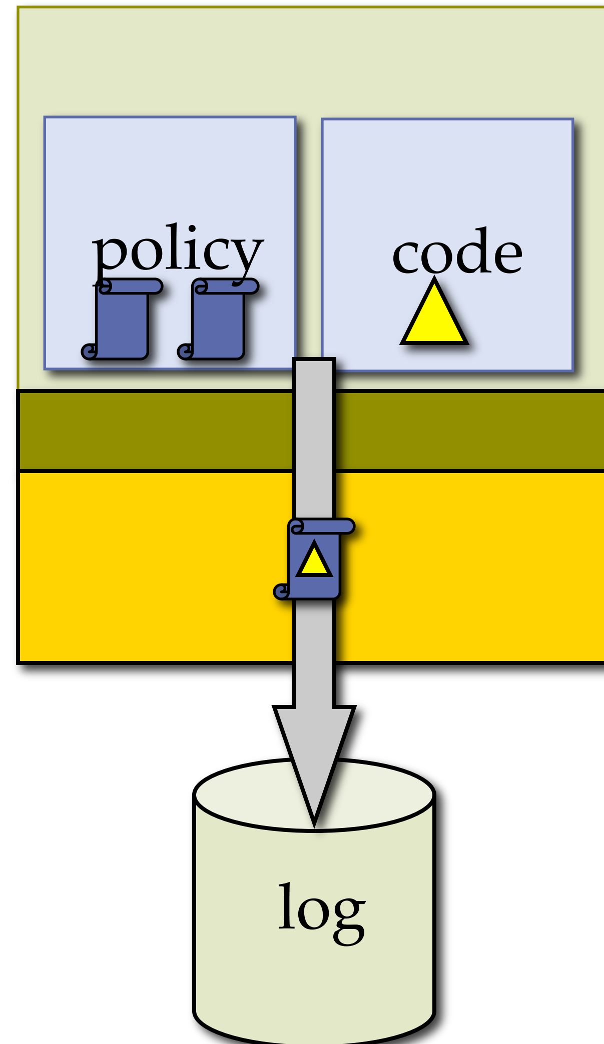
AURA: Principals and Keys



- For distributed systems, AURA also manages private keys
- Keys can create policy assertions sharable over the network
- Connected to the policy by AURA's notion of *principal*

Evidence-based Audit

- Connecting the contents of log entries to policy helps determine *what* to log.



Evidence-based Audit

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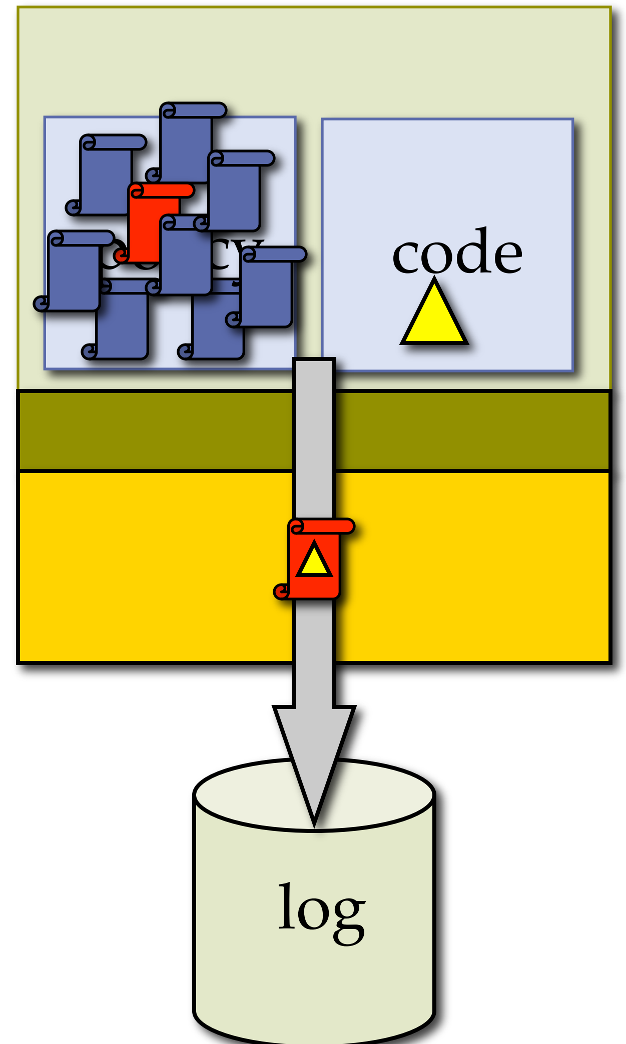
- Proofs contain structure that can help administrators find flaws or misconfigurations in the policy.

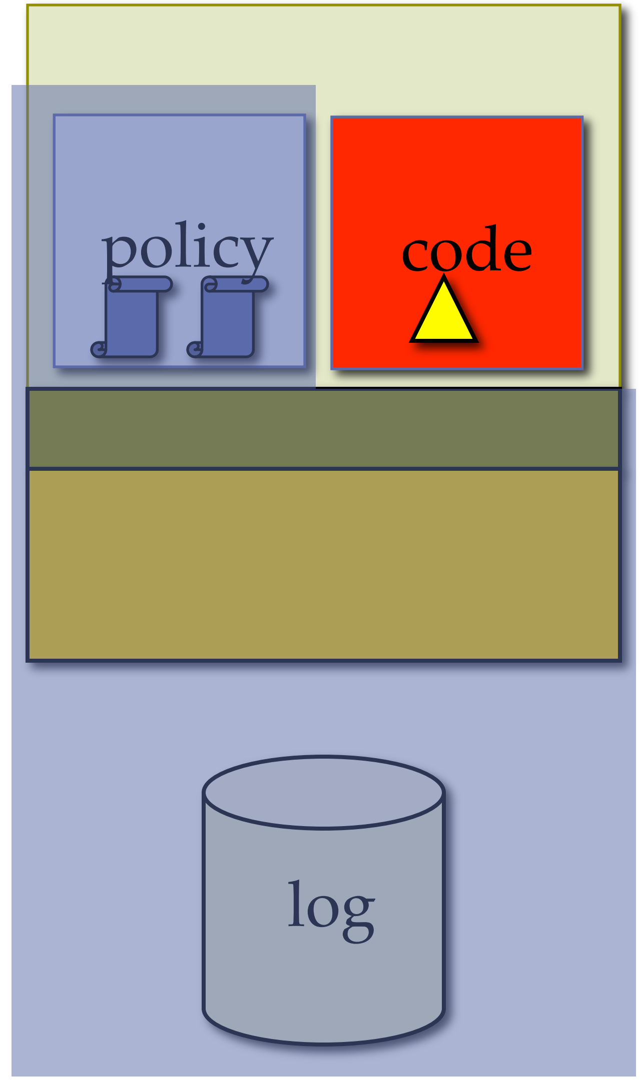


Evidence-based Audit

- Connecting the contents of log entries to policy helps determine *what* to log.

- Proofs contain structure that can help administrators find flaws or misconfigurations in the policy.

- Reduced TCB: Typed interface forces code to provide auditable evidence.



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AURA's Authorization Logic

- Policy propositions

φ ::= true

c

A says φ

α

$\varphi \wedge \varphi$

$\varphi \vee \varphi$

$\varphi \rightarrow \varphi$

$\forall \alpha.\ \varphi$

Encoded using
Π types and
inductive datatypes.

- Principals

  A,B,C … P,Q,R etc.

- Constructive logic:
  - proofs *are* programs
  - easy integration with software

- Access control in a Core Calculus of Dependency

  [Abadi: ICFP 2006]

Example: File system authorization

- P1: FS says (Owns A f1)
- P2: FS says (Owns B f2)
- …

- OwnerControlsRead:
  FS says $\forall$o,r,f. (Owns o f) → (o says (MayRead r f)) → (MayRead r f)

- Might need to prove: FS says (MayRead A f1)
- What are "Owns" and "f1"?

Decentralized Authorization

- Authorization policies require application-specific constants:
  - e.g. "MayRead B f" or "Owns A f"
  - There is no "proof evidence" associated with these constants
  - Otherwise, it would be easy to forge authorization proofs
- But, principal A should be able to create a proof of
  A says (MayRead B f)
  - No justification required -- this is a matter of policy, not fact!
- Decentralized implementation:
  - One proof that "A says T" is A's digital signature on a string "T"
  - written sign(A, "T")

Example Proof (1)

- P1: FS says (Owns A f1)
- OwnerControlsRead:

  FS says ∀o,r,f. (Owns o f) →
  (o says (MayRead r f)) →
  (MayRead r f)

- Direct authorization via FS's signature:

  sign(FS, "MayRead A f1")
  : FS says (MayRead A f1)

Example Proof (2)

- P1: FS says (Owns A f1)
- OwnerControlsRead:

  FS says ∀o,r,f. (Owns o f) → (o says (MayRead r f)) → (MayRead r f)

- Complex proof constructed using "bind" and "return"

```
bind p = OwnerControlsRead in
bind q = P1 in
   return FS (p A A f1 q sign(A,"MayRead A f1")))
         : FS says (MayRead A f1)
```

Authority in AURA

- How to create the value sign(A, "φ") ?
- Components of the software have *authority*
  - Authority modeled as possession of a private key
  - With A's authority :

    say("φ") evaluates to sign(A, "φ")

- What φ's should a program be able to say?
  - From a statically predetermined set (static auditing)
  - From a set determined at load time
- In any case: log which assertions are made

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AURA Programming Language

Static

Types: describe programs

int	FileHandle
string	prin
int -> int	pf φ

Propositions: specify policy

φ	A says φ
(φ ∧ ϕ)	∀α.T
(Owns A fh1)	(φ -> ϕ)

Dynamic

Programs: computations, I/O

3	fh1
"hello"	A
say(φ)	\x:t.e

Evidence: proofs/credentials

sign(A, "φ")

bind/return

\x:t.e

Programs | Policies

(Restricted) Dependent Types

- Policy propositions can mention program data
  - E.g. "f1" is a file handle that can appear in a policy
  - AURA restricts dependency to first order data types
  - Disallows computation at the type level – only values!

- Programming with dependent types:

  {x:T; U(x)} dependent pair* (* syntactic sugar)

  (x:T) → U(x) dependent functions

- Invariant: sign only types
  - Computation can't depend on signatures
  - But, can use predicates: {x:int; pf A says Good(x)}

Auditing Interfaces

- Type of the "native" read operation:

```
raw_read :   FileHandle → String
```

- AURA's runtime exposes it this way:

```
read : (f:FileHandle) →
         pf RT says (OkToRead self f) →
         {ans:String; pf RT says (DidRead f ans)}
```

- RT is a principal that represents the AURA runtime
- OKtoRead and DidRead are "generic" policies
  - The application implements its own policies about when it is OKtoRead by providing assertions, etc.
  - Parts of the runtime must delegate to the application

Signatures

- Assertions: uninhabited constants that construct Prop's

```
assert MayRead : Prin -> FileHandle -> Prop;
assert Owns : Prin -> FileHandle -> Prop;
```

- AURA supports mutually recursive datatypes and mutually inductively defined propositions:

```
data List: Type -> Type {
   | nil : (t:Type) -> List t
   | cons: (t:Type) -> t -> List t -> List t
}
data OwnerInfo : FileHandle -> Type {
   | oinfo : (f:FileHandle) -> (p:Prin)
             -> pf (self says (Owns p f)) -> OwnerInfo f
}
data And : Prop ->  Prop -> Prop {
   | both : (p:Prop) -> (q:Prop) -> p -> q -> And p q
}
```

More about Prop vs. Type

- We want the Prop fragment to be a logic:
  - Pure, strongly normalizing
  - Signature typing rules add a strong positivity constraint for Prop to rule out divergence

- We need to separate the Prop and Type fragments
  - Type fragment includes divergent terms (possibly other effects)
  - This is the purpose of the "pf" monad. A value of type "pf P" is of the form "return_p t" where "t" is a pure proof term that proves P.
  - It is possible to write a loop of type "pf P" by not one of type "P".

Example Program

- (see demo.core)

Formalizing Core AURA

- Lambda-cube-like representation with a very simple core:

$t ::= x \mid ctr \mid \lambda x{:}t_1.t_2 \mid t_1\ t_2 \mid (x{:}t_1) \rightarrow t_2 \mid$
$\quad \text{match } t_1\ t_2 \text{ with } \{b\} \mid (t_1 : t_2) \mid c$

- Plus these constants (special typechecking rules):

$c ::= \text{Type} \mid \text{Prop} \mid \text{Kind}$
$\quad \text{prin} \mid \text{says} \mid \text{return}_s \mid \text{bind}_s$
$\quad \text{self} \mid \text{sign}$
$\quad \text{pf} \mid \text{return}_p \mid \text{bind}_p$
$\quad \text{if}$

Coq Formalization

- Type system and operational semantics:
  - 30 rules in 4 mutually inductive predicates: wf_env, wf_tm, wf_branches, wf_brn
  - Signature checking: wf_sig, wf_bundle_tcrs, wf_bundle_ctrs, wf_ctr_decls
  - Conversion relation (for casts) that reflects dynamic equality checks into the static type system
  - Evaluation rules
- Correctness properties proved in Coq:
  - Type soundness and decidability of typechecking (~7000 loc)
  - Decidability of typechecking is simplified by:
    - Restricted dependency (only values)
    - Limited equality proofs available statically
- Paper proof of strong normalization of (a slightly simplified version of) the Prop fragment.

Observations about the Formalization

- Dealing with mutually recursive datatypes and pattern matching was a *lot* of work
  - Significant source of complexity for soundness and decidability
  - … hopefully reusable in other contexts (our lambda cube plus constants can probably be instantiated to other languages)

- Initial investment in formalization was heavy – many hours to implement the typing rules, etc.
  - But: having machine checked proofs is a big win, especially for large groups of collaborators.
  - It gets easier over time…

Open Questions

- AURA needed improvements:
  - Anonymous existential types / dependent type & inference
  - Richer dependent types?
  - Explicit / richer equality proofs?
  - Revocation/expiration of signed objects? [Garg and Pfenning]
  - Connection to program verification?
  - Correlate distributed logs?
- This story seems just fine for *integrity,* but what about *confidentiality*?
  - We have many ideas about connecting to information-flow analysis
  - Is there an "encryption" analog to "signatures" interpretation?
  - Encode confidentiality using “security monads” [work at Chalmers]

Conjecture: Non-security use?

- Carve up a program into principals
  - Perhaps by module?
- Allow principals to make arbitrary (dependent) logical assertions
  - Interfaces can specify constraints in this logic
  - (e.g. propositions regulate type equality)
- The "says" modality offers an escape hatch: no need to construct an actual proof
  - Cast uses "asserted equality" (not "verifiable equality")
  - "says" isolates components, allows assignment of *blame* and makes trust relationships explicit.
- Question: is this interesting? Useful? Does anyone know of any work similar to this?

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AURA's Status

- Have implemented an interpreter in F#
  - Many small examples programs
  - Working on larger examples
  - Goal: experience with proof sizes, logging infrastructure

- Planning to compile AURA to Microsoft .NET platform
  - Proof representation / compatibility with C# and other .NET languages
  - Luke Zarko is awesome
    - Penn undergrad applying this fall to Ph.D. programs for next year

AURA

- A language with support for authorization and audit
- Authorization logic
- Limited form of dependent types
- Language features that support secure systems

www.cis.upenn.edu/~stevez/sol

Thanks!