CRASH/SAFE: Clean-slate Co-design of a Secure Host Architecture

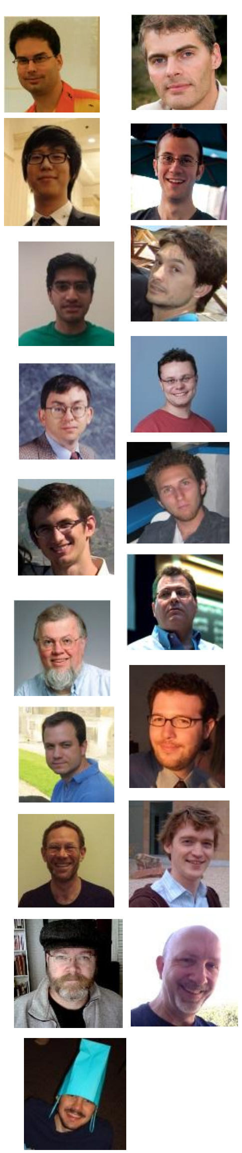
Cătălin Hrițcu

Penn
UNIVERSITY of PENNSYLVANIA

Outline

- **Overview of CRASH/SAFE project**
  – clean-slate co-design of a secure host architecture
- **Exceptions and information flow control (IFC)**
  – to appear at IEEE S&P 2013 (Oakland)
- **Testing noninterference with QuickCheck**
  – ready for ICFP 2013 (deadline in 24 hours)
- **Future directions**

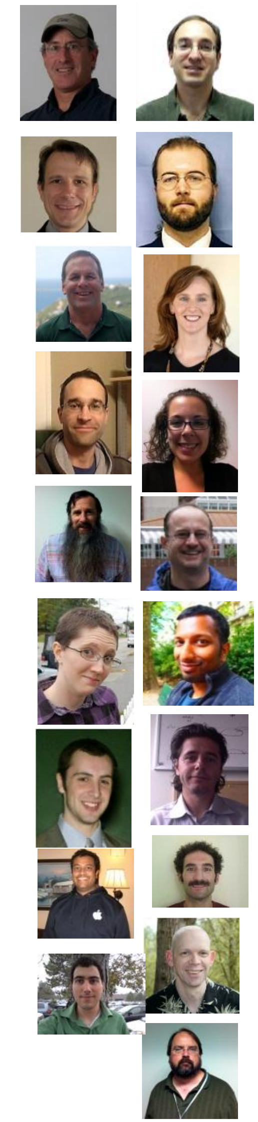
CRASH/SAFE project



- Academic partners (16):
  - **University of Pennsylvania** (11)
  - **Harvard University** (4)
  - **Northeastern University** (1)
- Industrial partners (24):
  - **BAE systems** (21) + **Clozure** (3)

40!

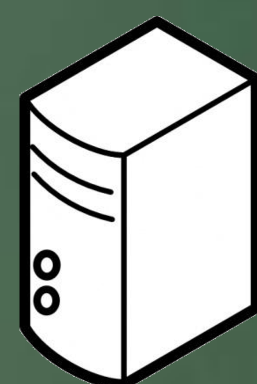
- Funded by DARPA
  - **C**lean-Slate Design of **R**esilient, **A**daptive, **S**ecure **H**osts



Clean-slate co-design of net host

Clean-slate co-design of net host

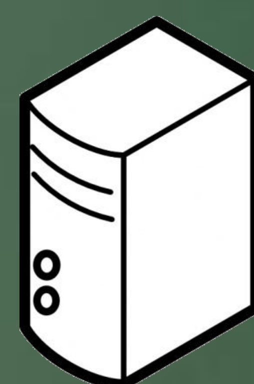
Primary goal:
design and implement a significantly more secure architecture, without backwards compatibility concerns



Clean-slate co-design of net host

Primary goal:
design and implement a significantly more secure architecture, without backwards compatibility concerns

New stack:
- language
- system
- hardware



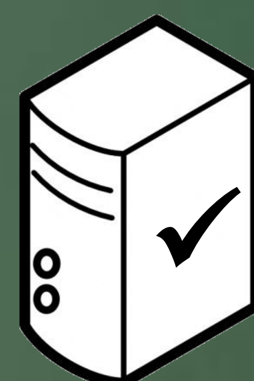
Clean-slate co-design of net host

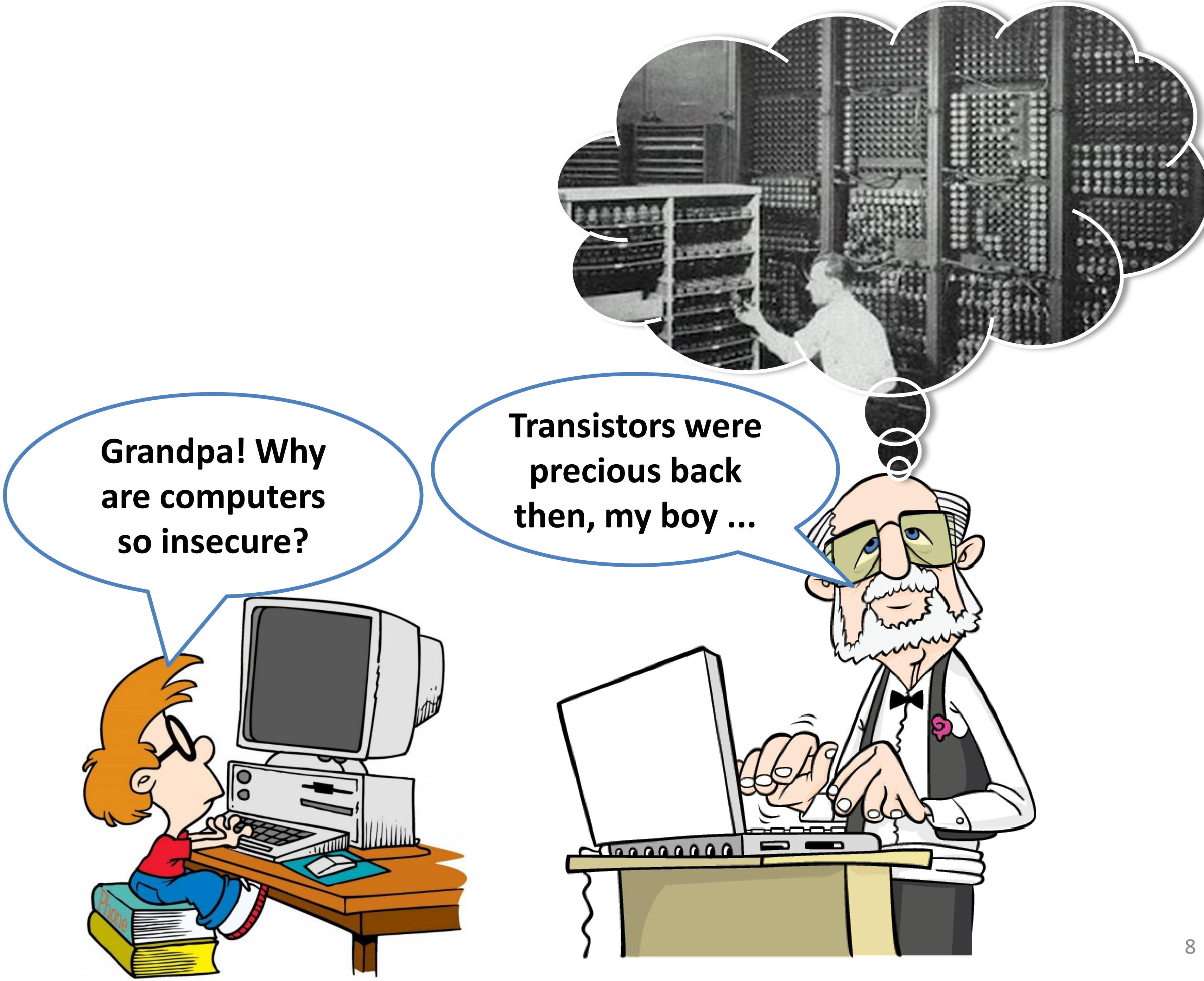
Primary goal:
design and implement a significantly more secure architecture, without backwards compatibility concerns

Secondary goal:
verify that it's secure (whatever that means)

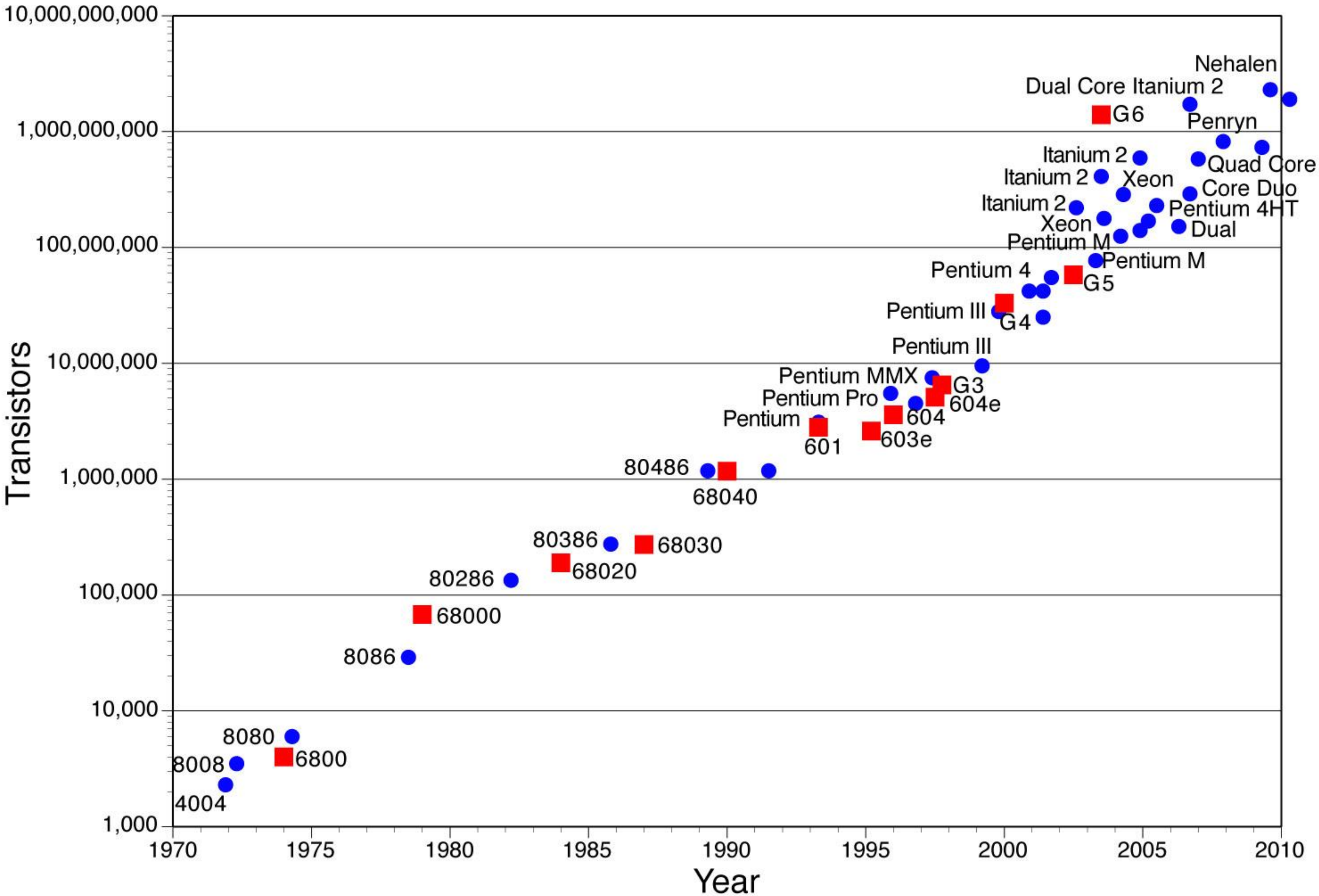
New stack:

- language
- system ✓
- hardware




Grandpa! Why are computers so insecure?
Transistors were precious back then, my boy ...
Phone

Hardware is now abundant



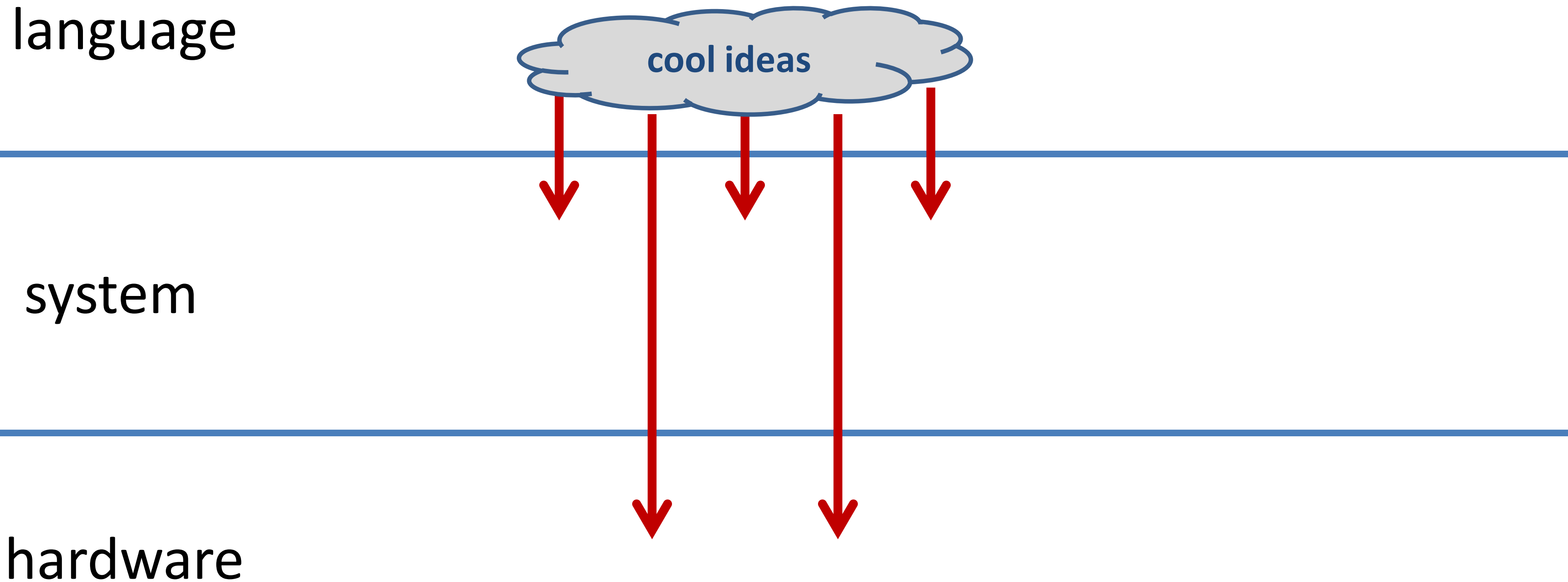
Time for a redesign targeting security!

language

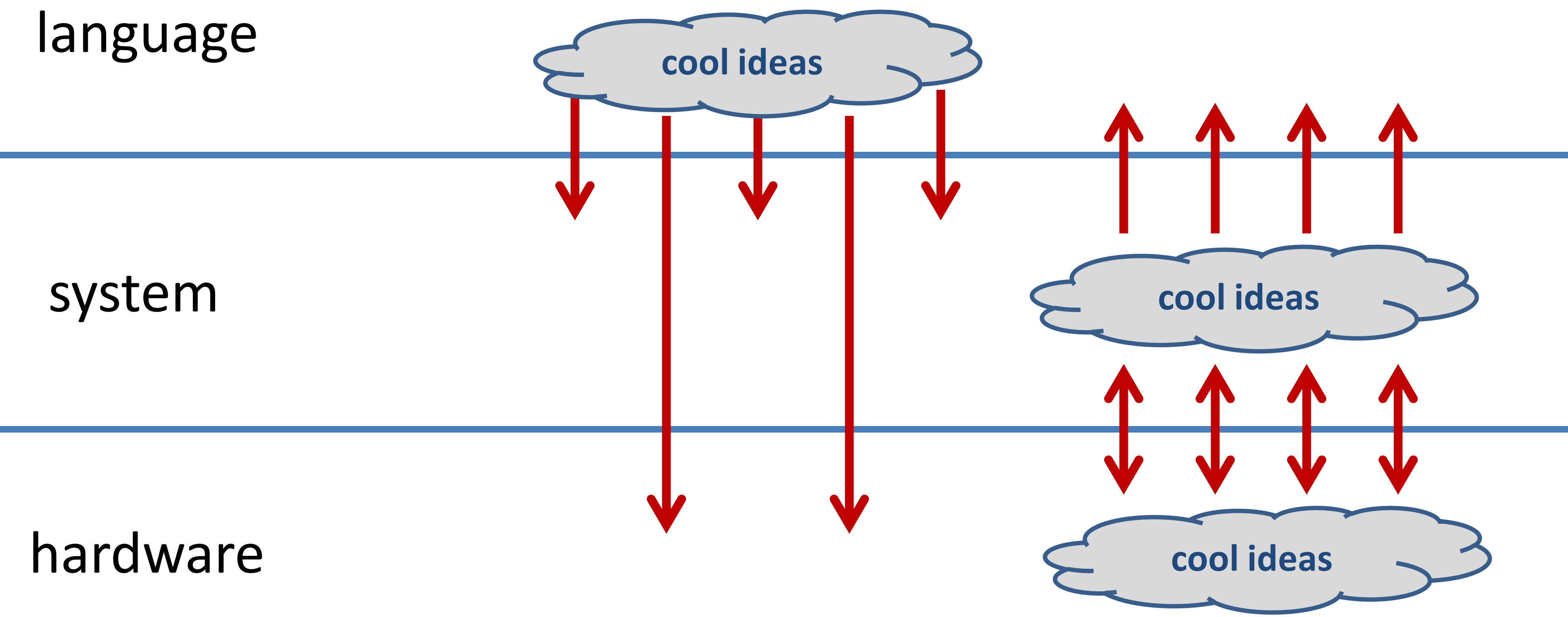
system

hardware

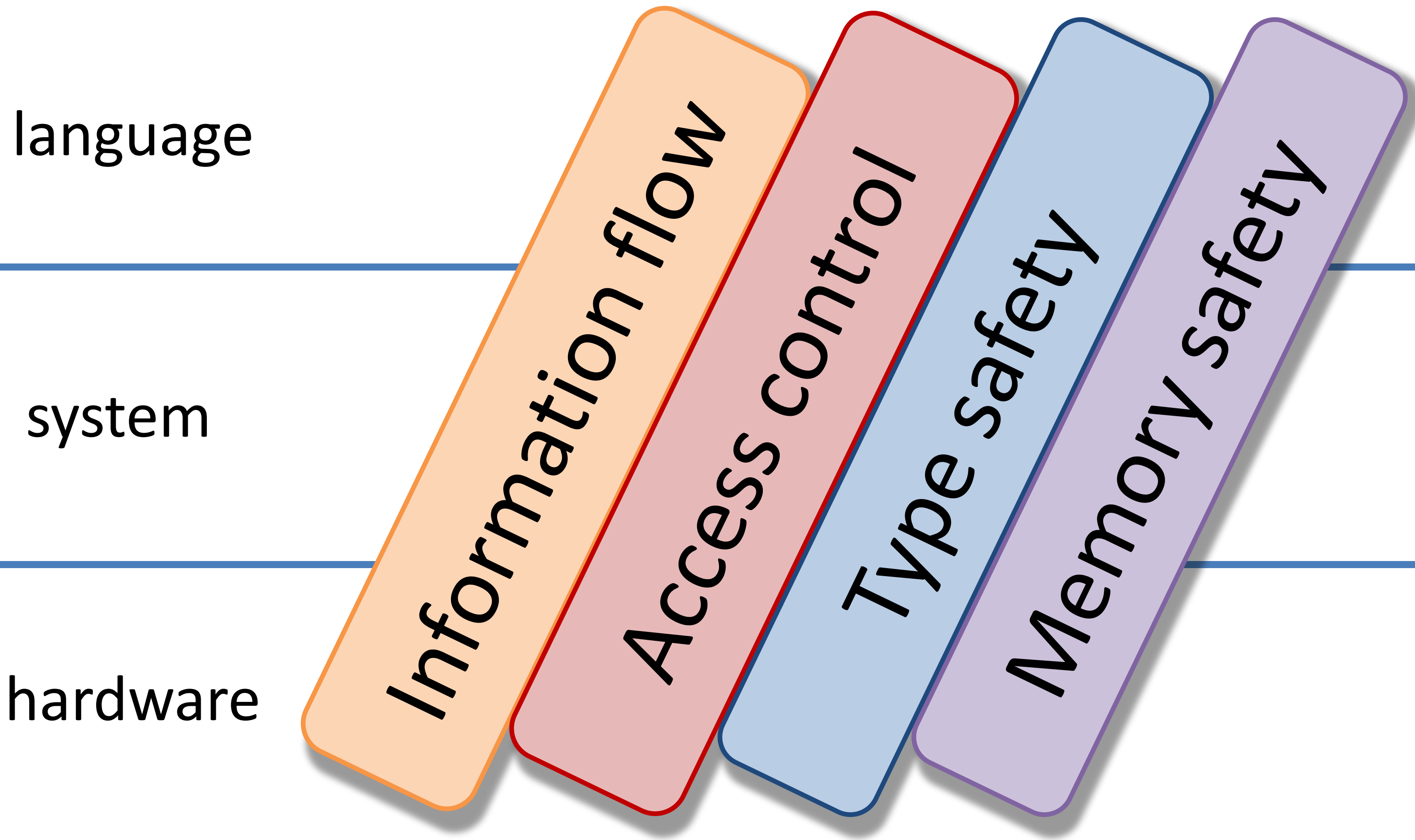
Time for a redesign targeting security!



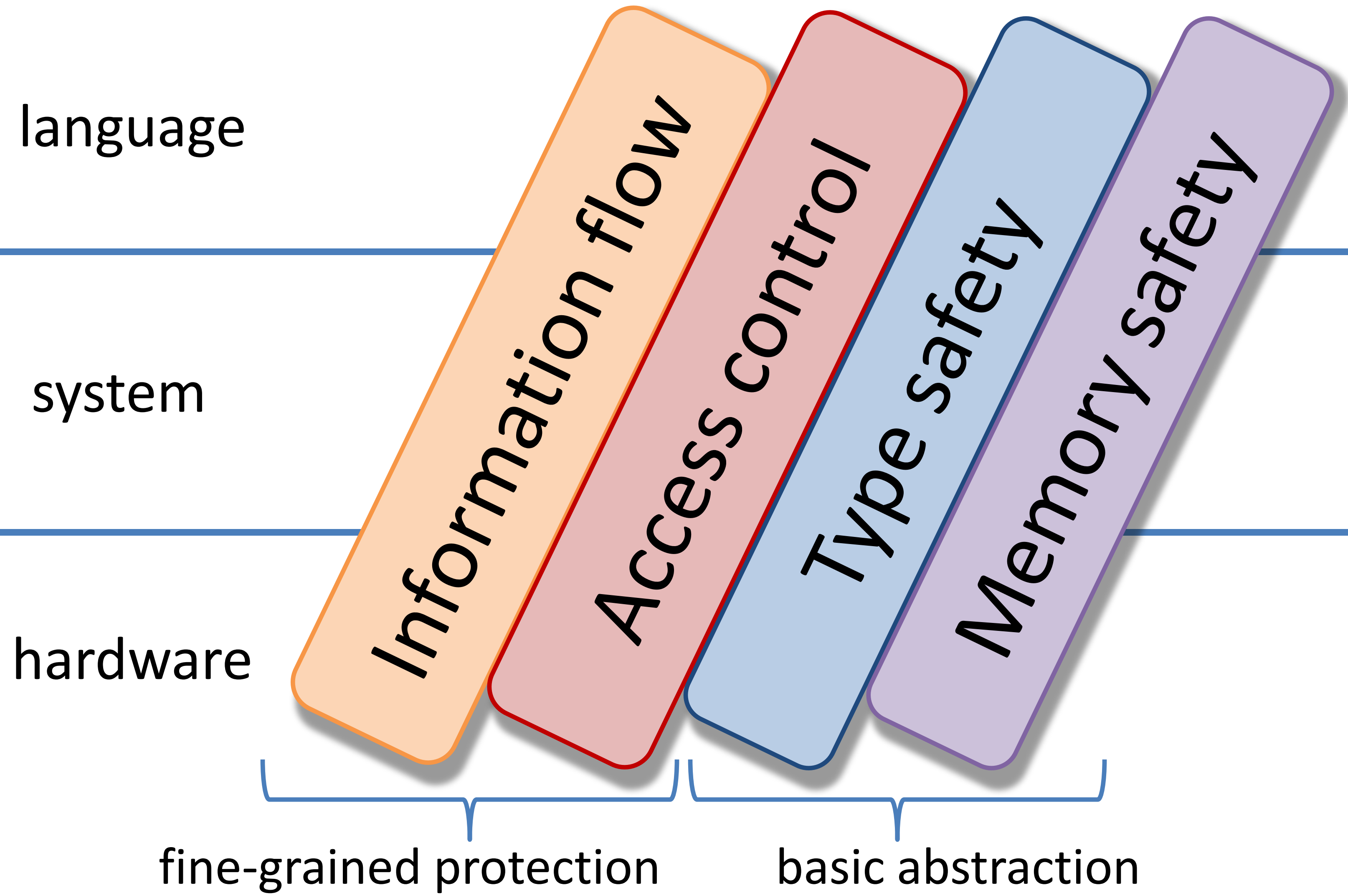
Time for a redesign targeting security!



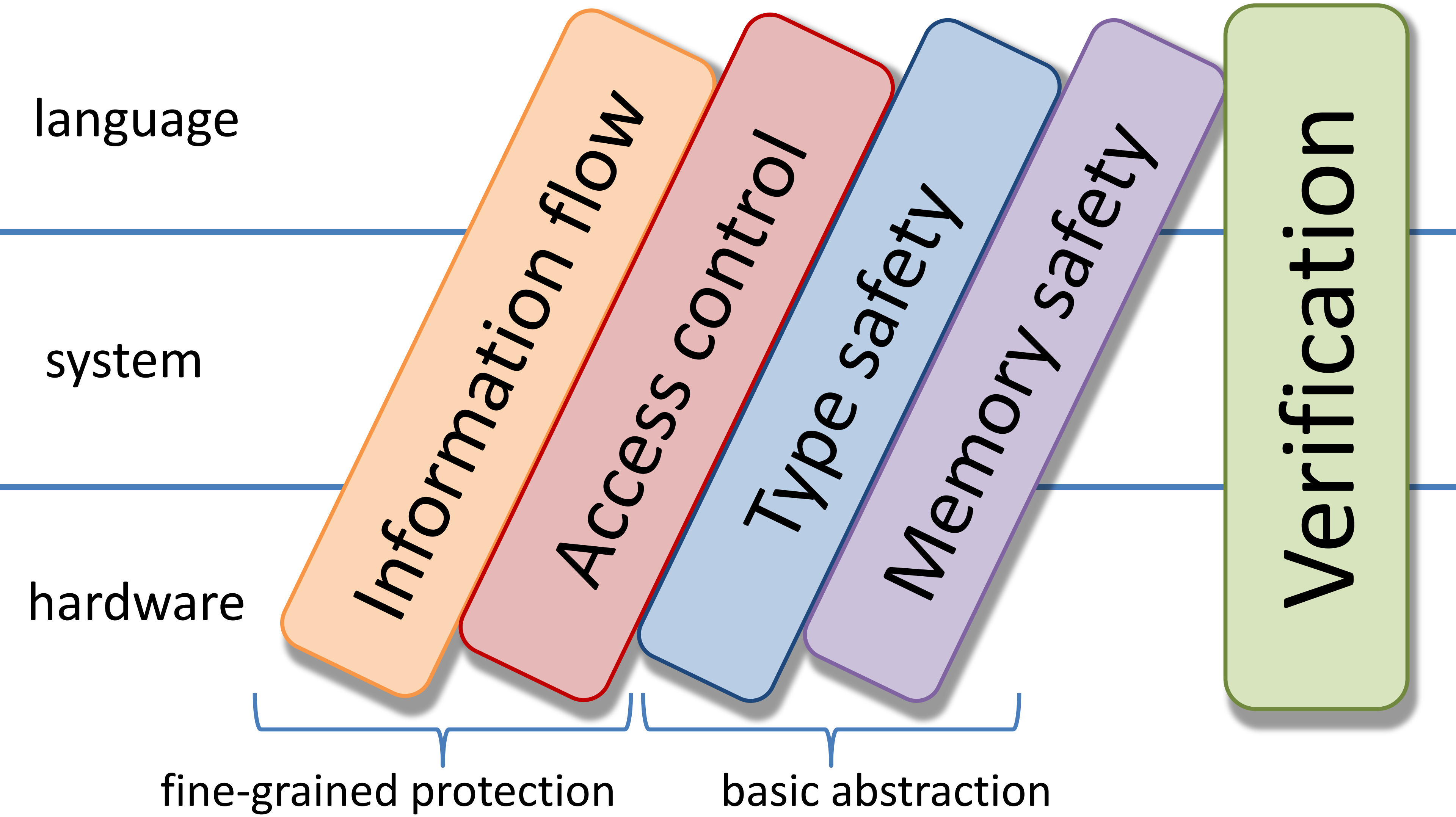
Time for a redesign targeting security!



Time for a redesign targeting security!



Time for a redesign targeting security!



Language (Breeze)

- testing ground for ideas we port to lower levels
- **type and memory safe** high-level language
  - dynamically typed + dynamically-checked contracts
- **functional core** (λ) + state(!) + concurrency (π)
  - message-passing communication (channels)

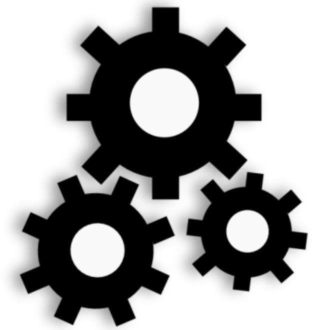
Language (Breeze)

- testing ground for ideas we port to lower levels
- **type and memory safe** high-level language
  - dynamically typed + dynamically-checked contracts
- **functional core** (λ) + state(!) + concurrency (π)
  - message-passing communication (channels)
- built-in **fine-grained protection mechanisms**:
  - values are attached **security labels** (e.g. public/secret)
  - **dynamic information flow control** (IFC)
  - **discretionary access control** (clearance)

Language (Breeze)

- testing ground for ideas we port to lower levels
- **type and memory safe** high-level language
  - dynamically typed + dynamically-checked contracts
- **functional core** (λ) + state(!) + concurrency (π)
  - message-passing communication (channels)
- built-in **fine-grained protection mechanisms**:
  - values are attached **security labels** (e.g. public/secret)
  - **dynamic information flow control** (IFC)
  - **discretionary access control** (clearance)
- novel **exception handling mechanism** (more later)

Runtime/operating system



- manages:
  - **time** - scheduler
  - **memory** - allocator, garbage collector
  - **communication and devices** - channels
  - **protection** – dynamic IFC and access control

Runtime/operating system

- manages:
  - **time** - scheduler
  - **memory** - allocator, garbage collector
  - **communication and devices** - channels
  - **protection** – dynamic IFC and access control
- *zero-kernel* operating system
  - reduced TCB even wrt microkernel
  - least privilege & privilege separation taken to extreme
  - kernel split into mutually distrustful federated services

Hardware

- all instructions have well-defined semantics
  - abstractions strictly enforced

Hardware

- all instructions have well-defined semantics
  - abstractions strictly enforced
- low-**fat pointers**
  - can’t access/write out of frame bounds

Hardware

- all instructions have well-defined semantics
  - abstractions strictly enforced
- low-**fat pointers**
  - can’t access/write out of frame bounds
- **dynamic types**
  - can’t turn ints into pointers (unforgeable **capabilities**)

Hardware

- all instructions have well-defined semantics
  - abstractions strictly enforced
- low-**fat pointers**
  - can’t access/write out of frame bounds
- **dynamic types**
  - can’t turn ints into pointers (unforgeable **capabilities**)
- **closures** (λ) **+ protected call stack**

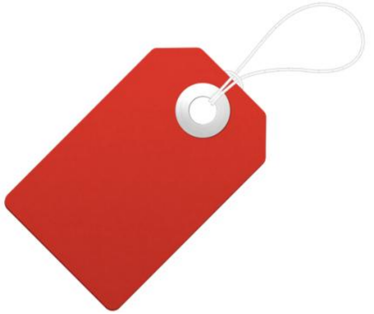
Hardware

- all instructions have well-defined semantics
  - abstractions strictly enforced
- low-**fat pointers**
  - can’t access/write out of frame bounds
- **dynamic types**
  - can’t turn ints into pointers (unforgeable **capabilities**)
- **closures** (λ) **+ protected call stack**
- **authority** + **gates** (authority switching closures)
  - fine-grained privilege separation / cheap system calls

Hardware

- all instructions have well-defined semantics
  - abstractions strictly enforced
- low-**fat pointers**
  - can’t access/write out of frame bounds
- **dynamic types**
  - can’t turn ints into pointers (unforgeable **capabilities**)
- **closures** (λ) **+ protected call stack**
- **authority** + **gates** (authority switching closures)
  - fine-grained privilege separation / cheap system calls
- programmable **tag management unit** (TMU)

Tag management



- **every word tagged** with arbitrary pointer
  – only operating system interprets these pointers
- **on each instruction** TMU looks up tags of operands in a **hardware rule cache**
  – found → rule provides tags on results (no delay)
  – not found → trap to software (protection server)
- extremely fine-grained access control + dynamic IFC enforced at the lowest level

All Your IFCException Are Belong To Us

Robust Exception Handling for Sound Fine-Grained Dynamic IFC

Cătălin Hrițcu, Michael Greenberg, Ben Karel,
Benjamin Pierce, Greg Morrisett

IEEE Symposium on Security & Privacy 2013 (Oakland)

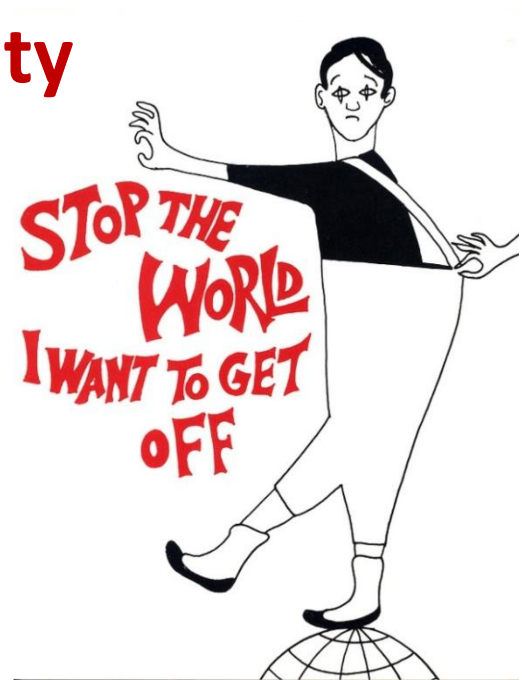
Exception handling

- we wanted reliable error recovery in Breeze
  - **recovery from all exceptions including IFC violations**
- however, existing work assumes errors are **fatal**

Exception handling

- we wanted reliable error recovery in Breeze
  - **recovery from all exceptions including IFC violations**
- however, existing work assumes errors are **fatal**
  - makes some things easier ... at the expense of others

+secrecy **+integrity** **–availability**

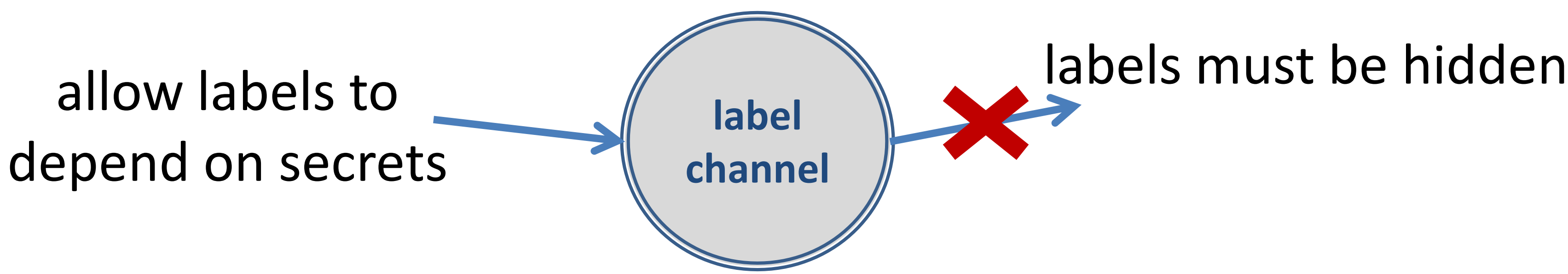


Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***out of*** label channel

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***<u>out of</u>*** label channel



Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***<u>out of</u>*** label channel

- secret bit: `s@secret`   `low <= secret <= top-secret`

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***<u>out of</u>*** label channel

- secret bit: `s@secret`   `low <= secret <= top-secret`

encode s into label

```
(if s then ()@secret
 else ()@top-secret);
```

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***<u>out of</u>*** label channel

- secret bit: `s@secret` `low <= secret <= top-secret`

```
let href = ref secret () in
.......

   href := (if s then ()@secret
             else ()@top-secret);
```

if branch – assignment works
else branch – IFCException

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***<u>out of</u>*** label channel

- secret bit: `s@secret` `low <= secret <= top-secret`

```
let href = ref secret () in
.......
try
  href := (if s then ()@secret
             else ()@top-secret);
  true
catch IFCException => false
```

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking either ***into*** or ***out of*** label channel

allow labels to depend on secrets

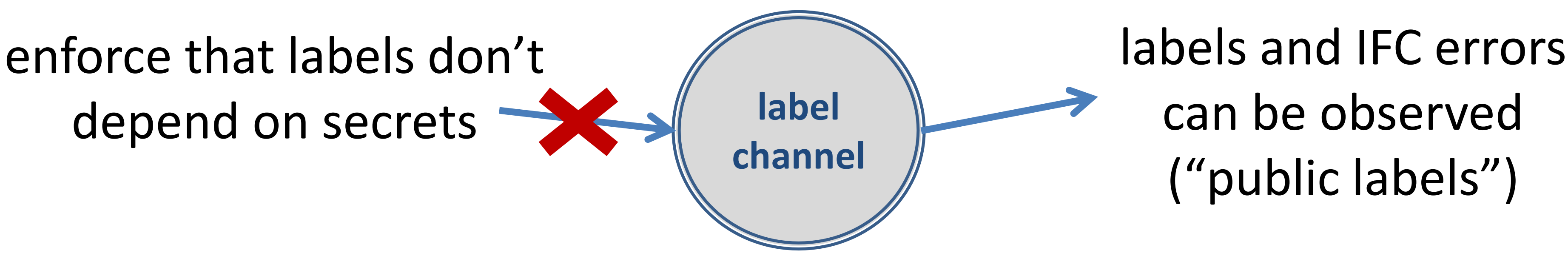
labels must be hidden

IFC errors must be hidden!
(and we don’t want that)

```
if s then ()@secret else ()@top-secret
```

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking ~~either~~ ***into*** ~~or~~ ~~***out of***~~ label channel

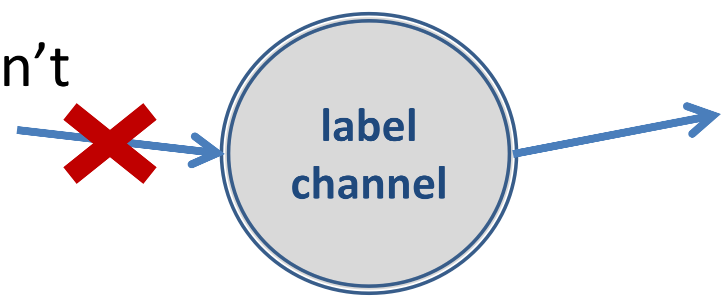



```
if s then ()@secret else ()@top-secret
```

Problem #1: IFC exceptions reveal information about labels

- labels are themselves information channels
- get soundness by preventing secrets from leaking ~~either~~ ***into*** ~~or ***out of***~~ label channel

enforce that labels don’t depend on secrets



labels and IFC errors can be observed (“public labels”)

Solution #1: brackets

```
top-secret[if s then ()@secret else ()@top-secret]
```

Problem #2: exceptions destroy control flow join points

- ending brackets need to be control flow join points, otherwise...
  - ```
    try
      let _ = secret[if h then throw Ex] in
      false
    catch Ex => true
    ```
    ```

Problem #2: exceptions destroy control flow join points

- ending brackets need to be control flow join points, otherwise...
  - ```
    try
      let _ = secret[if h then throw Ex] in
      false
    catch Ex => true
    ```
- brackets need to delay all exceptions!
  - `secret[if true@secret then throw Ex] => “(Error Ex)@secret”`
  - `secret [if false@secret then throw Ex] => “(Success ())@secret”`
    ```

Problem #2: exceptions destroy control flow join points

- ending brackets need to be control flow join points, otherwise...
  - ```
    try
      let _ = secret[if h then throw Ex] in
      false
    catch Ex => true
    ```
- brackets need to delay all exceptions!
  - `secret[if true@secret then throw Ex] => “(Error Ex)@secret”`
  - `secret [if false@secret then throw Ex] => “(Success ())@secret”`
- similarly for failed brackets
  - `secret[42@top-secret] => “(Error EBracket)@secret”`
    ```

Solution #2: Delayed exceptions

- **delayed exceptions unavoidable**
  – still have a choice how to propagate them
- we studied **two main alternatives**:
  1. **mix active and delayed exceptions** ($\lambda^{[\,]}_{throw}$)

Solution #2: Delayed exceptions

- **delayed exceptions unavoidable**
  – still have a choice how to propagate them
- we studied **two main alternatives**:
  1. **mix active and delayed exceptions** ($\lambda^{[\,]}_{throw}$)
  2. **only delayed exceptions** ($\lambda^{[\,]}_{NaV}$)
     - delayed exception = not-a-value (NaV)
     - NaVs are first-class replacement for values
     - NaVs propagated solely via data flow
     - NaVs are labeled and pervasive
     - simpler and more radical solution; implemented in Breeze

What’s in a NaV? Debugging aids!

- error message
  - `EDivisionByZero (“can’t divide %1 by 0”, 42)
- stack trace
  - pinpoints error **origin**
    (not the billion-dollar mistake!)
- propagation trace
  - how did the error make it here?

What’s in a NaV? Debugging aids!

- error message
  - `EDivisionByZero (“can’t divide %1 by 0”, 42)
- stack trace
  - pinpoints error **origin**
    (not the billion-dollar mistake!)
- propagation trace
  - how did the error make it here?

NaVs are compiler writer’s dream, especially if compiler is allowed to be imprecise about these debugging aids
(Greg Morrisett)

NaV-lax vs. NaV-strict behavior

- all non-parametric operations are NaV-strict
  - `NaV@low + 42@high => NaV@high`
- for parametric operations we can chose:

  NaV-lax or NaV-strict

  - `(fun x => 42) NaV => 42` or `=> NaV`

NaV-lax vs. NaV-strict behavior

- all non-parametric operations are NaV-strict
  - `NaV@low + 42@high => NaV@high`
- for parametric operations we can chose:

```
                              NaV-lax           or    NaV-strict
– (fun x => 42) NaV => 42                       or    => NaV
– Cons NaV Nil      => Cons NaV Nil             or    => NaV
```

NaV-lax vs. NaV-strict behavior

- all non-parametric operations are NaV-strict
  - `NaV@low + 42@high => NaV@high`
- for parametric operations we can chose:

```
                               NaV-lax            or   NaV-strict
– (fun x => 42) NaV => 42                 or   => NaV
– Cons NaV Nil      => Cons NaV Nil       or   => NaV
– (r := NaV,r=7)    => ((),r=NaV)         or   => (NaV,r=7)
```

NaV-lax vs. NaV-strict behavior

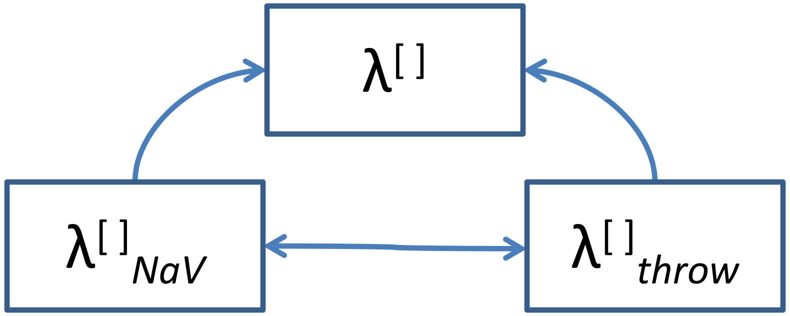
- all non-parametric operations are NaV-strict
  - `NaV@low + 42@high => NaV@high`
- for parametric operations we can chose:

	NaV-lax	or	NaV-strict
– `(fun x => 42) NaV`	`=> 42`	`or`	`=> NaV`
– `Cons NaV Nil`	`=> Cons NaV Nil`	`or`	`=> NaV`
– `(r := NaV,r=7)`	`=> ((),r=NaV)`	`or`	`=> (NaV,r=7)`

- NaV-strict behavior reveals errors earlier
  - but it also introduces additional IFC constraints
  - applied everywhere it makes brackets useless
- in Breeze the programmer can choose
  - in formal development NaV-lax everywhere

Formal results

- proved termination-insensitive **noninterference** in Coq for $\lambda^{[\,]}$, $\lambda^{[\,]}_{NaV}$, and $\lambda^{[\,]}_{throw}$
  - for $\lambda^{[\,]}_{NaV}$ even with all debugging aids; **error-sensitive**
- in our setting NaVs and catchable exceptions have **equivalent expressive power**
  - translations validated by QuickChecking extracted code



Summary for IFC exceptions

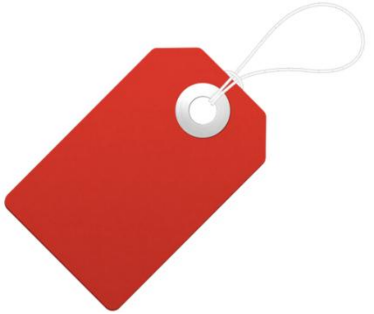
- reliable error handling **possible** even for sound fine-grained dynamic IFC systems
- two mechanisms ($\lambda^{[\,]}_{NaV}$ and $\lambda^{[\,]}_{throw}$)
  – **all errors recoverable**, even IFC violations
  – **necessary** ingredients: **sound public labels** (brackets) + **delayed exceptions**
  – quite **radical design** (not backwards compatible!)
  – we believe delayed exceptions **applicable to static IFC**

Testing Noninterference, Quickly

Cătălin Hriţcu, John Hughes, Benjamin C. Pierce,
Antal Spector-Zabusky, Dimitrios Vytiniotis,
Arthur Azevedo de Amorim, Leonidas Lampropoulos

ready for submission to
International Conference on Functional Programming (ICFP 2013)

protection server

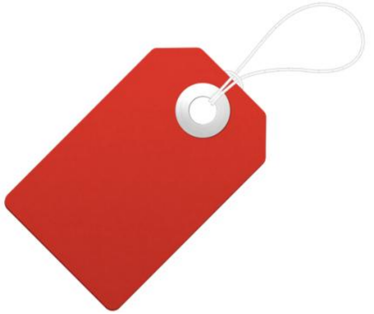


- most security-critical & novel component of our system
  - best target for verification

machine
running protection server code

noninterference (security)

protection server



- most security-critical & novel component of our system
  - best target for verification

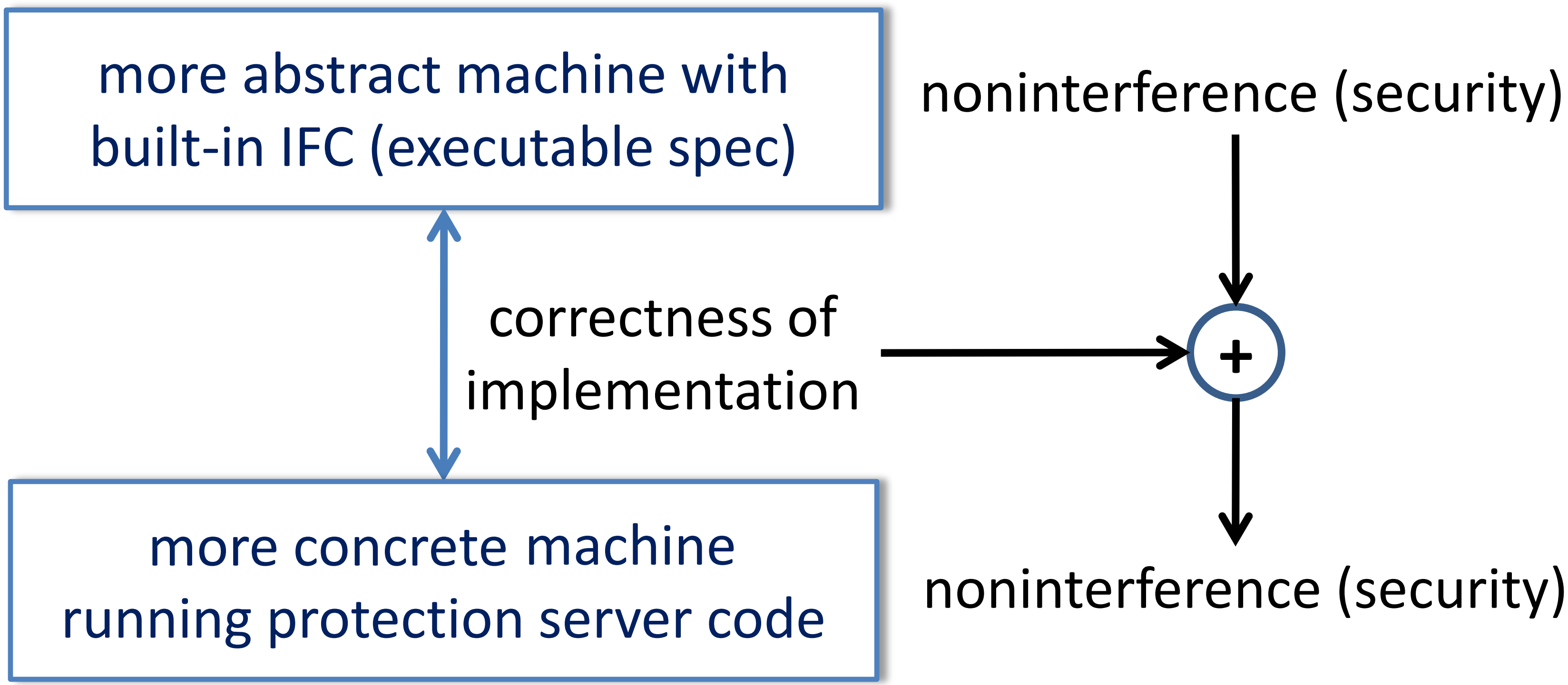
more abstract machine with
built-in IFC (executable spec)

more concrete machine
running protection server code

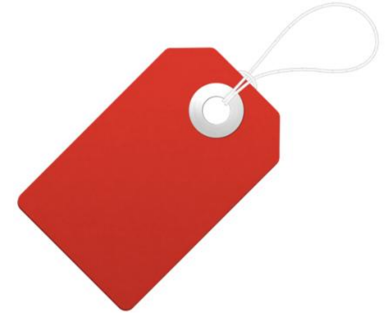
noninterference (security)

protection server

- most security-critical & novel component of our system
  - best target for verification

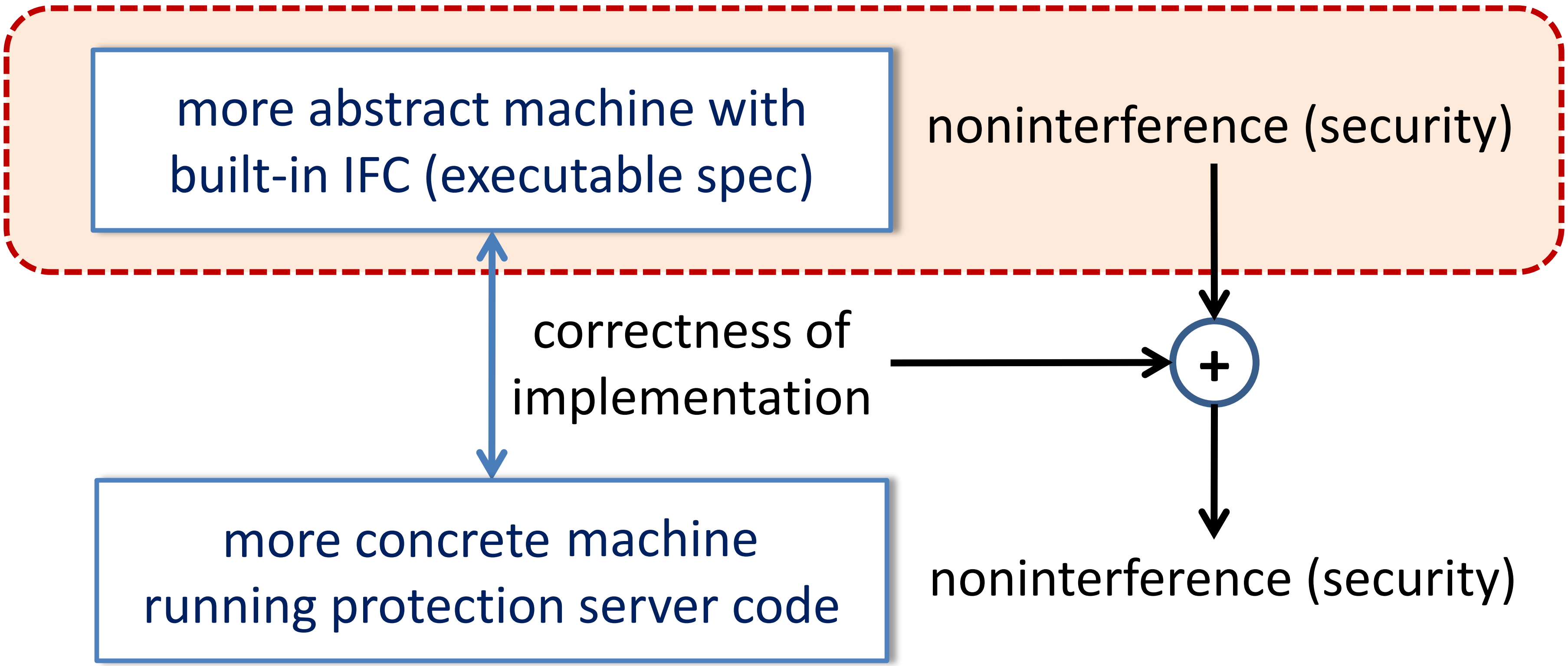


protection server



- most security-critical & novel component of our system
  - best target for verification

Can we QuickCheck this?



Yes we can!

- random testing noninterference of pico-machine
  - simple stack machine with dynamic IFC (10 instrs.)
    - Push, Load, Store, Add, Sub, Noop, Jump, Call, Ret, Halt

Yes we can!

- random testing noninterference of pico-machine
  - simple stack machine with dynamic IFC (10 instrs.)
    - Push, Load, Store, Add, Sub, Noop, Jump, Call, Ret, Halt
  - designing sound IFC mechanism still tricky!
    - Jump / Call – to secret address raises PC label
    - Ret – unwinds stack, taints result, restores PC label
    - Store – no-sensitive-upgrade check [Austin&Flanagan, '09]: pc-label `join` label-of-address <= label-of-value-stored-at-address

Yes we can!

- random testing noninterference of pico-machine
  - simple stack machine with dynamic IFC (10 instrs.)
    - Push, Load, Store, Add, Sub, Noop, Jump, Call, Ret, Halt
  - designing sound IFC mechanism still tricky!
    - Jump / Call – to secret address raises PC label
    - Ret – unwinds stack, taints result, restores PC label
    - Store – no-sensitive-upgrade check [Austin&Flanagan, '09]: pc-label `join` label-of-address <= label-of-value-stored-at-address
- we proved noninterference for this in Coq in 1 week! why bother with testing?

Yes we can!

- random testing noninterference of pico-machine
  - simple stack machine with dynamic IFC (10 instrs.)
    - Push, Load, Store, Add, Sub, Noop, Jump, Call, Ret, Halt
  - designing sound IFC mechanism still tricky!
    - Jump / Call – to secret address raises PC label
    - Ret – unwinds stack, taints result, restores PC label
    - Store – no-sensitive-upgrade check [Austin&Flanagan, '09]: pc-label `join` label-of-address <= label-of-value-stored-at-address
- we proved noninterference for this in Coq in 1 week! why bother with testing?
  - we hope that QuickCheck will scale better than Coq to the much more complicated real SAFE machine (~110 instrs.)

How do we do it?

- Clever program generation strategies

gen. strategy	# bugs found	mean time to find	max time to find
naive	4 out of 6	3030.30ms	> 300s
weighted	4 out of 6	201.20ms	> 300s
+ sequences	6 out of 6	16.45ms	300s
+ smart integers	6 out of 6	5.85ms	16.66s
+ gen. by exec.	6 out of 6	1.51ms	1.52s

How do we do it?

- Clever program generation strategies

gen. strategy	# bugs found	mean time to find	max time to find
naive	4 out of 6	3030.30ms	> 300s
weighted	4 out of 6	201.20ms	> 300s
+ sequences	6 out of 6	16.45ms	300s
+ smart integers	6 out of 6	5.85ms	16.66s
+ gen. by exec.	6 out of 6	1.51ms	1.52s

- Shrinking counterexamples

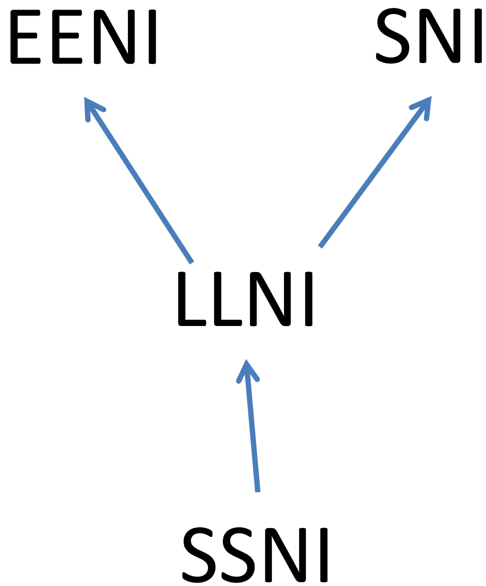
How do we do it?

- Clever program generation strategies

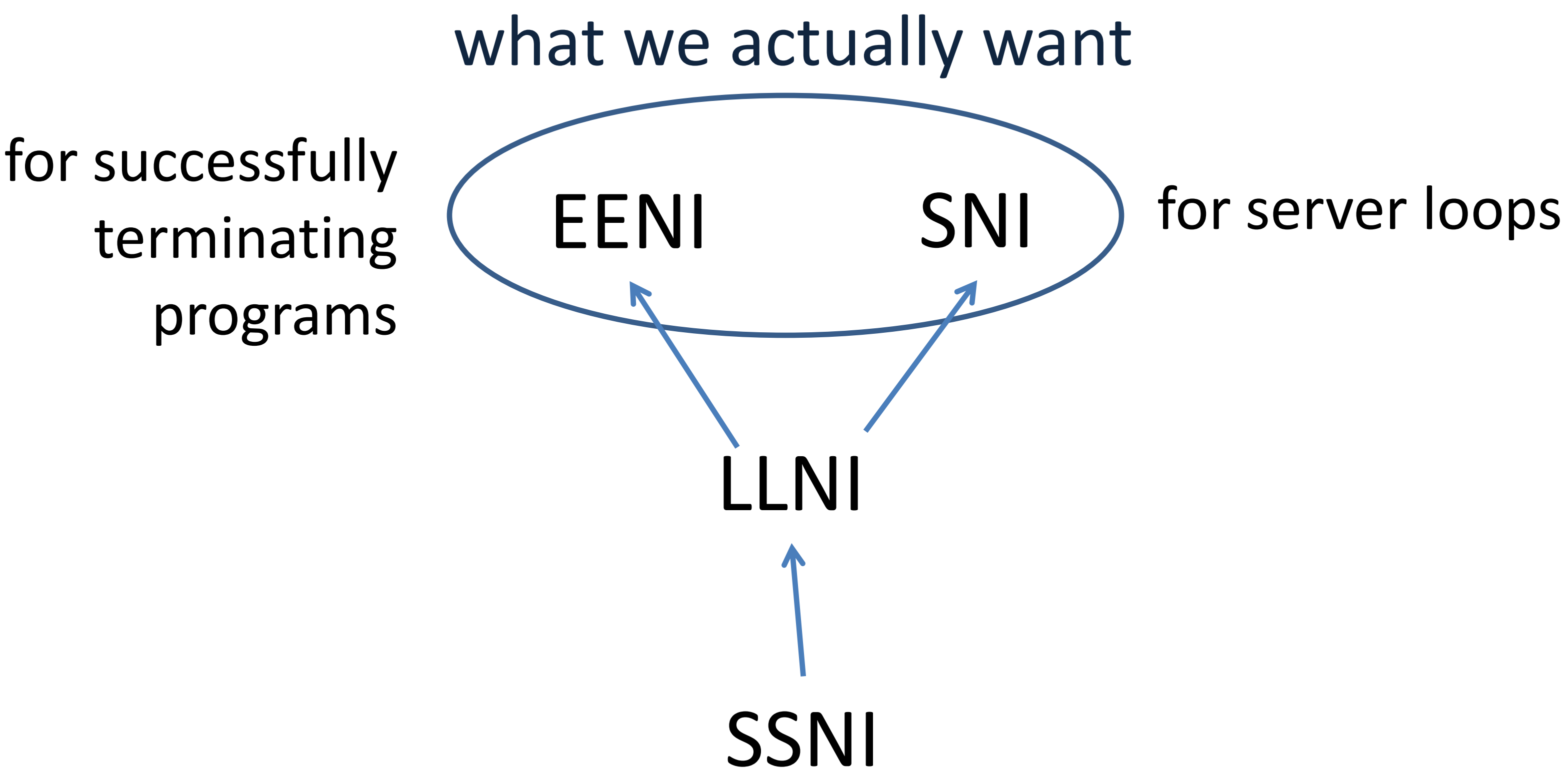
gen. strategy	# bugs found	mean time to find	max time to find
naive	4 out of 6	3030.30ms	> 300s
weighted	4 out of 6	201.20ms	> 300s
+ sequences	6 out of 6	16.45ms	300s
+ smart integers	6 out of 6	5.85ms	16.66s
+ gen. by exec.	6 out of 6	1.51ms	1.52s

- Shrinking counterexamples
- Stronger noninterference properties

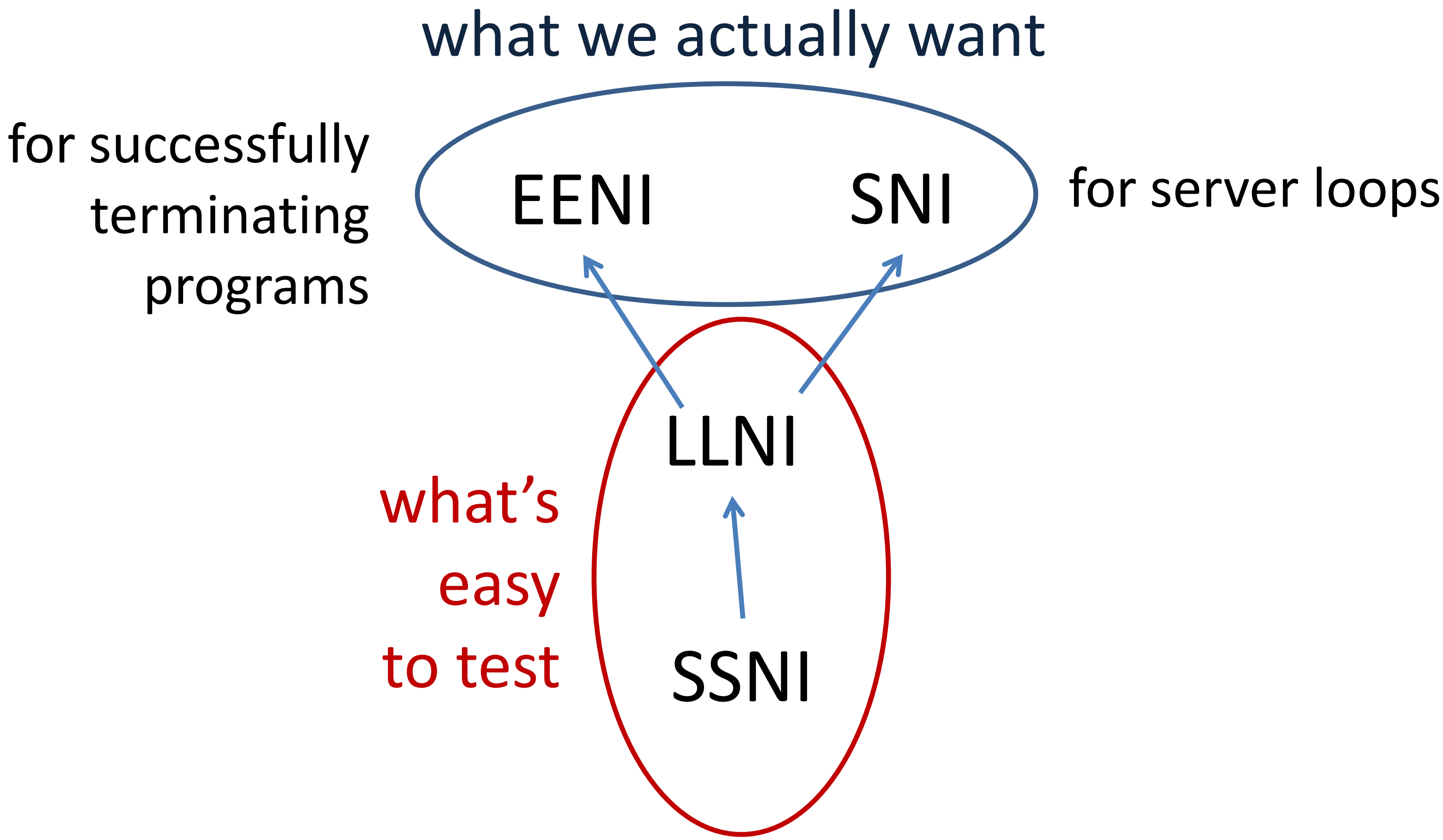
noninterference



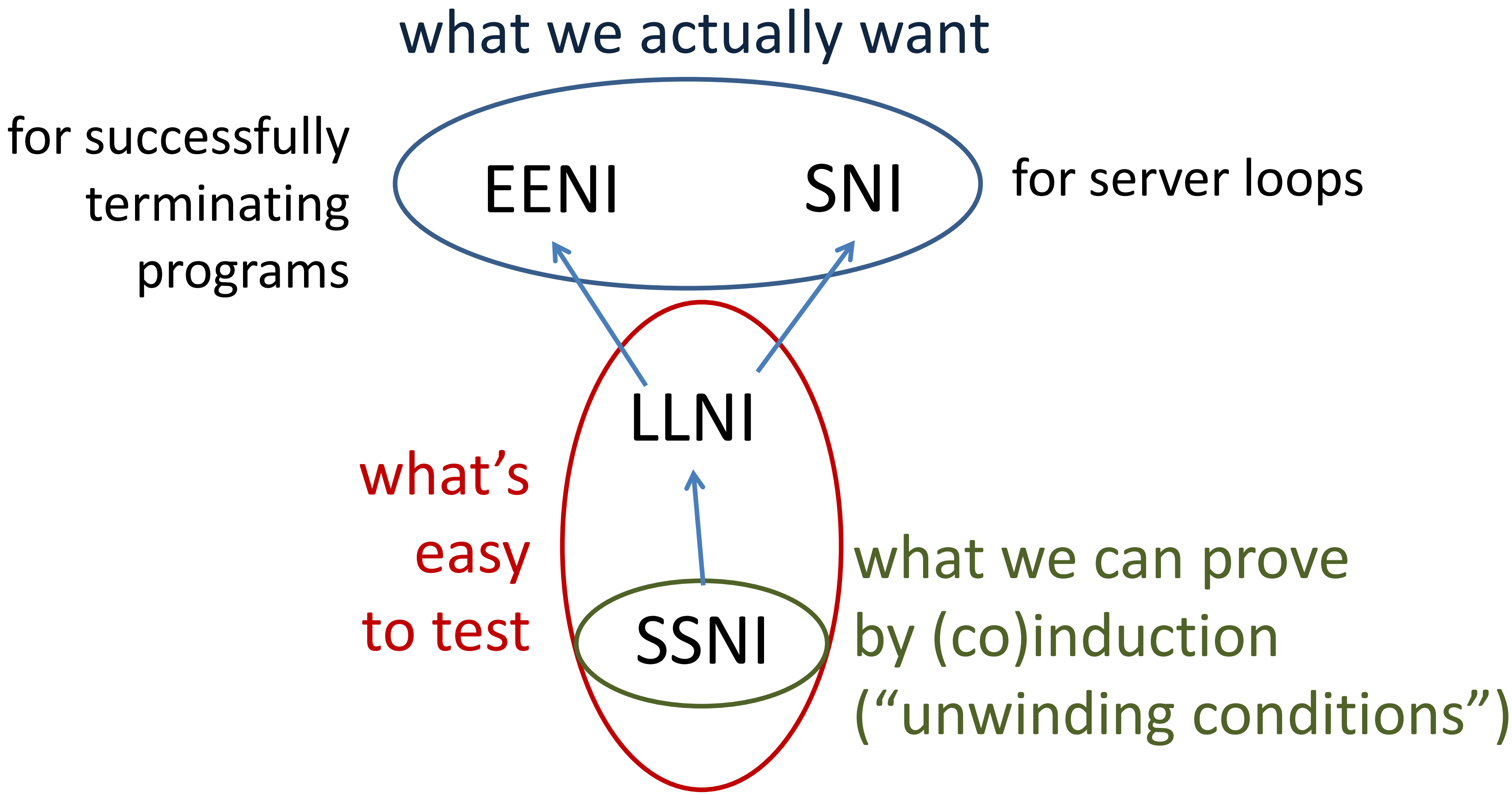
noninterference



noninterference



noninterference

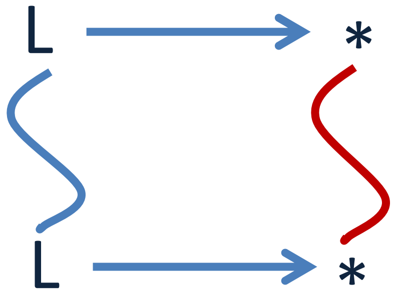


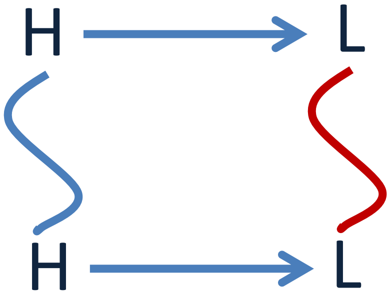
End-to-end noninterference (EENI)

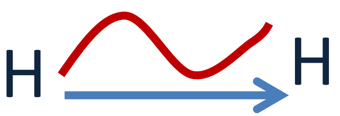
what we actually want for terminating programs

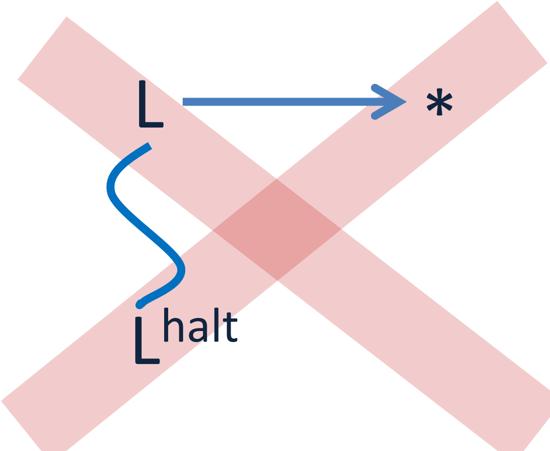
Single-step noninterference (SSNI)

easy to test and suitable for proof (“unwinding conditions”)









Experiments

- Stronger properties discover bugs much faster

strategy	# bugs found	mean time to find	max time to find
EENI + GenByExec	14 out of 14	549.45ms	300.00s
LLNI + GenByExec	14 out of 14	17.13ms	0.90s
SSNI + Naive	14 out of 14	26.70ms	0.45s
SSNI + TinyStates	14 out of 14	4.68ms	0.03s

- SSNI is very cool, but ...
  – SSNI requires discovering stronger invariants
  – invariants of SAFE machine are very complicated

Ongoing work on CRASH/SAFE

- verifying simple protection server in Coq
  - micro-machine: hardware types, dynamic allocation, principal generation, public labels
  - joint with Benjamin Pierce, Delphine Demange, Andrew Tolmach
- protecting data integrity with signatures
  - meaning(lessness) of IFC endorsement; reviving trademarks [Moris '73]
  - beyond data abstraction (dynamic sealing): caching contracts
- fine-grained higher-order containment
- Breeze design paper
- Tag management unit (TMU) design paper
- implementing Breeze labels cryptographically

Future directions

- Formally verified privacy-preserving distributed applications (e.g. ones based on zero-knowledge proofs)

protecting personal information

+

digital credentials

→ idemix · U-Prove · Higgins (an Eclipse project, Personal Data Service)

privacy-enabled identity systems

"proving you are over 18 without revealing your age"

Future directions

- Formally verified privacy-preserving distributed applications (e.g. ones based on zero-knowledge proofs)

protecting
personal information

digital credentials

idemix
U-Prove
eclipse
an Eclipse project
Higgins
Personal Data Service

privacy-enabled identity systems

“proving you are over 18 without revealing your age”

- Fine-grained access control and integrity protection for mobile devices

THE END