When Good Components Go Bad

Formally Secure Compilation Despite Dynamic Compromise

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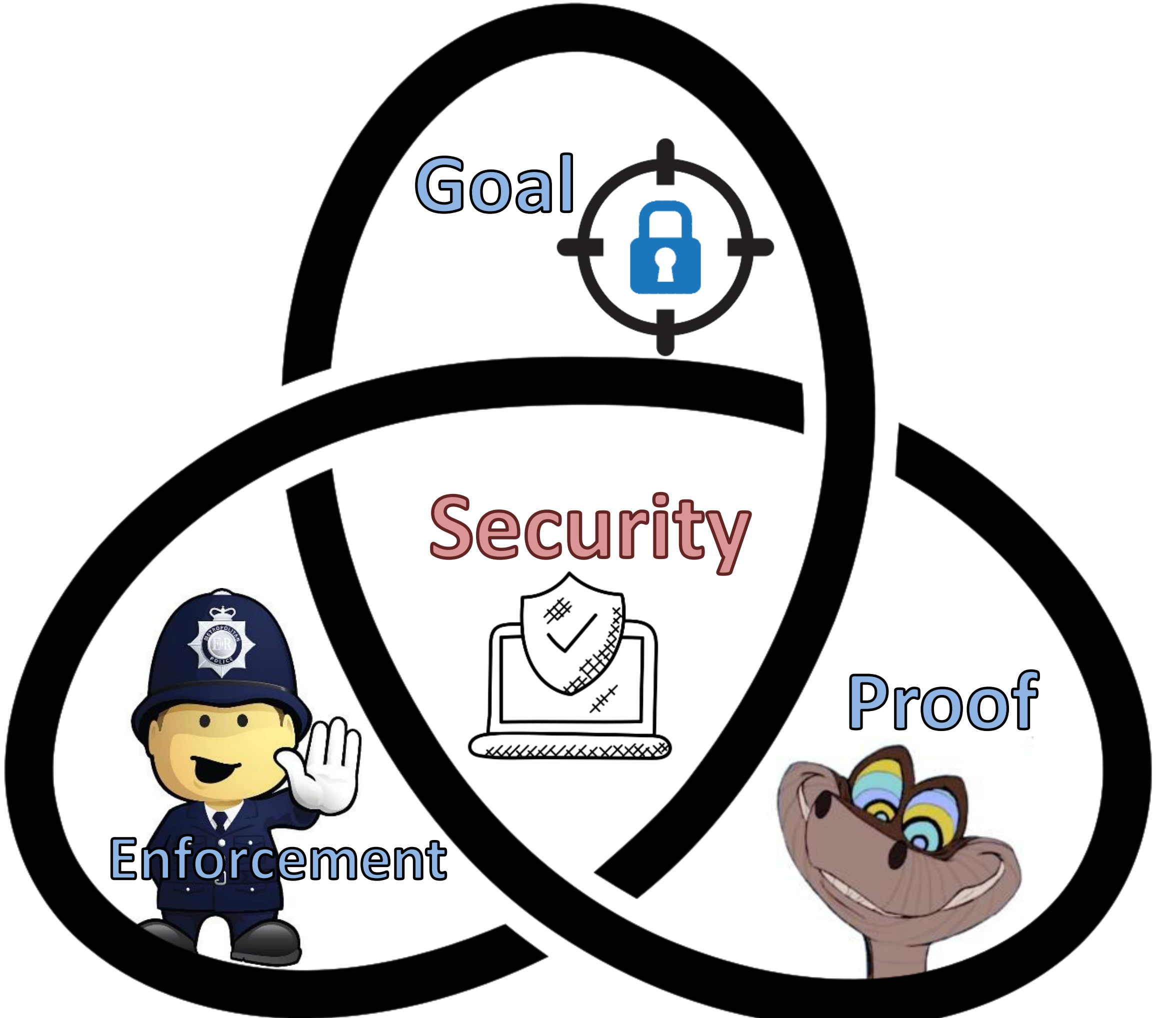
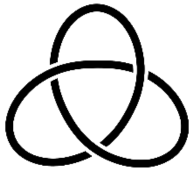

Goal
Security
Proof
Enforcement



Security foundations research is about making this diagram mathematically formal

1. Security Goal [What are we trying to achieve?]

- **negative definition**: What (kind of) attacks are we trying to prevent?
- **positive definition**: What security property are we aiming for?

2. Security Enforcement [How can we effectively achieve it?]

- **static**: informal audit, program verification, type systems, ...
- **dynamic**: reference monitors, hardware mechanisms, crypto, ...
- **trade off security** vs. precision, efficiency, compatibility, ...

3. Security Proof [How can we make sure we achieved it?]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Security proof

Easier and more scalable

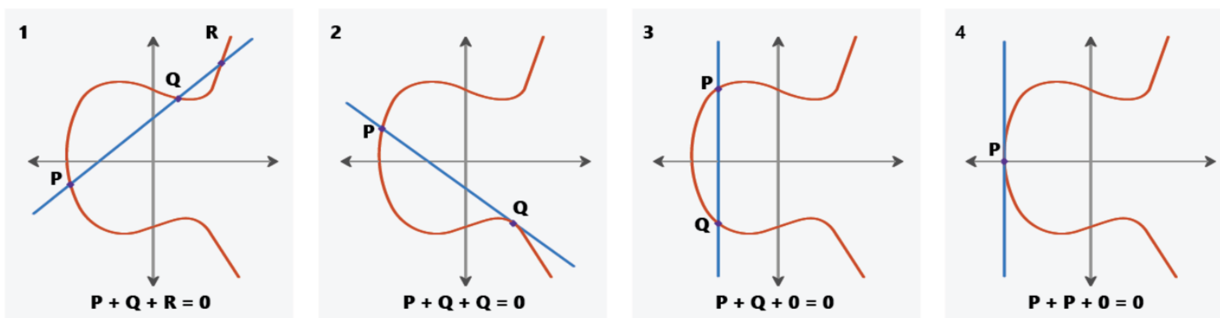
- **Marketing snake oil**: trussst me, it isss very sssecure
- ...
- **Security experts, metrics, standards**
- **Security testing**, red teaming, bounty programs
- ...
- **Mathematical proofs** with various levels of rigor
- **Formal, machine-checked proofs**
  - in a proof assistant like Coq, Isabelle, HOL, F*, EasyCrypt, ...
  - about **abstract models** or **concrete implementations**
  - under various **assumptions** and **trusted computing base**

Better assurance

EasyCrypt

EverCrypt cryptographic provider offers developers greater security assurances

April 2, 2019 | By Jonathan Protzenko, Researcher; Bryan Parno, Associate Professor, Carnegie Mellon University



Project Everest is a multiyear collaborative effort focused on building a verified, secure communications stack designed to improve the security of HTTPS, a key internet safeguard. This post, about the high-performance industrial-grade EverCrypt cryptographic provider, is the second in a series exploring the groundbreaking work, which is available on GitHub now.

EverCrypt: Verified Crypto Provider

- **Verified C (HACL*)**: ChachaPoly, SHA2+3, Blake2, Curve25519, ...
- **Verified X64 ASM (Vale)**: AES-GCM, Poly1305, Curve25519, ...
- **Good efficiency**, comparable to libcrypto or libsodium
- **Readable** C and ASM code
- **Deployed in production**
  - Mozilla Firefox (NSS)
  - Microsoft WinQUIC

- **Project Everest**, extending this to:
  - verified TLS implementation
  - verified HTTPS stack

EverCrypt formally

1. Security Goals

- **Memory safety** (no buffer overflows, use-after-frees, double-frees, ...)
- **Functional correctness** (code implements a simpler math function)
- **Side-channel resistance** (secret independent control & mem accesses)
- **Cryptographic security** (e.g. auth, int, and conf of AEAD constructions)

2. Security Enforcement

- **static**: program verification in F* for safety and correctness
- side-channel resistance and crypto security involve paper proofs

3. Security Proof

- **milestone**: 100.000+ lines of verifiably correct code, shipping
- **still**: big trusted computing base, some interesting proofs on paper

Formally Secure Compartmentalization

When Good Components Go Bad (CCS 2018)

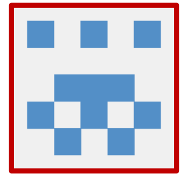
Beyond Good and Evil (CSF 2016)

Micro-Policies (IEEE S&P 2015)

Core team at Inria Paris

Carmine Abate

Rob Blanco



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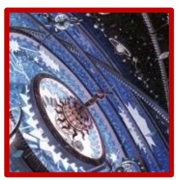

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Inherently insecure languages like C

- any **buffer overflow** can be catastrophic
- ~100 different **undefined behaviors**
  in the usual C compiler:
  - **use after frees and double frees, invalid type casts, signed integer overflows, ...**
- **root cause**, but very challenging to fix:
  - **efficiency**, precision, scalability, backwards compatibility, deployment

Compartmentalization mitigation

- **Break up security-critical applications** into **mutually distrustful components** with **clearly specified privileges**
- **Enforce this component abstraction all the way down**
  - separation, static privileges, call-return discipline, types, ...
- **Compartmentalizing compilation chain:**
  - compiler, linker, loader, runtime, system, hardware
- **Base this on efficient enforcement mechanisms:**
  - **OS processes (all web browsers)**
  - **WebAssembly (web browsers)**
  - **software fault isolation (SFI)**
  - hardware enclaves (SGX)
  - capability machines
  - tagged architectures

1. Security Goal

[What are we trying to achieve?]

- **Hoping for strong security guarantees one can make fully water-tight**
  - beyond just "increasing attacker effort"
- **Intuitively, if we use compartmentalization ...**

... **a vulnerability in one component does not immediately destroy the security of the whole application**

... **since each component is protected from all the others**

... and each component receives protection as long as it has not been compromised (e.g. by a buffer overflow)

Can we formalize this intuition?

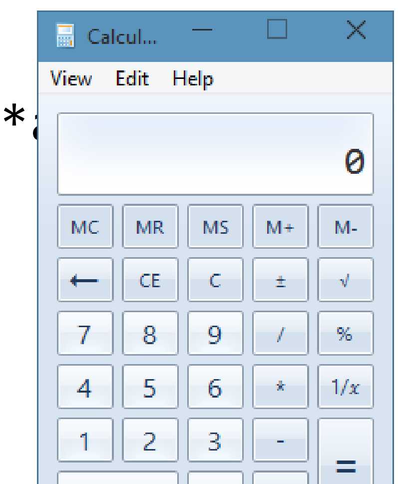
What is a compartmentalizing compilation chain supposed to enforce precisely?

Formal definition expressing the end-to-end security guarantees of compartmentalization

Challenge formalizing security of mitigations

- **We want source-level security reasoning principles**
  - easier to **reason about security in the source language** if and application is compartmentalized
- **... even in the presence of undefined behavior**
  - can't be expressed at all by source language semantics!
  - **what does the following program do?**

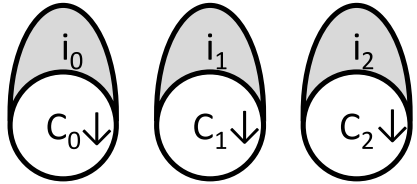
```
#include <string.h>
int main (int argc, char **
    char c[12];
    strcpy(c, argv[1]);
    return 0;
}
```



Compartmentalizing compilation should ...

- **Restrict spatial scope** of undefined behavior
  - **mutually-distrustful components**
    - **each component protected from all the others**
- **Restrict temporal scope** of undefined behavior
  - **dynamic compromise**
    - **each component gets guarantees as long as it has not encountered undefined behavior**
    - i.e. the mere existence of vulnerabilities doesn't necessarily make a component compromised

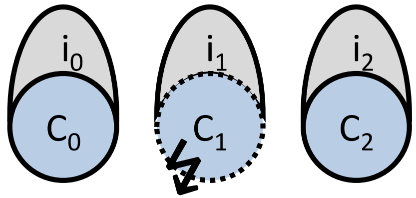
Security definition: If



$\rightsquigarrow t$ then

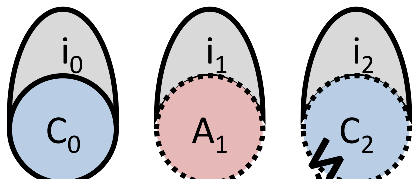
∃ a sequence of component compromises explaining the finite trace t in the source language, for instance $t = m_1 \cdot m_2 \cdot m_3$ and

(1)



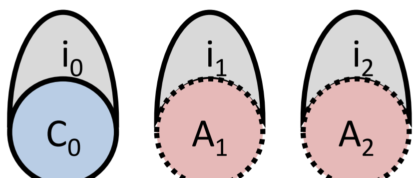
$\rightsquigarrow^* m_1 \cdot \mathrm{Undef}(C_1)$

(2) $\exists A_1.$



$\rightsquigarrow^* m_1 \cdot m_2 \cdot \mathrm{Undef}(C_2)$

(3) $\exists A_2.$



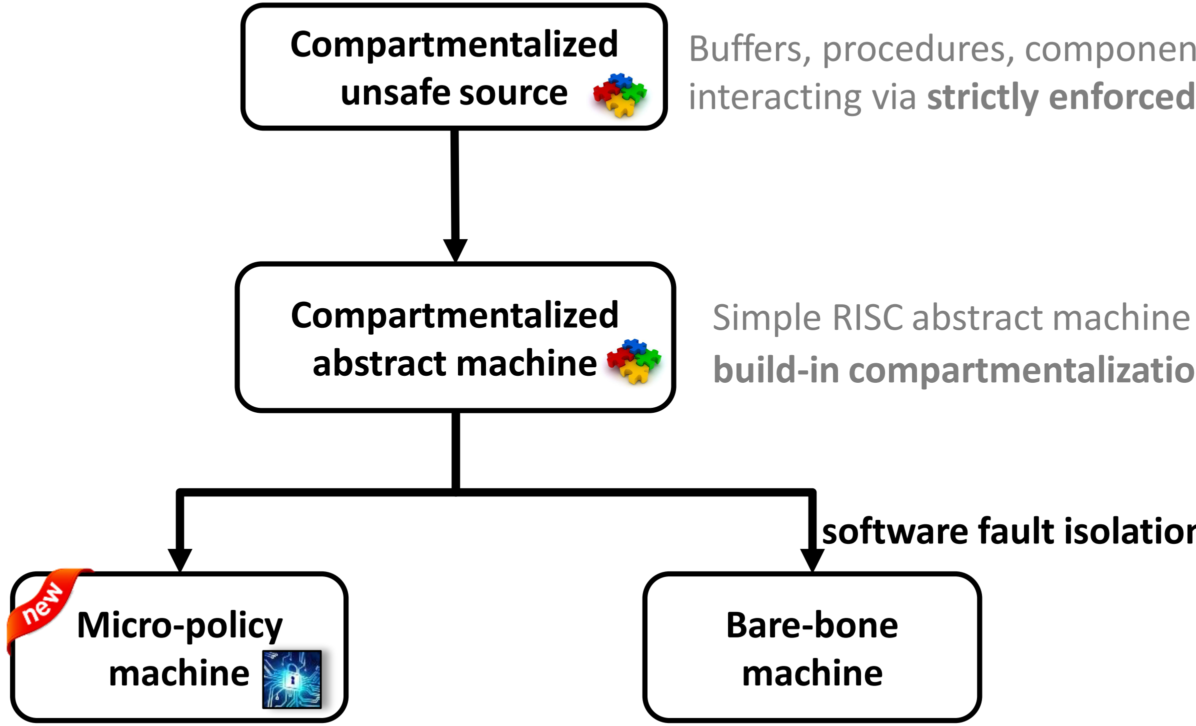
$\rightsquigarrow m_1 \cdot m_2 \cdot m_3$

Finite trace records which component encountered undefined behavior and allows us to rewind execution

2. Security Enforcement

[How can we effectively enforce this?]

Proof-of-concept secure compilation chain



Buffers, procedures, components interacting via **strictly enforced interfaces**

Simple RISC abstract machine with **build-in compartmentalization**

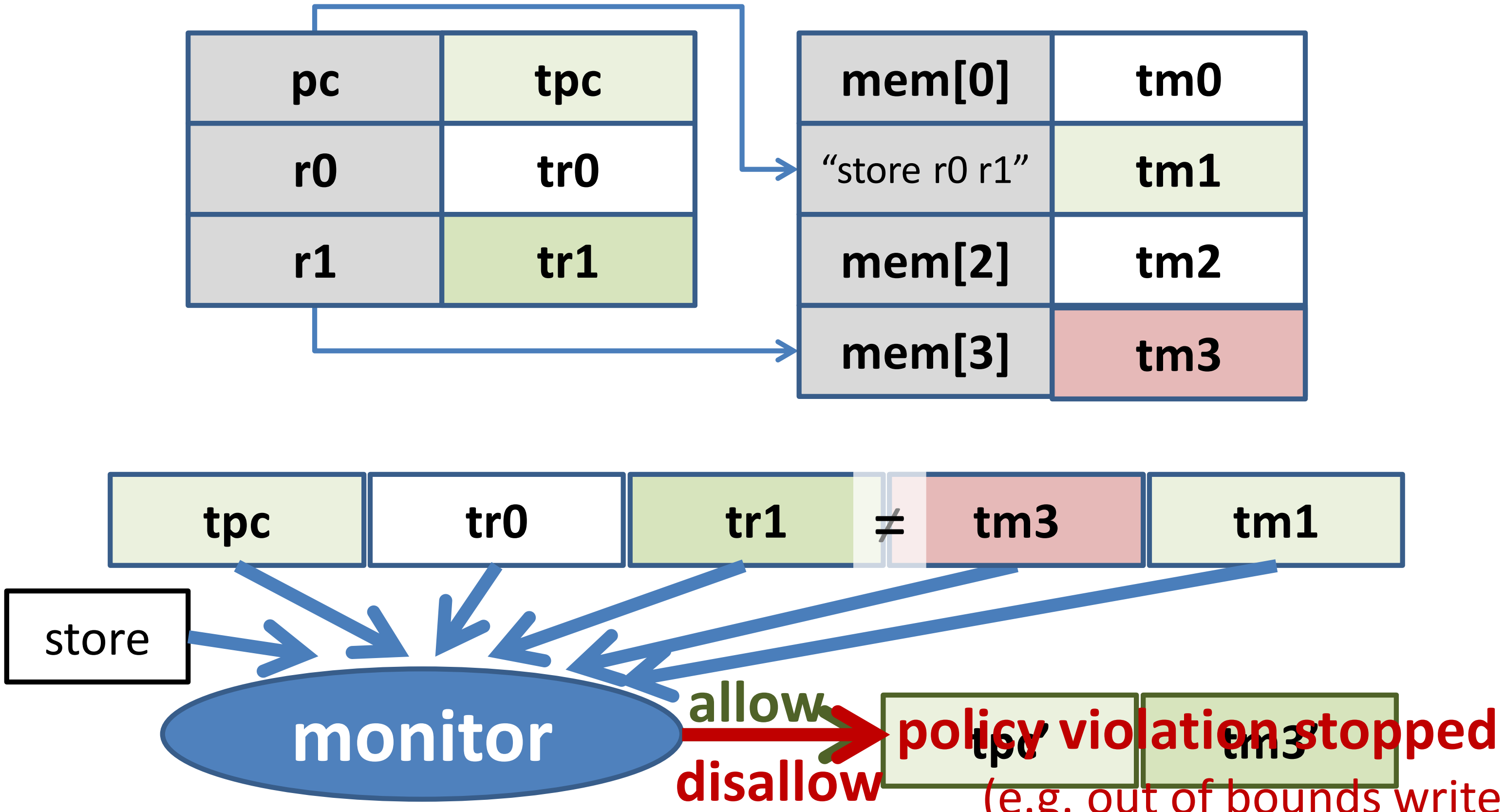
Tag-based reference monitor enforcing:
- component separation
- procedure call and return discipline
(linear capabilities / linear entry points)

Inline reference monitor enforcing:
- component separation
- procedure call and return discipline
(program rewriting, shadow call stack)

Expectation: other enforcement mechanisms should work as well

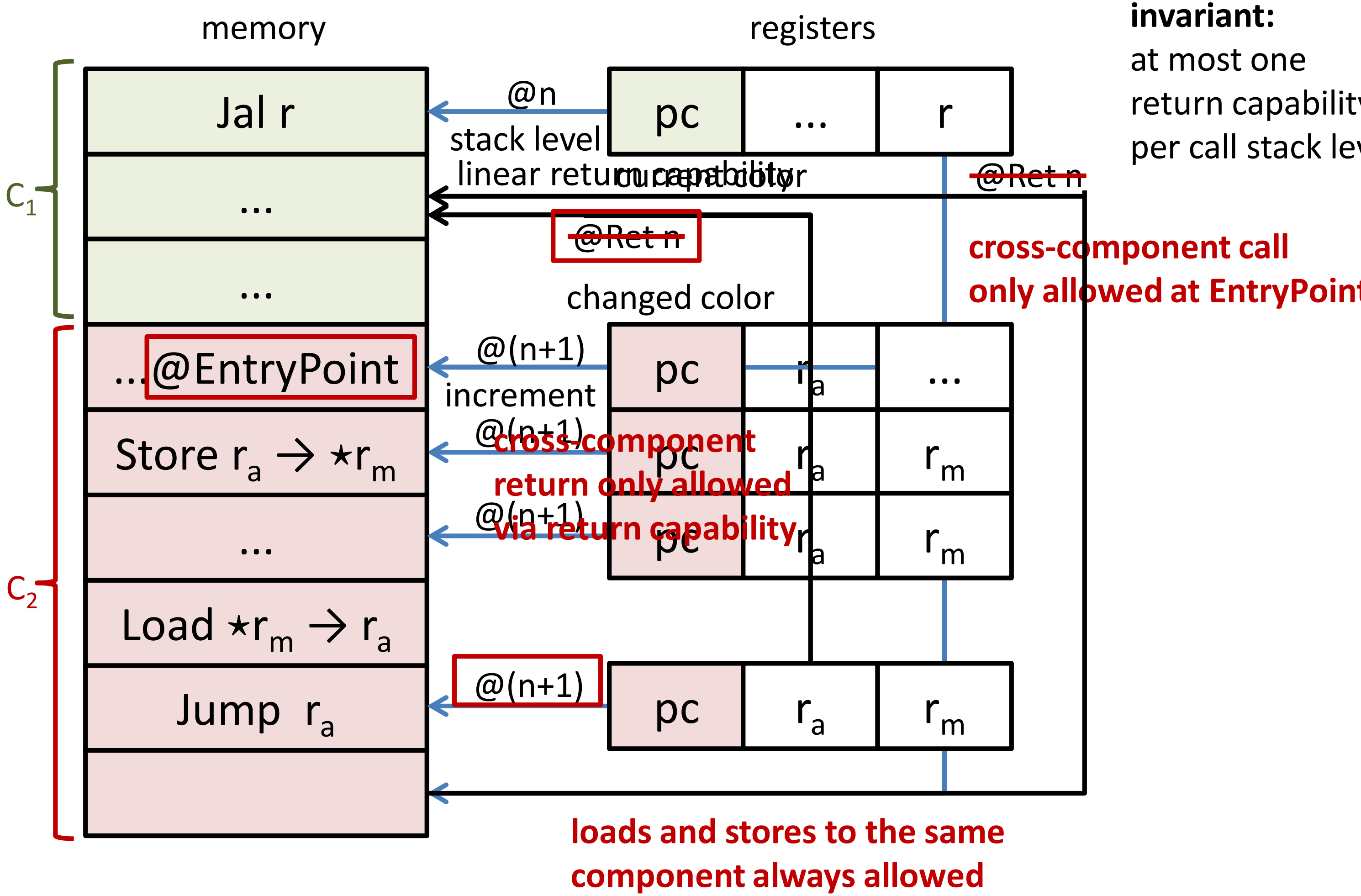
Micro-Policies [Oakland'15, ASPLOS '15,...]

software-defined, hardware-accelerated, tag-based monitoring



software monitor's decision is hardware cached

Compartmentalization micro-policy

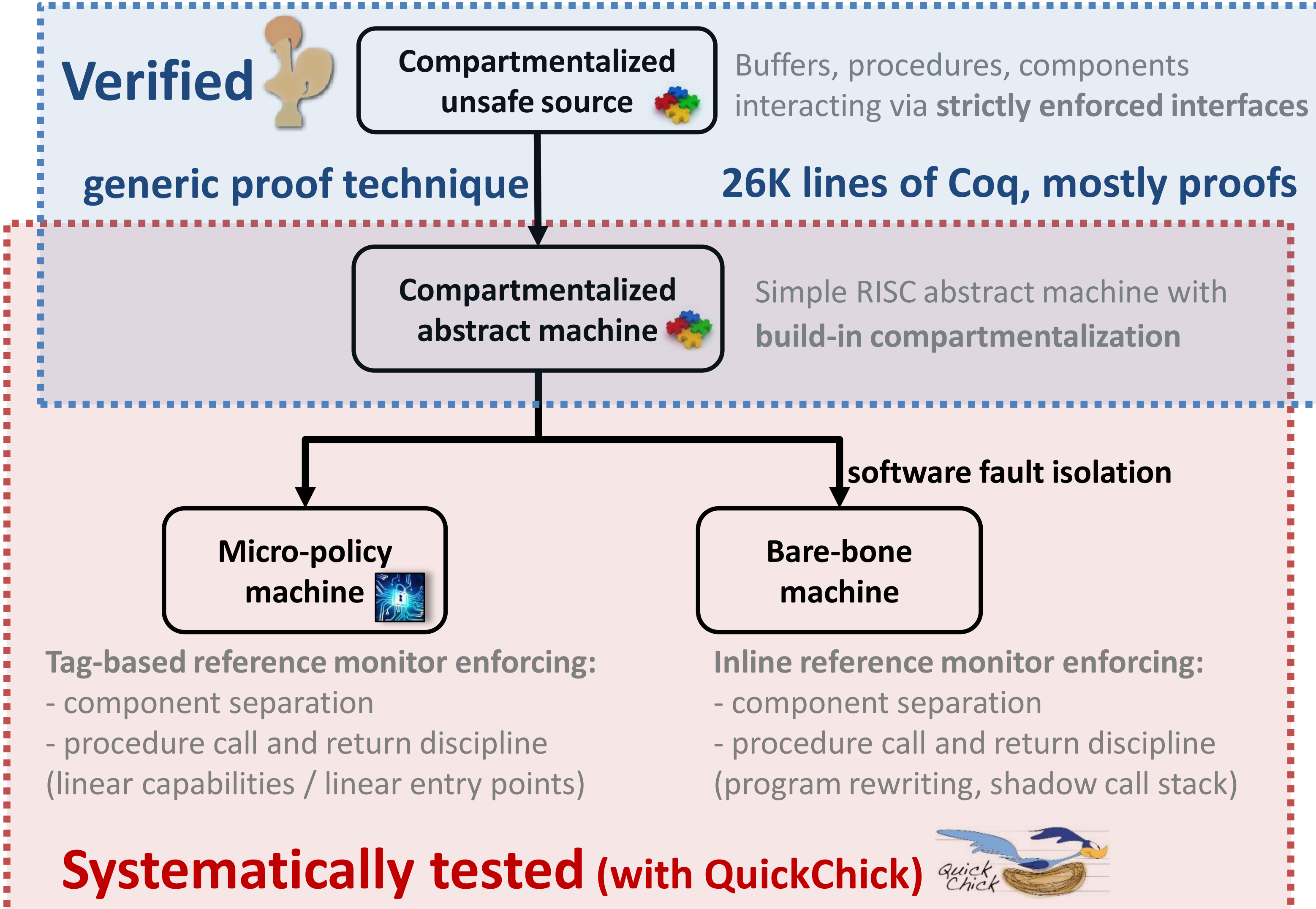


invariant:
at most one
return capability
per call stack level

3. Security Proof

[How can we make sure we achieved our goal?]

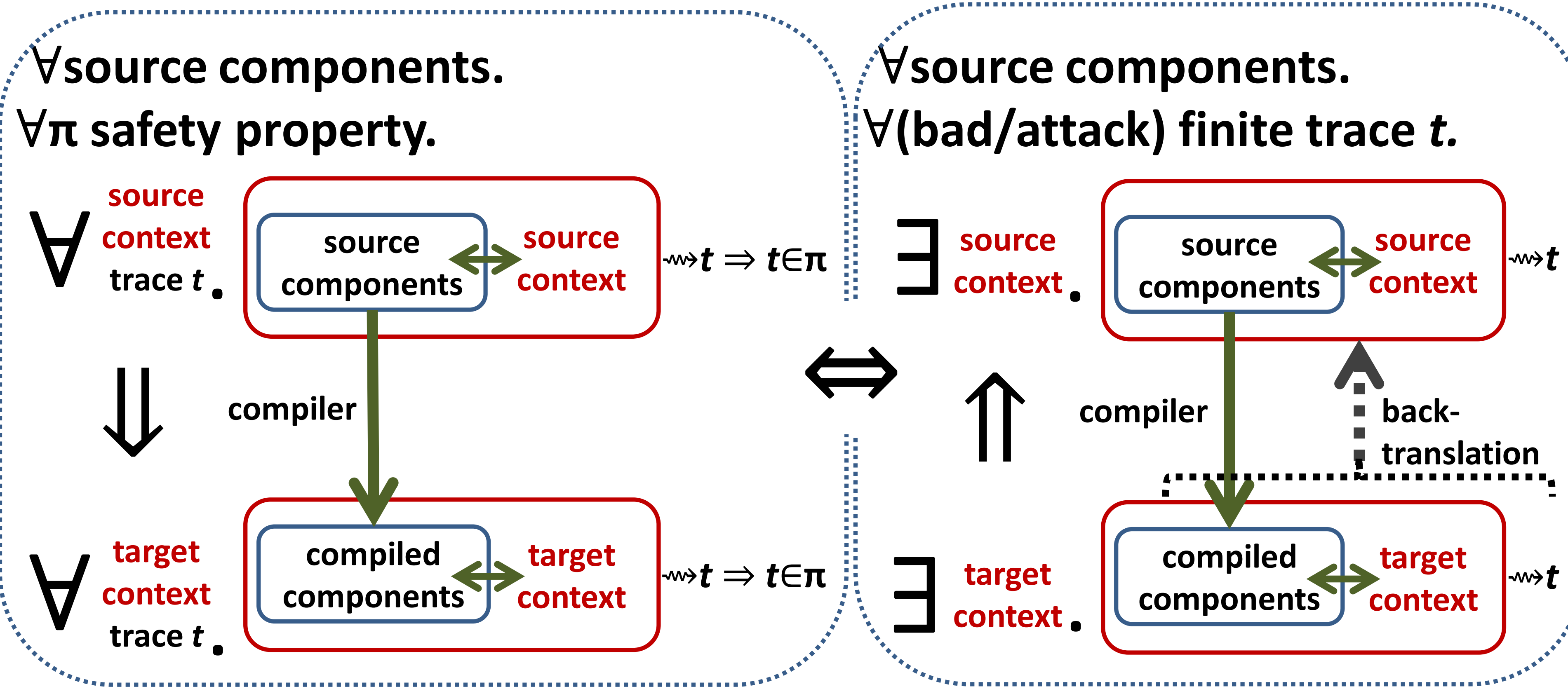
Proof-of-concept formally secure compilation chain in Coq



https://secure-compilation.github.io

We reduce our proof goal to a variant of:

Robust Safety Preservation



robust preservation of safety

proof-oriented characterization

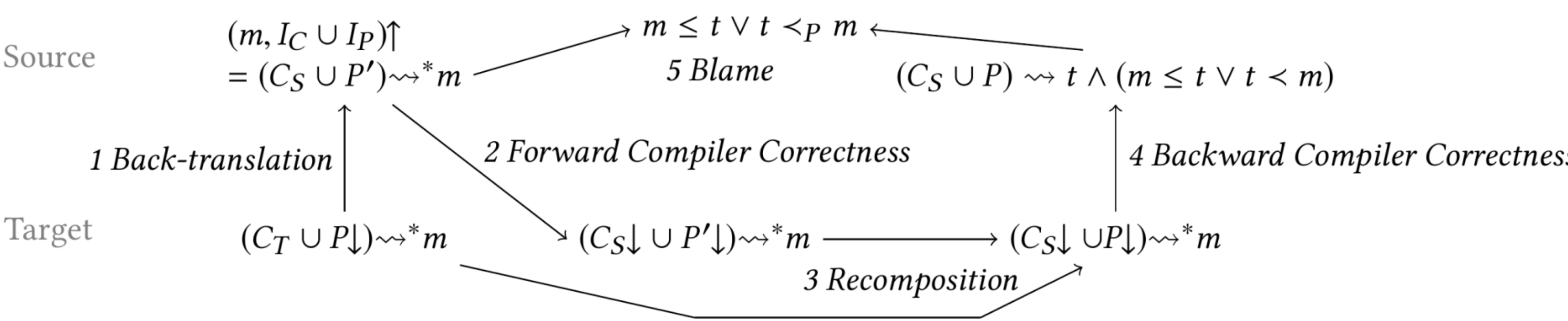
Simple and scalable proof technique

(for our variant of Robust Safety Preservation)

1. back-translating **finite trace prefix** to **whole source programs**

2+4. compiler correctness proof (à la CompCert) **used as a black-box**

3+5. simulation proofs



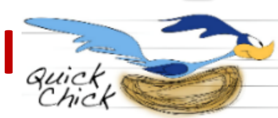
When Good Components Go Bad

1. **Goal: formally secure compartmentalization**

   – **first definition** supporting **mutually distrustful components** and **dynamic compromise**
   – **restricting undefined behavior spatially** and **temporally**

2. **Enforcement: proof-of-concept secure compilation chain**
   – **software fault isolation** or **tag-based reference monitor**

3. **Proof: combining formal proof and property-based testing**
   – **Generic proof technique** that **extends** and **scales well**



Making this more practical ... next steps:

- **Scale formally secure compilation chain to C language**
  - allow **shared memory** (ongoing) and **pointer passing** (capabilities)
  - eventually support enough of C to **measure and lower overhead**
  - check whether hardware support (tagged architecture) is faster
- **Extend all this to dynamic component creation**
  - rewind to when compromised component was created
- **... and dynamic privileges**
  - capabilities, dynamic interfaces, history-based access control, ...
- **From robust safety to hypersafety (confidentiality)** [CSF'19]
- **Secure compilation of EverCrypt, miTLS, ...**

My dream: secure compilation at scale

language

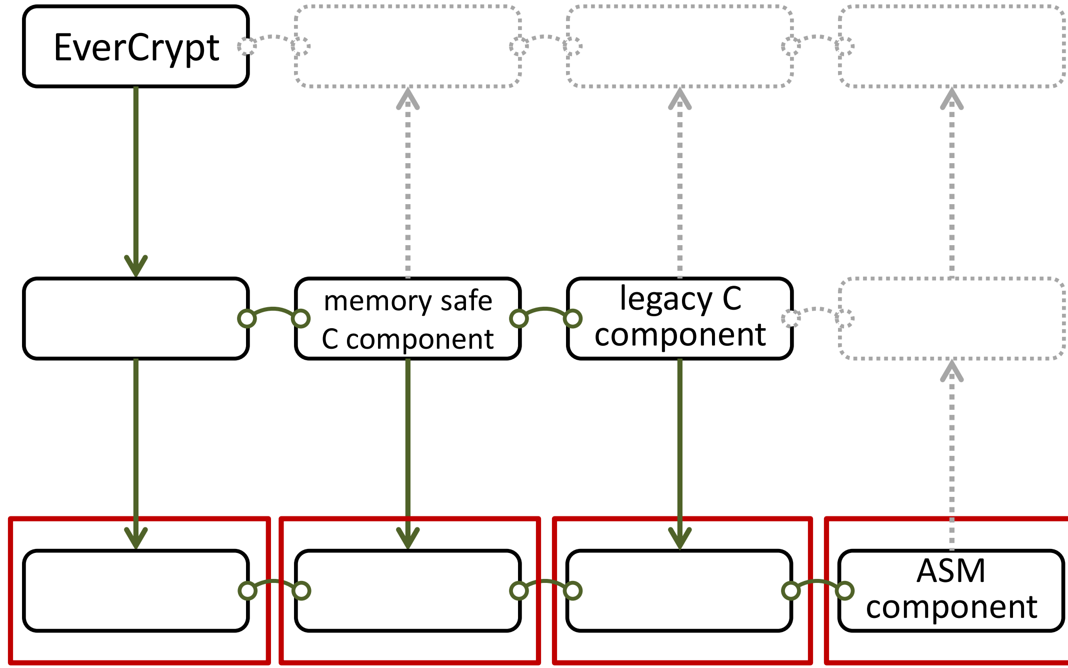
C language

+ components

+ memory safety

ASM language

(RISC-V + micro-policies)



Going beyond Robust Preservation of Safety [CSF'19]

relational hyperproperties
(trace equivalence)

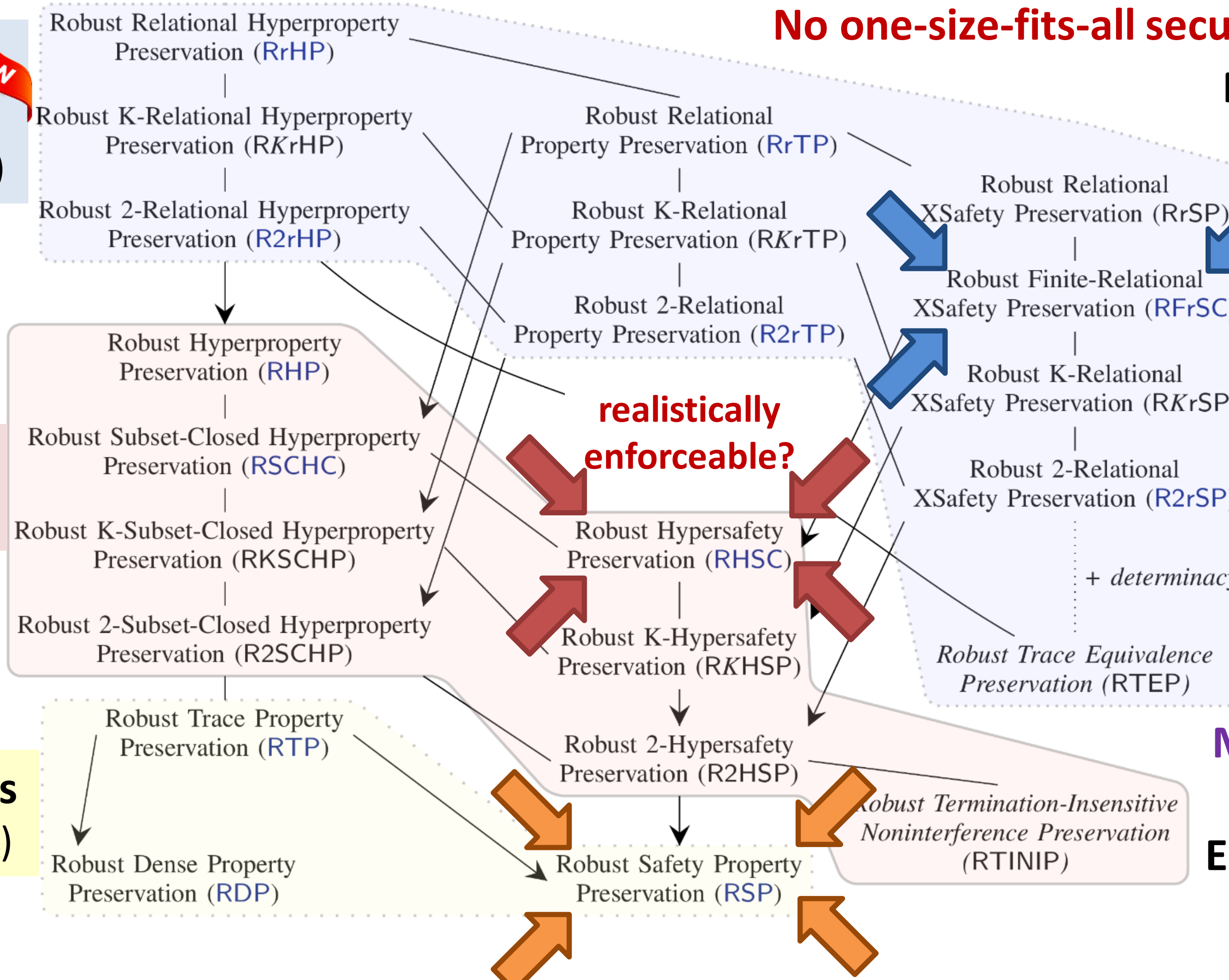
+ code confidentiality

hyperproperties
(noninterference)

+ data confidentiality

trace properties
(safety & liveness)

only integrity



No one-size-fits-all security criterion

More secure

current proof technique

More efficient to enforce

Easier to prove

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