When Good Components Go Bad

Formally Secure Compilation Despite Dynamic Compromise

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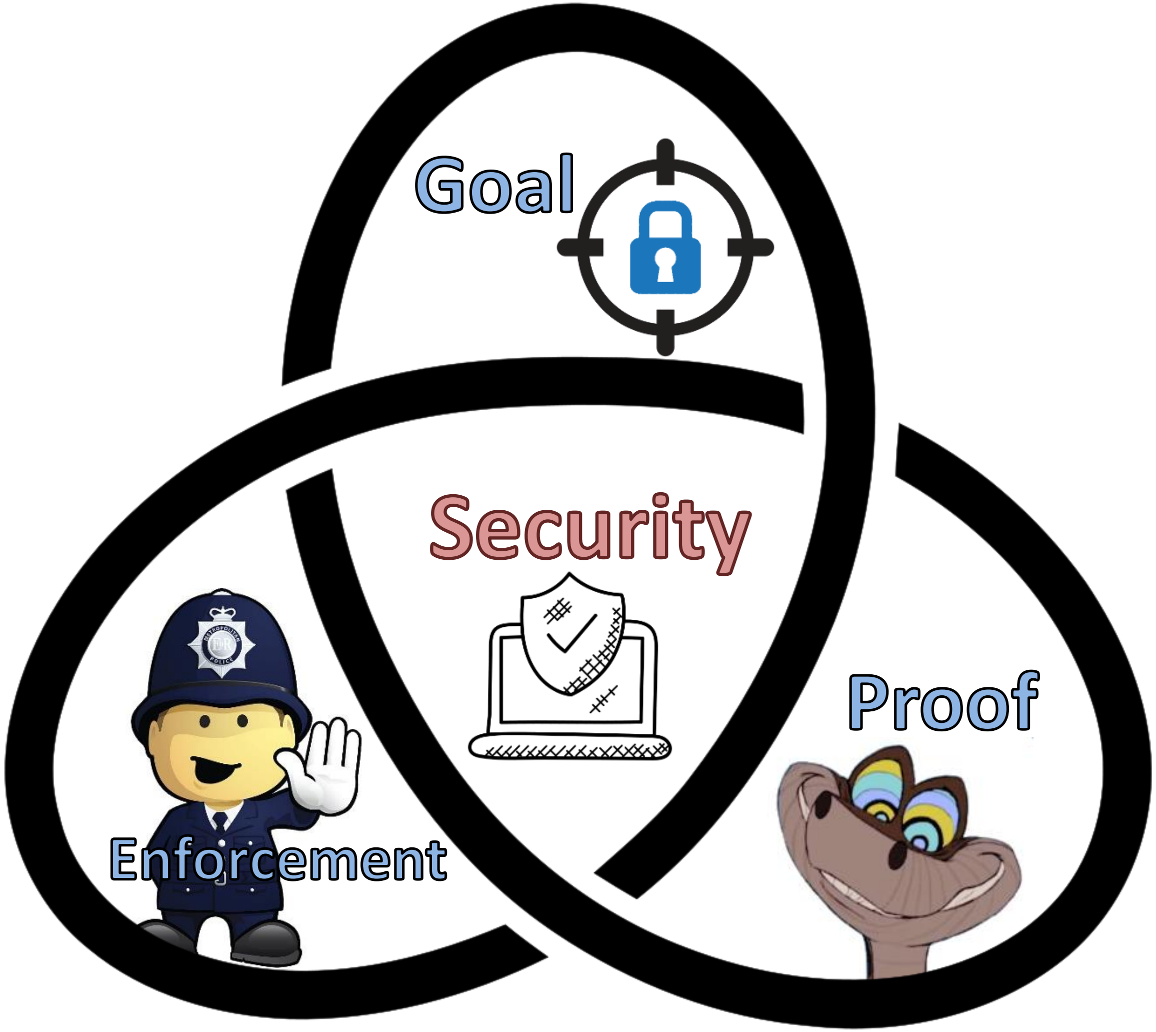
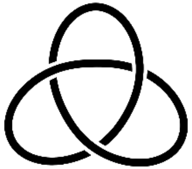


Goal

Security

Enforcement

Proof



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

- **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**

Easier and more scalable

↕

Better assurance

Formally Secure Compartmentalization

When Good Components Go Bad (CCS 2018)

Beyond Good and Evil (CSF 2016)

Core team at Inria Paris


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IL BACIO DEL PANE

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Chi ha detto che il buon cioccolato è solo svizzero?

Cioccolato per passione dal 1903

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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?

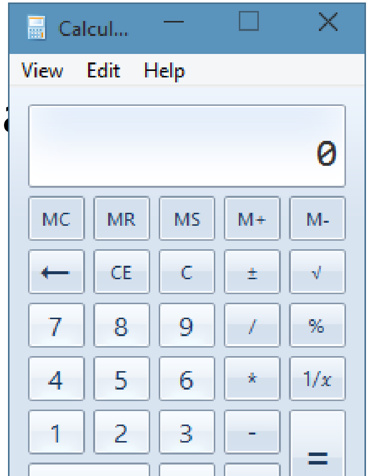
What is a compartmentalizing compilation chain supposed to enforce precisely?

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?**

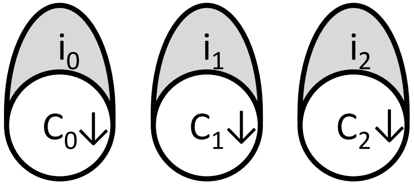
```
#include <string.h>
int main (int argc, char **
    char c[12];
    strcpy(c, argv[1]);
    return 0;
}
```



Compartmentalizing compilation should ...

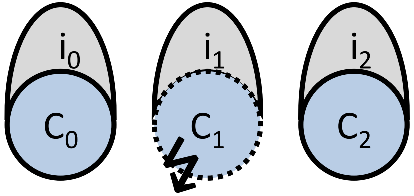
- **Restrict spatial scope** of undefined behavior
  - **mutually-distrustful components**
    - **each component protected from all the others**
- **Restrict temporal scope** of undefined behavior
  - **dynamic compromise**
    - **each component gets guarantees as long as it has not encountered undefined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

Security definition:

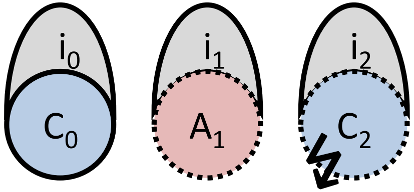
If 

$\rightsquigarrow t$ then

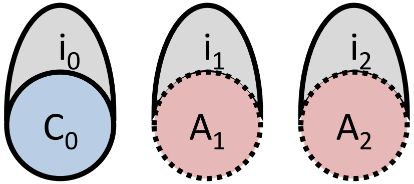
∃ a sequence of component compromises explaining the finite trace *t* in the source language, for instance $t=m_1\cdot m_2\cdot m_3$ and

(1) 

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

(2) $\exists A_1.$ 

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

(3) $\exists A_2.$ 

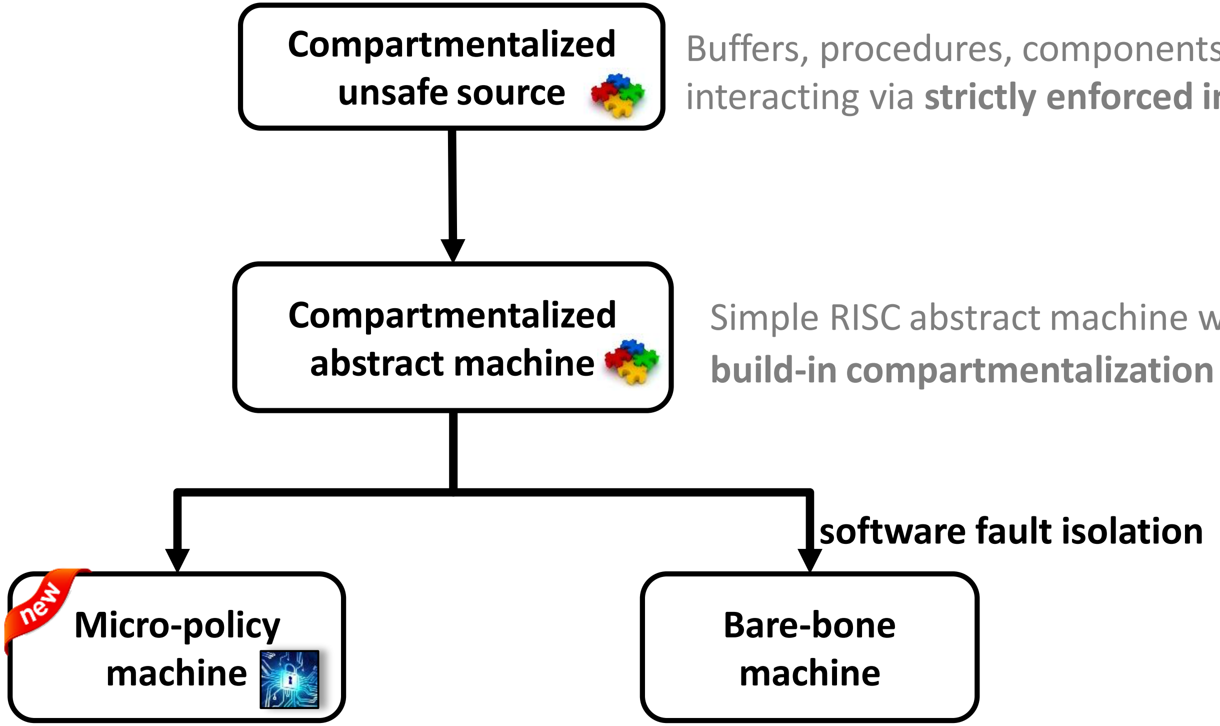
$\rightsquigarrow m_1\cdot m_2\cdot m_3$

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



Compartmentalized unsafe source

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

Compartmentalized abstract machine

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

software fault isolation

Micro-policy machine

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

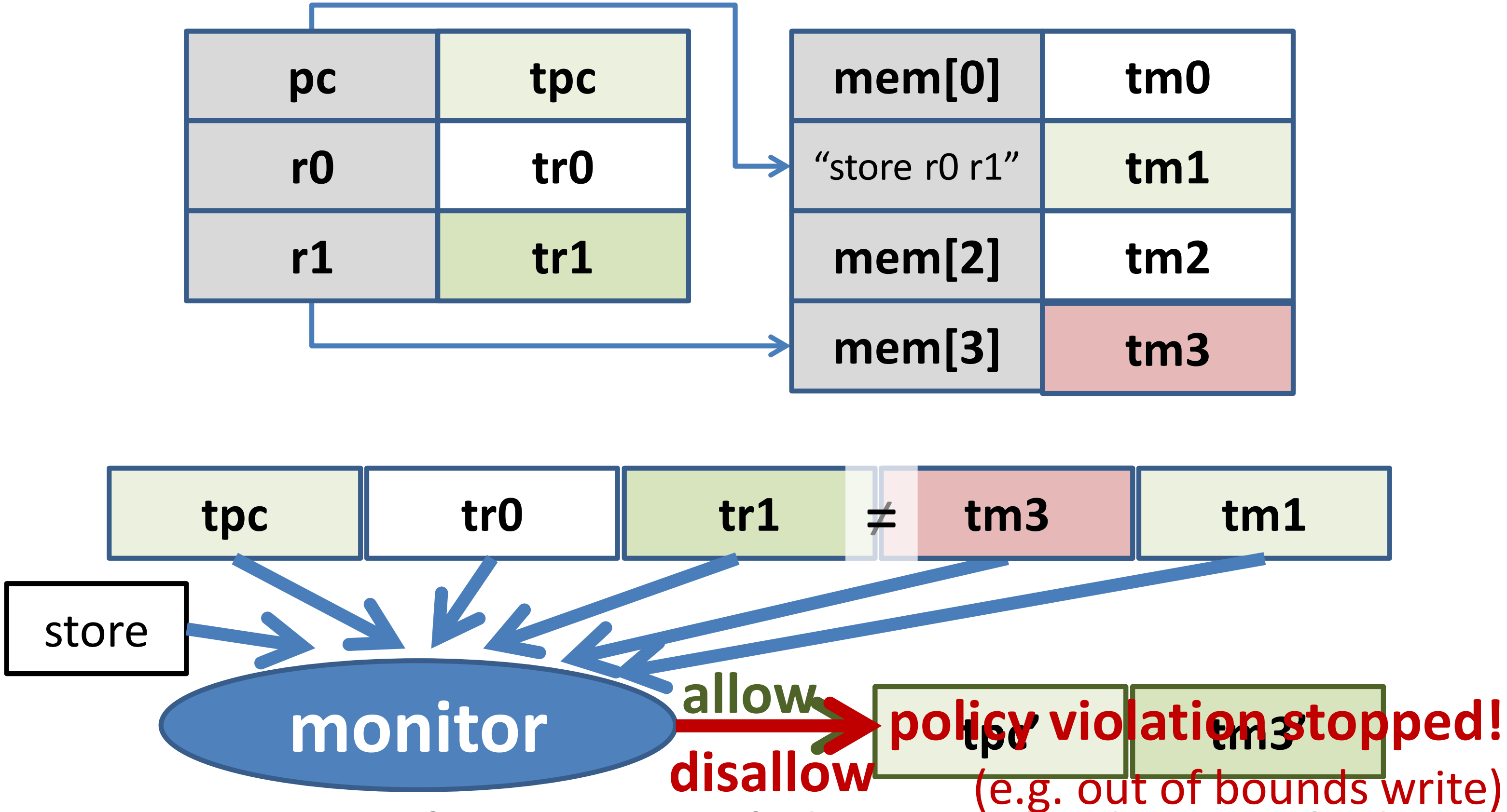
Bare-bone machine

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



pc	tpc
r0	tr0
r1	tr1

mem[0]	tm0
"store r0 r1"	tm1
mem[2]	tm2
mem[3]	tm3

tpc	tr0	tr1 ≠ tm3	tm1

store

monitor

allow

tpc'

tm3'

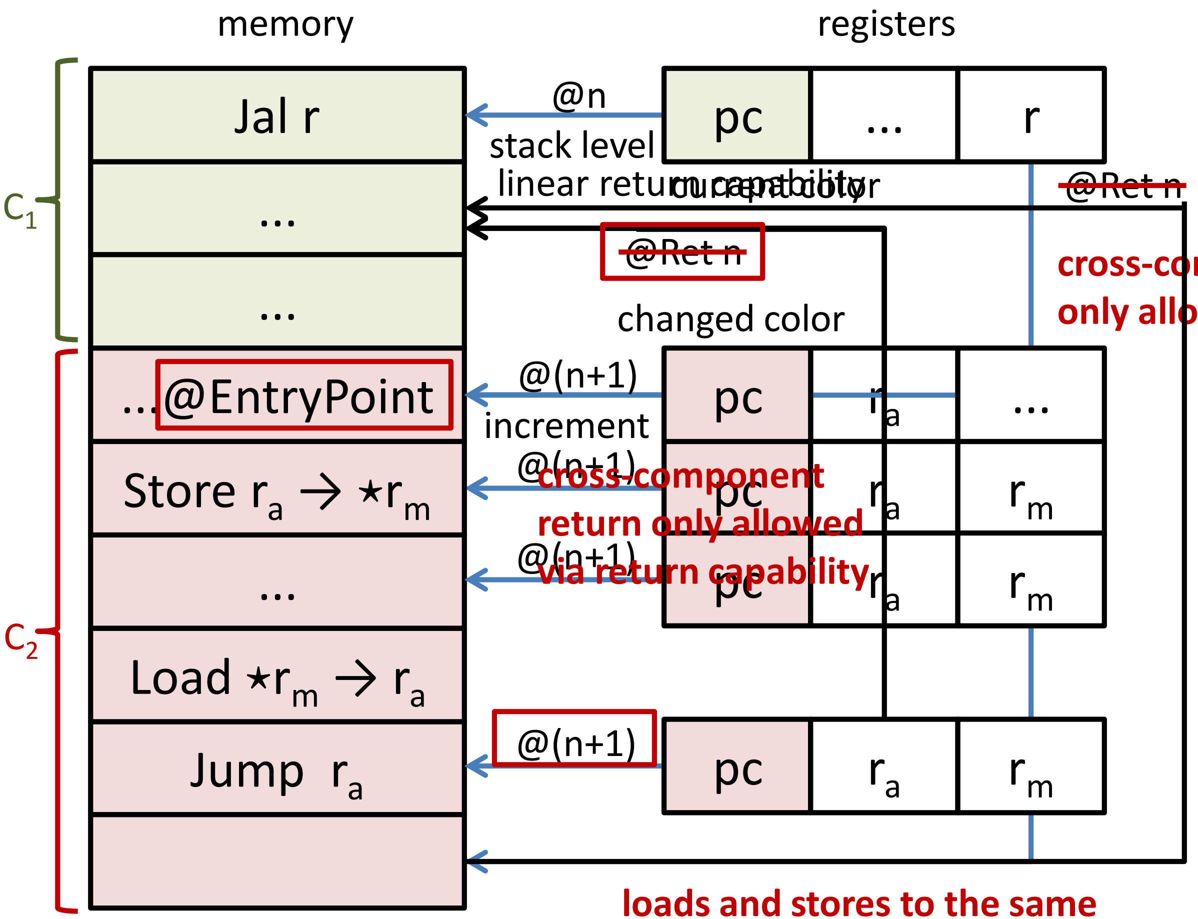
disallow

policy violation stopped!

(e.g. out of bounds write)

software monitor's decision is hardware cached

Compartmentalization micro-policy



invariant:
at most one
return capability
per call stack level

cross-component call only allowed at EntryPoint

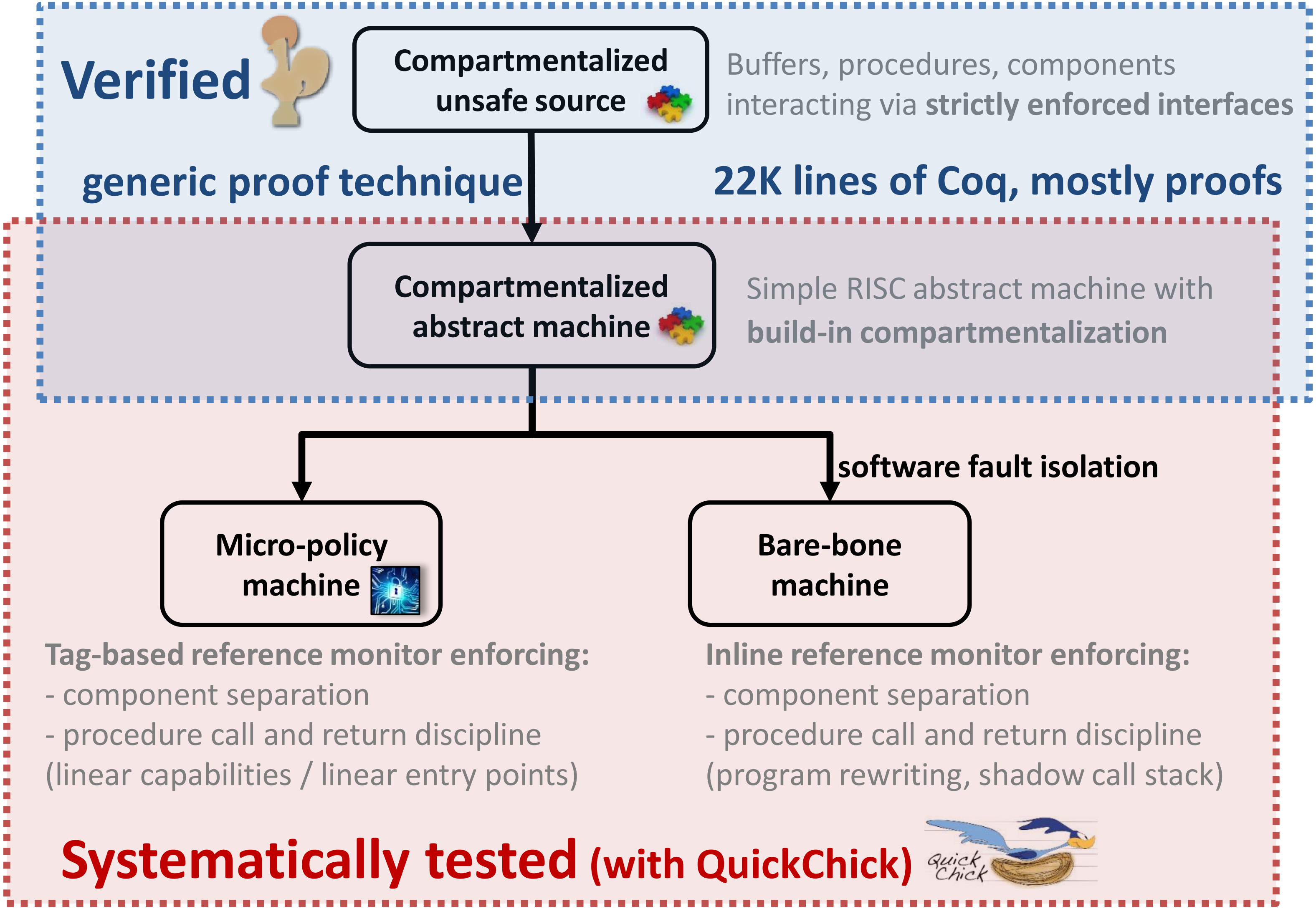
cross-component return only allowed via return capability

loads and stores to the same component always allowed

3. Security Proof

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

Proof-of-concept formally secure compilation chain in Coq



Verified

Compartmentalized unsafe source

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

generic proof technique

22K lines of Coq, mostly proofs

Compartmentalized abstract machine

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

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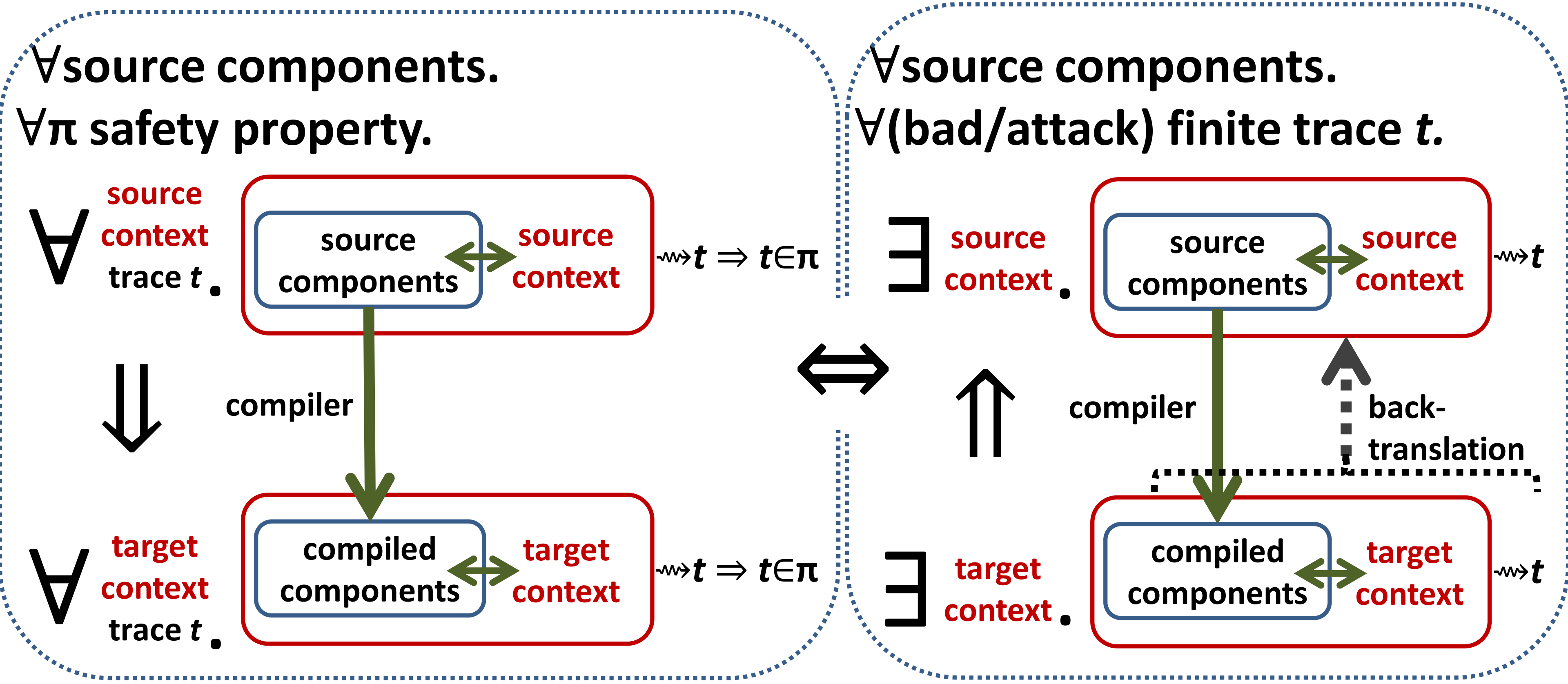
(program rewriting, shadow call stack)

Systematically tested (with QuickChick)

https://secure-compilation.github.io

We reduce our proof goal to a variant of:

Robust Safety Preservation



∀source components.

∀π safety property.

∀ source context trace t. source components ↔ source context $\rightsquigarrow t \Rightarrow t \in \pi$

⇓ compiler

∀ target context trace t. compiled components ↔ target context $\rightsquigarrow t \Rightarrow t \in \pi$

robust preservation of safety

⇔

∀source components.

∀(bad/attack) finite trace *t*.

∃ source context. source components ↔ source context $\rightsquigarrow t$

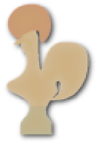
⇑ compiler

back-translation

∃ target context. compiled components ↔ target context $\rightsquigarrow t$

proof-oriented characterization

Simple and scalable proof technique

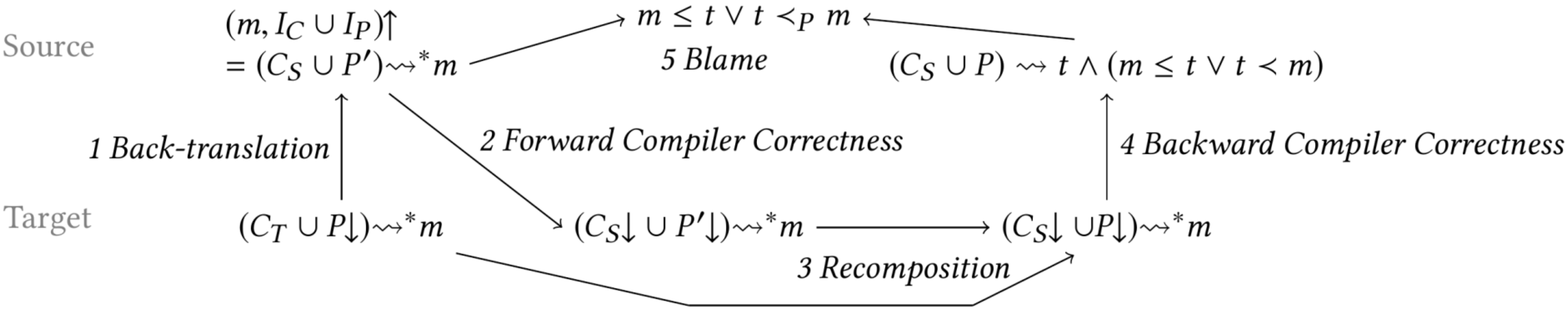


(for our variant of Robust Safety Preservation)

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. also simulation proofs, but at a single level



$$\begin{tikzcd}
\text{Source} & {(m, I_C \cup I_P)\uparrow = (C_S \cup P')\rightsquigarrow^* m} \arrow[r, "5\ \mathit{Blame}"'] \arrow[dr, "2\ \mathit{Forward\ Compiler\ Correctness}"] & m \le t \lor t \prec_P m & (C_S \cup P) \rightsquigarrow t \land (m \le t \lor t \prec m) \arrow[l] \\
\text{Target} & (C_T \cup P\downarrow)\rightsquigarrow^* m \arrow[u, "1\ \mathit{Back\text{-}translation}"] \arrow[rr, bend right, "3\ \mathit{Recomposition}"'] & (C_S\downarrow \cup P'\downarrow)\rightsquigarrow^* m \arrow[r] & (C_S\downarrow \cup P\downarrow)\rightsquigarrow^* m \arrow[u, "4\ \mathit{Backward\ Compiler\ Correctness}"']
\end{tikzcd}$$

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:

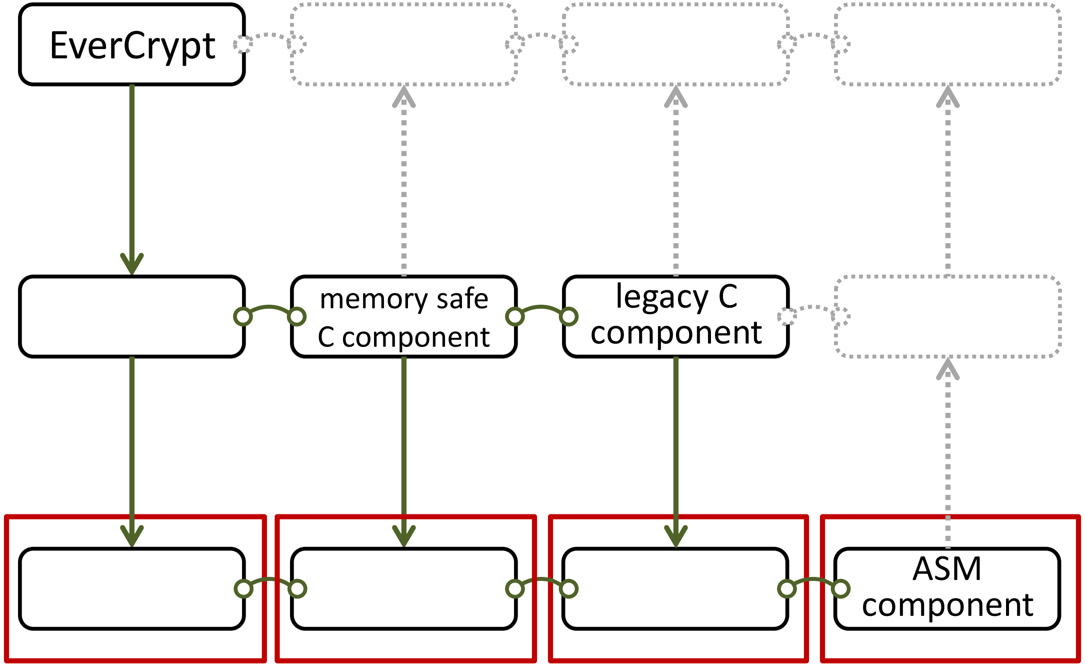
- **Scale formally secure compilation chain to C language**
  - allow **shared memory** (ongoing) and **pointer passing** (capabilities)
  - eventually support enough of C to **measure and lower overhead**
  - check whether hardware support (tagged architecture) is faster
- **Extend all this to dynamic 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)



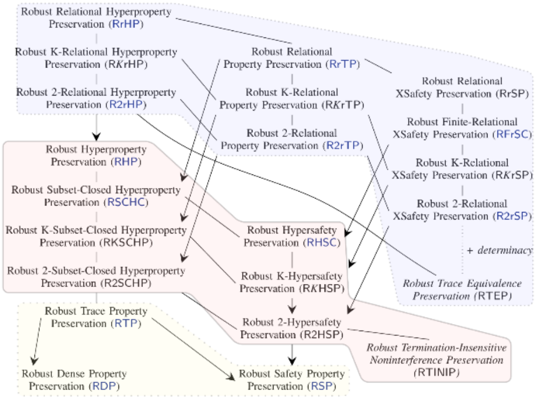
EverCrypt

memory safe
C component

legacy C
component

ASM
component

Going beyond Robust Preservation of Safety



Journey Beyond Full Abstraction (CSF 2019)

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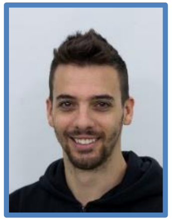


Marco Patrignani
Stanford & CISPA

Going beyond Robust Preservation of Safety [CSF'19]

relational hyperproperties new
(trace equivalence)

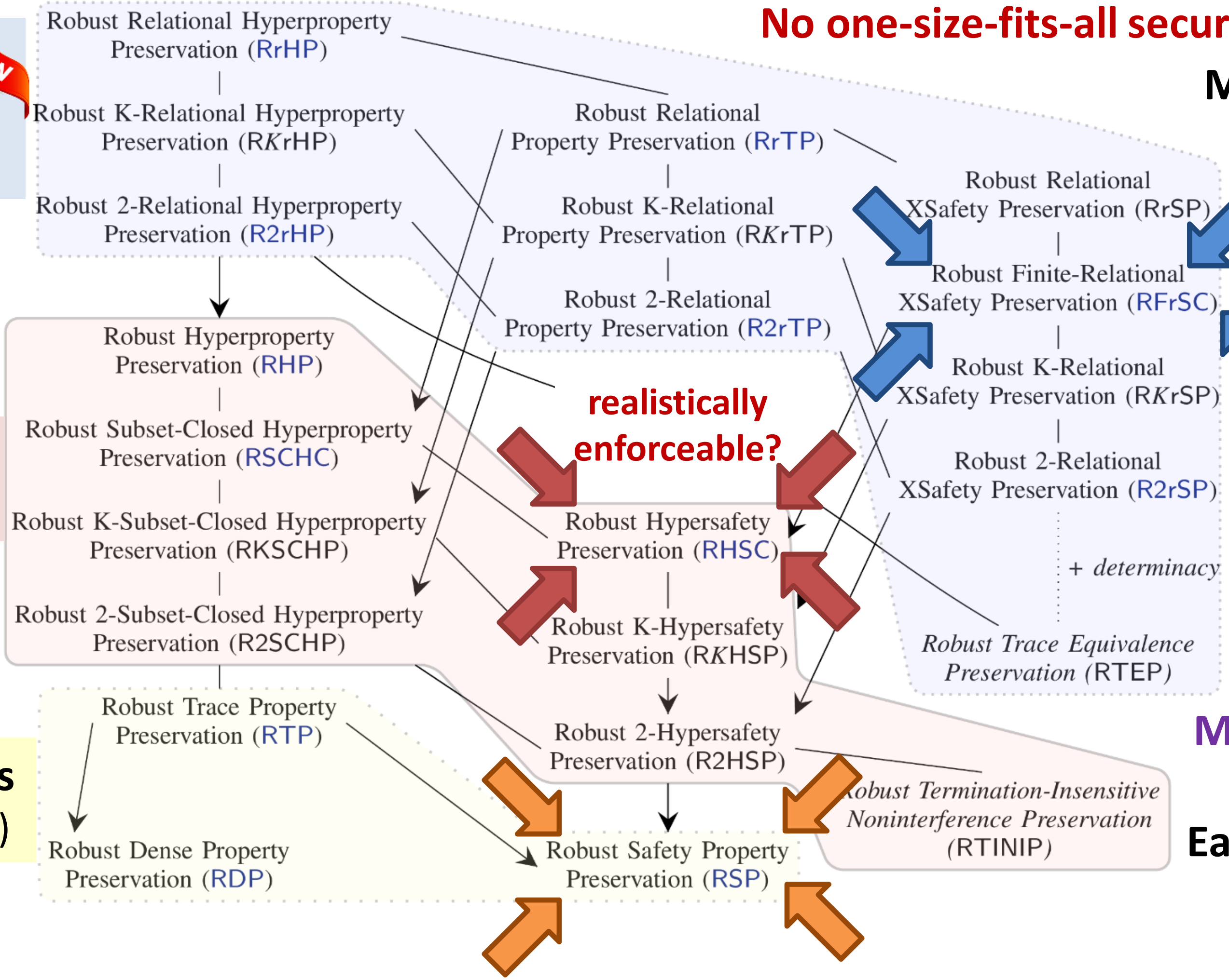
+ code confidentiality

hyperproperties
(noninterference)

+ data confidentiality

trace properties
(safety & liveness)

only integrity



Robust Relational Hyperproperty Preservation (RrHP)

Robust K-Relational Hyperproperty Preservation (RKrHP)

Robust 2-Relational Hyperproperty Preservation (R2rHP)

Robust Relational Property Preservation (RrTP)

Robust K-Relational Property Preservation (RKrTP)

Robust 2-Relational Property Preservation (R2rTP)

Robust Relational XSafety Preservation (RrSP)

Robust Finite-Relational XSafety Preservation (RFrSC)

Robust K-Relational XSafety Preservation (RKrSP)

Robust 2-Relational XSafety Preservation (R2rSP)

+ *determinacy*

Robust Trace Equivalence Preservation (RTEP)

Robust Hyperproperty Preservation (RHP)

Robust Subset-Closed Hyperproperty Preservation (RSCHC)

Robust K-Subset-Closed Hyperproperty Preservation (RKSCHP)

Robust 2-Subset-Closed Hyperproperty Preservation (R2SCHP)

Robust Hypersafety Preservation (RHSC)

Robust K-Hypersafety Preservation (RKHSP)

Robust 2-Hypersafety Preservation (R2HSP)

Robust Termination-Insensitive Noninterference Preservation (RTINIP)

Robust Trace Property Preservation (RTP)

Robust Dense Property Preservation (RDP)

Robust Safety Property Preservation (RSP)

realistically enforceable?

No one-size-fits-all security criterion

More secure

current proof technique

More efficient to enforce

Easier to prove

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