SECOMP: Formally Secure Compilation of Compartmentalized C Programs

Cătălin Hrițcu, MPI-SP, Bochum

Hiring: PostDoc, interns, PhD students

Joint work with
Carmine Abate, Cezar-Constantin Andrici, Sven Argo, Arthur Azevedo de Amorim, Roberto Blanco, Ştefan Ciobâcă, Adrien Durier, Akram El-Korashy, Boris Eng, Ana Nora Evans, Guglielmo Fachini, Deepak Garg, Aïna Linn Georges, Théo Laurent, Dongjae Lee, Guido Martínez, Marco Patrignani, Benjamin Pierce, Exequiel Rivas, Marco Stronati, Éric Tanter, Jérémy Thibault, Andrew Tolmach, Théo Winterhalter, ...

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

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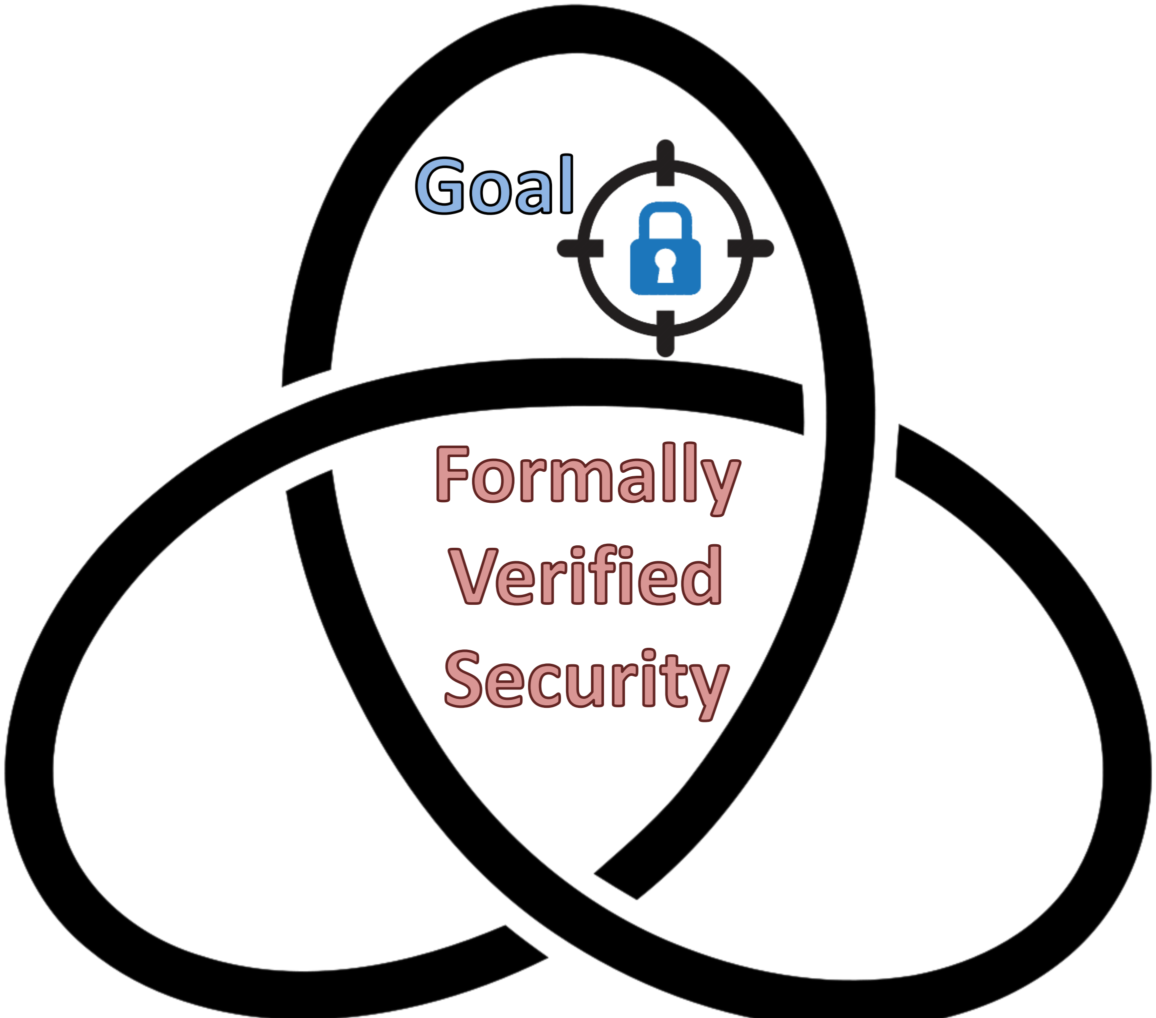
- **Targeting various enforcement mechanisms**
  - software-fault isolation (SFI), capability machines, ...

Formally Verified Security


Goal
Formally
Verified
Security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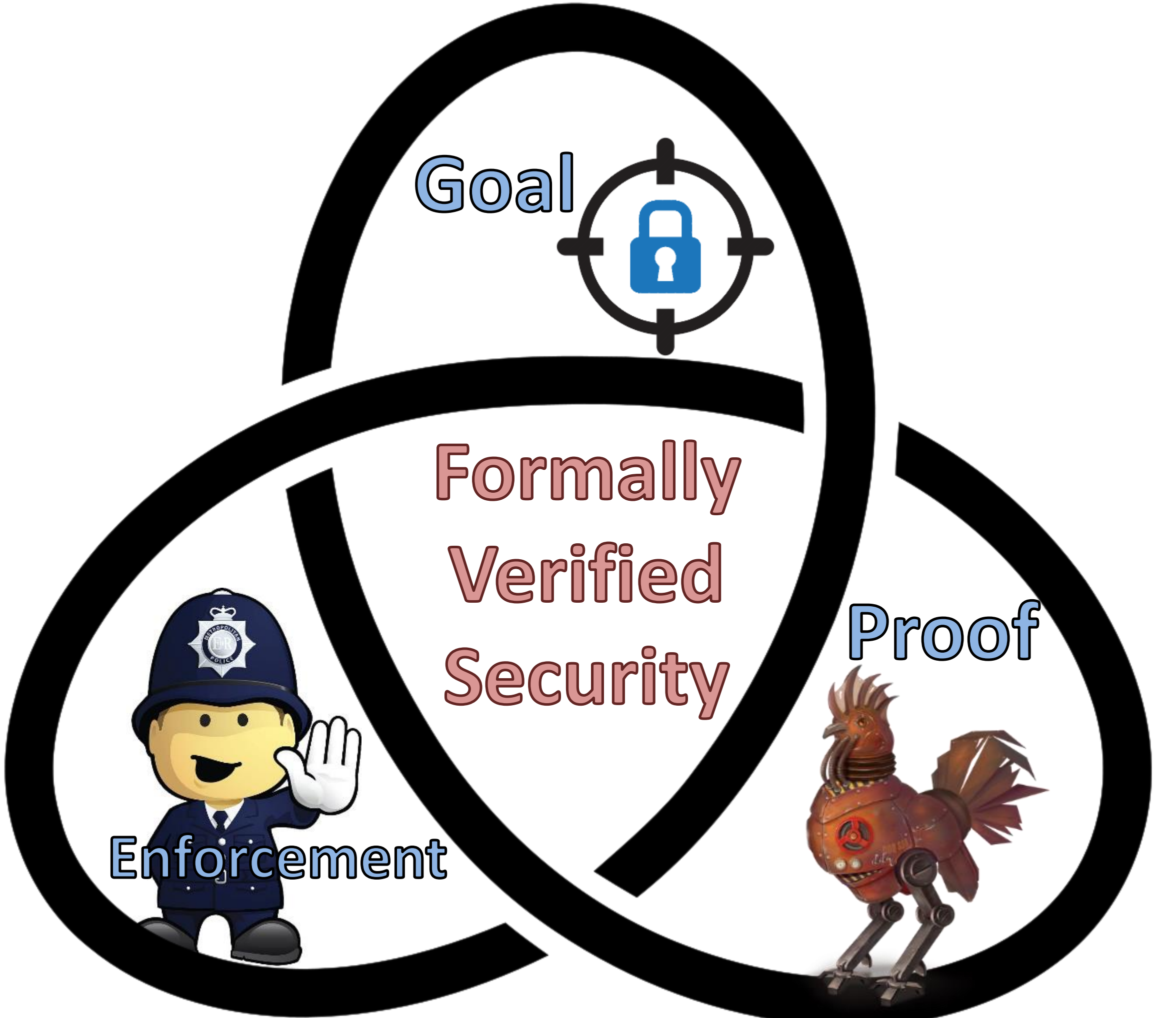
Enforcement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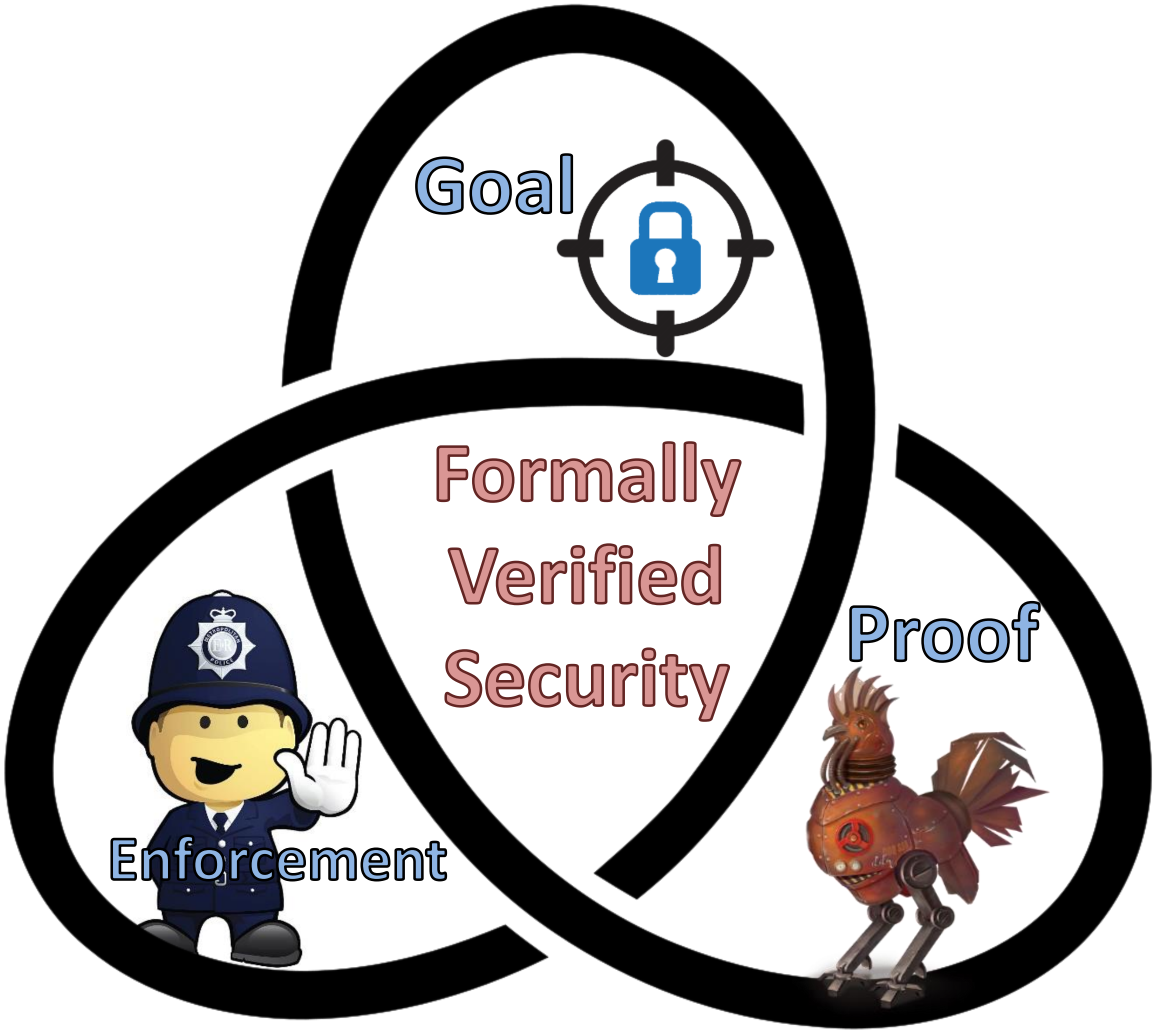
Formally Secure Compilation of C Compartments



1. Security Goal

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- **As a warmup, I will first show an easier definition**
  - **protecting 1 trusted compartment from 1 untrusted one (arbitrary ASM)**
  - **trusted compartment has no vulnerabilities, e.g. formally verified**
    - e.g. EverCrypt verified crypto library, shipping in Firefox, Linux Kernel, ...
    - e.g. simple verified web server, linked with unverified libraries [POPL'24]
- **What does it mean to securely compile such a verified compartment against linked adversarial target-level code?**

Preserving security against adversarial contexts

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∀ security property π

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verified program

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verified program

satisfies π

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∀ F*code verified program ⟷ F* code satisfies π

Preserving security against adversarial contexts

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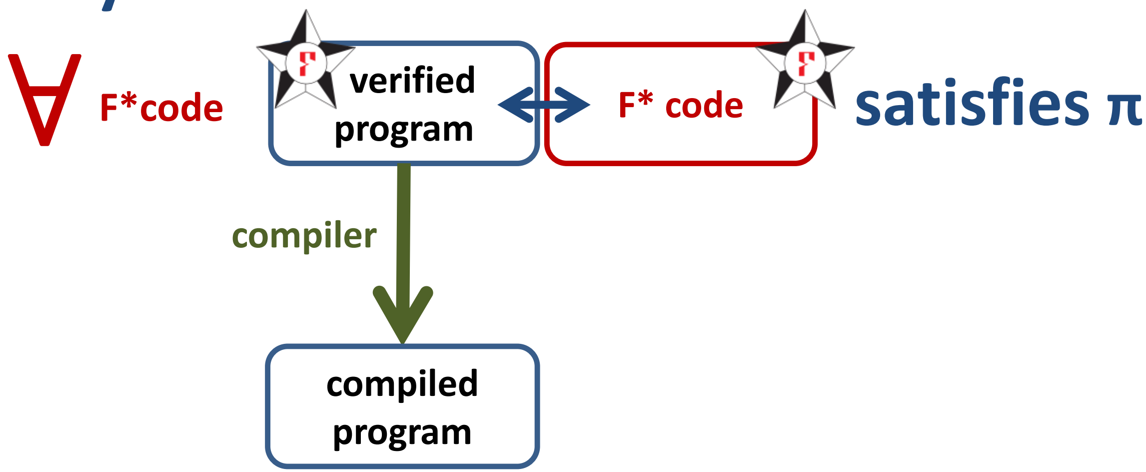

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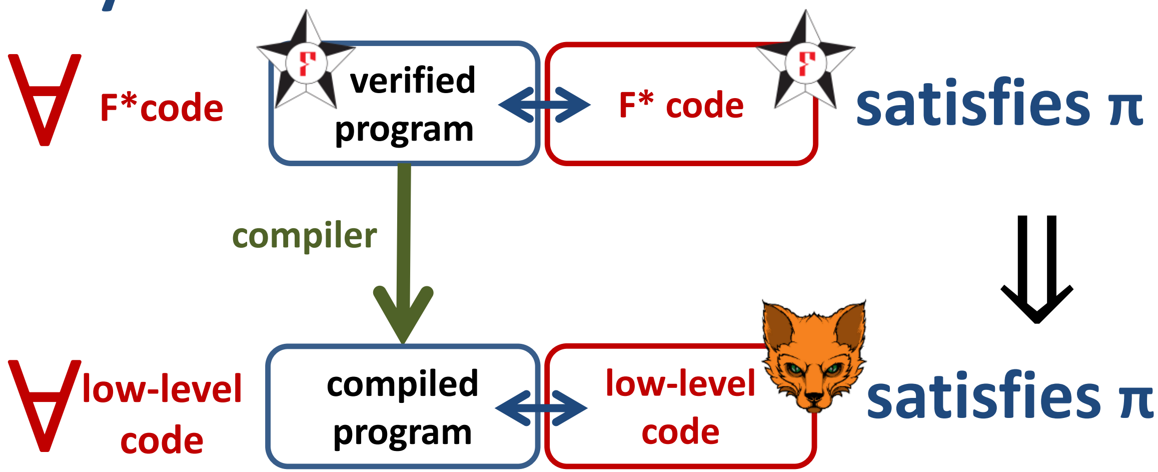

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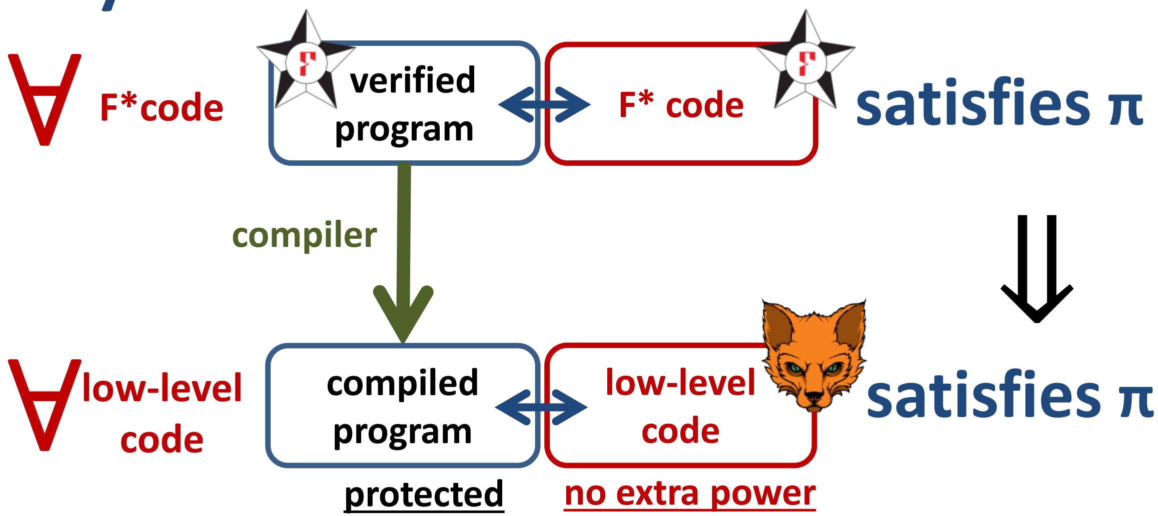

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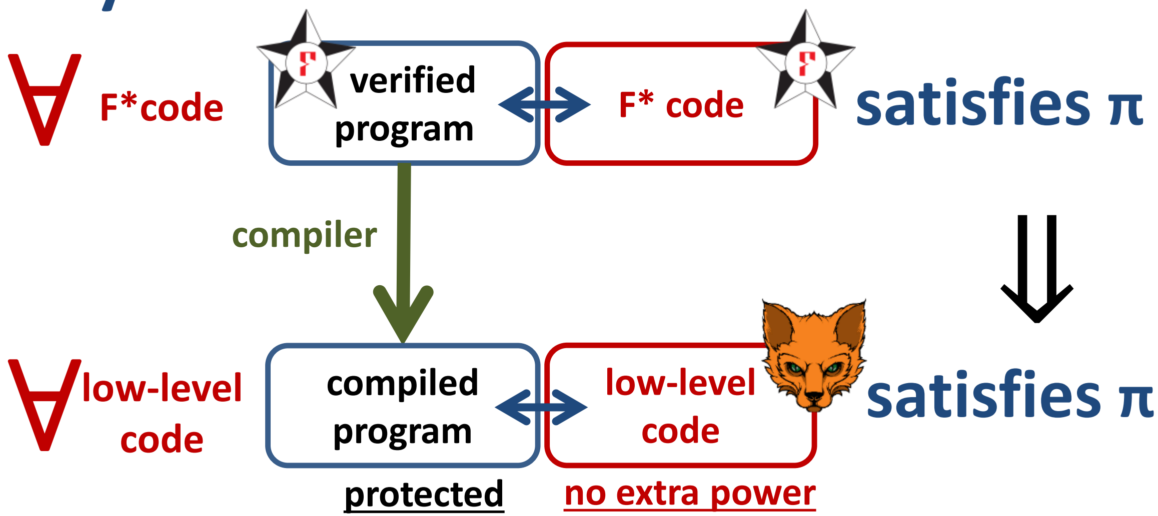

Where π can e.g. be "the web server's private key is not leaked"

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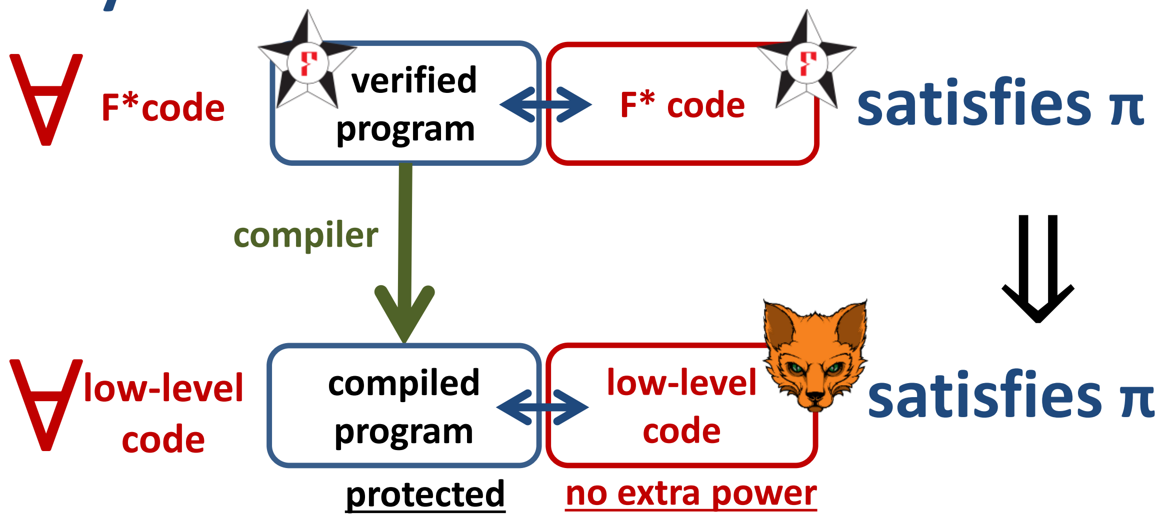

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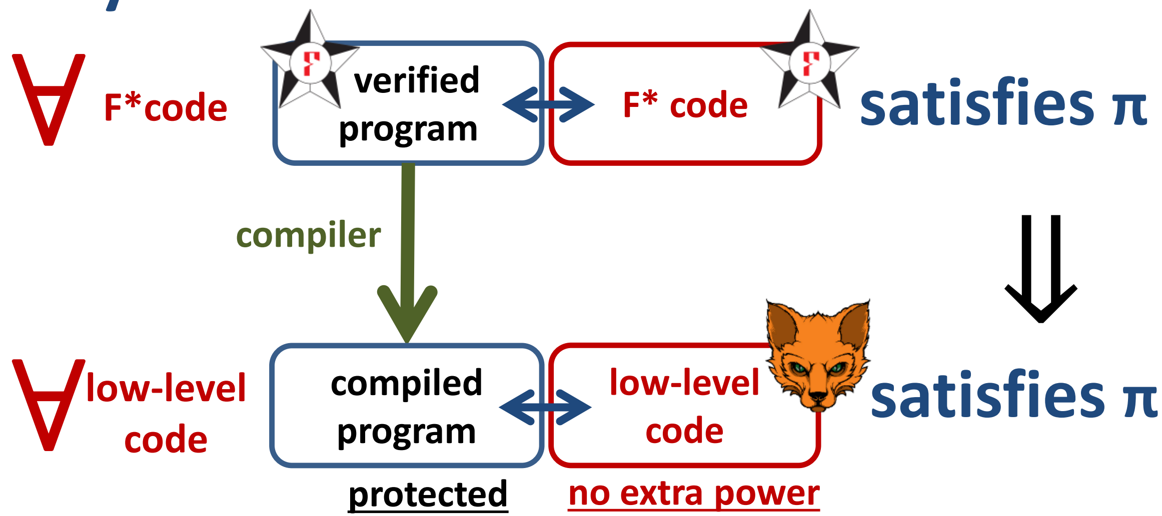

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We explored many classes of properties one can preserve this way ...

Journey Beyond Full Abstraction [CSF'19, ESOP'20, TOPLAS'21]

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trace properties
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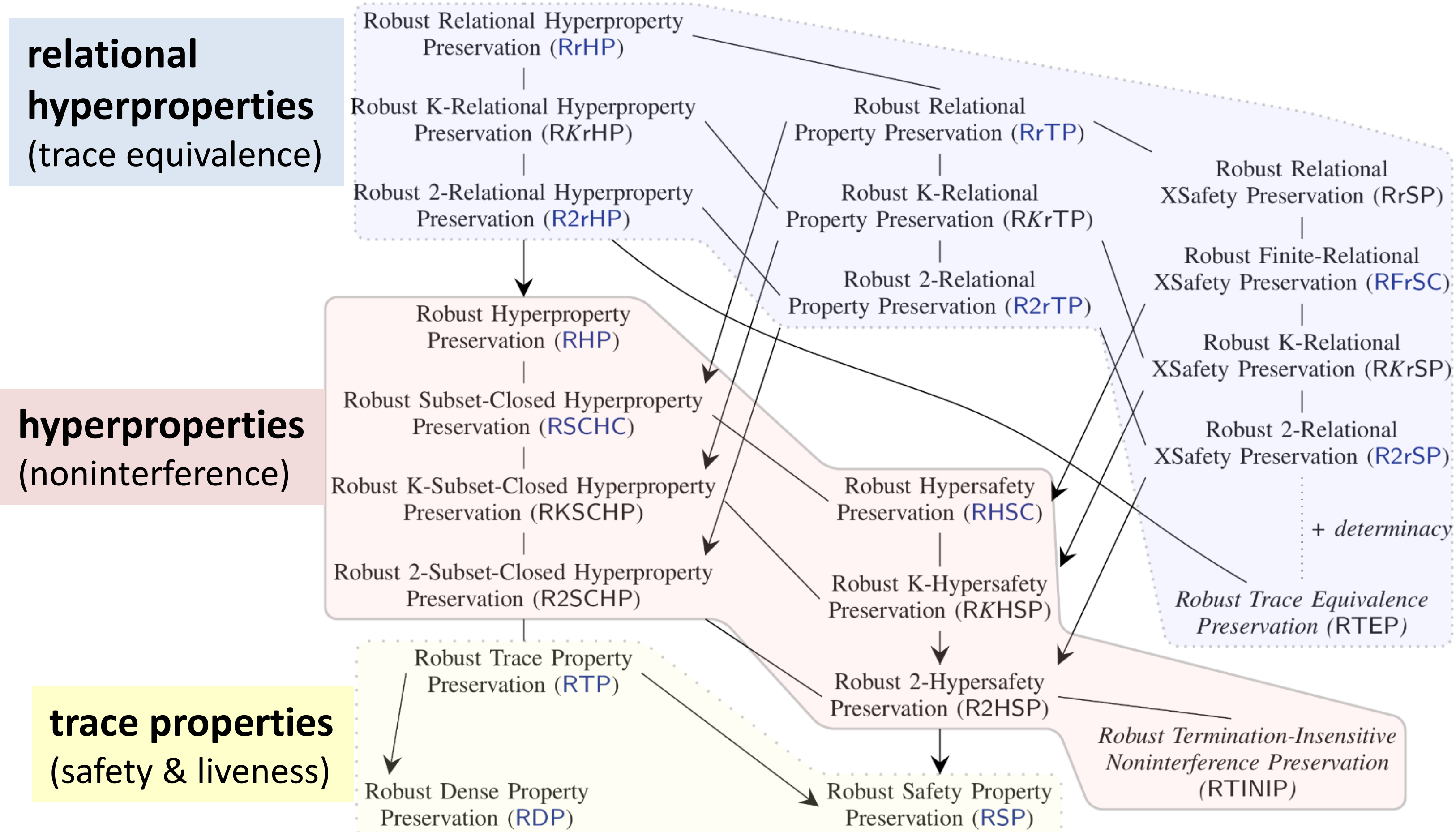

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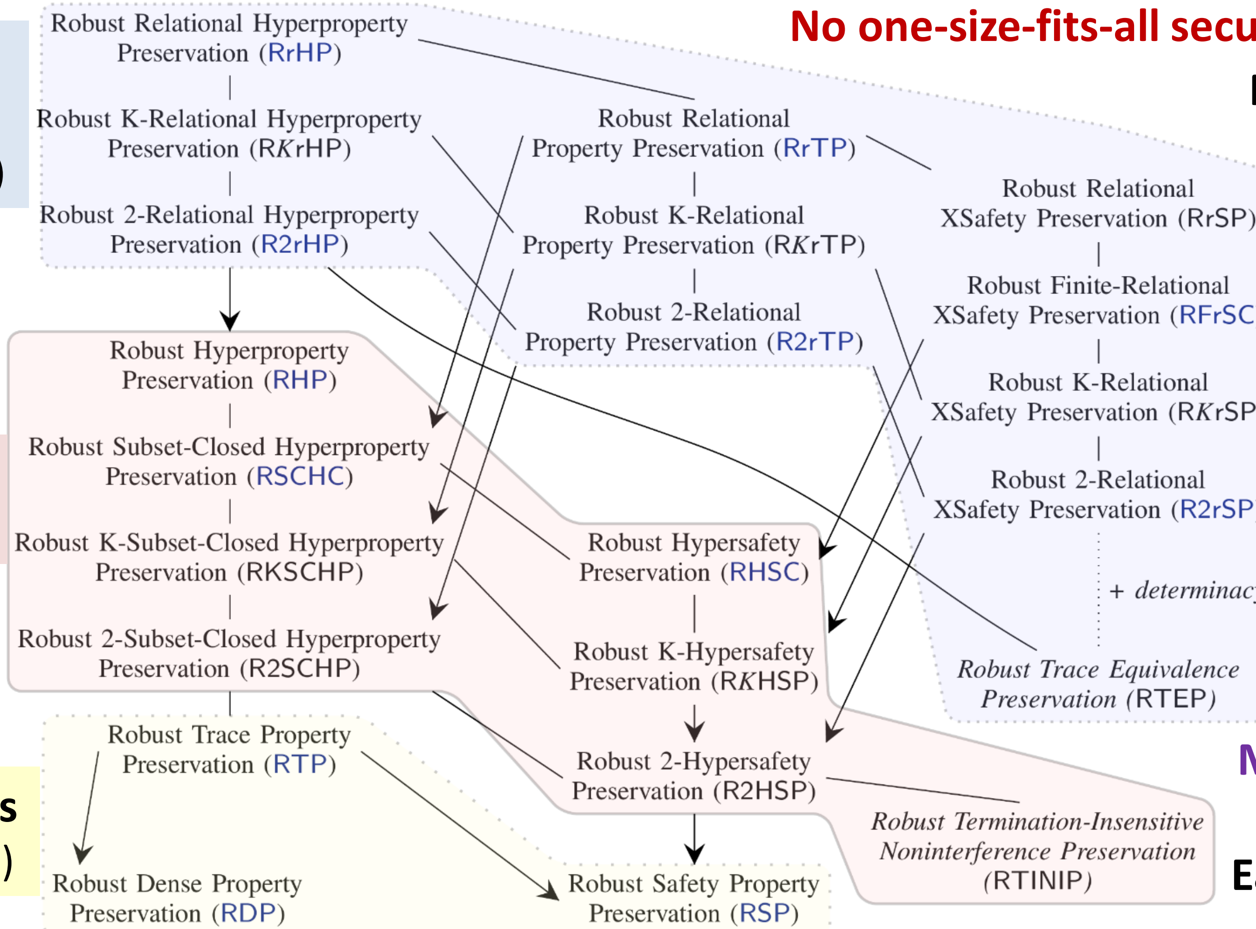

No one-size-fits-all security criterion

More secure

More efficient to enforce

Easier to prove

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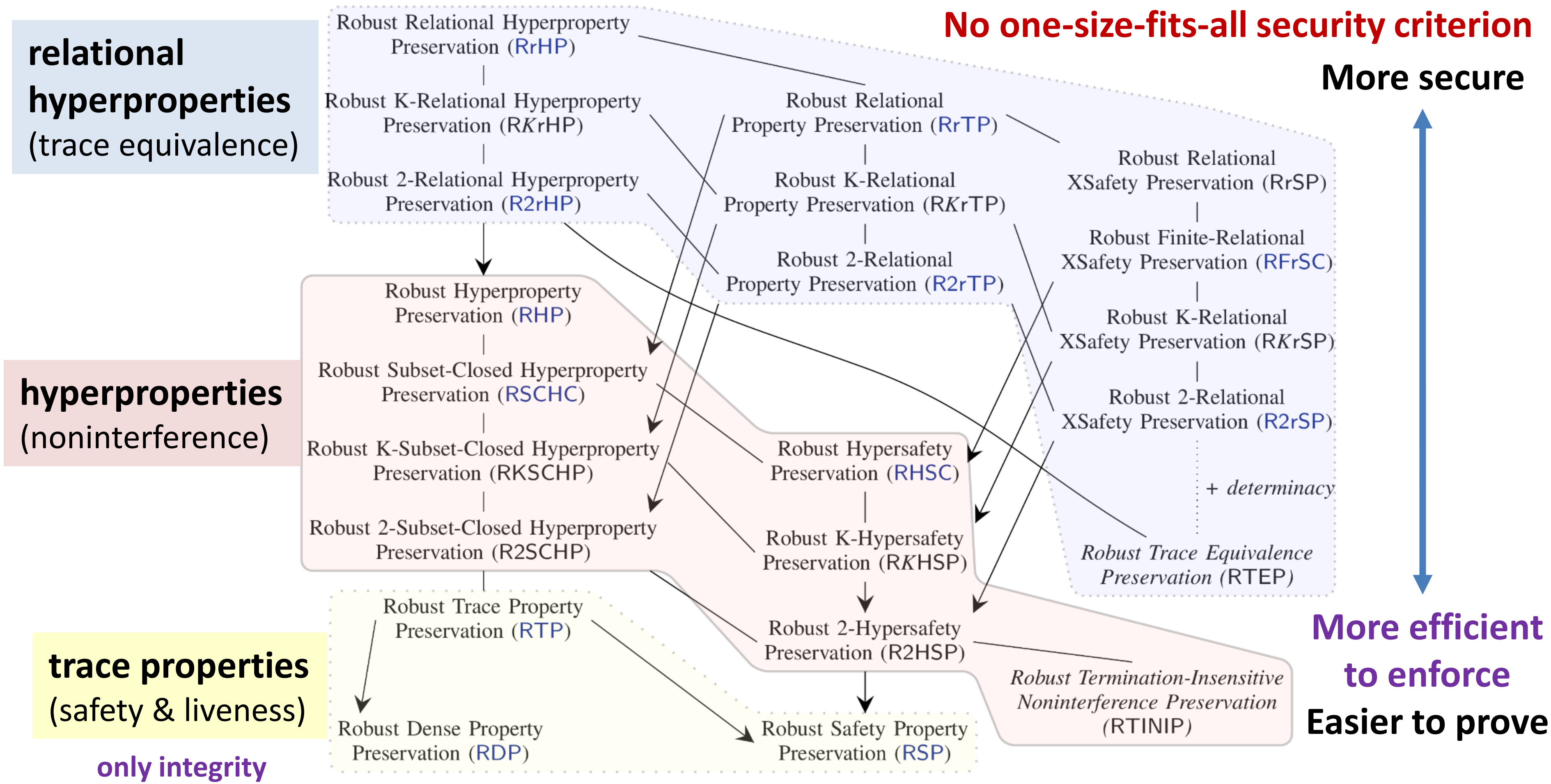

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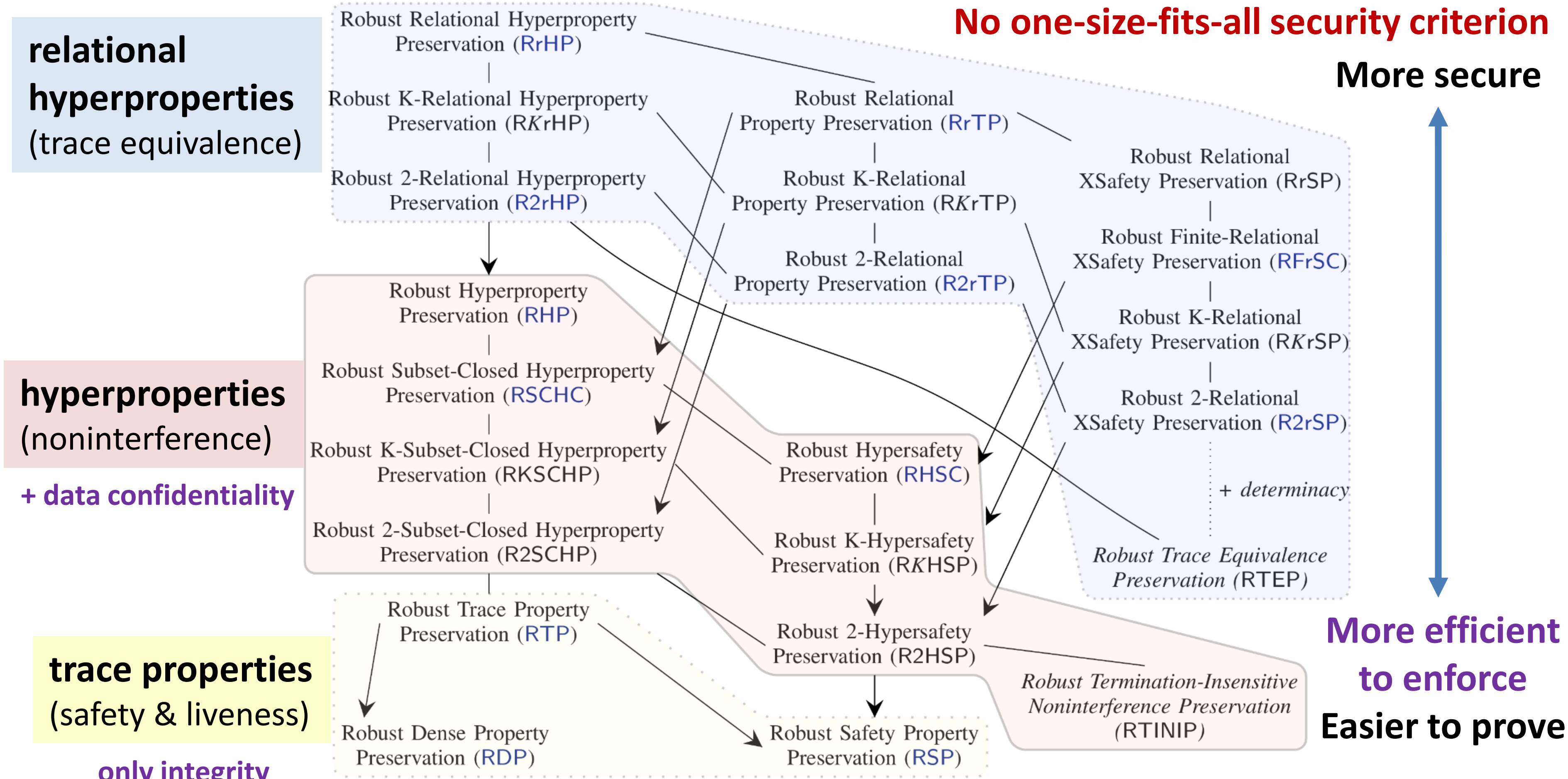

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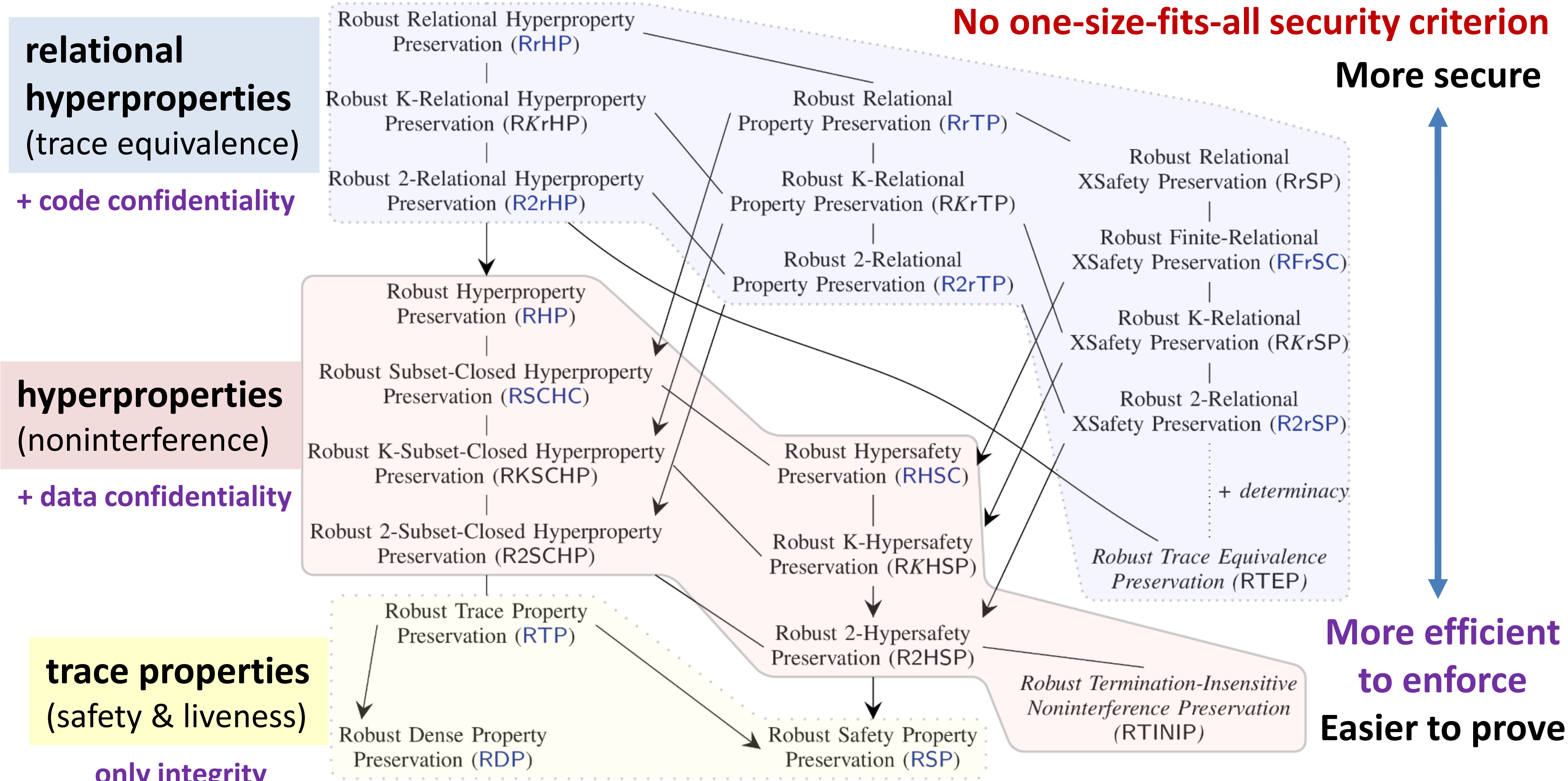

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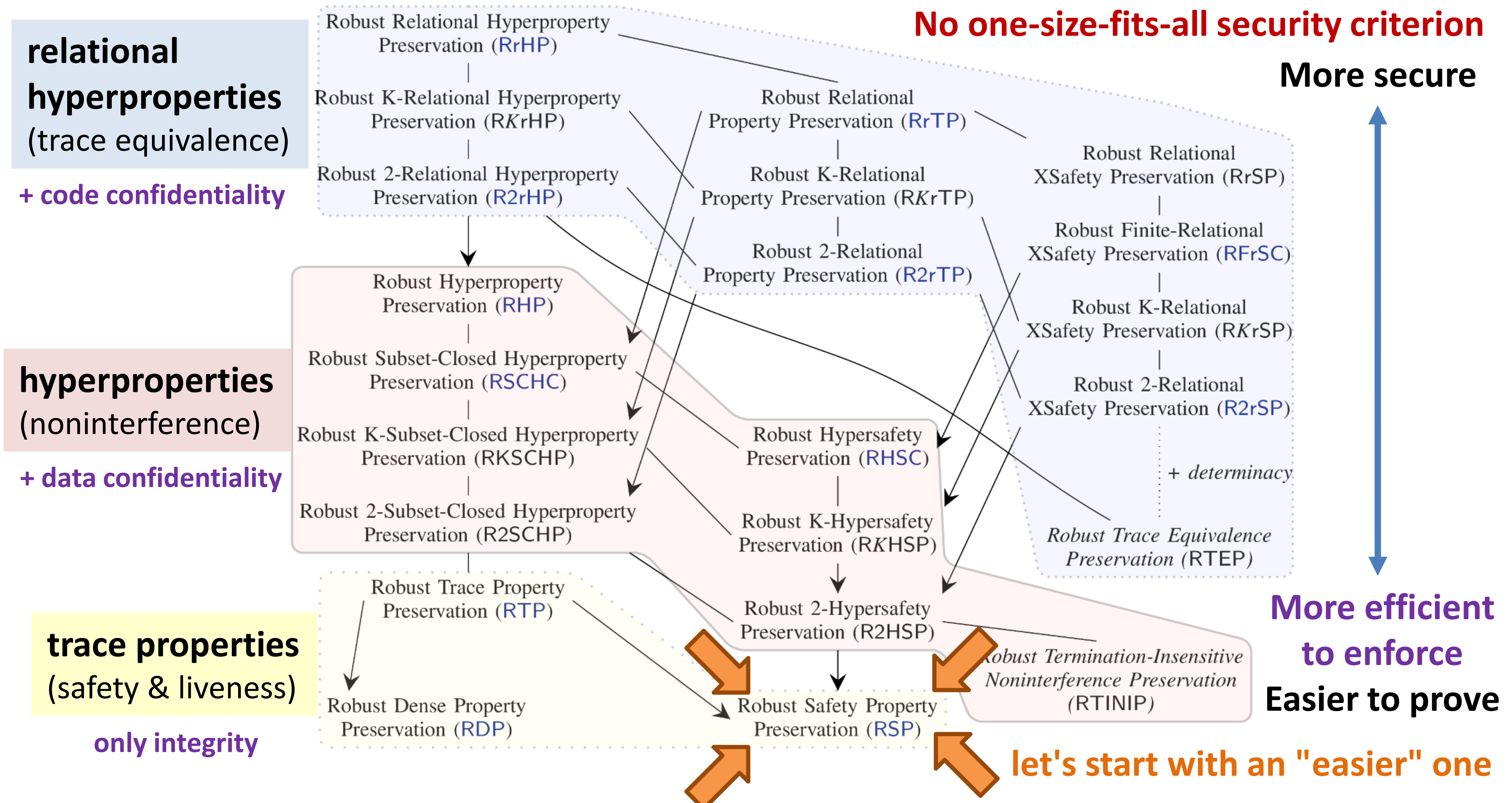


Journey Beyond Full Abstraction [CSF'19, ESOP'20, TOPLAS'21]

No one-size-fits-all security criterion

More secure

relational hyperproperties (trace equivalence)

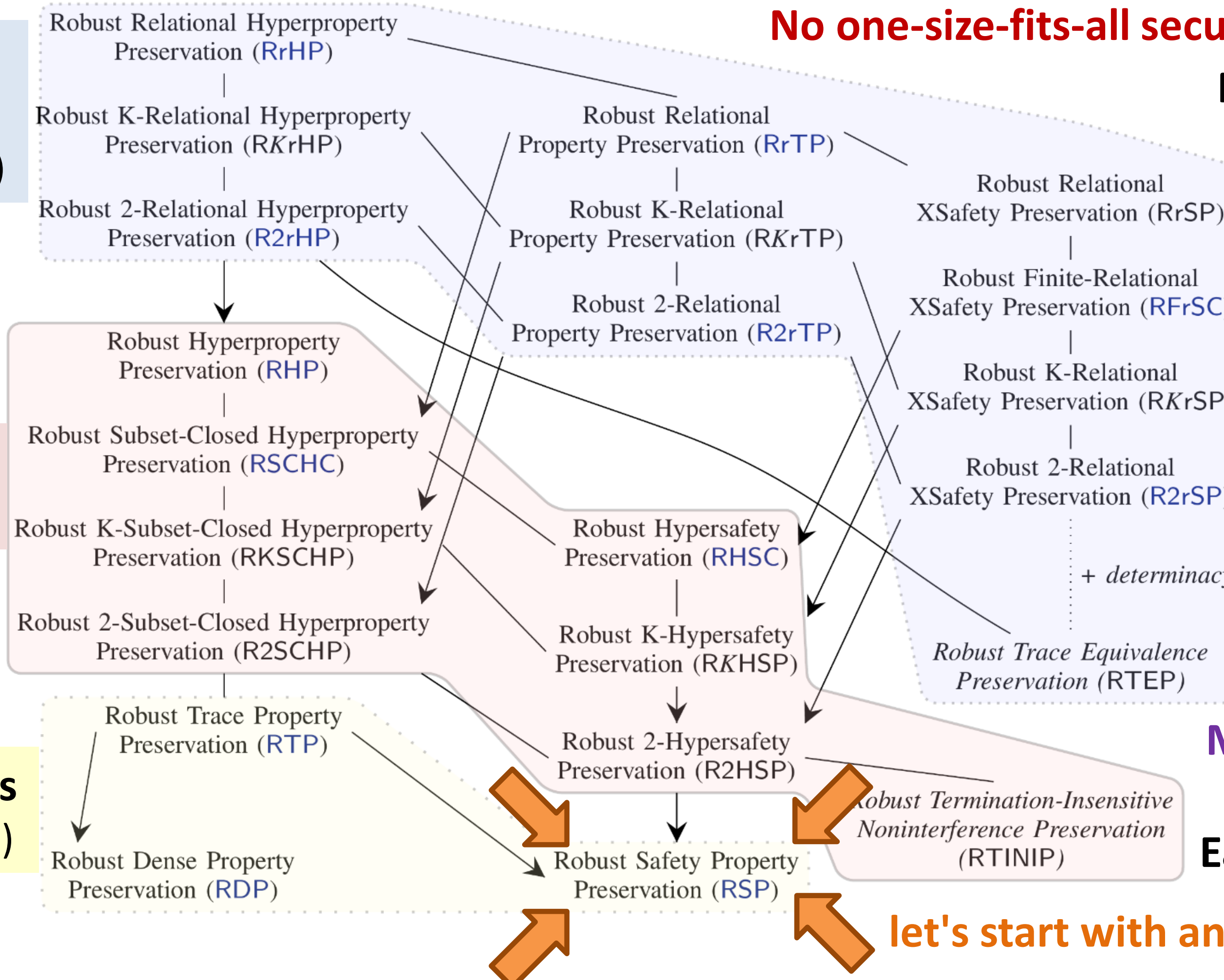
+ code confidentiality

hyperproperties (noninterference)

+ data confidentiality

trace properties (safety & liveness)

only integrity



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Easier to prove

let's start with an "easier" one

fine for code without vulnerabilities (e.g. verified) , but ...

Extra challenges in defining secure compilation for vulnerable C compartments [CSF'16, CCS'18]

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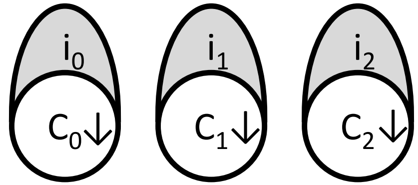
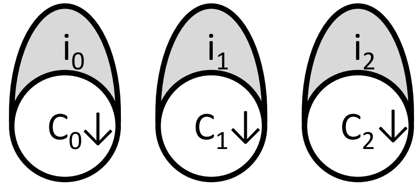
- Program split into **many mutually distrustful compartments**
- **We don't know which compartments will be compromised**
  - **every compartment should be protected from all the others**
- **We don't know when a compartment will be compromised**
  - **every compartment should receive protection until compromised**

Security definition: If 

$\rightsquigarrow_{\text{machine}}$ m then

Security definition: If 

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

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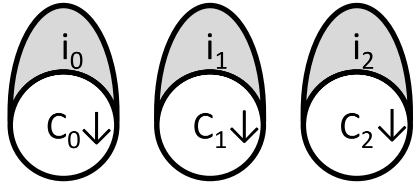

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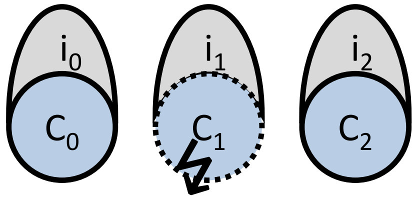

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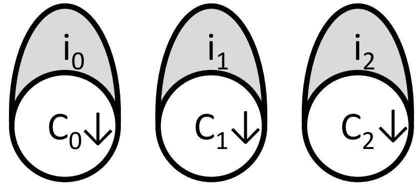

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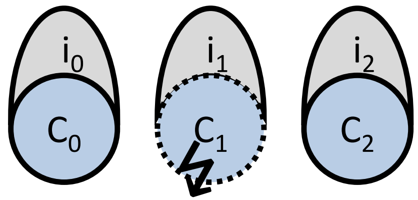

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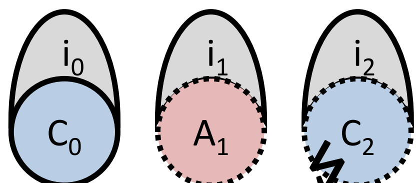

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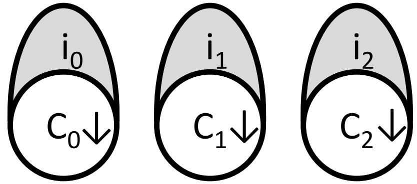

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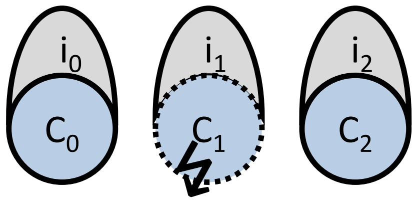

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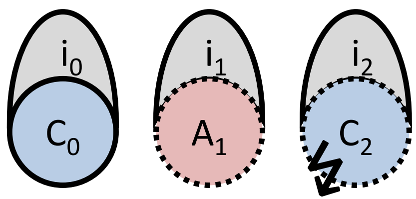

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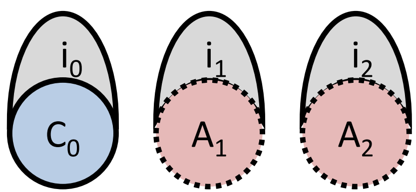

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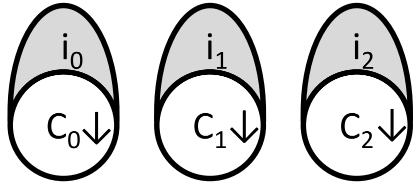

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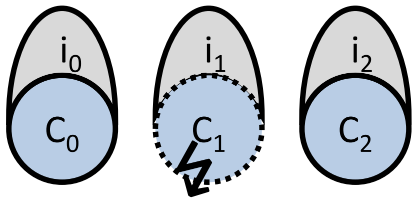

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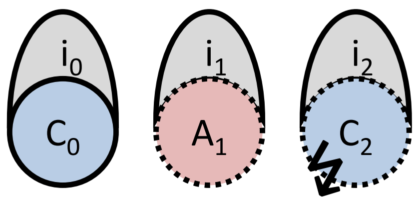

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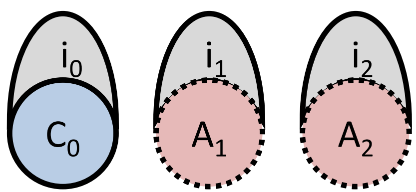

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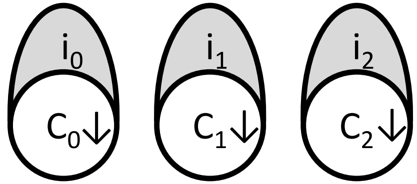
Finite trace *m* records which compartment encountered undefined behavior and allows us to rewind execution

Security definition: If 

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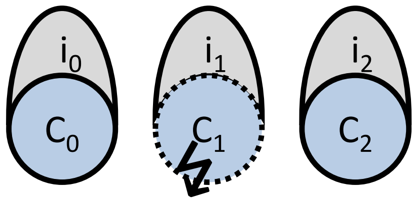
(1) 

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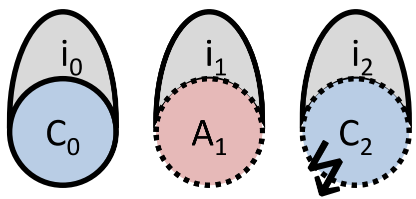
(2) $\exists A_1.$ 

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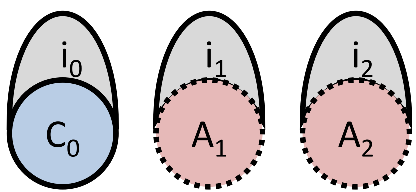
(3) $\exists A_2.$ 

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We can reduce this to a **variant of robust safety preservation** [CCS'18]

We reduce our security goal to a variant of:

Robust Safety Preservation

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∀source compartments.

∀π safety property.

∀ source context trace *t* . [[source compartments] source context] ⇝ *t* ⇒ *t*∈π

⇓

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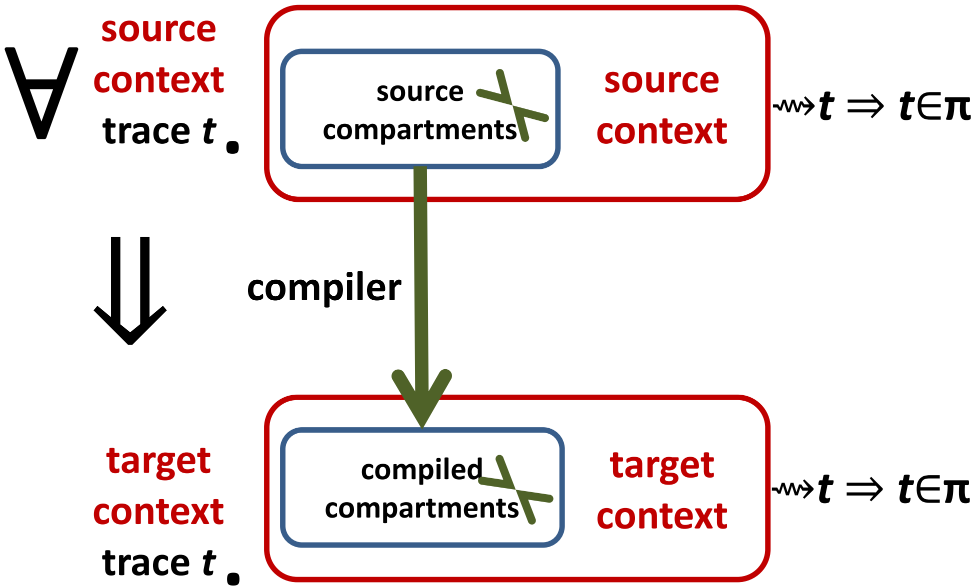

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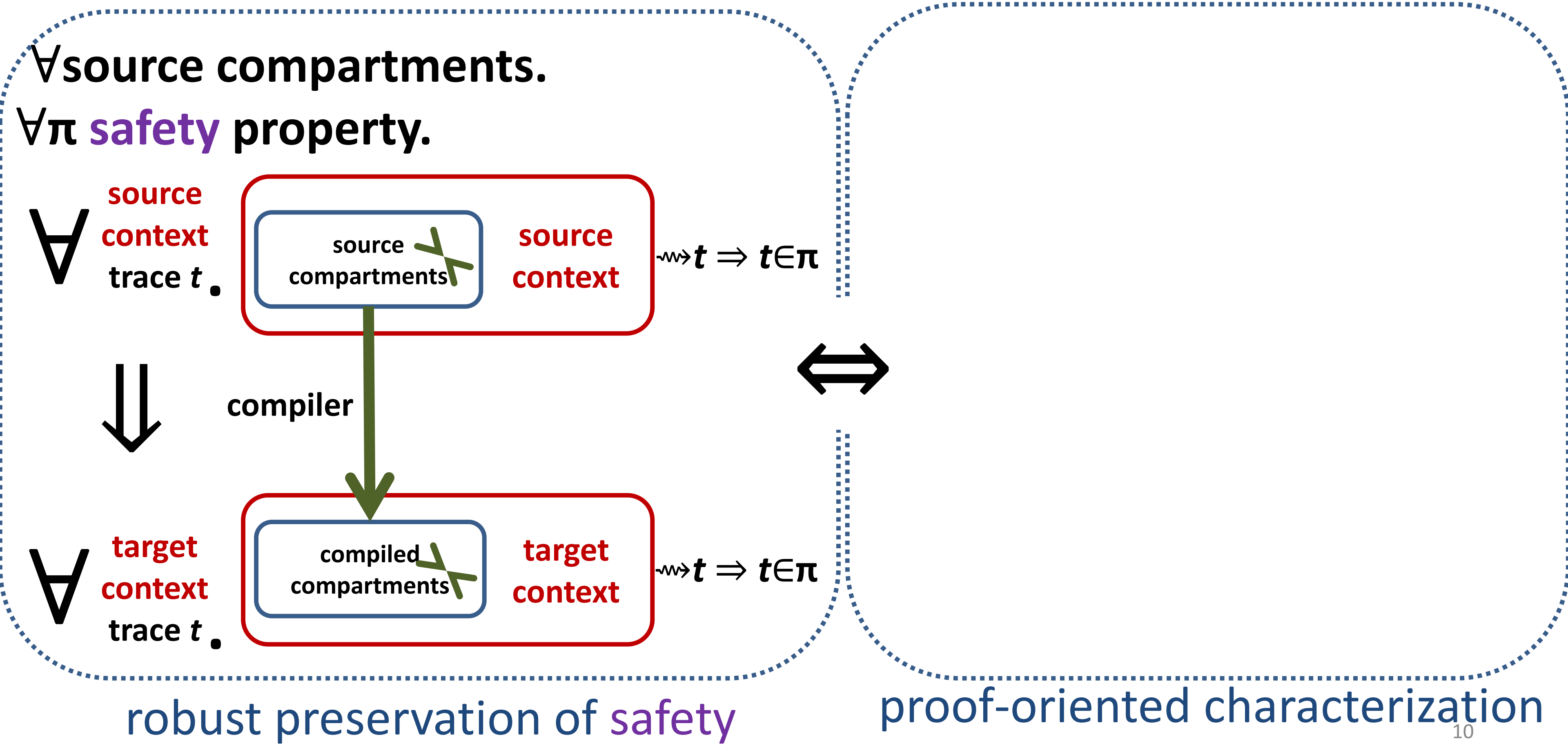

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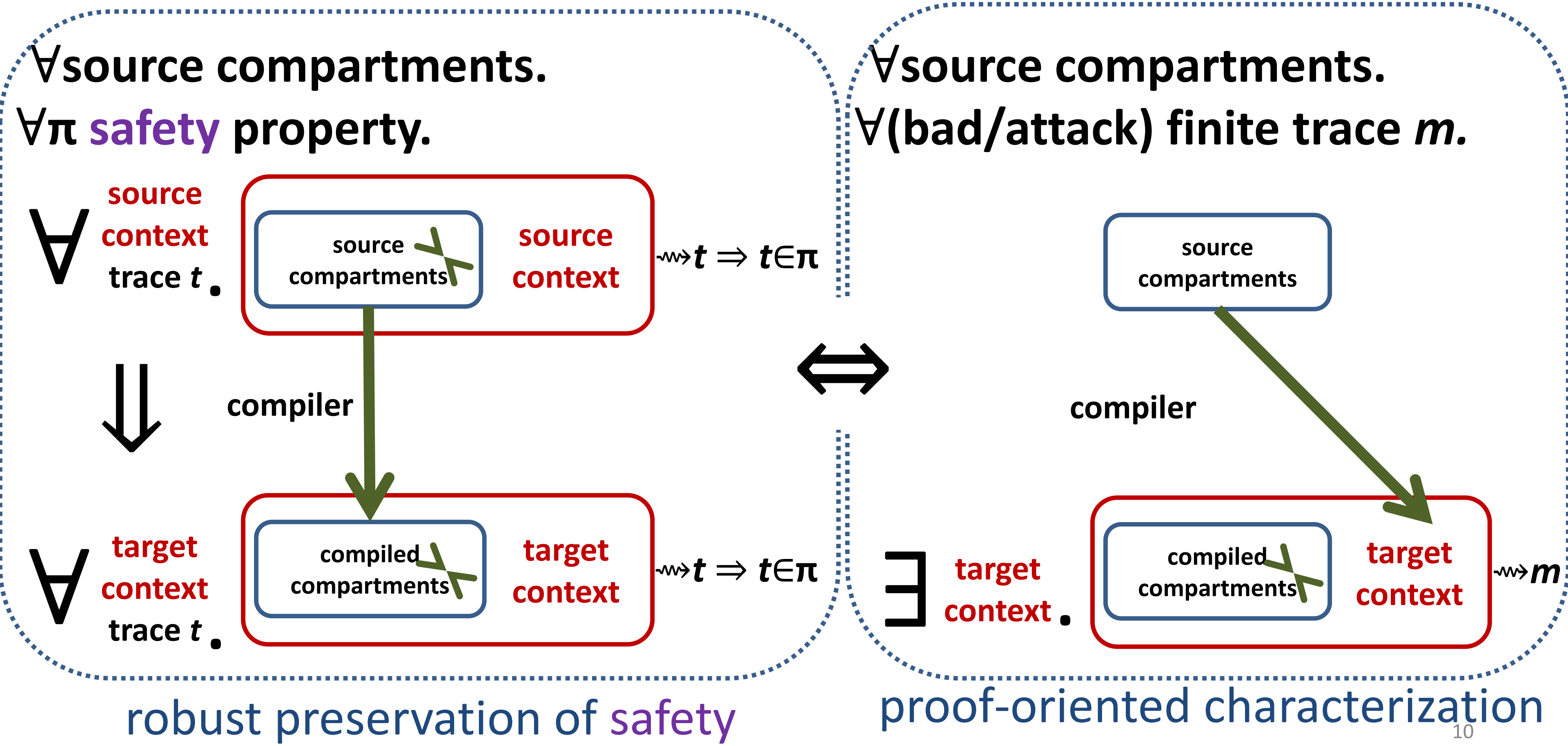

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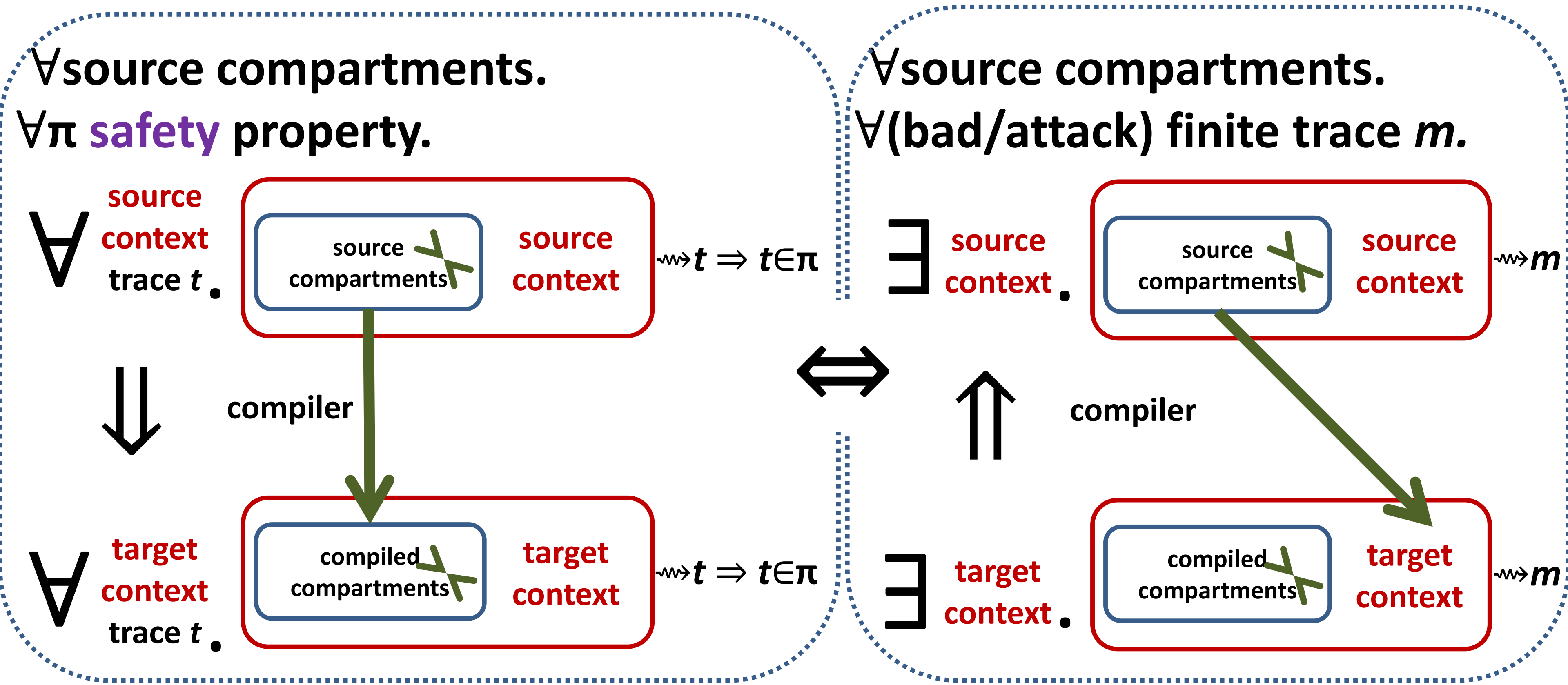

robust preservation of safety

proof-oriented characterization

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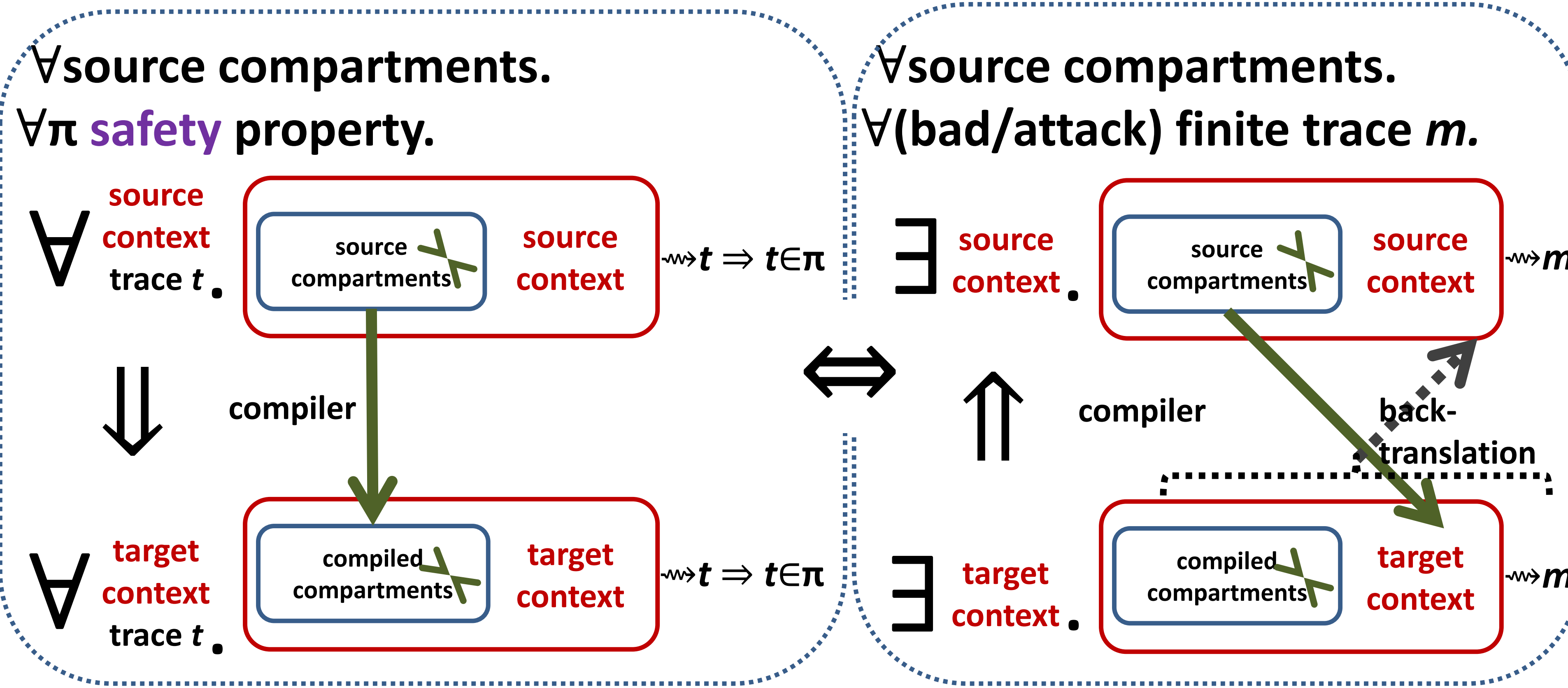

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2. Security Enforcement

CompCert C
with compartments

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SECOMP: CompCert extended with secure compartments

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CompCert RISC-V ASM with compartments

magically secure semantics

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CompCert RISC-V ASM with compartments

magically secure semantics

Software-Fault Isolation

vanilla ASM

Micro-Policies: ASM with programmable tags

[POPL'14, S&P'15, ASPLOS'15, POST'18, CCS'18, CSF'23]

Hardware-accelerated enforcement

2. Security Enforcement

CompCert C with compartments

SECOMP: CompCert extended with secure compartments

CompCert RISC-V ASM with compartments

magically secure semantics

Software-Fault Isolation

vanilla ASM

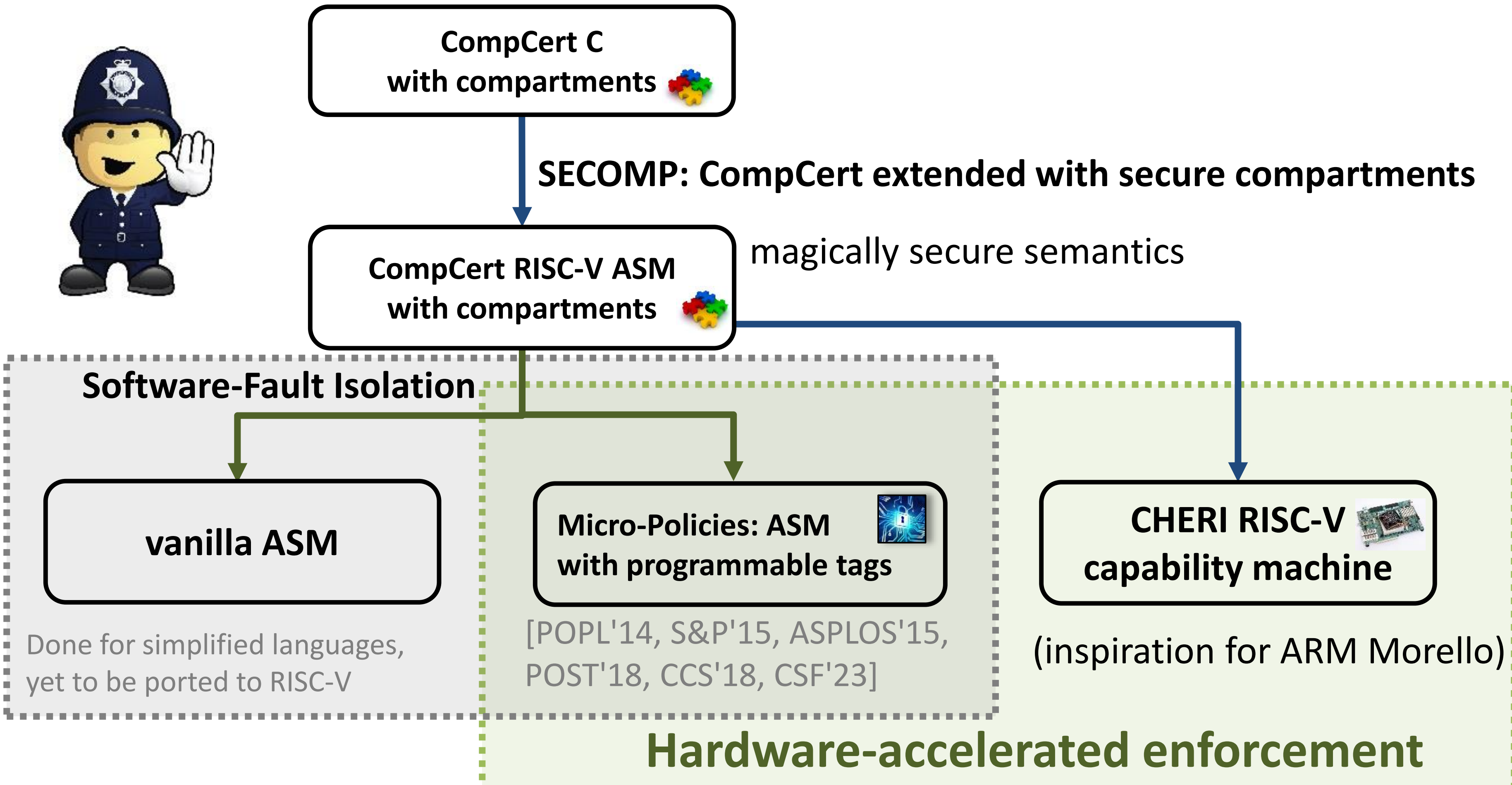
Done for simplified languages, yet to be ported to RISC-V

Micro-Policies: ASM with programmable tags

[POPL'14, S&P'15, ASPLOS'15, POST'18, CCS'18, CSF'23]

Hardware-accelerated enforcement

2. Security Enforcement



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comp_main imports comp_fib[fib]
comp_main imports_syscall printf scanf

comp_main int input;

comp_main int main() {
  scanf("%d", &input);
  int r = fib(input);
  printf("fib(%d) = %d\n", n, r);
  return 0;
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Prevented: memory is private

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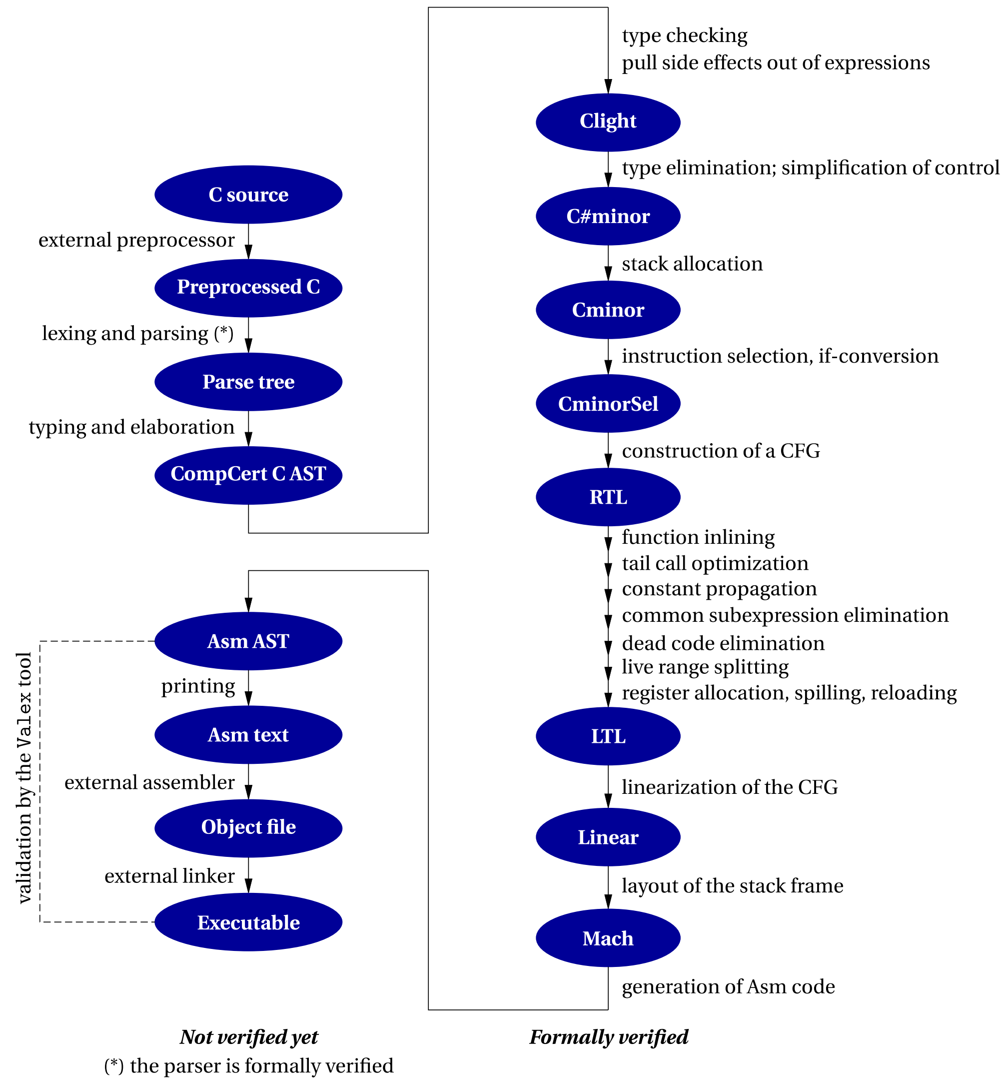

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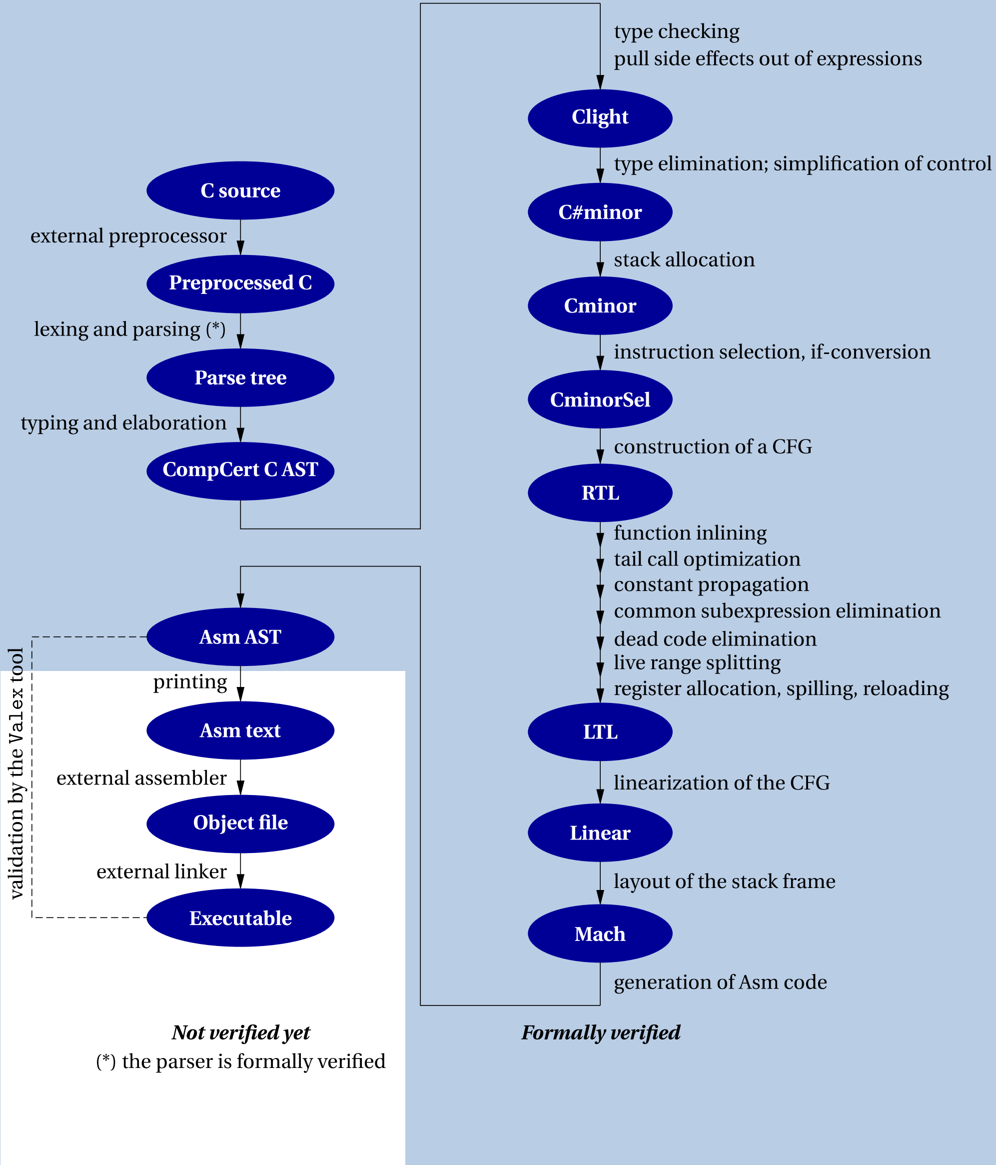
all 19 verified compilation passes* from Clight to RISC-V ASM (magically secure semantics)



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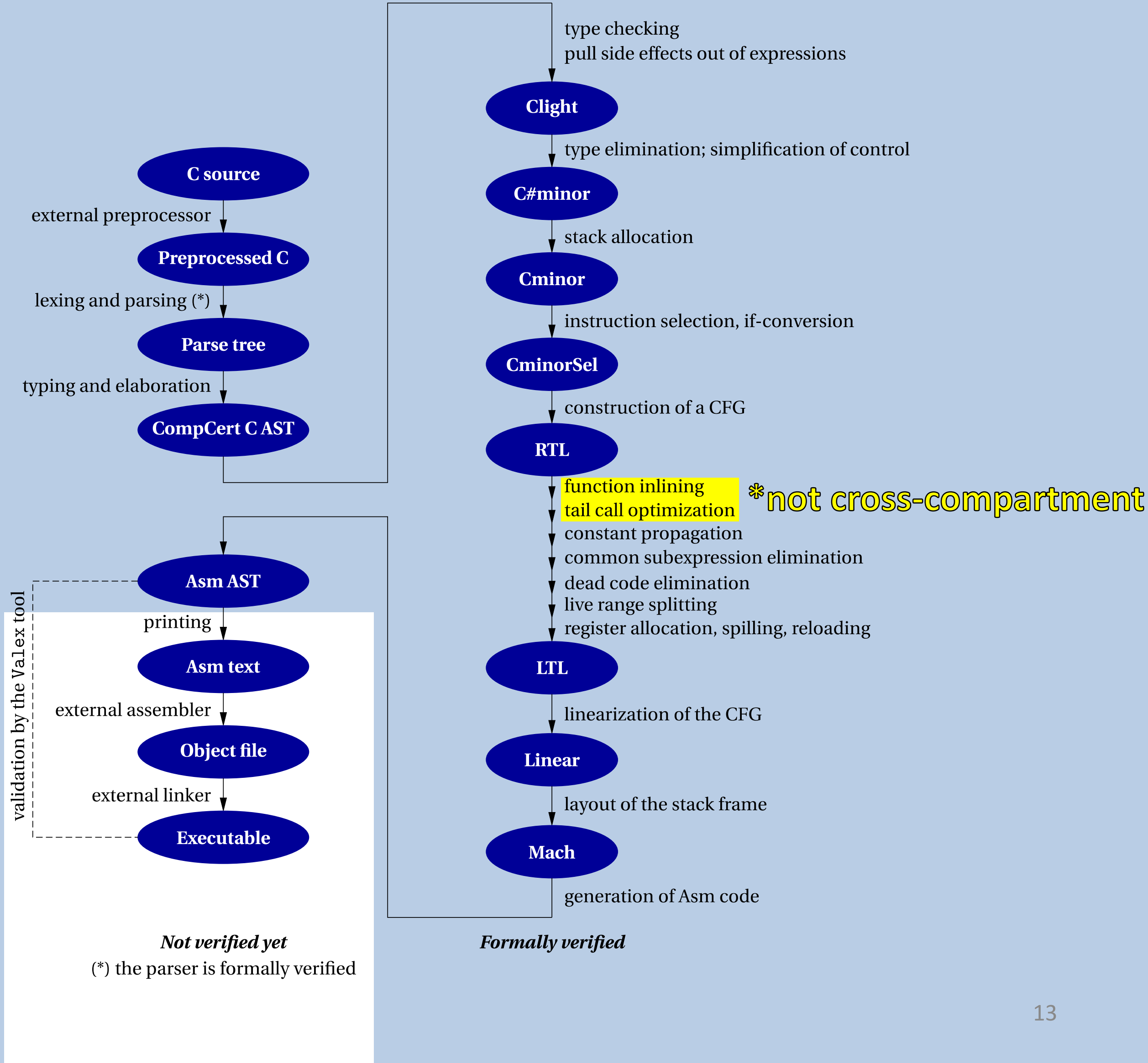

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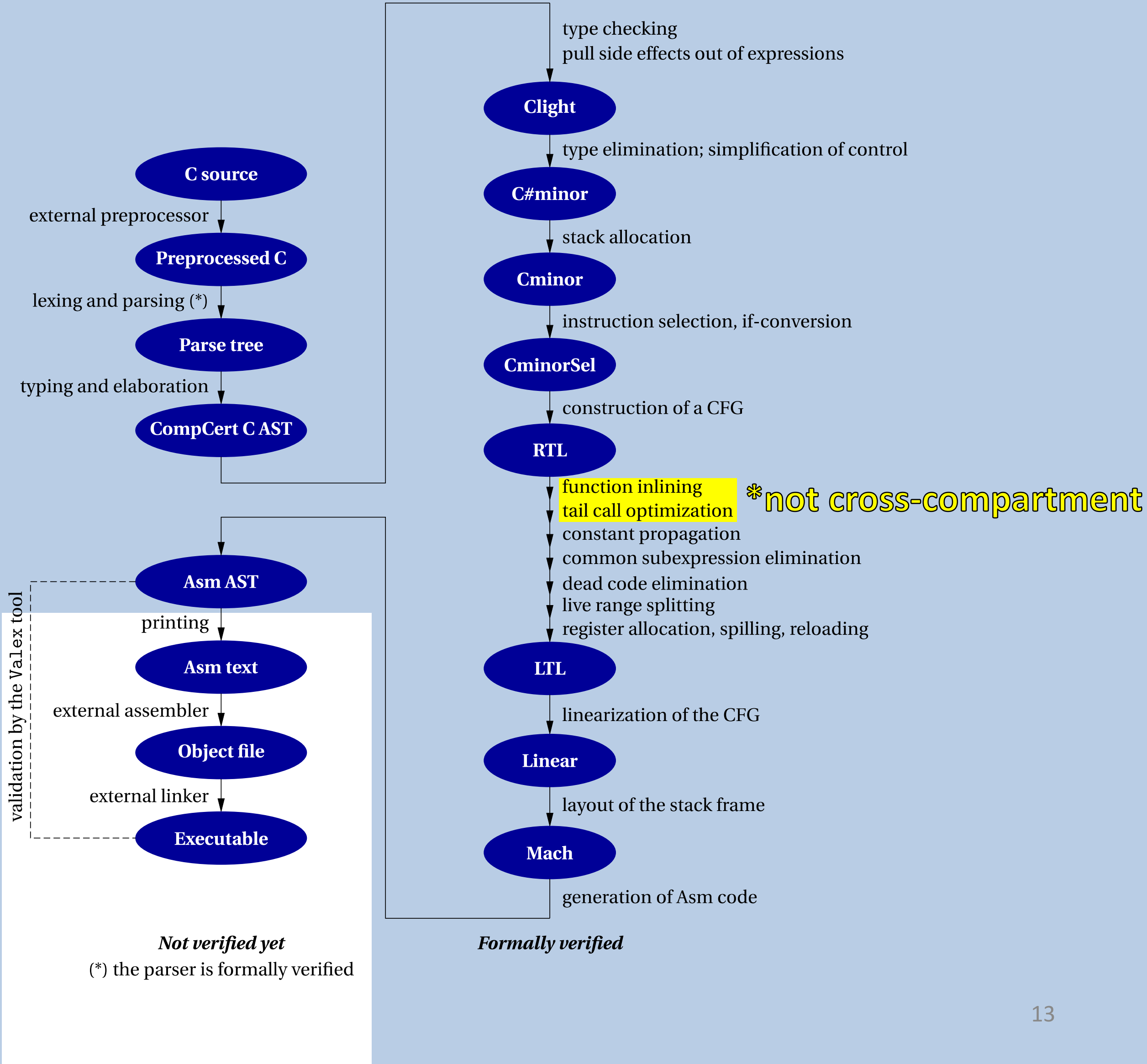
extended compiler correctness
12+ KLoC, only 9.4% change
reused for security



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- **Need to protect stack-spilled call arguments**
  - so that malicious caller cannot exploit callbacks
    to covertly change arguments of a previous call
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- **Abstract machine with magically secure semantics**
  - independent of actual enforcement (lower-level backends)

Capabilities Backend

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- Mutual distrustful compartments: **capability-protected wrappers**
  - on calls and returns clear registers and
    prevent passing capabilities between compartments
- Also investigating **calling convention based solely on wrappers**
  - no new kind of capability over what CHERI already provides
  - but more interesting stack layout (not a single contiguous block)

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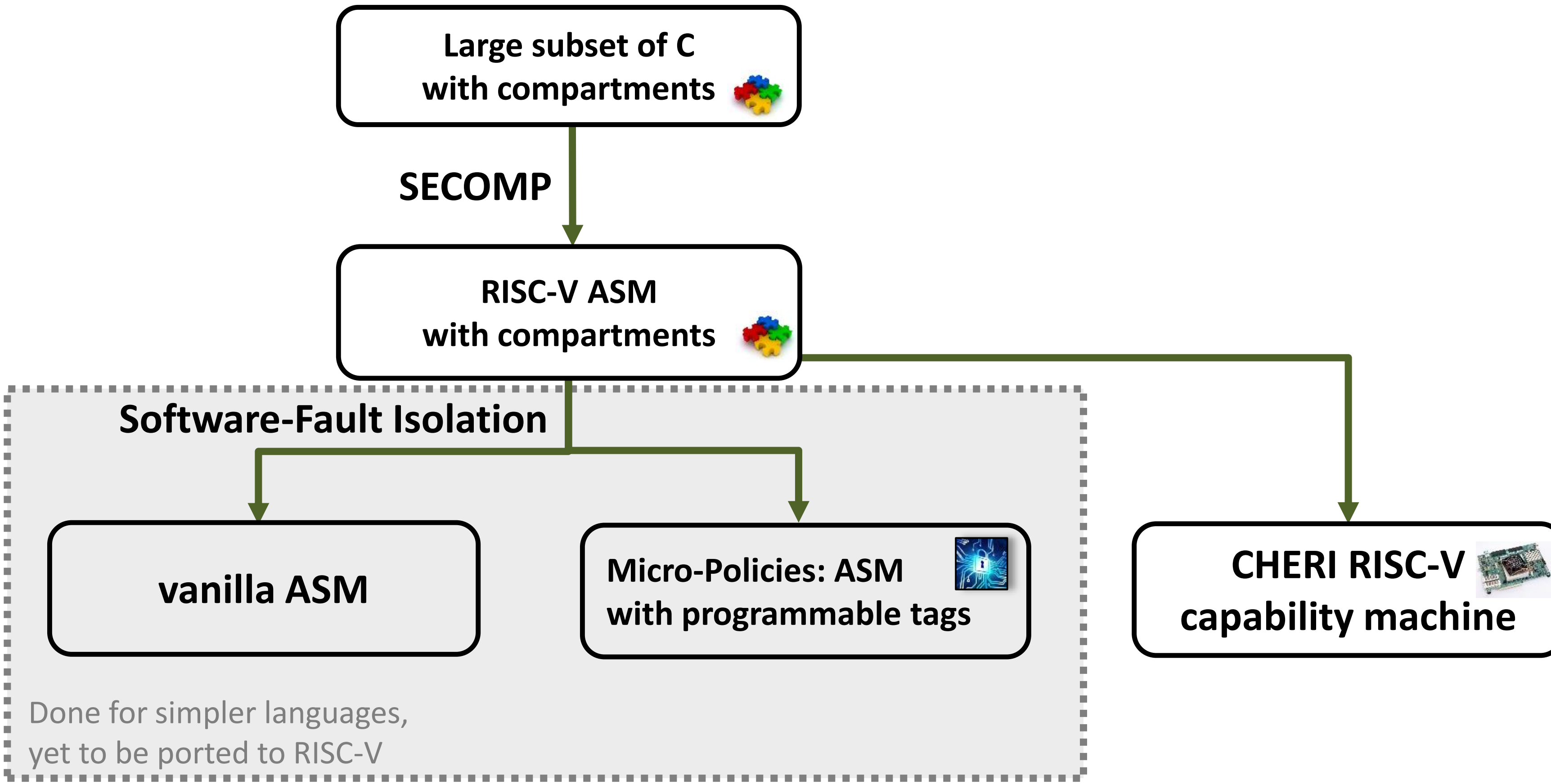
- we propose a **more scalable proof technique**
- we focus on **machine-checked proofs** in the Coq proof assistant
  - with **property-based testing** stopgap [POPL'17, ICFP'13, ITP'15, JFP'16]
    - to find wrong conjectures early
    - to deal with the parts we couldn't (yet) verify

Secure Compilation Proofs in Coq



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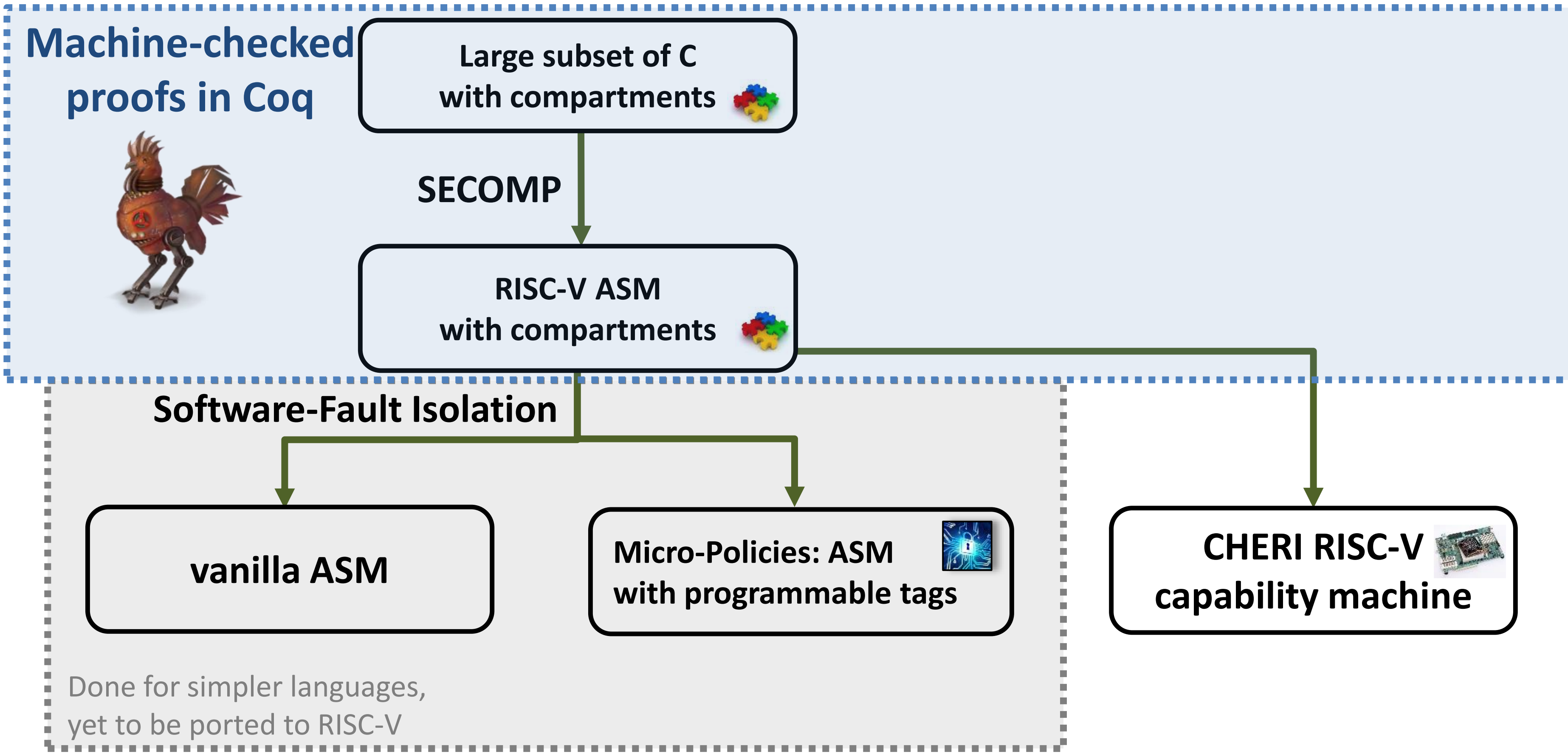

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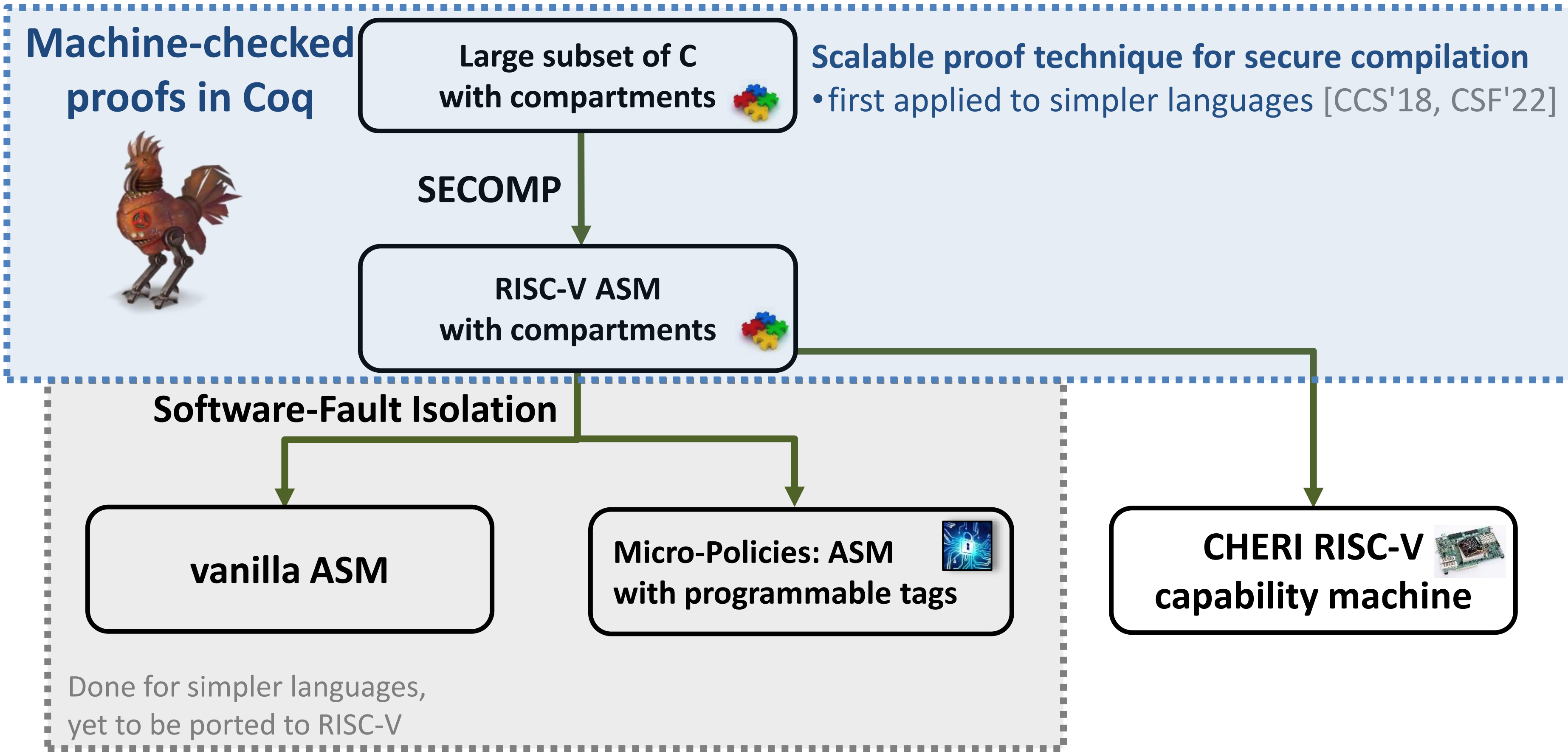

Secure Compilation Proofs in Coq

Machine-checked proofs in Coq

Large subset of C with compartments

SECOMP

RISC-V ASM with compartments

Scalable proof technique for secure compilation
- first applied to simpler languages [CCS'18, CSF'22]
- then scaled up to C compartments [CCS'24]
  - this reuses extended CompCert correctness proof
  - verified strong full-abstraction-like property (~38K LoC)

Software-Fault Isolation

vanilla ASM

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Quick Chick

Systematic testing

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Big verification challenge for the future

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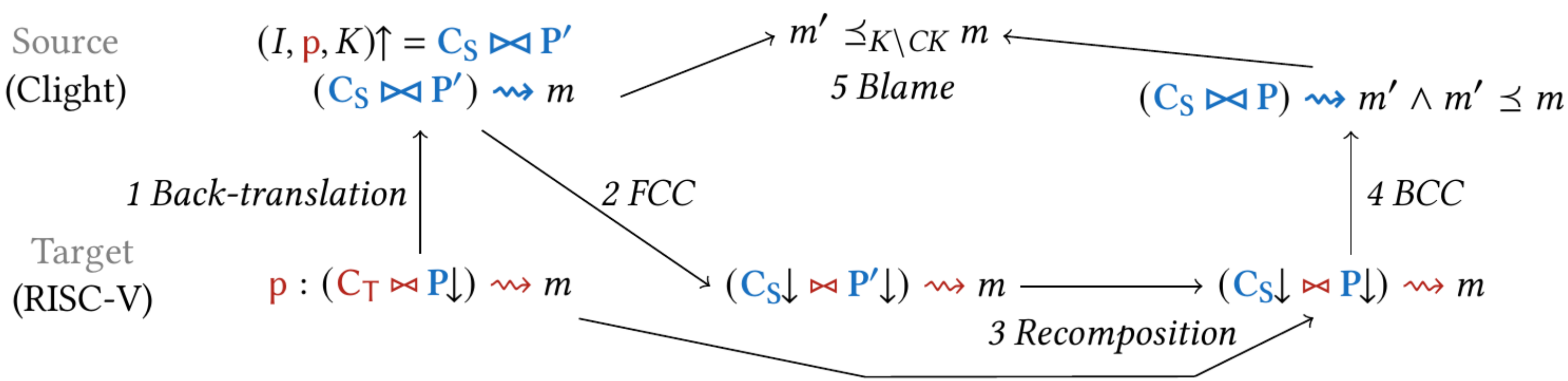

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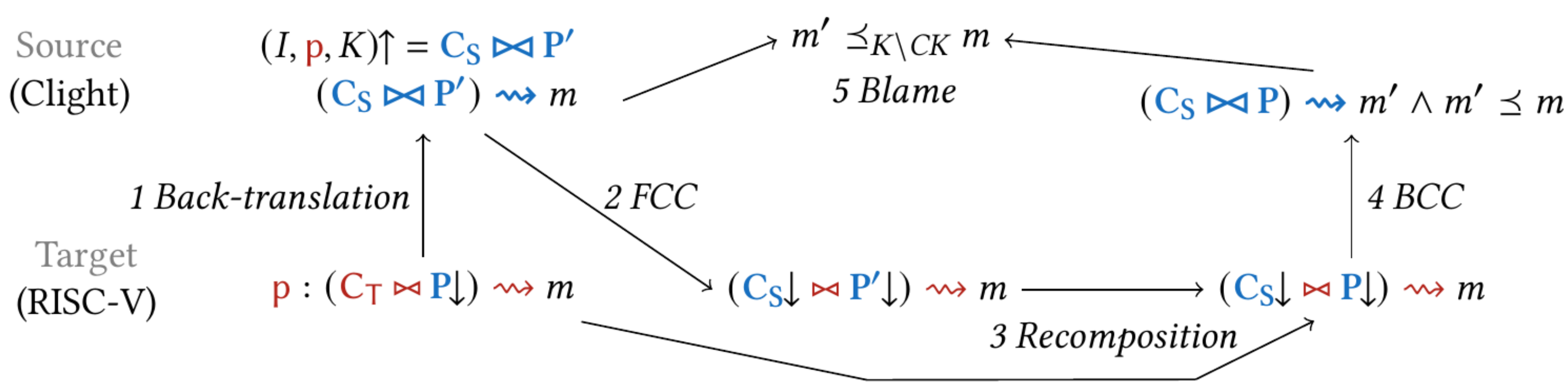

Challenging proof engineering for scaling this to CompCert [CCS'24]

Recomposition for SECOMP RISC-V

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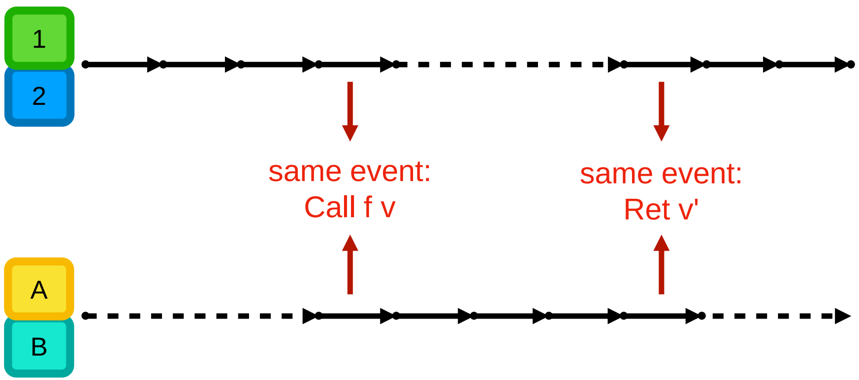
From two synchronized RISC-V executions



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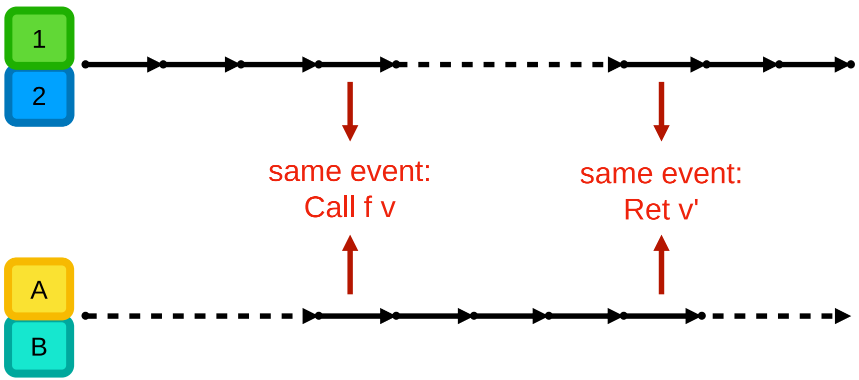

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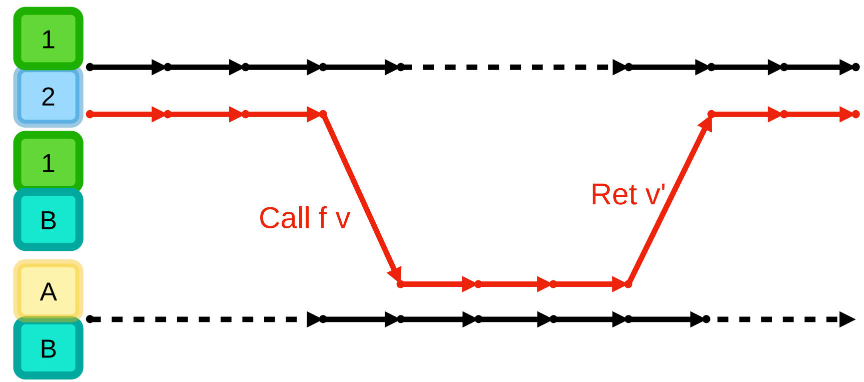

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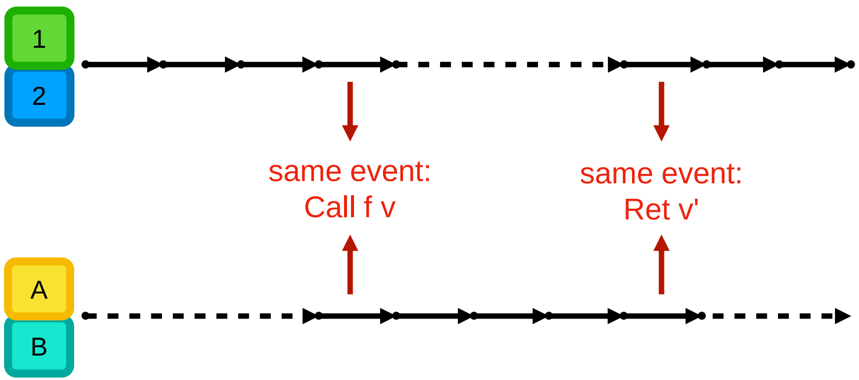

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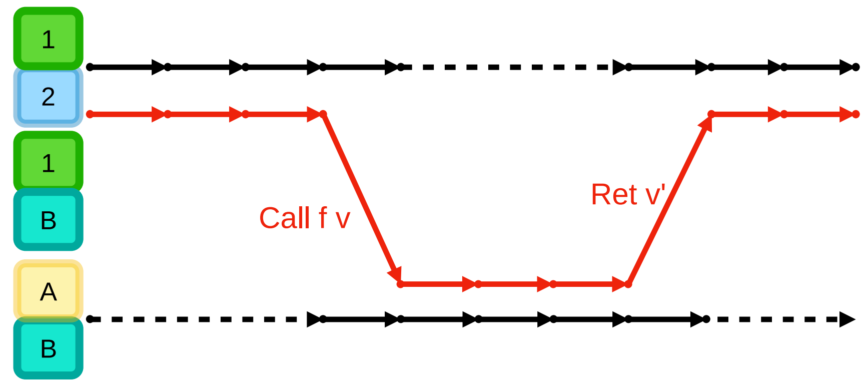
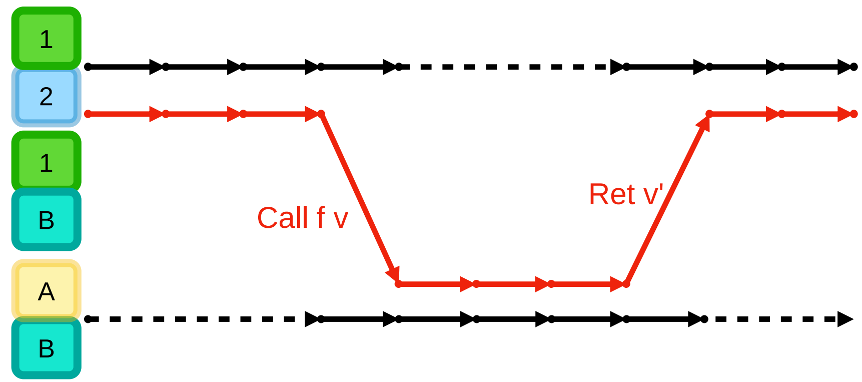


Challenging 3-way simulation proof with subtle invariants

Generic diagrams for recomposition

8 generic 3-way simulation diagrams for proving recomposition



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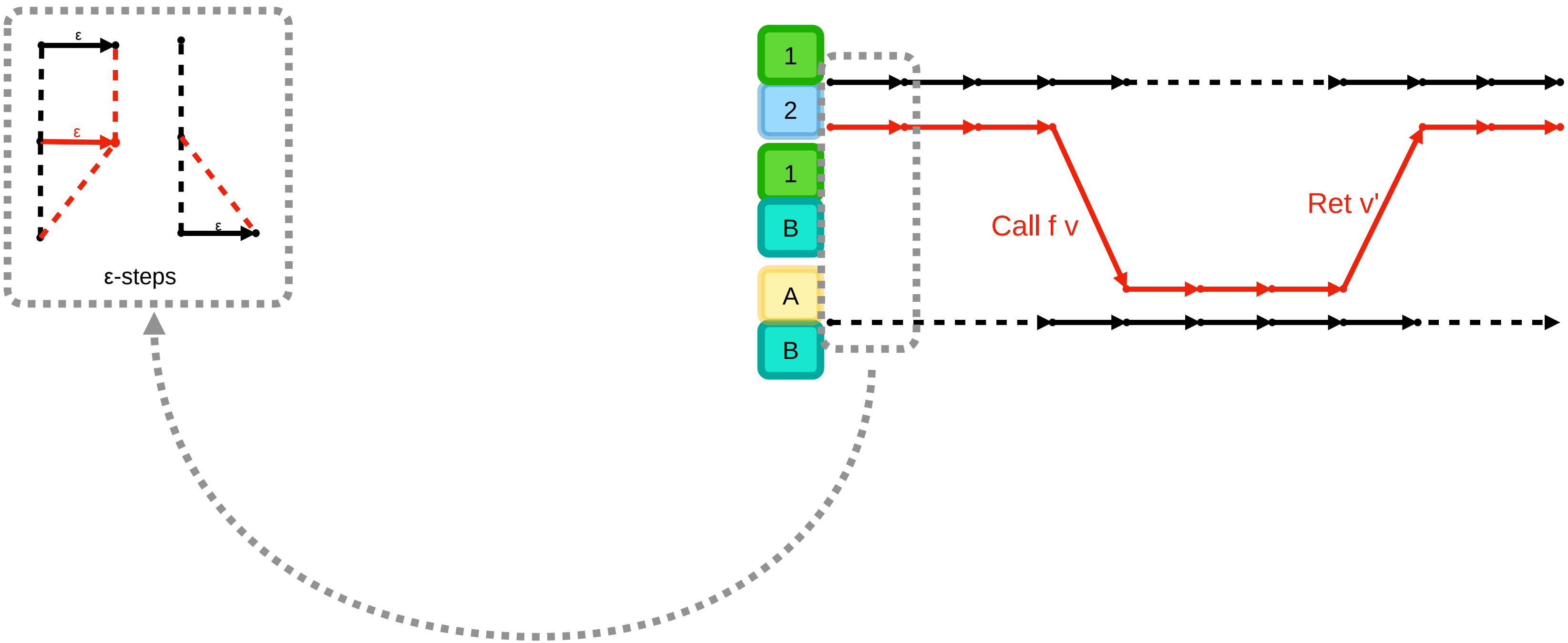

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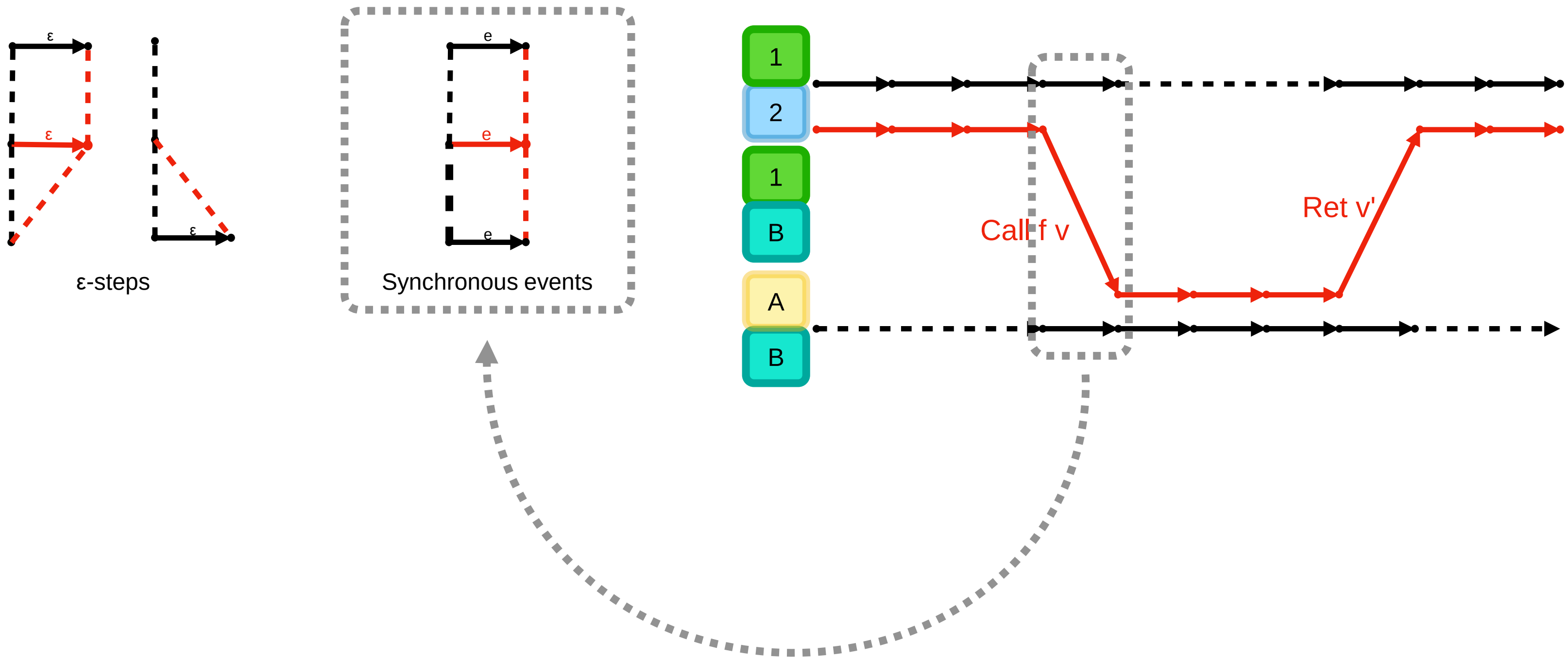

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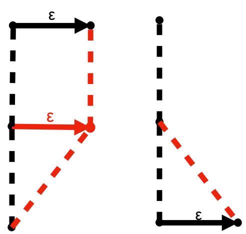
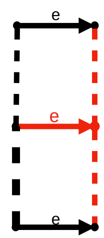
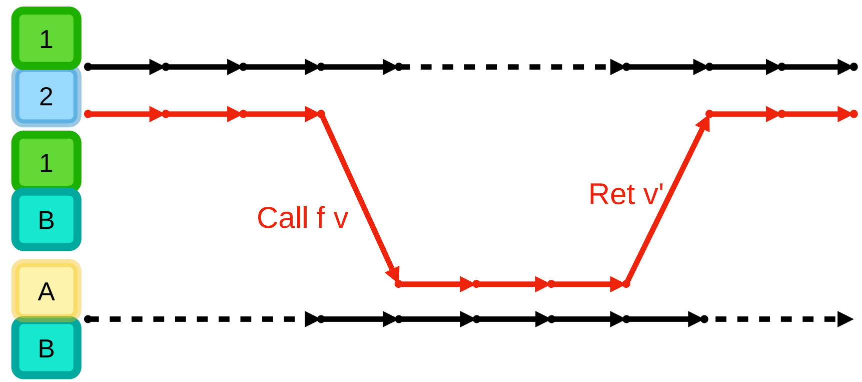


ε-steps



Synchronous events



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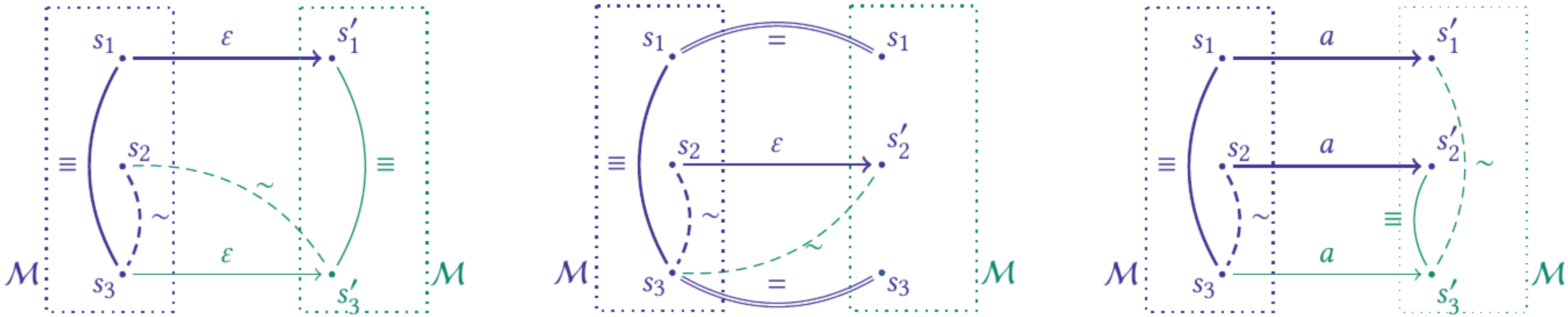
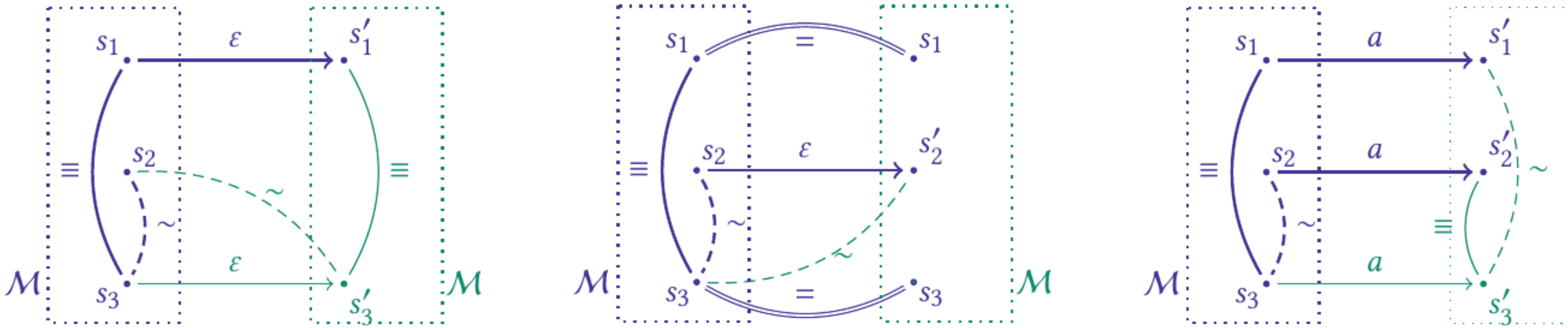


(a) Silent step in strongly related states **(b) Silent step in weakly related states** **(c) Non-silent step with swapping relations**

Figure 4: Recomposition diagrams

+ 5 more such diagrams

Generic diagrams for recomposition



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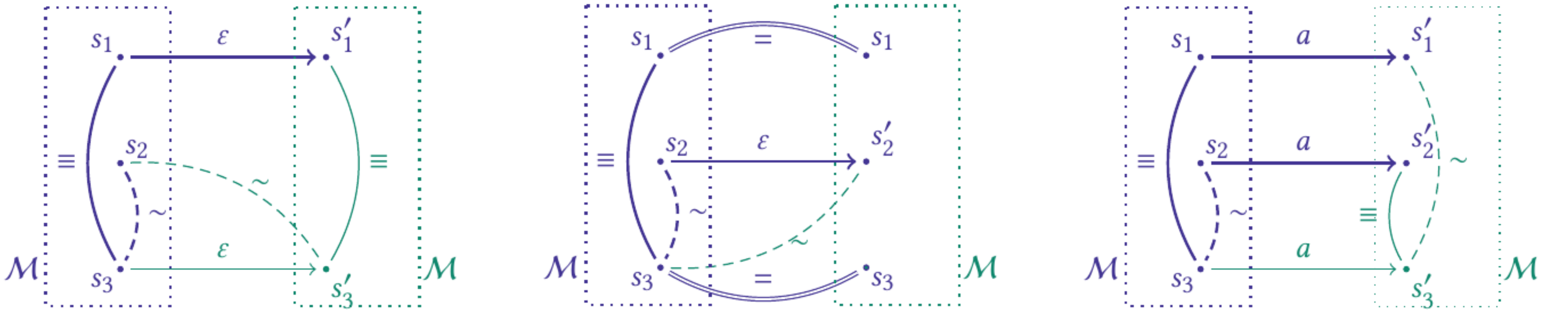

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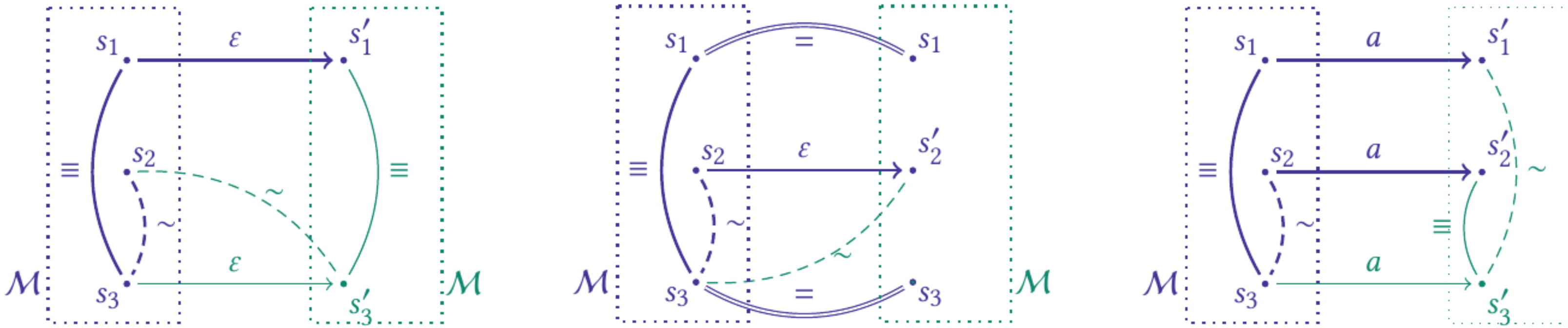

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first compiler for realistic language proved to offer strong security guarantees for compartmentalized code

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- **These backends do the actual security enforcement**
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- **Verifying backends is challenging though**
  - more concrete view of memory as array of bytes (vs CompCert one)
  - once code stored in memory, can no longer hide all the information about compartment's code (code layout leaks)
    - proof step inspired by full abstraction doesn't work all the way down (recomposition)

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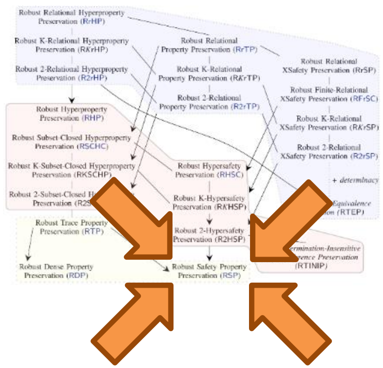

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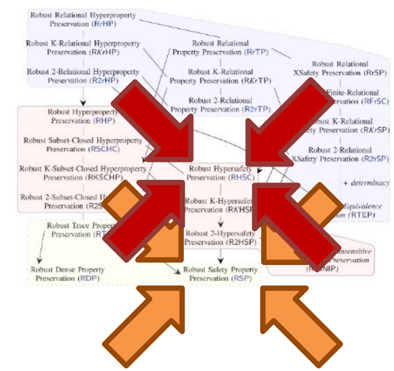

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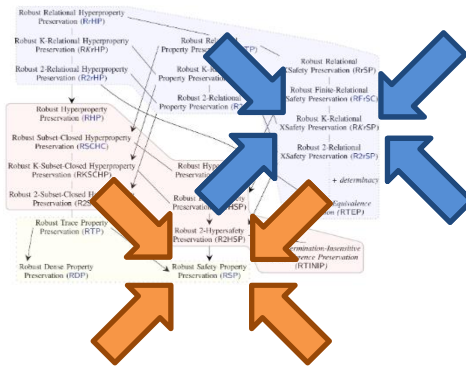

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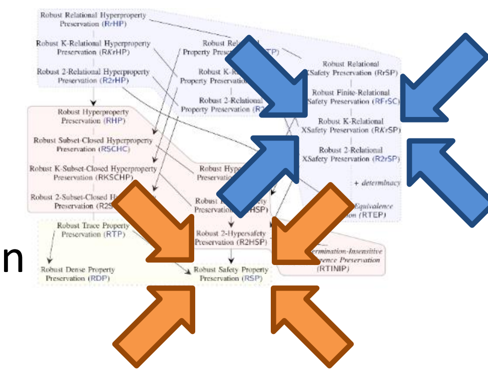
    - secure compilation criteria strictly stronger than full abstraction
    - can do this for CompCert, but won't hold for backends

  [Jérémy Thibault et al, CSF'19 + more ongoing work]



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- **Combining this with compartmentalization practically interesting**
  - Especially for languages like Wasm, which are used for same-process isolation

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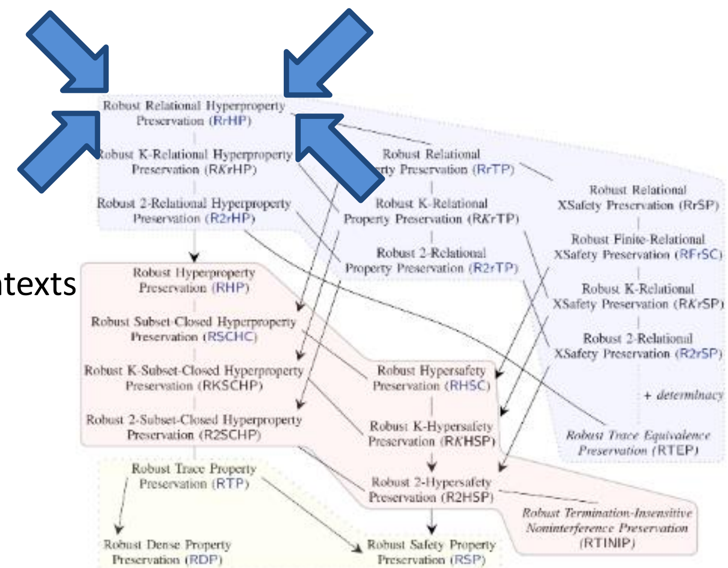
    - first step towards formally secure F*-OCaml interoperability



SECOMP: Formally Secure Compilation of Compartmentalized C Programs

1. Goal: formalized end-to-end security guarantees

- preserve properties **against adversarial contexts**
- we overcame additional challenges to support **mutually distrustful compartments** and **dynamic compromise**

2. Enforcement: protect abstractions all the way down

- **Extended CompCert languages with compartments**
- **Unverified backend targeting CHERI RISC-V capability machine**

3. Proof: verify security of our compilation chain

- **more scalable proof technique machine-checked in Coq**
- **first compiler for realistic language proved to offer strong security guarantees for compartmentalized code**