My Journey in Secure Compilation

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My companions on this journey:

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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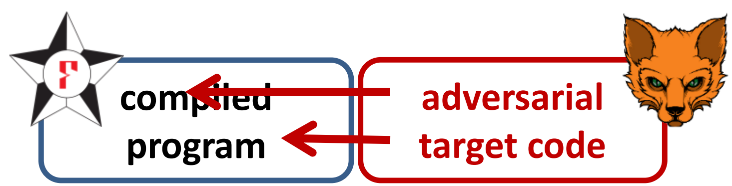

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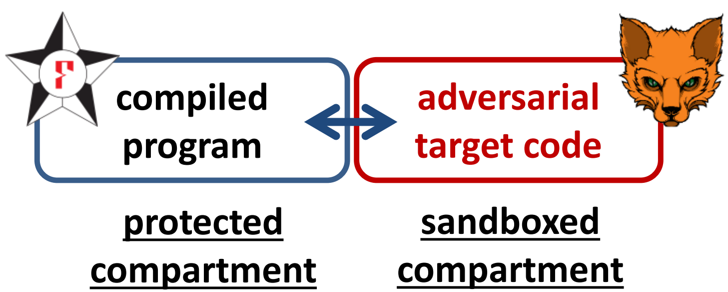

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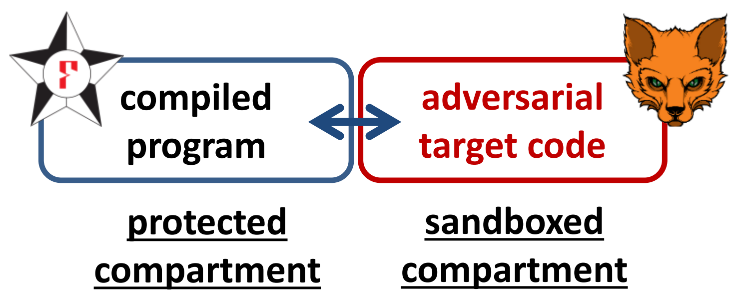

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  - **various enforcement mechanisms for sandboxing untrusted code**: software-fault isolation (SFI), capability machines, tagged architectures, ...
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- **This is very challenging:**
  - **the originally proposed formal criterion was fully abstract compilation** [Abadi, Protection in programming-language translations. 1999]

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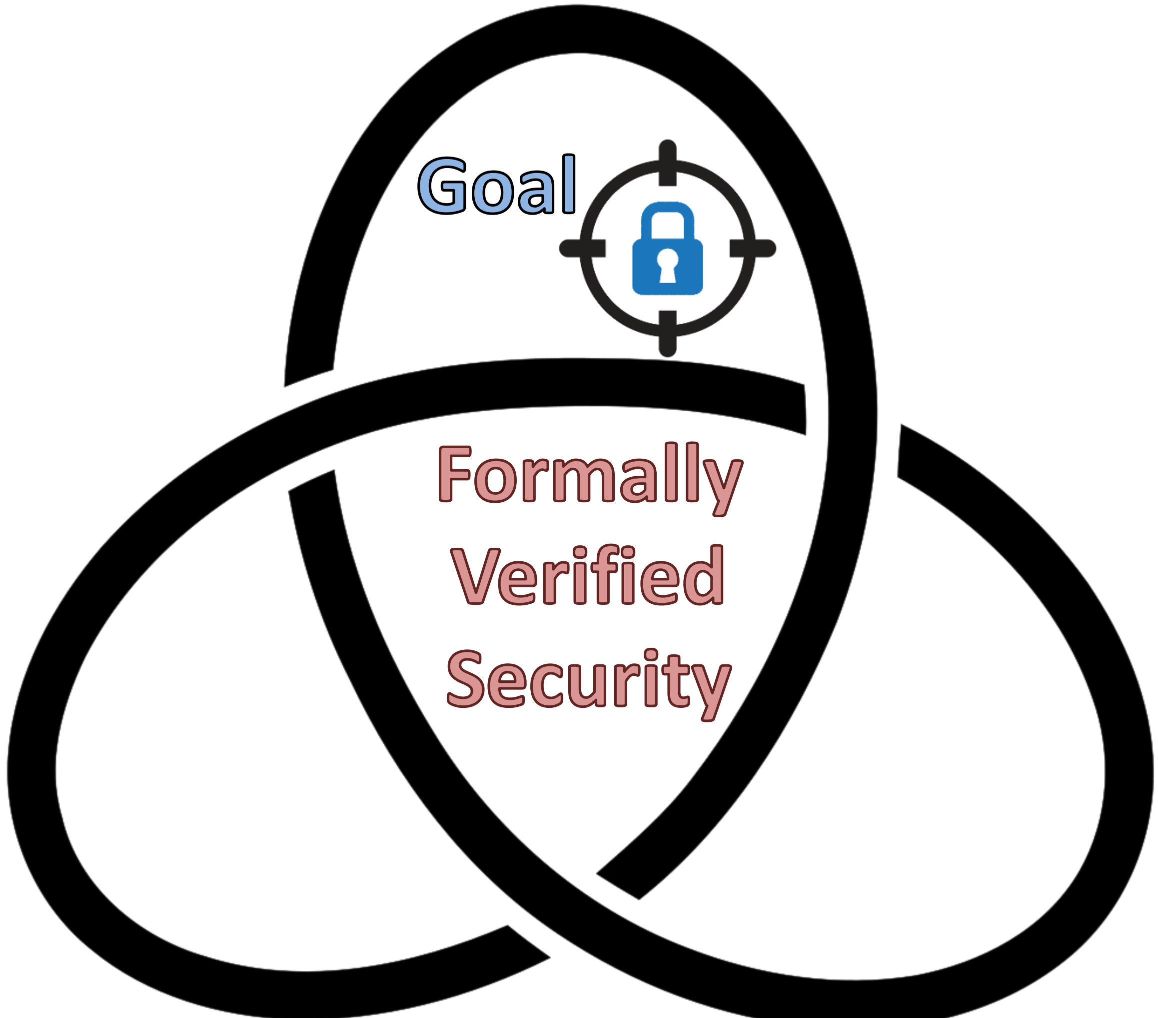
- **Secure compilation chain that protects these abstractions**
  - all the way down, at compartment boundaries (hopefully more efficient than removing UB)
  - against compartments dynamically compromised by undefined behavior
  - using the same kind of enforcement mechanisms for **compartmentalization**

Formally Verified Security


Goal
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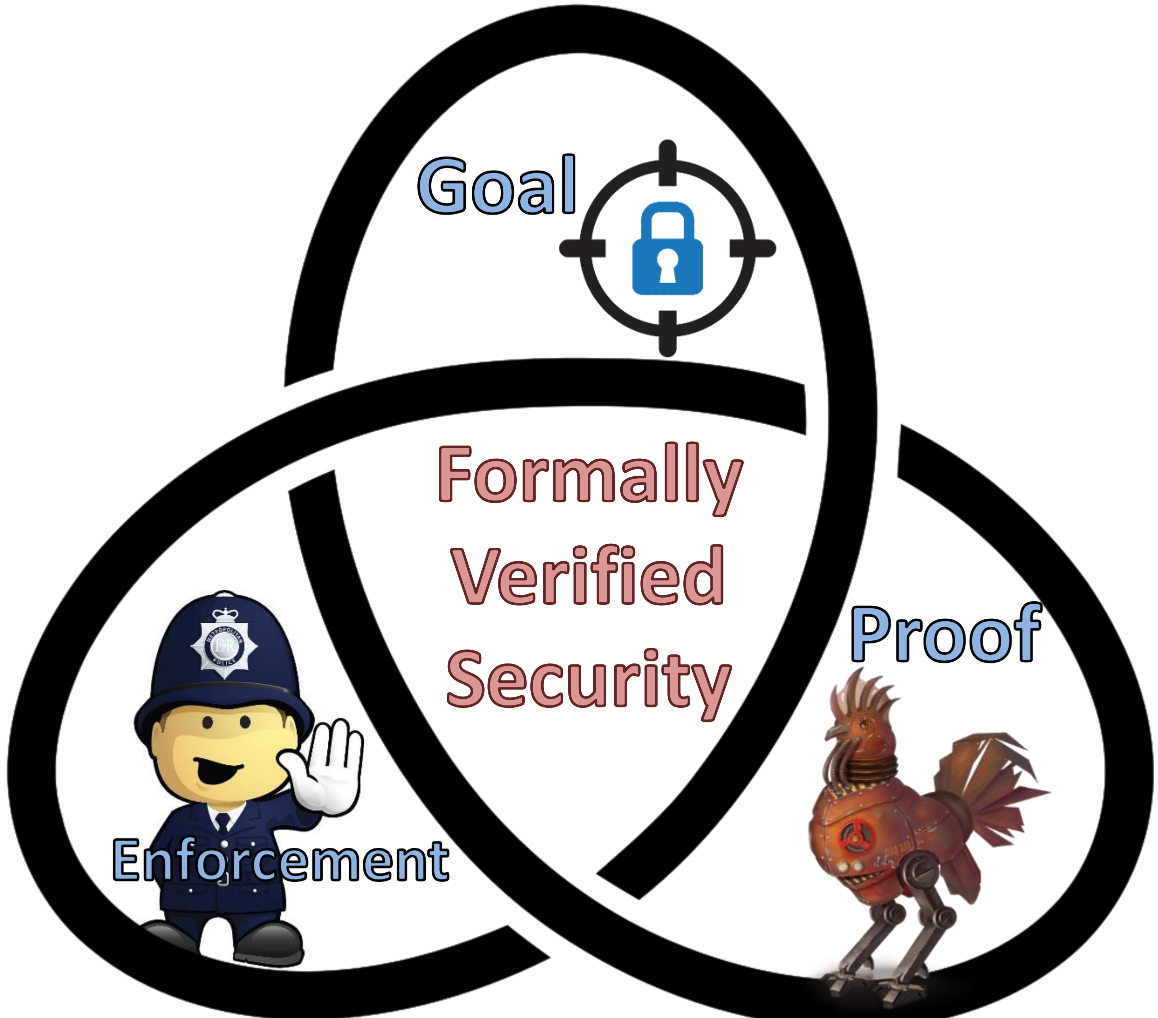
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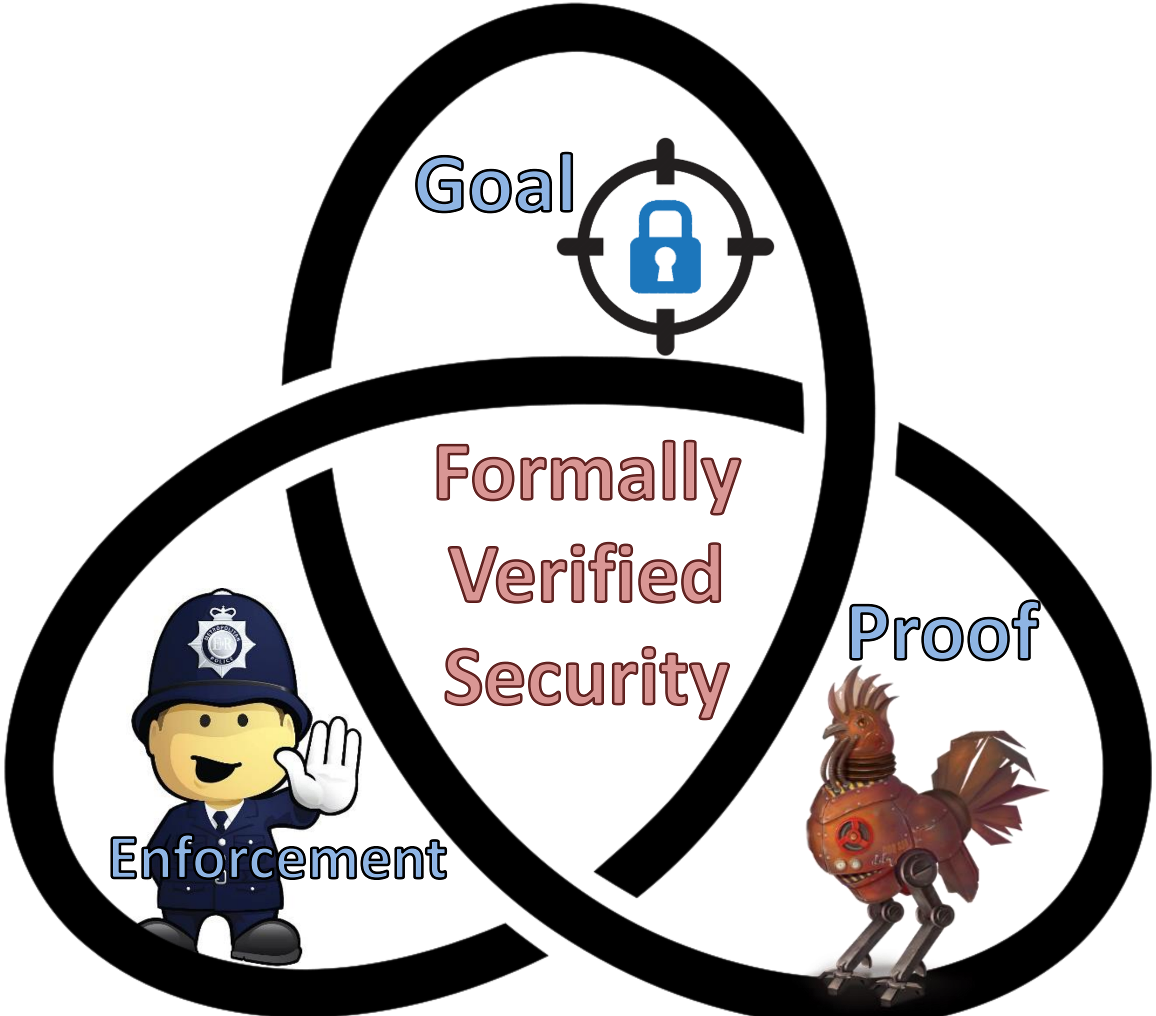

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  - **no "low-level" attacks introduced by compilation and linking**

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∀ F*code [source program ↔ F* code] satisfies π

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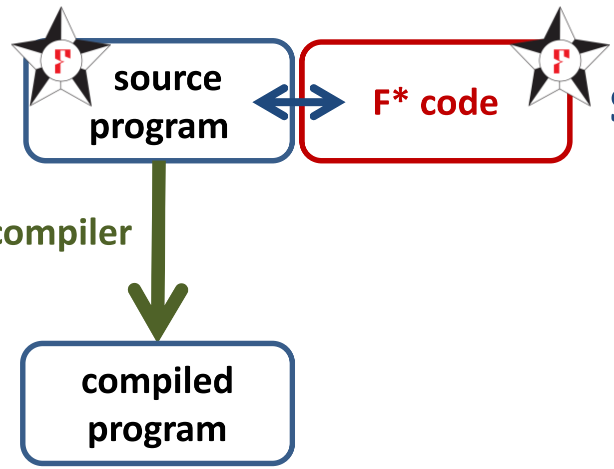

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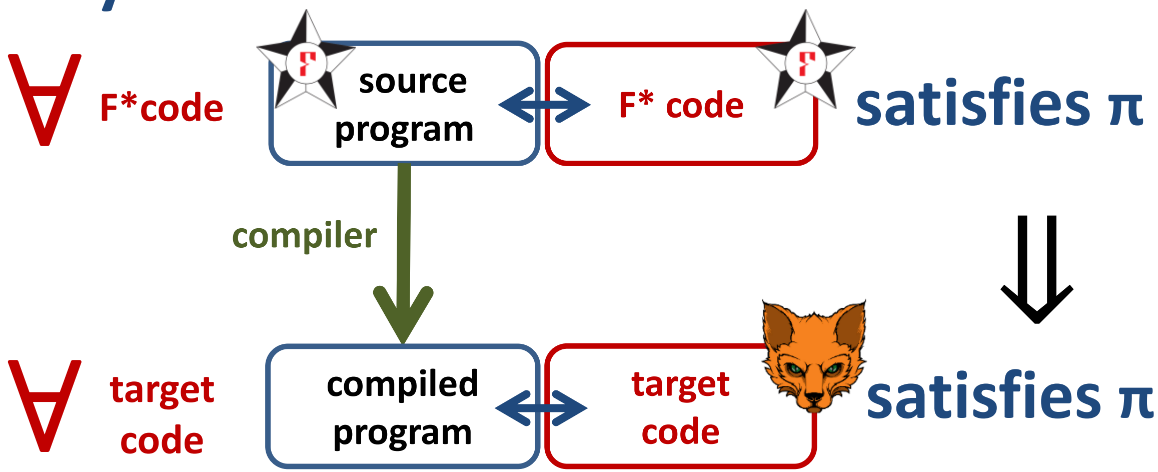

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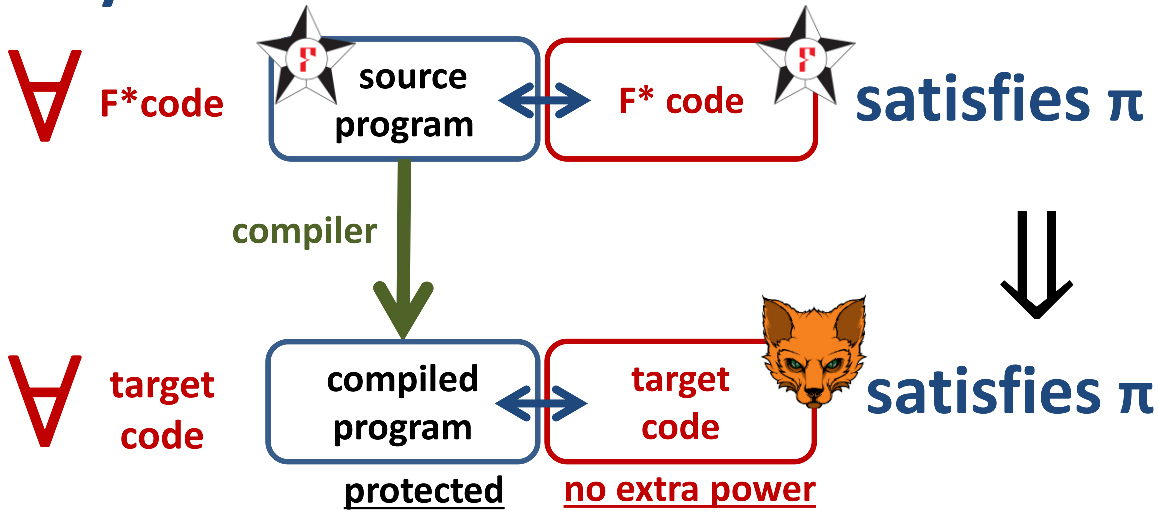

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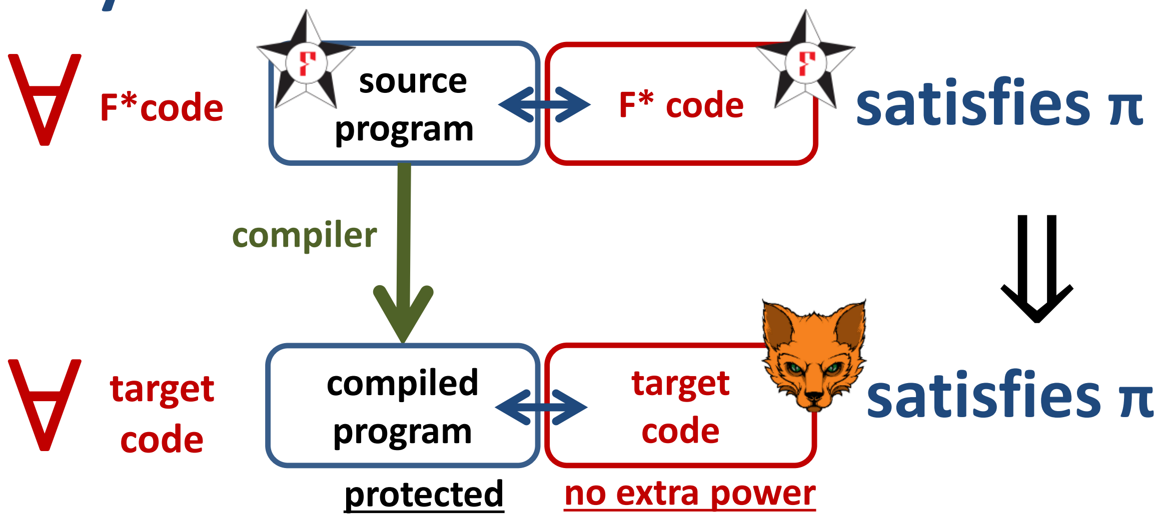

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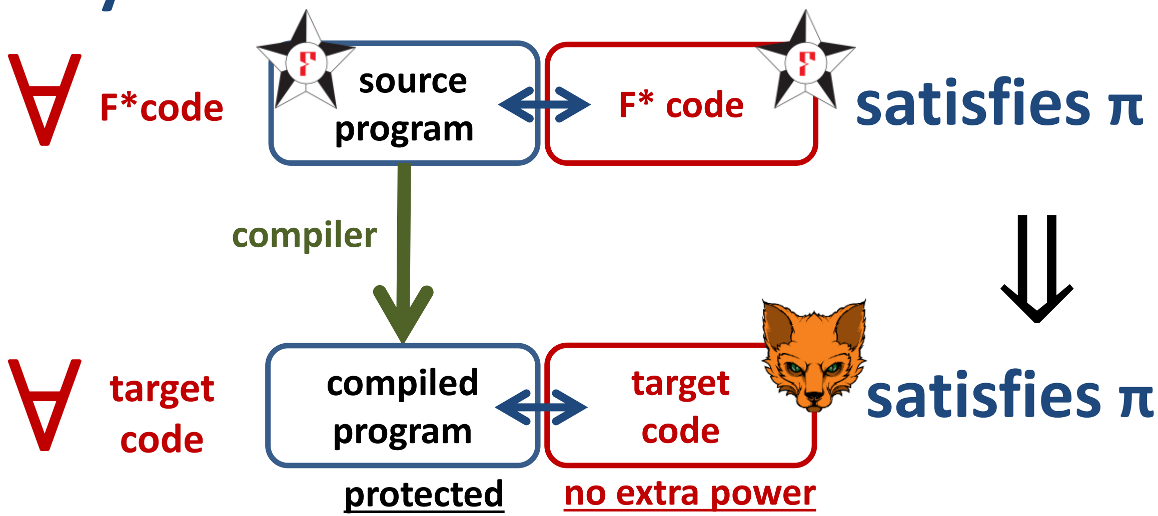

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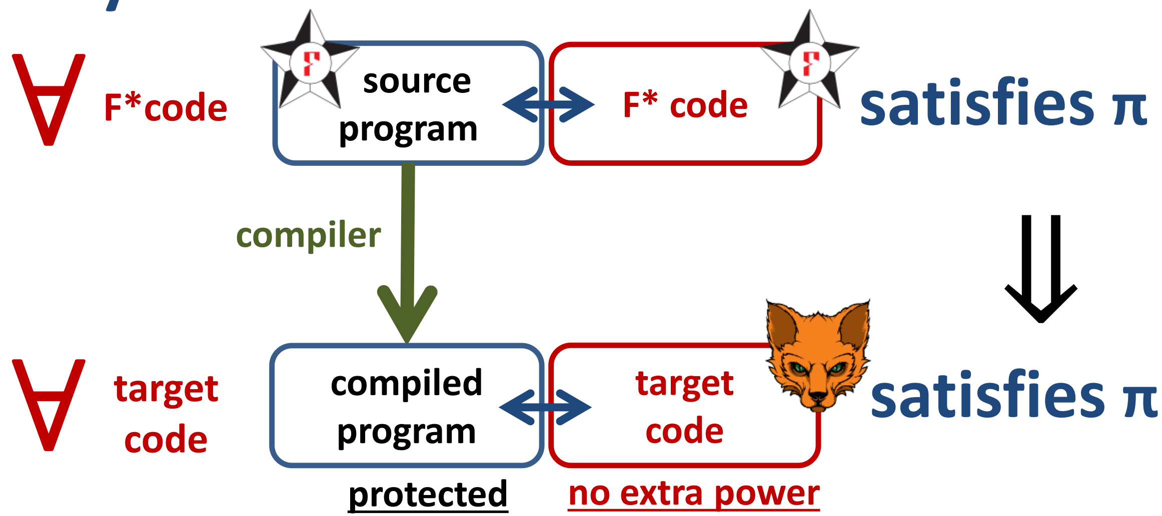

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We explored many classes of properties one can preserve this way ...

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

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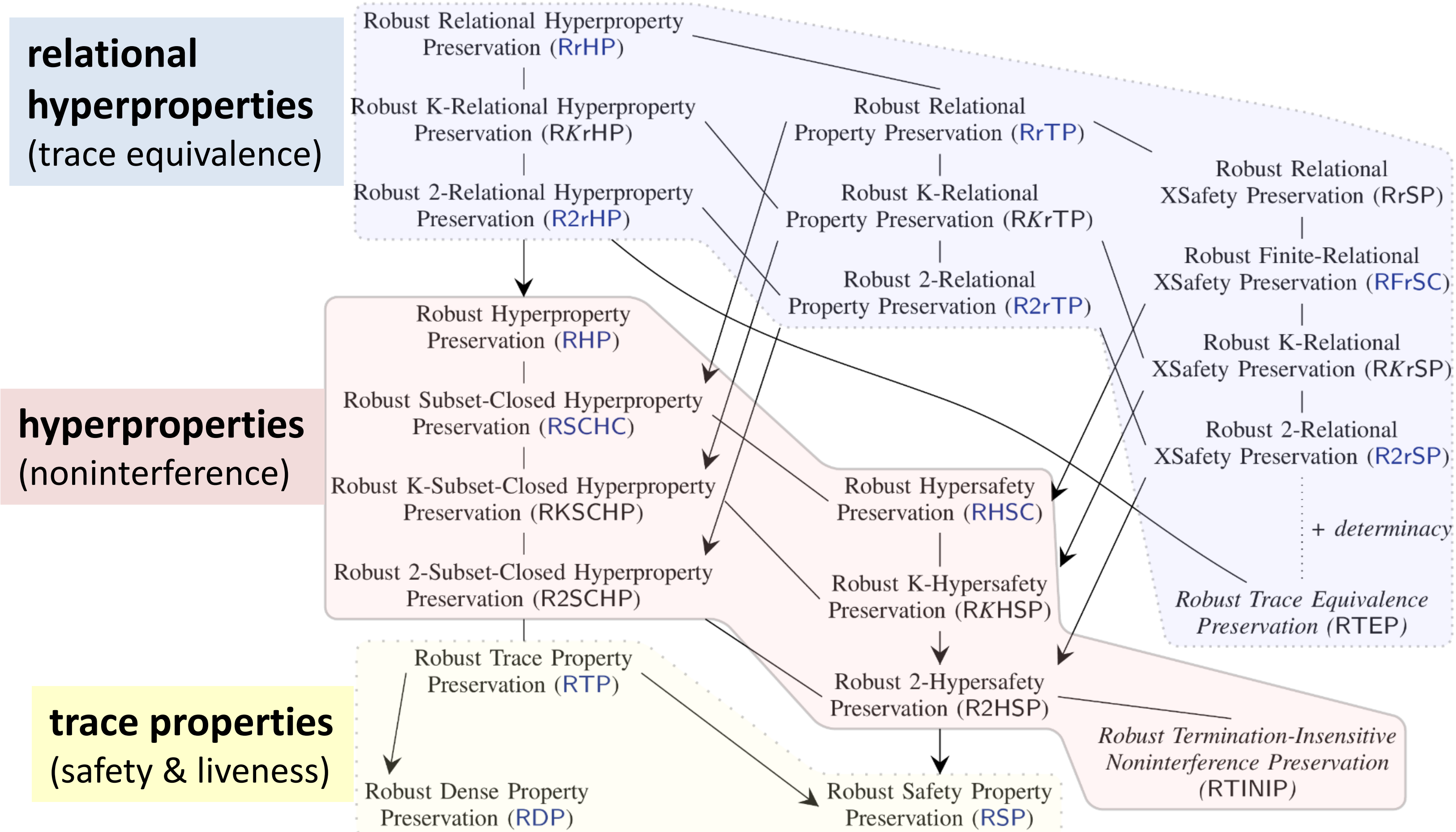

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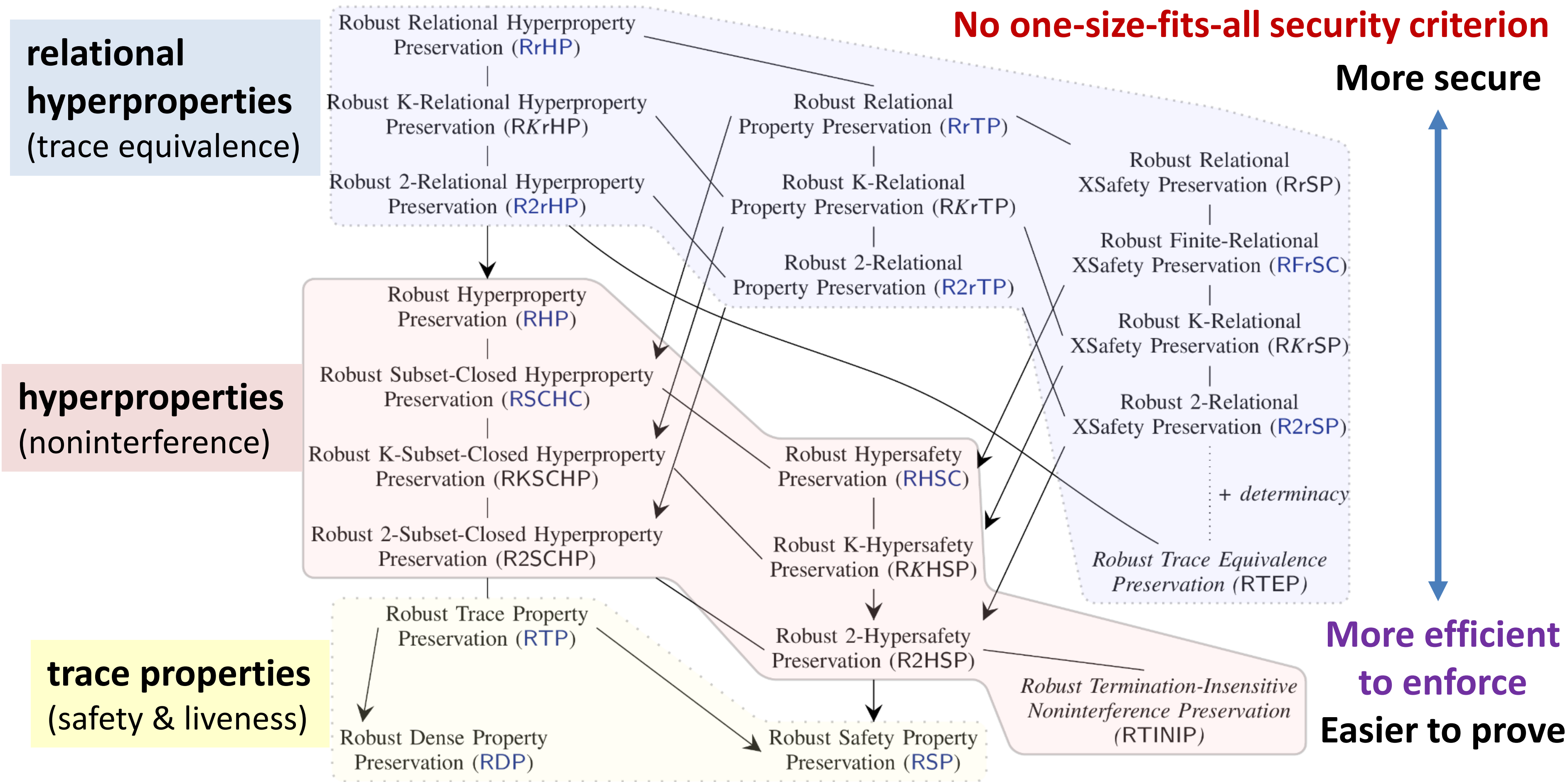

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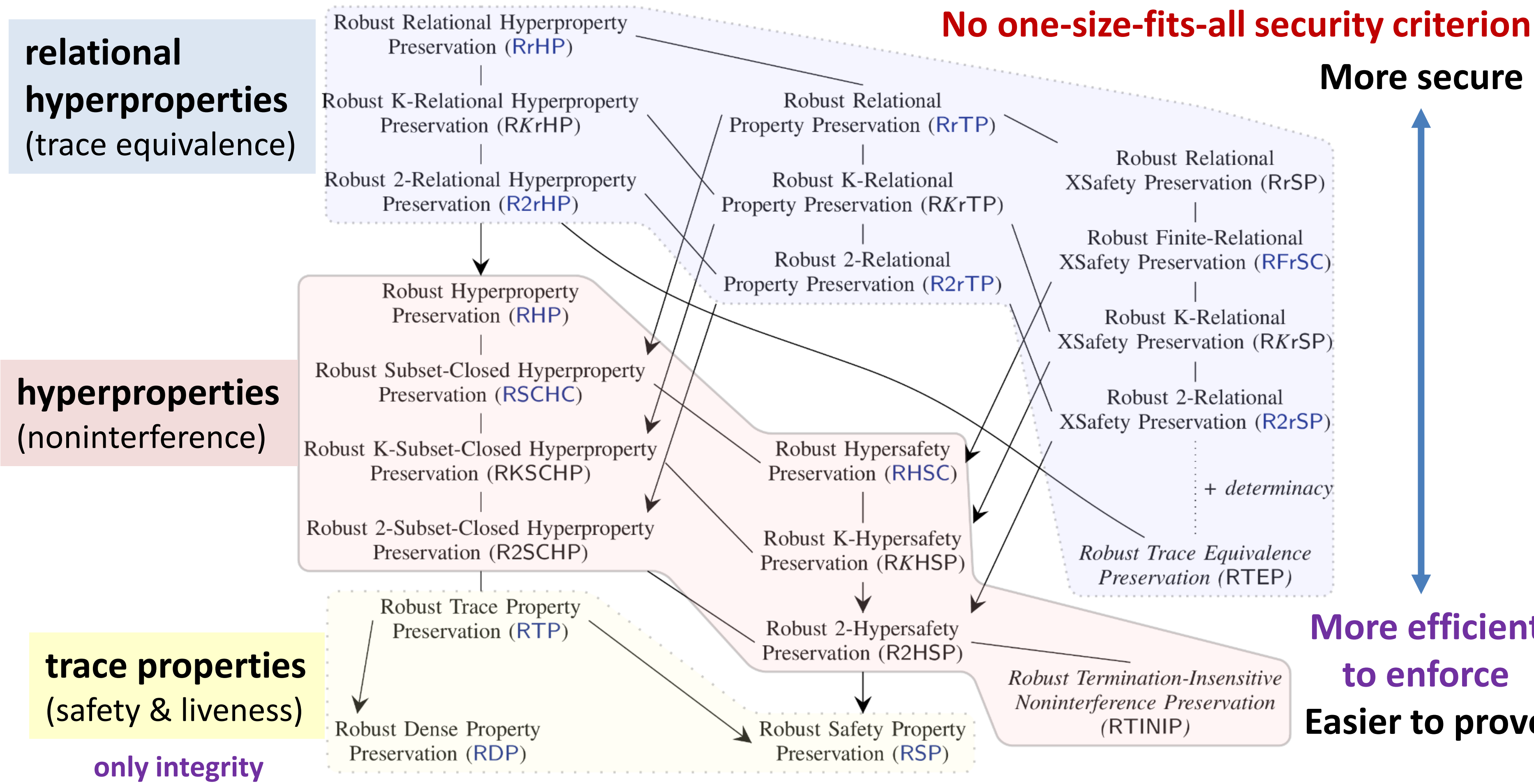

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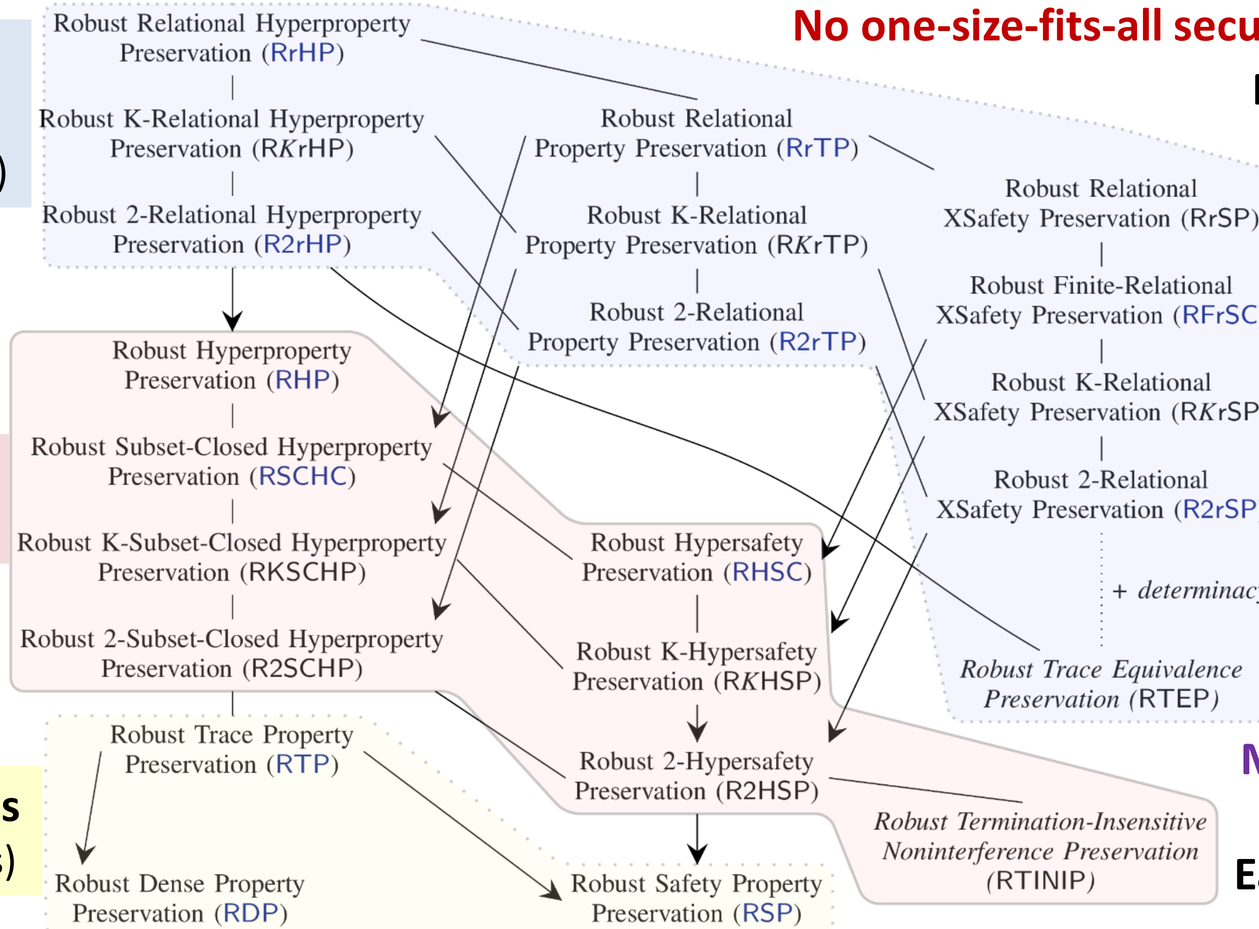

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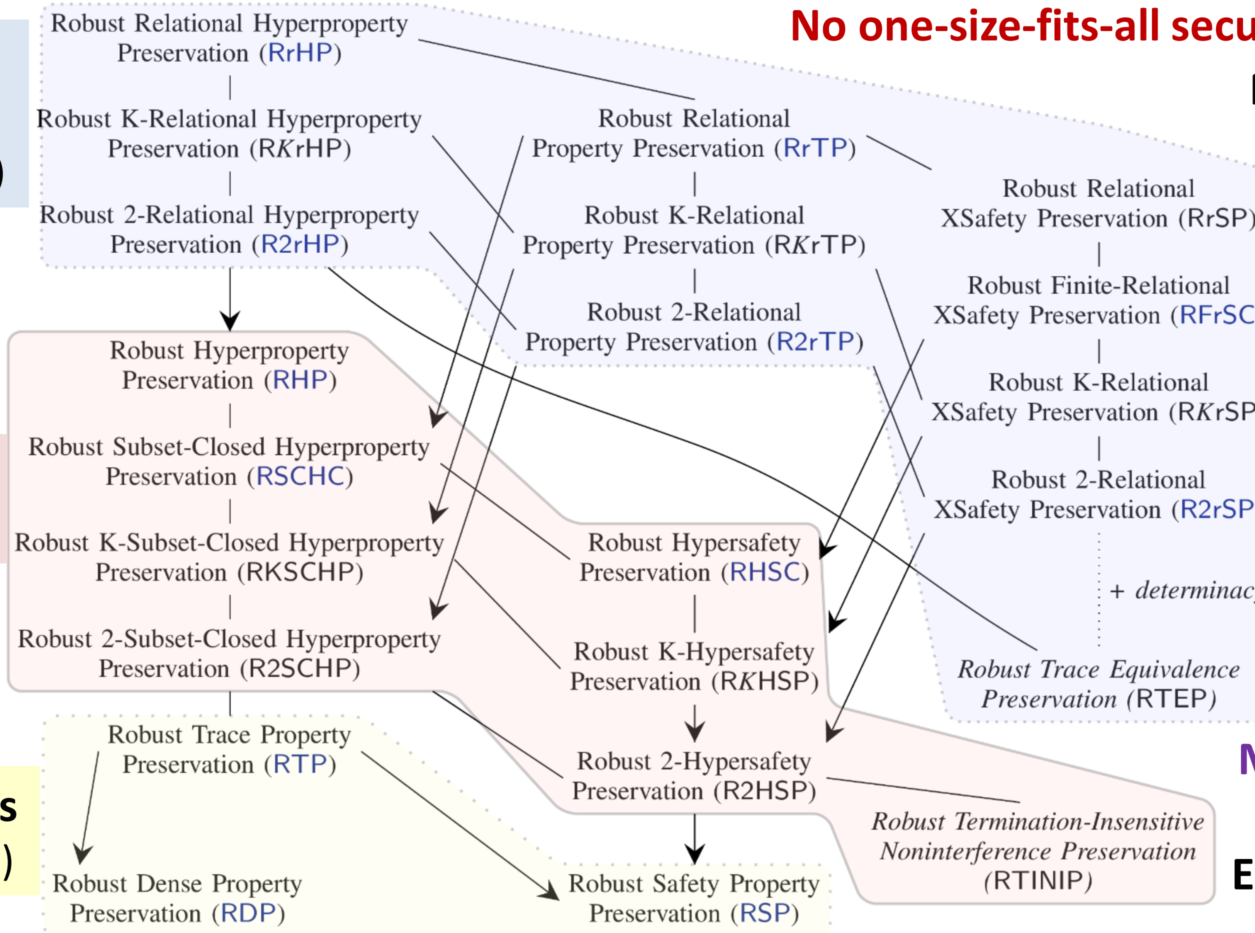

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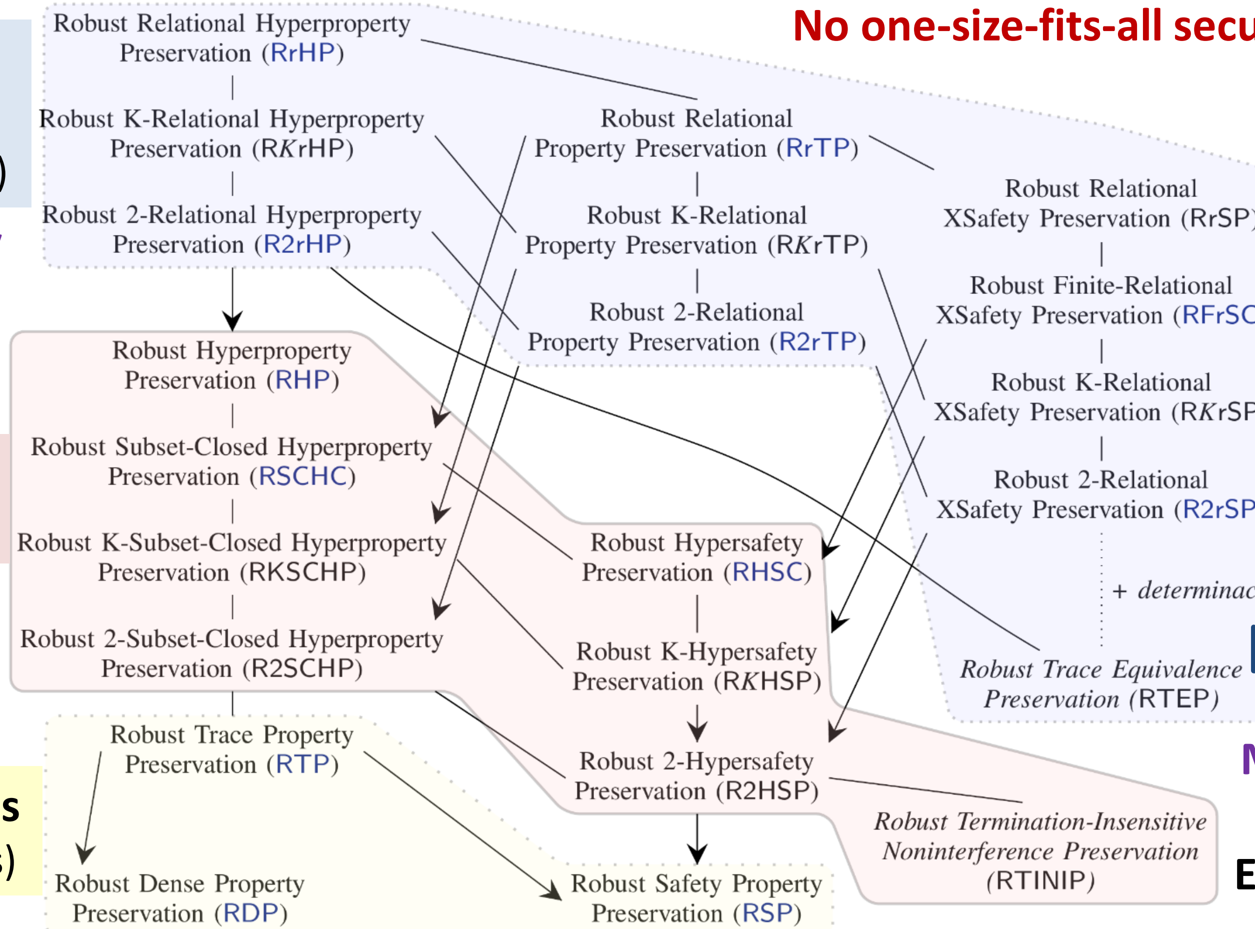

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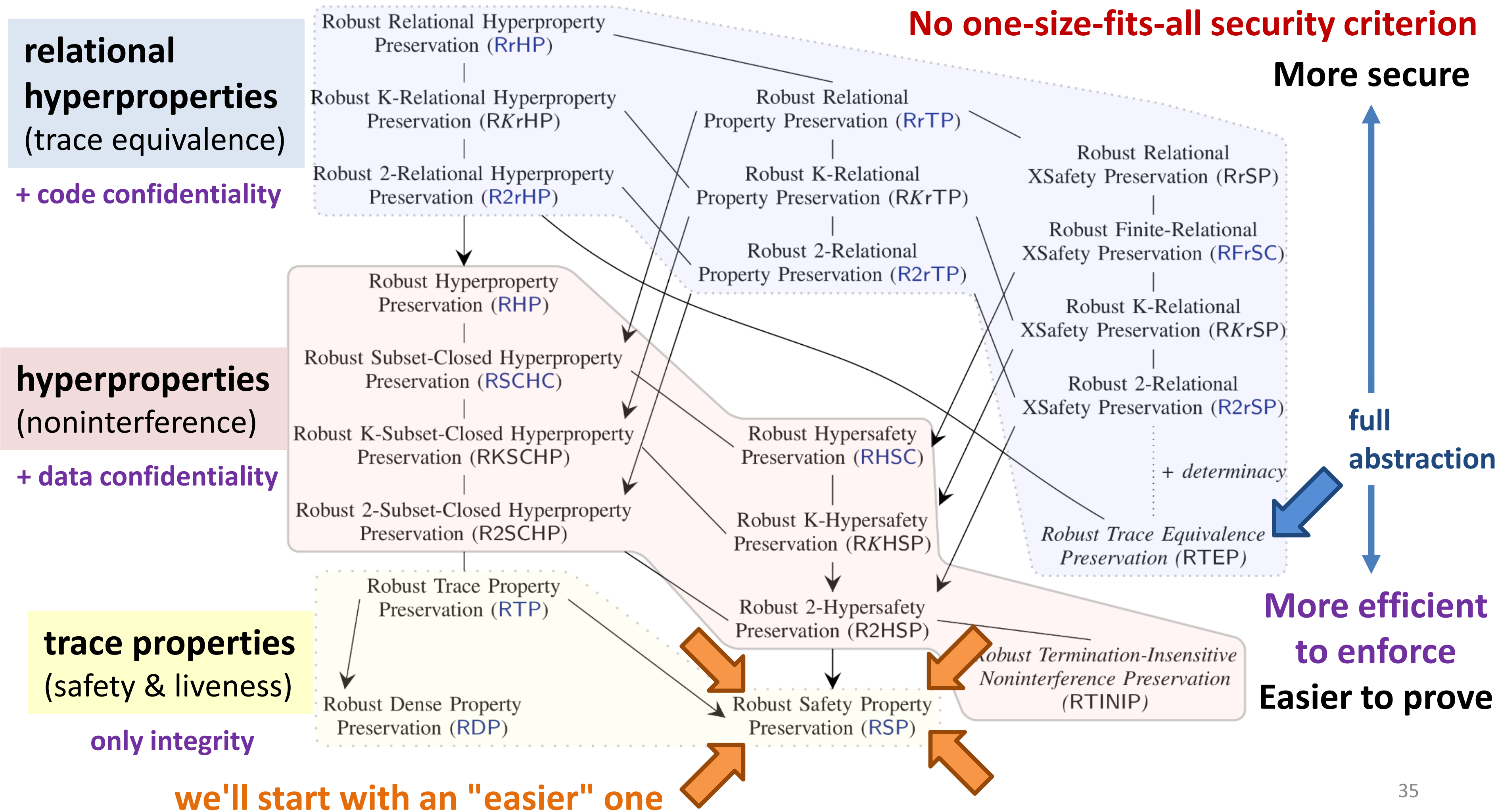

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⇓

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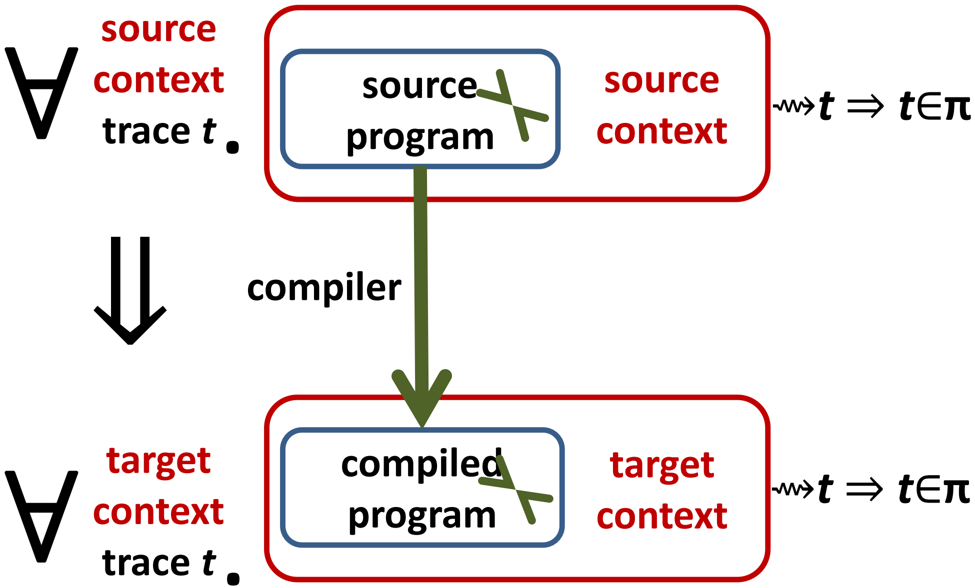

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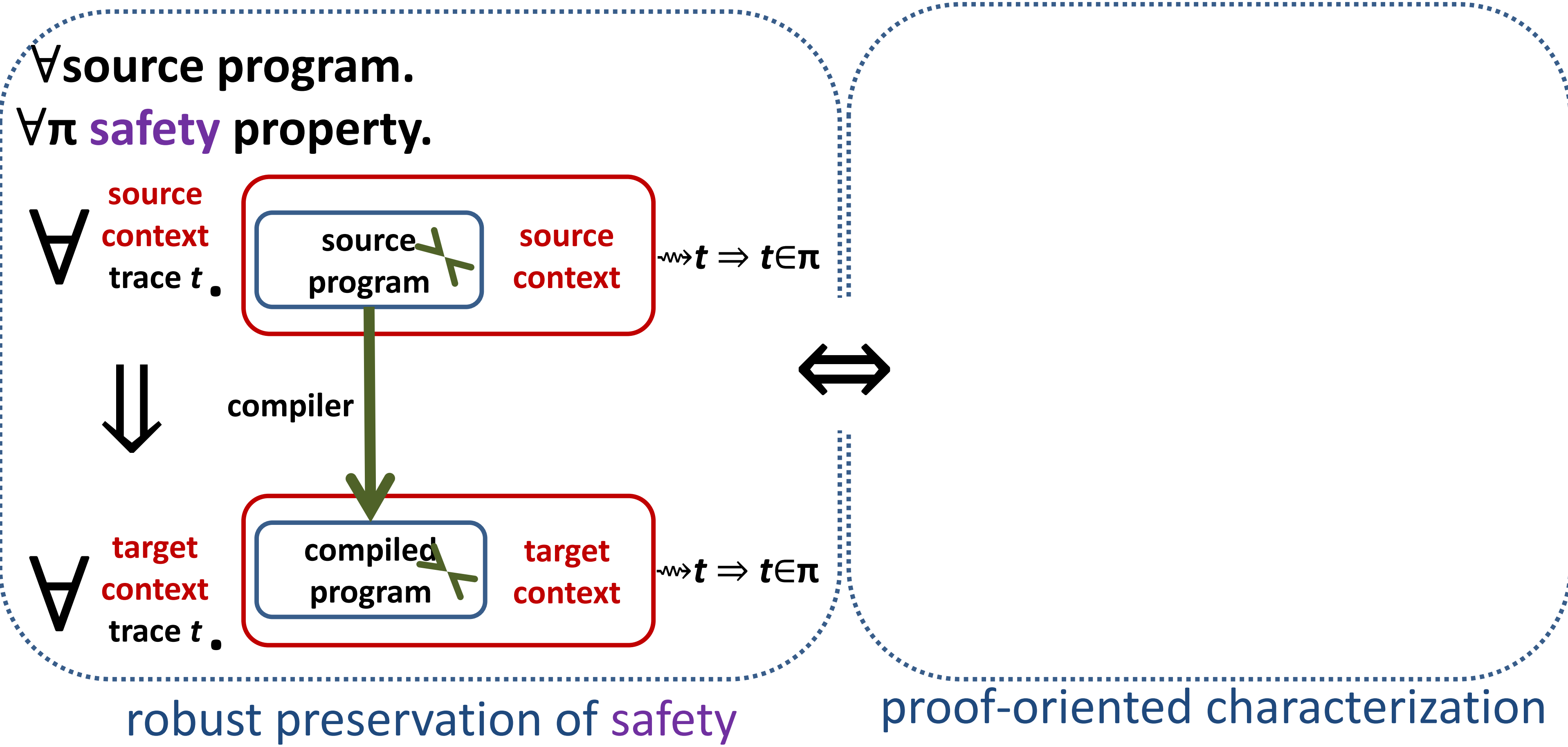

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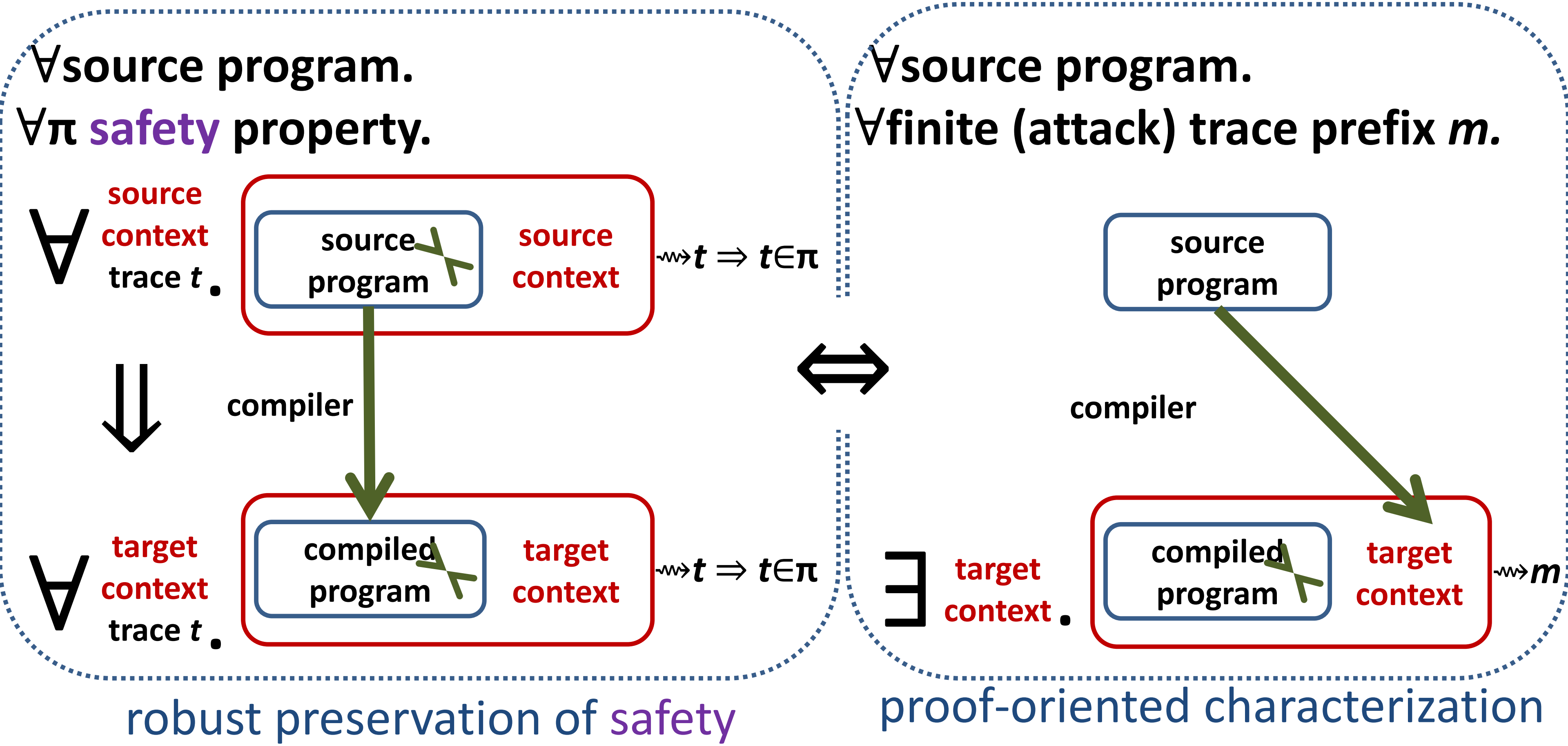

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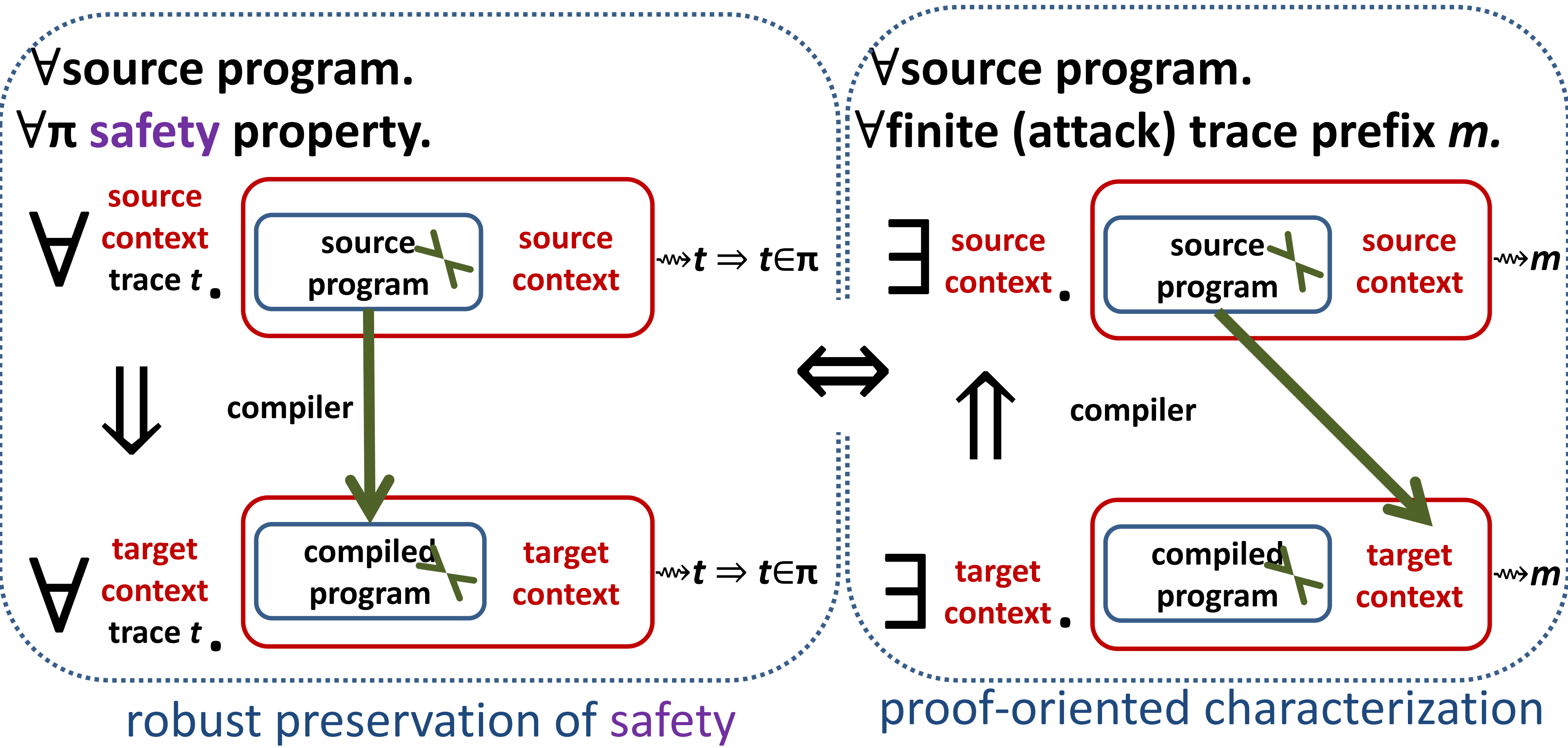

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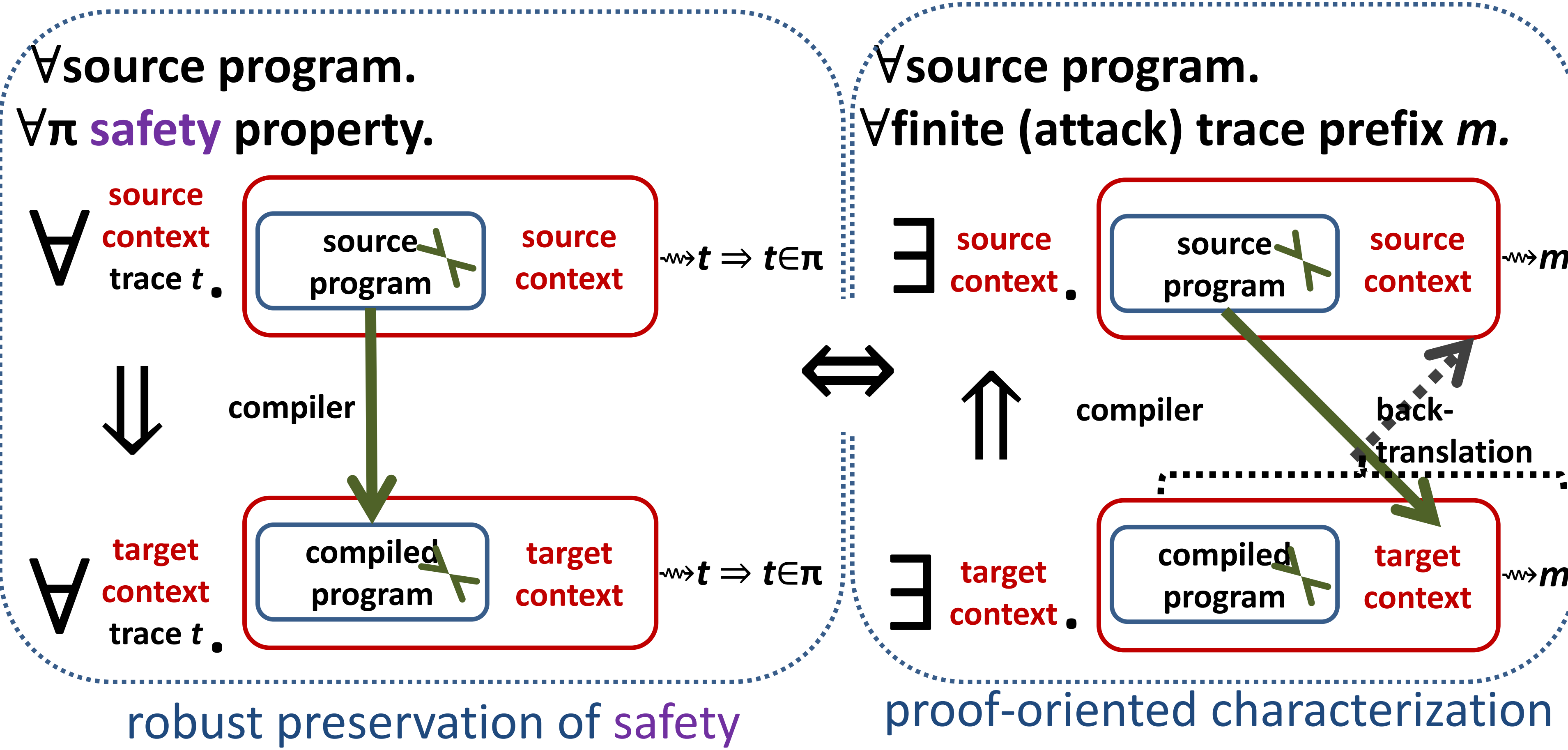

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- **Question B:**
  What does it mean for a compilation chain for <u>vulnerable</u> C compartments to be secure?

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  - **every compartment should receive protection until compromised**

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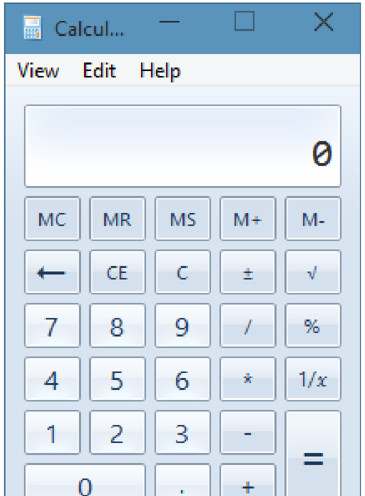

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Key idea: secure compartmentalization <u>restricts the scope</u> of undefined behavior:
(1) **spatially**, to only the compartment encountering it
(2) **temporally**, only give up on a compartment once compromised

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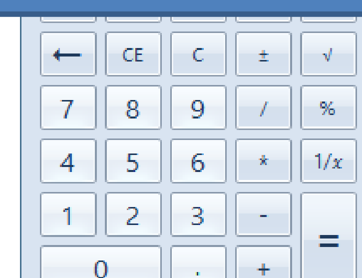
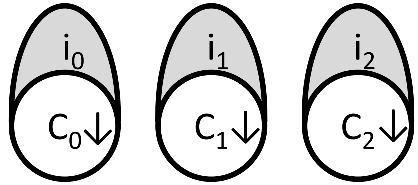


Security definition: If 

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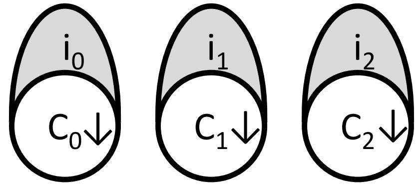
Security definition: If 

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

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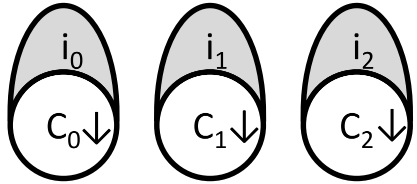

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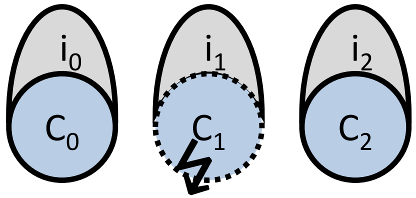

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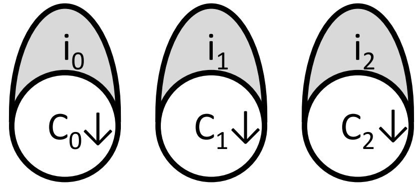
Security definition: If 

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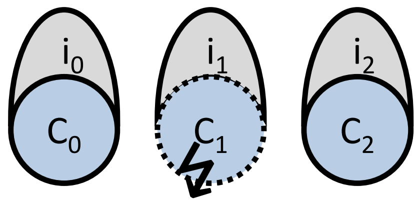
(1) 

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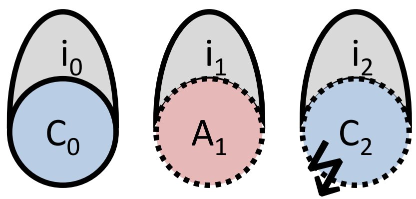
(2) $\exists A_1.$ 

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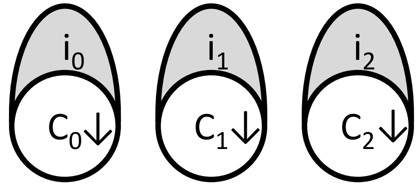
Security definition: If 

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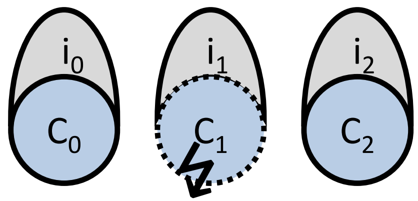
(1) 

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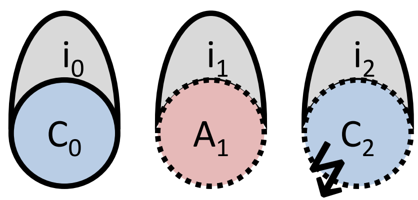
(2) $\exists A_1$. 

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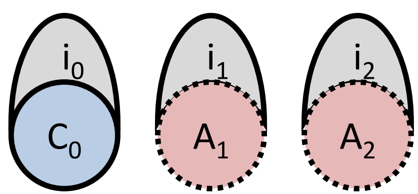
(3) $\exists A_2$. 

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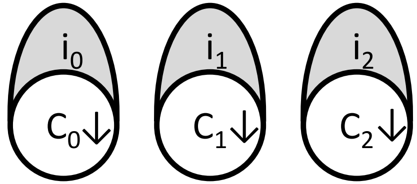
Security definition: If 

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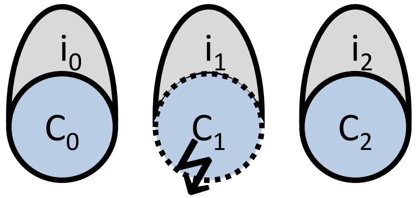
(1) 

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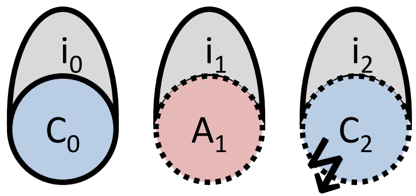
(2) $\exists A_1.$ 

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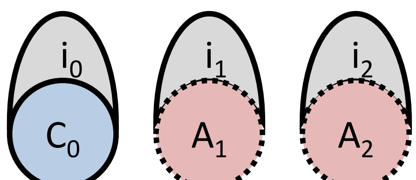
(3) $\exists A_2.$ 

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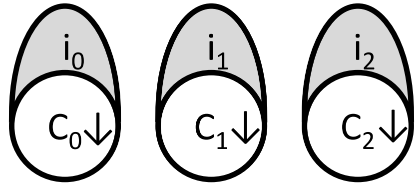

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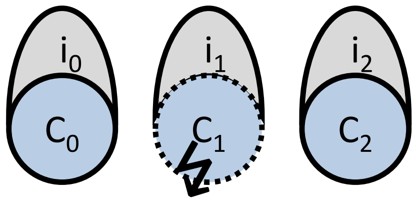

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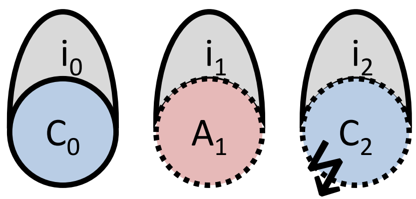

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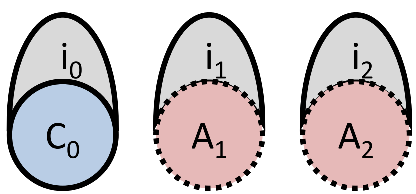

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We can reduce this to a **variant of robust safety preservation** [CCS'18]

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**

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Micro-Policies: ASM with programmable tags

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

Hardware-accelerated enforcement

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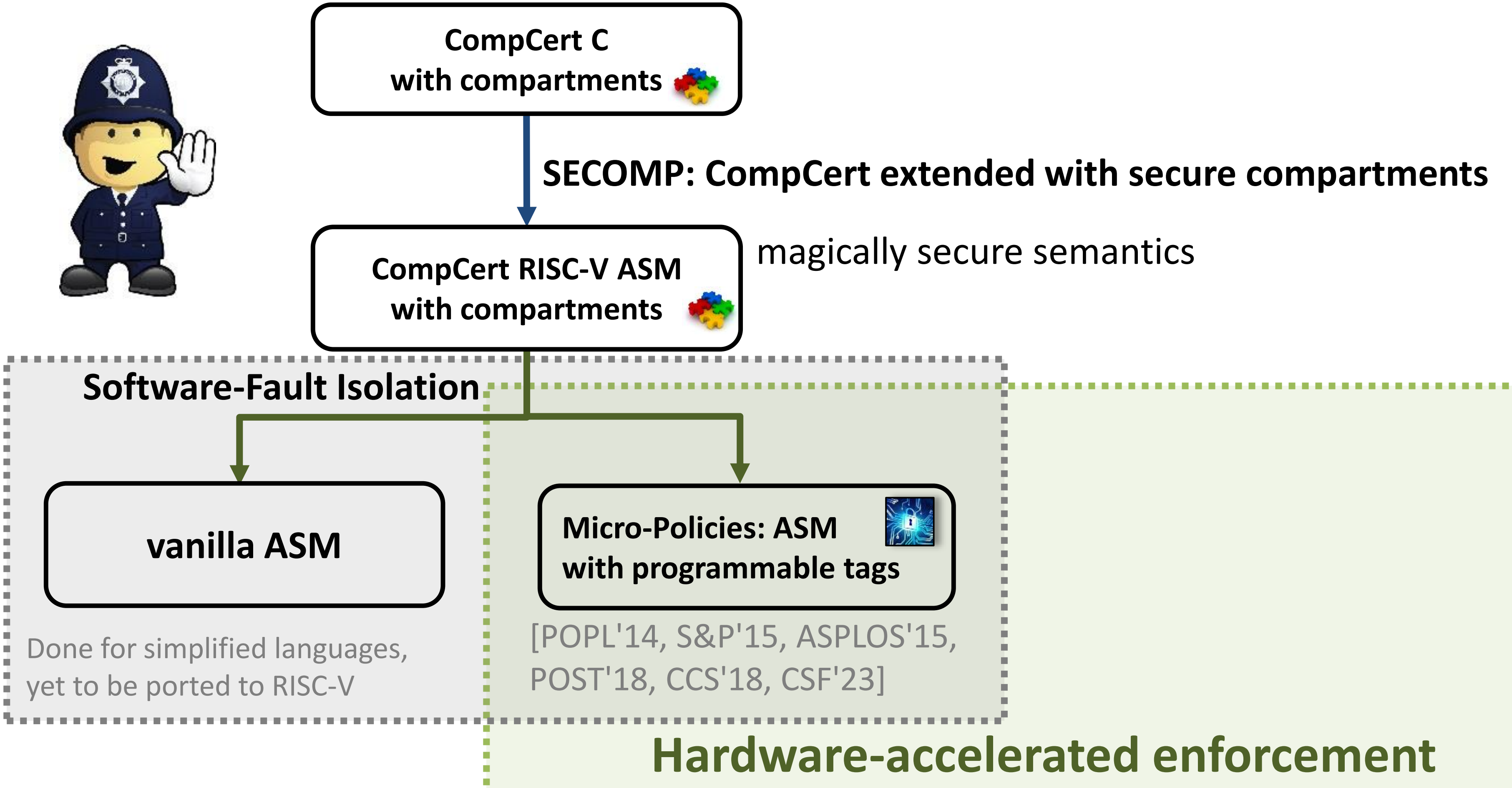

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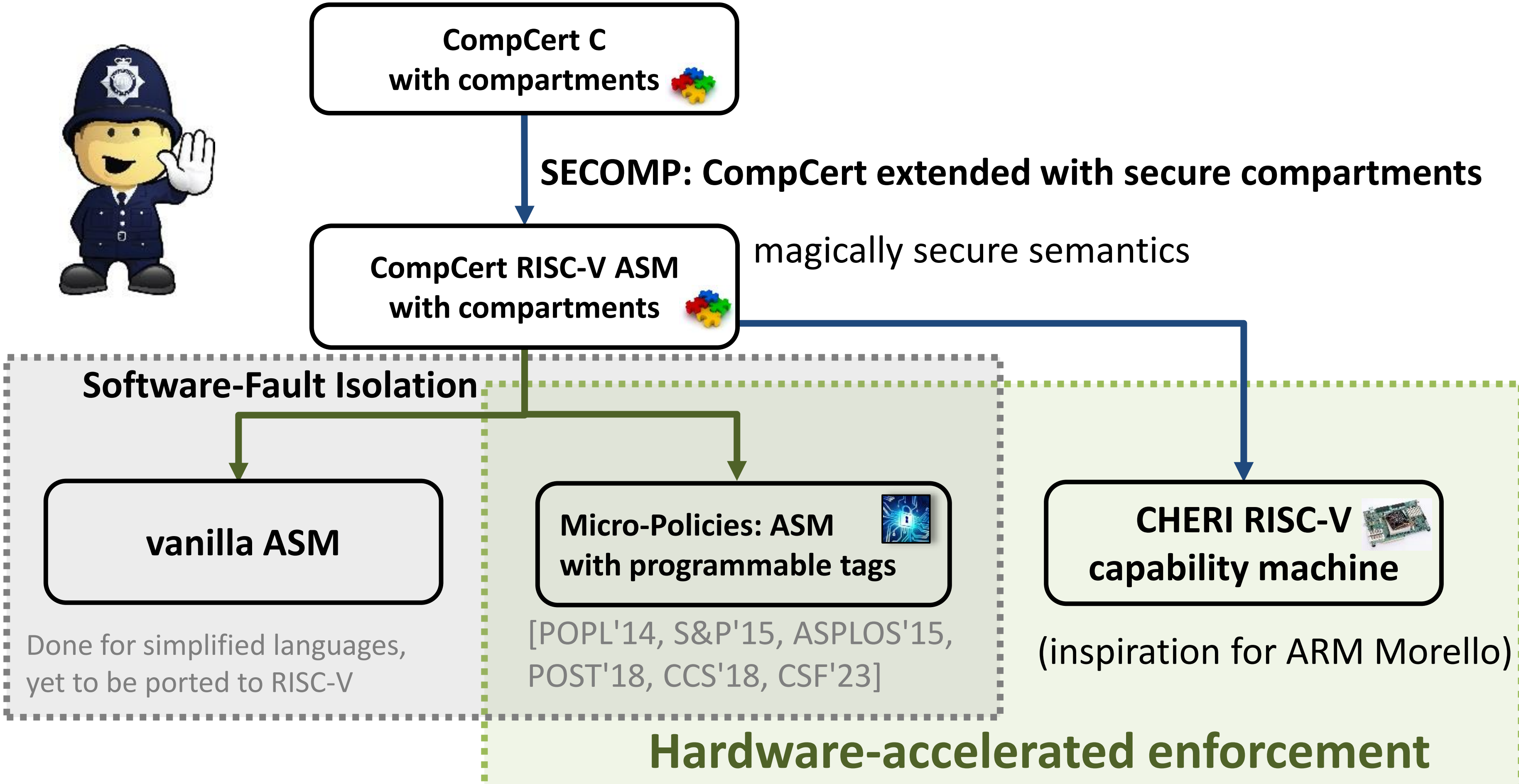

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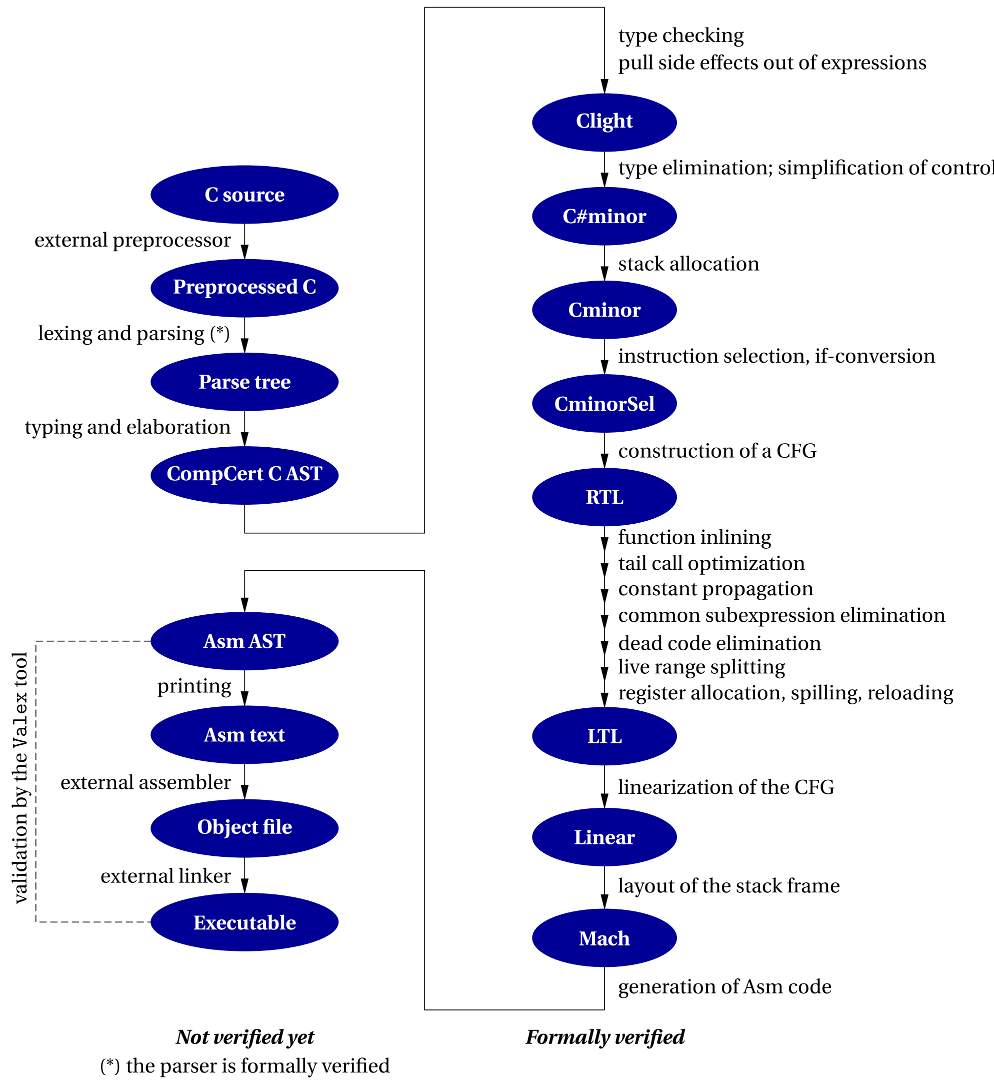

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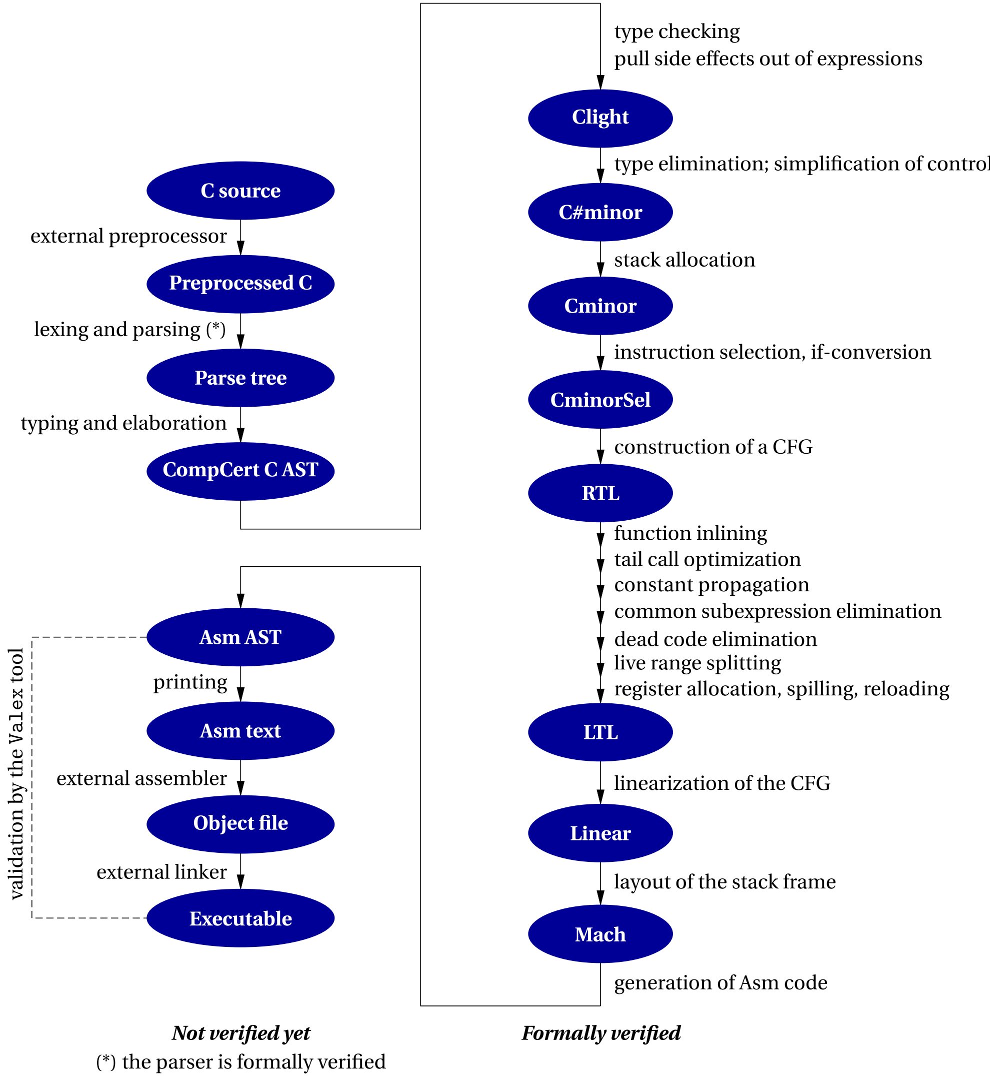

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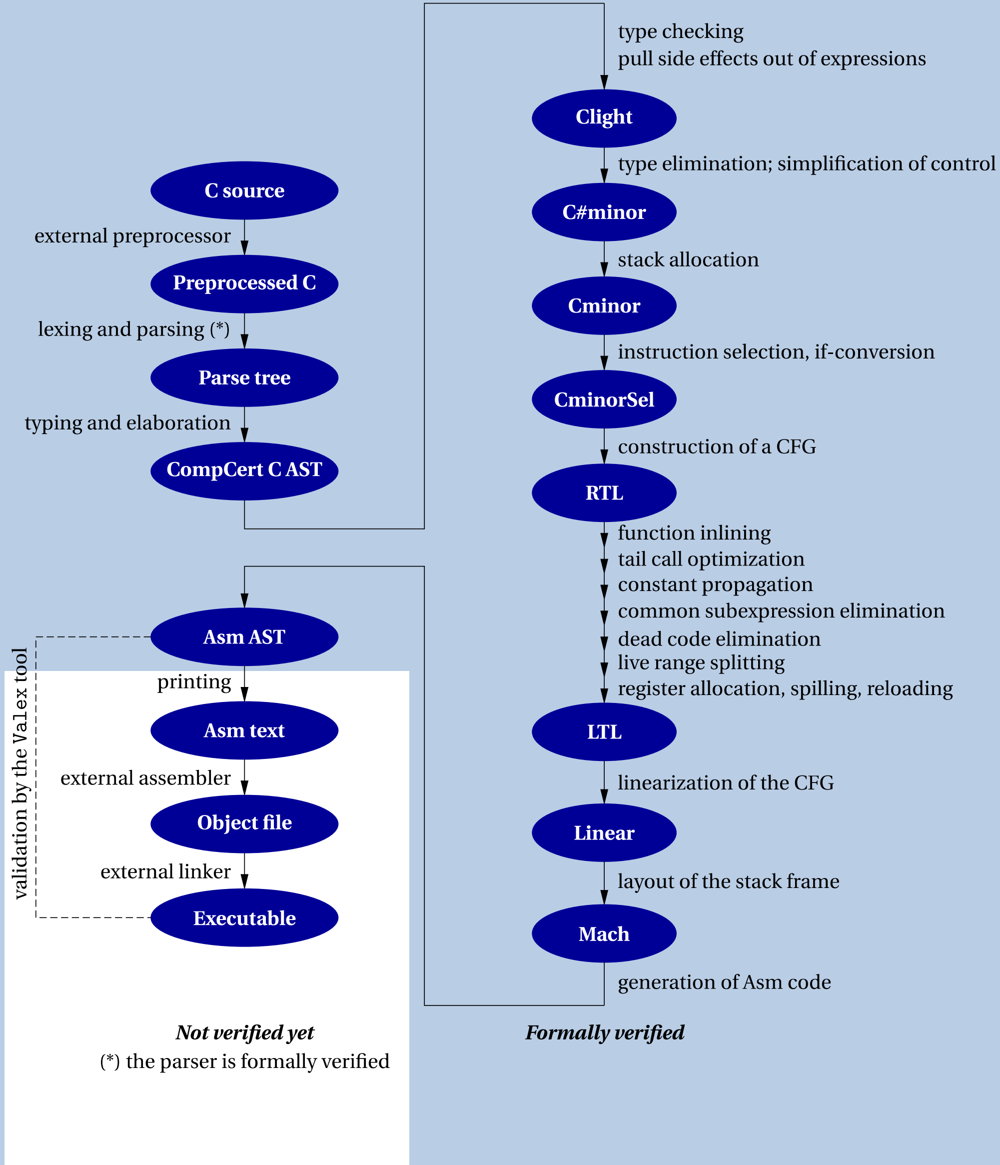

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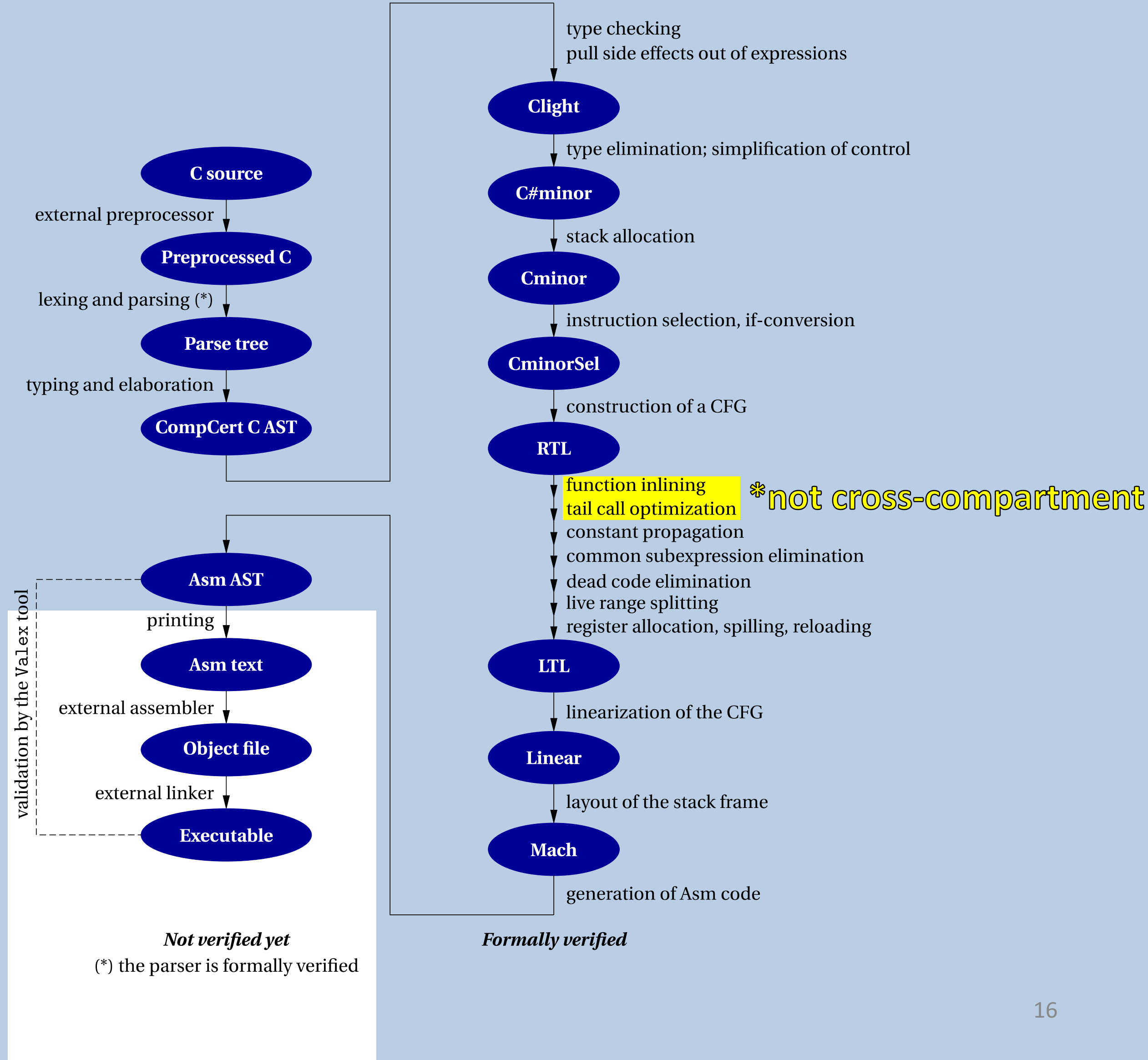

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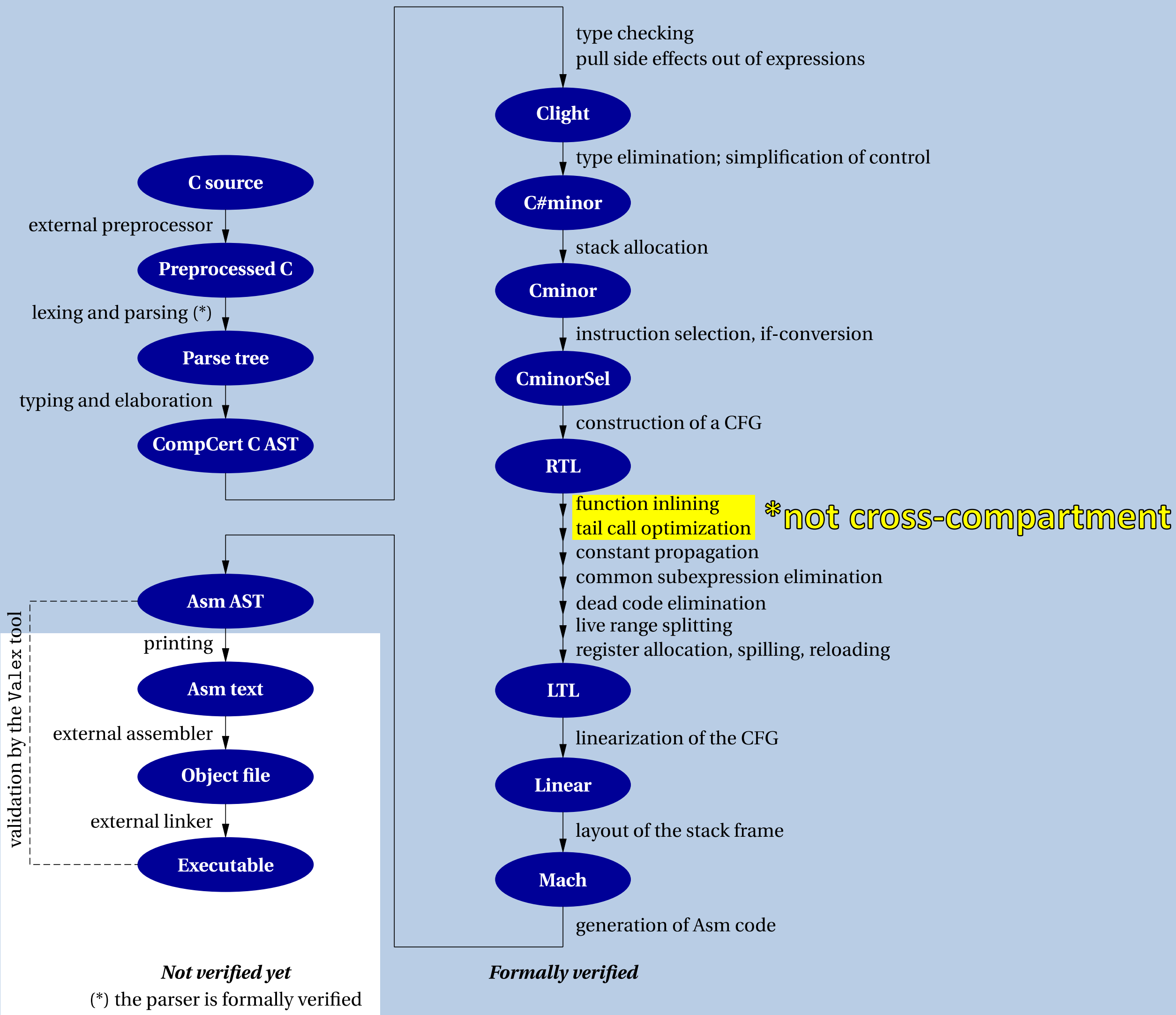

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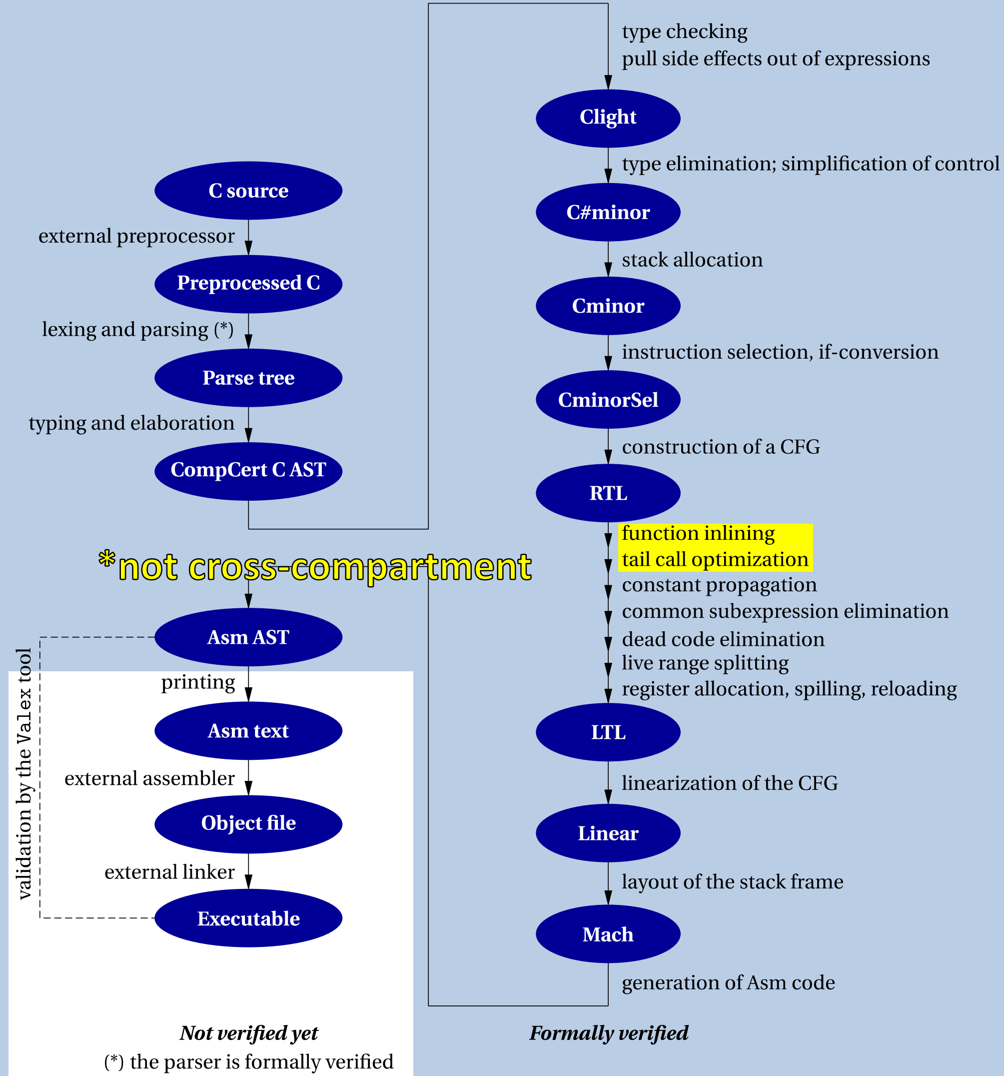
extended compiler correctness
18K LoC, only 13.6% change,
reused for security



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- Mutual distrustful compartments: **capability-protected wrappers**
  – on calls and returns clear registers and prevent passing capabilities between compartments

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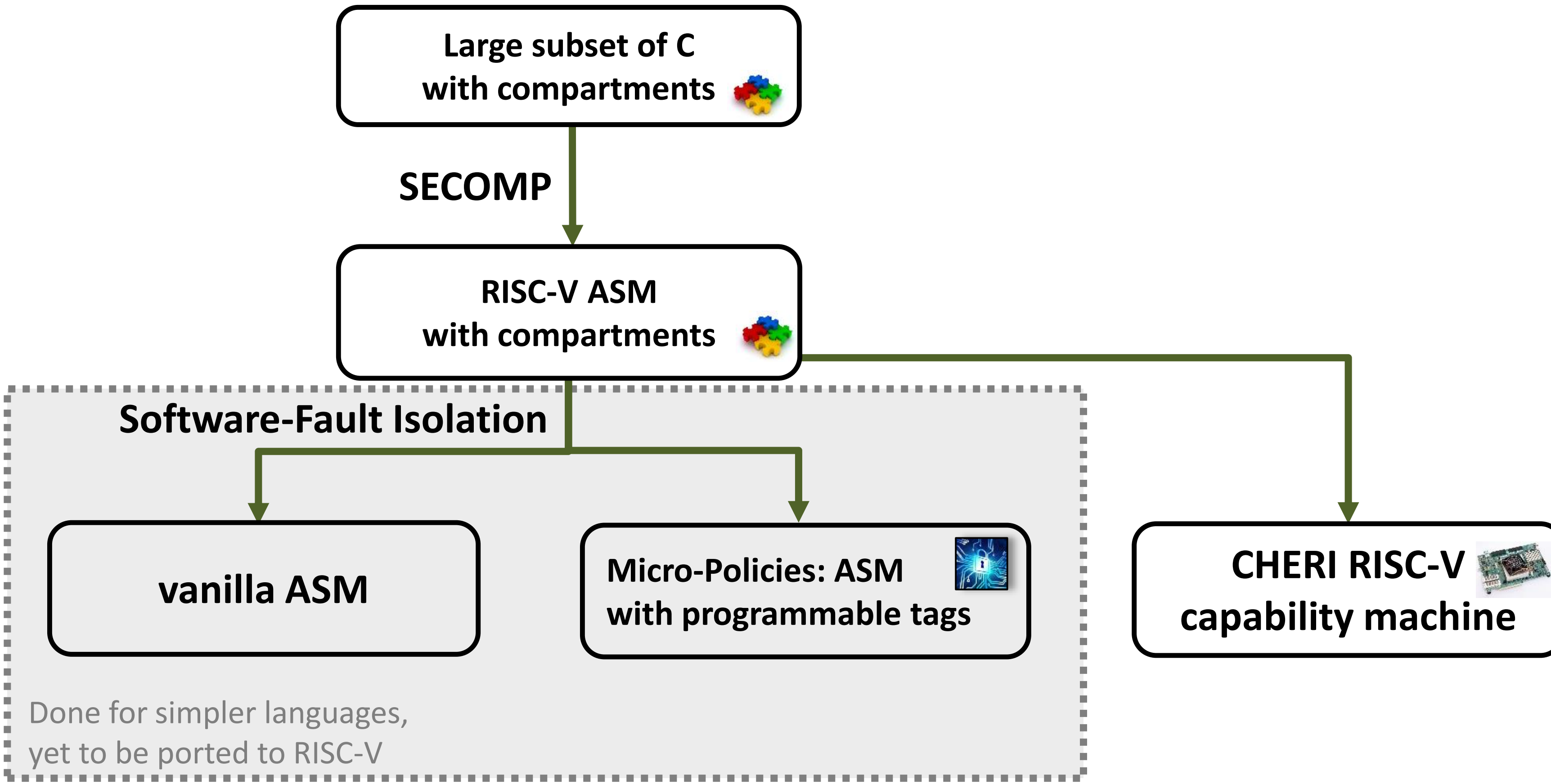
- we do **machine-checked proofs** in the Coq proof assistant
- as stopgap we use **property-based testing** [POPL'17, ICFP'13, ITP'15, JFP'16]
    - to find wrong conjectures early
    - to deal with the parts we couldn't (yet) verify

Secure Compilation Proofs in Coq



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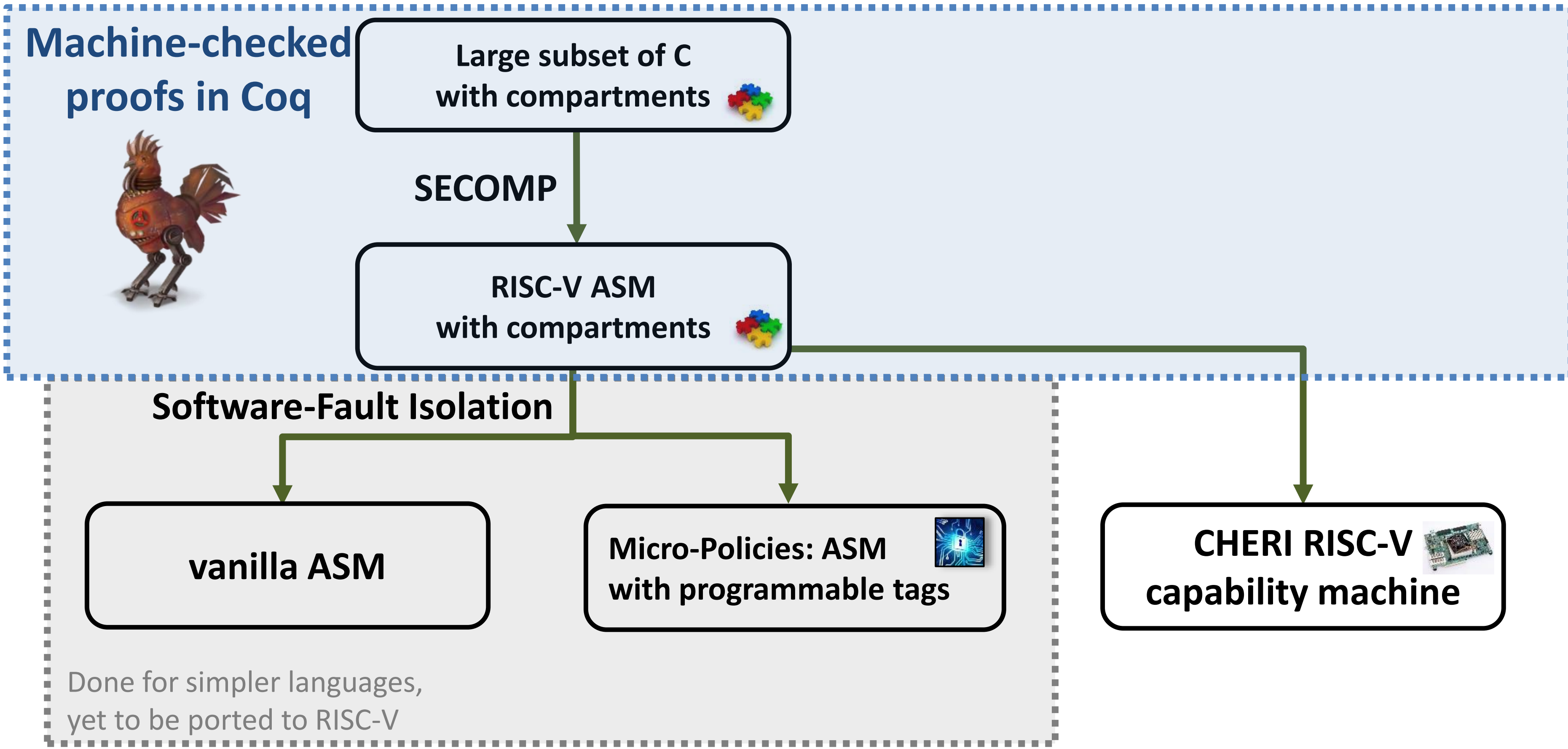

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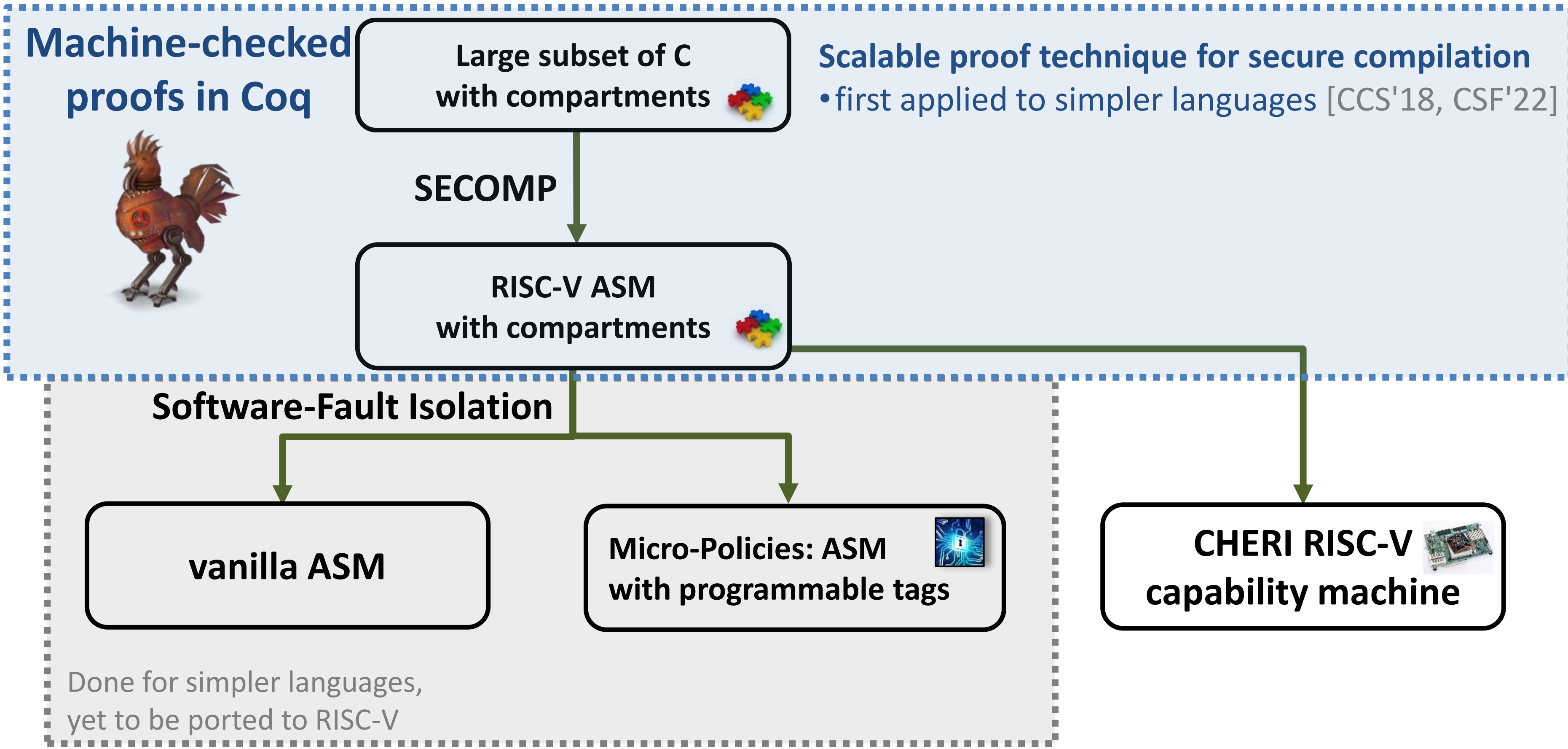

Secure Compilation Proofs in Coq

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]
  - reuses extended CompCert correctness proof (~130K LoC)
  - verified strong secure compilation property (+ ~43K 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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- **Verifying backends is challenging though**
  - e.g. 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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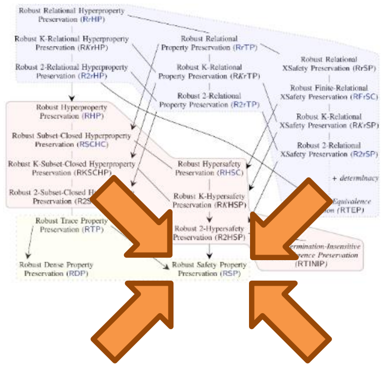

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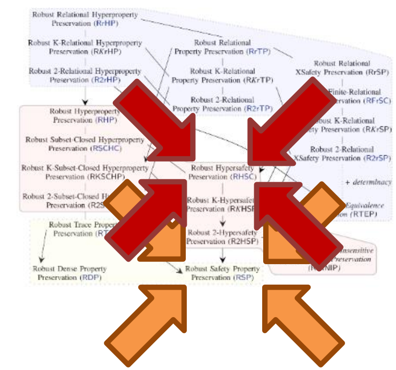

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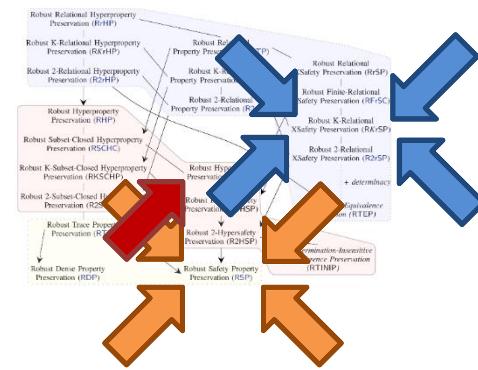

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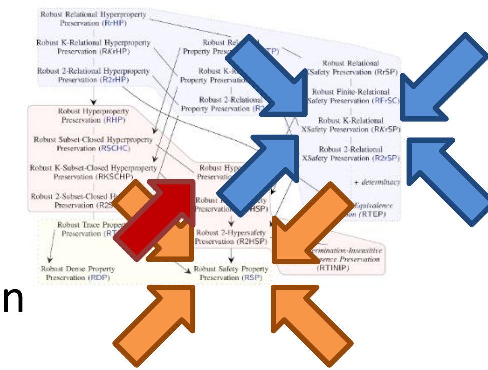

- **Beyond preserving safety against adversarial contexts**
  - towards preserving **hyperproperties** (data confidentiality)
  - even **relational hyperproperties** (observational equivalence)
    - secure compilation criteria strictly stronger than full abstraction
    - can do this for CompCert, but won't hold for backends

[Jérémy Thibault et al, CSF'19 + ongoing work first presented at PriSC'21]

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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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