The Quest for Formally Secure Compartmentalizing Compilation

Cătălin Hrițcu

Habilitation Defense

My research in the last 7 years

Secure Compilation

Program Verification

Tag-based Monitoring

Property-Based Testing

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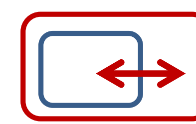

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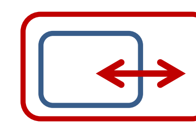

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Part 1: formalize what it means to solve this problem

Devastating low-level attacks

Part 2: give meaning to compartmentalization mitigation

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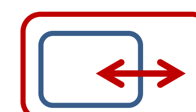

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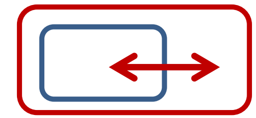
Part 1 of 2

Secure Interoperability with Lower-Level Code



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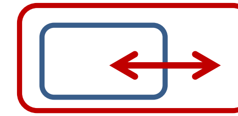

Carmine Abate
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Rob Blanco
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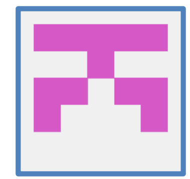
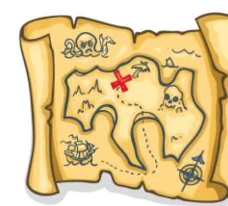


Jérémy Thibault
Inria Paris

Marco Patrignani
Stanford & CISPA

Journey Beyond Full Abstraction

https://arxiv.org/abs/1807.04603



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  - **coding patterns specific to cryptographic code**
    - abstract types and interfaces for defending against side-channel attacks

Recherche

20/09/2017

EPI Prosecco: high assurance cryptography for Mozilla Firefox

Mozilla Firefox

Mozilla Security Blog

SEP 13 2017

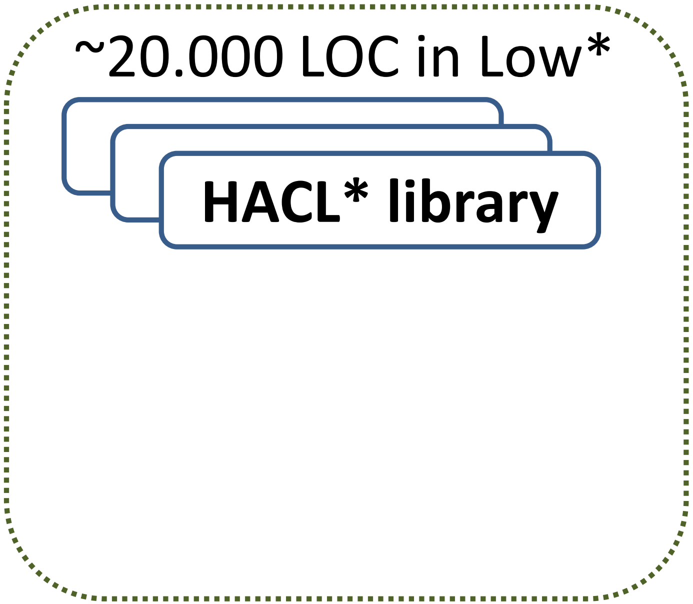
Verified cryptography for Firefox 57

Benjamin Beurdouche

Traditionally, software is produced in this way: write some code, maybe do some code rev
run unit-tests, and then hope it is correct. Hard experience shows that it is very hard for
programmers to write bug-free software. These bugs are sometimes caught in manual tes
but many bugs still are exposed to users, and then must be fixed in patches or subsequen
versions. This works for most software, but it's not a great way to write cryptographic soft
users expect and deserve assurances that the code providing security and privacy is well

Originally, [the HACL* project] is a joint effort between
(CMU, INRIA, Microsoft Research) to produce a [Hig
written in the F* formal verification language] and ger

But abstractions not enforced when compiling and linking with adversarial low-level code



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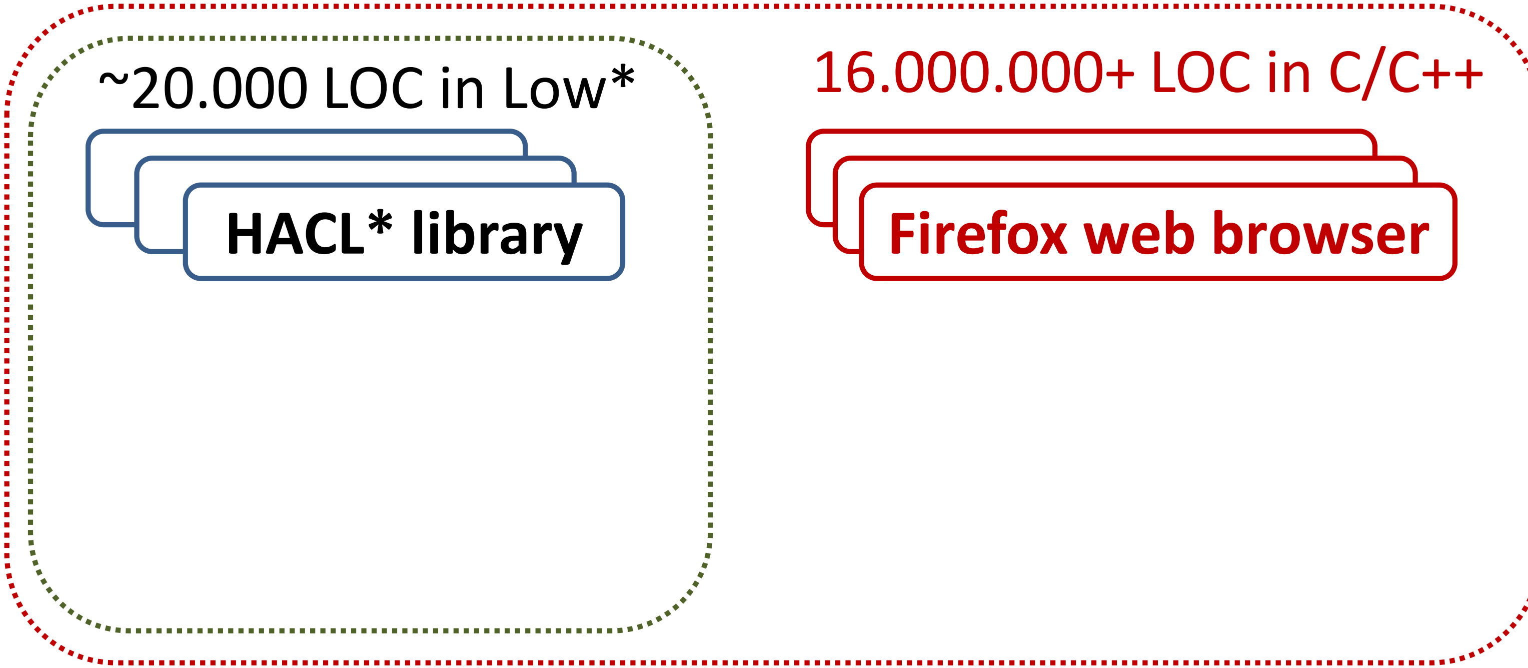

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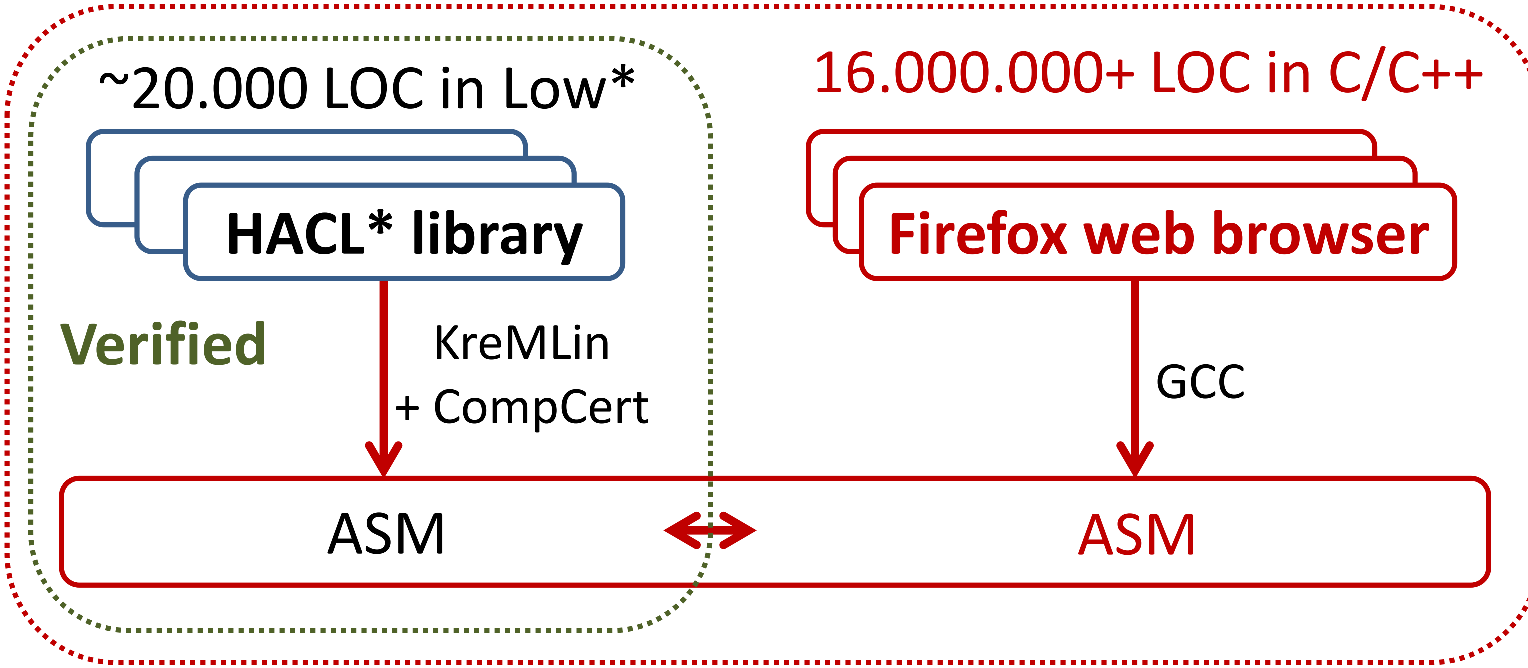

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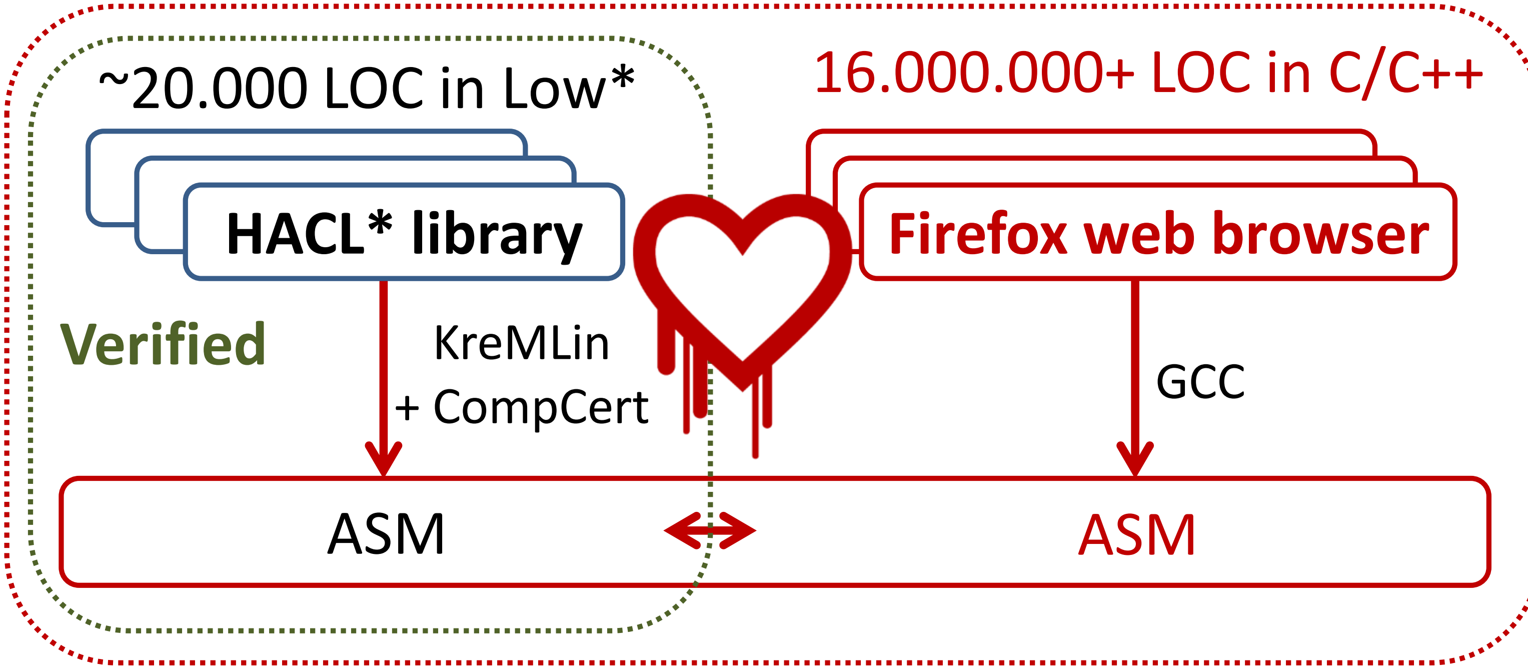

Insecure interoperability: linked code can read and write data and code, jump to arbitrary instructions, smash the stack, ...

Secure compilation chains

- Protect source-level abstractions
  even against linked adversarial low-level code
  - **various enforcement mechanisms**: processes, SFI, ...
  - shared responsibility: compiler, linker, loader, OS, HW

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  – **adversarial target-level context cannot break the security of compiled program** any more than some source-level context
  – **no "low-level" attacks**

Robustly preserving security

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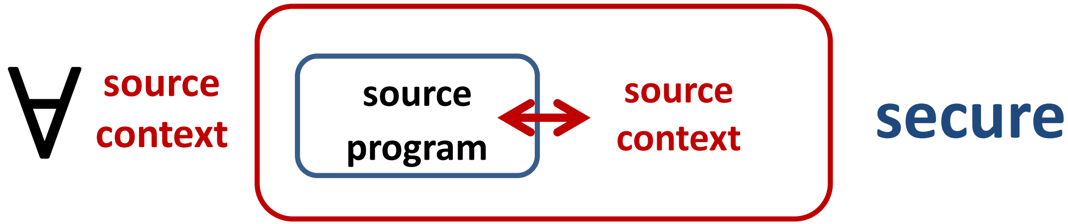

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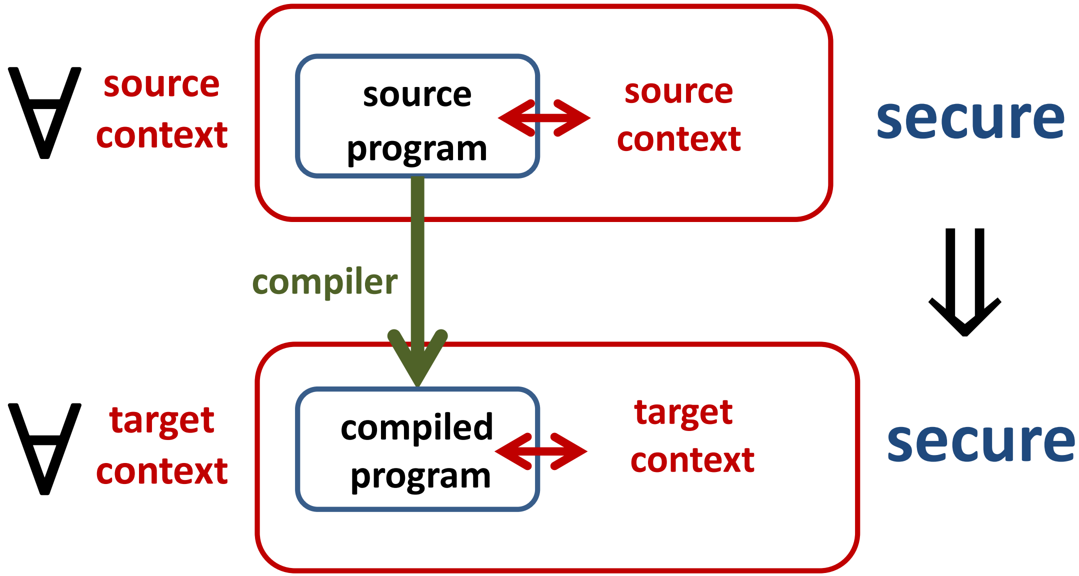

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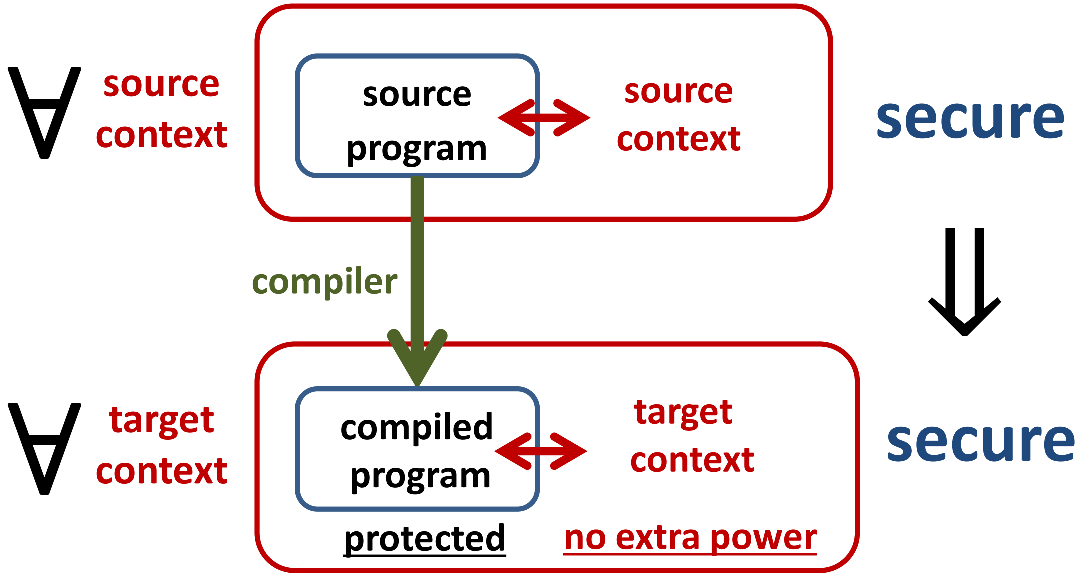

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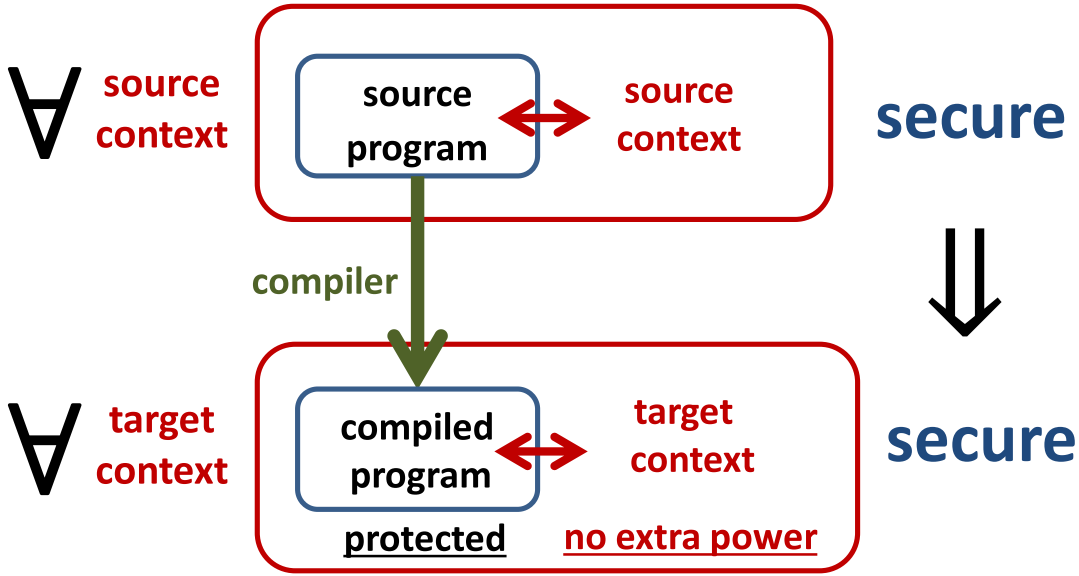

But what should "secure" mean?

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trace properties
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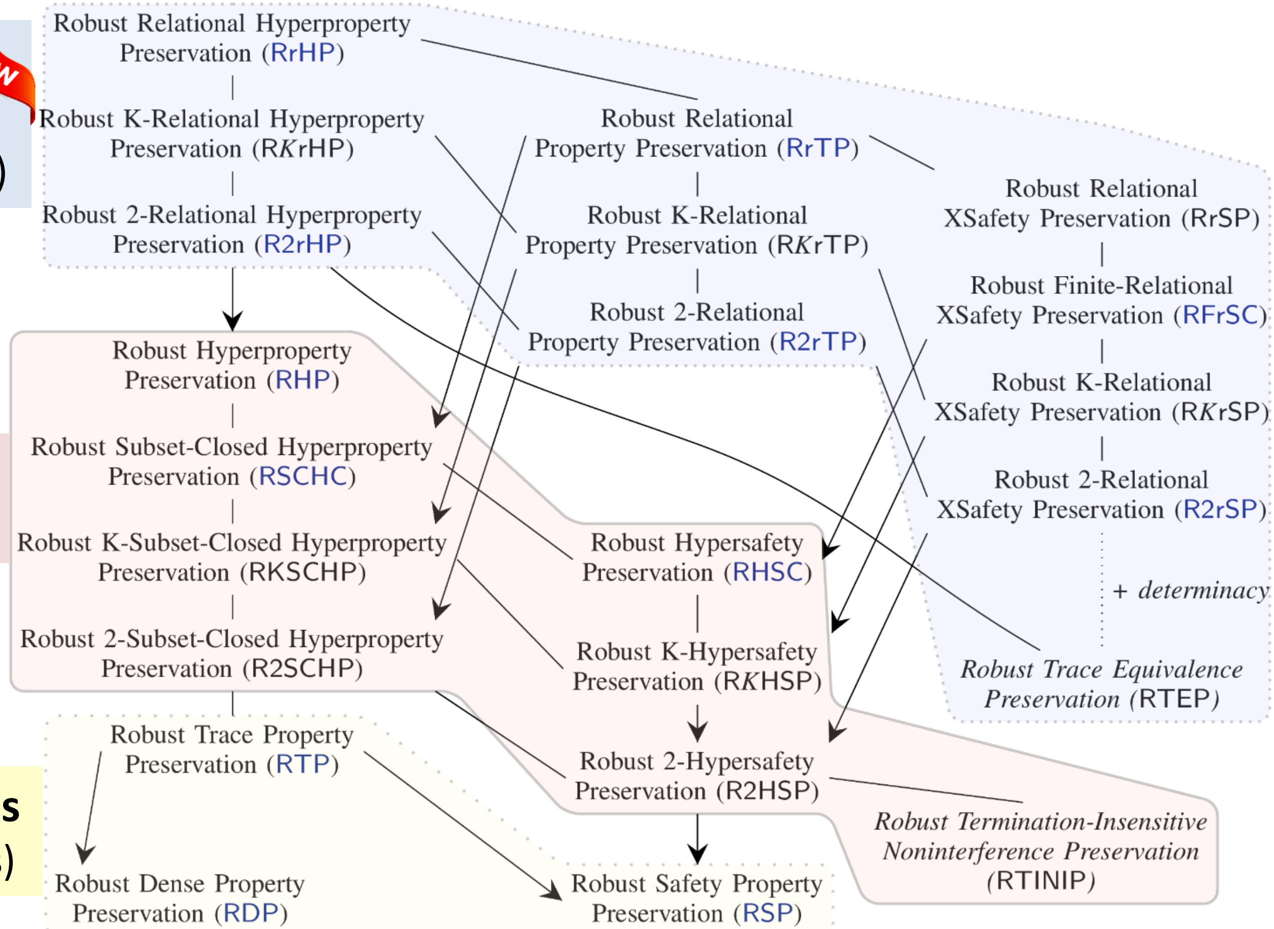

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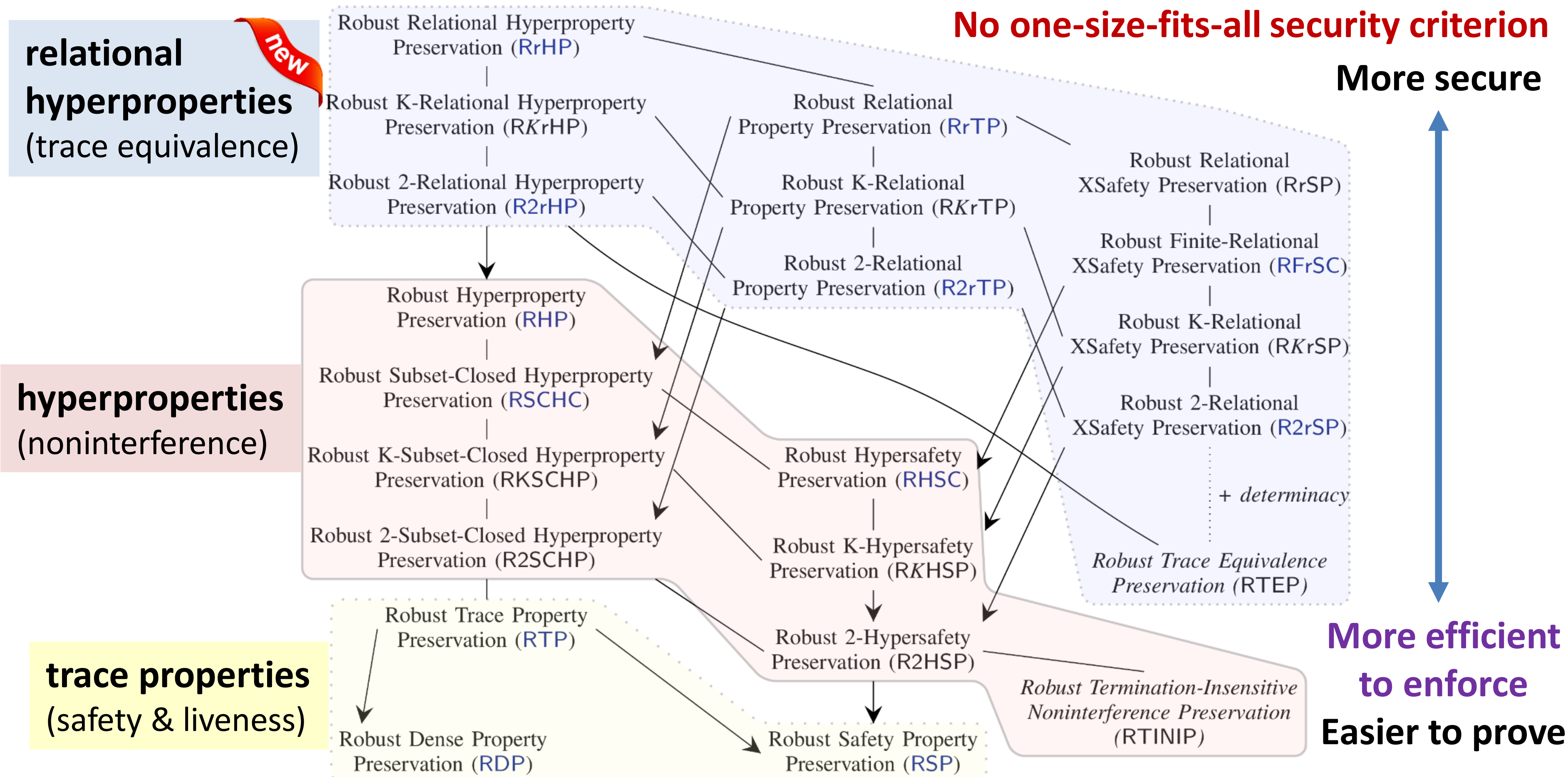

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No one-size-fits-all security criterion

More secure

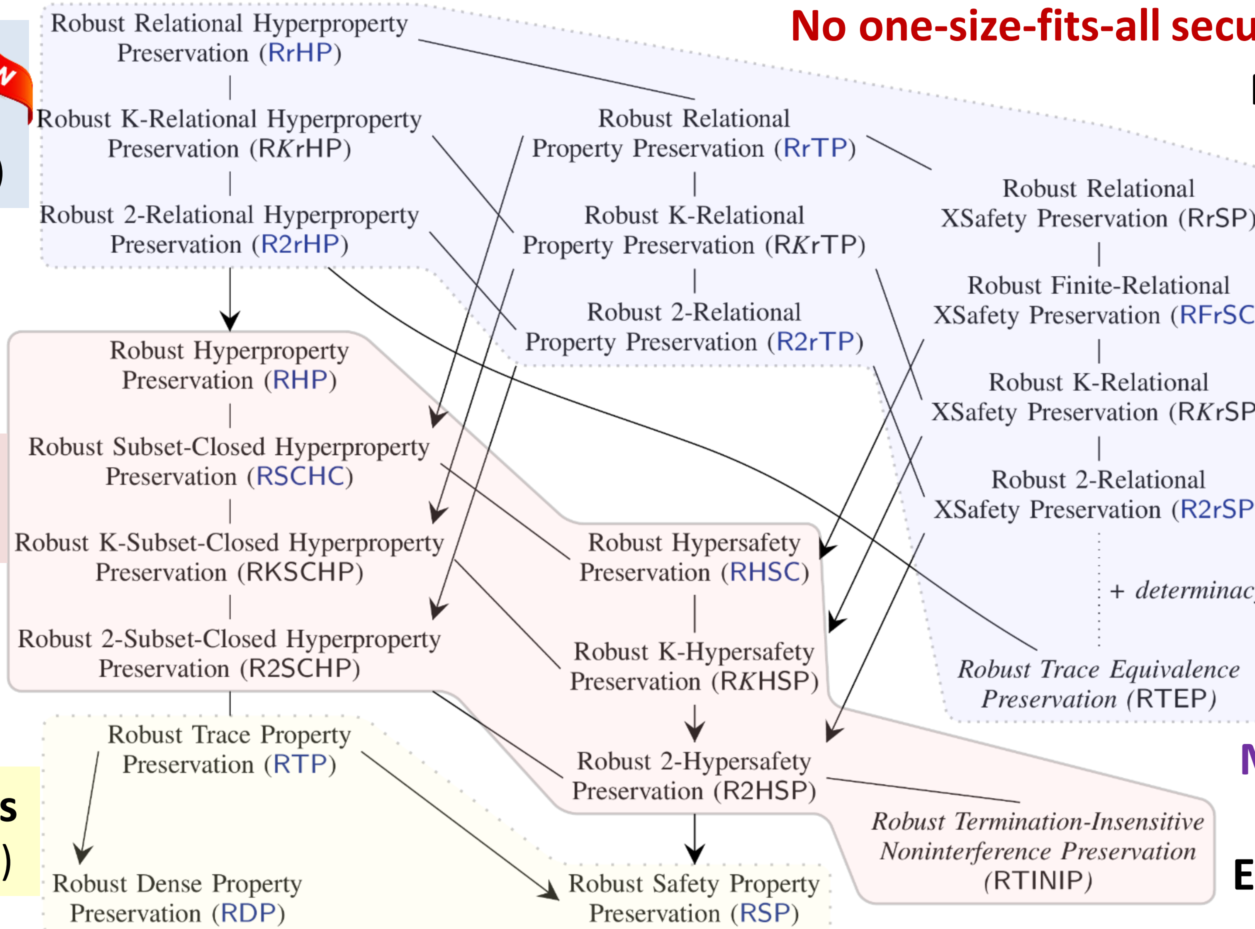
relational hyperproperties (trace equivalence)

new

hyperproperties (noninterference)

trace properties (safety & liveness)

only integrity



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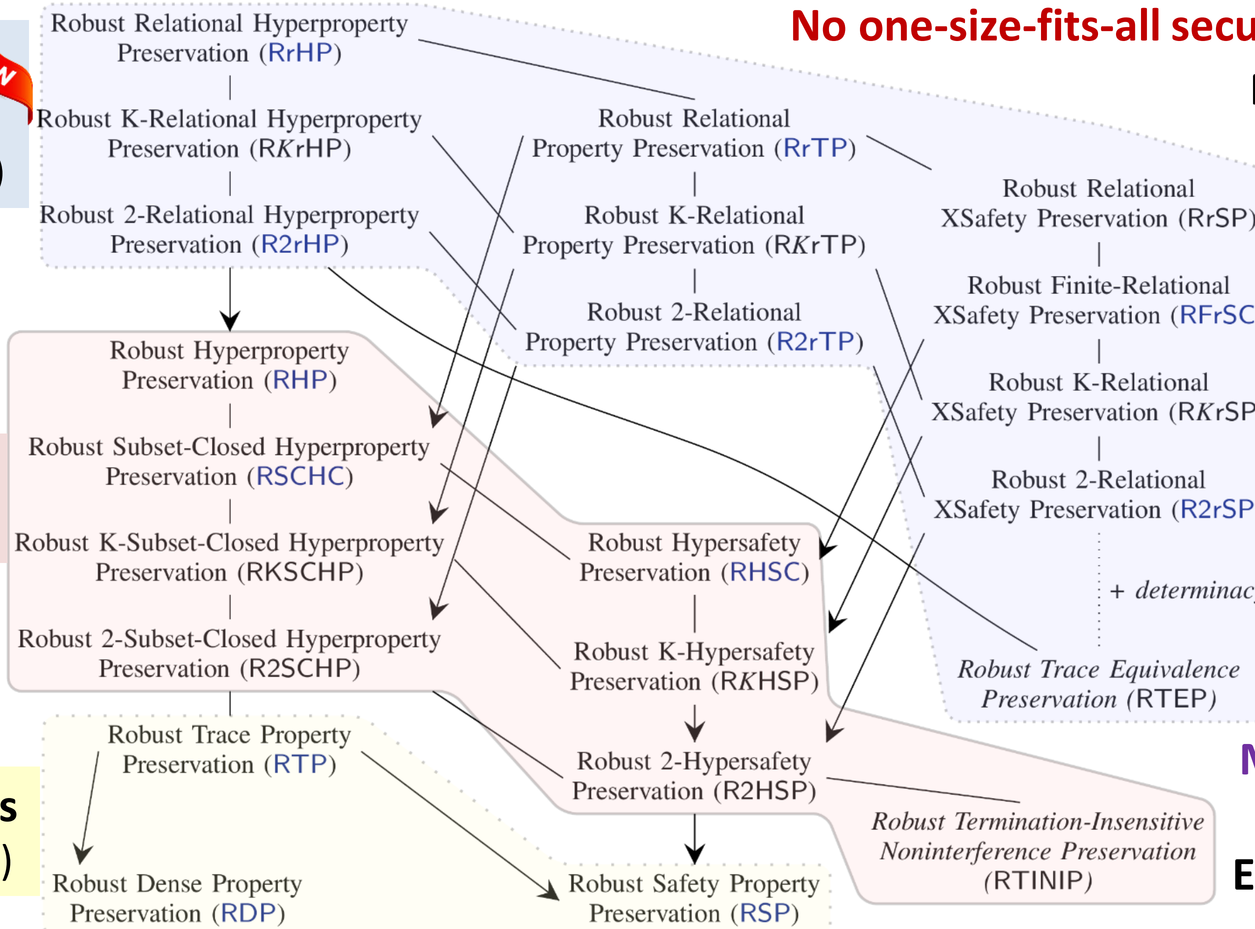

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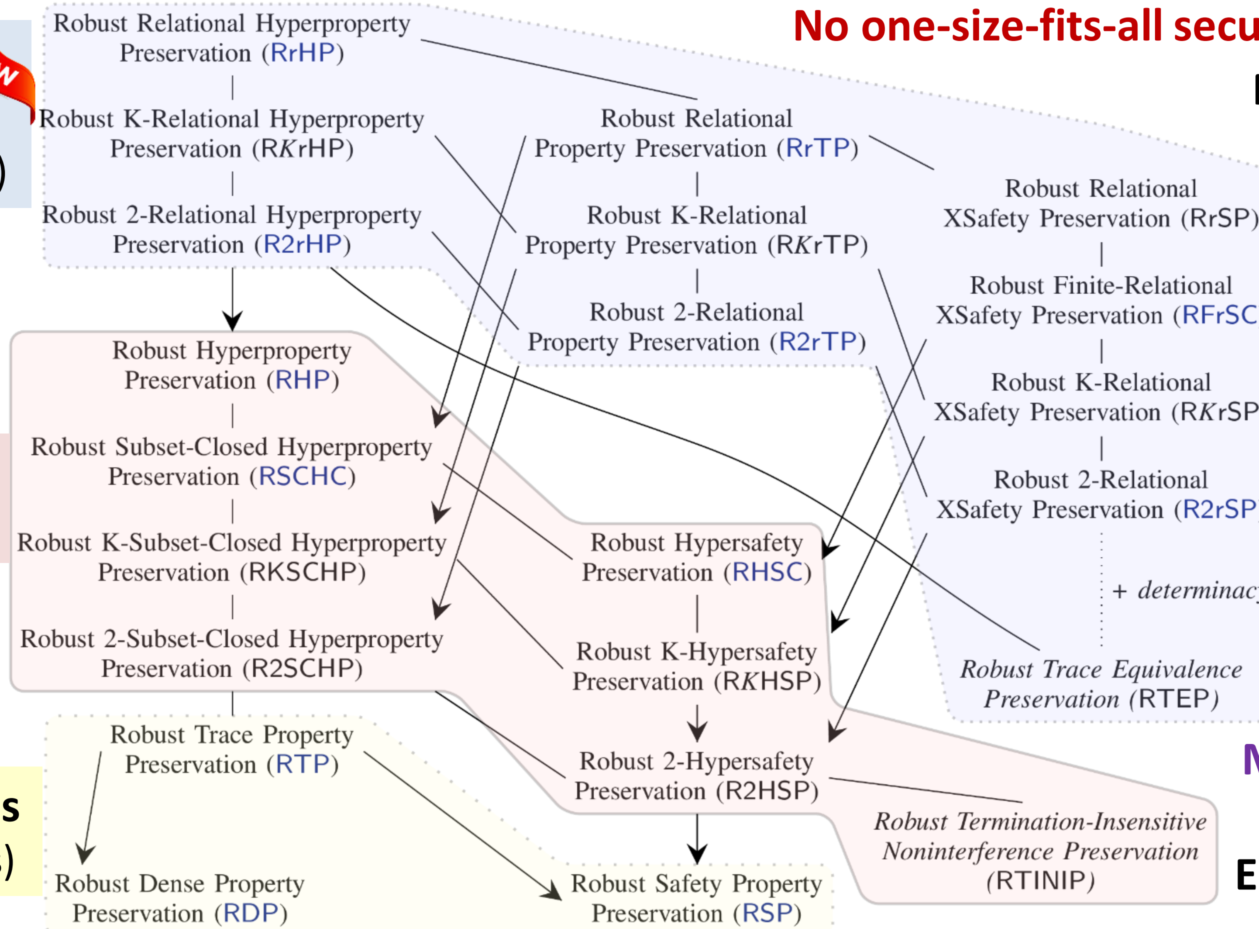

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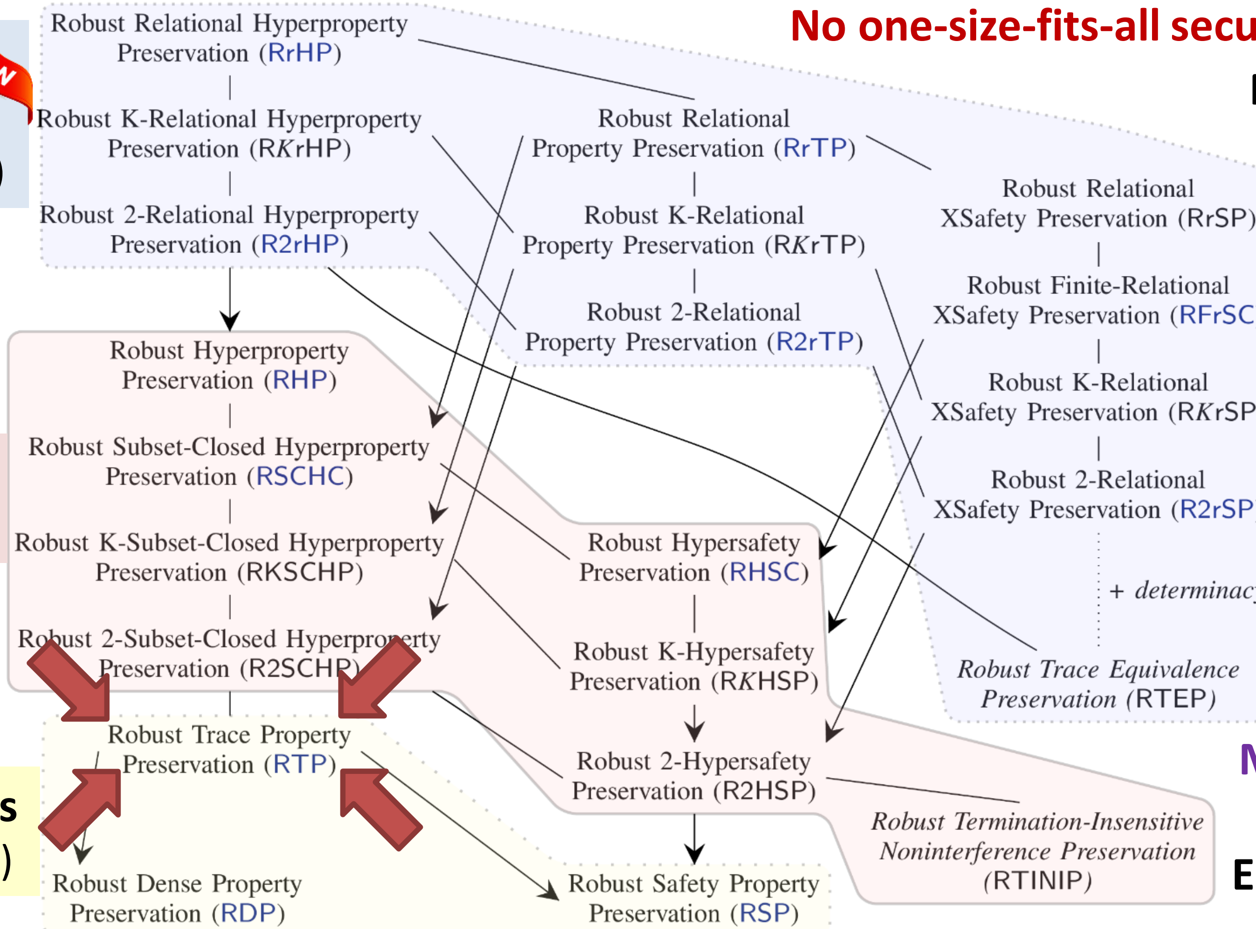

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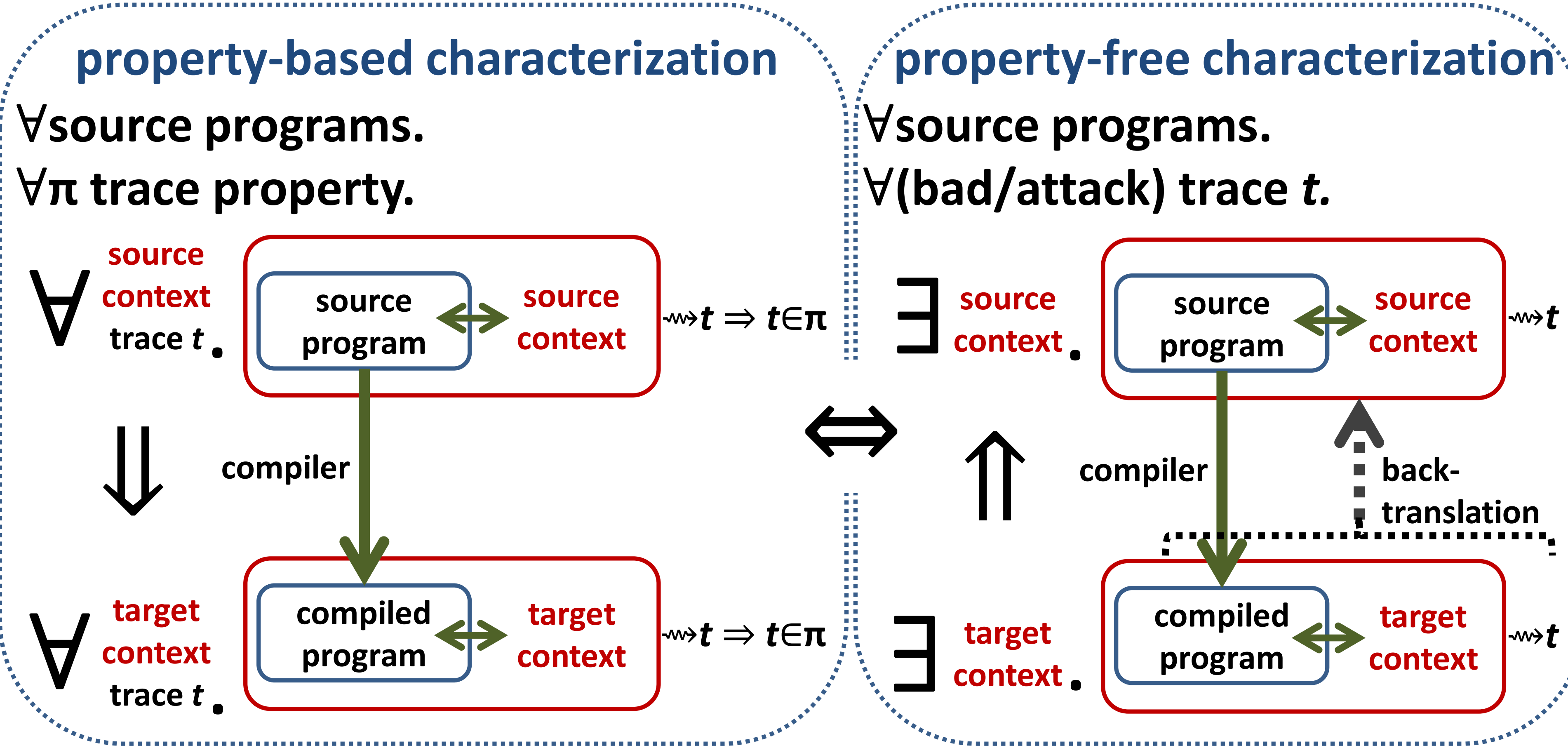
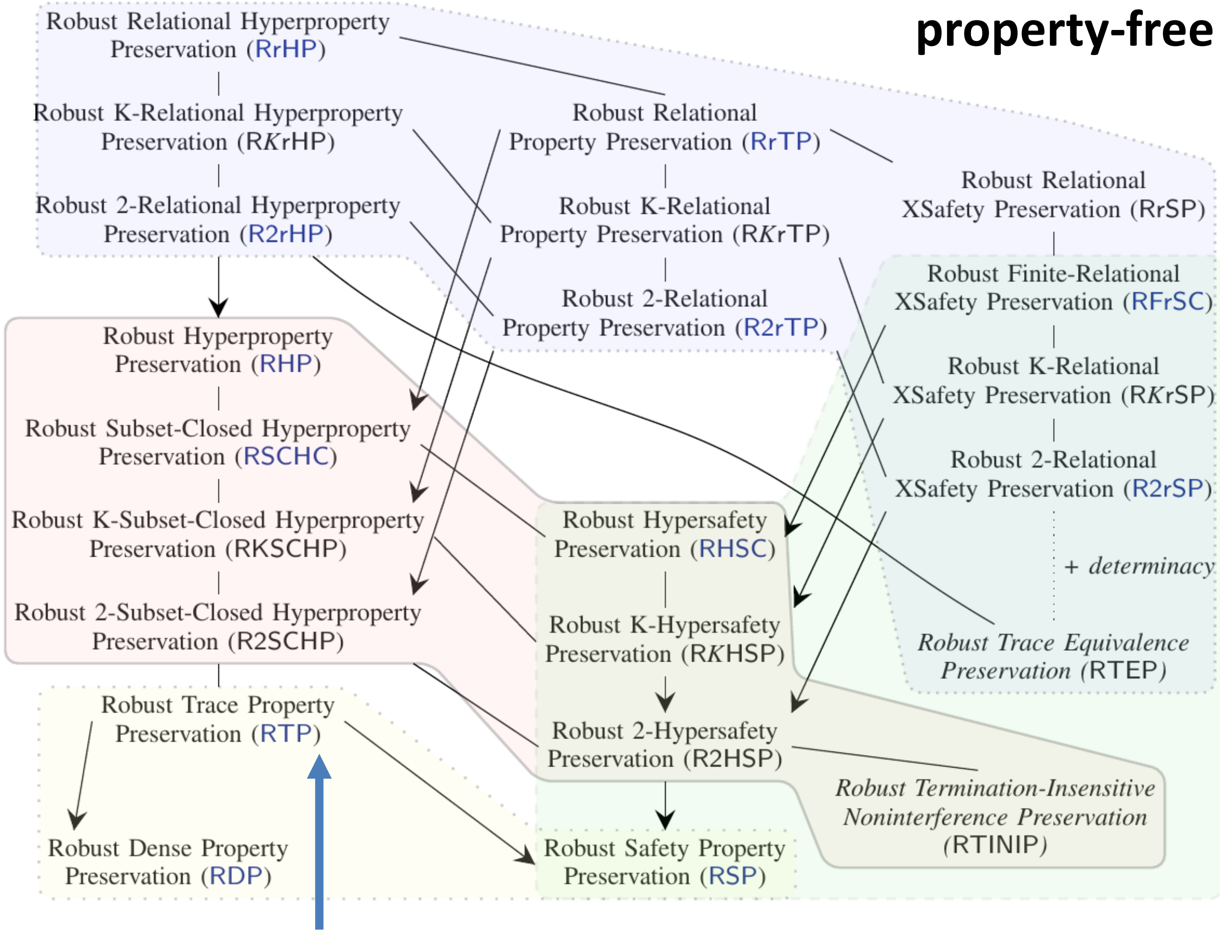
Robust Trace Property Preservation



what one can achieve

how one can prove it

Some of the proof difficulty is manifest in property-free characterization



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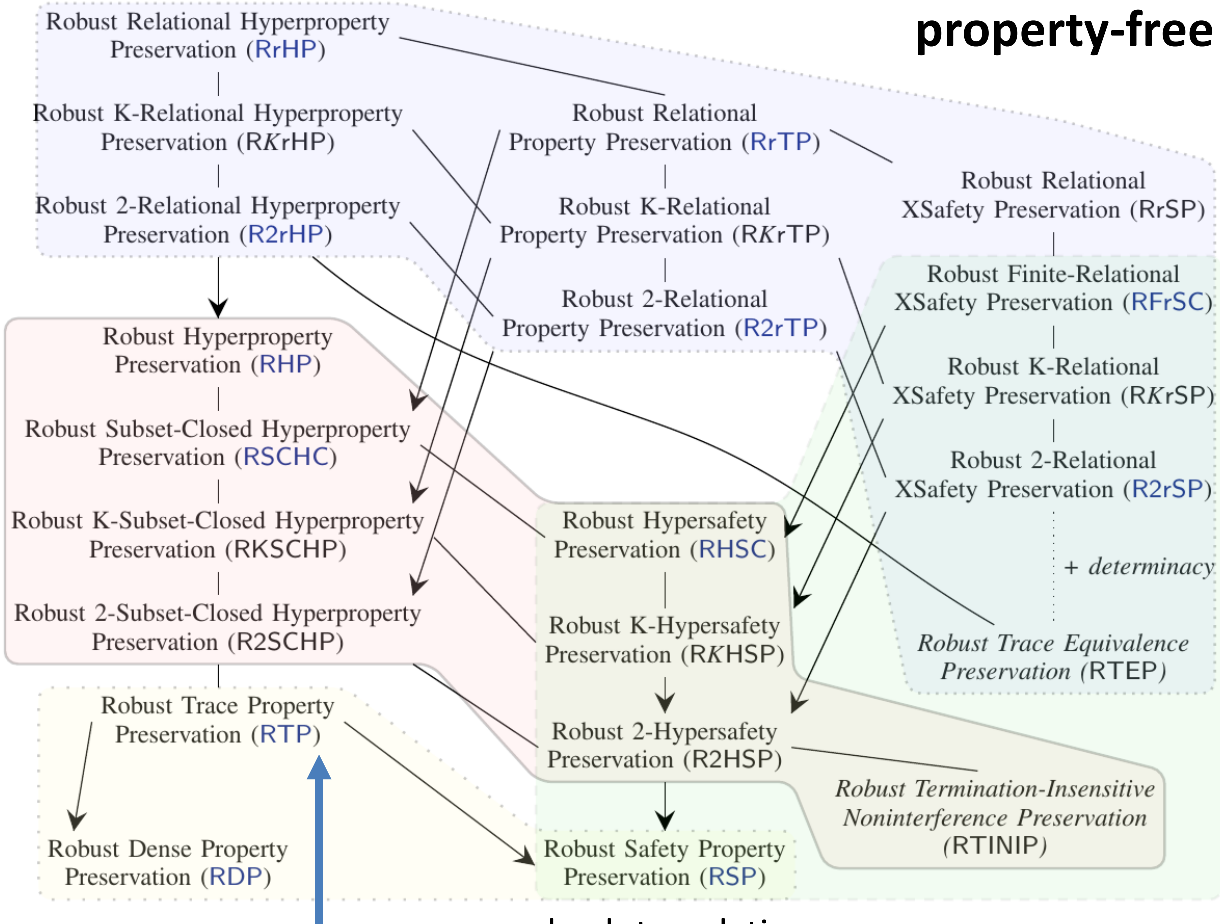

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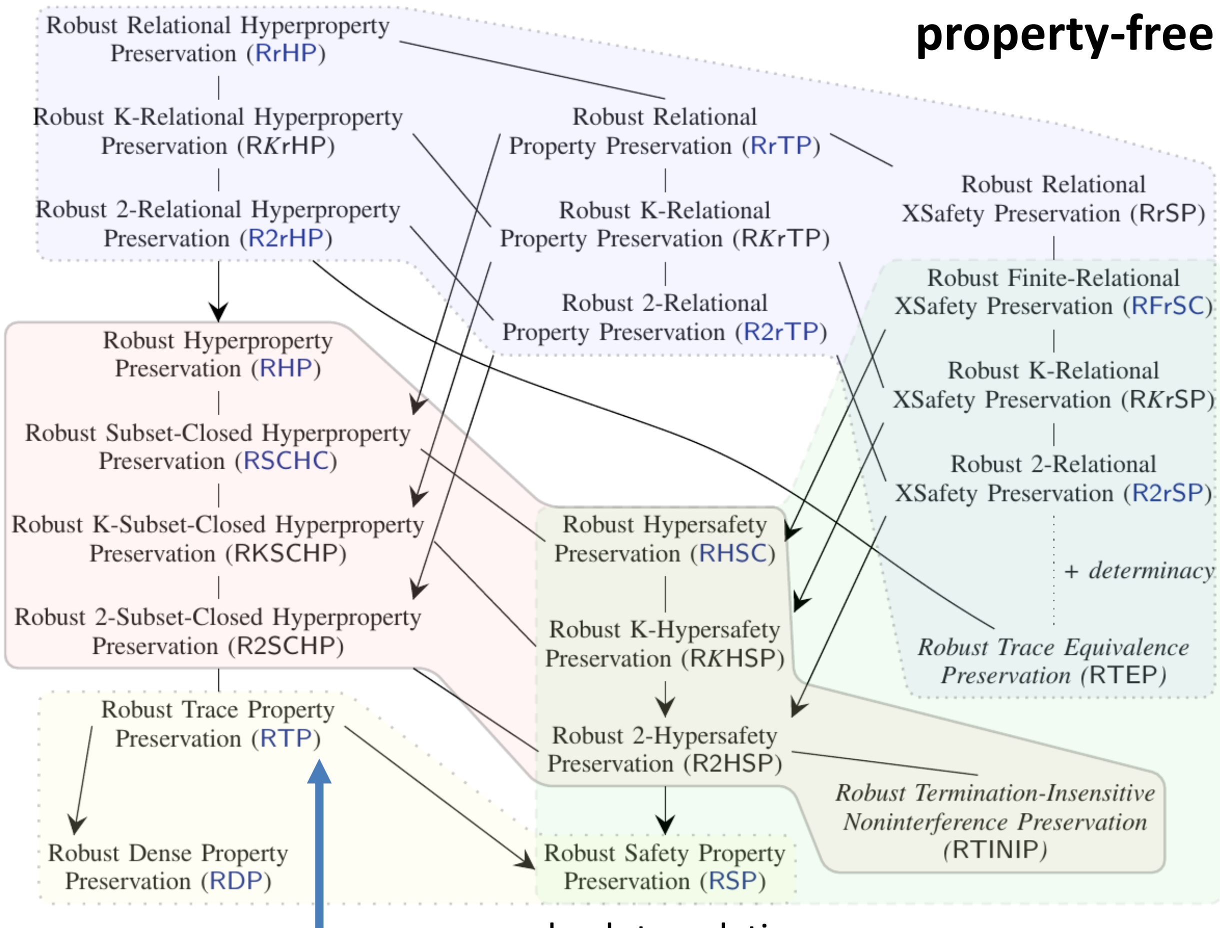

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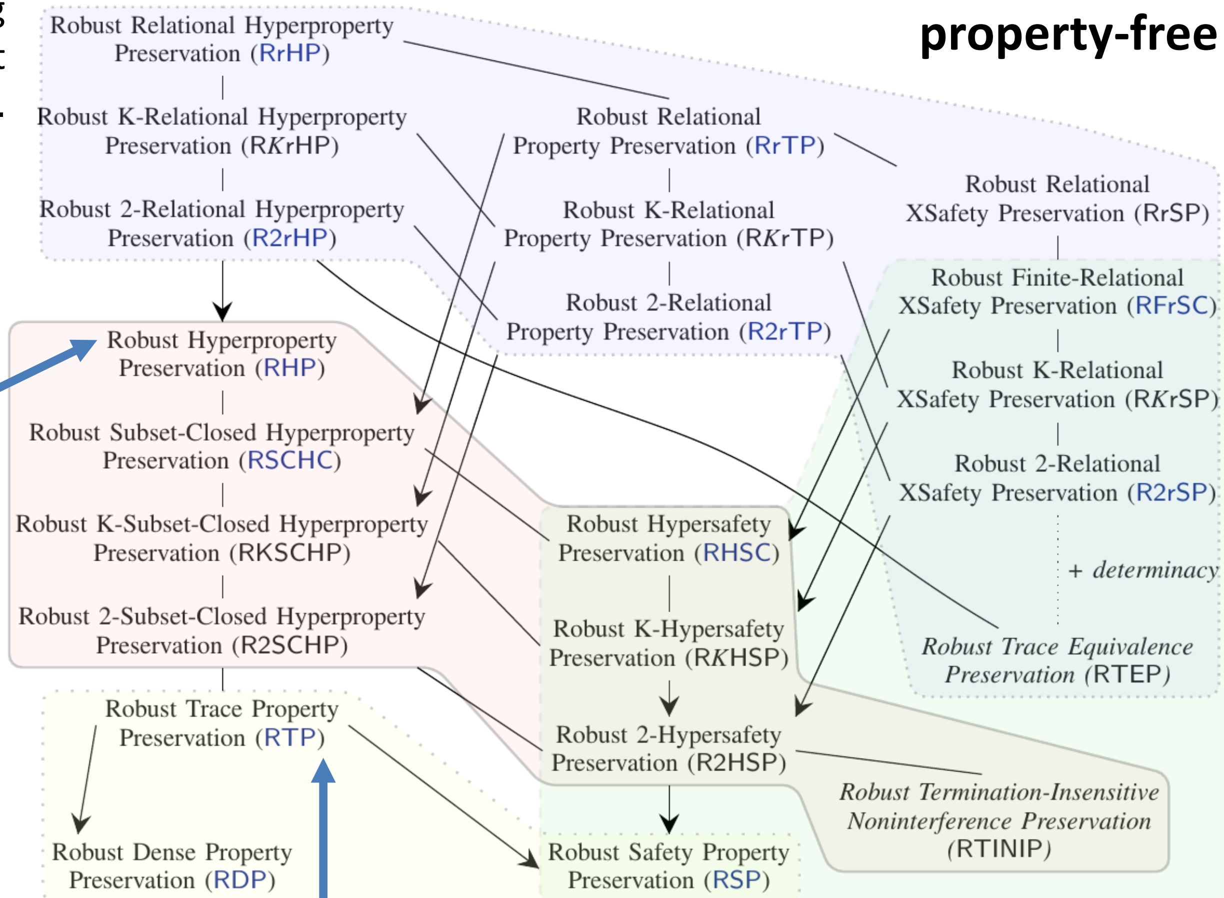

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  - implications, **collapses**, **separations results**

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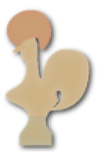

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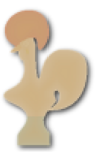

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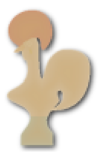

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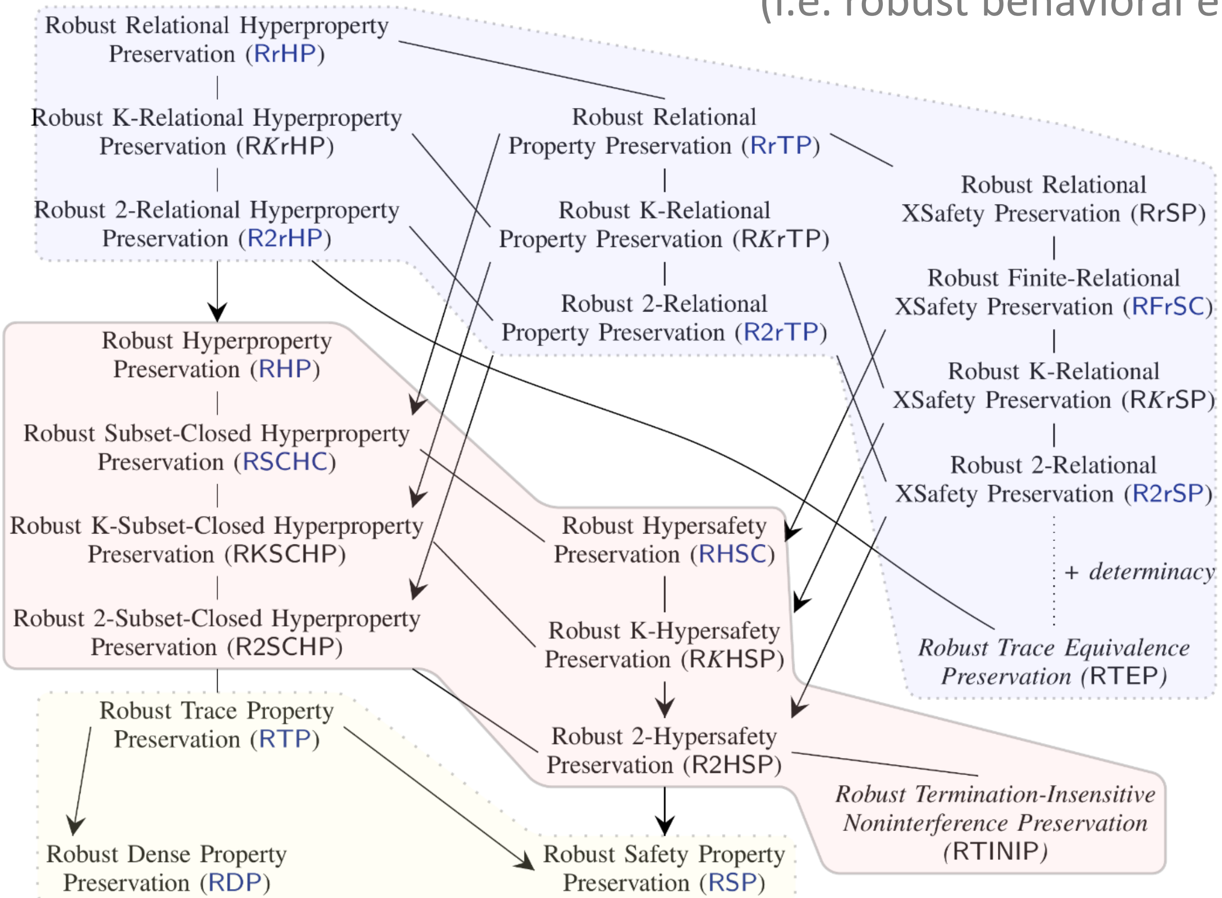

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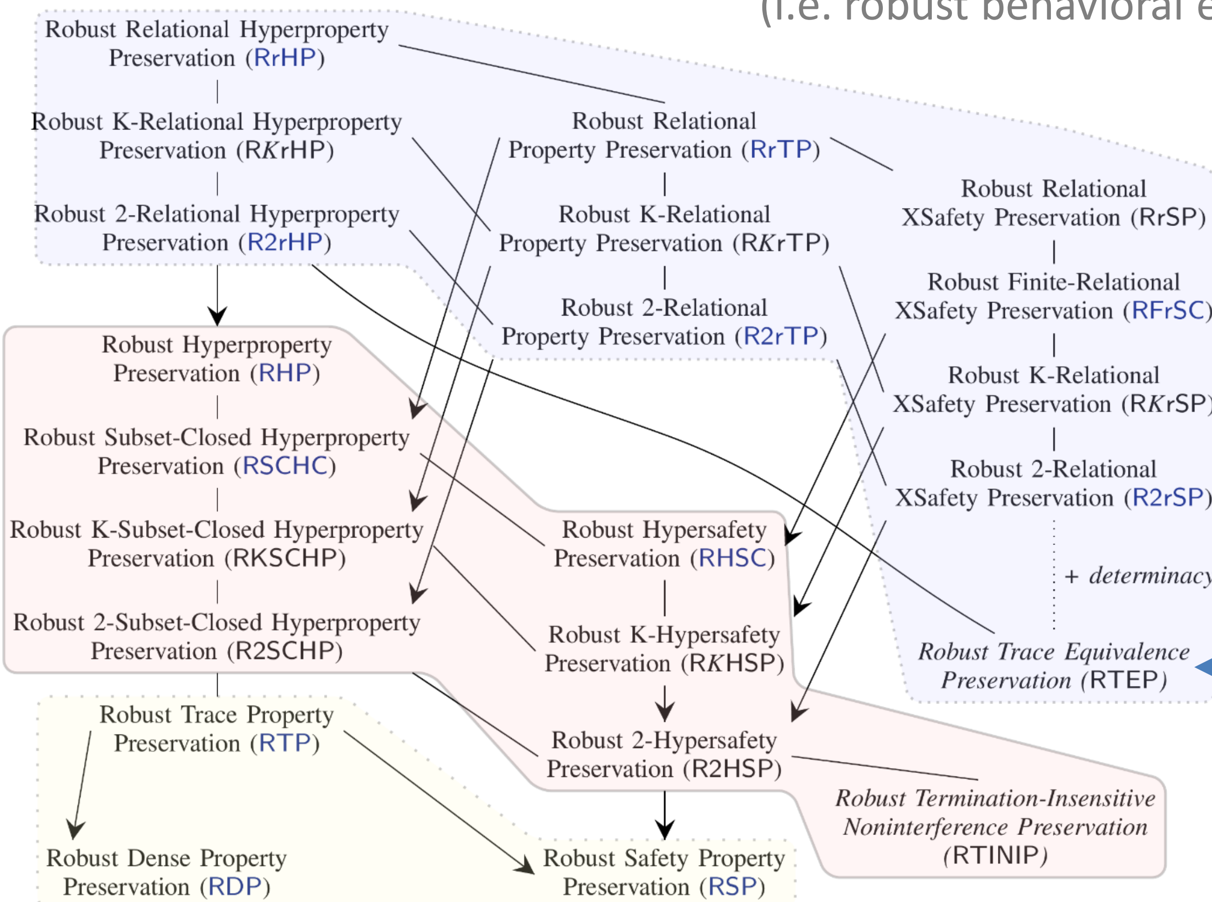

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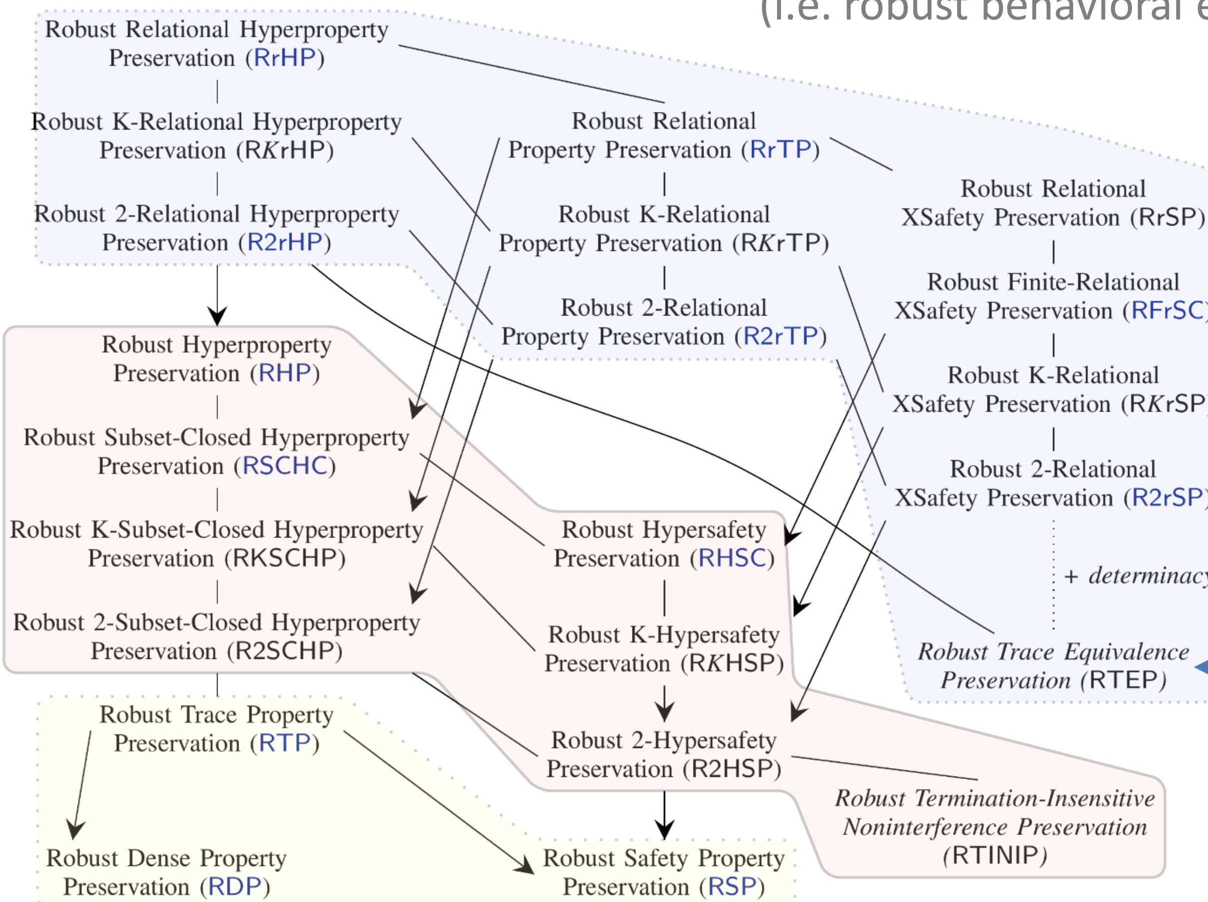

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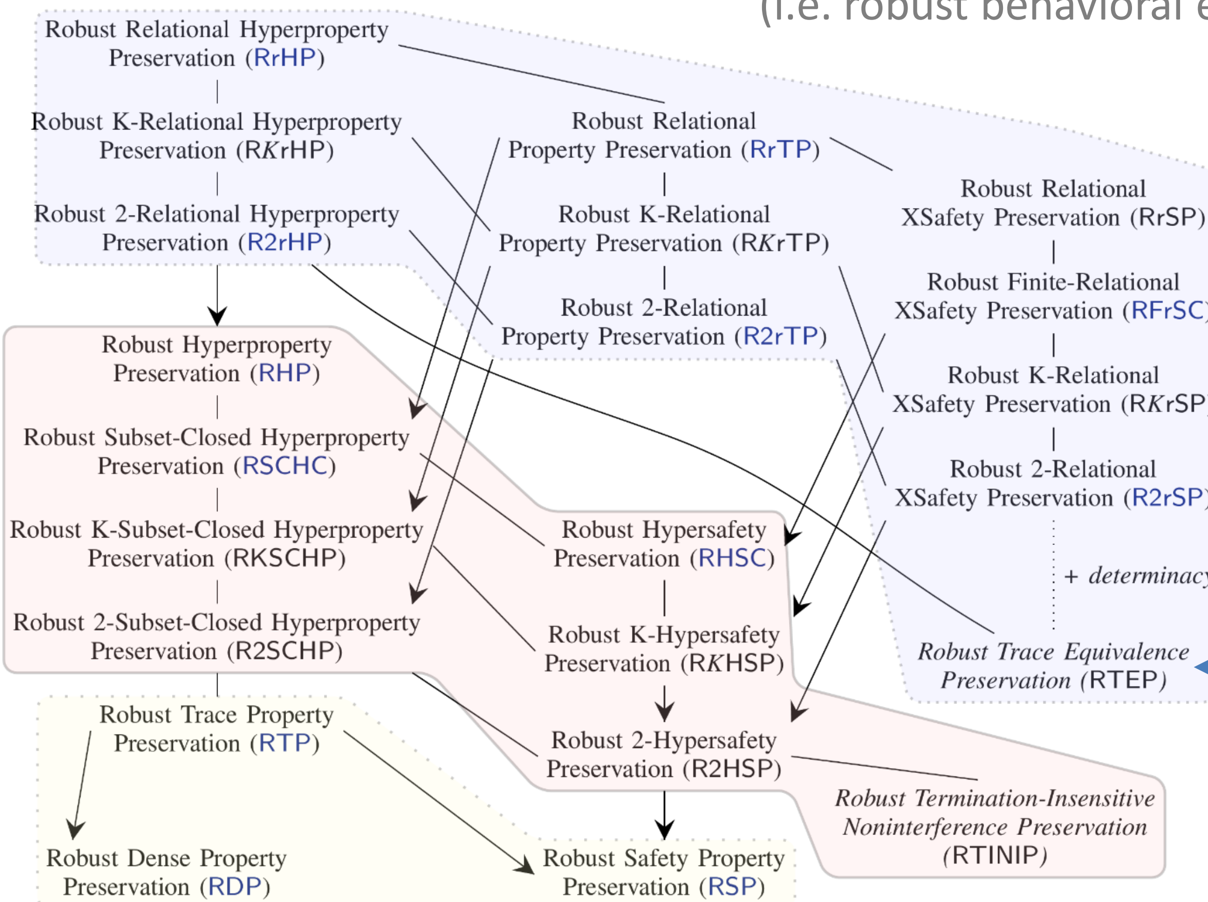

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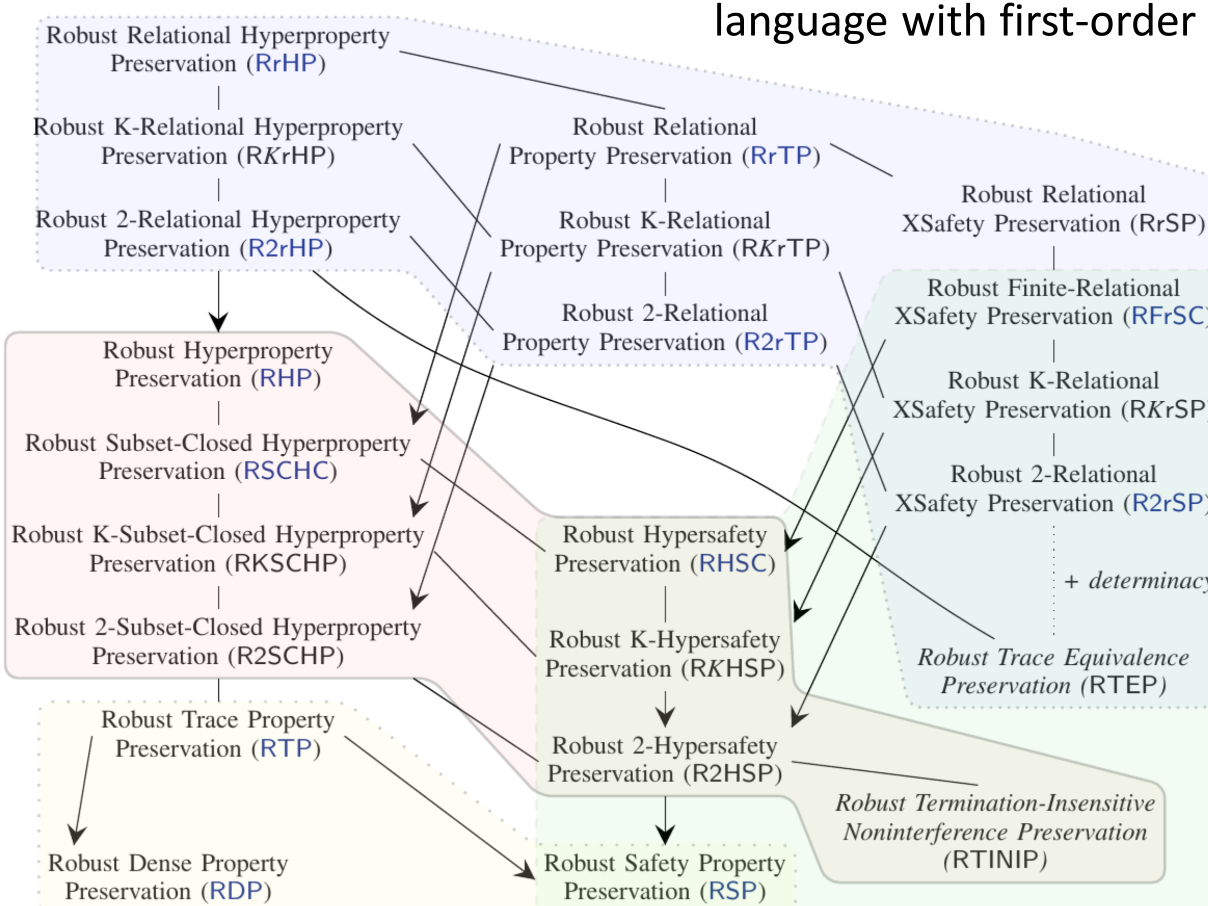
Embraced and extended™ proof techniques

for simple translation from statically to dynamically typed language with first-order functions and I/O



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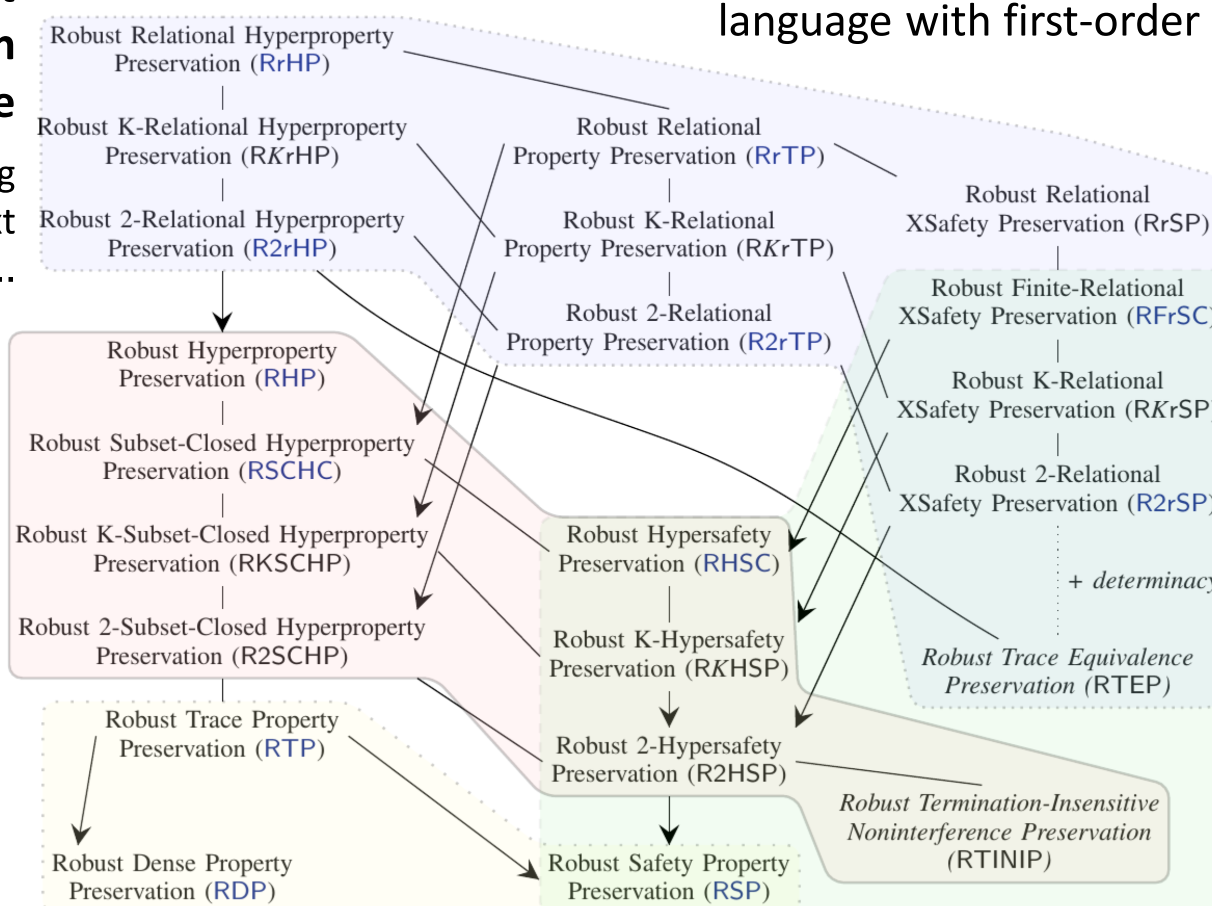
strongest criterion achievable

back-translating context $\forall C_T \exists C_S \forall P \forall t\ldots$



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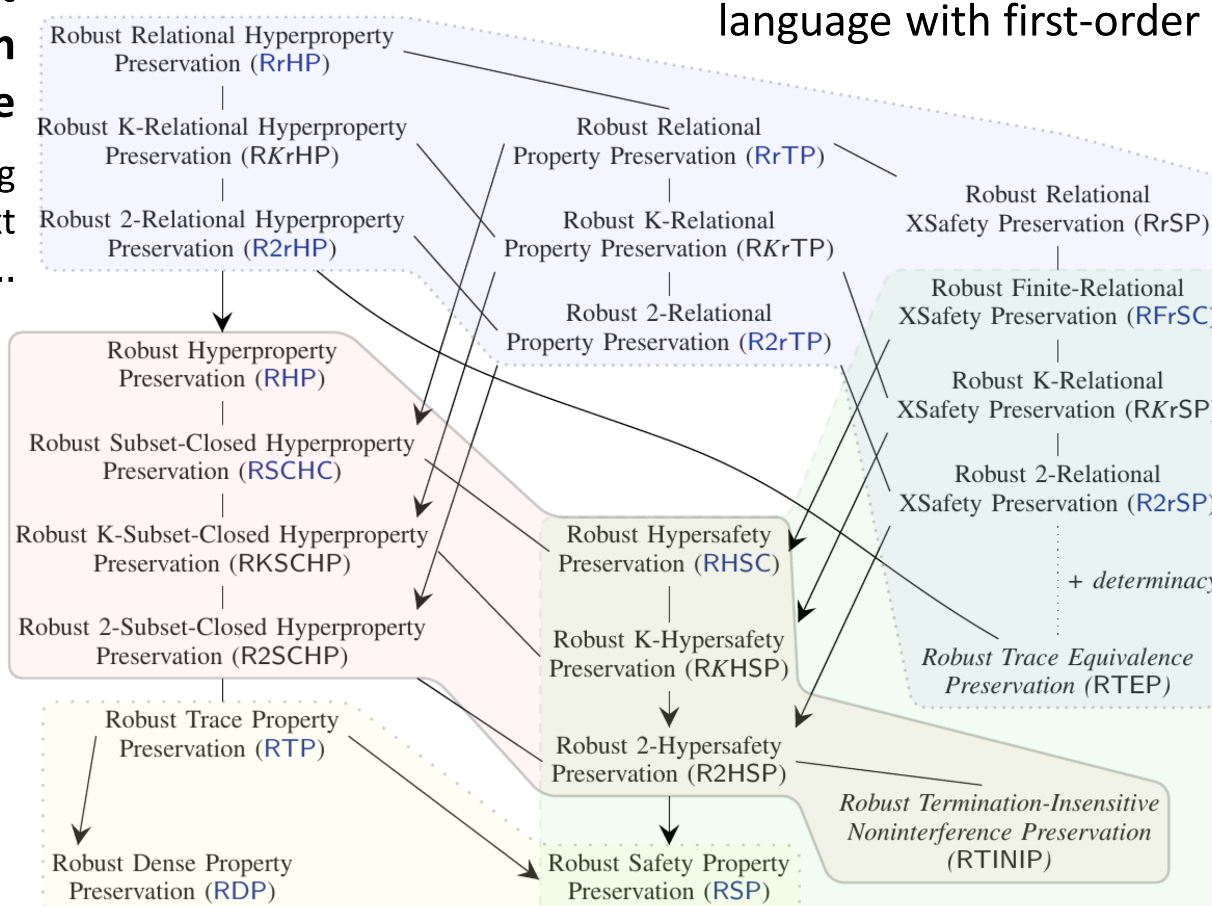

generic technique applicable

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Some open problems

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  - **More realistic languages and compilation chains**
- **Verifying robust satisfaction for source programs**
  - partial semantics, program logics, logical relations, ...
- **Exploring other kinds of secure compilation**
  - target observations richer than source observations
  - generalize **noninterference preservation** **with side-channels**?

Part 2 of 2

Secure Compilation for Unsafe Languages

When Good Components Go Bad (CCS 2018)

Beyond Good and Evil (CSF 2016)

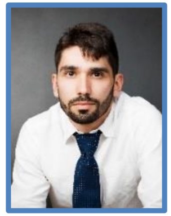
Micro-Policies (IEEE S&P 2015)

A verified information-flow architecture (POPL 2014)

When Good Components Go Bad

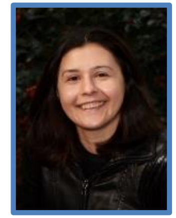
Computer and Communications Security (CCS 2018)

Carmine Abate



Arthur Azevedo de Amorim

Rob Blanco



Ana Nora Evans

Guglielmo Fachini

Cătălin Hrițcu

Théo Laurent

Benjamin Pierce

Marco Stronati

Andrew Tolmach

Inria Paris CMU U. Virginia Portland State UPenn

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

Compartmentalization mitigation

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- **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

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

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We answer this question:

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

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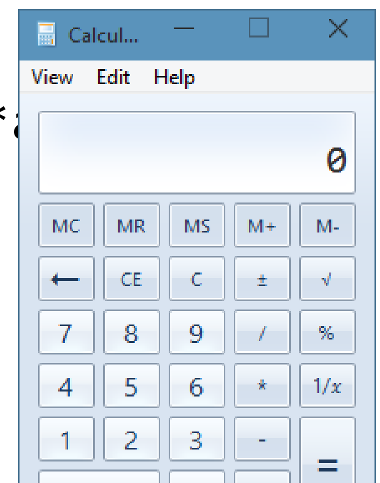

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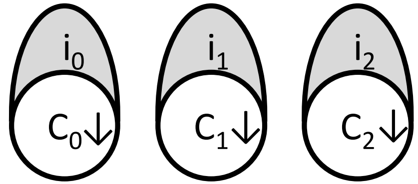
- **Restrict temporal scope** of undefined behavior
  - **dynamic compromise**
    - **each component gets guarantees as long as it has not encountered undefined behavior**
    - i.e. the mere existence of vulnerabilities doesn't necessarily make a component compromised

Security definition: If



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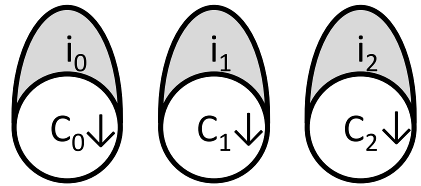

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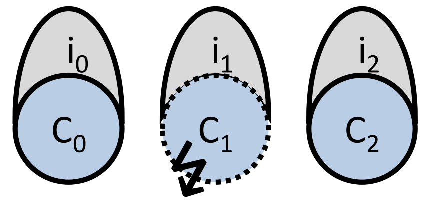
∃ a sequence of component compromises explaining the finite trace t in the source language, for instance $t=m_1 \cdot m_2 \cdot m_3$ and

(1)



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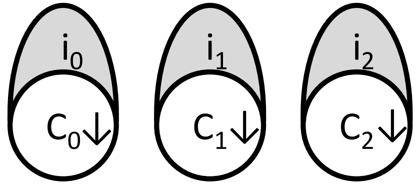
Security definition: If 

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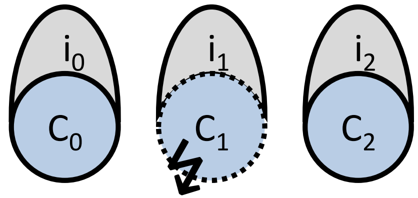
(1) 

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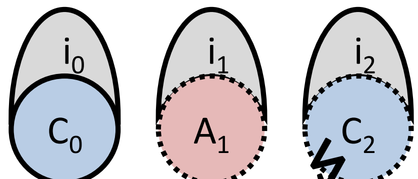
(2) $\exists A_1$. 

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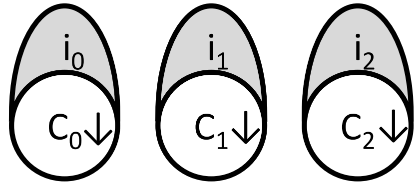

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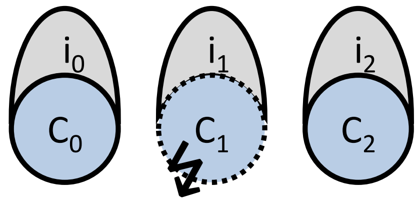

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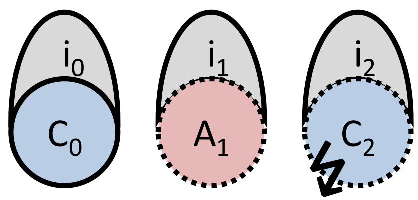

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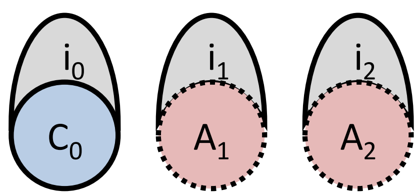

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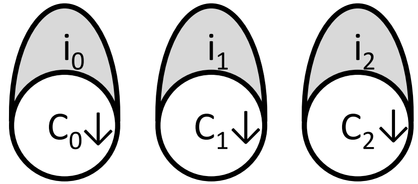

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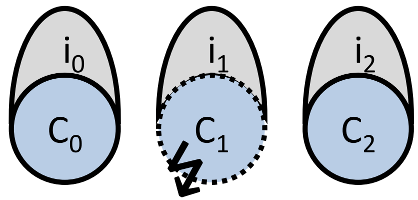

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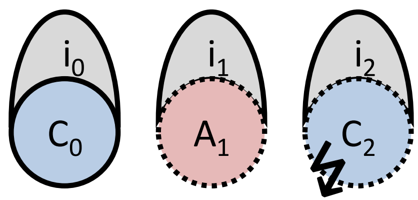

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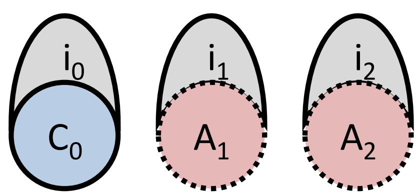

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Finite trace records which component encountered undefined behavior and allows us to rewind execution

How can we prove this?

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When compilation and back-translation are **compositional**, previous definition reduces to (a variant of)
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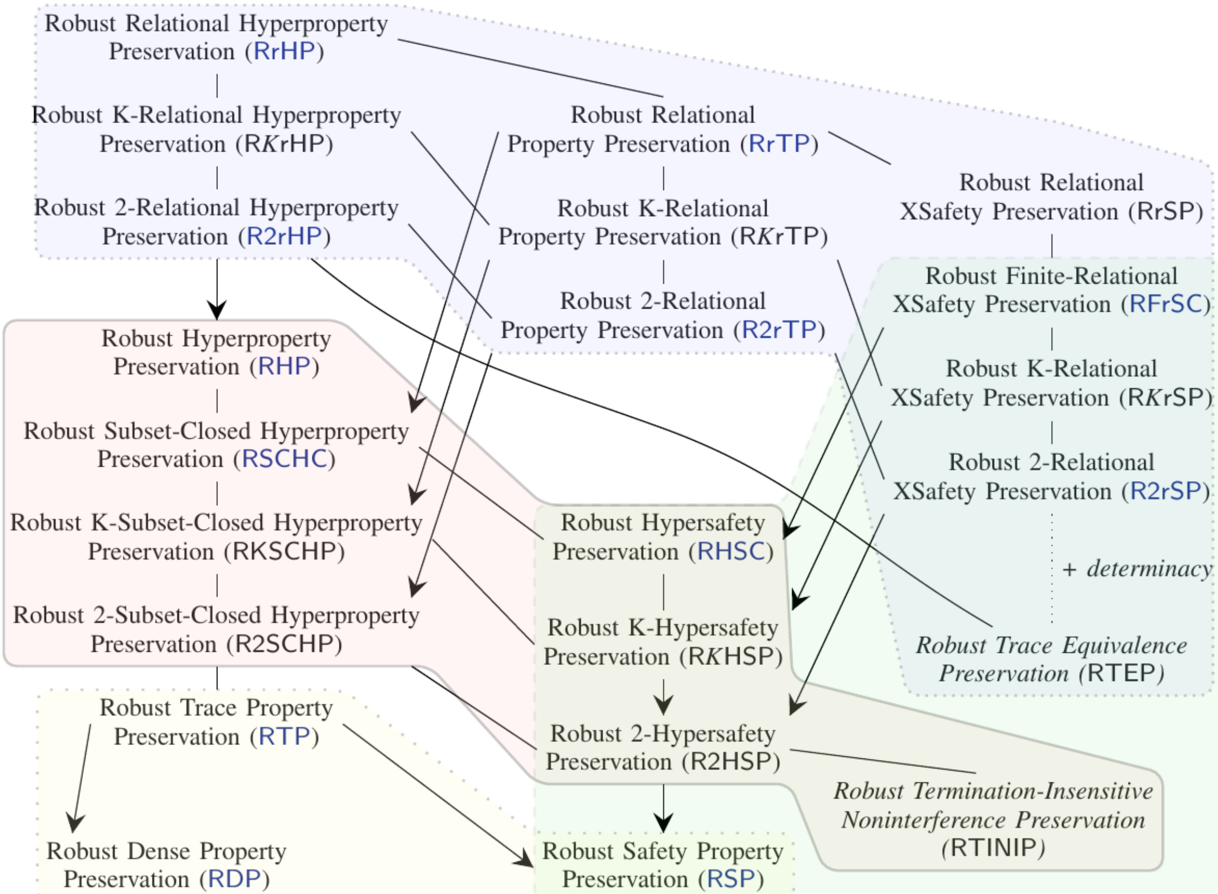
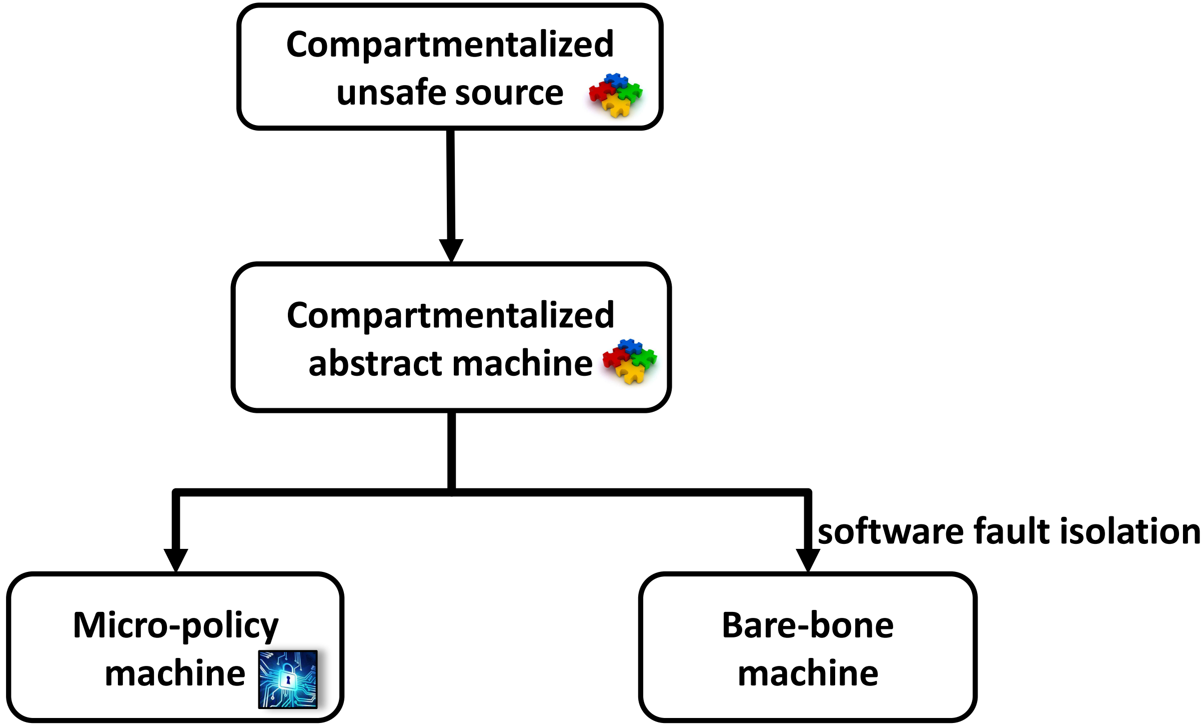


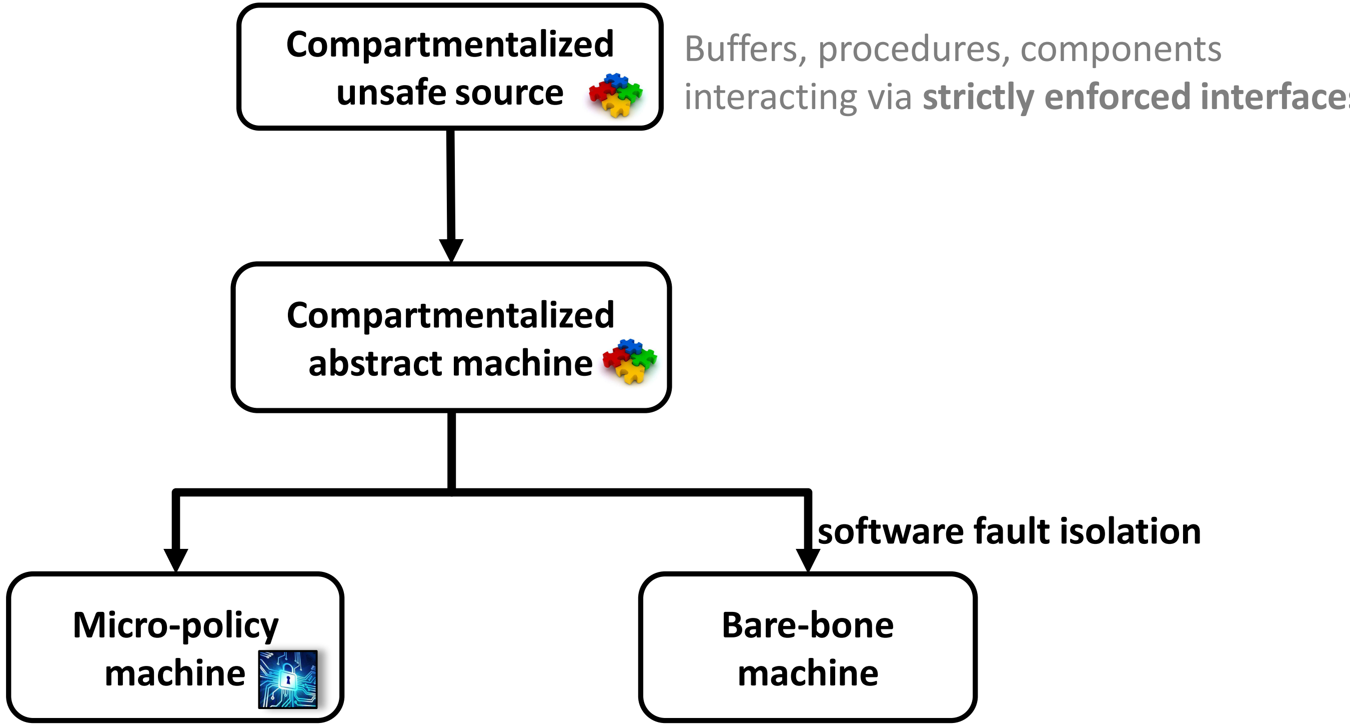
back-translating finite trace prefix $\forall P \forall C_T \forall m \leq t \exists C_S \ldots$

When compilation and back-translation are **compositional**, previous definition reduces to (a variant of) **Robust Safety Preservation**

Proof-of-concept formally secure compilation chain in Coq

Illustrates our formal definition


Compartmentalized unsafe source
Compartmentalized abstract machine
software fault isolation
Micro-policy machine
Bare-bone machine


Compartmentalized unsafe source
Buffers, procedures, components interacting via **strictly enforced interfaces**
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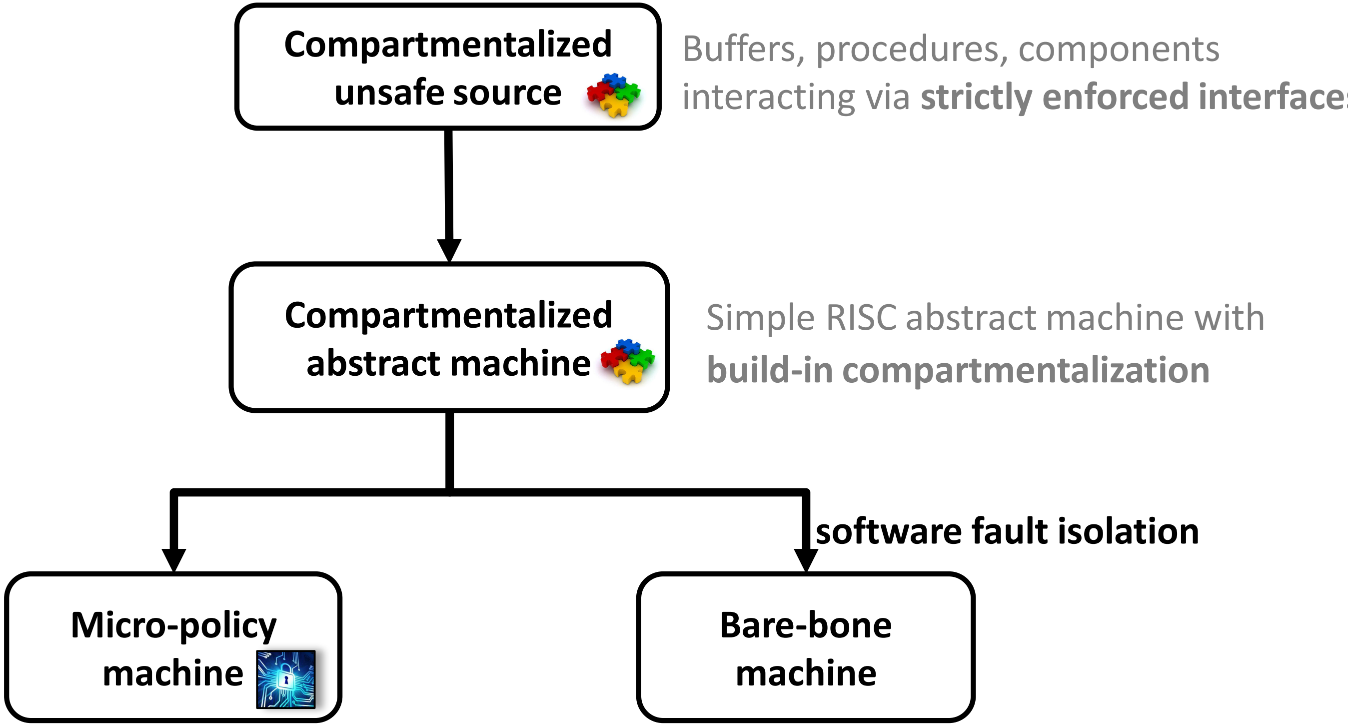
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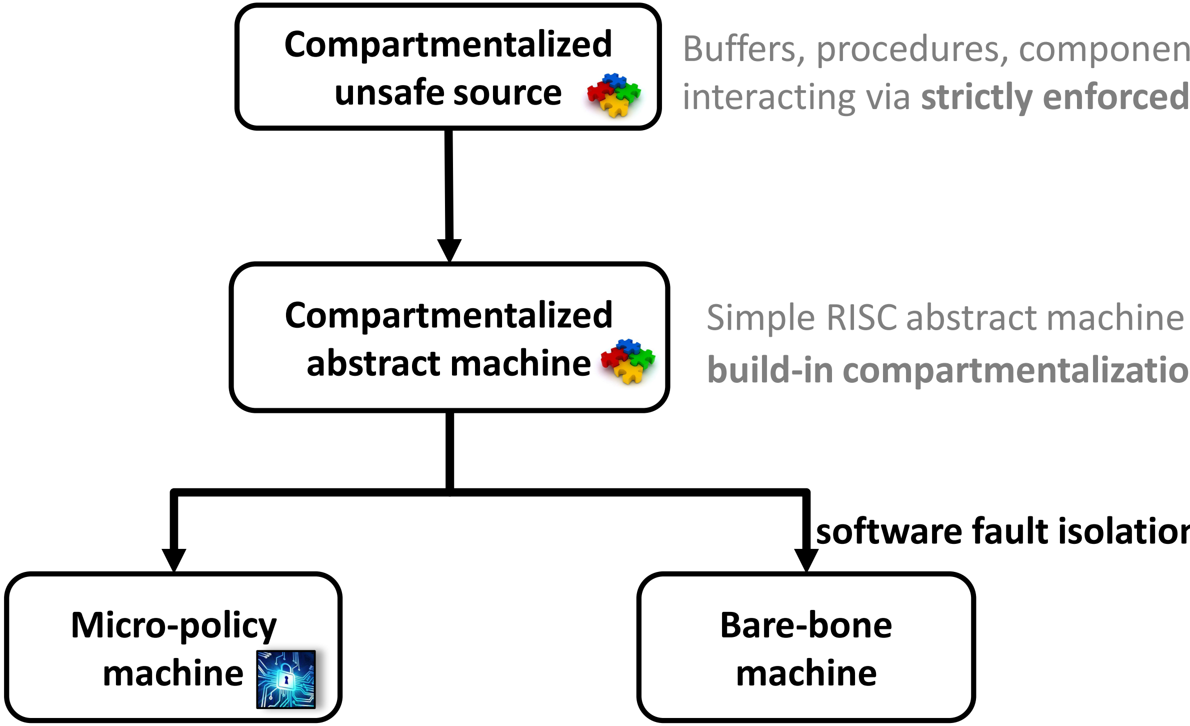

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Simple RISC abstract machine with **build-in compartmentalization**

Tag-based reference monitor enforcing:
- component separation
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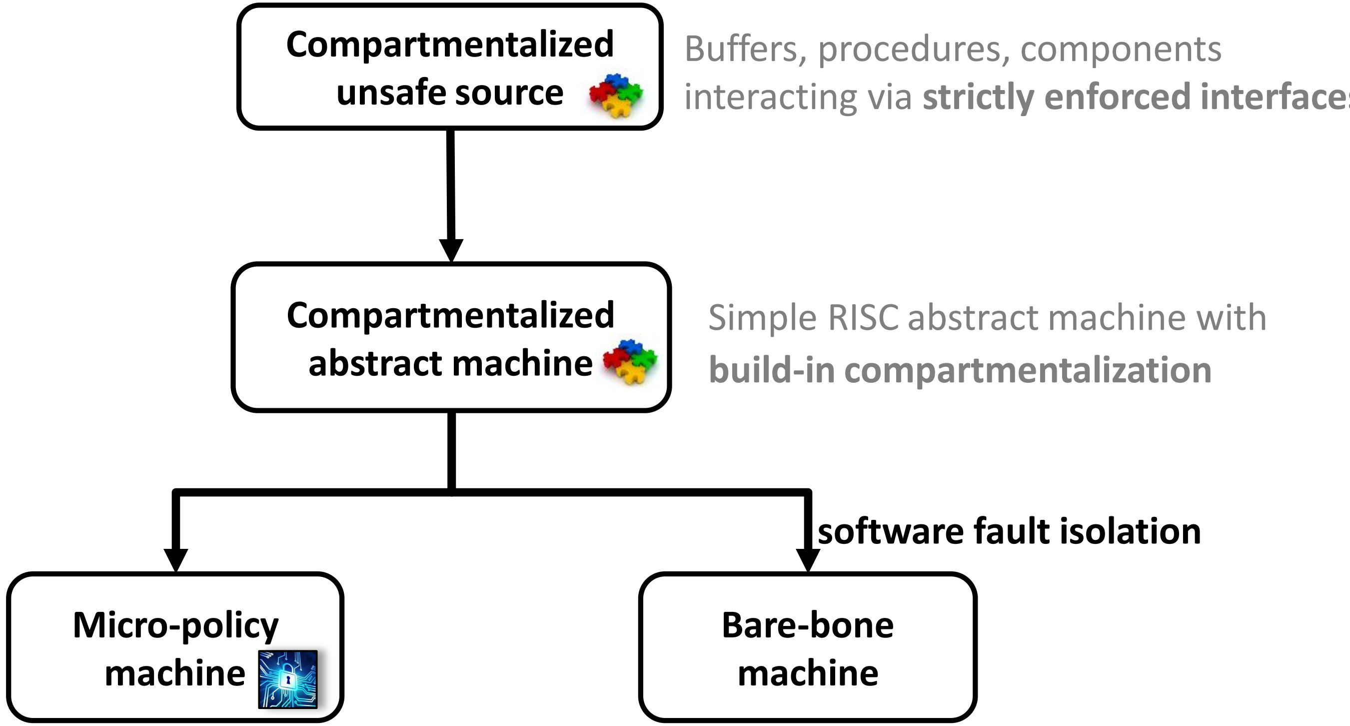
(linear capabilities / linear entry points)



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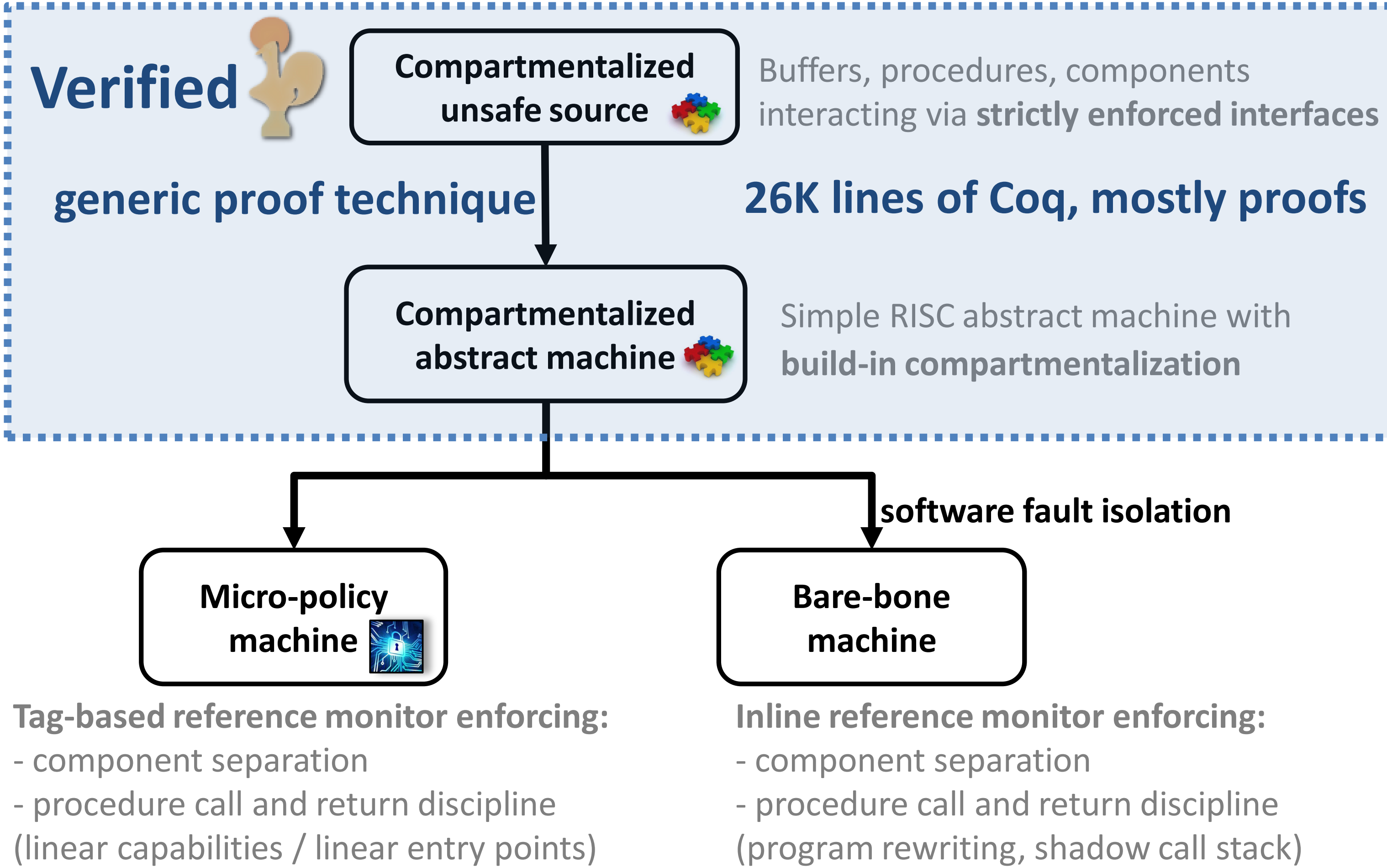
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Systematically tested (with QuickChick)

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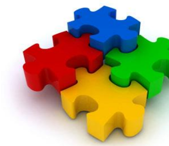

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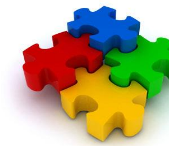

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- Generic definition and proof technique
  - we expect them to extend and scale well

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- **Secure compilation of Low*** using components, contracts, sealing, ...

My dream: secure compilation at scale

Low* language
(safe C subset in F*)

miTLS

C language
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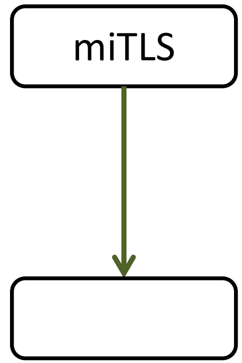

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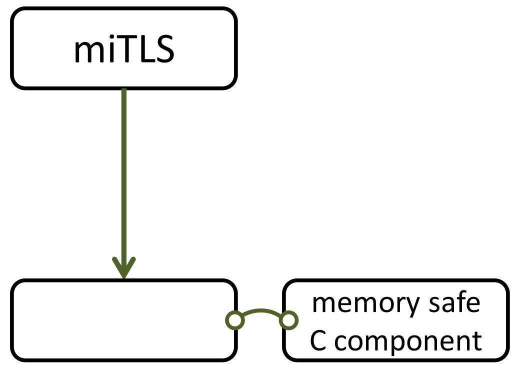

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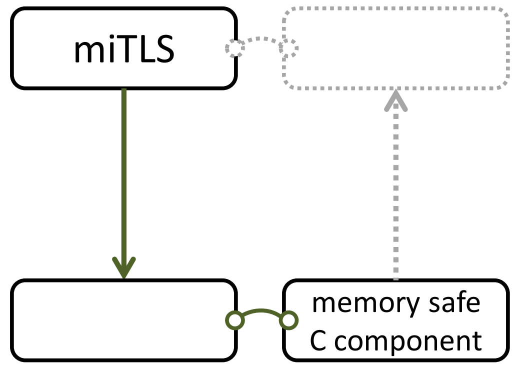

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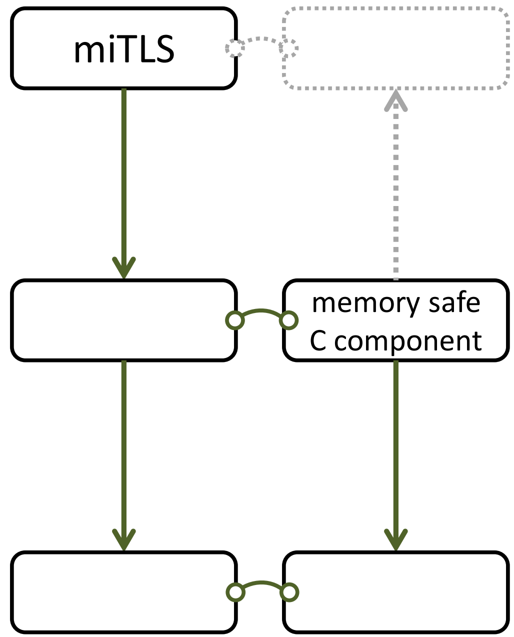

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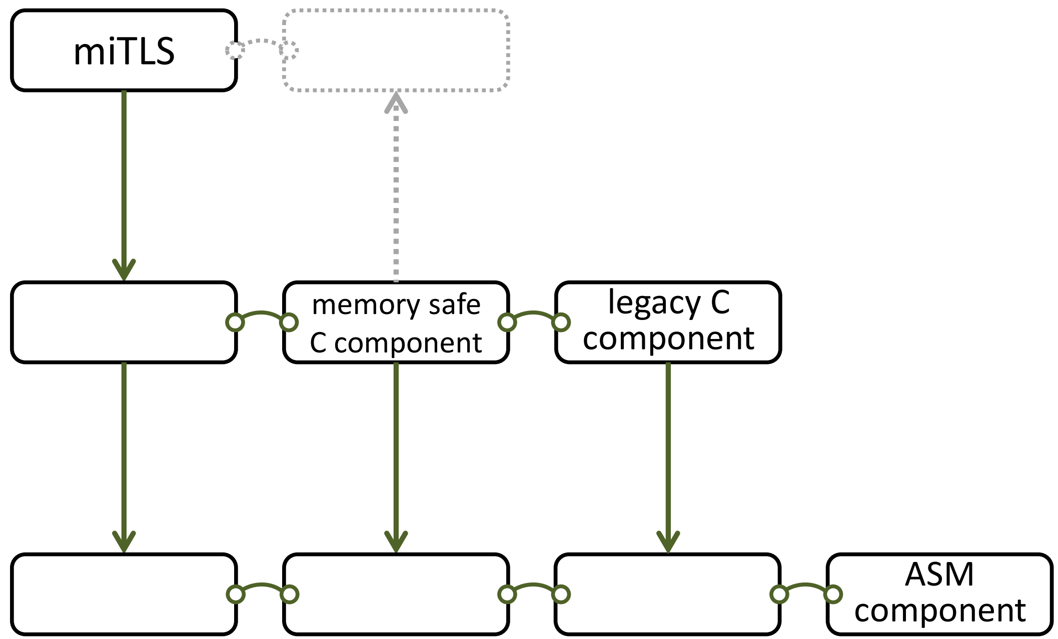

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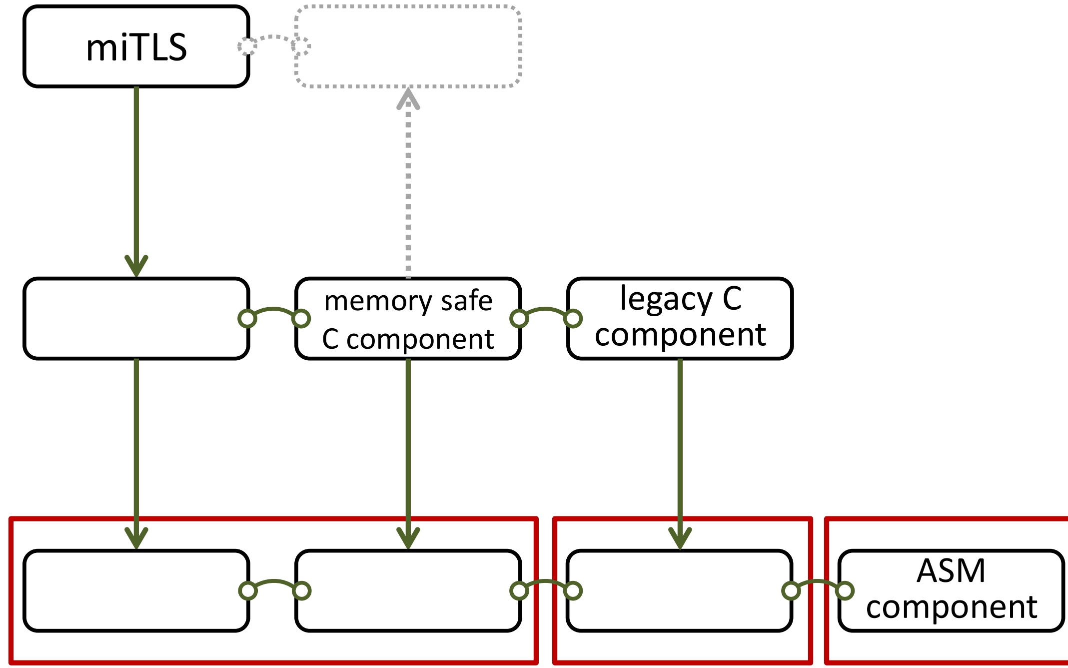

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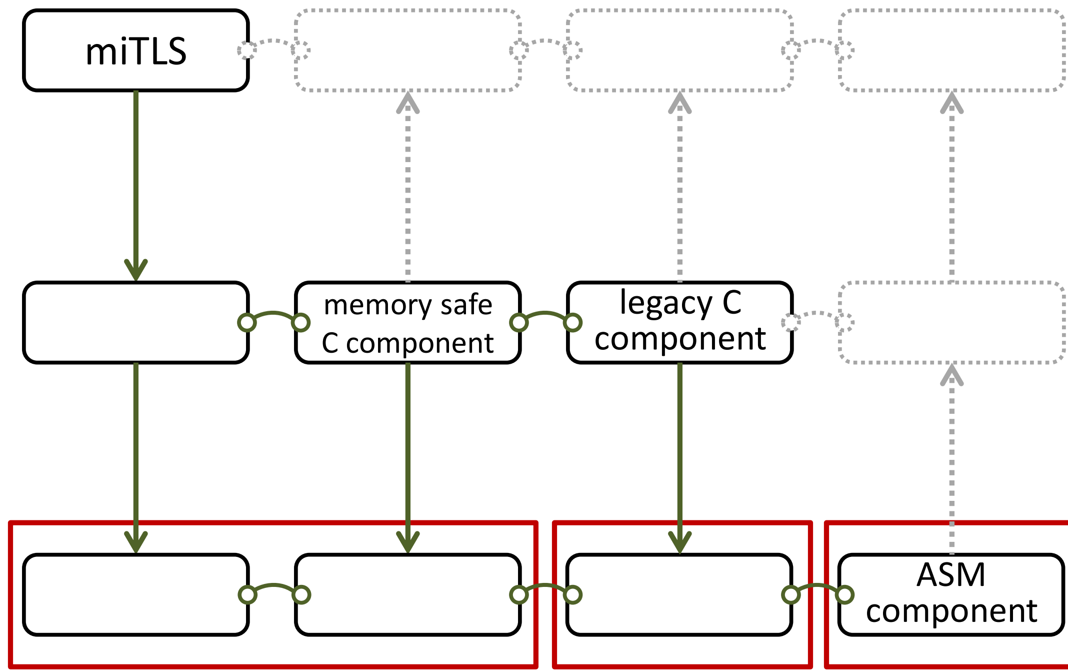

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We're HIRING **PostDocs & Researchers**

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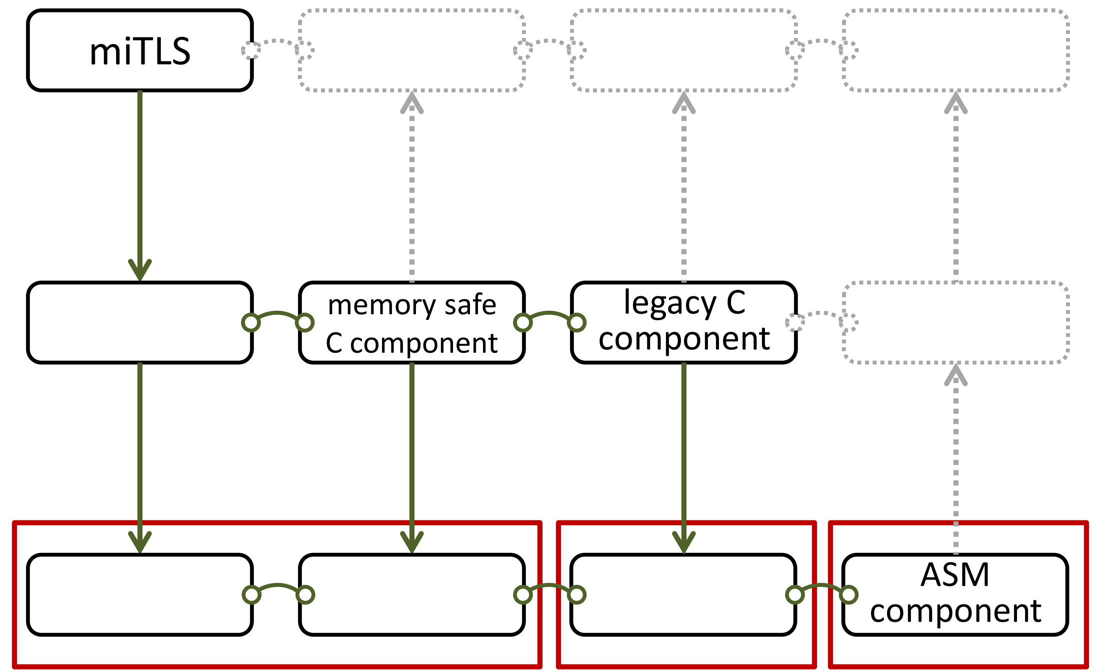

Thank you

Past group members:

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Anna Bednarik
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Clément Pit-Claudel
Danel Ahman
Diane Gallois-Wong
Guglielmo Fachini
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Simon Forest
Tomer Libal
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Yannis Juglaret
Zoe Paraskevopoulou

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Kenji Maillard
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Gilles Barthe
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David Pichardie
Karthik Bhargavan
Tamara Rezk
Xavier Leroy

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Benjamin Lipp
Bruno Blanchet
Denis Merigoux
Elizabeth Labrada
Éric Tanter
Graham Steel
Harry Halpin
Karthik Bhargavan
Marina Polubelova
Mathieu Mourey
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Stela Hrițcu