Formally Secure Compilation

Cătălin Hrițcu

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https://secure-compilation.github.io

Devastating low-level attacks

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inherently insecure languages like C/C++

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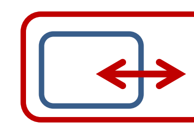
insecure interoperability with lower-level code

- even code in **more secure languages (Java, OCaml, Rust)** has to interoperate with **low-level code (C, C++, ASM)**
- **insecure interoperability**: all source-level guarantees lost



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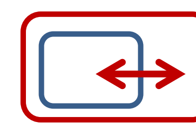

- **insecure interoperability**: all source-level guarantees lost

Part 1: formalize what it means to solve this problem

Devastating low-level attacks

Part 2: give meaning to mitigation (protected components)

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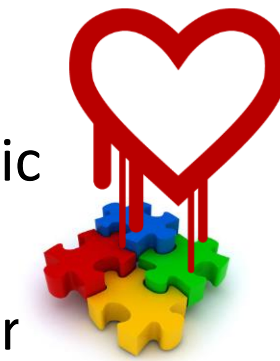

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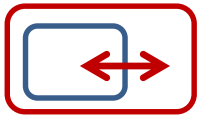

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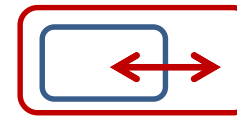
Part 1 of 2

Secure Interoperability with Lower-Level Code



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U. Trento

Deepak Garg
MPI-SWS

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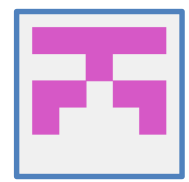

Jérémy Thibault
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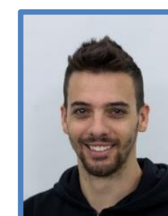

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Stanford

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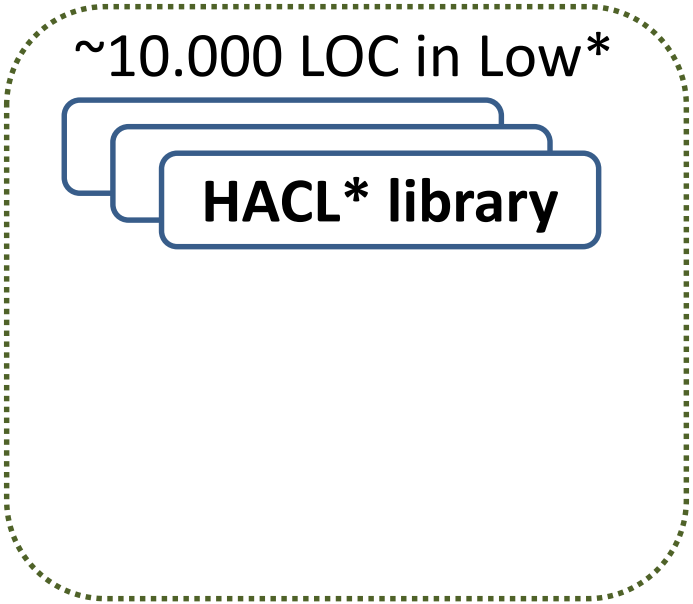
  - **most features of verification systems like Coq and Dafny**
  - **patterns specific to cryptographic code**

Abstractions not enforced when linking with adversarial low-level code



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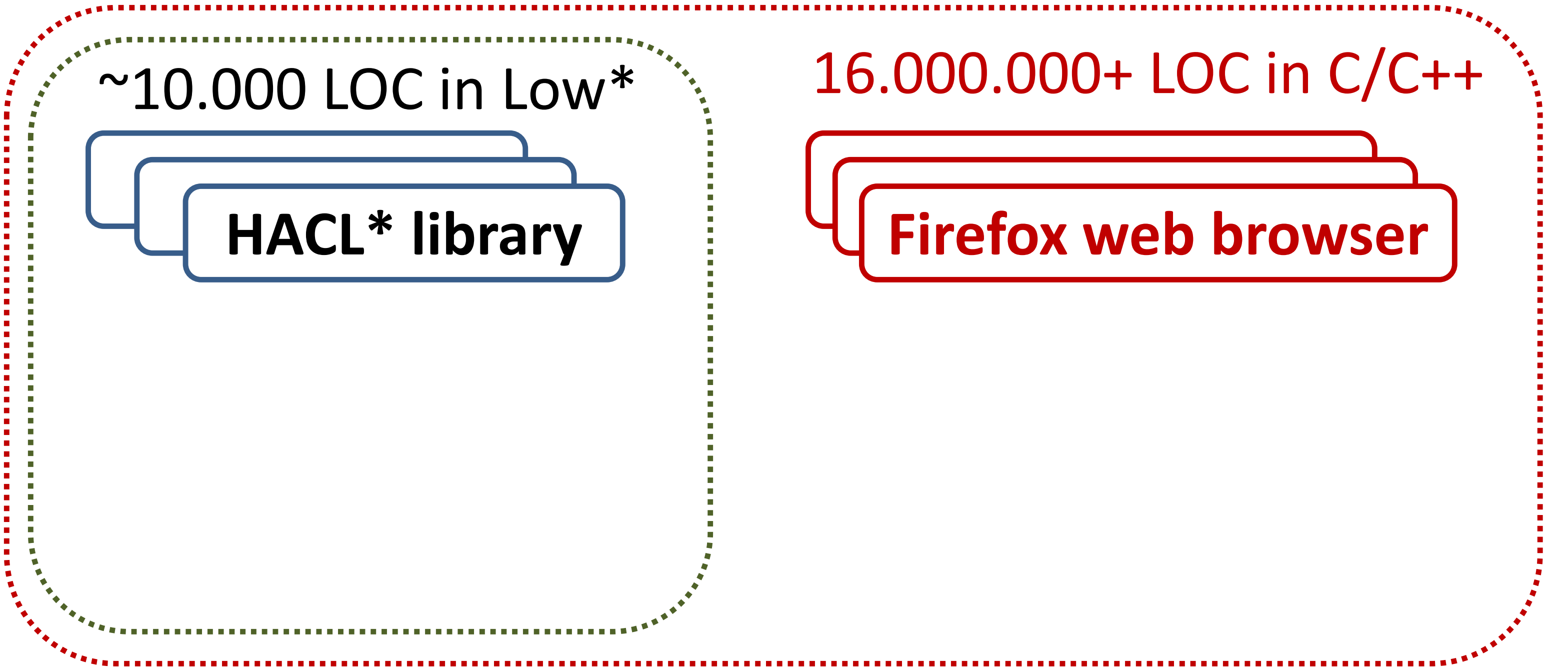

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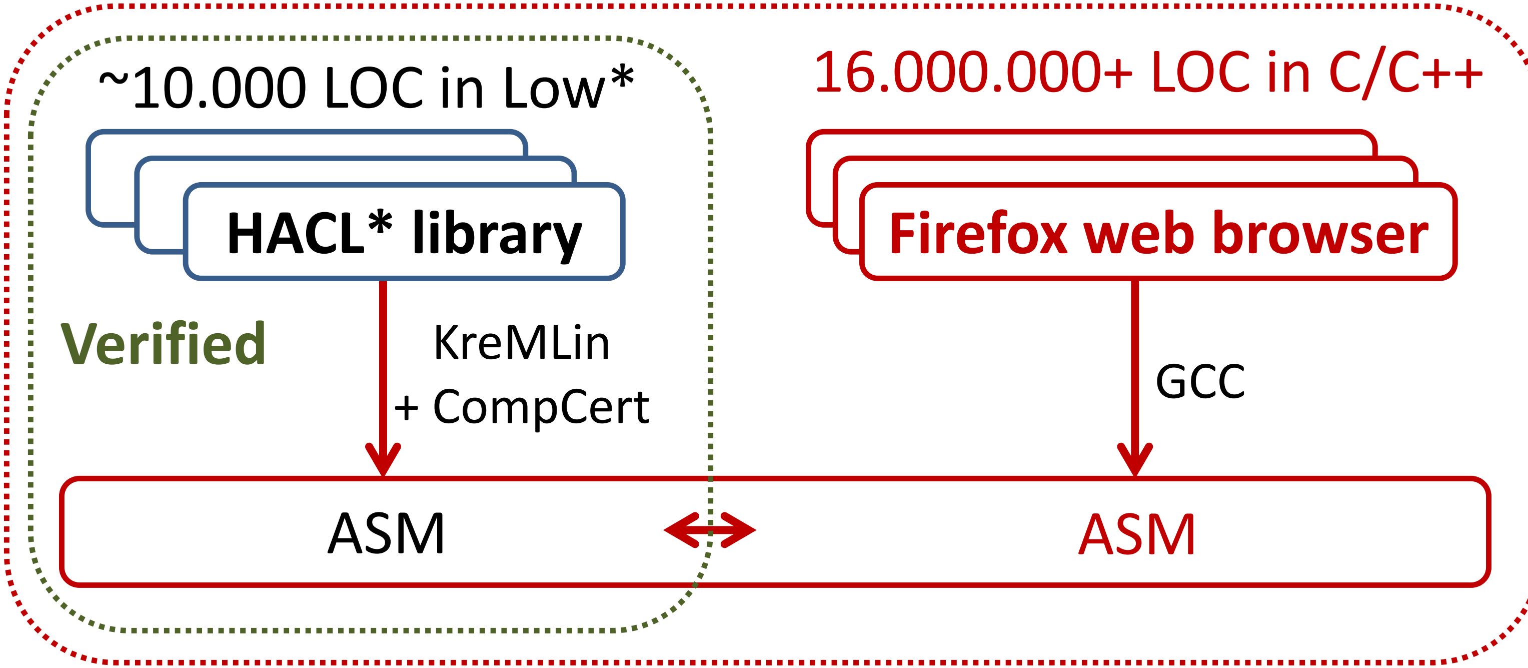

Insecure interoperability: compromised (or malicious) application linking in miTLS can easily **read and write miTLS's data and code**, **jump to arbitrary instructions**, **smash the stack**, ...

Secure compilation

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- **Enable source-level security reasoning**
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  - **no "low-level" attacks**
  - **no need to worry about the compilation chain** (compiler, linker, loader, runtime, system, hardware)

Source-level security reasoning

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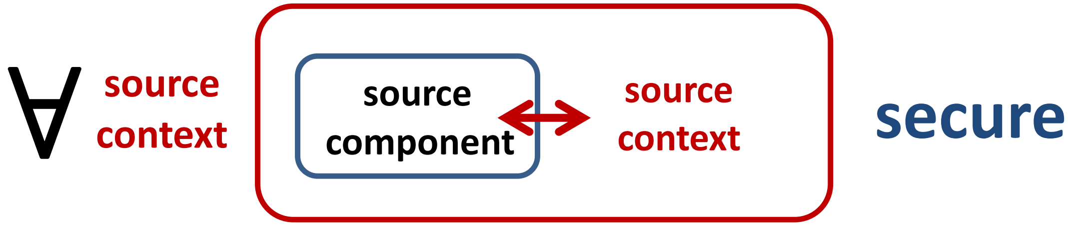

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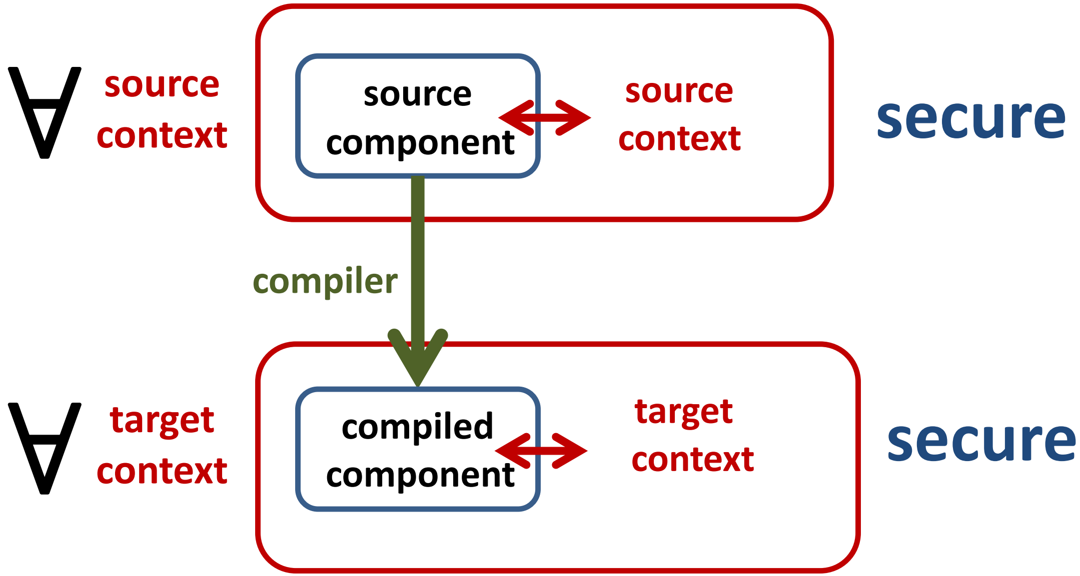

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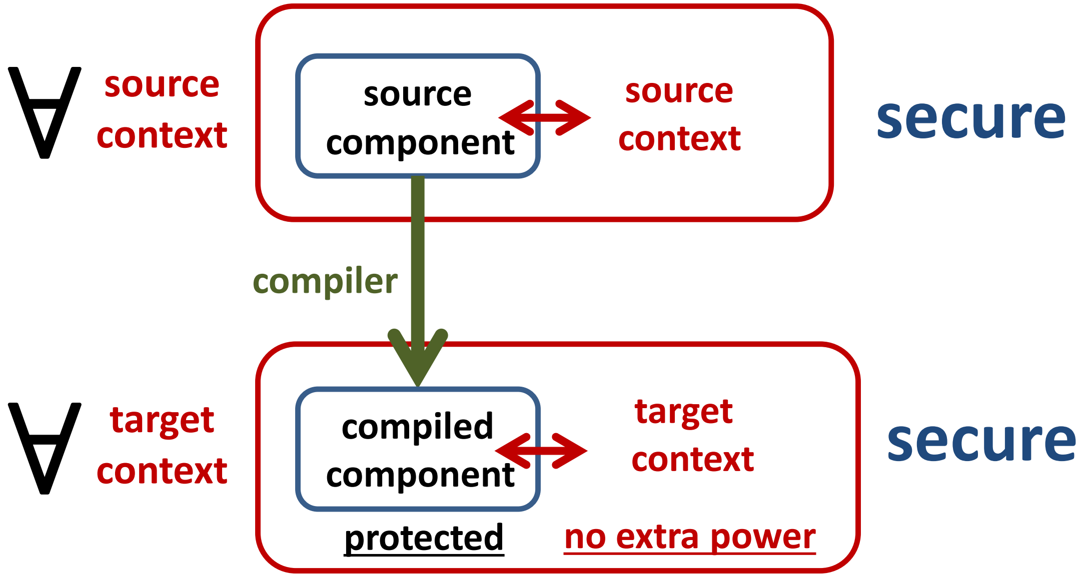

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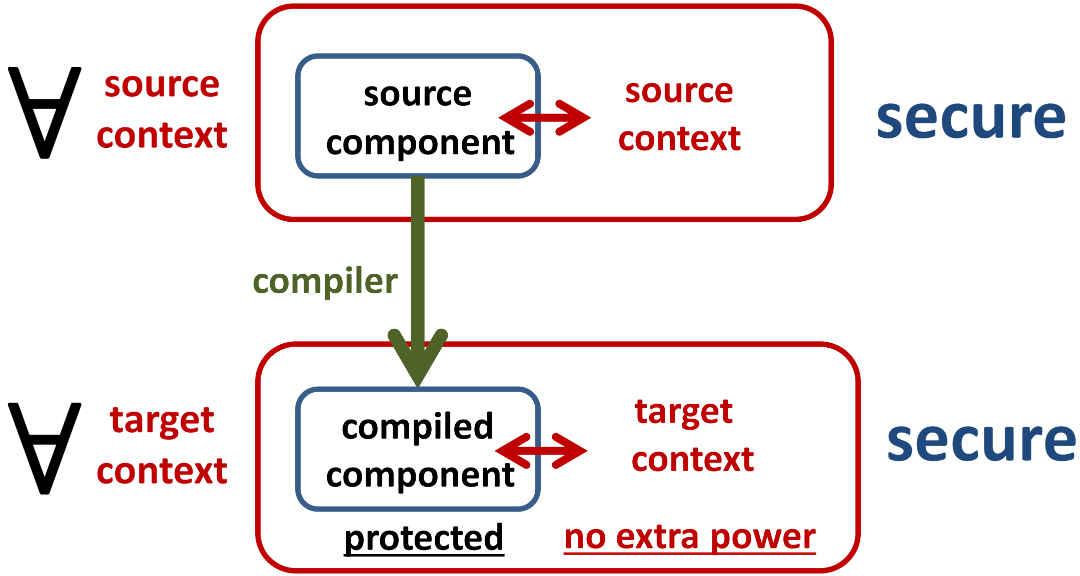

But what does "secure" mean?

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  - **hyperproperties** (e.g. noninterference)
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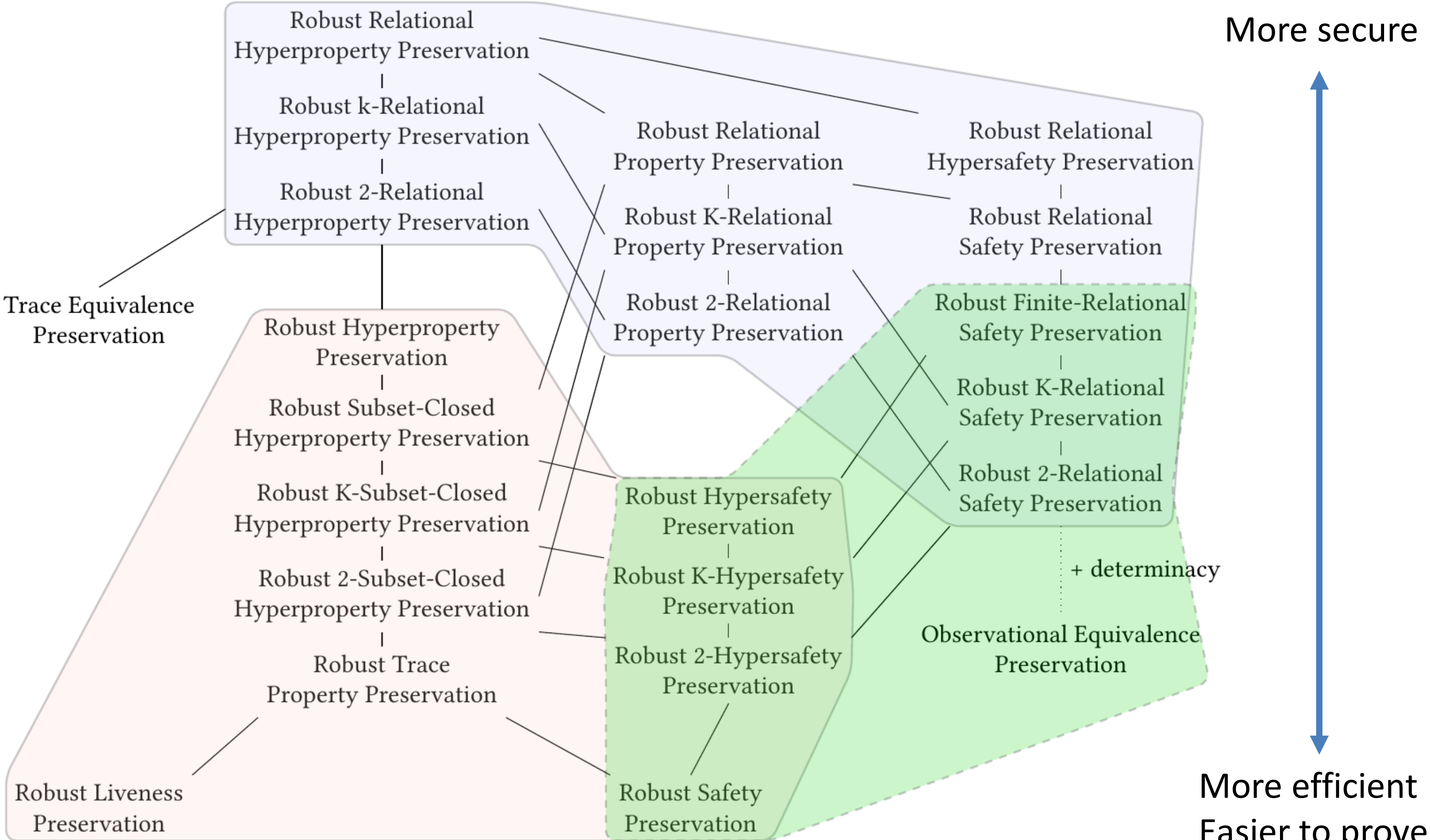
- **No "one-size-fits-all solution"**
  - e.g. full abstraction does **not** imply the other criteria we study
  - **stronger** criteria are **harder** to achieve and prove, both challenging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More secure
More efficient
Easier to prove

Robust Trace Property Preservation

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∀source component.

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

⇓

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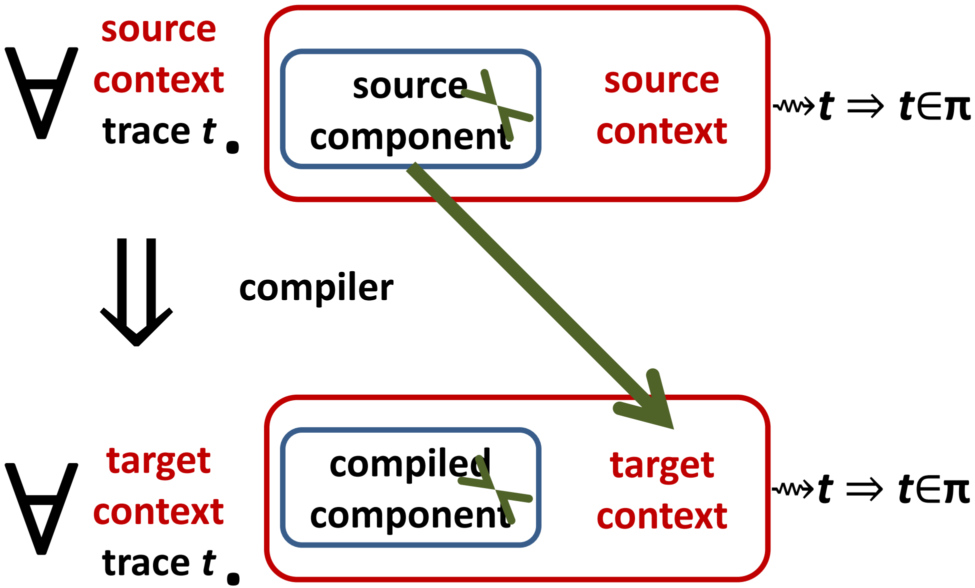

Robust Trace Property Preservation

property-based characterization

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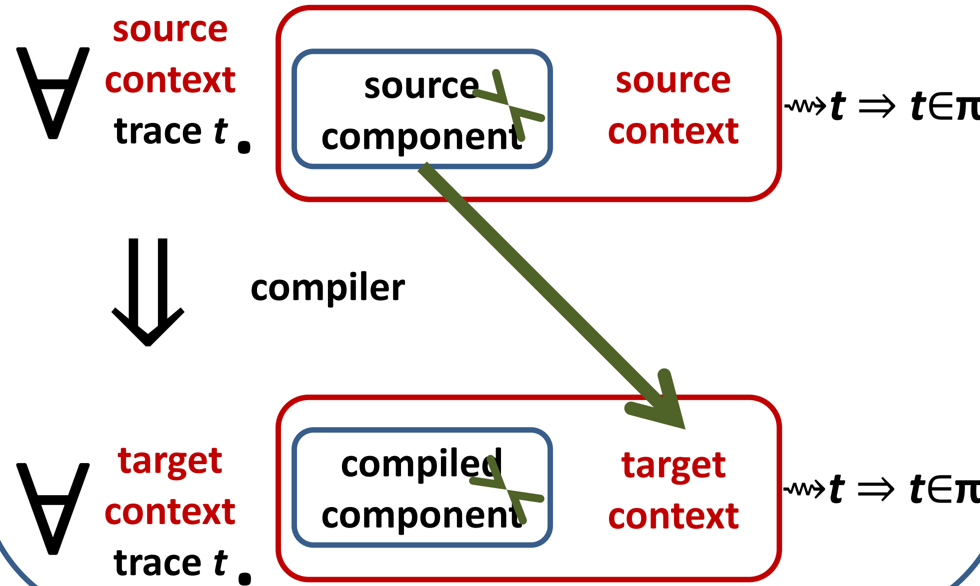

preservation of **robust** satisfaction

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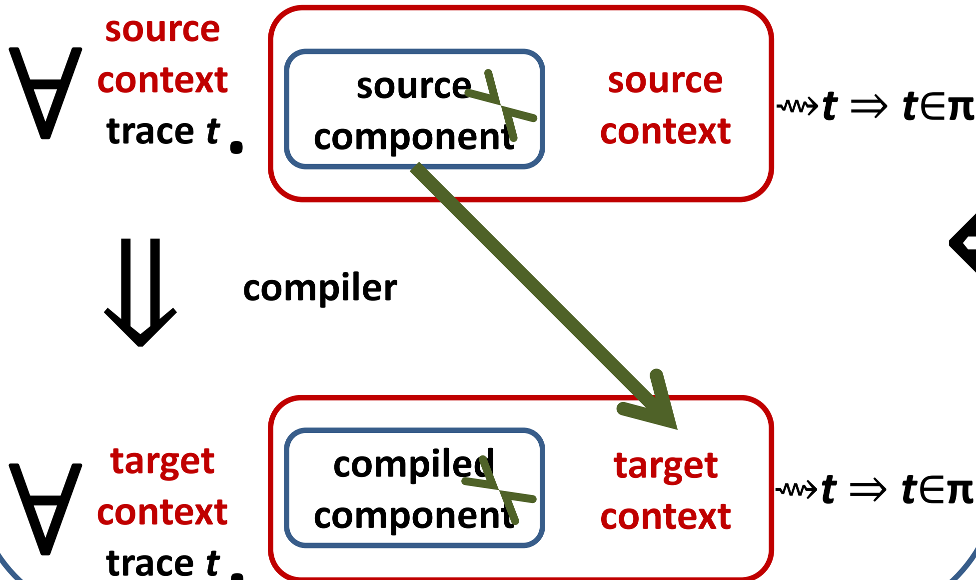

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property-free characterization

preservation of **robust** satisfaction

how one can prove it

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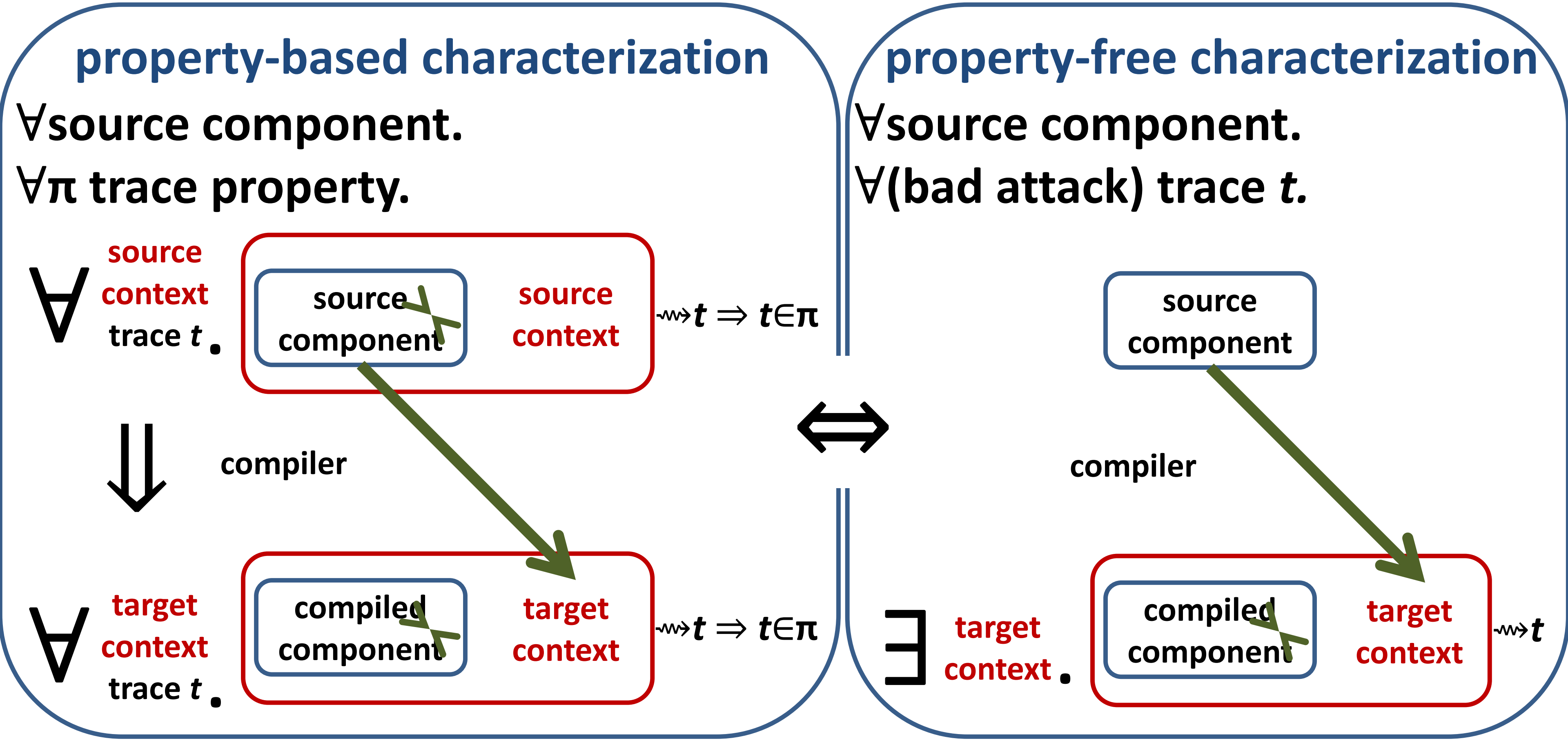

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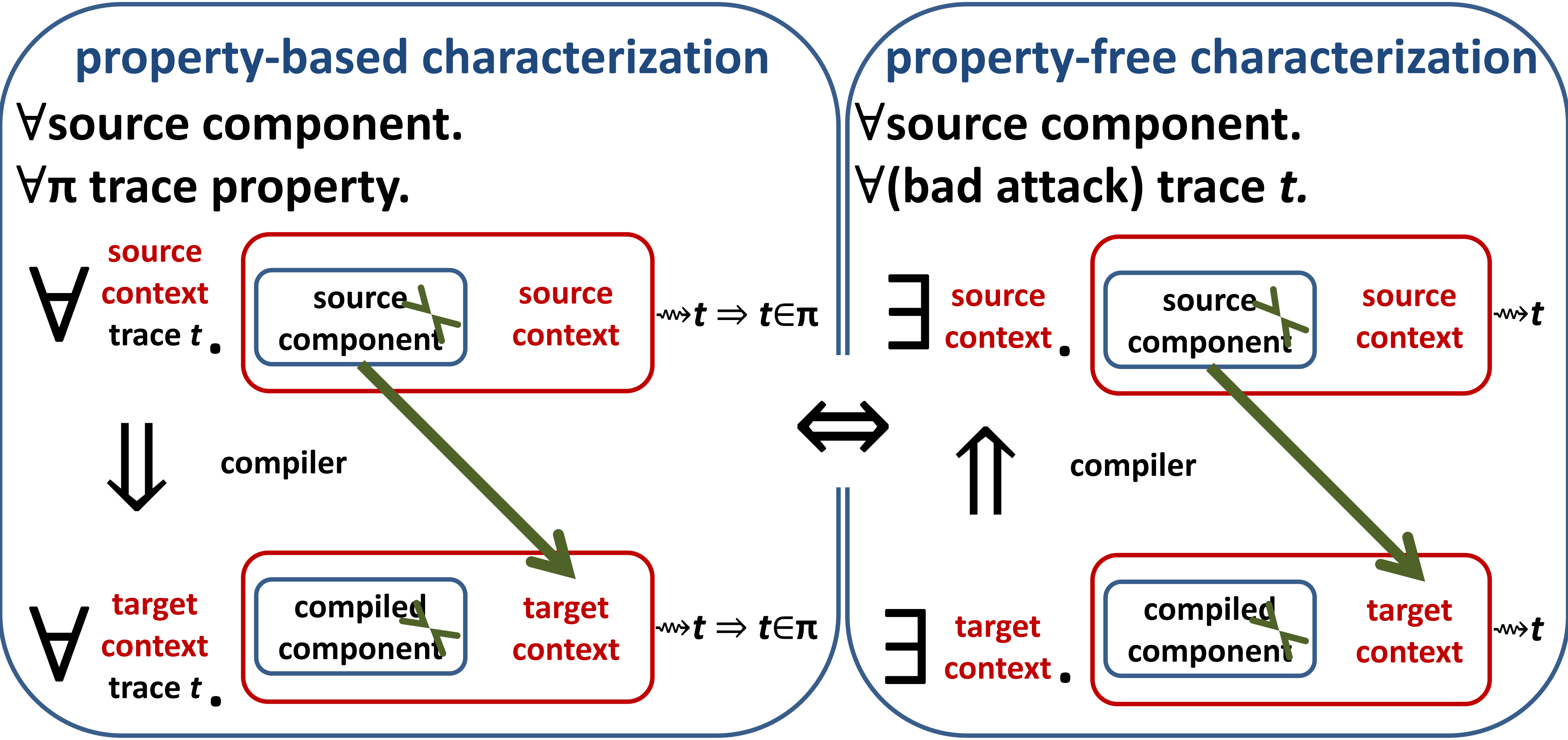

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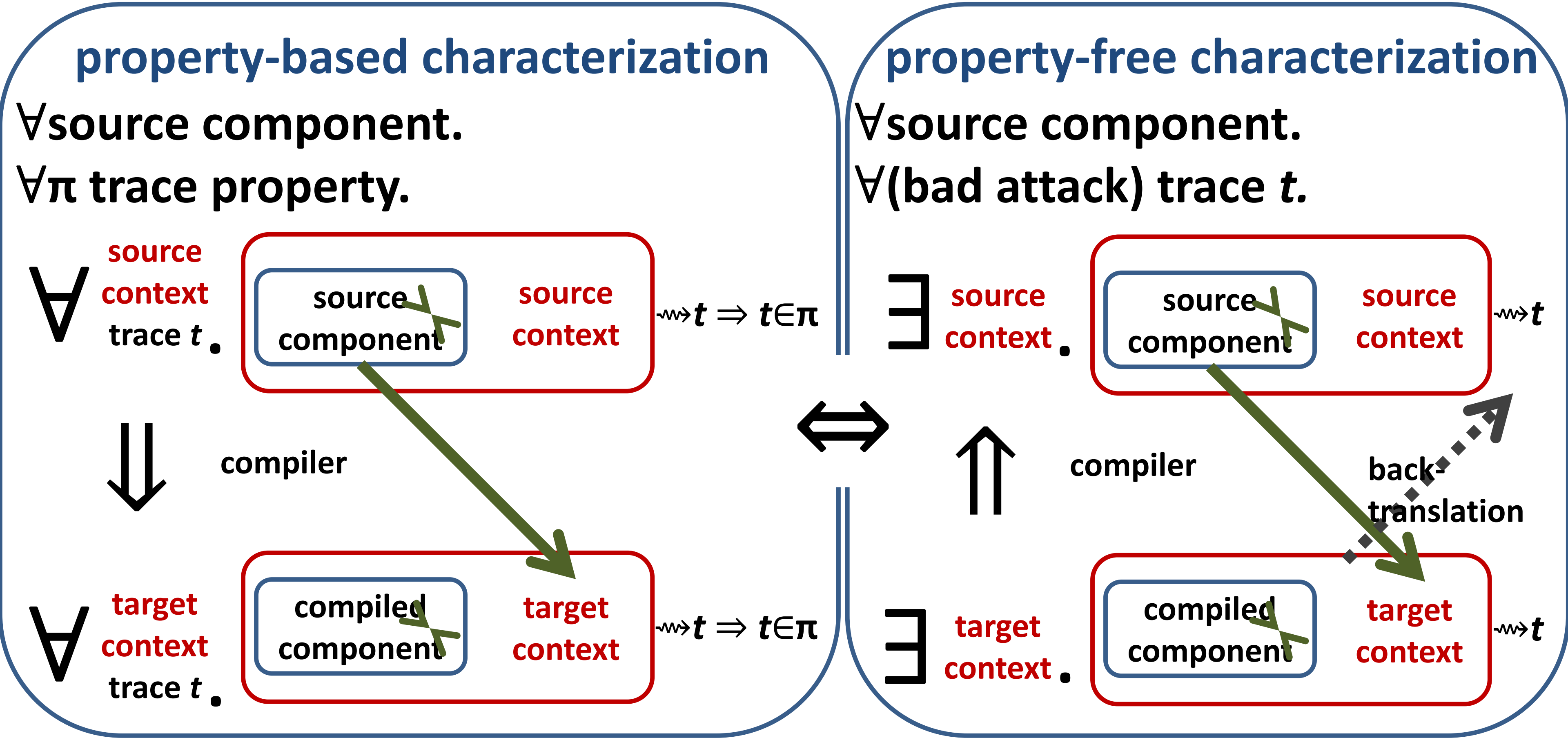

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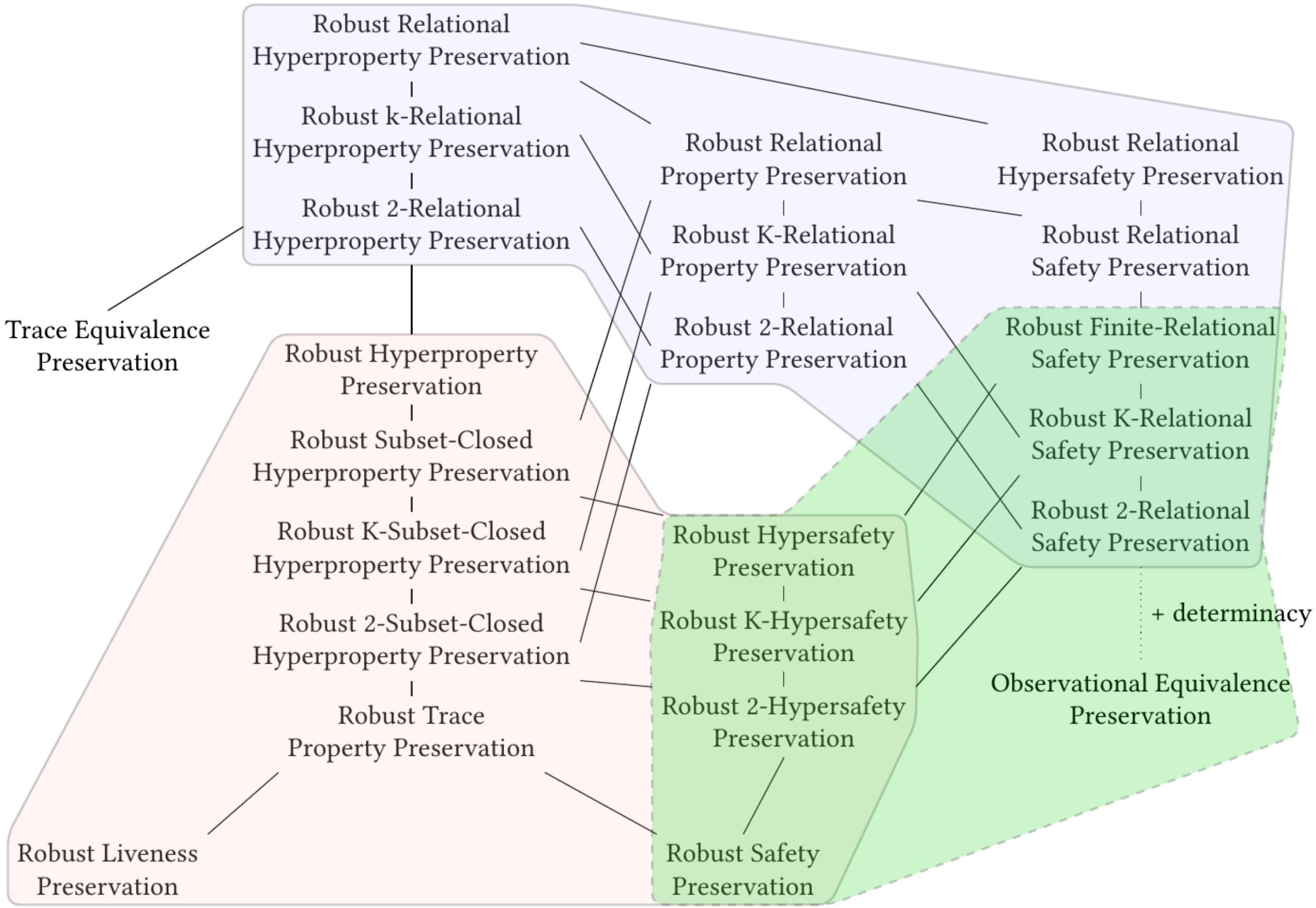

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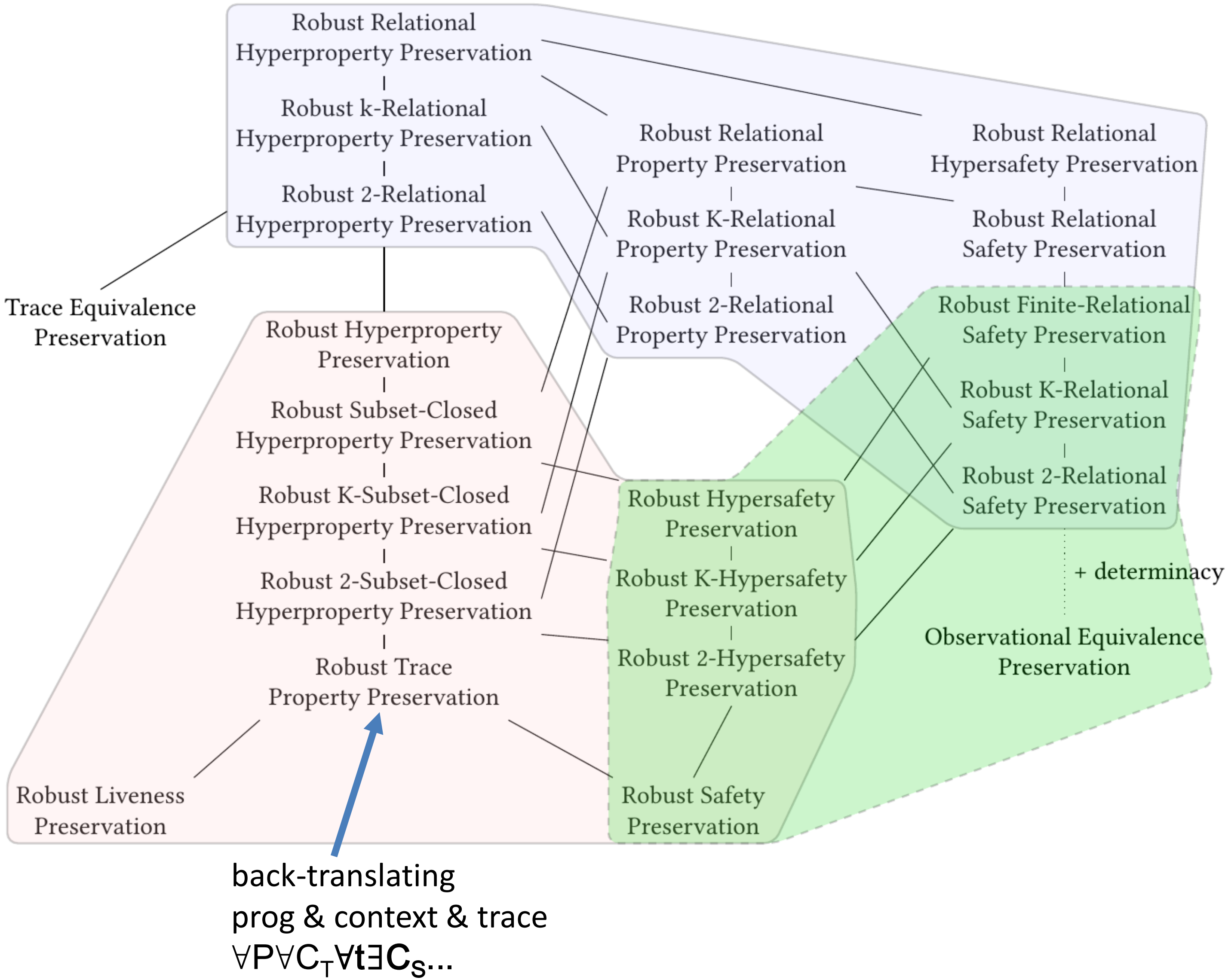
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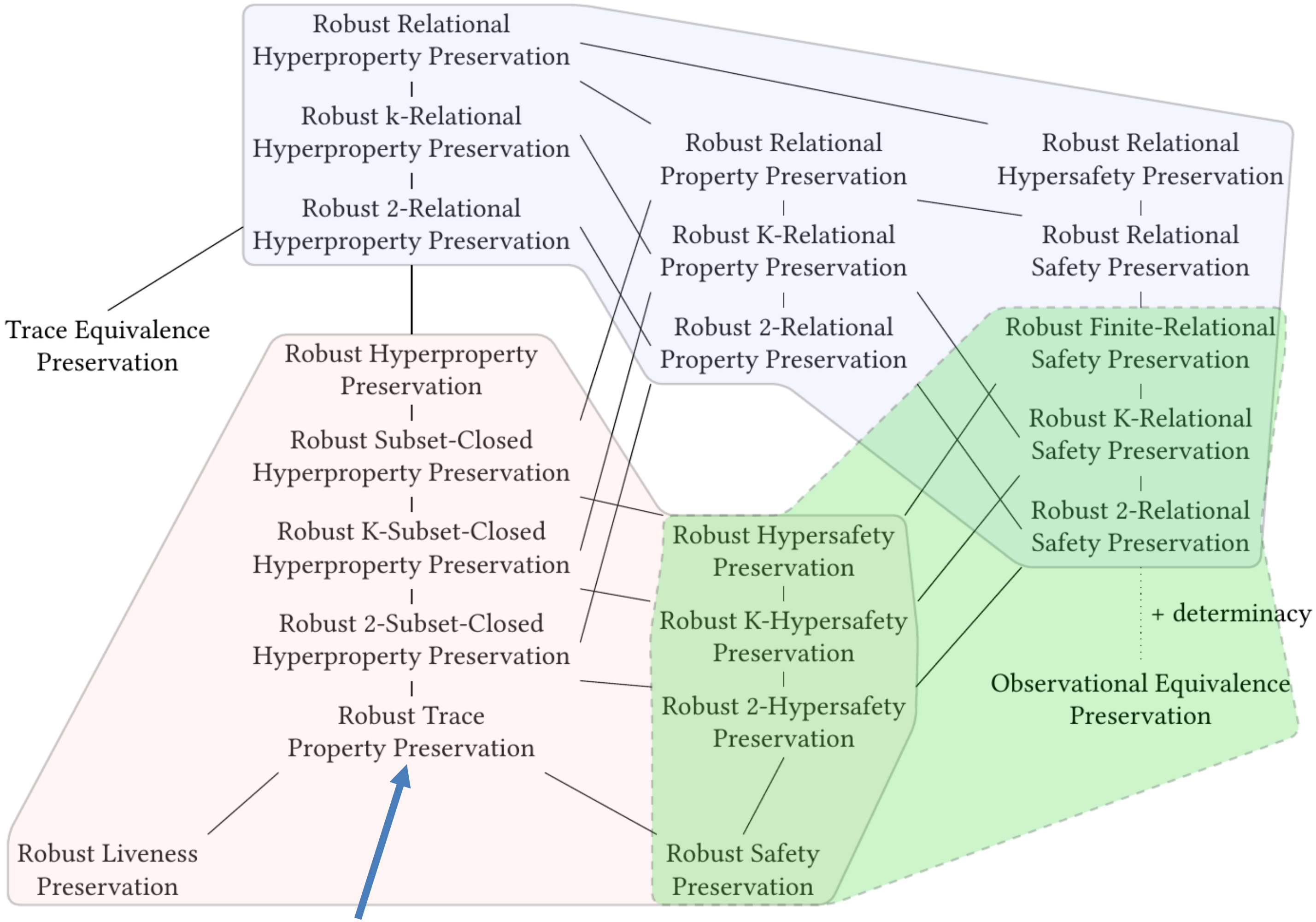
back-translating
prog & context & trace
∀P∀C_T∀t∃C_S...



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$\forall P \forall C_T \forall \mathbf{t} \exists \mathbf{C_S}$...

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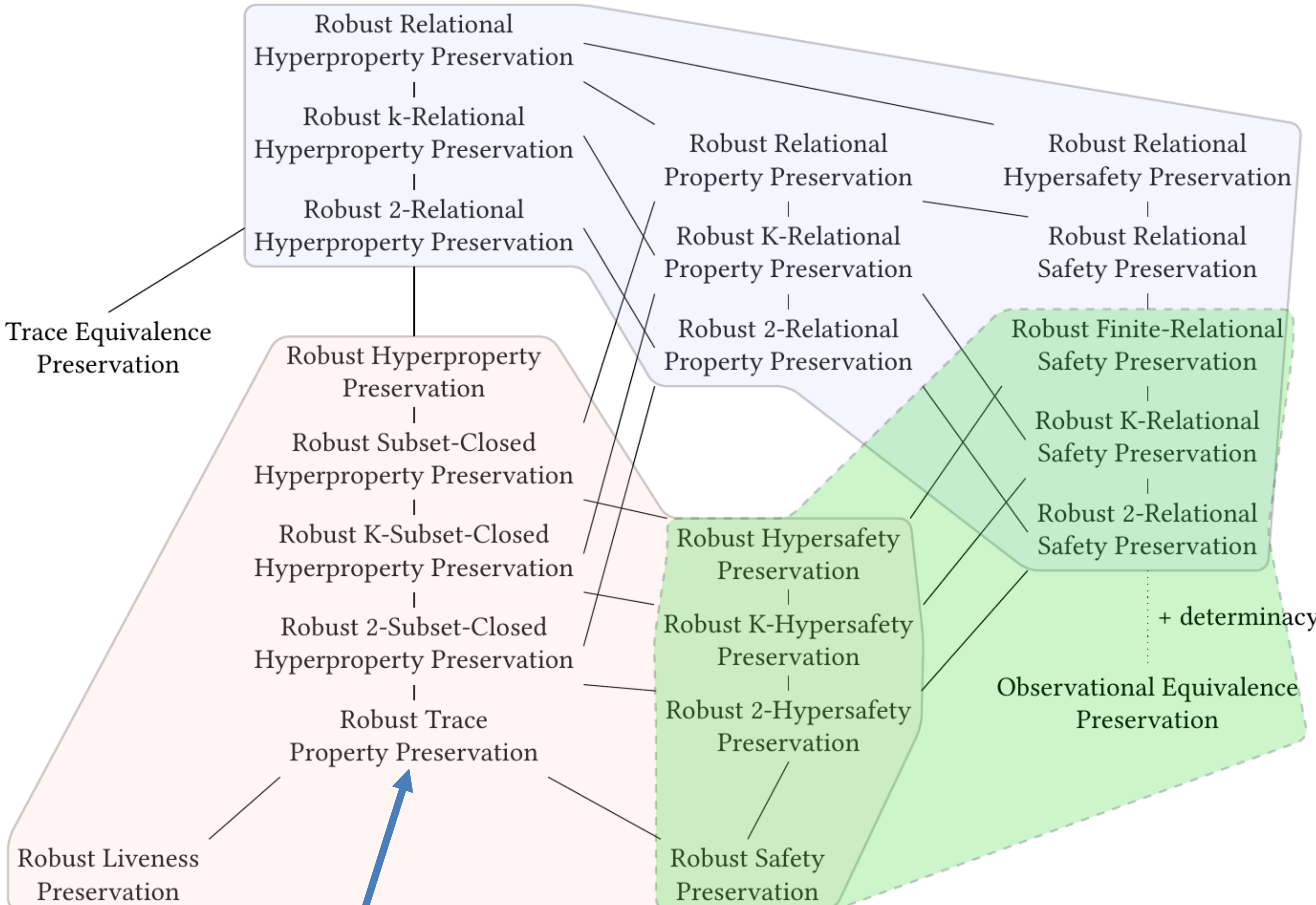

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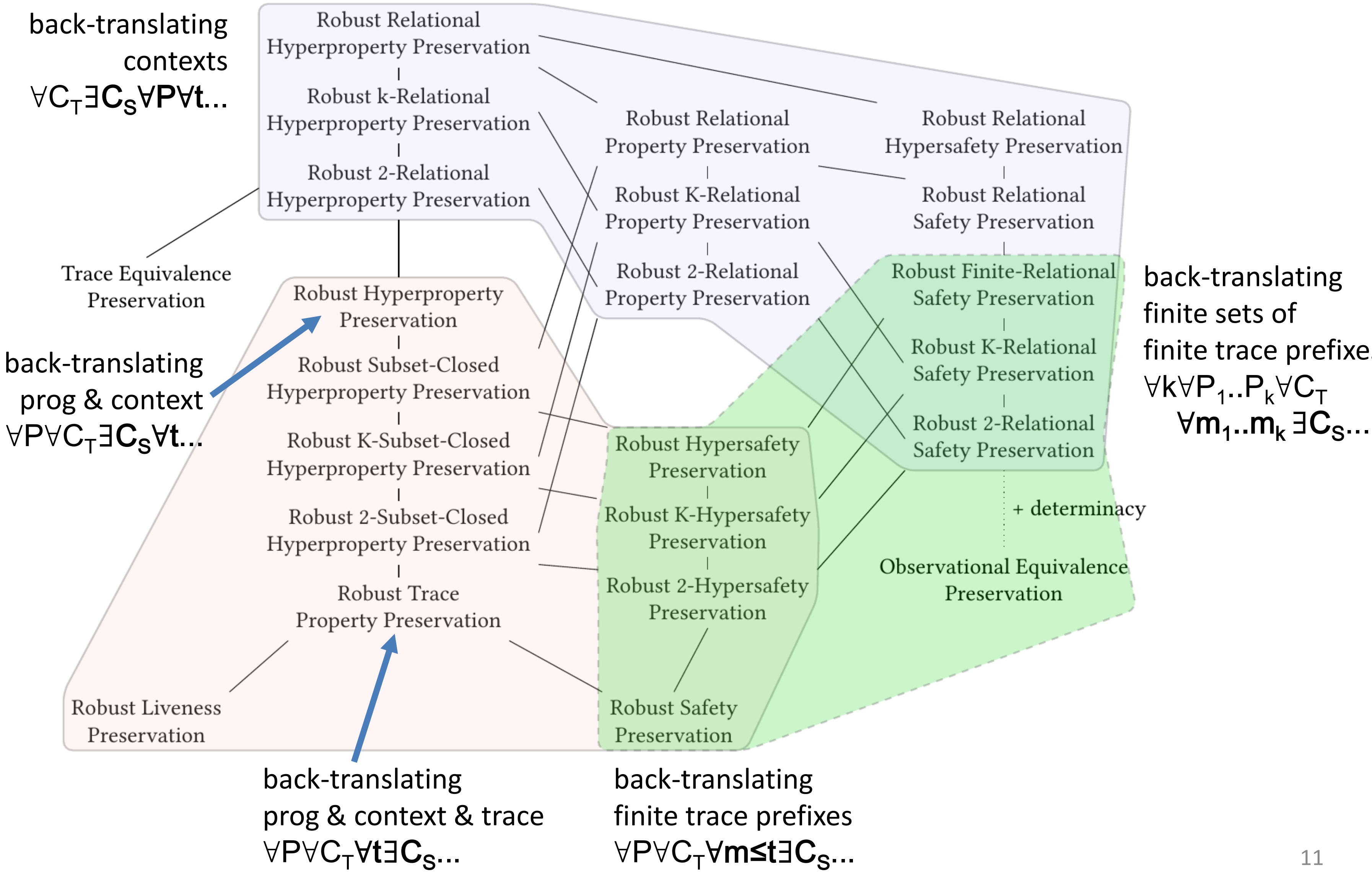
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  - **Separation results** (e.g. robust safety/liveness preservation strictly weaker than robust trace property preservation)
  - **Surprising collapse** between preserving all hyperproperties and preserving just hyperliveness
- Showed that **even strongest criterion is achievable**
  - for simple translation from a statically to a dynamically typed language with first-order functions and I/O

Some open problems

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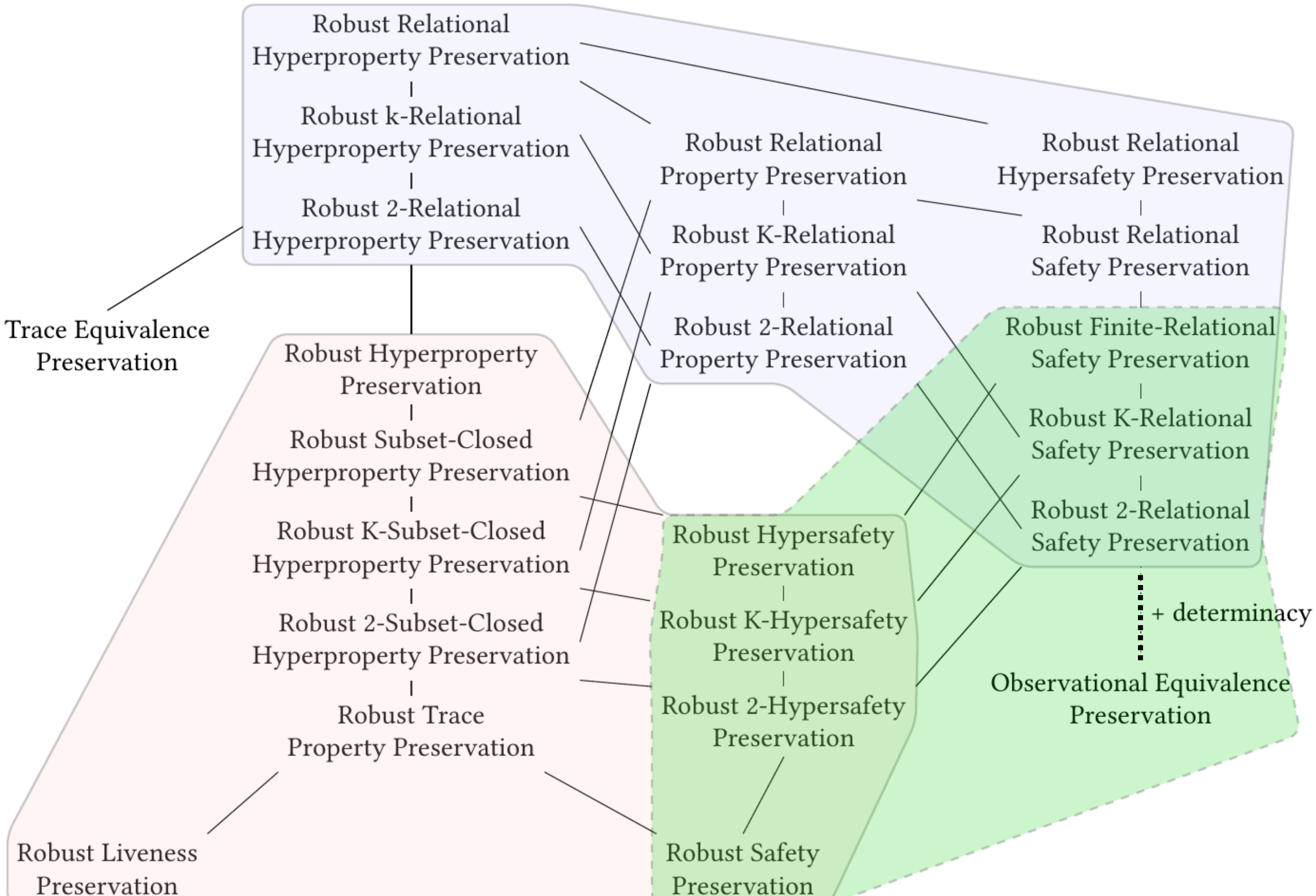
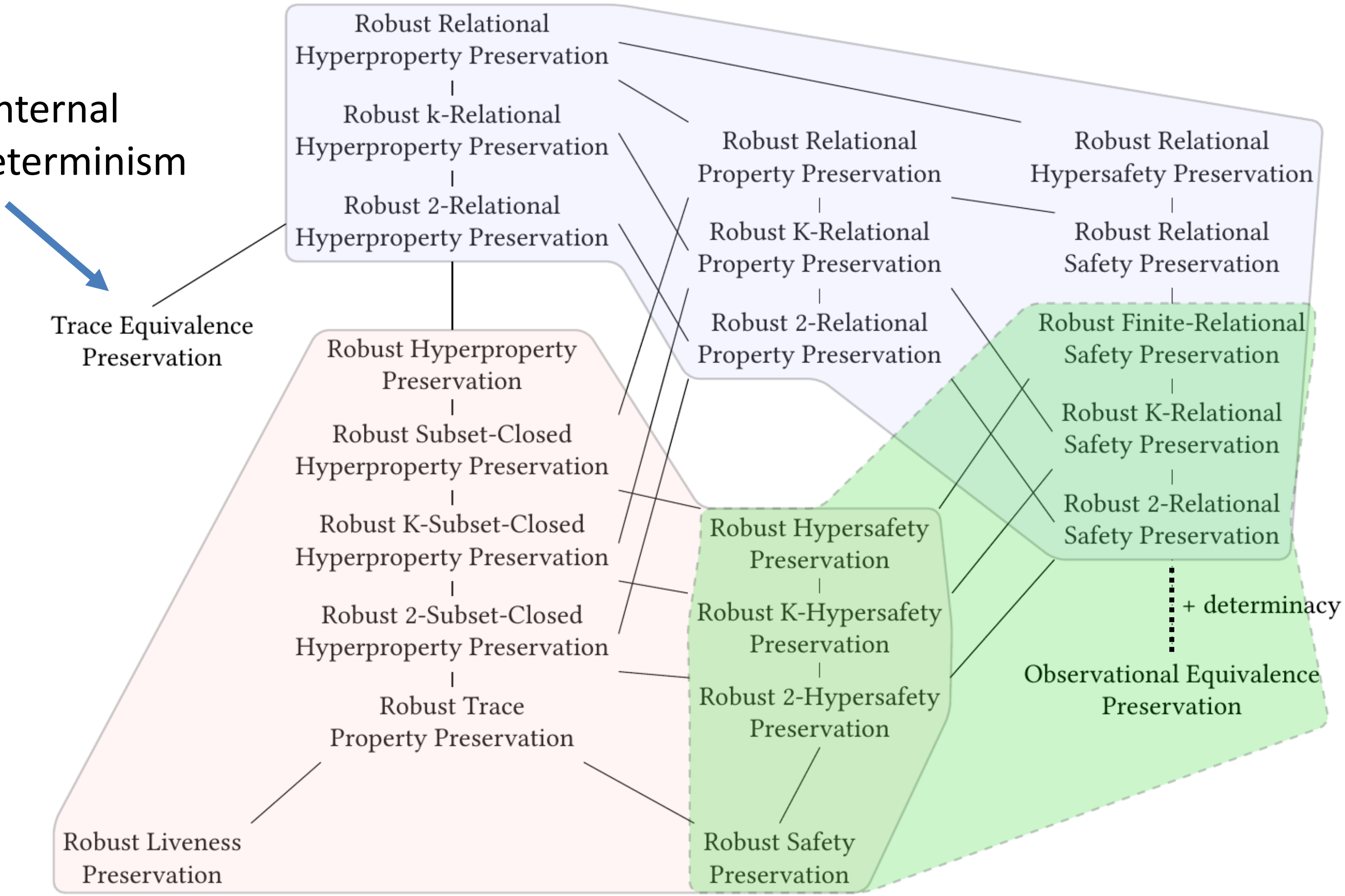
  - Achieve **noninterference preservation** in realistic attacker model **with side-channels**
  - **Efficient enforcement mechanisms**
- **Scalable proof techniques for other criteria**
  - (hyper)liveness preservation (possible?)
- **Nontrivial relation between source and target traces**

Where is full abstraction?



Where is full abstraction?

with internal nondeterminism



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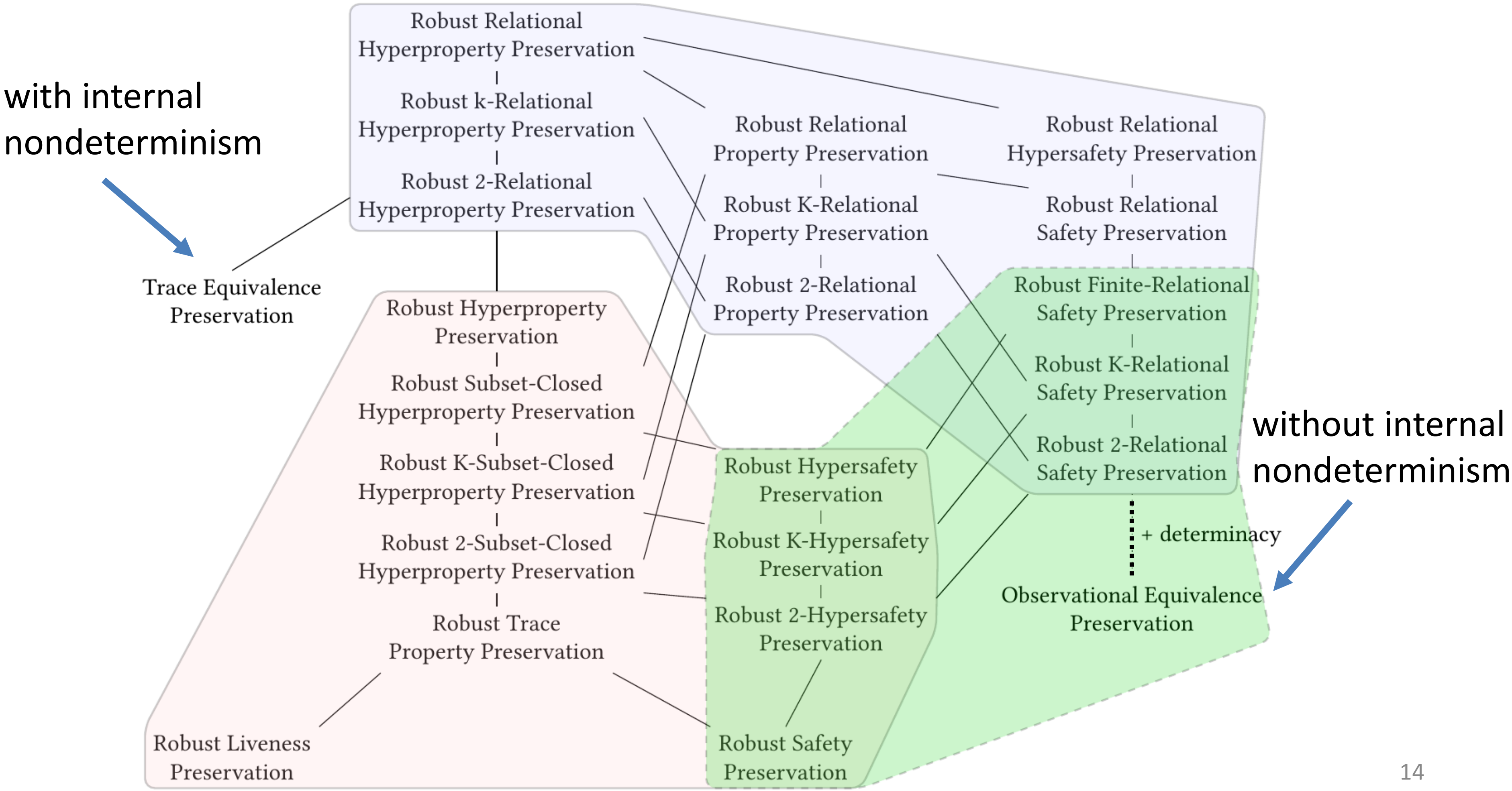

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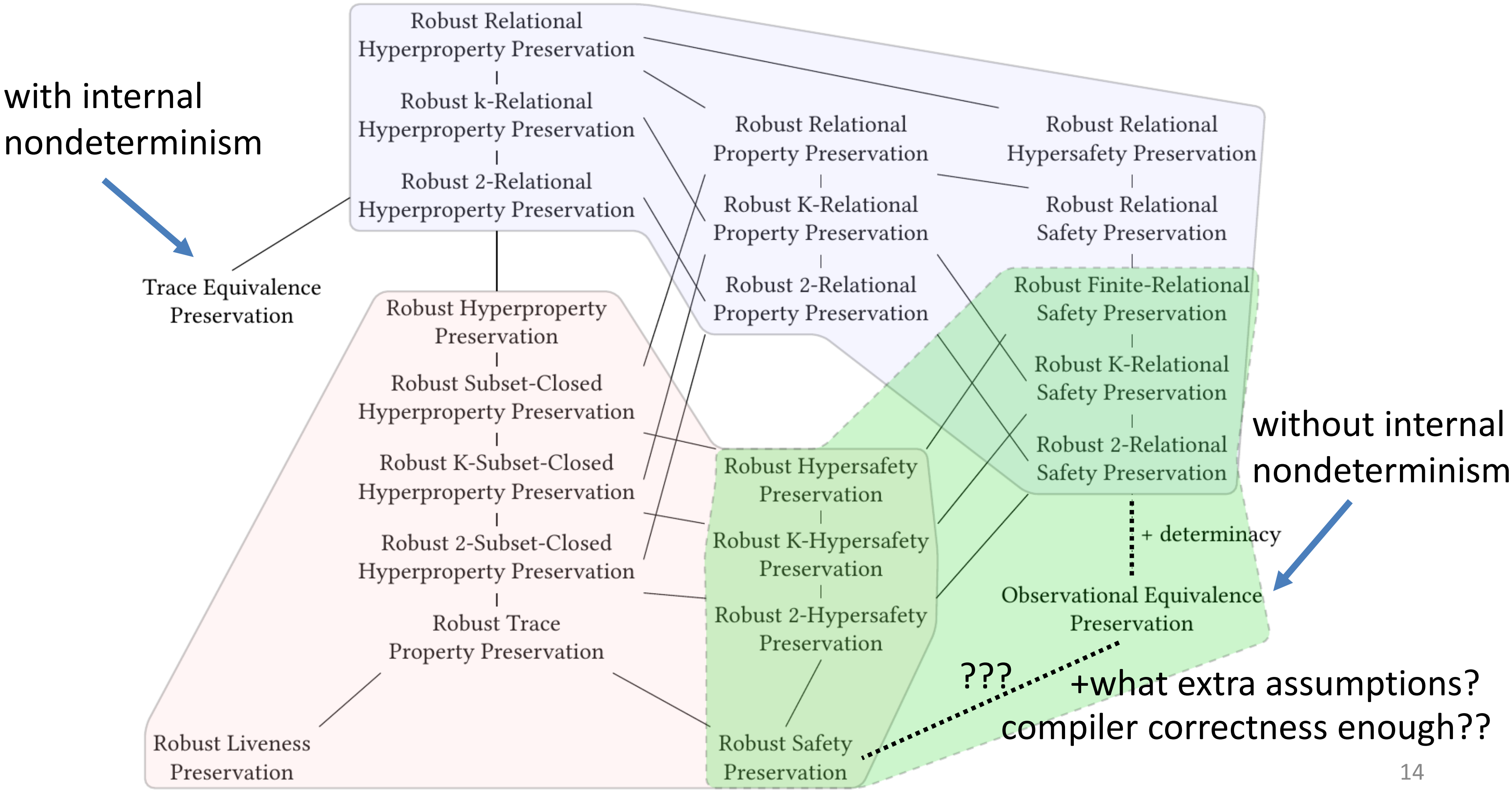


Part 2 of 2

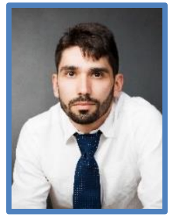
When Good Components Go Bad

Secure Compilation Despite Dynamic Compromise

https://arxiv.org/abs/1802.00588

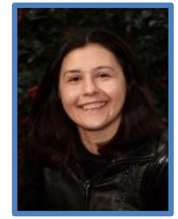
Collaborators for Part 2

Carmine Abate



Arthur Azevedo de Amorim

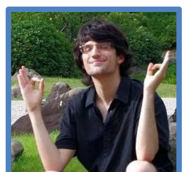
Rob Blanco



Ana Nora Evans

Guglielmo Fachini

Cătălin Hrițcu



Yannis Juglaret

Théo Laurent

Benjamin Pierce

Marco Stronati

Andrew Tolmach

Inria Paris CMU U. Virginia U. Trento Paris 7 ENS Paris Portland State UPenn

Undefined behavior

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

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$ gcc target.c
$ ./a.out haha
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zsh: segmentation fault (core dumped)
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zsh: segmentation fault (core dumped)
$ ./exploit.sh | a.out
```
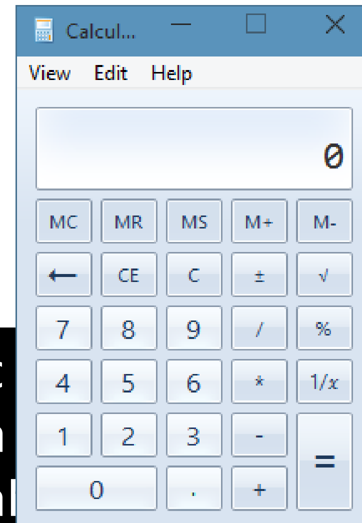

Undefined behavior

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



erflow

```
$ gcc target.c
$ ./a.out haha
$ ./a.out hahal                haha
zsh: segmentation fault (core dumped)
$ ./exploit.sh | a.out
```

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Goal 2: Build secure compilation chains

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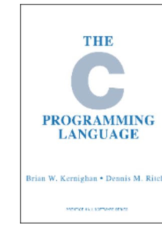

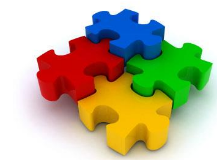

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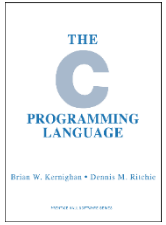

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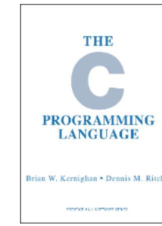

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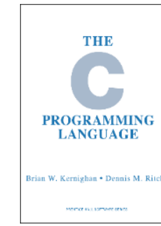
- **Use efficient enforcement mechanisms:**
  - OS processes (all web browsers) — WebAssembly (web browsers)
  - software fault isolation (SFI) — capability machines
  - hardware enclaves (SGX) — tagged architectures



Goal 1: Formalizing the security of compartmentalizing compilation

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  - GCC and LLVM **currently violate** this model

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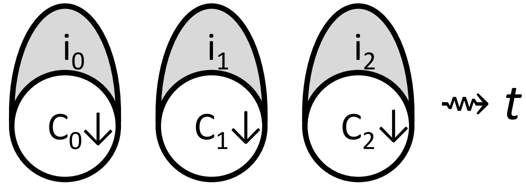
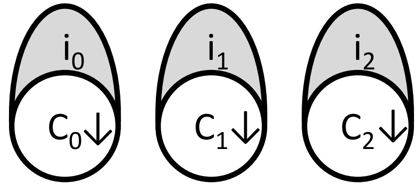
- the mere existence of vulnerabilities doesn't immediately make a component compromised

If  then

If 

⇝ *t* then

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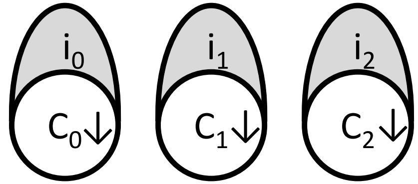
If 

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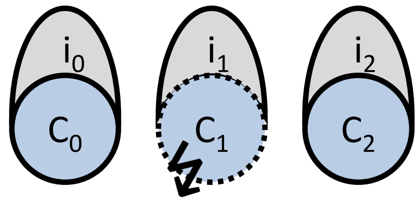
(0) 

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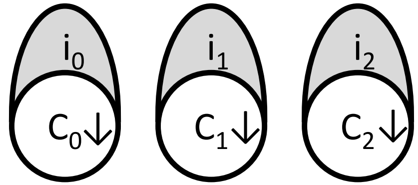
If  ⇝ t then

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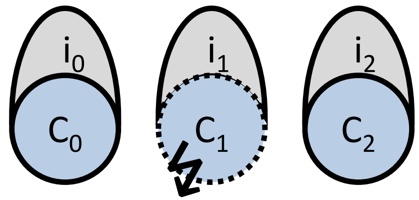
(0)  ⇝* m_1;Undef(C_1)

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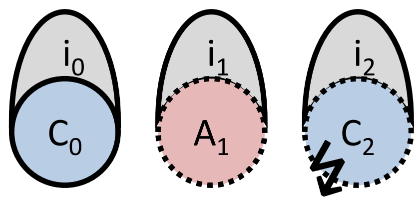
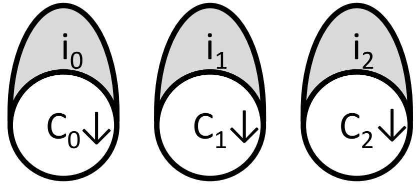
(1) ∃A_1.  ⇝* m_2;Undef(C_2)

If  ⇝ t then

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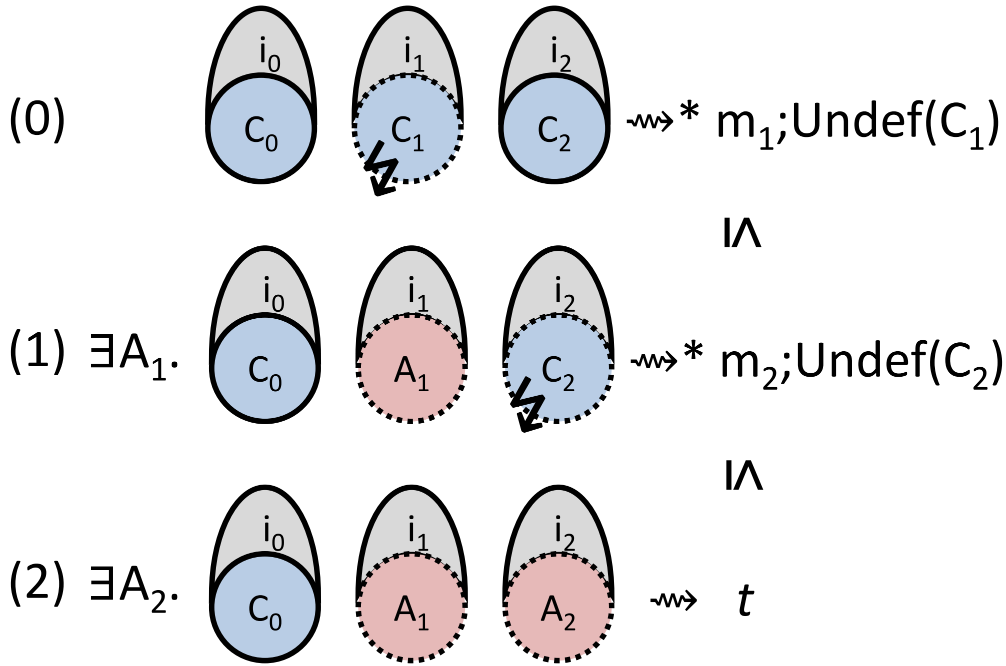
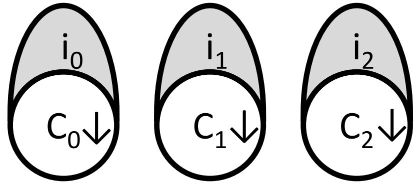


If 

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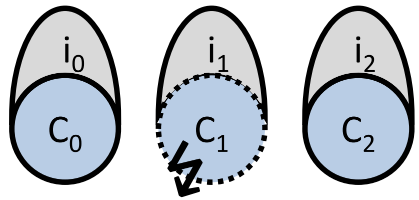
(0) 

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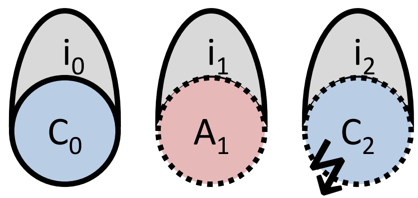
(1) $\exists A_1.$ 

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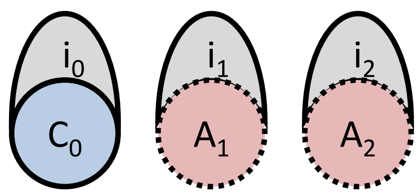
(2) $\exists A_2.$ 

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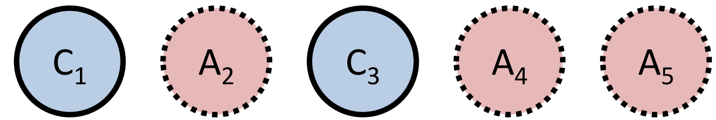
Trace is very helpful
- detect undefined behavior
- rewind execution

Now we know what these words mean!

(at least in the setting of compartmentalization for unsafe low-level languages)

Mutual distrust



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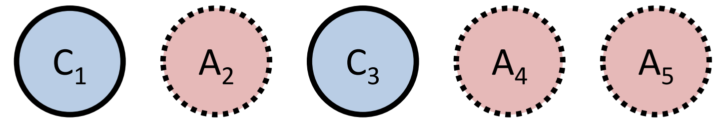

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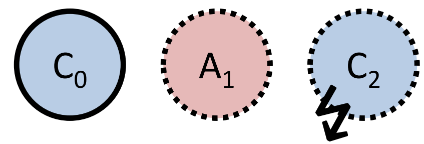

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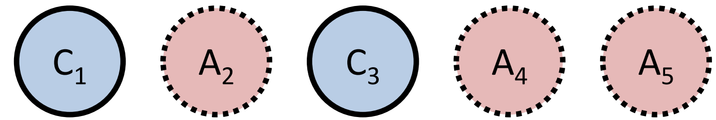
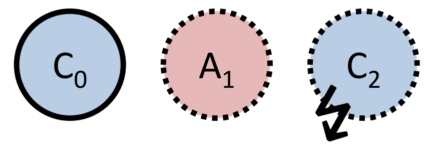
Mutual distrust 

Dynamic compromise 

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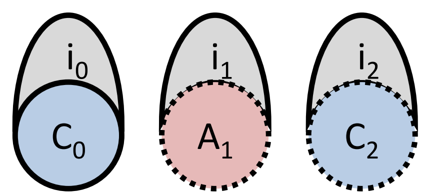
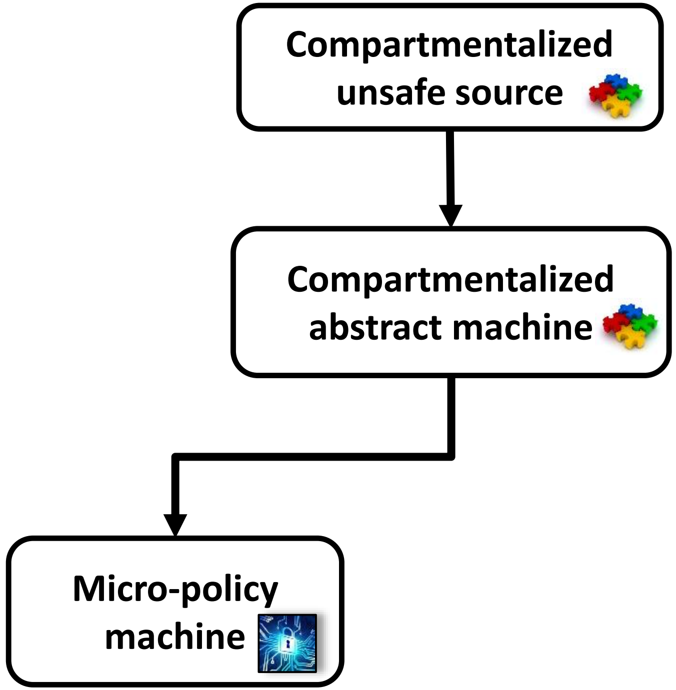
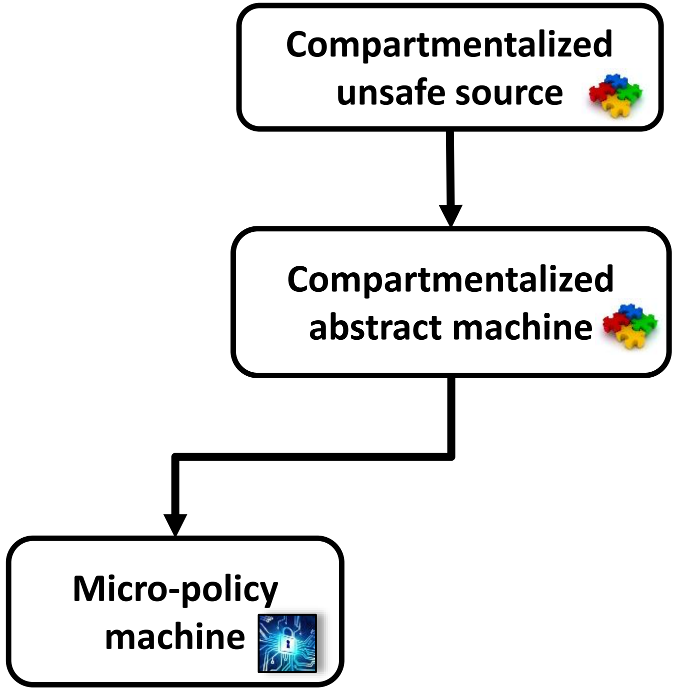
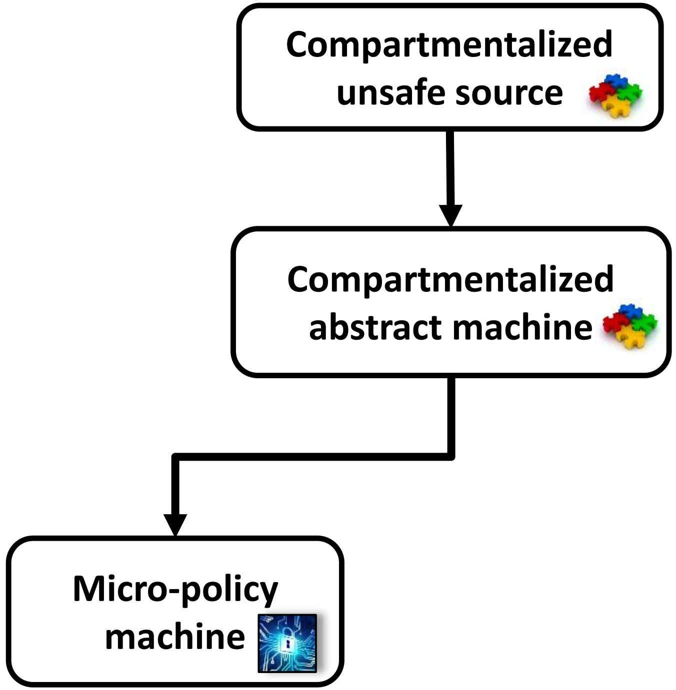
Static privilege 

Goal 2: Towards building secure compilation chains


Compartmentalized unsafe source
Compartmentalized abstract machine
Micro-policy machine



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



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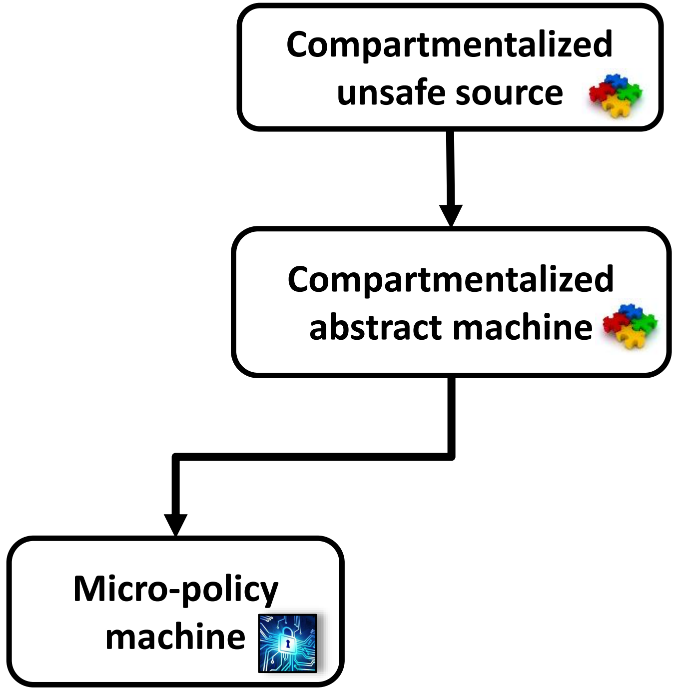

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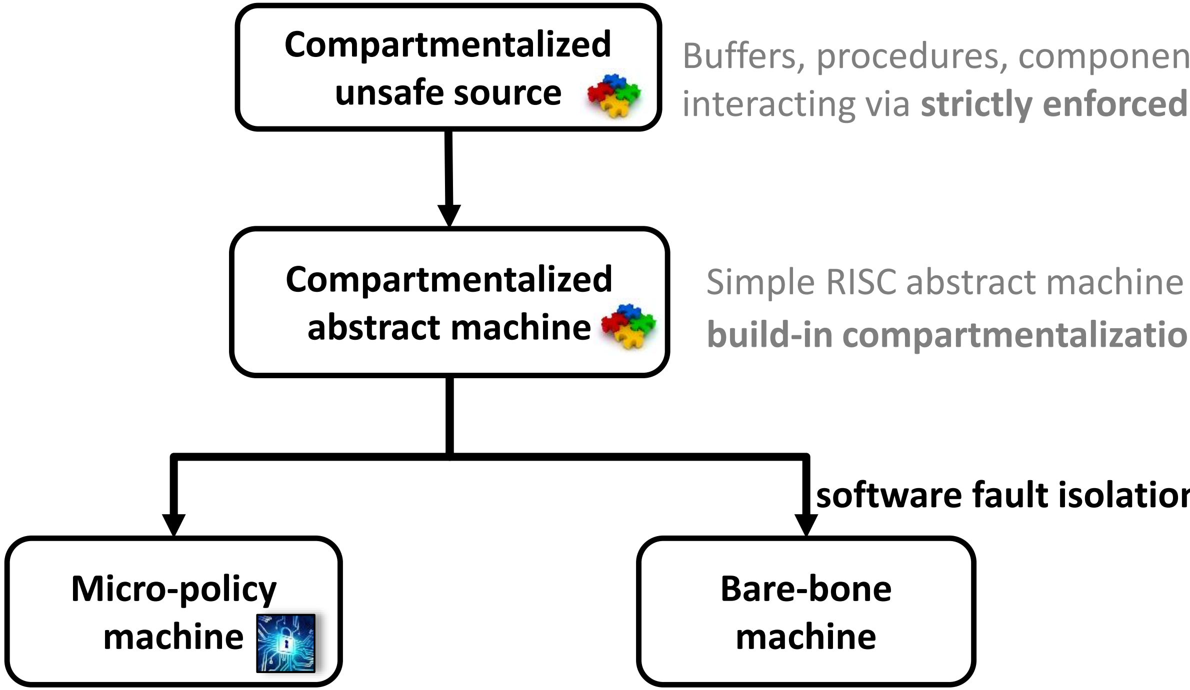

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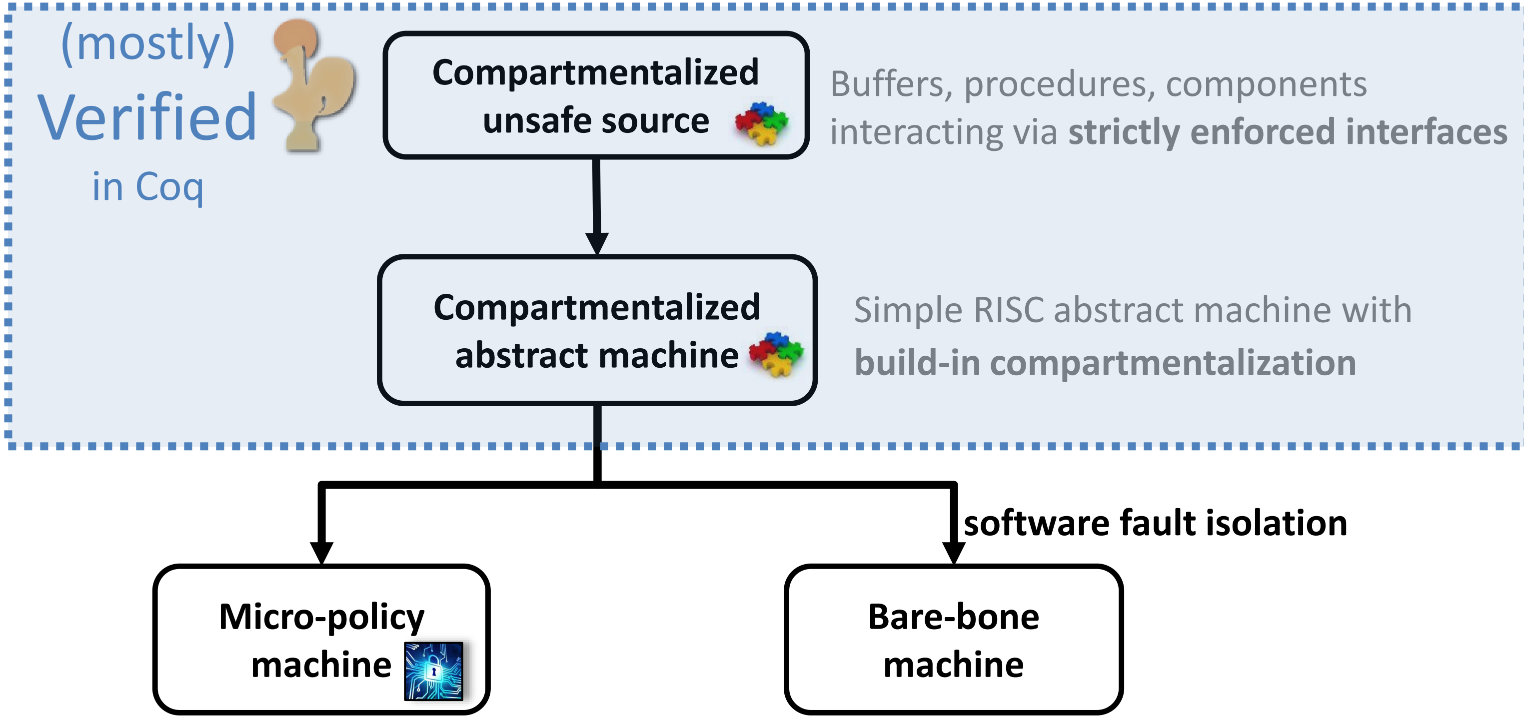

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software fault isolation

Bare-bone machine

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Systematically tested (with QuickChick)

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Wrapping up

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  - **exploring a continuum, security vs efficiency tradeoff**
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- **We're hiring!**
  - PostDocs, Young Researchers, Interns, PhD students

BACKUP SLIDES

More goals of secure compilation

- **Enabling source-level security reasoning**
- **Making the source language safer**
  – memory and type safety, less/no undefined behavior
- **Making it easier to express security intent**
  – marking secrets, specifying security properties
- **Making exploits more difficult**
  – CFI, CPI, stack protection, randomization, diversity

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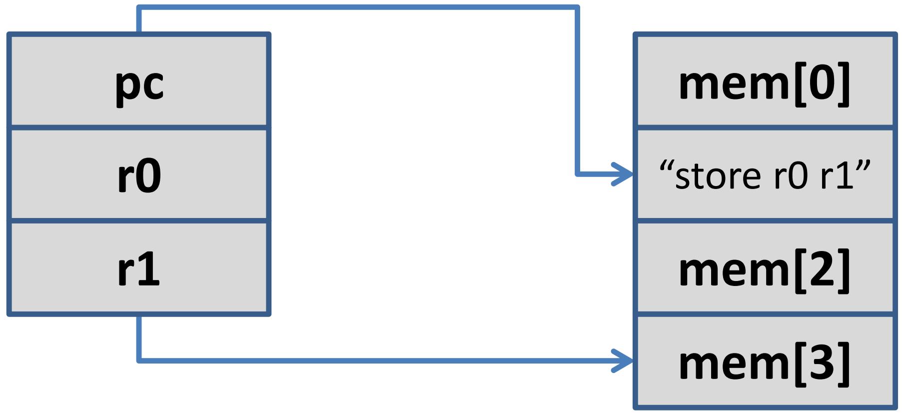

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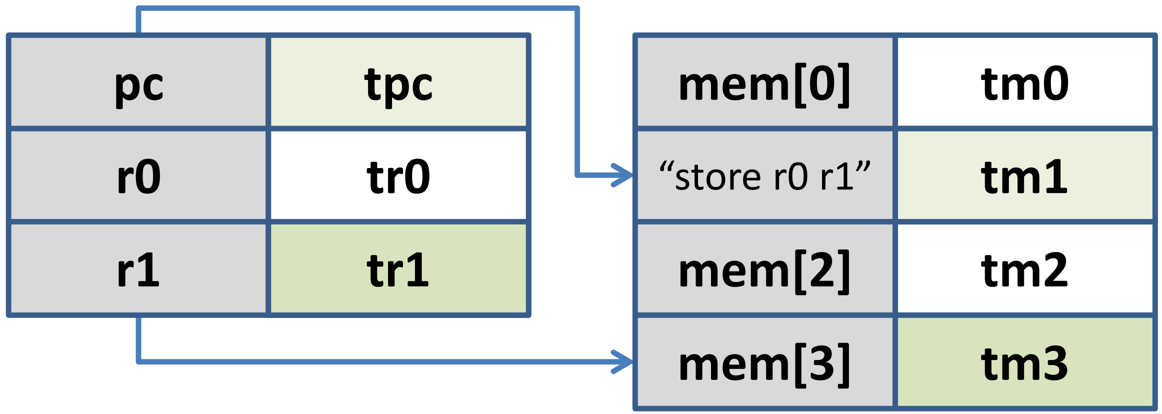

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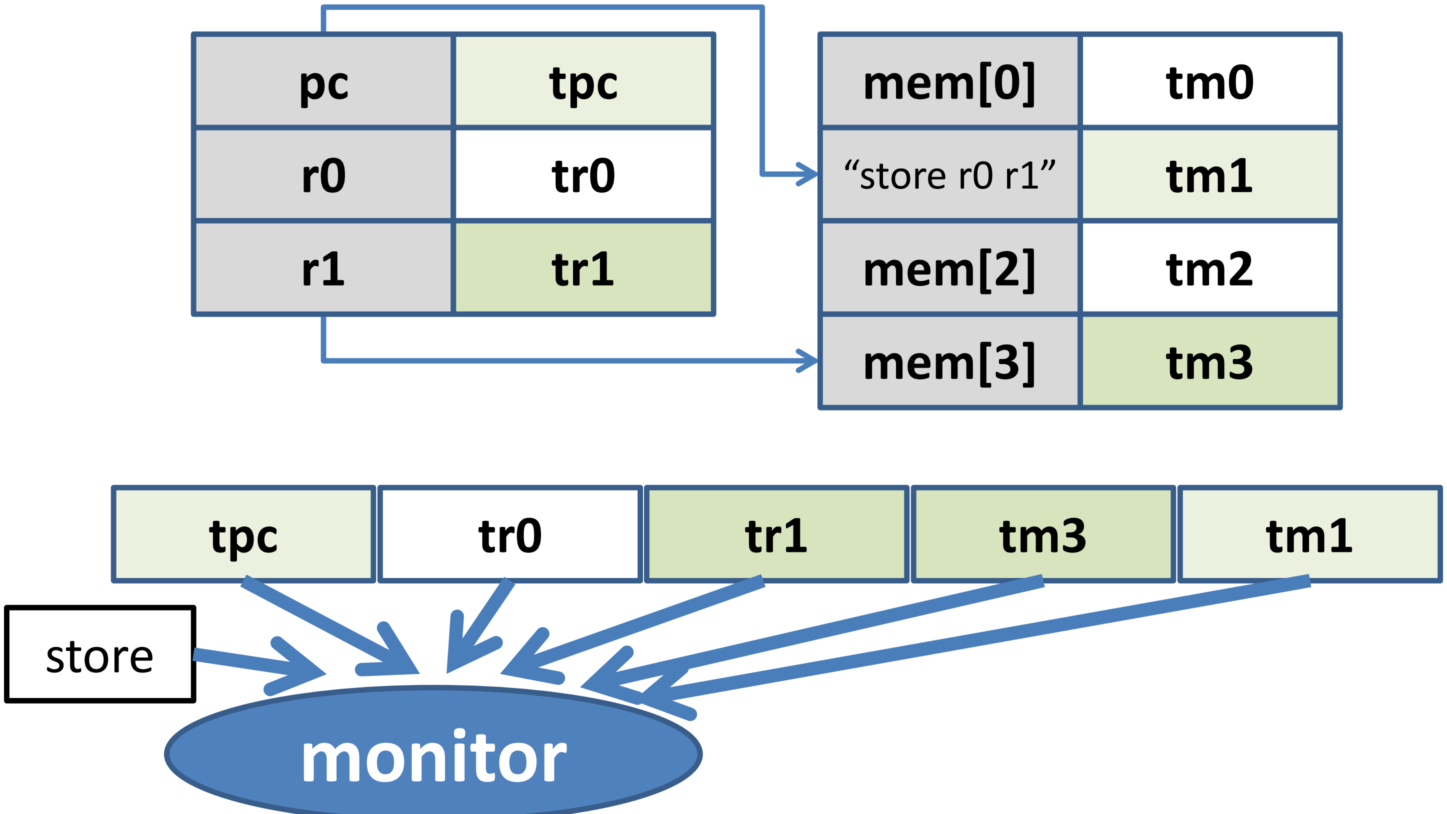

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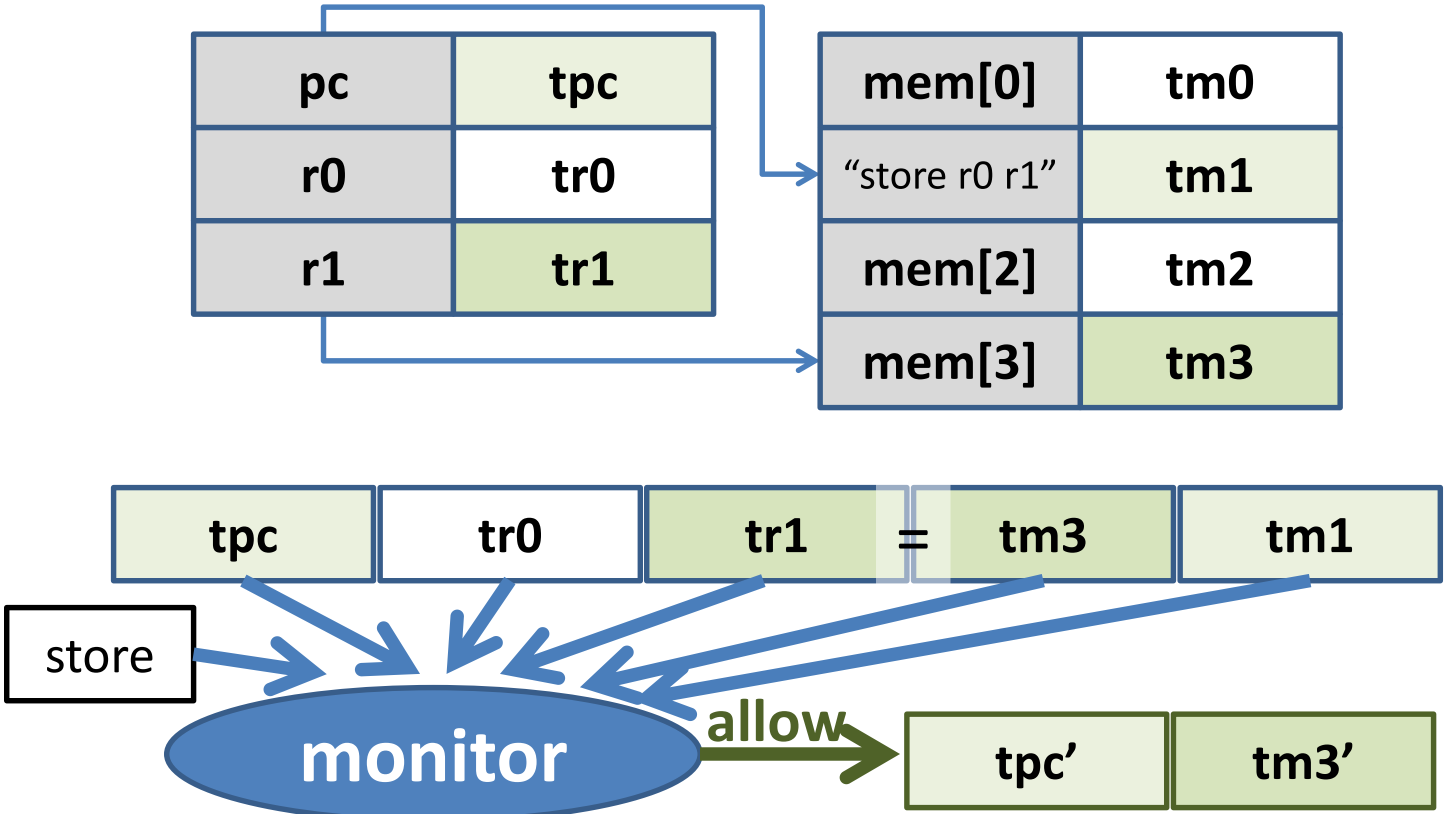

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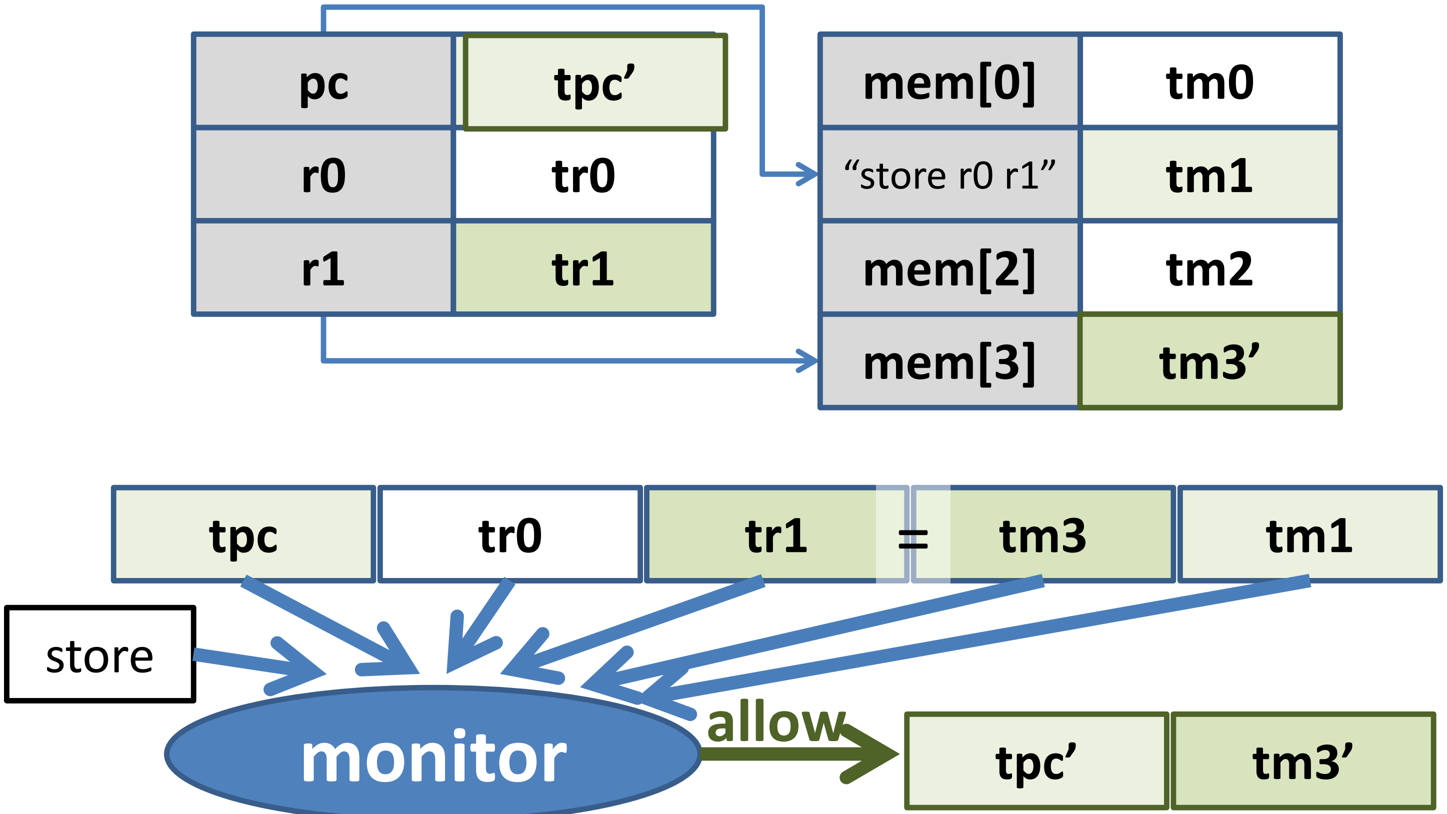

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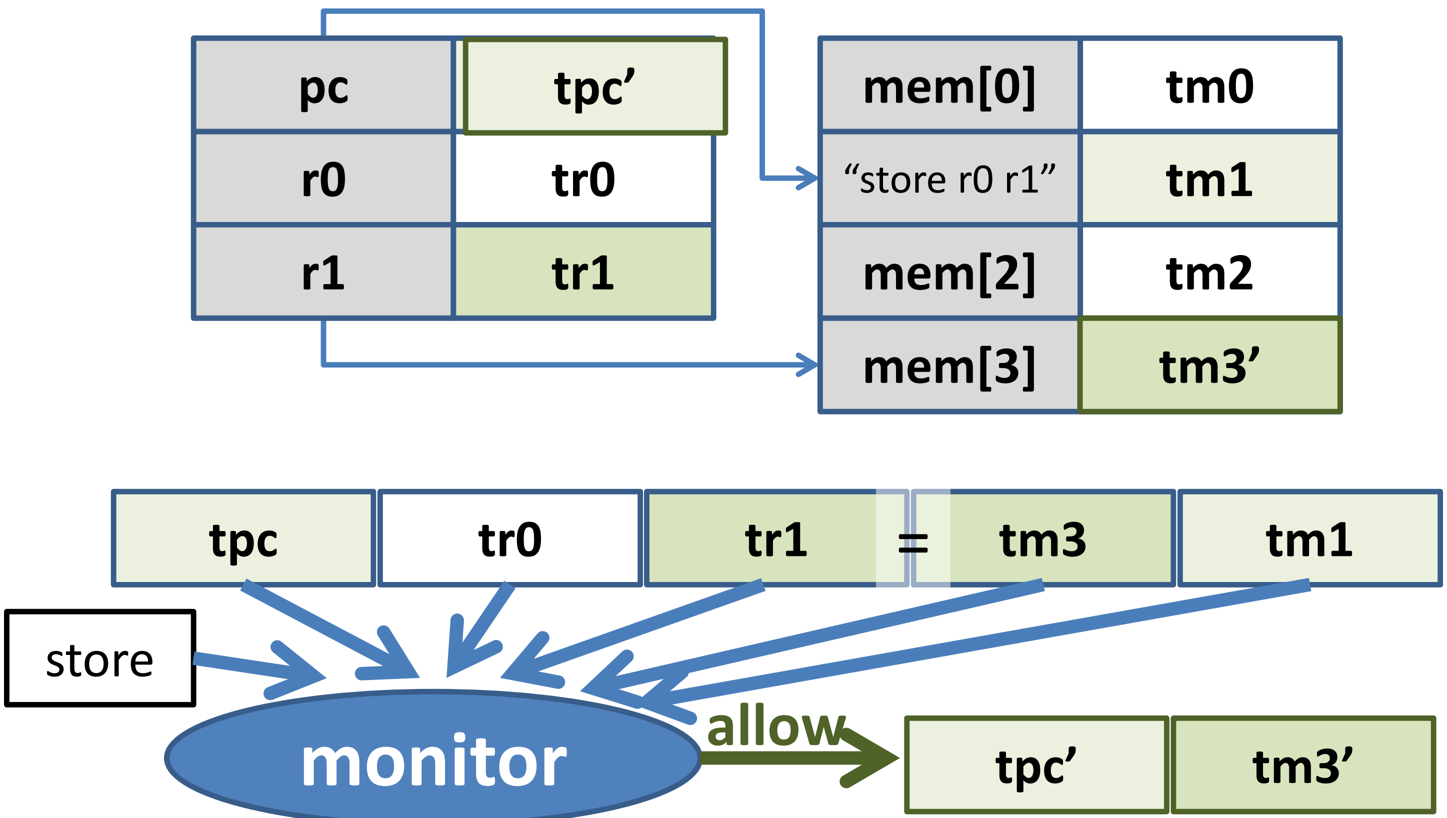

software monitor’s decision is hardware cached

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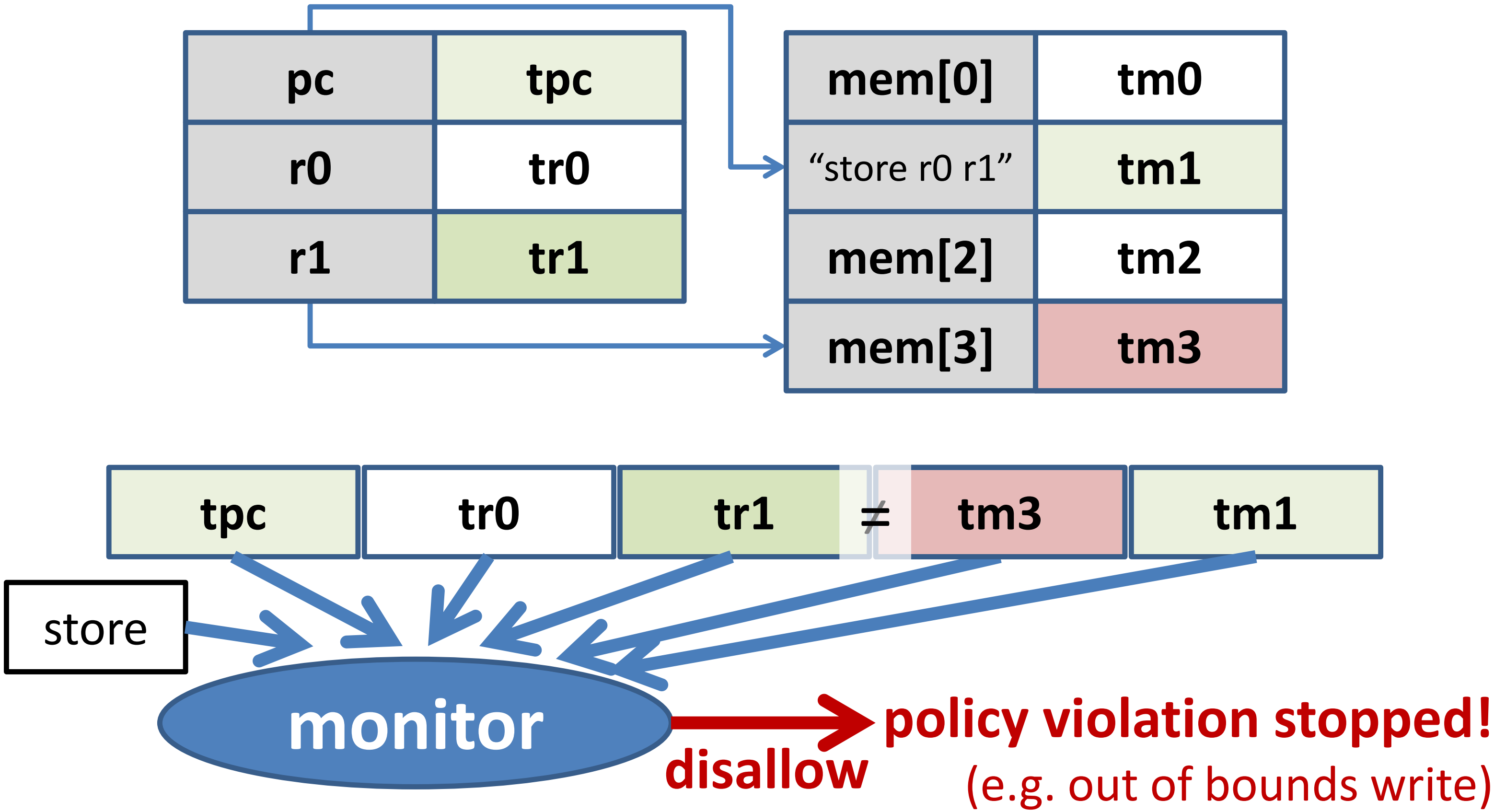

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DRAPER DOVER MICROSYSTEMS

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Evaluated (<10% runtime overhead) [ASPLOS'15]

spec