SECOMP

Efficient Formally Secure Compilers to a Tagged Architecture

Cătălin Hrițcu

Inria Paris

(visiting researcher at Microsoft until end of November)

(member of Everest expedition)

https://secure-compilation.github.io/

it’s all relative ☺

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- **devastating low-level vulnerabilities**
- **programming languages, compilers, and hardware architectures**
  - designed in an era of scarce hardware resources
  - too often trade off security for efficiency
- **the world has changed** (2016 vs 1972*)
  - security matters, hardware resources abundant
  - time to revisit some tradeoffs

* "...the number of UNIX installations has grown to 10, with more expected..."
-- *Dennis Ritchie and Ken Thompson, June 1972*

Hardware architectures

- **Today’s processors are mindless bureaucrats**
  - “write past the end of this buffer” ... *yes boss!*
  - “jump to this untrusted integer” ... *right boss!*
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"Spending silicon to improve security"

Unsafe low-level languages

- C (1972) and C++ **undefined behavior**
  - including buffer overflows, checks too expensive
  - compilers optimize aggressively assuming undefined behavior will simply not happen

THE
C
PROGRAMMING
LANGUAGE

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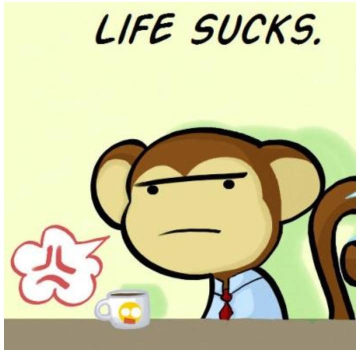

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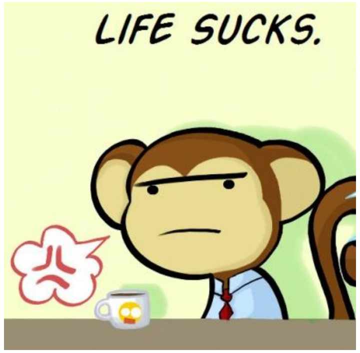

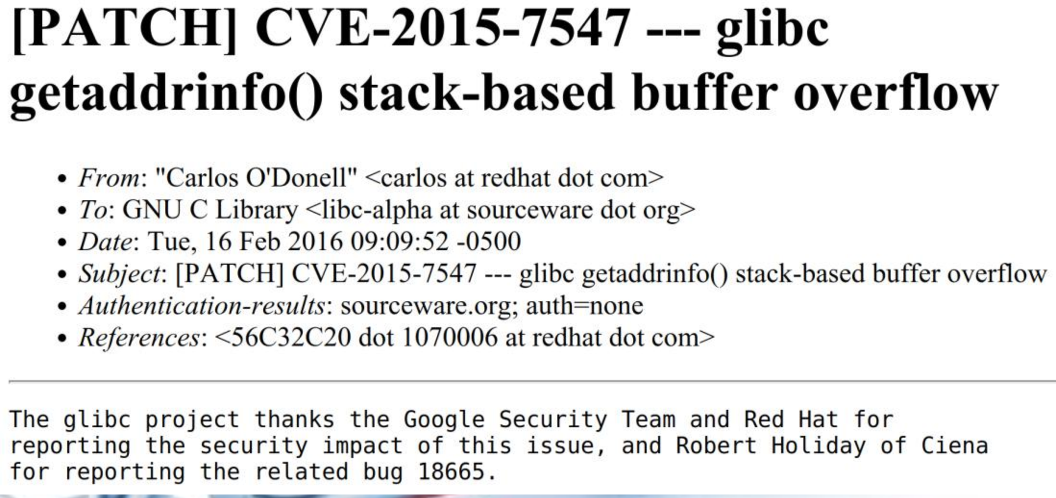

[PATCH] CVE-2015-7547 --- glibc getaddrinfo() stack-based buffer overflow

- *From*: "Carlos O'Donell" <carlos at redhat dot com>
- *To*: GNU C Library <libc-alpha at sourceware dot org>
- *Date*: Tue, 16 Feb 2016 09:09:52 -0500
- *Subject*: [PATCH] CVE-2015-7547 --- glibc getaddrinfo() stack-based buffer overflow
- *Authentication-results*: sourceware.org; auth=none
- *References*: <56C32C20 dot 1070006 at redhat dot com>

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The glibc project thanks the Google Security Team and Red Hat for
reporting the security impact of this issue, and Robert Holiday of Ciena
for reporting the related bug 18665.
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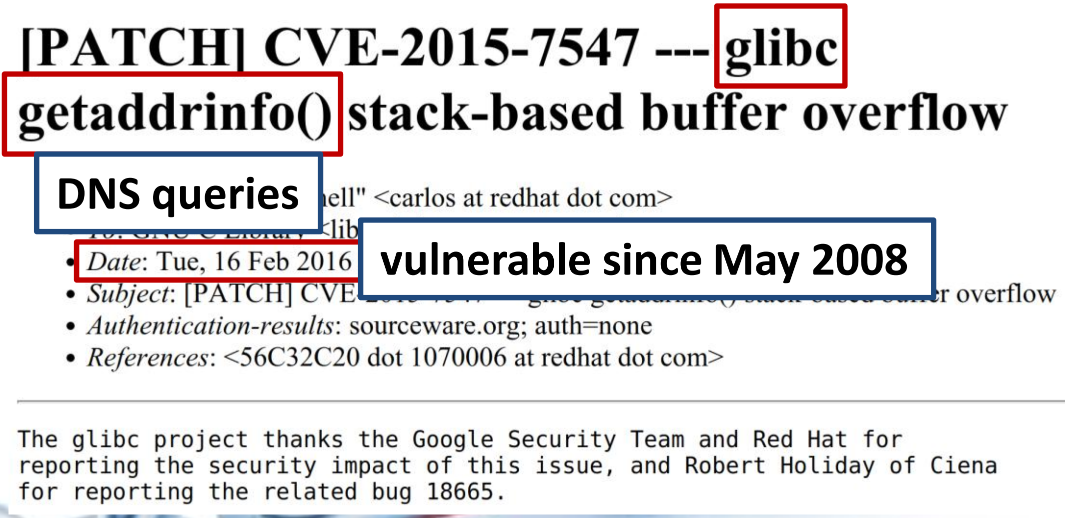

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DNS queries

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vulnerable since May 2008

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Safer high-level languages?

- **memory safe** (at a cost)

OCaml
F#
Java
#
Haskell

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- **useful abstractions** for writing secure code:
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Safer high-level languages?

OCaml F#

Java Haskell

- **memory safe** (at a cost)
- **useful abstractions** for writing secure code:
  - GC, type abstraction, modules, immutability, ...
- **not immune to low-level attacks**
  - large runtime systems, in C++ for efficiency
  - **unsafe interoperability with low-level code**
    - libraries often have large parts written in C/C++
    - **enforcing abstractions all the way down too expensive**

Teasing out 2 different problems

- **1. inherently insecure low-level languages**
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Teasing out 2 different problems

- **1. inherently insecure low-level languages**
  - **memory unsafe**: any buffer overflow can be catastrophic allowing remote attackers to gain complete control
- **2. unsafe interoperability with lower-level code**
  - even code written in **safer high-level languages** has to interoperate with **insecure low-level libraries**
  - **unsafe interoperability:** all high-level safety guarantees lost

Key enabler: Micro-Policies

software-defined, hardware-accelerated, tag-based monitoring

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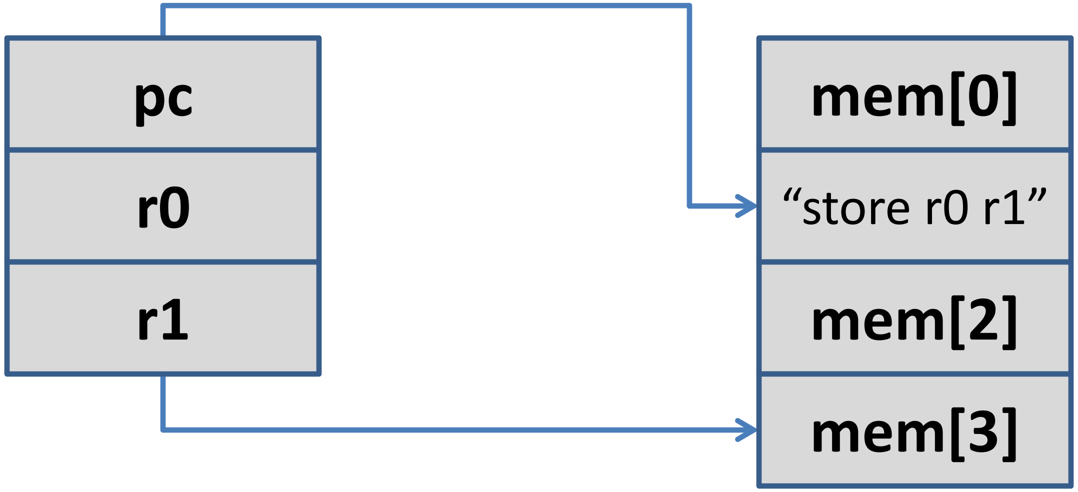

pc

r0

r1

mem[0]

"store r0 r1"

mem[2]

mem[3]

Key enabler: Micro-Policies

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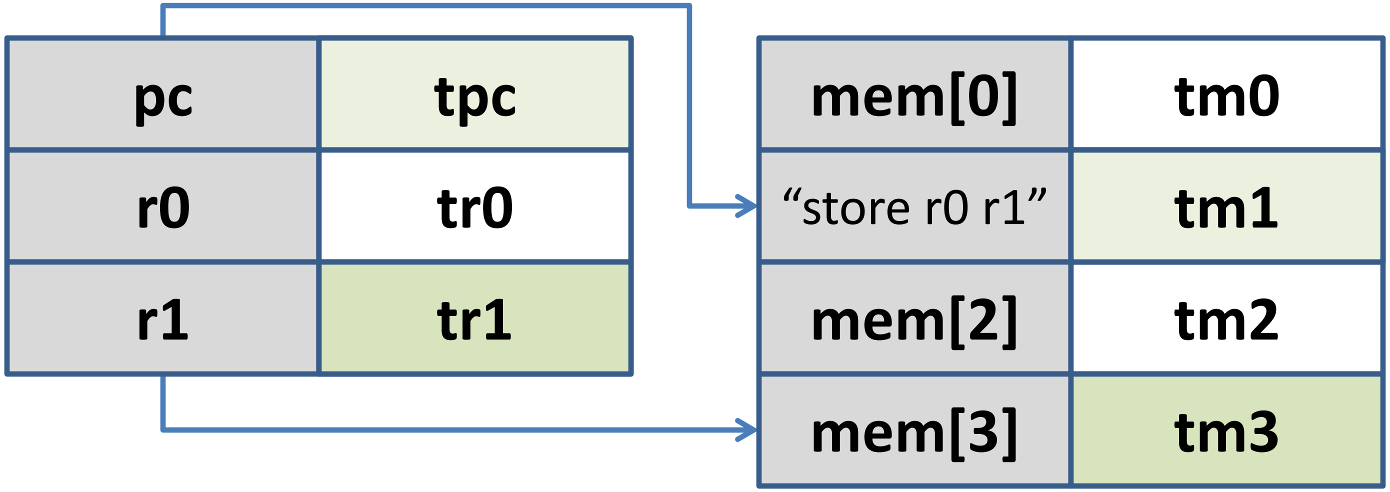

pc	tpc
r0	tr0
r1	tr1

mem[0]	tm0
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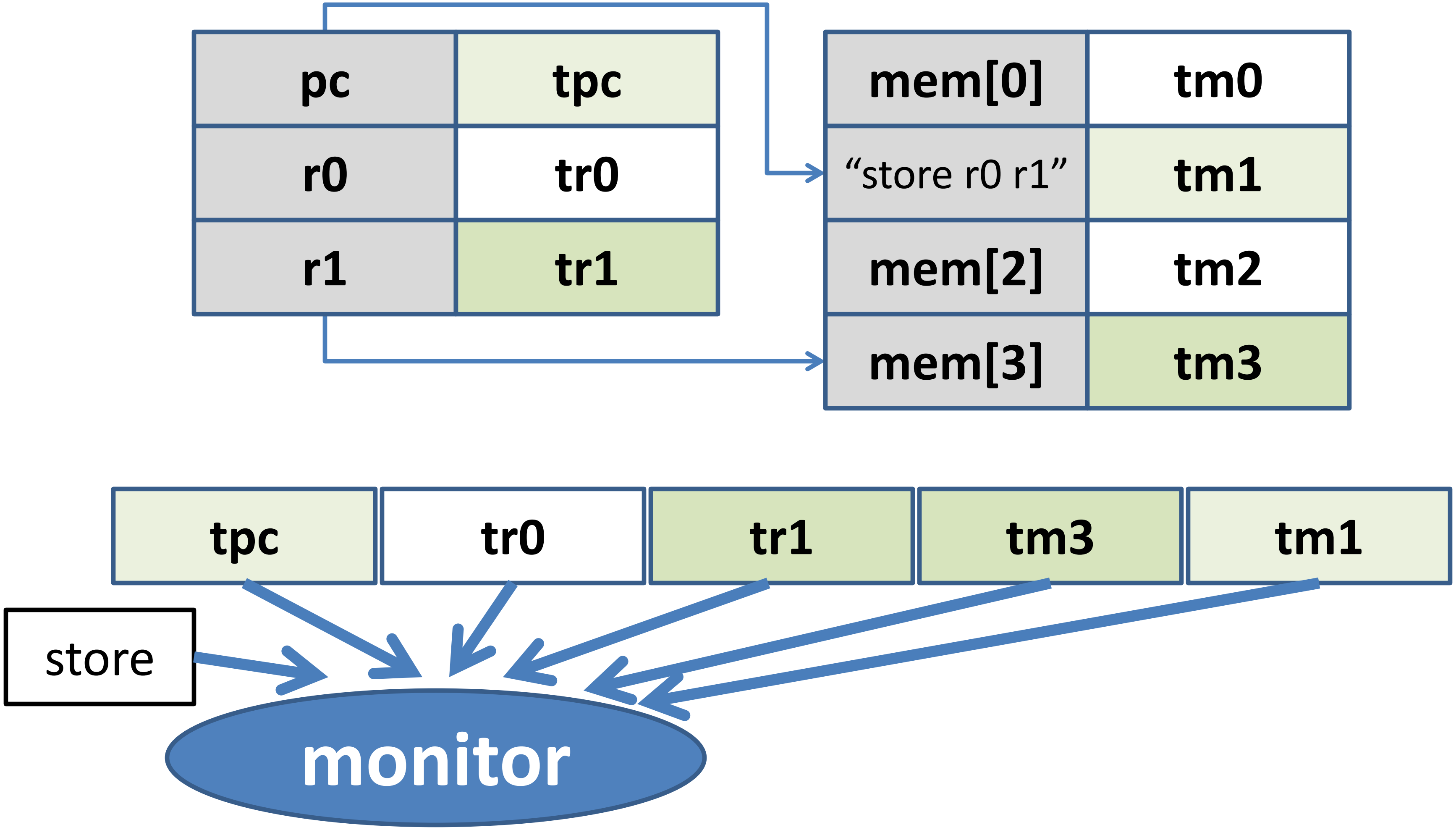

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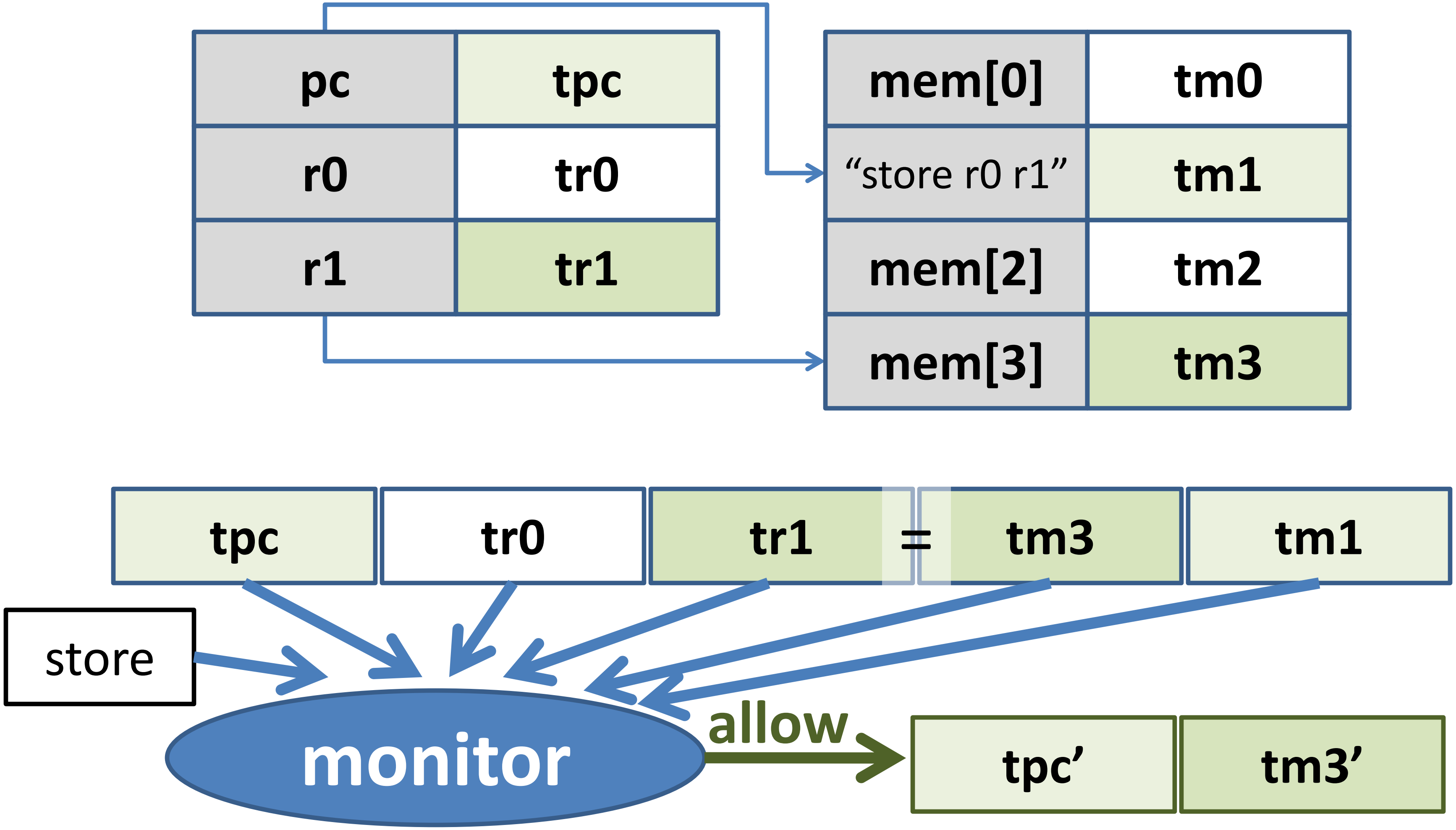

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tpc | tr0 | tr1 = tm3 | tm1

store

monitor

allow

tpc' | tm3'

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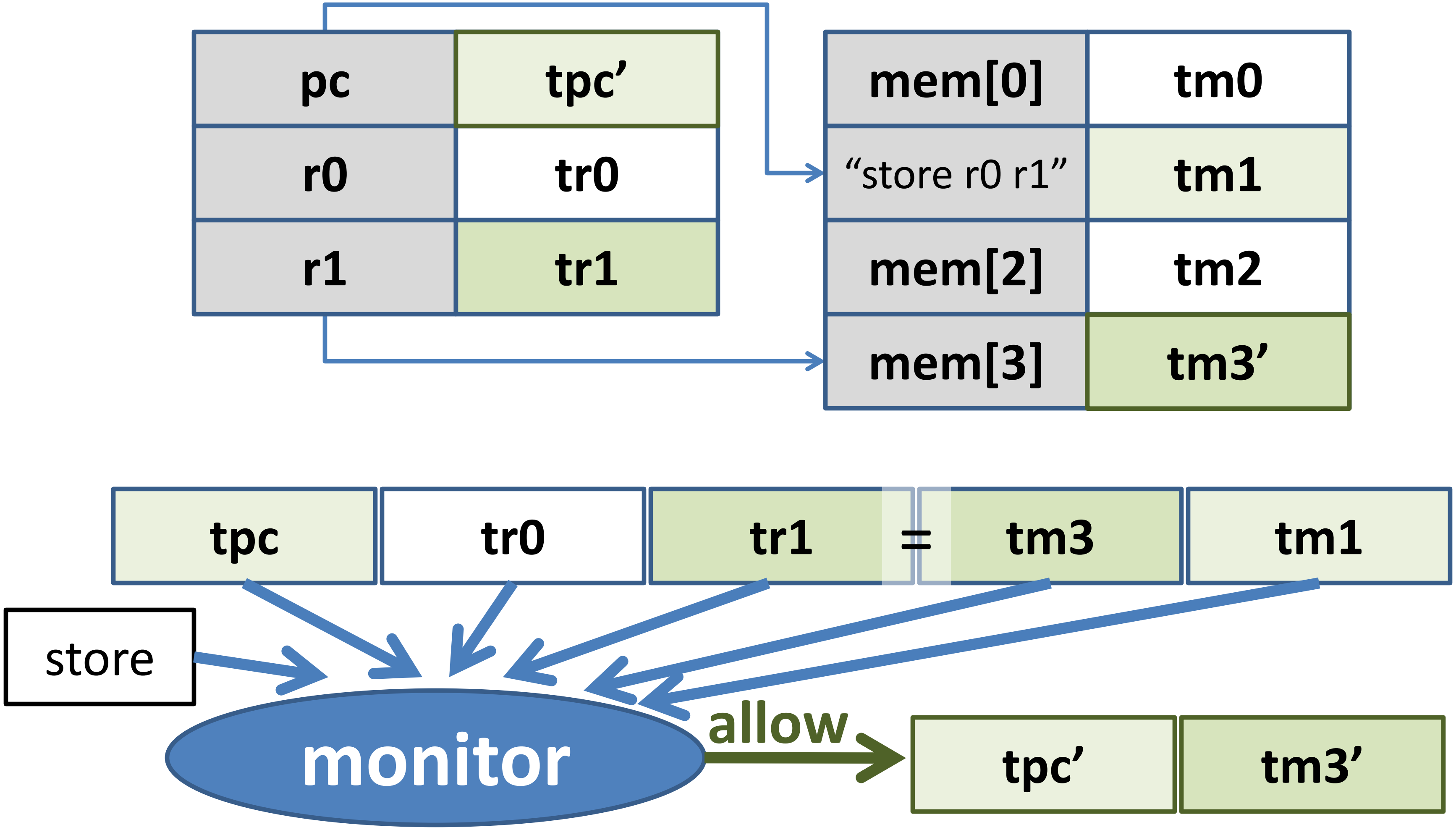

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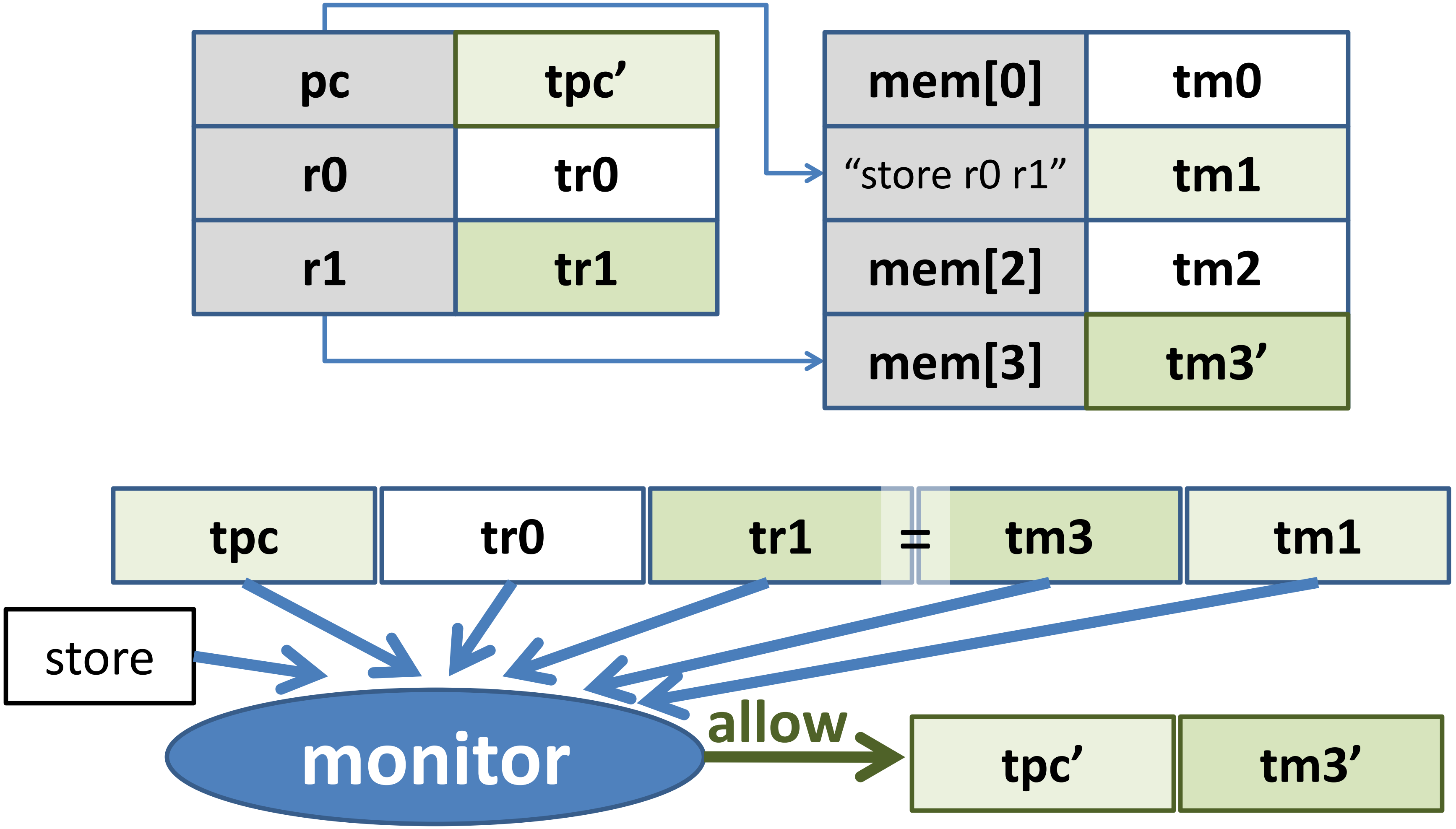

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software monitor’s decision is hardware cached

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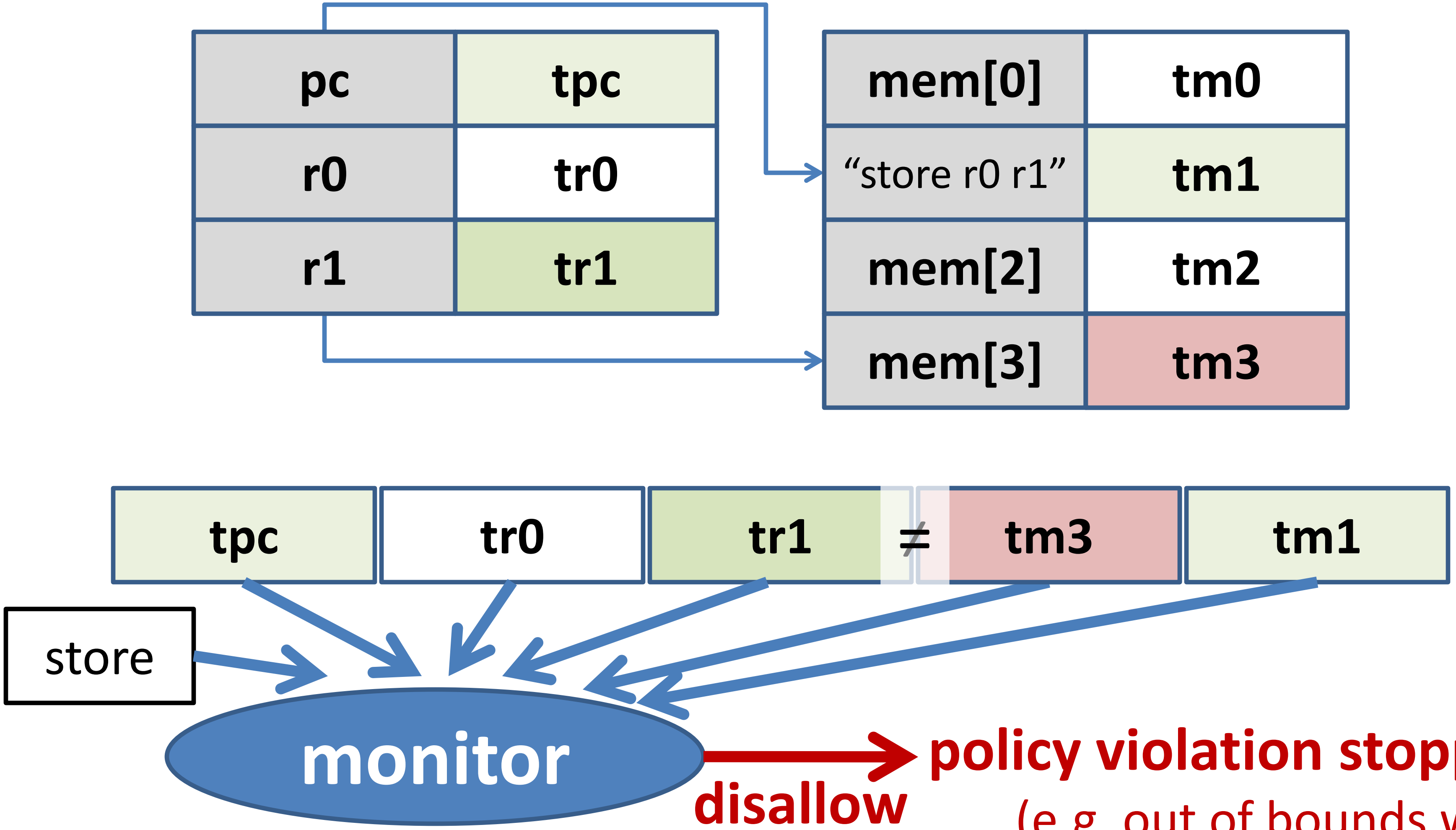

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tpc	tr0	tr1 ≠	tm3	tm1

disallow

policy violation stopped!

(e.g. out of bounds write)

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- **secure** and **simple** enough to verify security in Coq
- **real**: FPGA implementation on top of RISC-V

DRAPER bluespec

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- dynamic sealing
- heap memory safety
- code-data separation
- control-flow integrity (CFI)
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Way beyond MPX, SGX, SSM, etc

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Verified
(in Coq)
[Oakland’15]

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

spec

Micro-Policies team

- **Formal methods** & **architecture** & **systems**
- **Current team**:
  - *Inria Paris*: **Cătălin Hrițcu, Marco Stronati** (until recently **Yannis Juglaret**, **Boris Eng**)
  - *UPenn*: **André DeHon**, **Benjamin Pierce, Arthur Azevedo de Amorim**, **Nick Roessler**
  - *Portland State*: **Andrew Tolmach**
  - *MIT:* **Howie Shrobe, Stelios Sidiroglou-Douskos**
  - *Industry*: **Draper Labs, Bluespec Inc**

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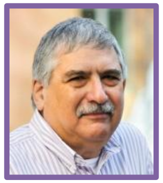
- **Spinoff of past project: DARPA CRASH/SAFE (2011-2014)**



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SECOMP grand challenge

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Use micro-policies to build **the first efficient formally secure compilers** for **realistic programming languages**

1. **Provide secure semantics for low-level languages**
   - C with protected components and memory safety
2. **Enforce secure interoperability with lower-level code**
   - ASM, C, and F* [= OCaml/F# + verification]

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holy grail of secure compilation, enforcing abstractions all the way down

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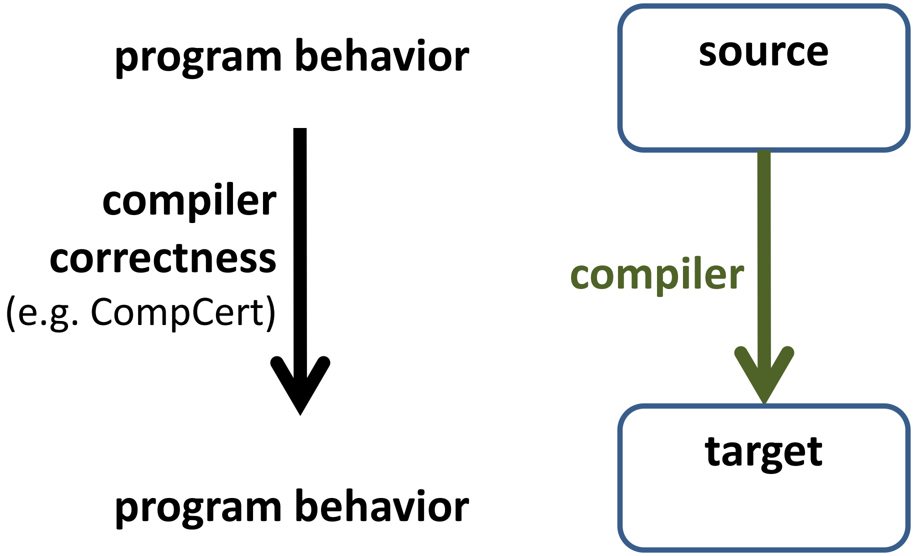

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compiler correctness (e.g. CompCert)

program behavior

source

compiler

target

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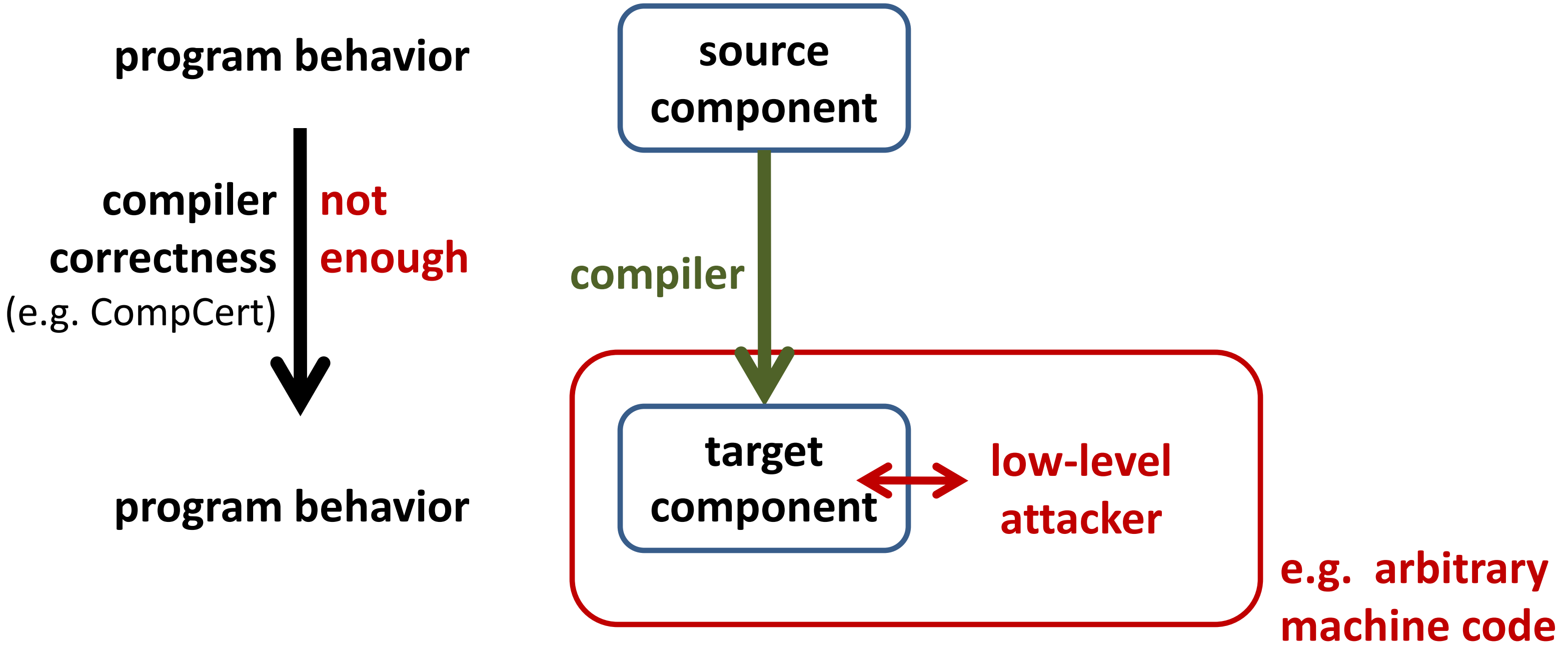

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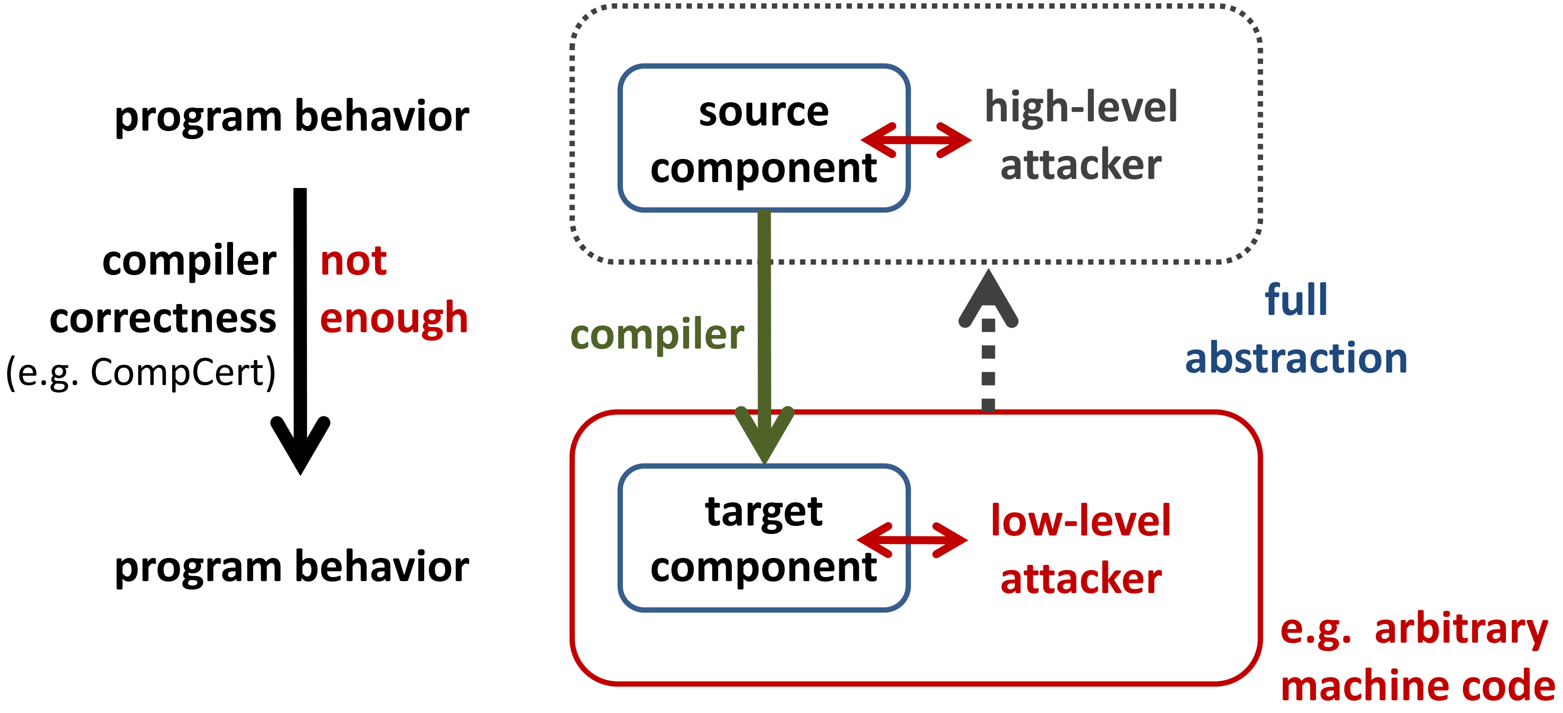

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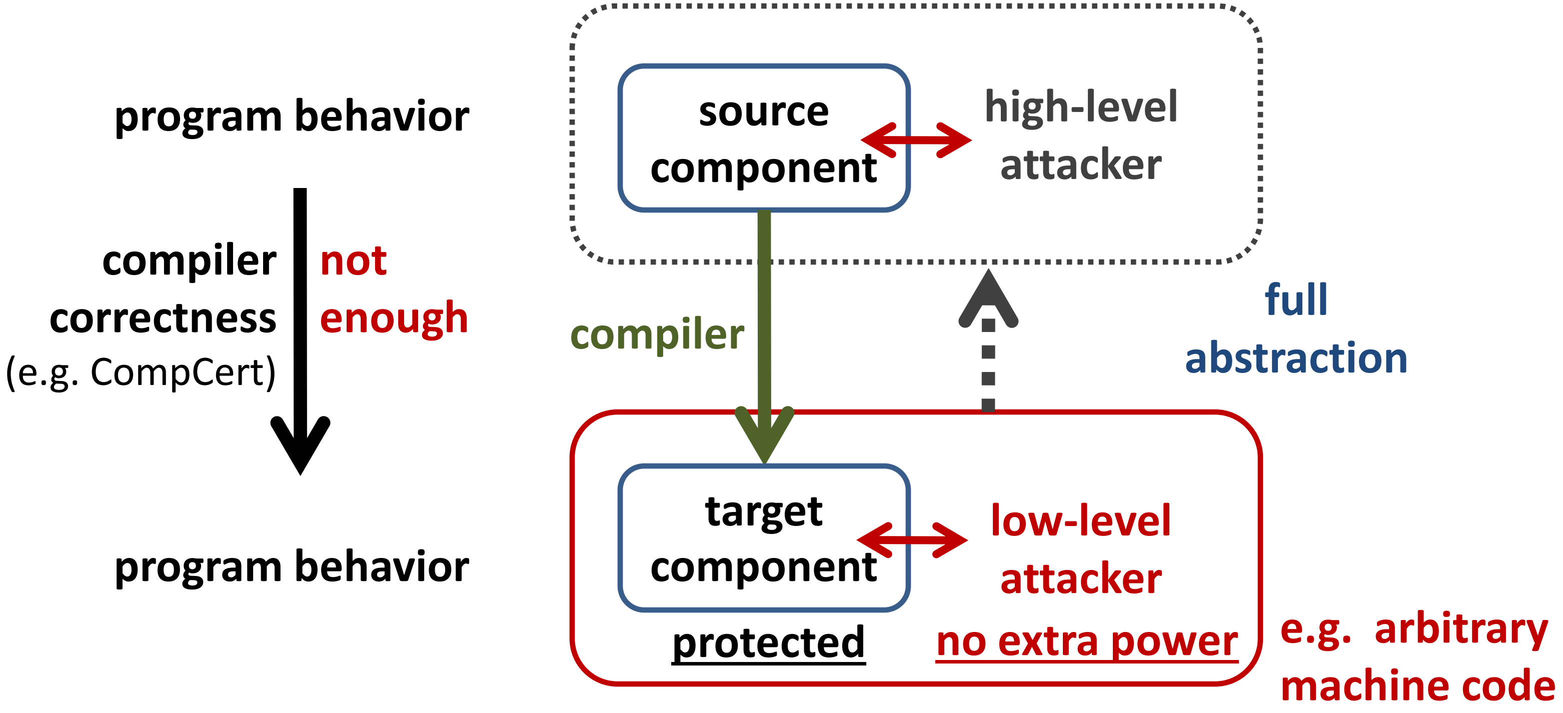

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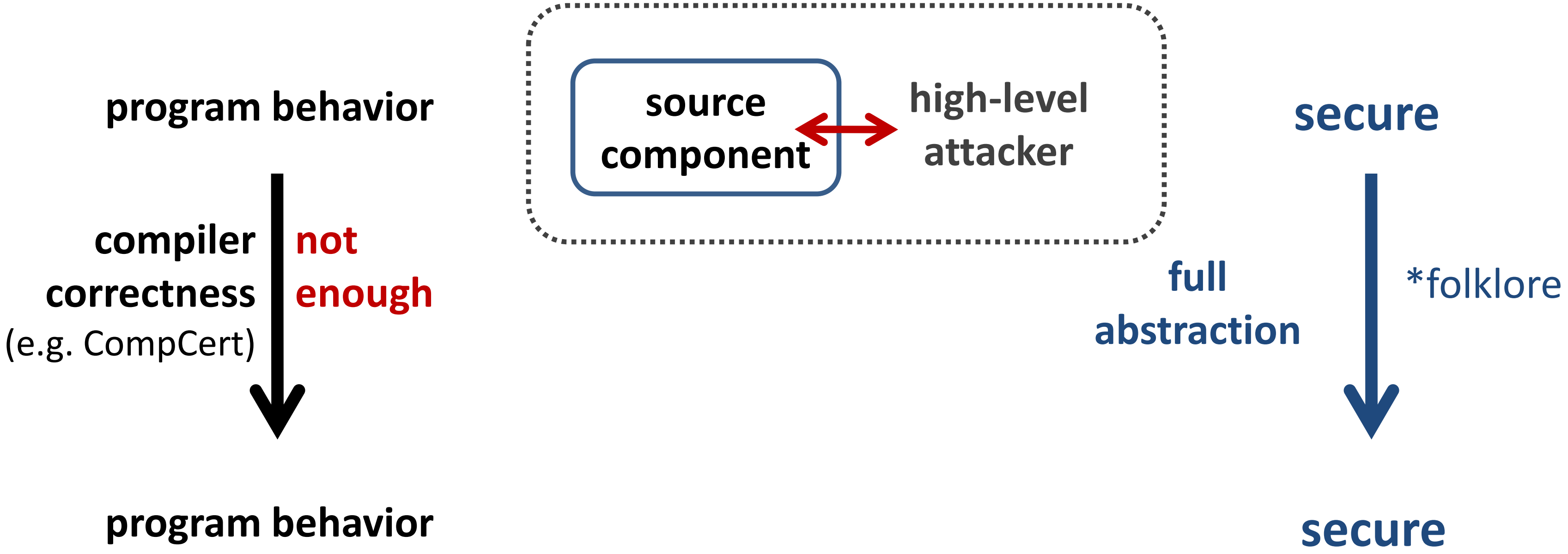

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full abstraction

secure

*folklore

secure

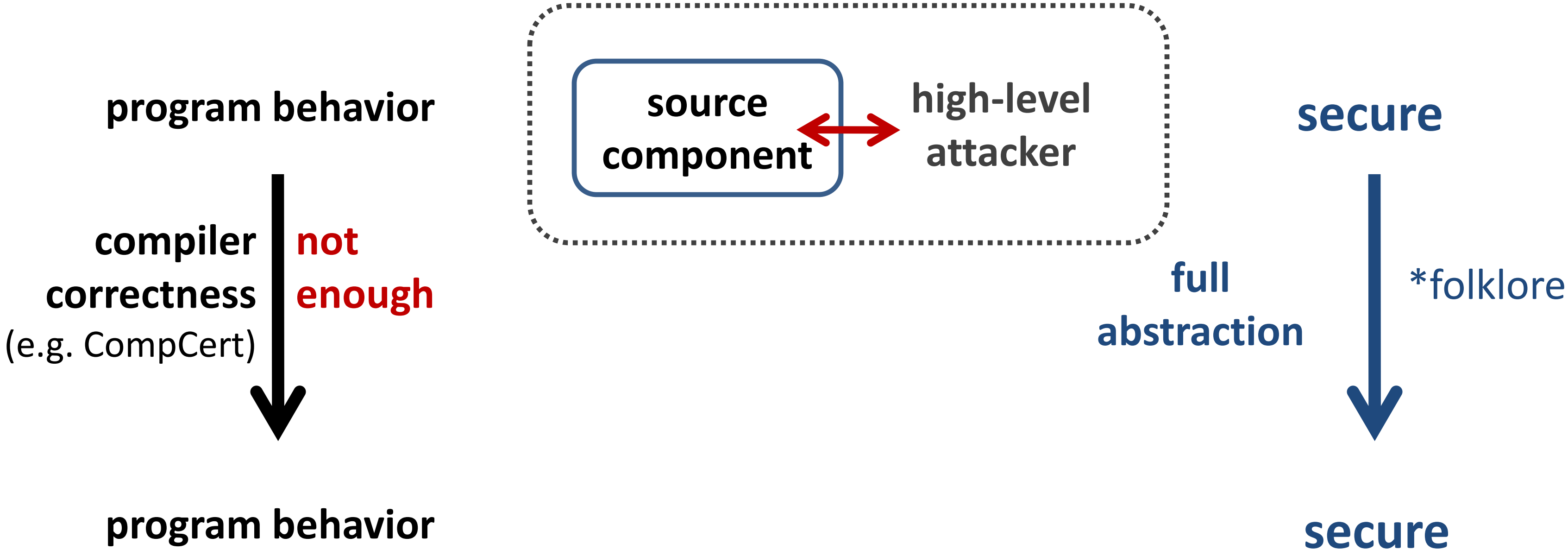
Benefit: sound security reasoning in the source language

forget about compiler chain (linker, loader, runtime system)

forget that libraries are written in a lower-level language not efficiently achievable today

Formally verify: full abstraction

holy grail of secure compilation, enforcing abstractions all the way down



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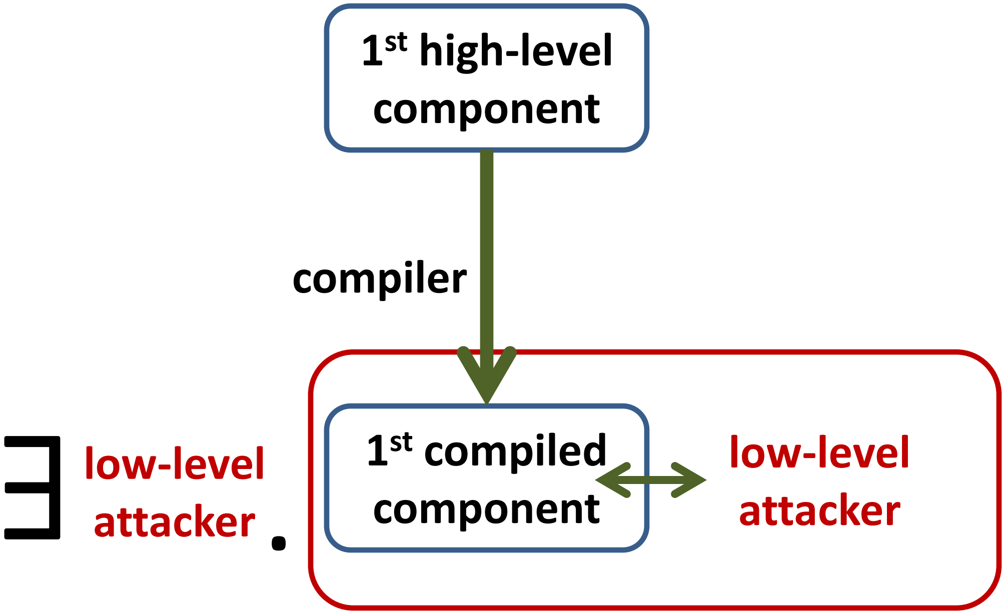

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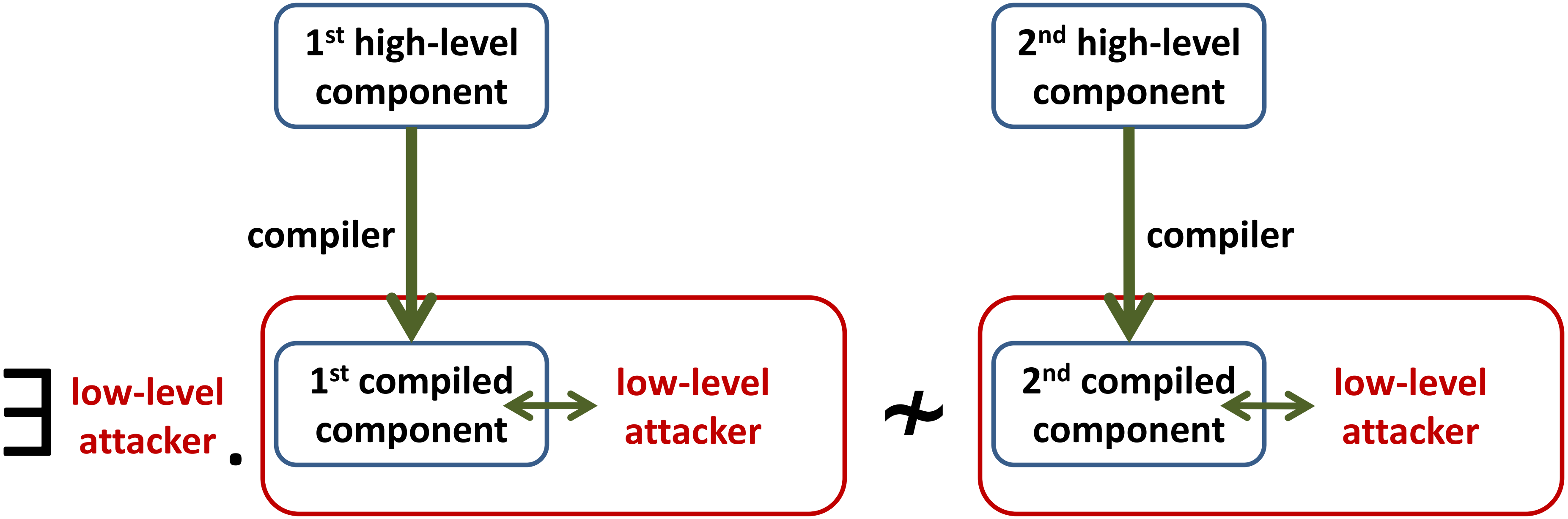


1st high-level component

compiler

2nd high-level component

compiler

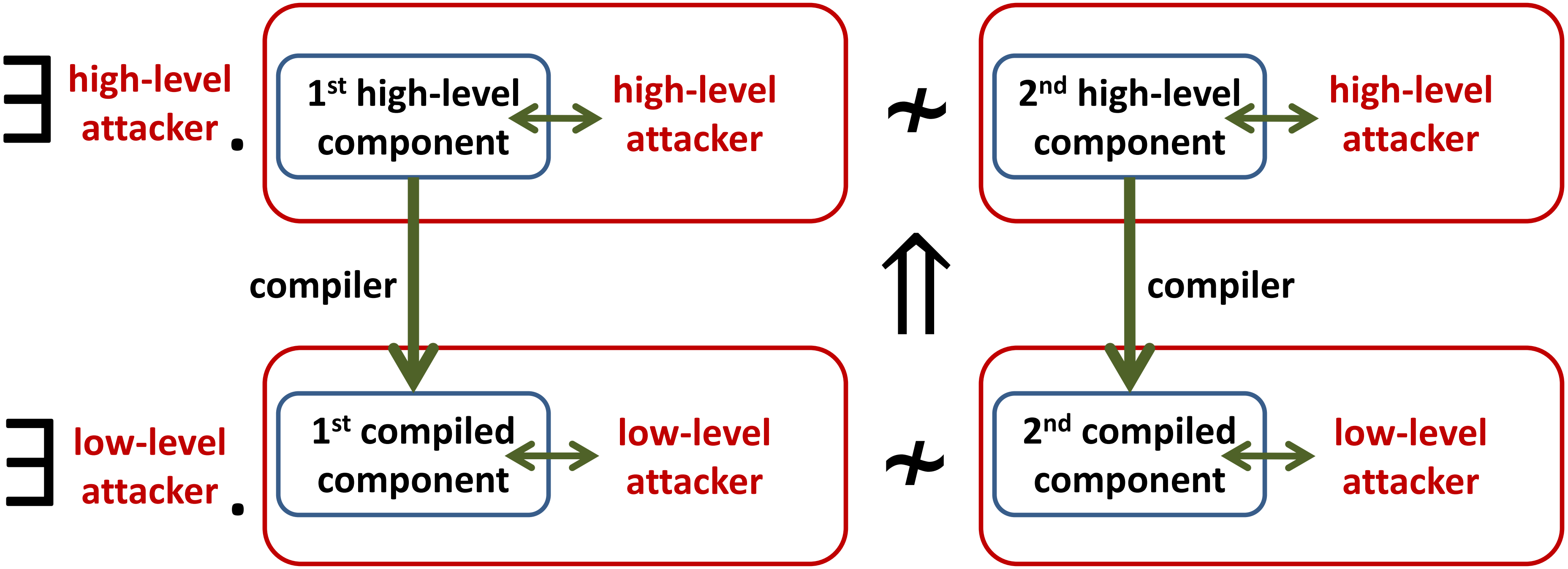
∃ low-level attacker .

1st compiled component ↔ low-level attacker

≁

2nd compiled component ↔ low-level attacker

Fully abstract compilation, definition



$\exists$ high-level attacker .

1st high-level component ↔ high-level attacker

$\nsim$

2nd high-level component ↔ high-level attacker

compiler

$\Uparrow$

compiler

$\exists$ low-level attacker .

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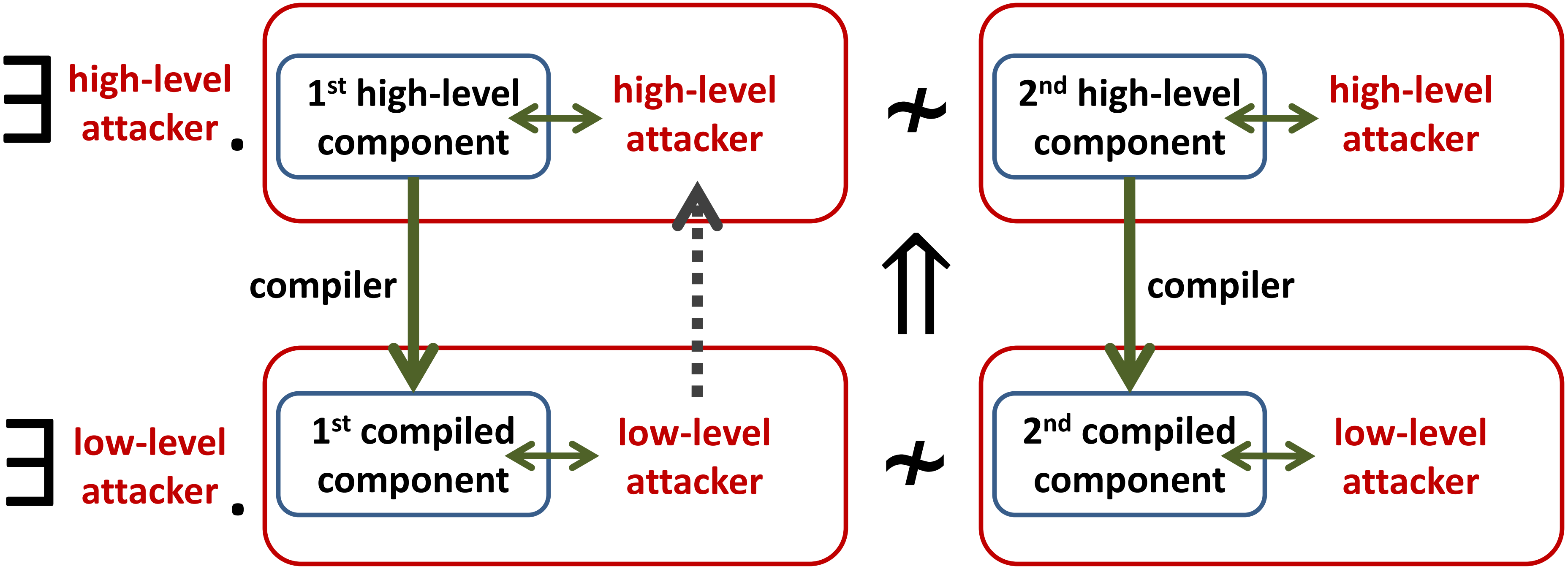

SECOMP: achieving full abstraction at scale

F* language
(OCaml/F# + verification)

miTLS*

C language
+ memory safety
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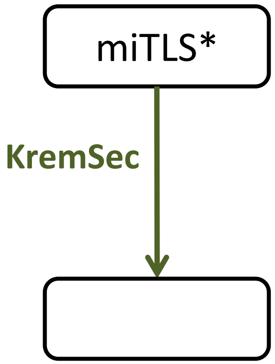

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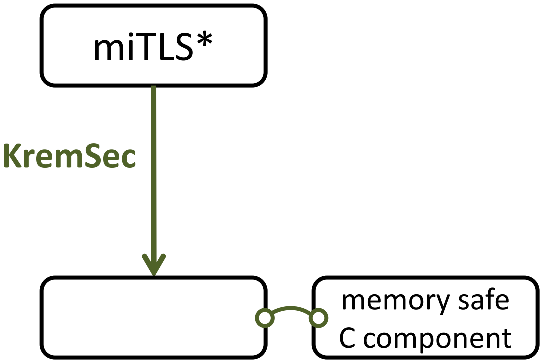

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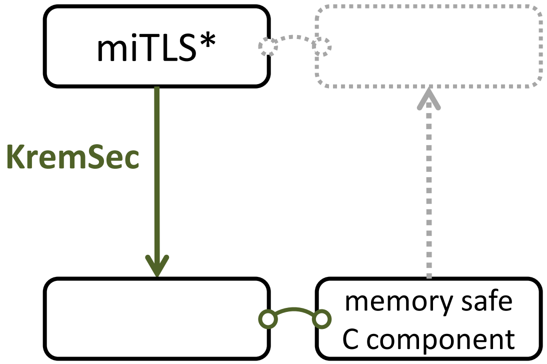

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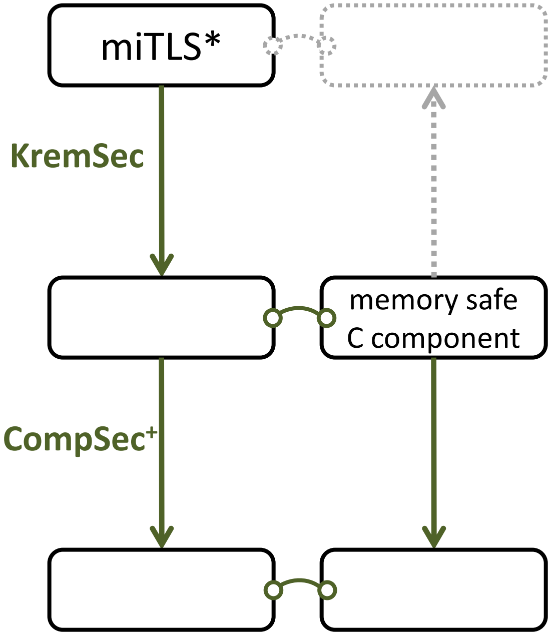

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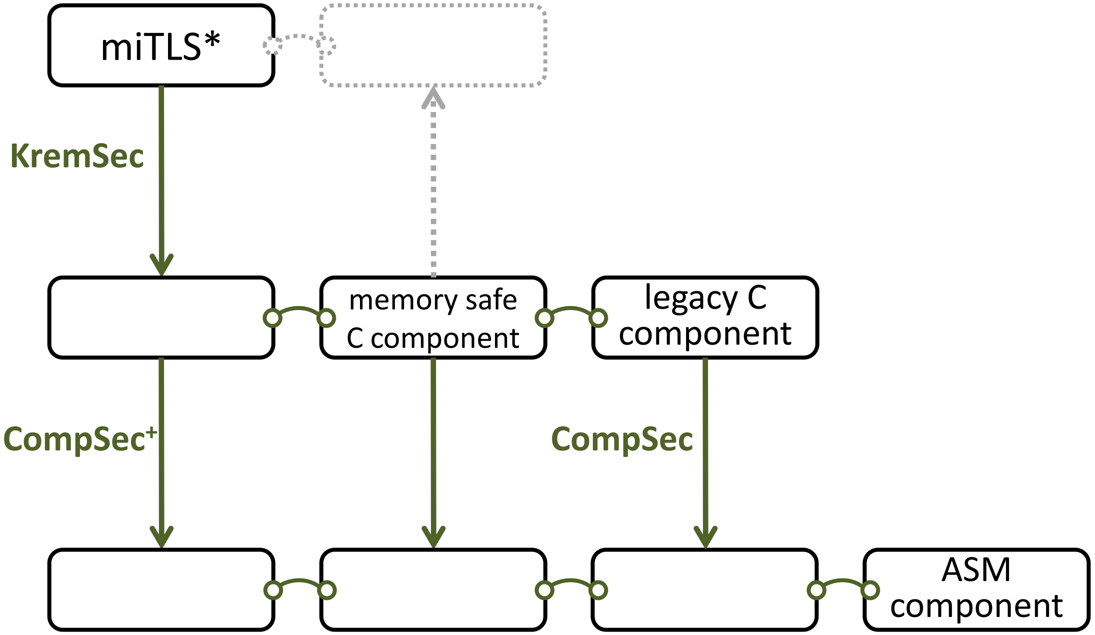

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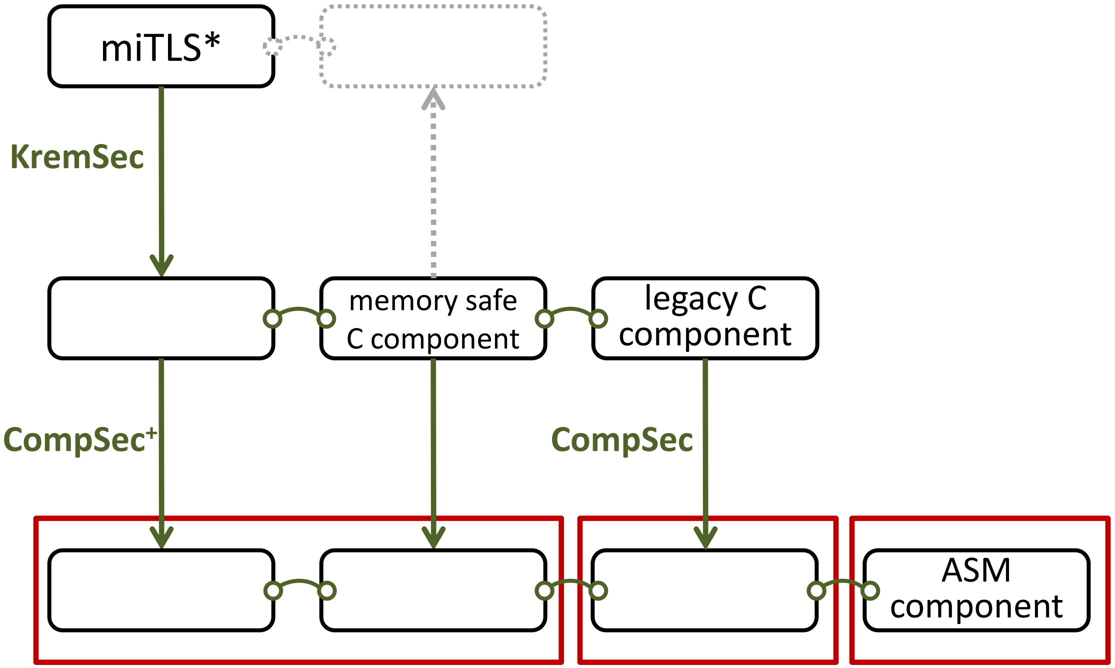

miTLS*

KremSec

memory safe C component

legacy C component

CompSec$^+$

CompSec

ASM component

protecting component boundaries

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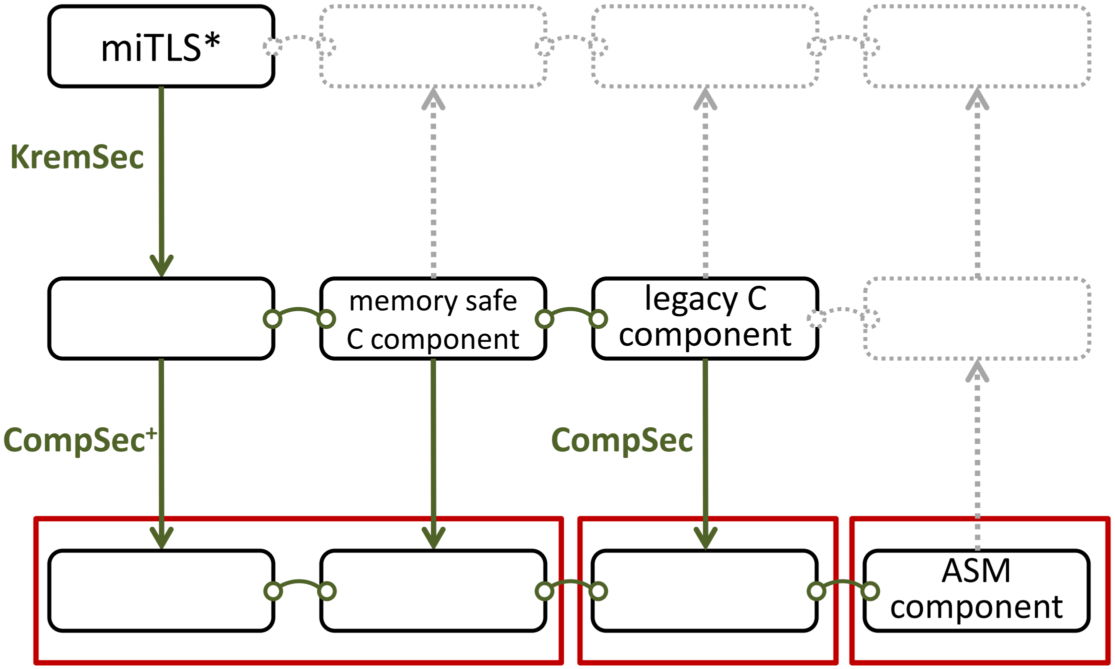

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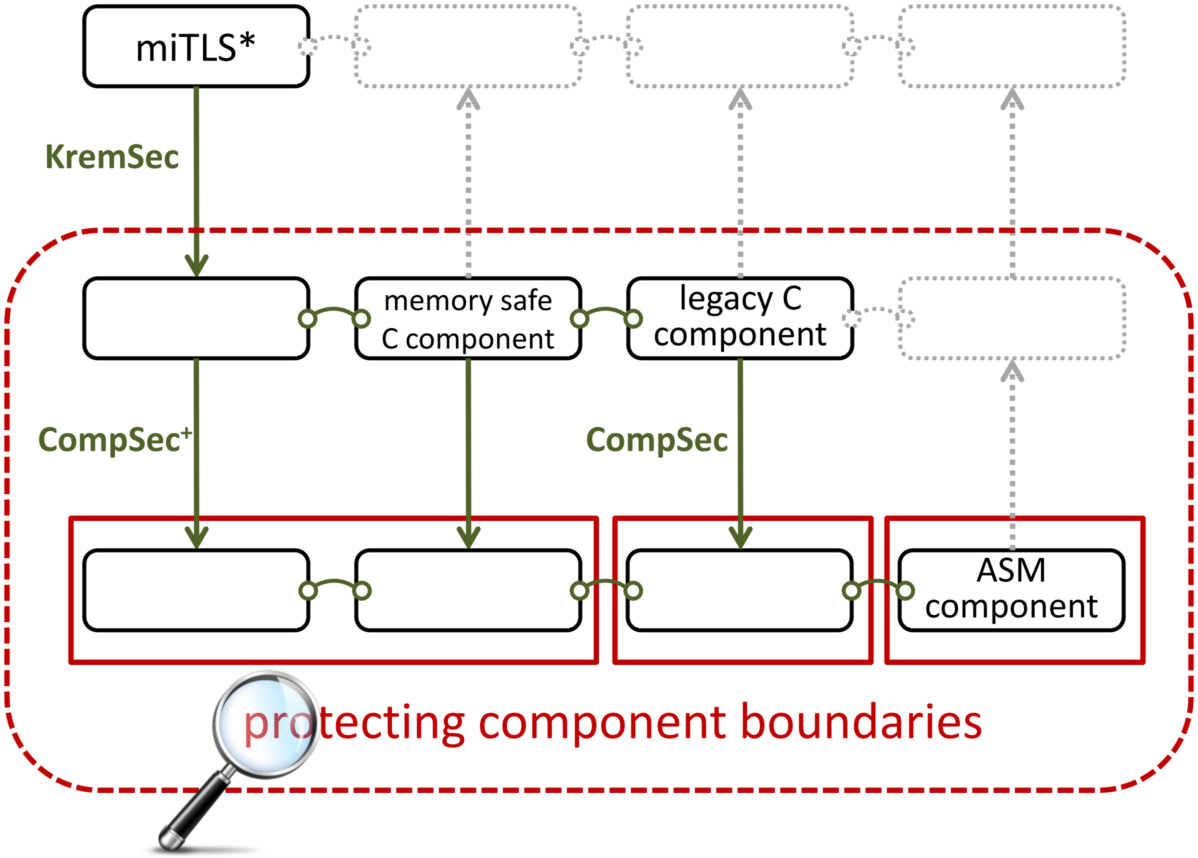

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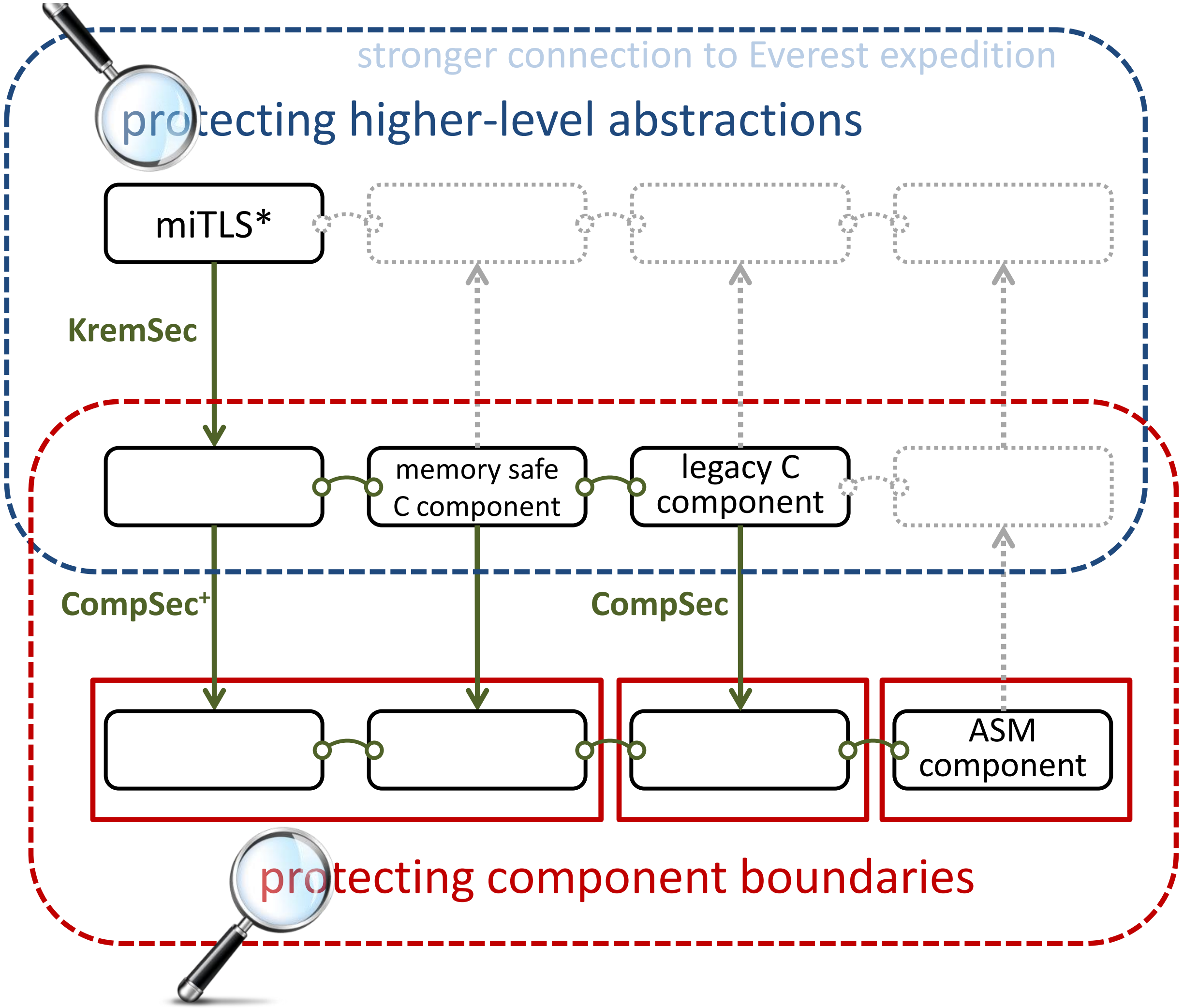
ASM language
(RISC-V + micro-policies)


stronger connection to Everest expedition
protecting higher-level abstractions
miTLS*
KremSec
memory safe
C component
legacy C
component
CompSec$^+$
CompSec
ASM
component
protecting component boundaries

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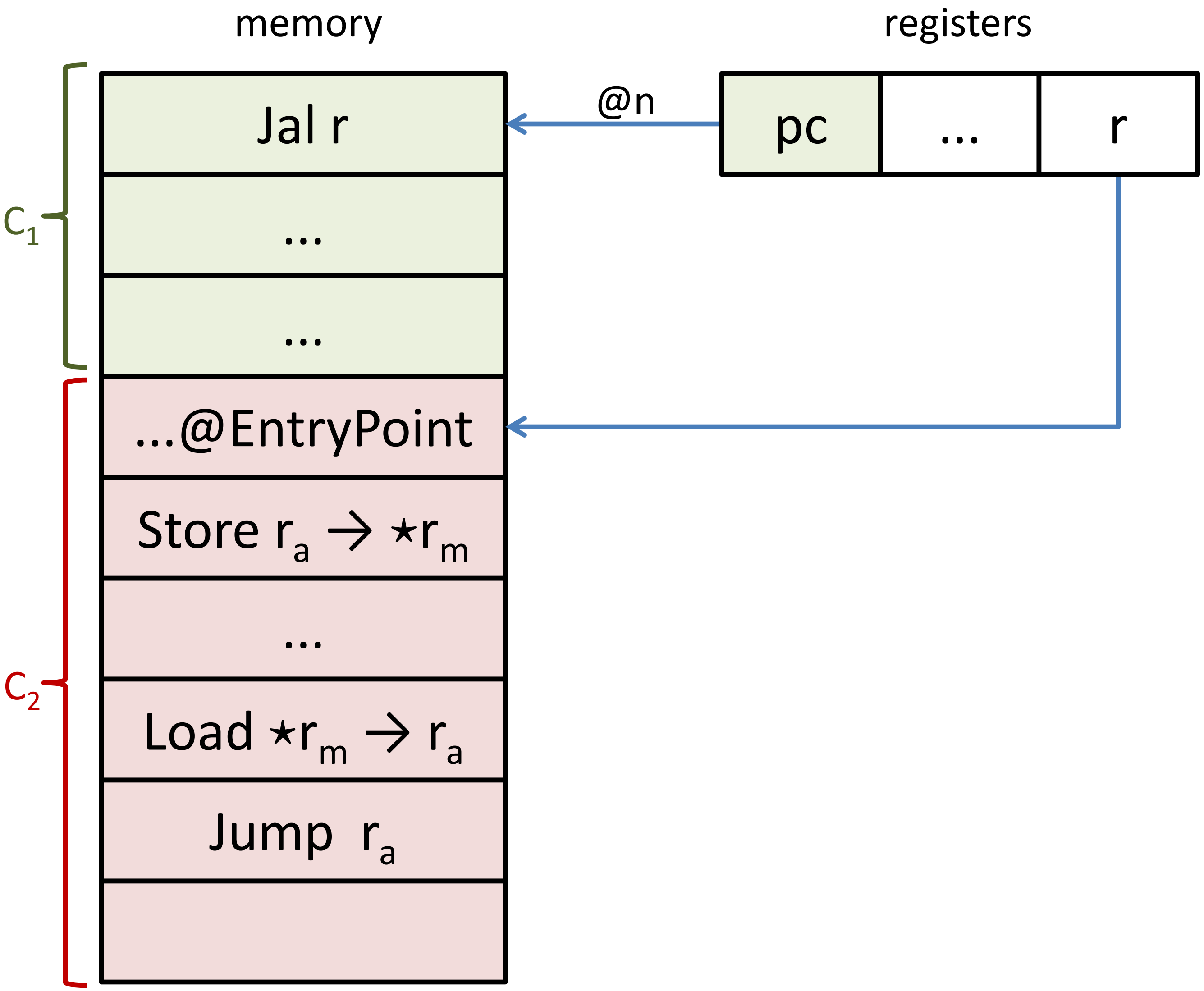
Recent work, joint with Yannis Juglaret et al

Compartmentalization micro-policy



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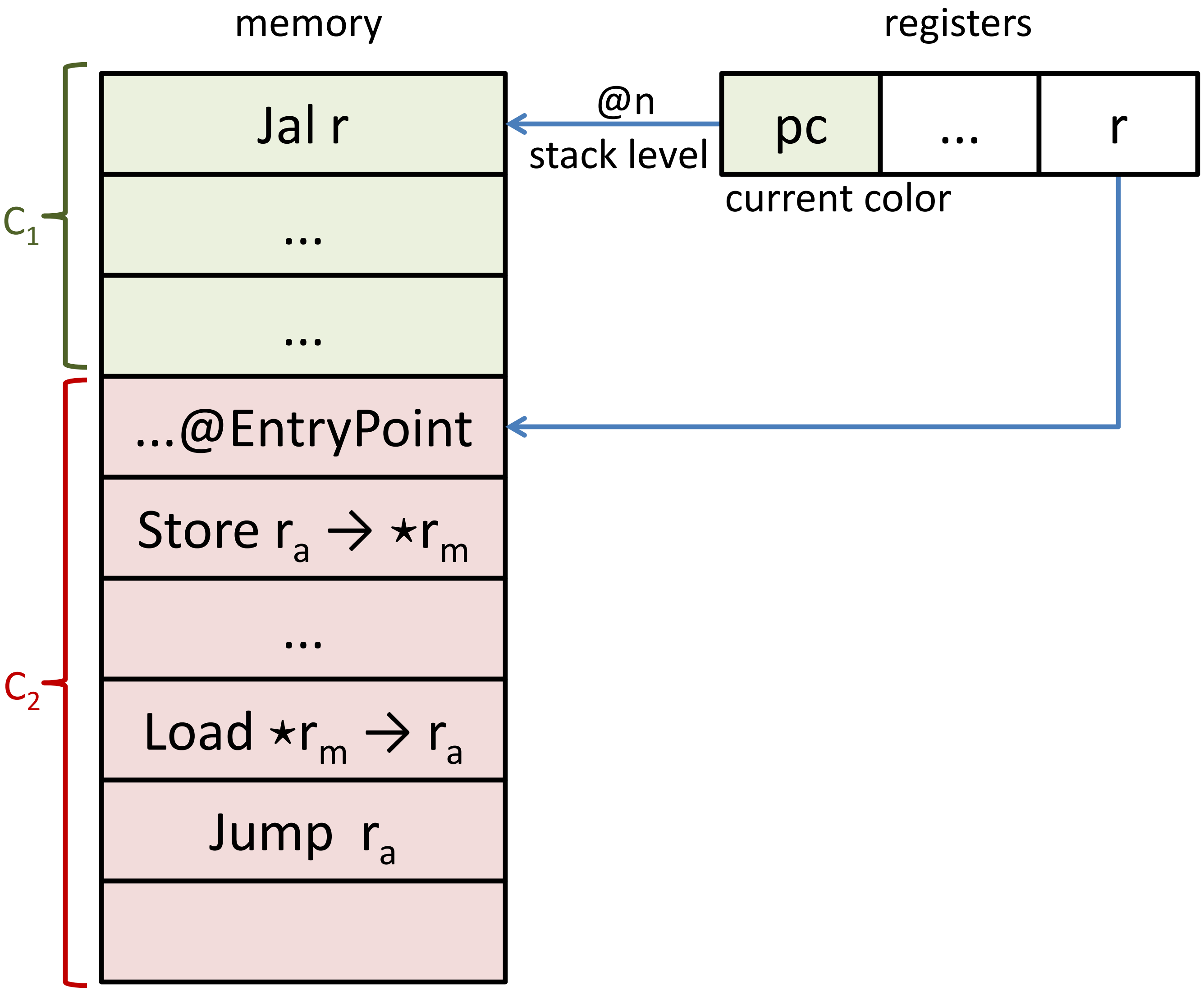

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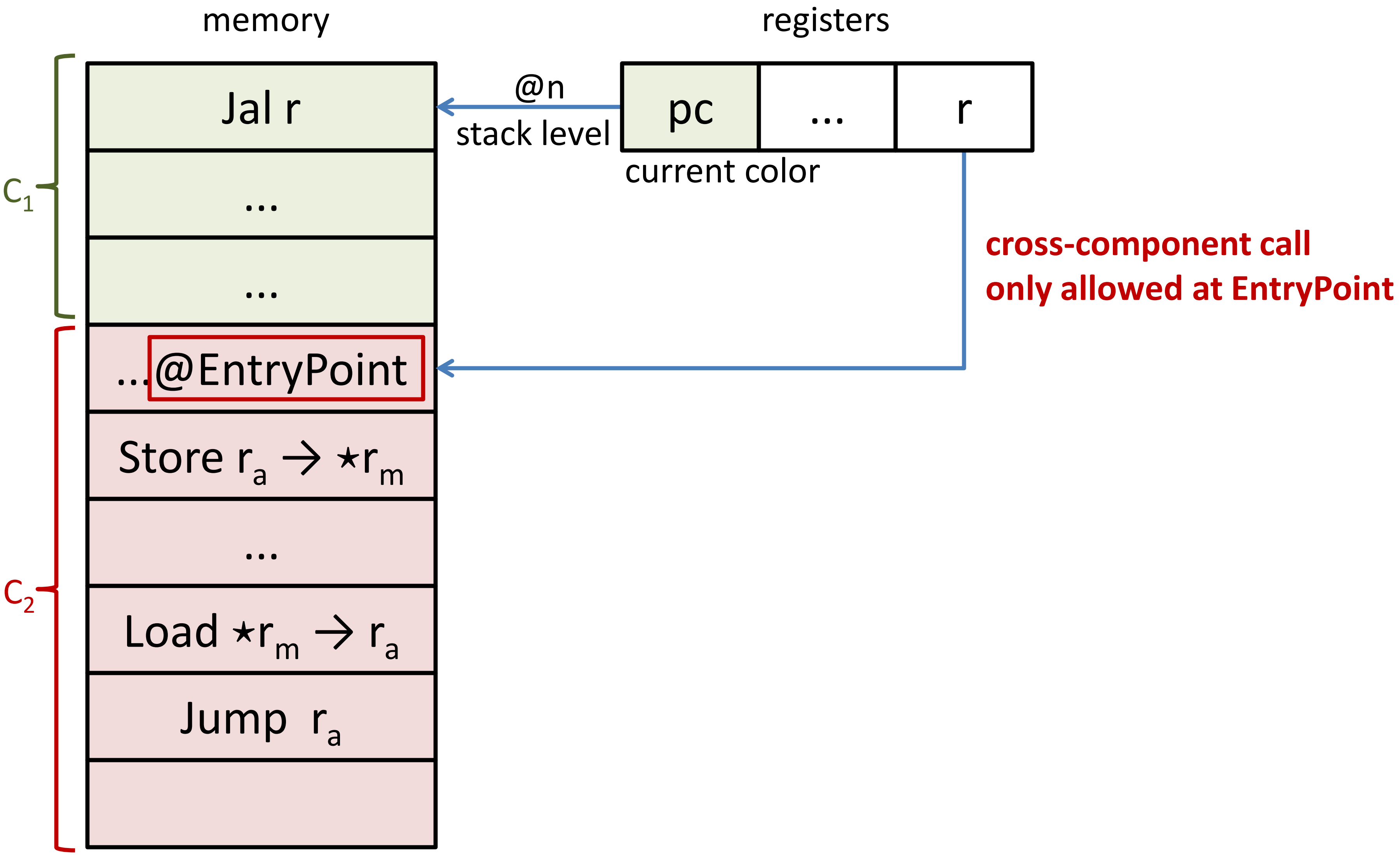

cross-component call only allowed at EntryPoint

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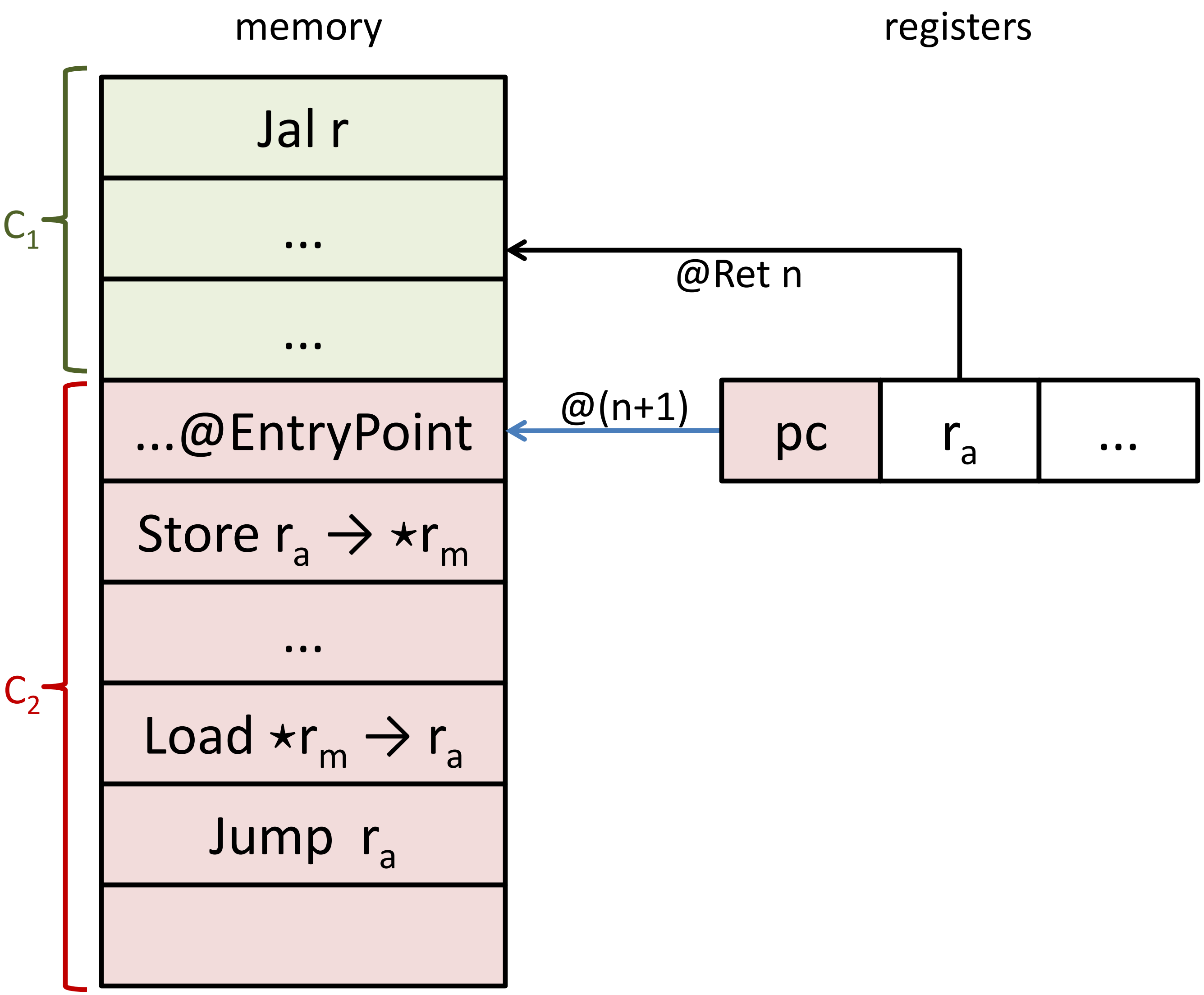

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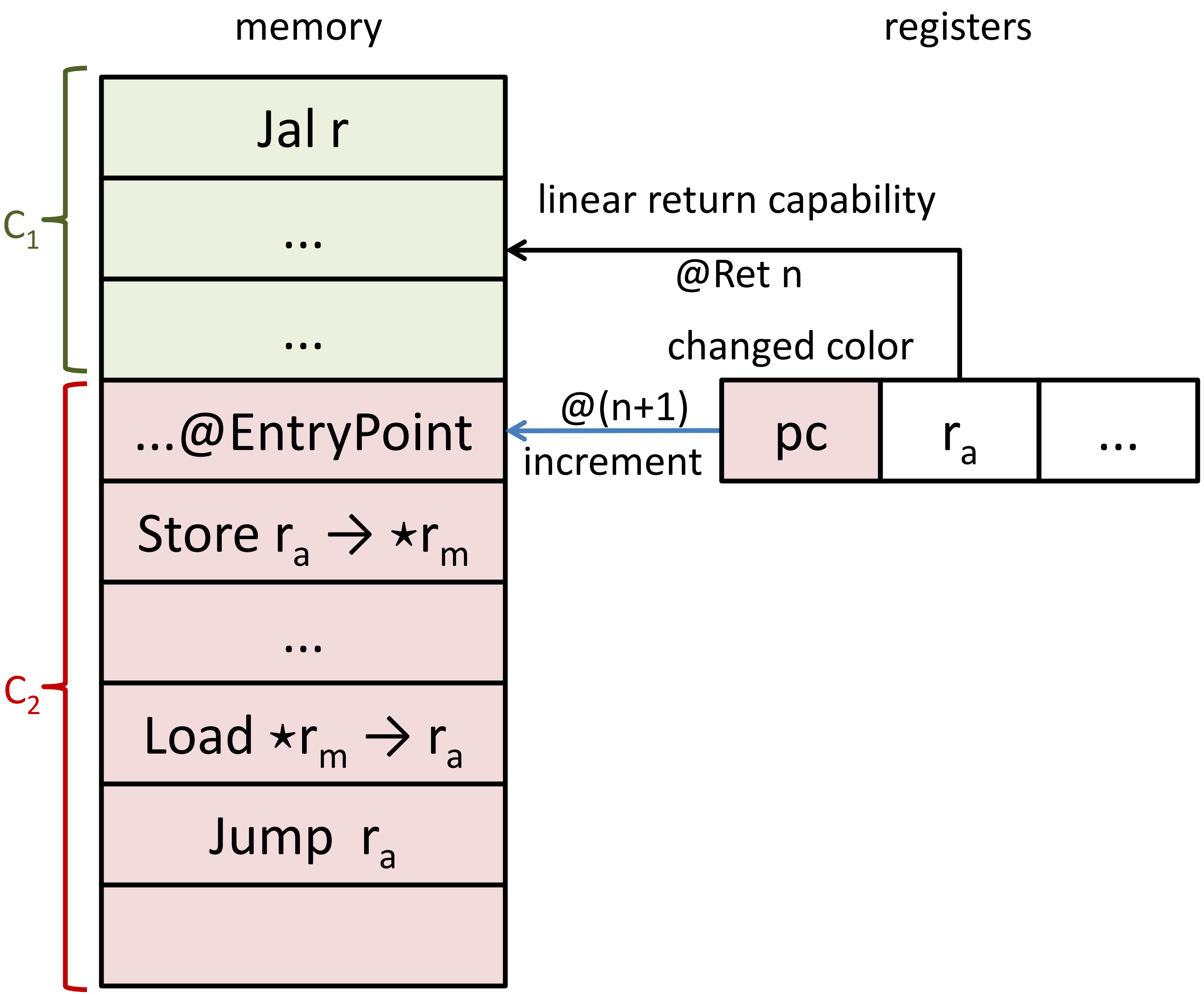

memory

registers

C_1

Jal r

...

...

linear return capability

@Ret n

changed color

C_2

...@EntryPoint

@(n+1)

increment

pc

r_a

...

Store $r_a \rightarrow \star r_m$

...

Load $\star r_m \rightarrow r_a$

Jump r_a

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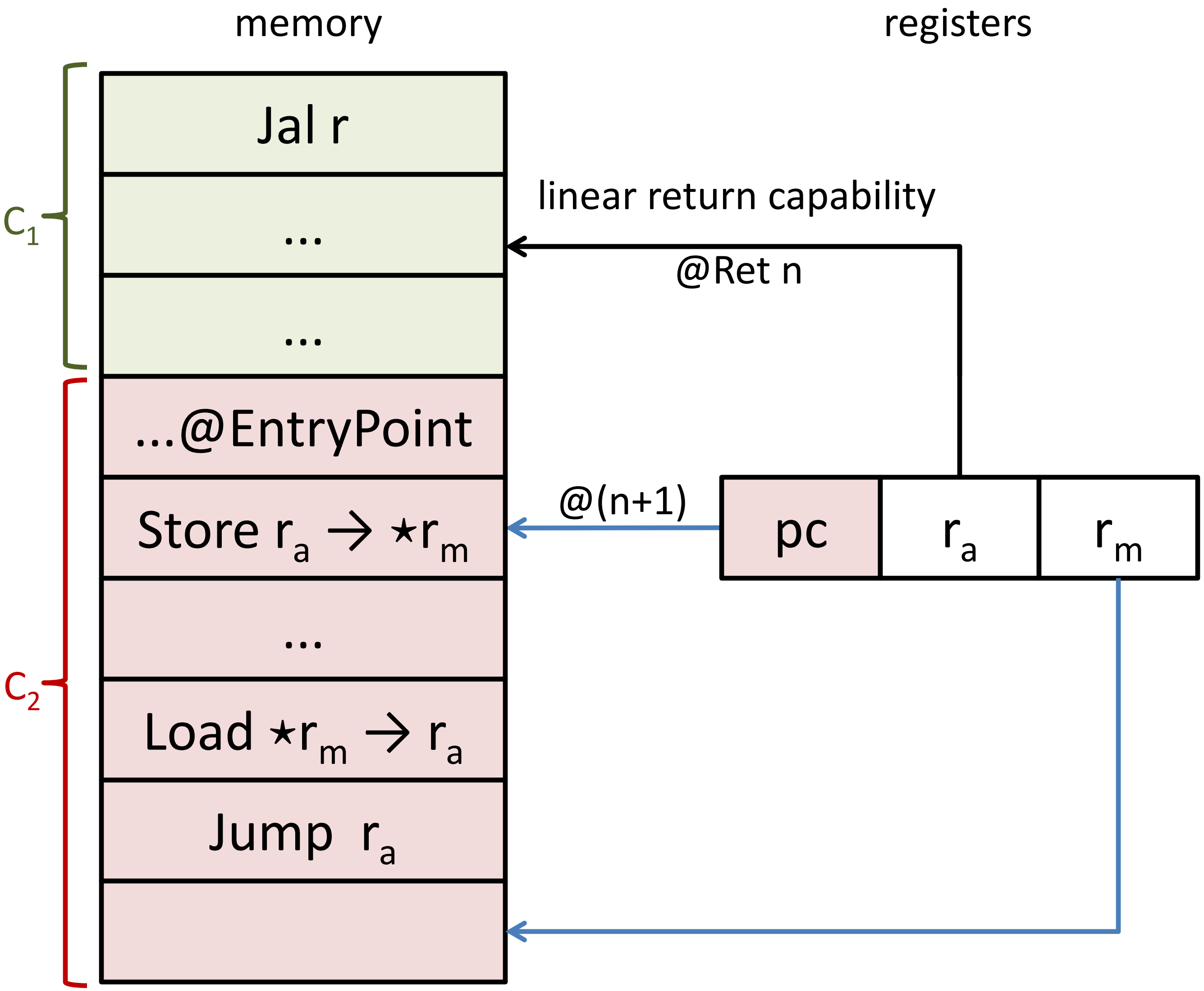

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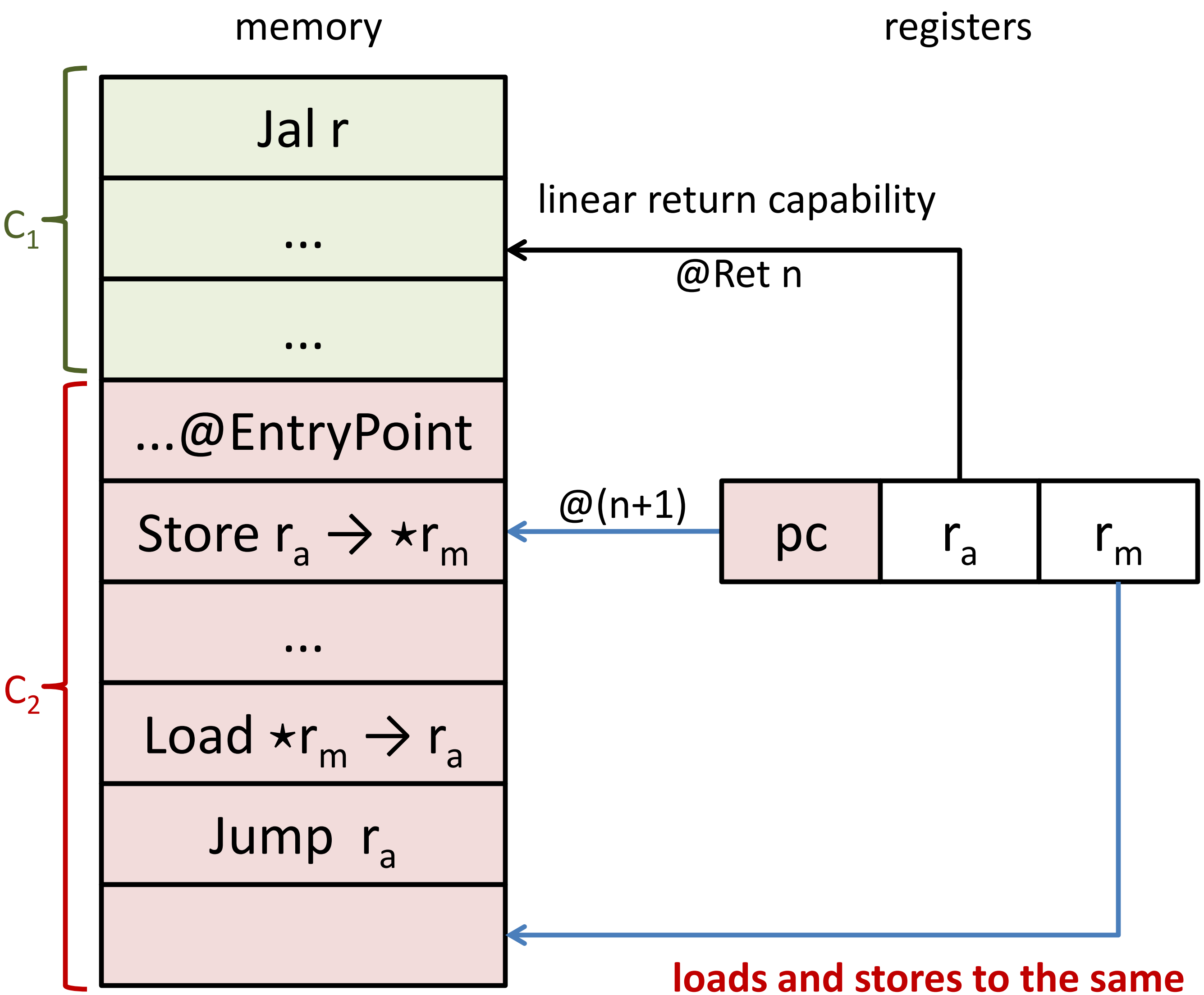

loads and stores to the same component always allowed

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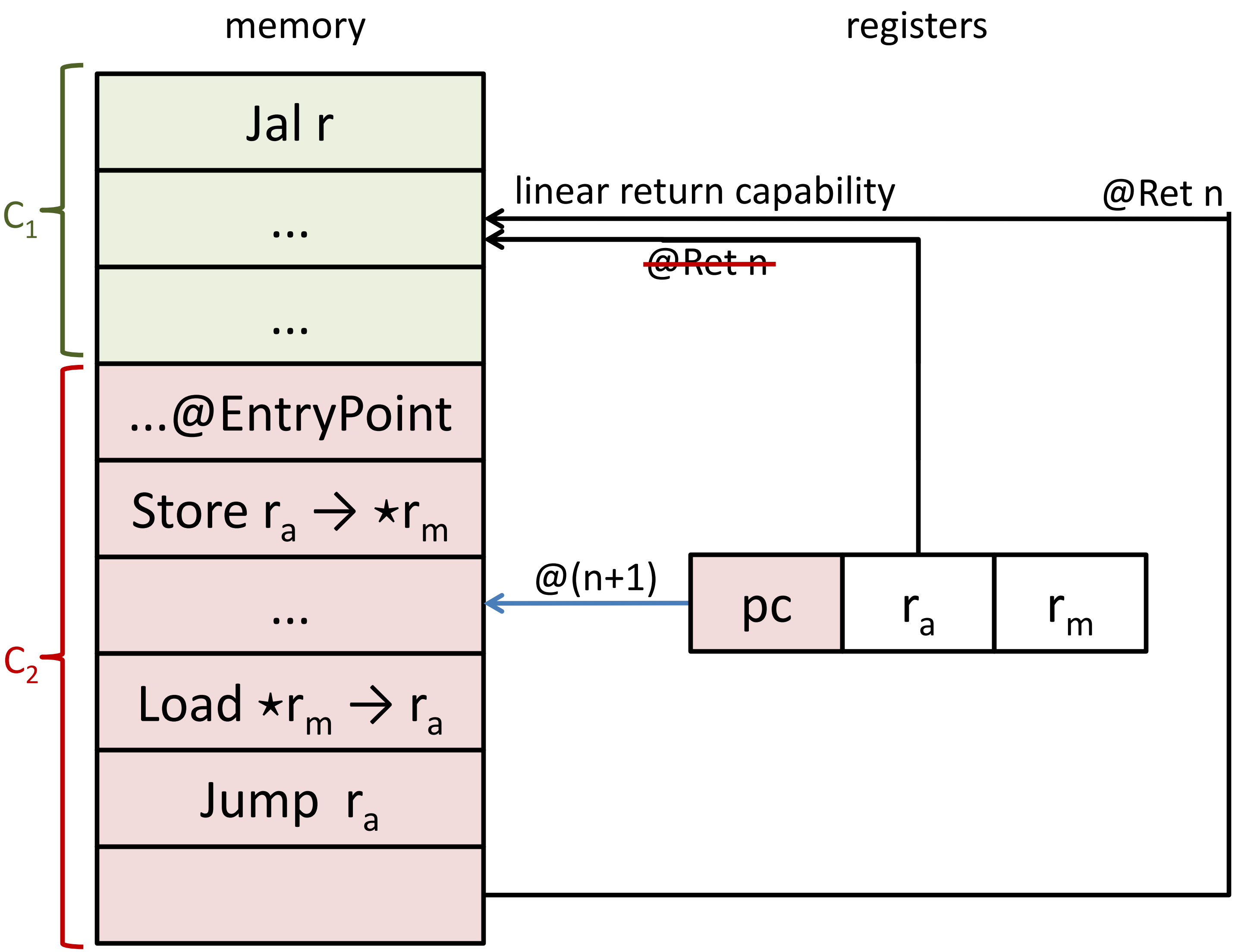

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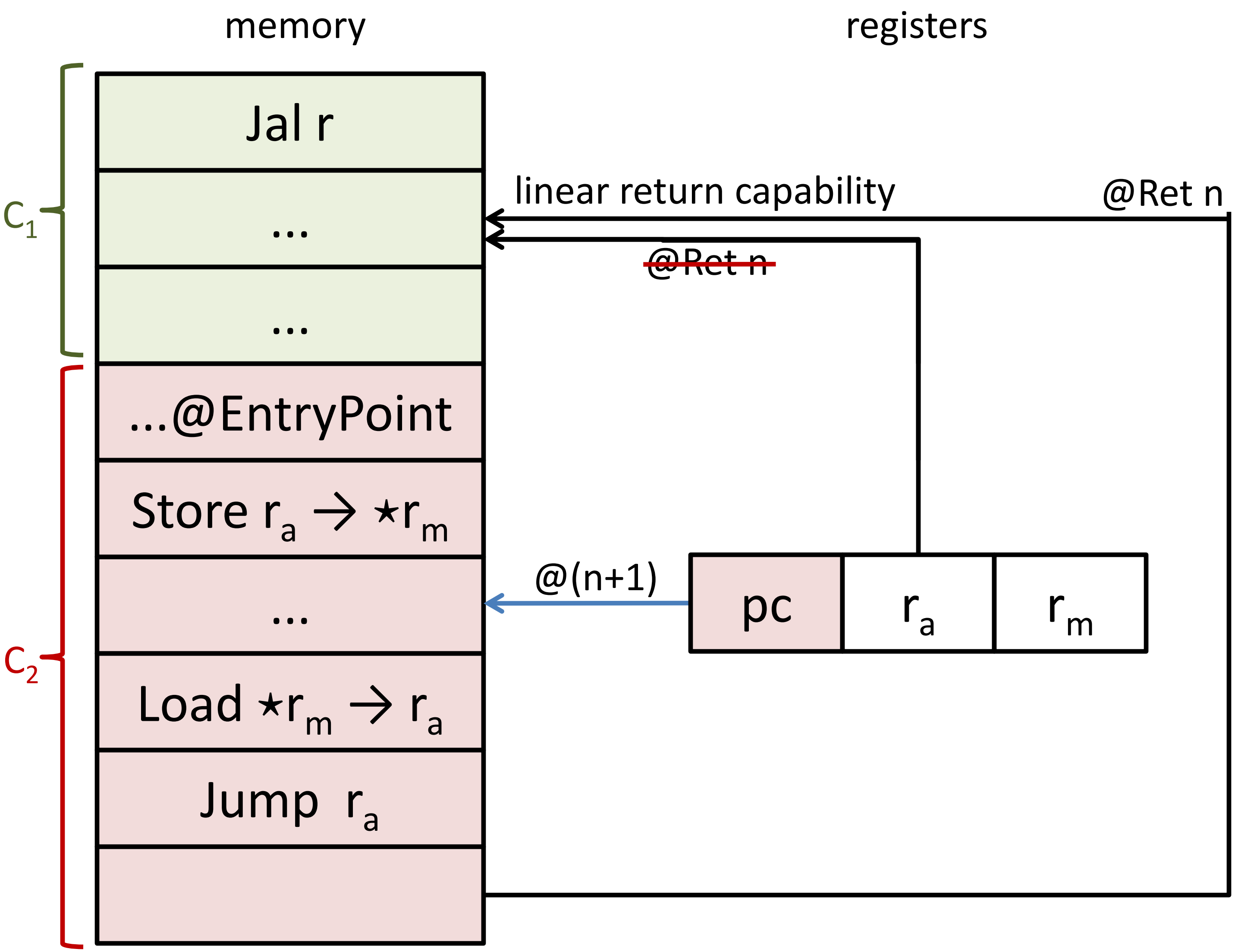

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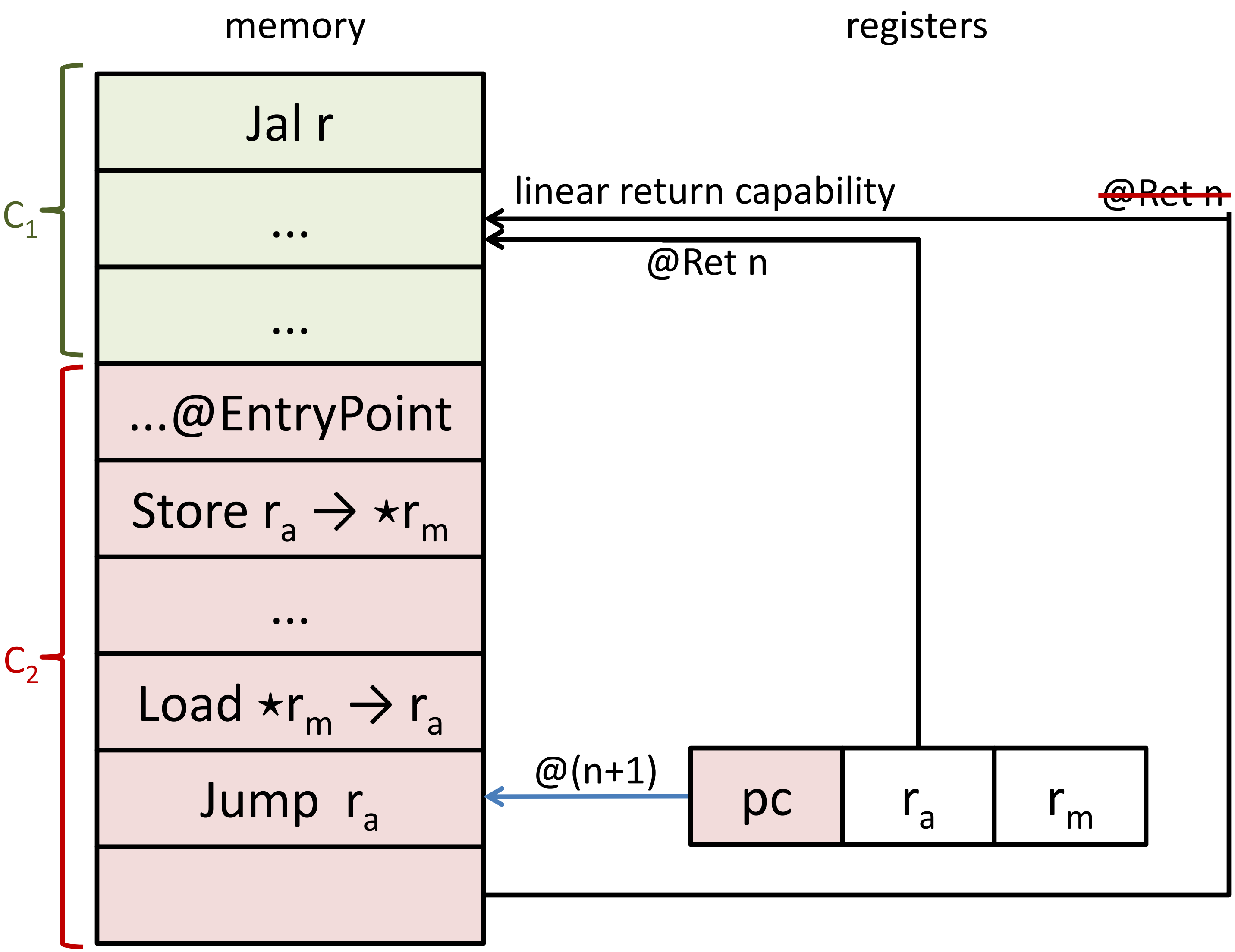

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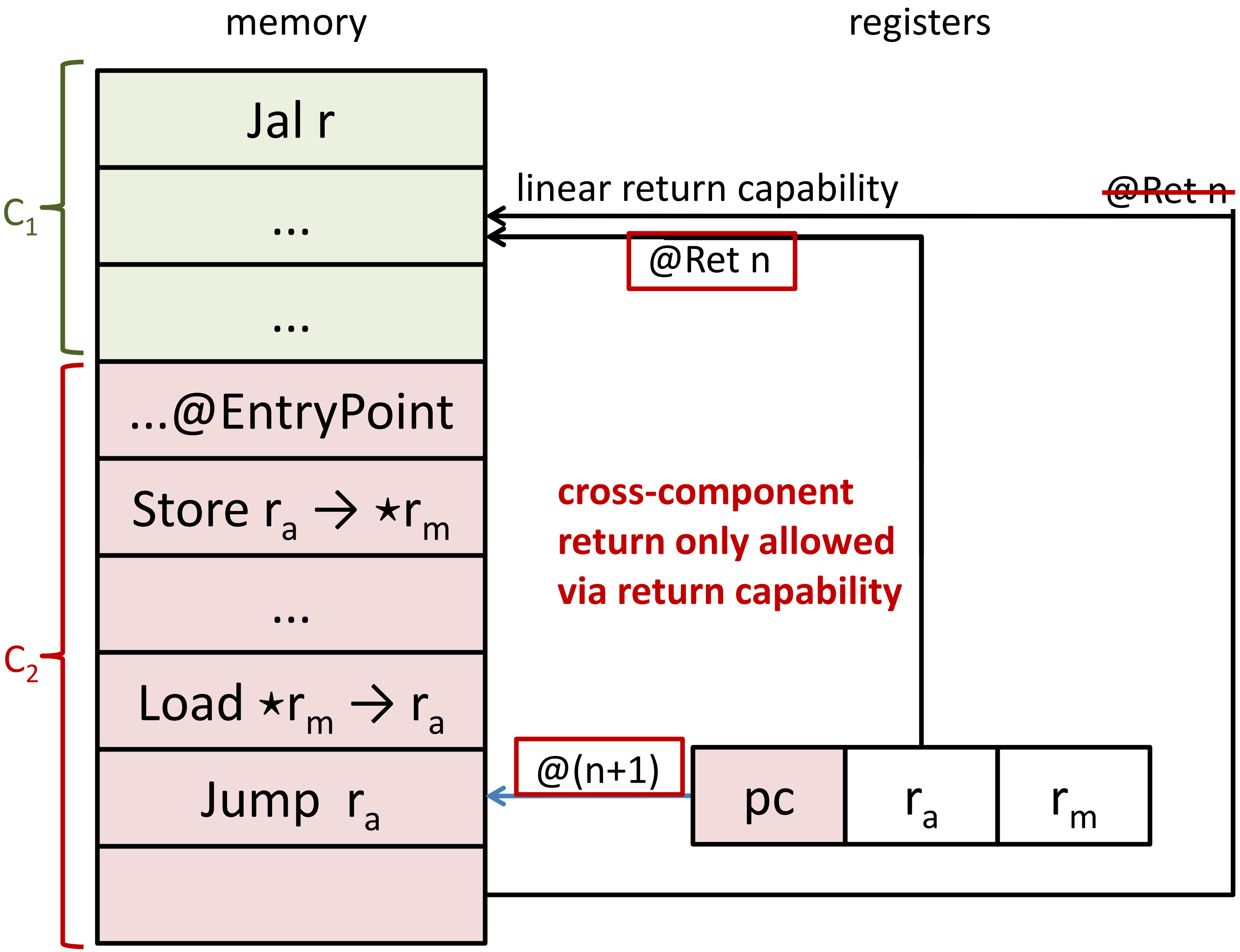

cross-component return only allowed via return capability

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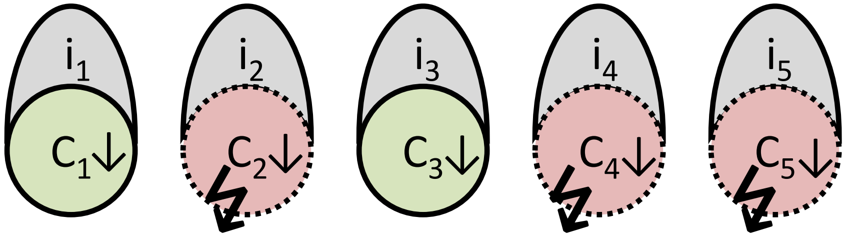
Secure compartmentalizing compilation (SCC)

∀compromise scenarios.



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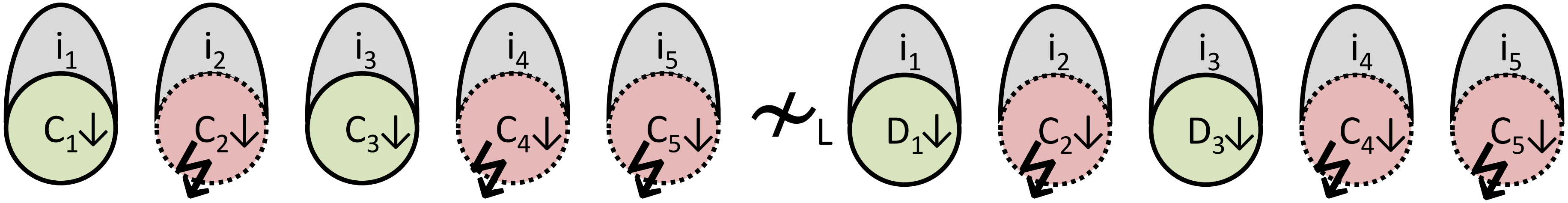

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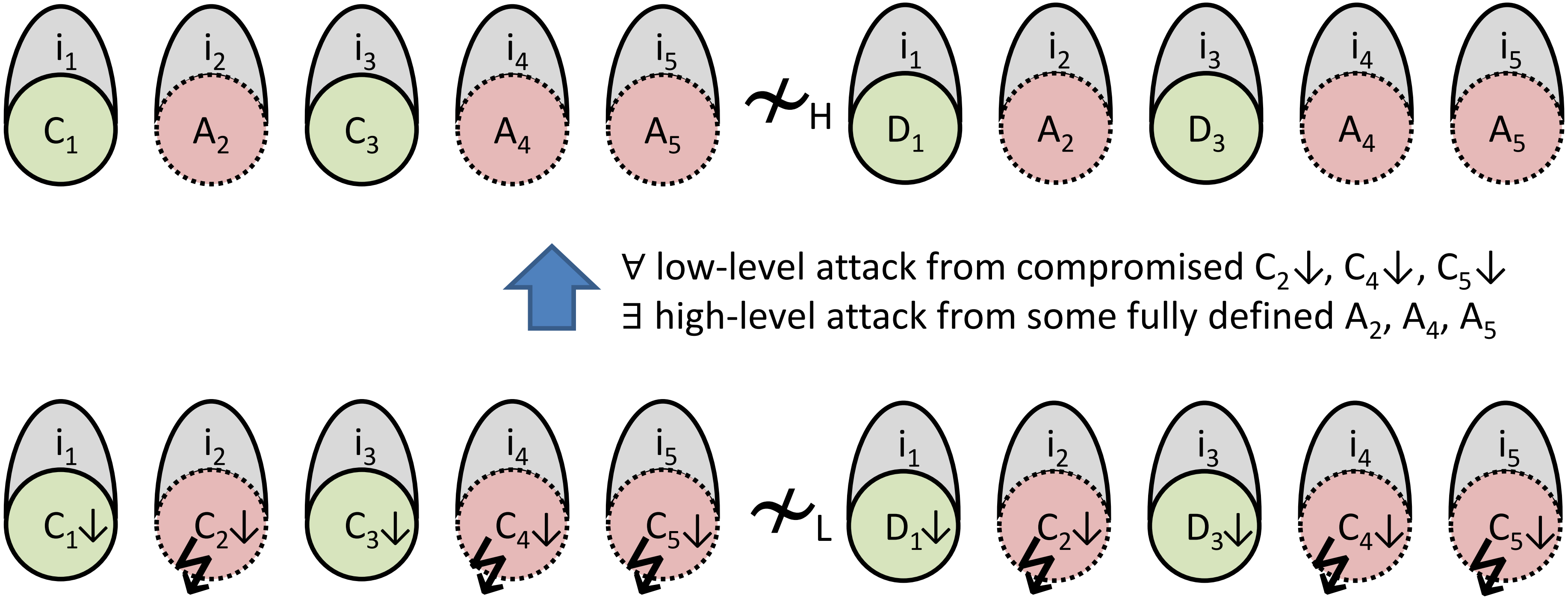
i_1 i_2 i_3 i_4 i_5
C_1 A_2 C_3 A_4 A_5
$\not\sim_H$
i_1 i_2 i_3 i_4 i_5
D_1 A_2 D_3 A_4 A_5
i_1 i_2 i_3 i_4 i_5
$C_1\downarrow$ $C_2\downarrow$ $C_3\downarrow$ $C_4\downarrow$ $C_5\downarrow$
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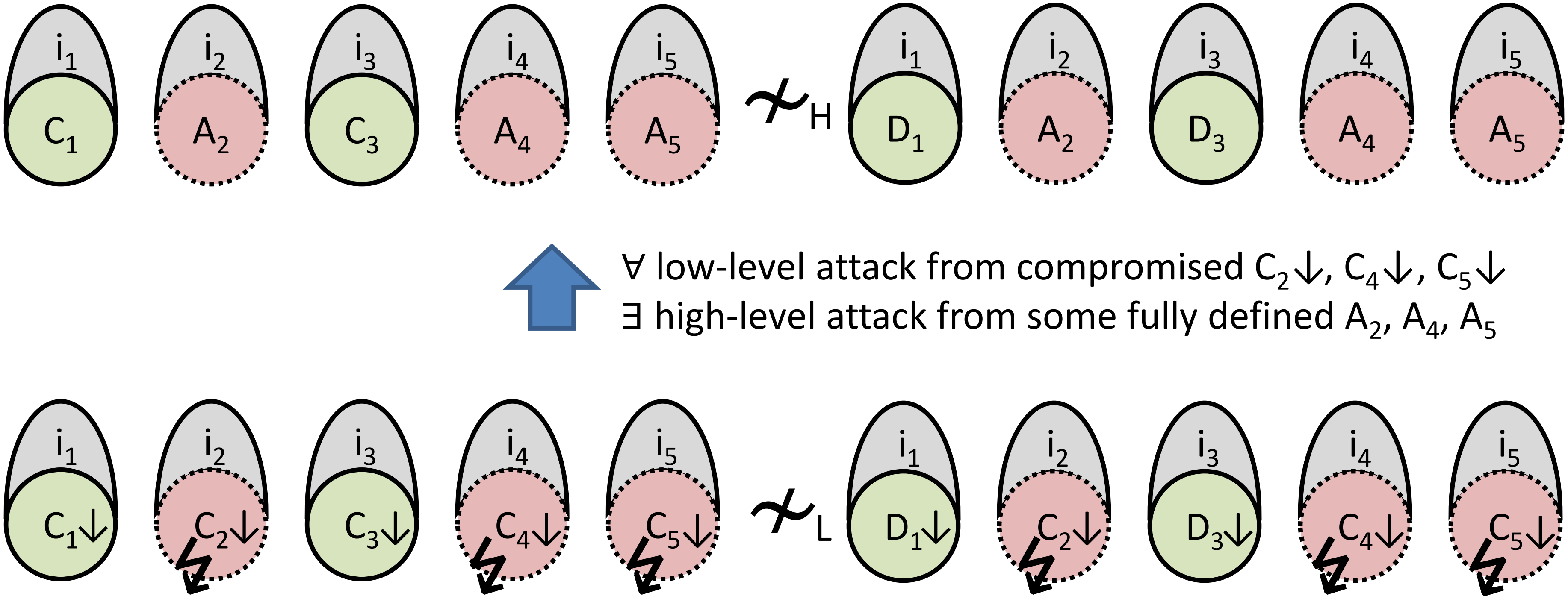
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follows from “structured full abstraction

for unsafe languages” + “separate compilation”

[Beyond Good and Evil, Juglaret, Hritcu, et al, CSF’16]

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  - types, value immutability, opaqueness of closures, parametricity (dynamic sealing), GC vs malloc/free, ...

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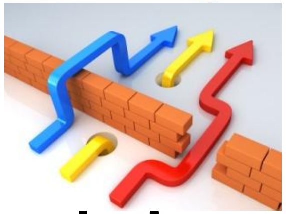
  - **push these limits further and combine with static analysis**



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- **improve transparency**
  - **allowing more safe behaviors**
  - e.g. statically detect which copy of linear return capability the code will use to return
  - in this case unsound static analysis is fine

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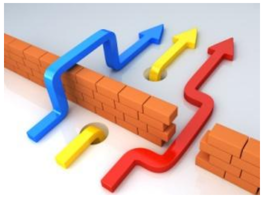

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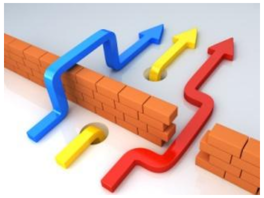

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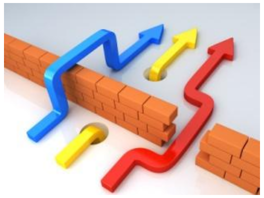

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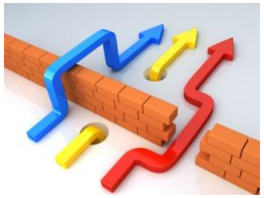

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- Most of this is **vaporware** at this point but ...
  - building a community, looking for collaborators, and hiring

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- **Secure compilation meetings (very informal)**
  - 1st at Inria Paris in August 2016
  - 2nd in Paris on 15 January 2017 before POPL at UPMC
  - Work in progress proposal for Dagstuhl seminar in 2018
  - **build larger research community, identify open problems, bring together communities** (hardware, systems, security, languages, verification, ...)

BACKUP SLIDES

- Looking for excellent **interns**, **PhD students**, **PostDocs**, **starting researchers**, and **engineers**
- We can also support outstanding candidates in the **Inria permanent researcher competition**

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What secure compilation adds over compositional compiler correctness

- **mapping back arbitrary low-level contexts**
- **preserving integrity properties**
  - robust compilation phrased in terms of this
- **preserving confidentiality properties**
  - full abstraction and preservation of hyper-safety phrased in terms of this
- **stronger notion of components and interfaces**
  - secure compartmentalizing compilation adds this

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- **Problems not just with effort/scale**
  - devising good **proof techniques** for full abstraction is a hot research topic of it's own

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- **Secure micro-policy composition**
  - micro-policies are **interferent** reference monitors
  - one micro-policy's behavior can break another's guarantees
    - e.g. composing anything with IFC can leak

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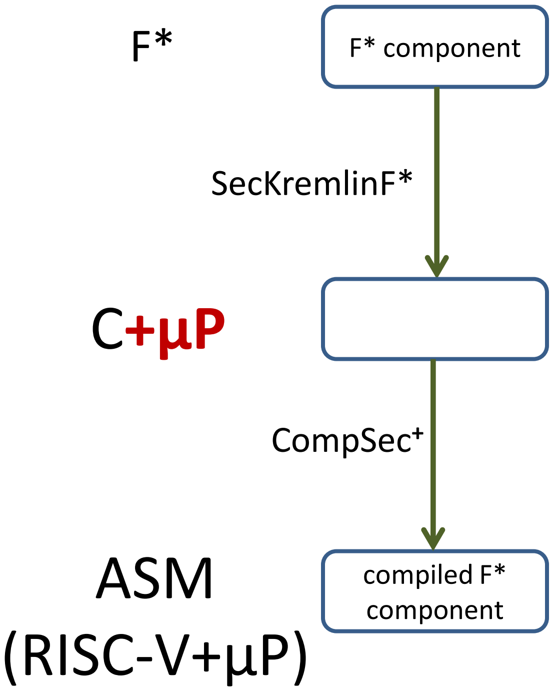

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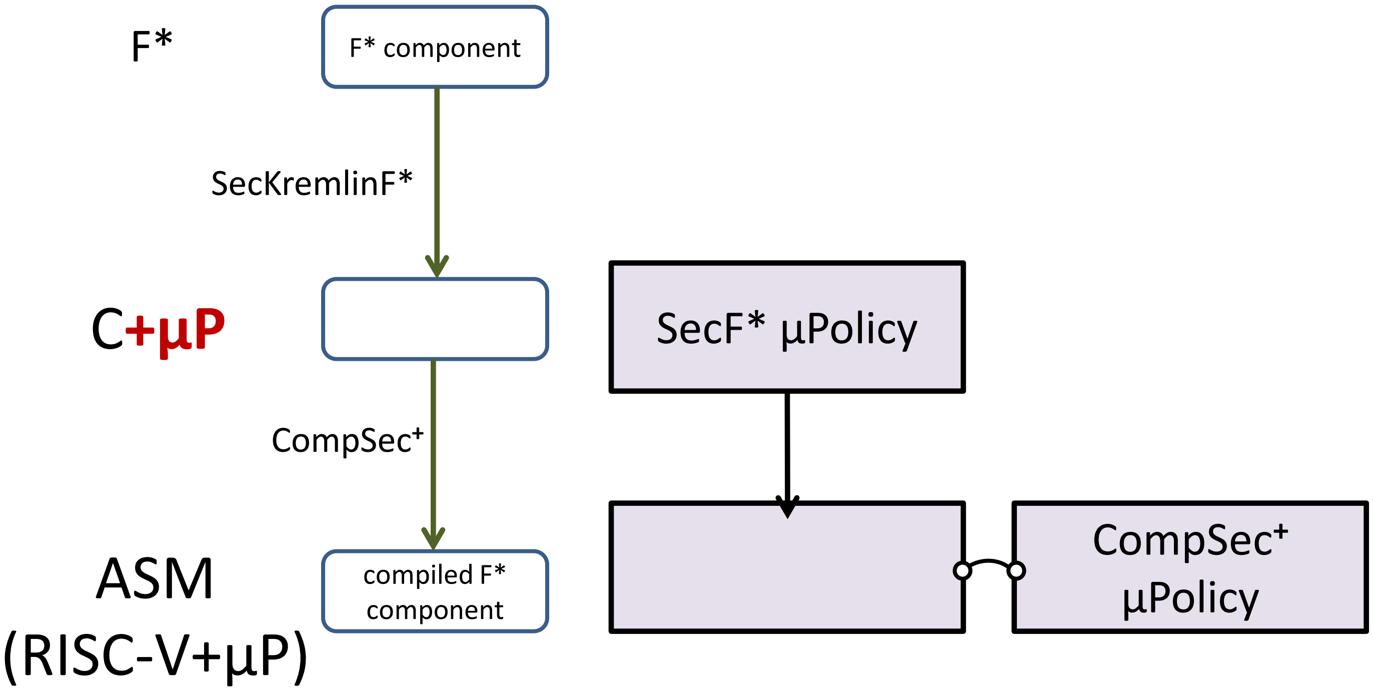

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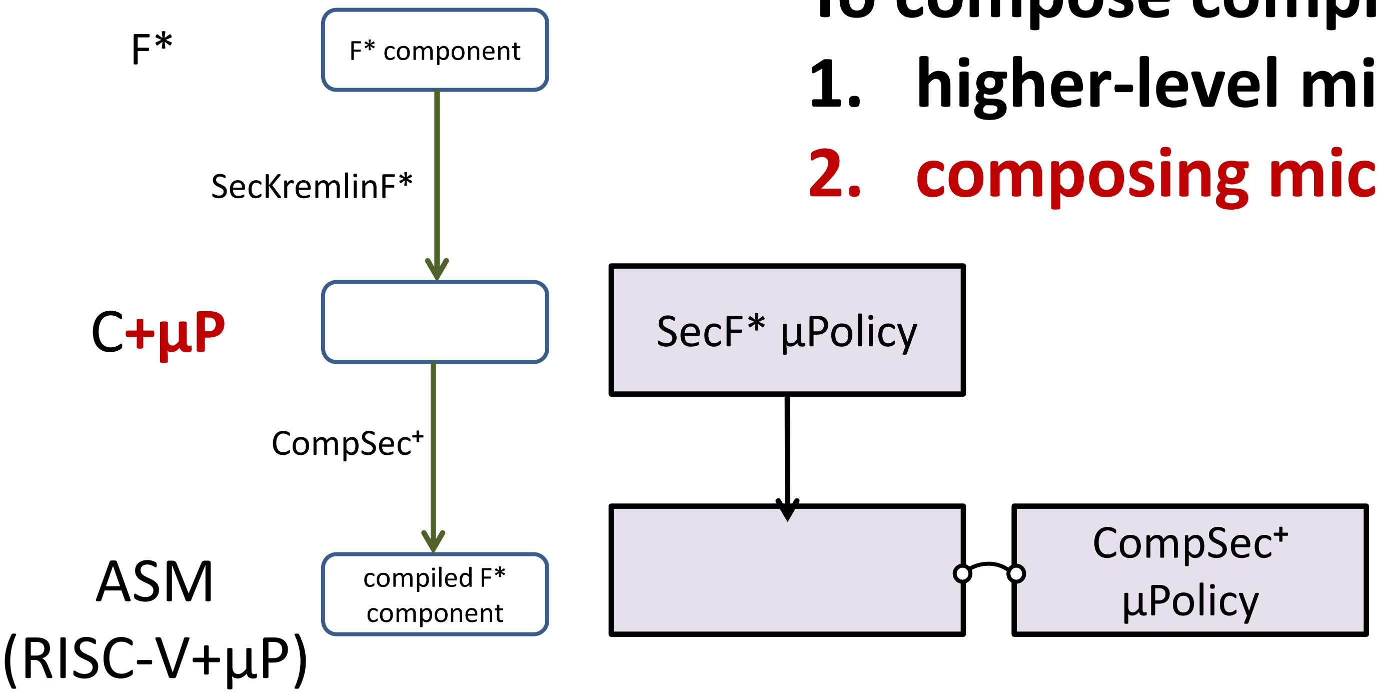
2. **composing micro-policies**



User-specified higher-level policies

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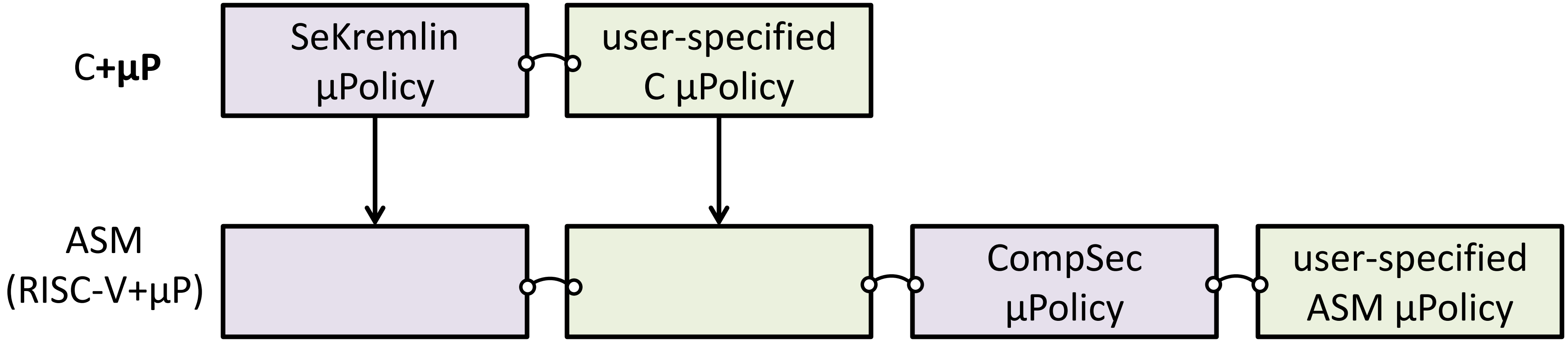

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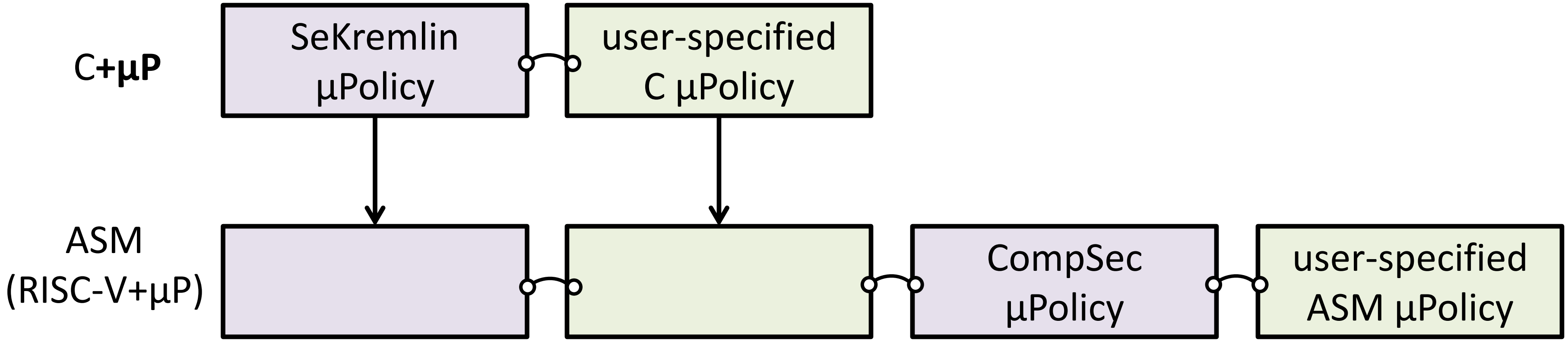

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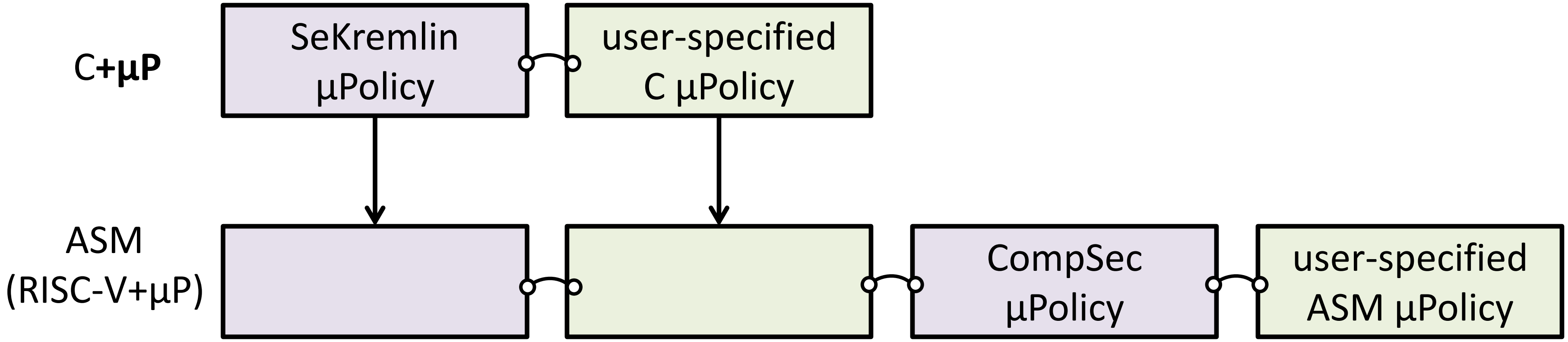

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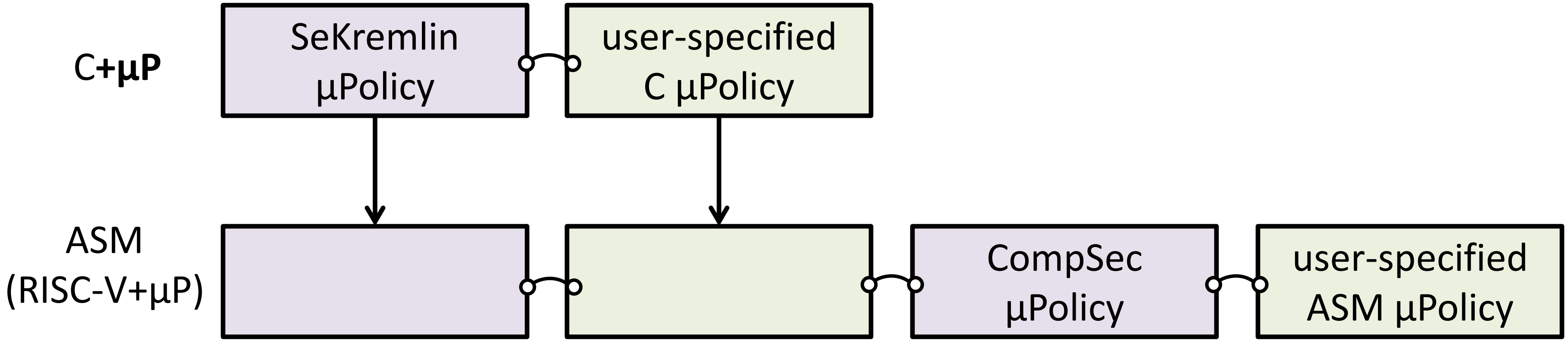
- Bad news: **secure micro-policy composition is hard!**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