SECOMP

Efficient Formally Secure Compilers to a Tagged Architecture

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Prosecco team

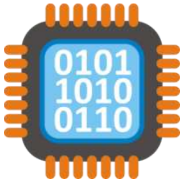
Computers are insecure

- **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

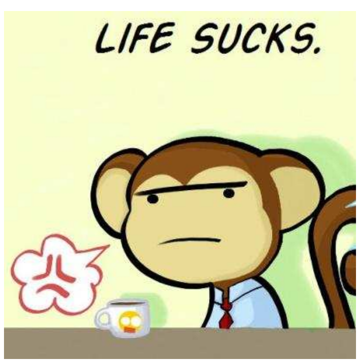


- **Today's processors are mindless bureaucrats**
  - "write past the end of this buffer" ... yes boss!
  - "jump to this untrusted integer" ... right boss!
  - "return into the middle of this instruction" ... sure boss!
- **Software bears most of the burden for security**
- **Manufacturers have started looking for solutions**
  - 2015: Intel Memory Protection Extensions (MPX) and Intel Software Guard Extensions (SGX)
  - 2016: Oracle Silicon Secured Memory (SSM)

"Spending silicon 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
- **Programmers bear the burden for security**
  - just write secure code ... all of it



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

DNS queries

...ell" <carlos at redhat dot com>

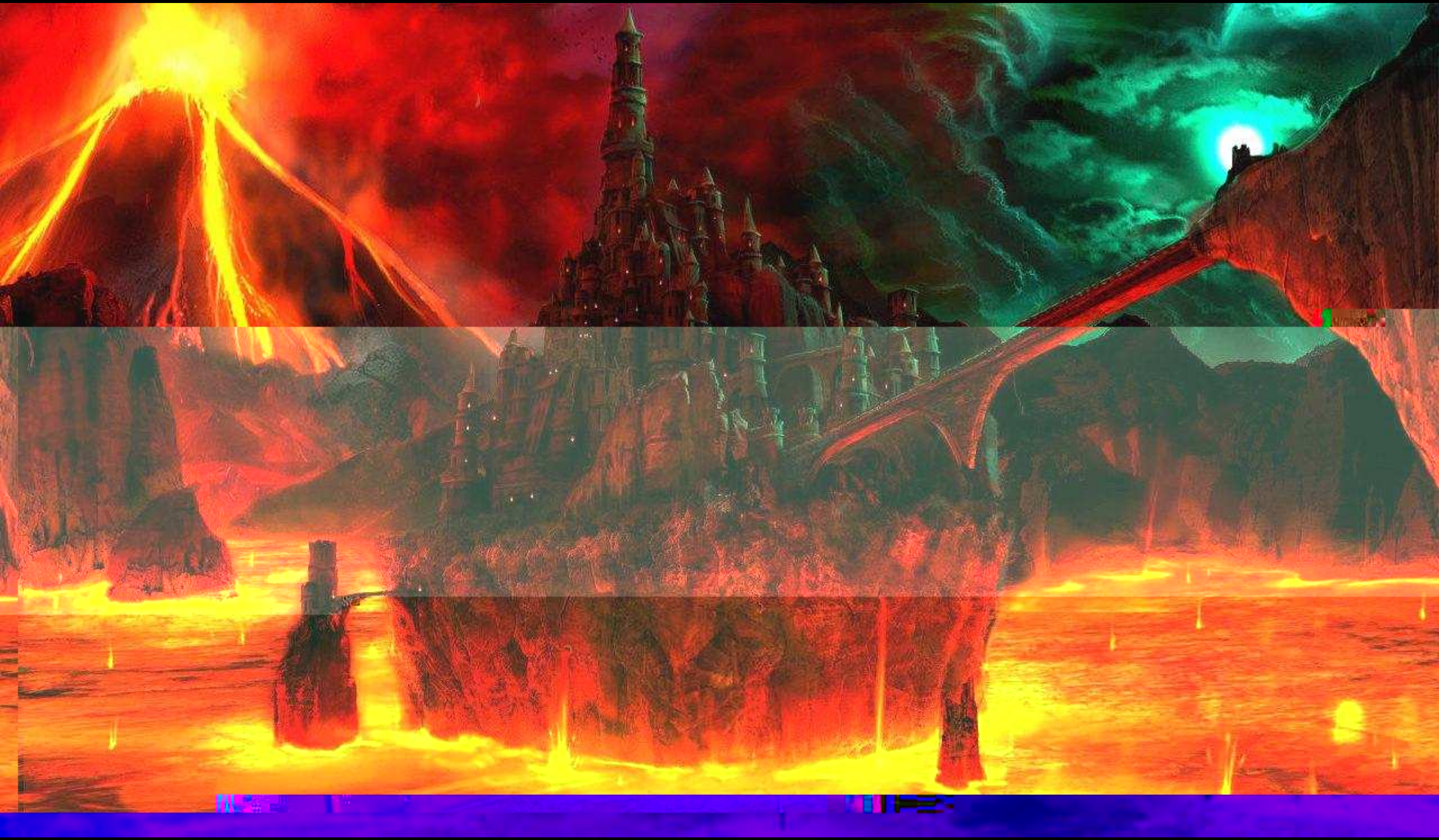
vulnerable since May 2008

- *Date*: Tue, 16 Feb 2016 0...
- *Subject*: [PATCH] CVE-2... overflow
- *Authentication-results*: sourceware.org; auth=none
- *References*: <56C32C20 dot 1070006 at redhat dot com>

```
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.
```

Safer high-level languages

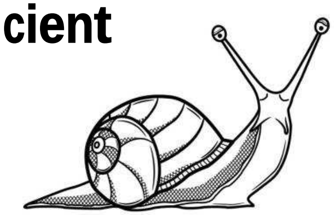
- **memory safe** (at a cost)
- **useful abstractions** for writing secure code:
  - GC, type abstraction, modules, immutability, ...
- **not immune to low-level attacks**
  - large runtime systems, in C++ for efficiency
  - **unsafe interoperability with low-level code**
    - libraries often have large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



Summary of the problem

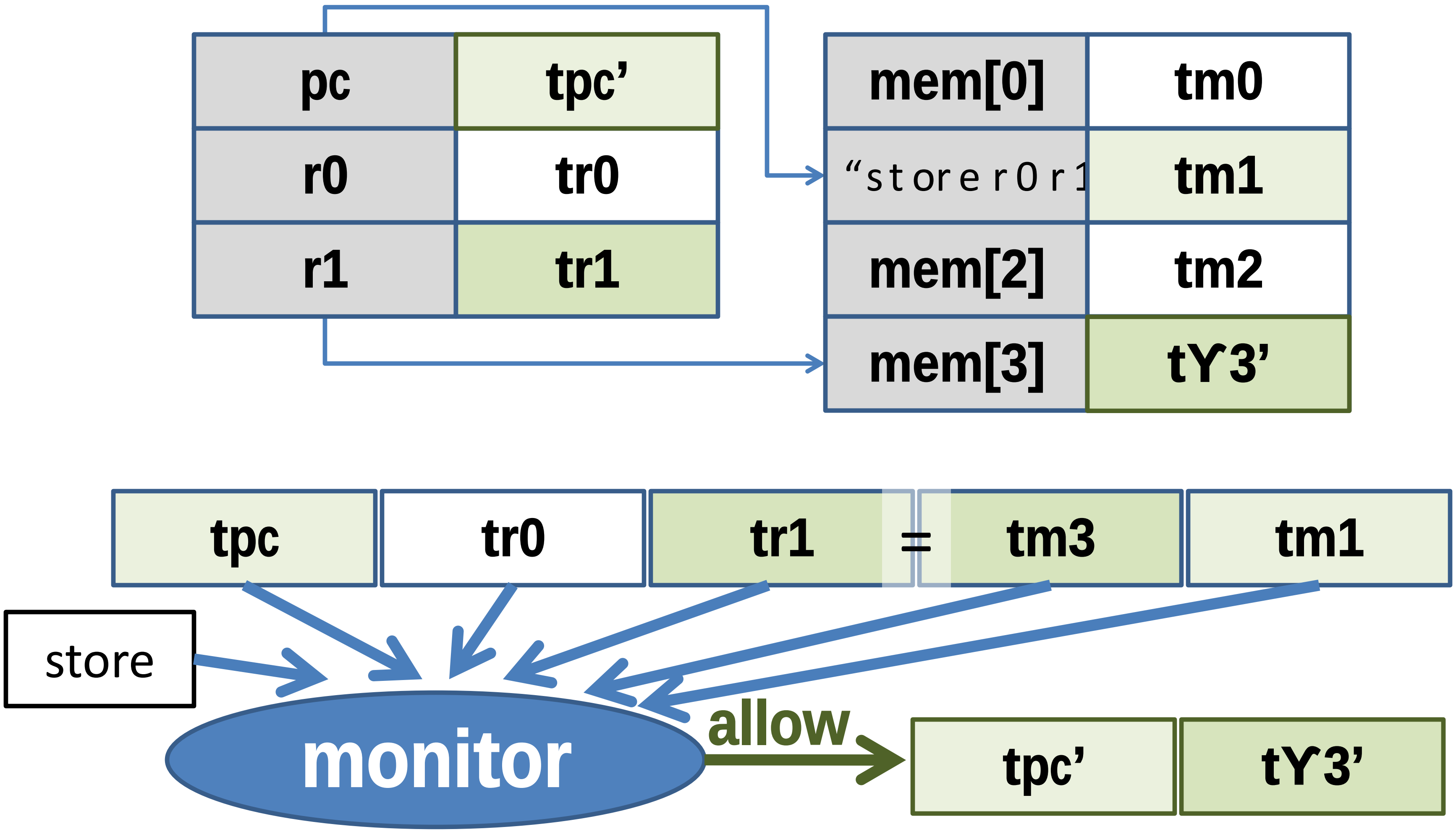
- **1. inherently insecure low-level languages**
  - **memory unsafe**: any buffer overflow can be catastrophic allowing remote attackers to gain complete control

- **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
- **Today’s layǵuages & ǑoϒpiIers plagued ōy low-level attacks**
  - **hardware provides no appropriate security mechanisms**
  - fixing this purely in software would be way **too inefficient**



Key enabler: Micro-Policies

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



software Yoyitor’s deǑisioy is hardware ǑaǑhed

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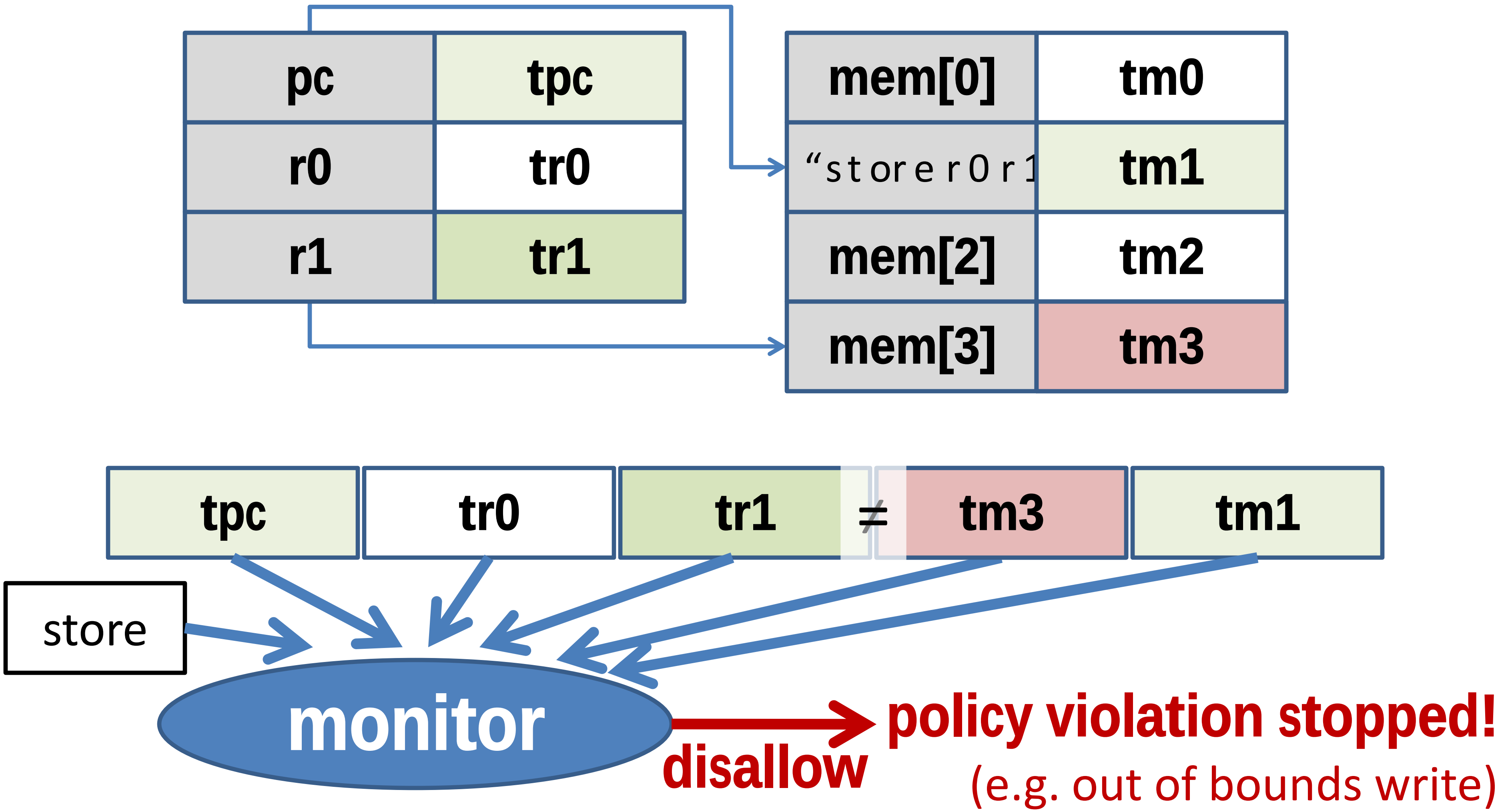


Micro-policies are cool!

- **low level + fine grained**: unbounded per-word metadata, checked & propagated on each instruction
- **flexible**: tags and monitor defined by software
- **efficient**: software decisions hardware cached
- **expressive**: complex policies for secure compilation
- **secure** and **simple** enough to verify security in Coq
- **real**: FPGA implementation on top of RISC-V

DRAPER bluespec

Expressiveness

- information flow control (IFC) [POPL’ 14]
- monitor self-protection
- protected compartments
- dynamic sealing
- heap memory safety
- code-data separation
- control-flow integrity (CFI)
- taint tracking
- ...

Verified
(in Coq)
[Oakland’ 15]

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

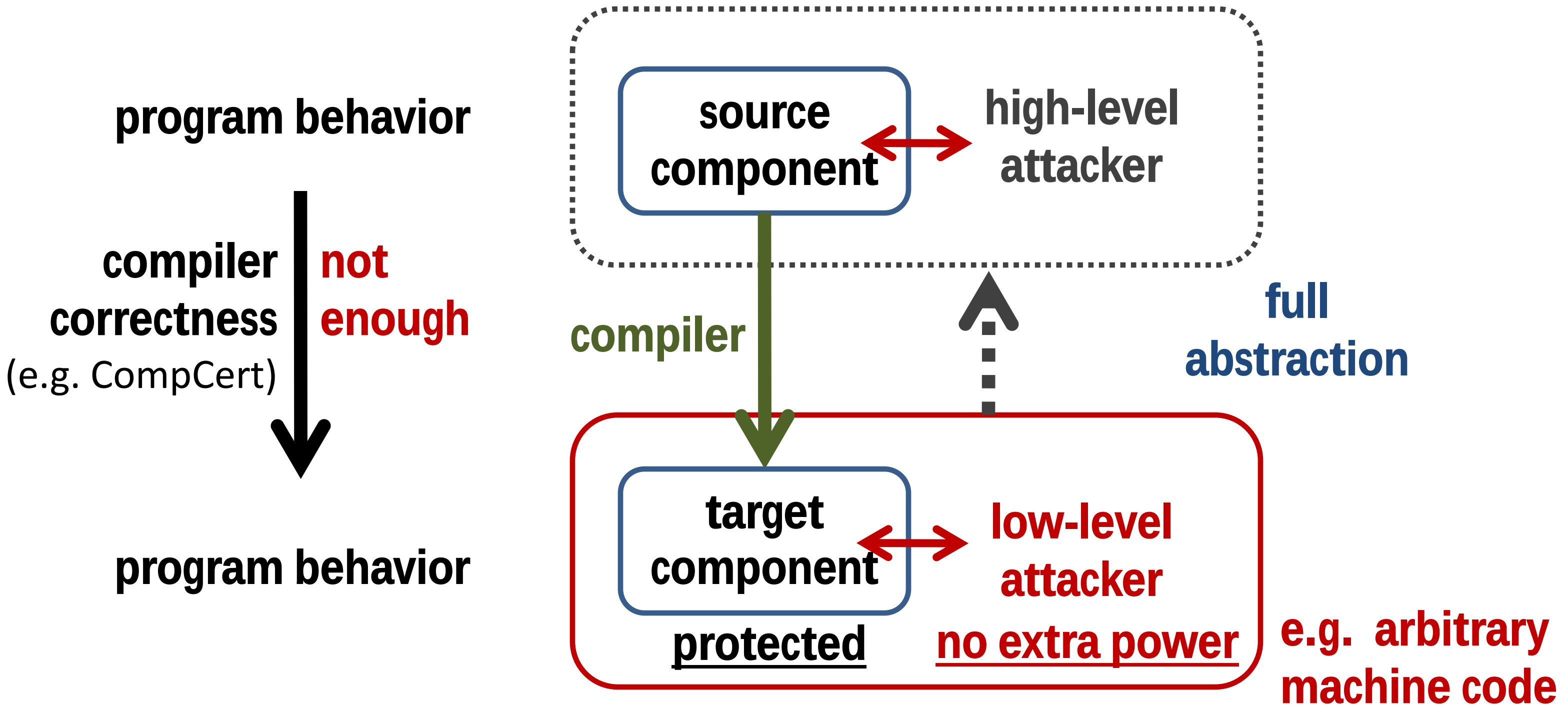
SECOMP grand challenge

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* [F* = ML + verification]

Formally verify: full abstraction

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



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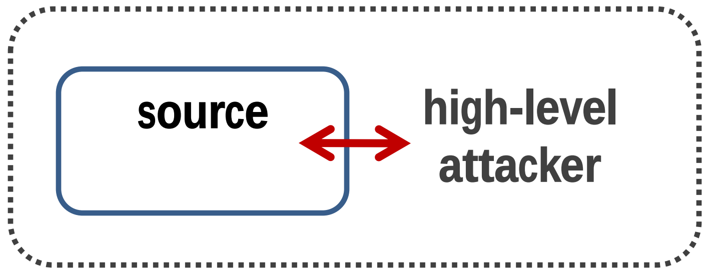
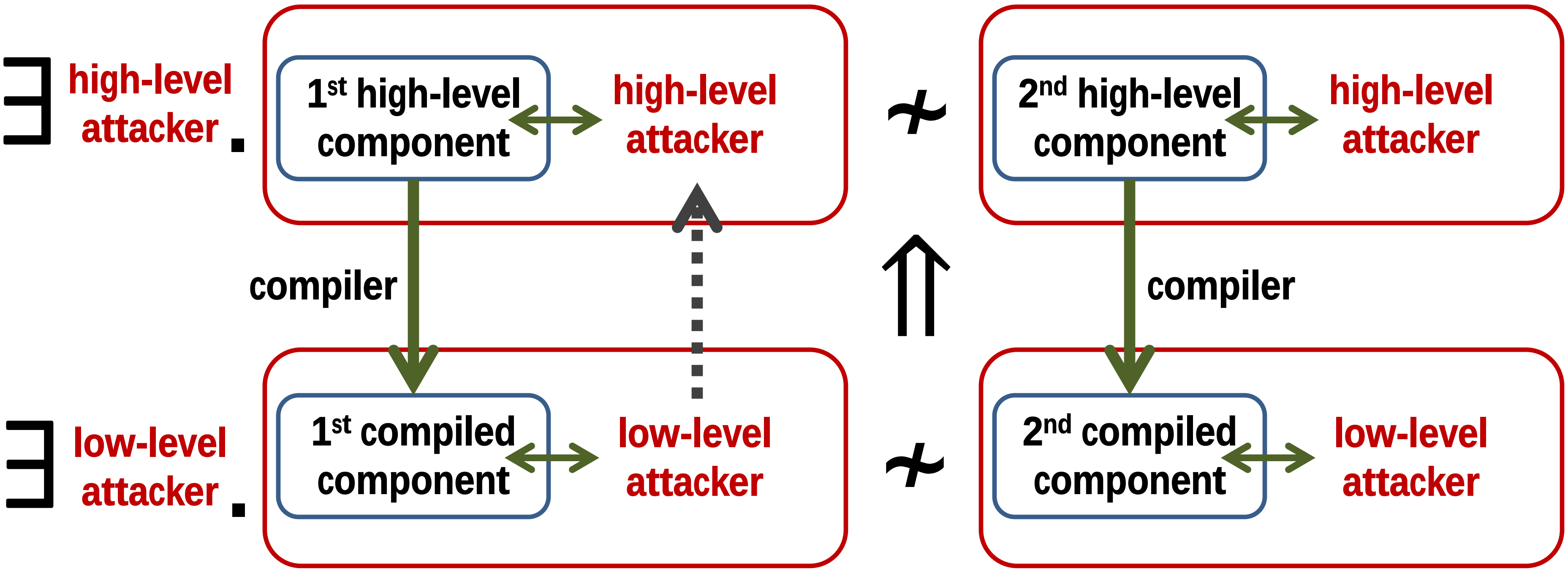


Benefit: sound security reasoning in the source language

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

forget that libraries are written in a lower-levc572(es)-9.99k3.973 rg

Fully abstract compilation, definition

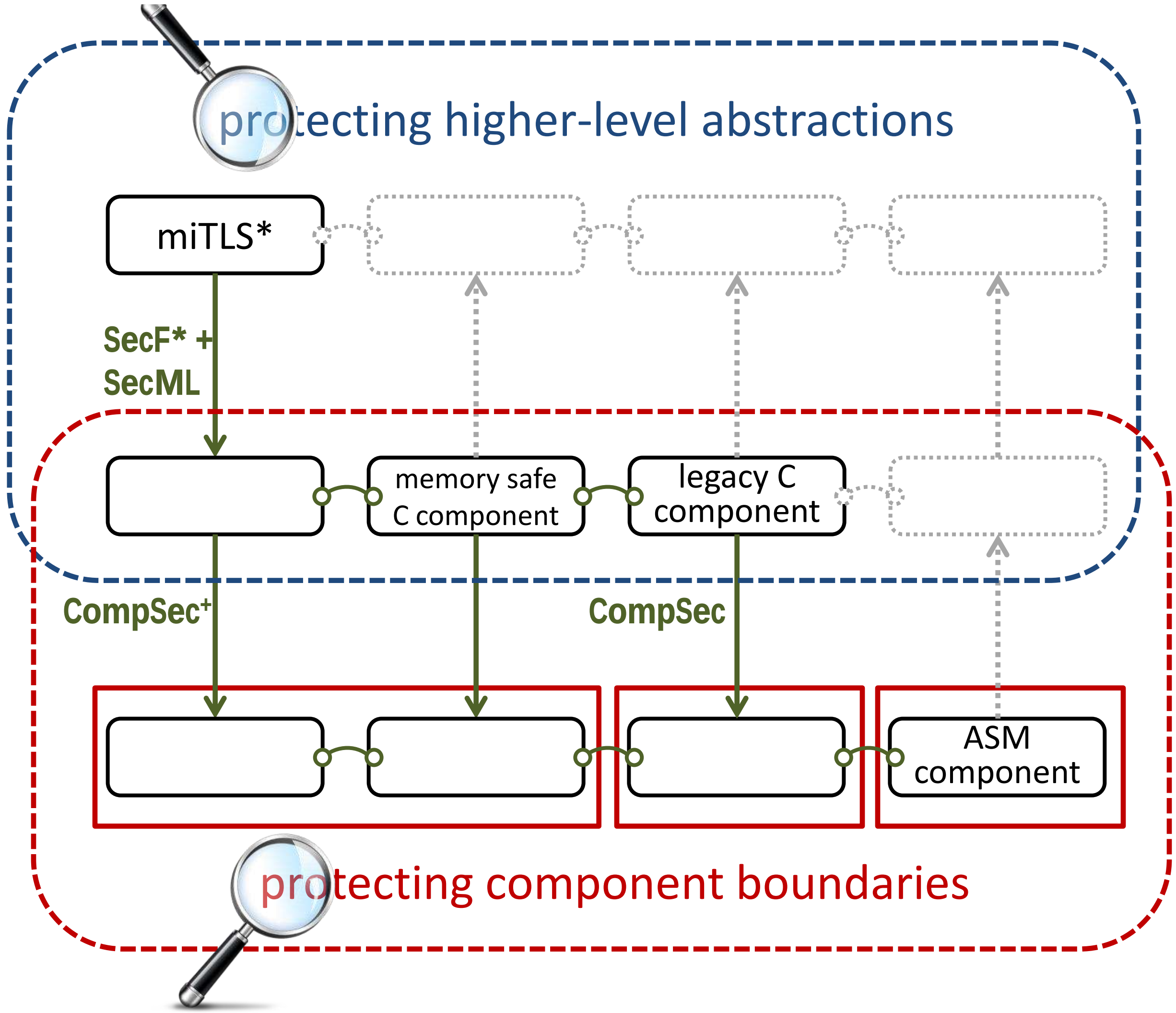


SECOMP: achieving full abstraction at scale

F* language
(ML + verification)

C language
+ memory safety
+ components

ASM language
(RISC-V + micro-policies)



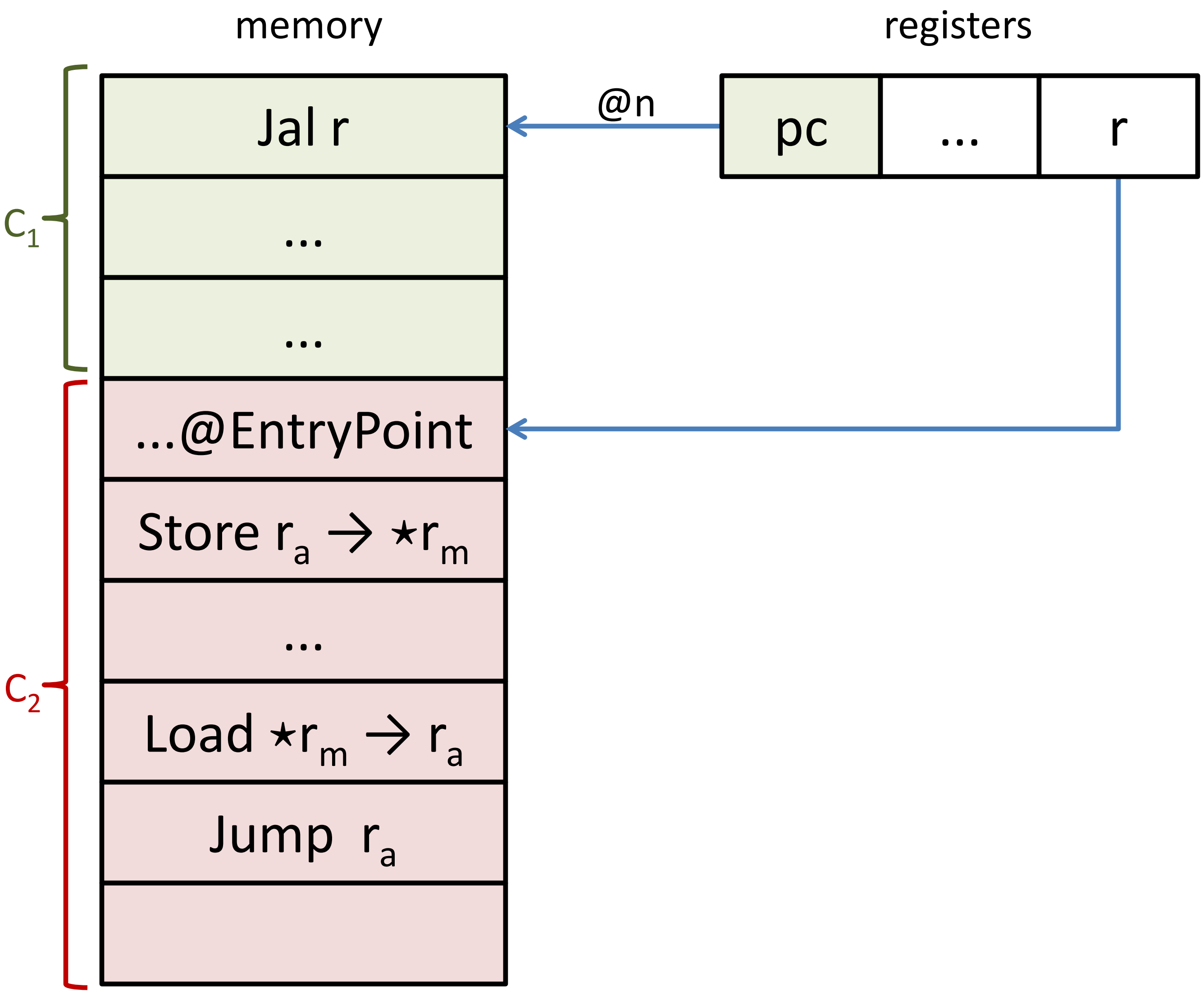
Protecting component boundaries

- **Add mutually distrustful components to C**
  - interacting only via **strictly enforced interfaces**
- **CompSec compiler chain** (based on CompCert)
  - propagate interface information to produced binary
- **Micro-policy simultaneously enforcing**
  - component separation
  - type-safe procedure call and return discipline

- **Interesting attacker model**
  - extending full abs. to mutual distrust + unsafe source

Recent preliminary work, joint with Yannis Juglaret et al

Compartmentalization micro-policy



[Towards a Fully Abstract Compiler Using Micro-Policies, Juglaret et al, TR 2015]

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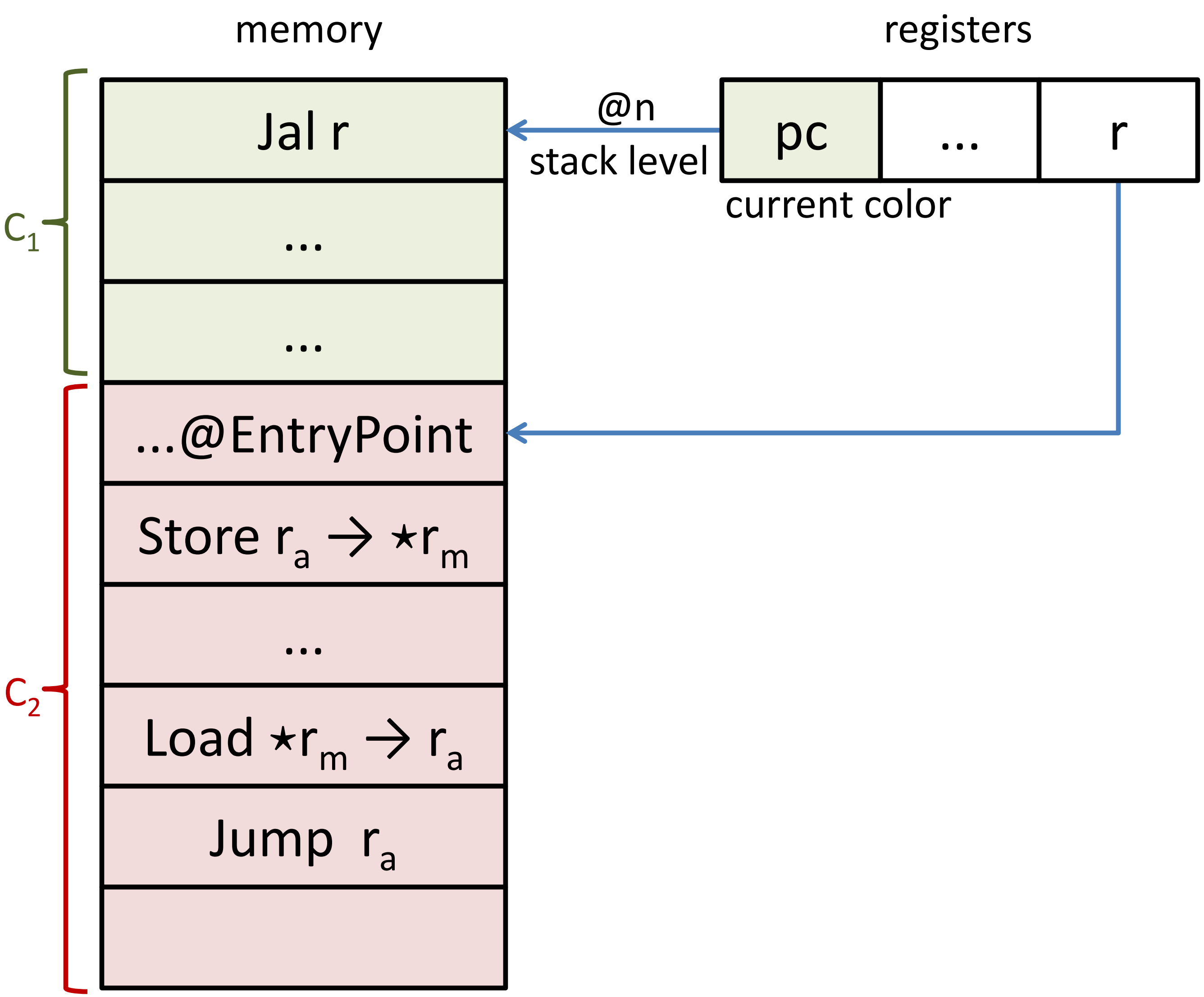

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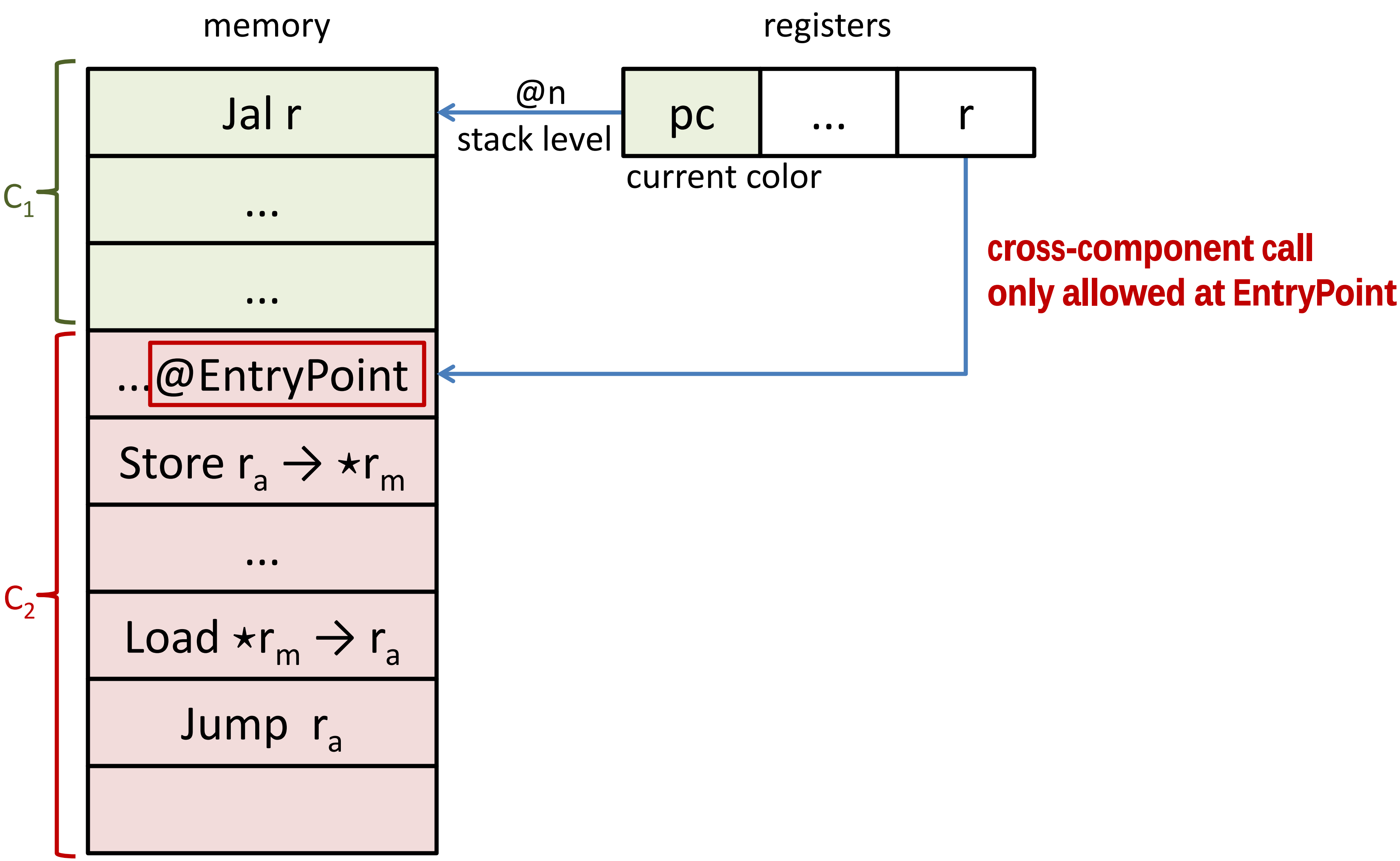

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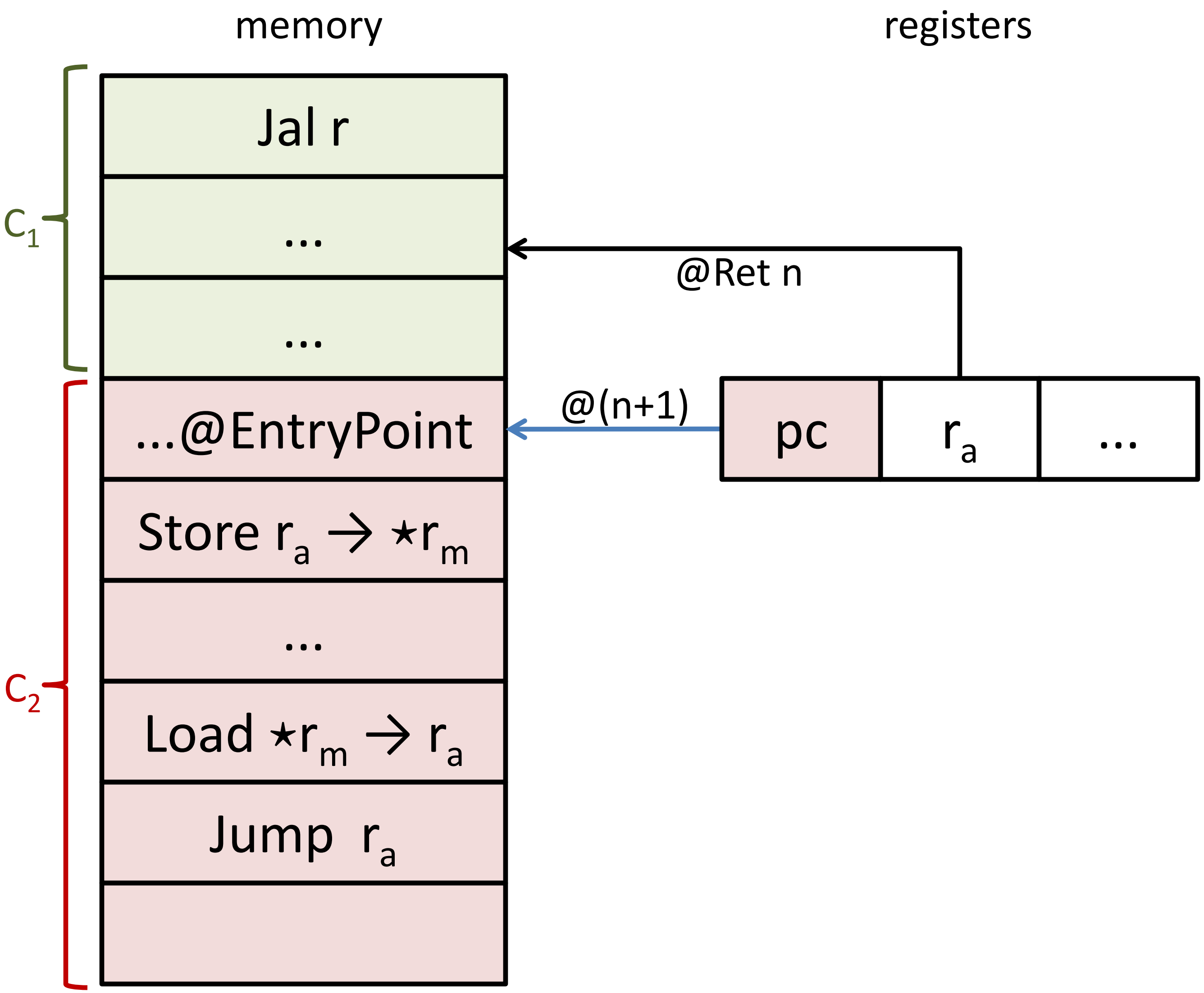

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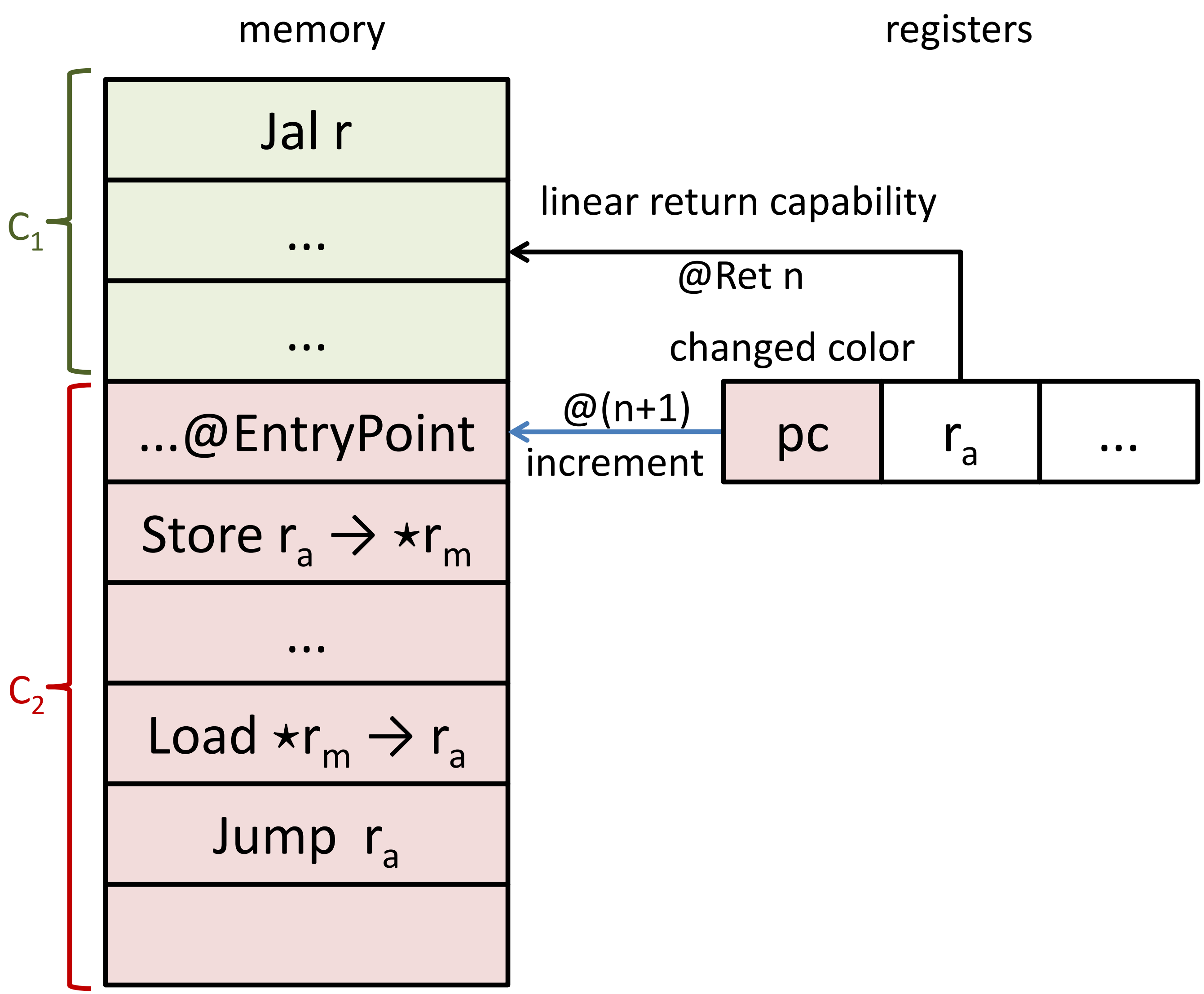

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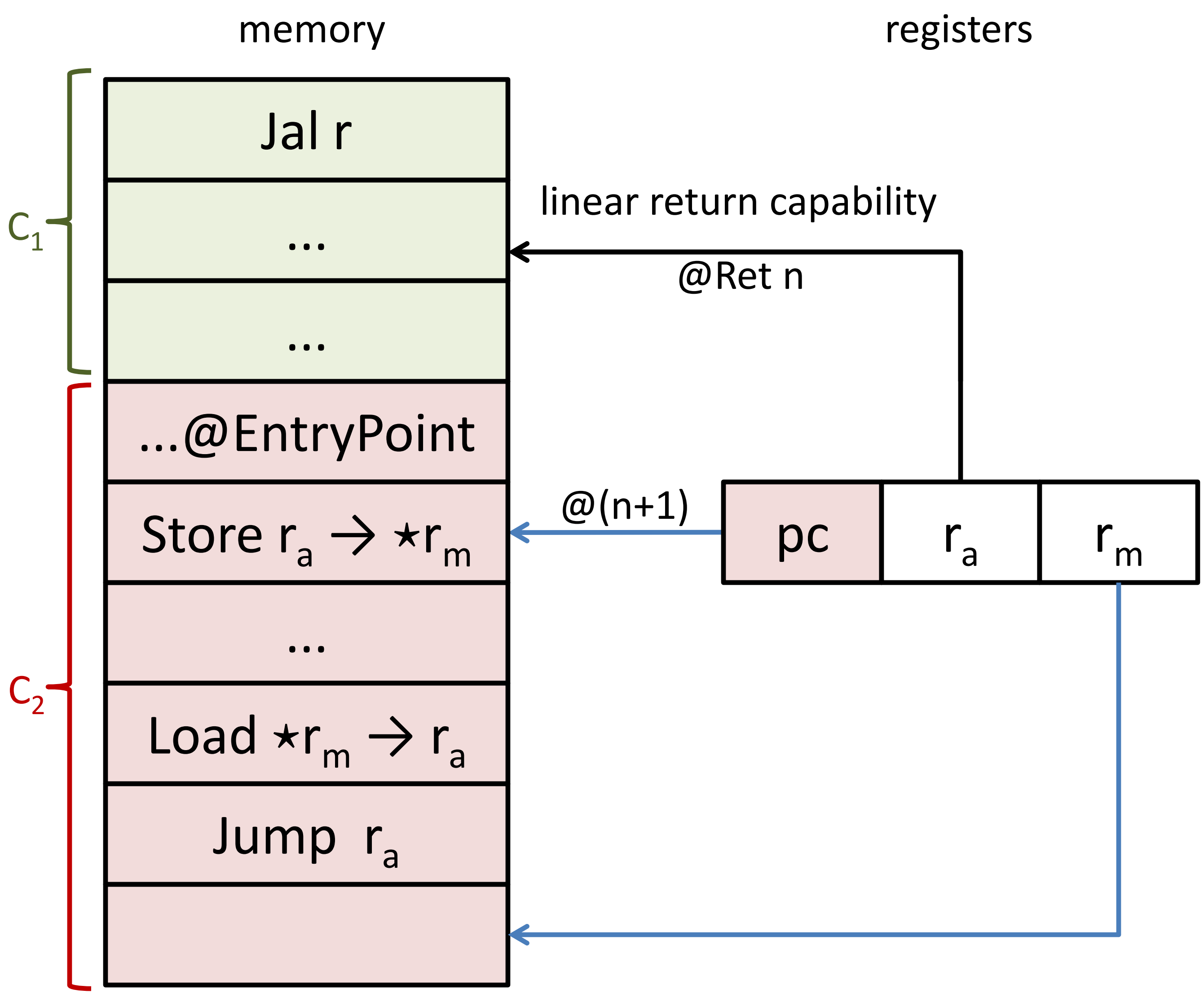

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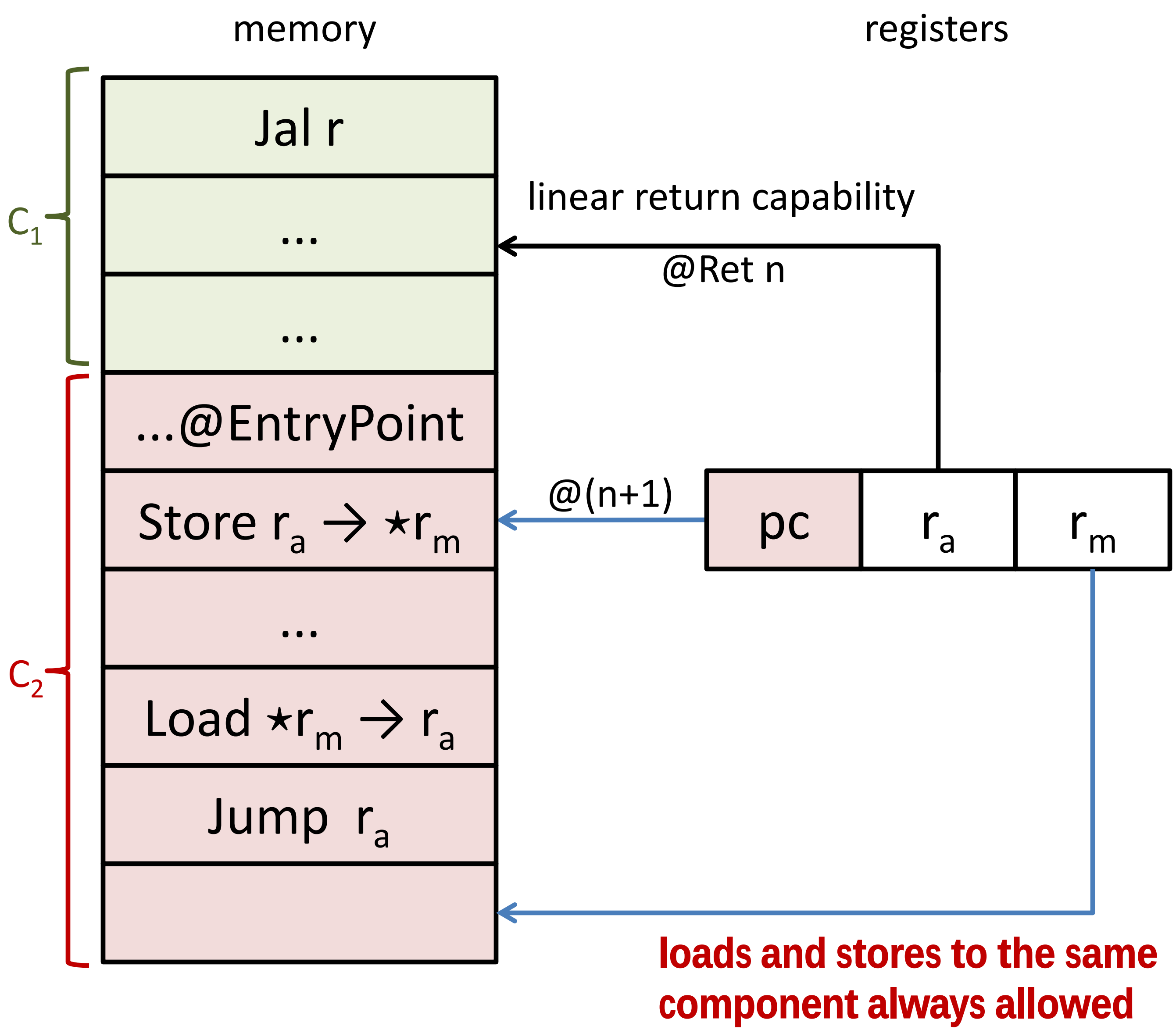

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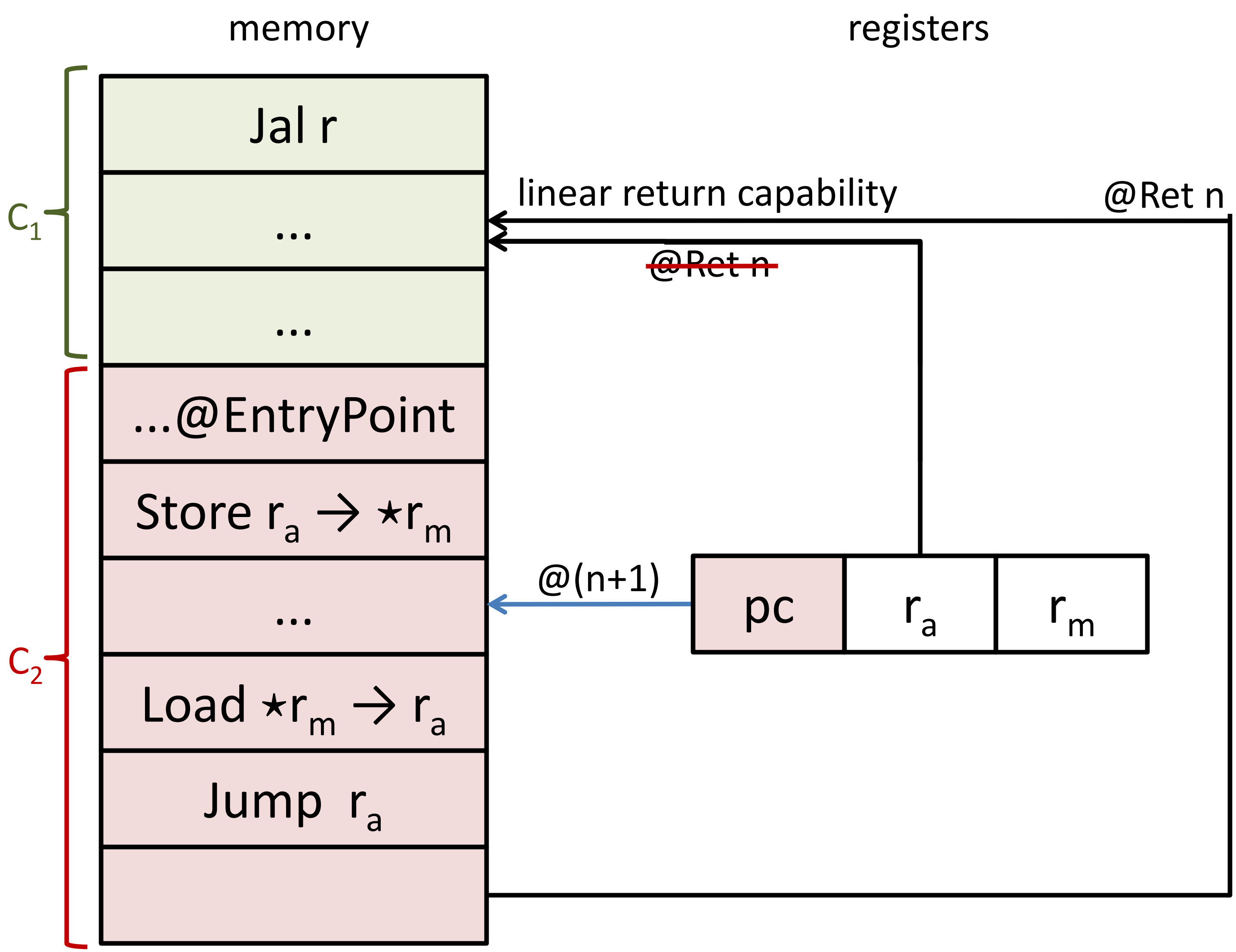

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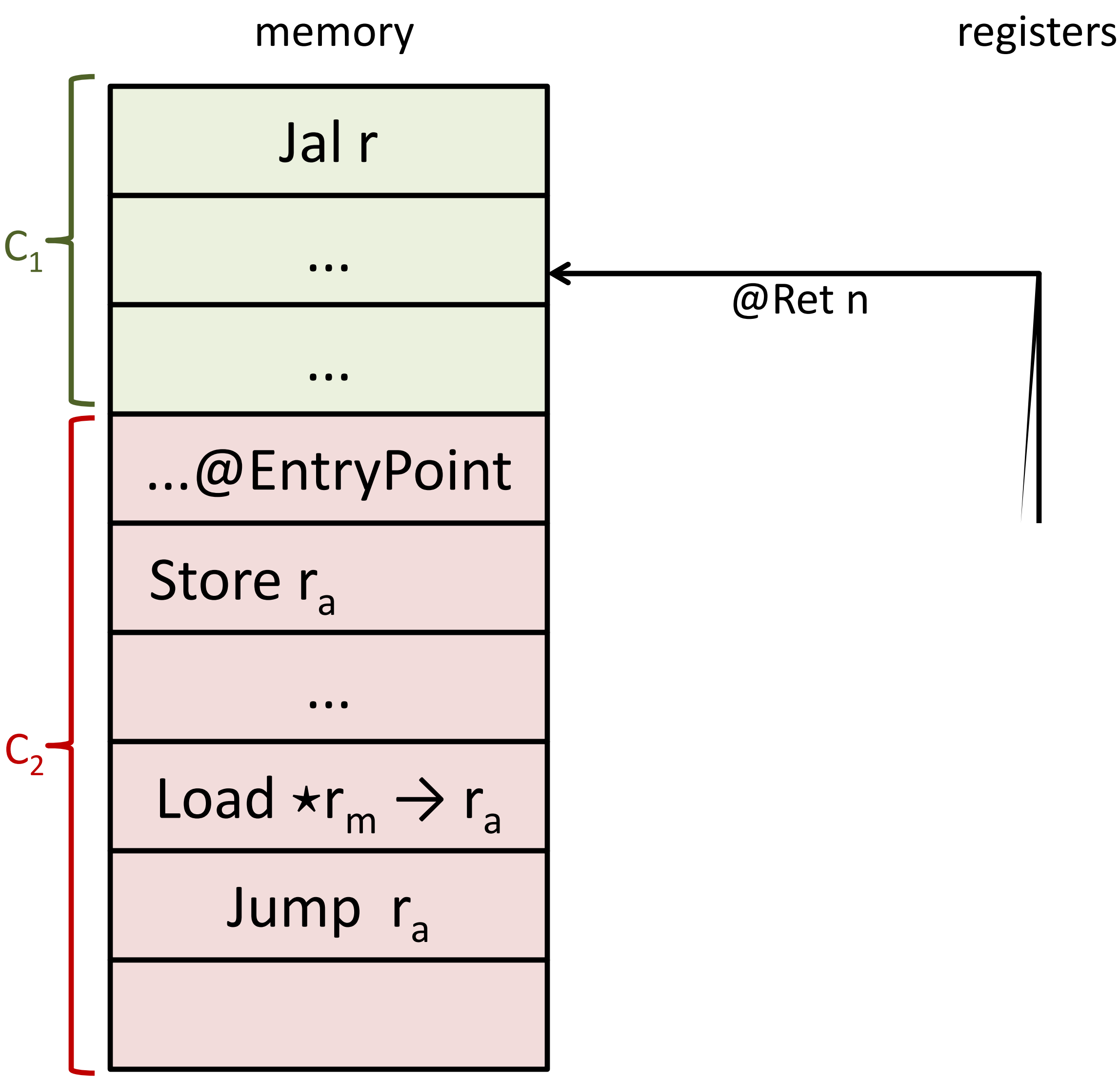
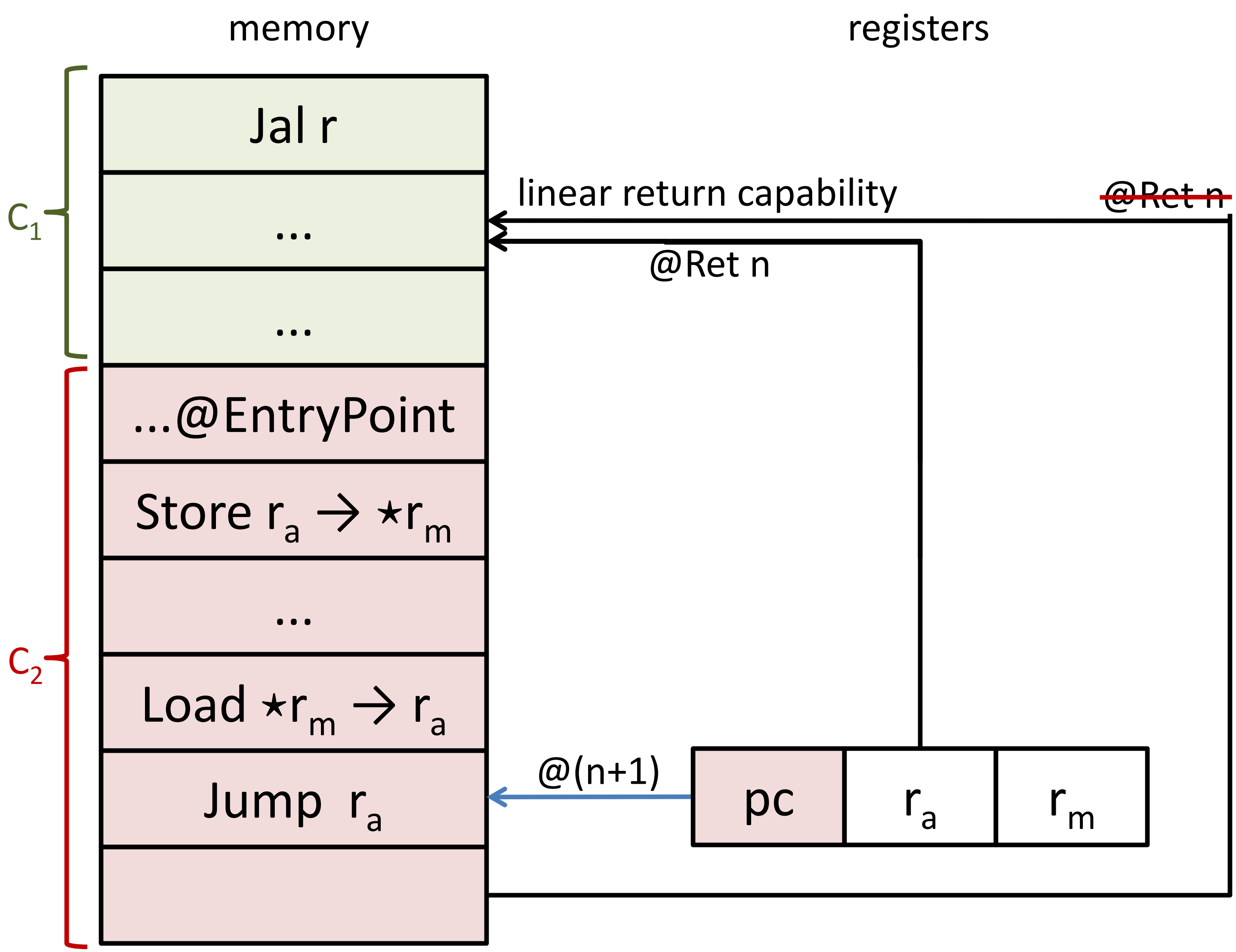


Compartmentalization micro-policy

invariant:
at most one return capability per call stack level



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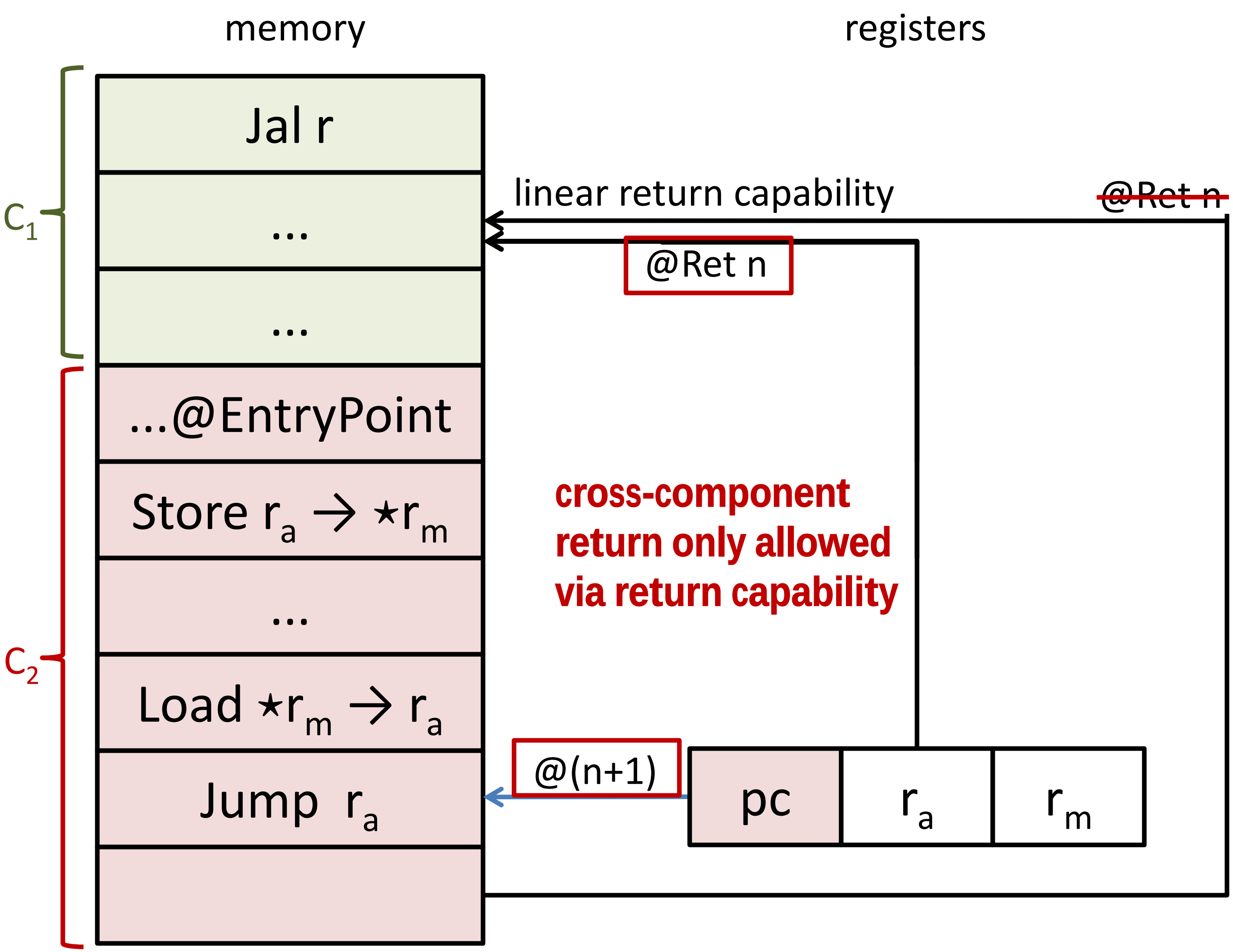
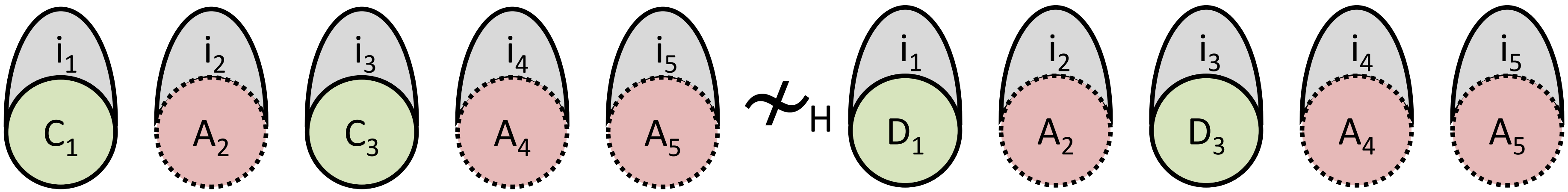


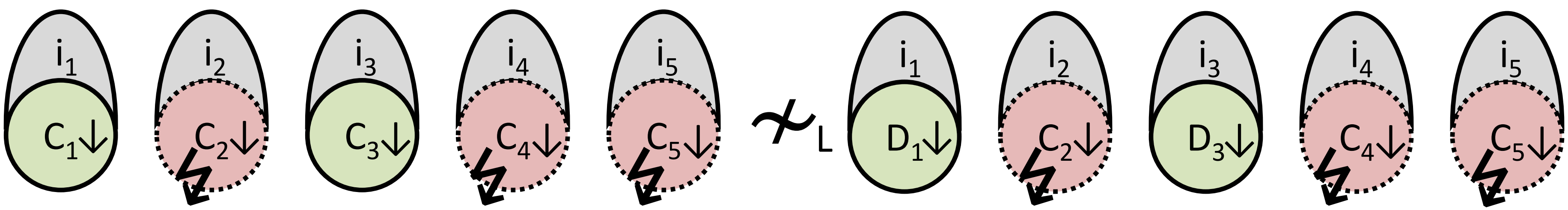
invariant:
at most one return capability per call stack level

Secure compartmentalizing compilation (SCC)

∀compromise scenarios.



∀ low-level attack from compromised C_2↓, C_4↓, C_5↓
∃ high-level attack from some fully defined A_2, A_4, A_5

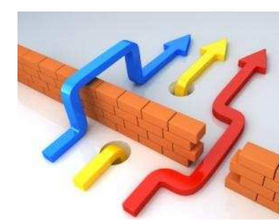


follows from "structured full abstraction for unsafe languages" + "separate compilati

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

Protecting higher-level abstractions

- **ML abstractions we want to enforce with micro-policies**
  – types, value immutability, opaqueness of closures, parametricity (dynamic sealing), GC vs malloc/free, ...
- **F*: enforcing full specifications using micro-policies**
  – some can be turned into **contracts,** checked dynamically
  – fully abstract compilation of F* to ML **trivial for ML interfaces** (because F* allows and tracks effects, as opposed to Coq)
- **Limits of purely-dynamic enforcement**



  – functional purity, termination, relational reasoning
  – **push these limits further and combine with static analysis**

SECOMP focused on dynamic enforcement
but static analysis could help too

- **Improving efficiency**
  - removing spurious checks
  - just that by using micro-policies our compilers add few explicit checks
  - e.g. turn off memory safety checking for a statically memory safe component that never sends or receives pointers
- **Improving transparency**
  - allowing more safe behaviors
  - e.g. we could statically detect which copy of the linear return capability the code will use to return (in this case static analysis untrusted)

Micro-policies:
remaining fundamental challenges

- **Micro-policies for C and ML**
  - needed for vertical compiler composition
  - will put micro-policies in the hands of programmers
- **Secure micro-policy composition**
  - micro-policies are **interferent** reference monitors
  - one micro-policy's behavior can break another's guaran
    - e.g. composing anything with IFC can leak

Beyond full abstraction

- Is full abstraction always the right notion of secure compilation? The right attacker model?
- **Similar properties**
  - secure compartmentalizing compilation (SCC)
  - preservation of hyper-safety properties [Garg et al.]
- **Strictly weaker properties** (easier to enforce!):
  - robust compilation (integrity but no confidentiality)
- **Orthogonal properties**:
  - memory safety (enforcing CompCert memory model)

What secure compilation adds over compositional compiler correctness

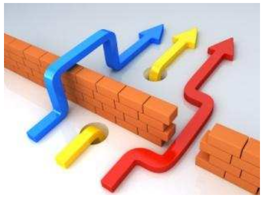
- **mapping back arbitrary low-level contexts**
- **preserving integrity properties**
  - robust compilation phrased in terms of this
- **preserving confidentiality properties**
  - full abstraction and preservation of hyper-safety phrased in terms of this
- **stronger notion of components and interfaces**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

Verification and testing

- So far all secure compilation work **on paper**
  - but one can't verify an interesting compiler on pa
- SECOMP will use **proof assistants**: Coq and F*
- **Reduce effort**
  - better automation (e.g. based on SMT like in F*)
  - integrate testing and proving (QuickChick and Luck)
- **Problems not just with effort/scale**
  - devising good **proof techniques** for full abstraction is a hot research topic of it's own

SECOMP in a nutshell

- **We need more secure languages, compilers, hardware**
- **Key enabler: micro-policies** (software-hardware protection)
- **Grand challenge: the first efficient formally secure compilers** for **realistic programming languages** (C, ML, F*)
- **Answering challenging fundamental questions**
  - attacker models, proof techniques
  - secure composition, micro-policies for C and ML



- **Achieving strong security properties like full abstraction**
  - \+ testing and proving formally that this is the case
- **Measuring & lowering the cost of secure compilation**

- Most of this is **vaporware** at this point but ...
  - building a community, looking for collaborators, and hiring
    ... **in order to try to make some of this real**

- Looking for excellent **interns**, **PhD students**, **PostDocs**, **starting researchers**, and **engineers**
- Prosecco can also support outstanding candidates in the **CR2 competition**

Collaborators & Community

- **Current collaborators from Micro-Policies project**
  - UPenn, MIT, Portland State, Draper Labs
- **Looking for additional collaborators**
  - Several other researchers working on **secure compilation**
    - Deepak Garg (MPI-SWS), Frank Piessens (KU Leuven), Amal Ahmed (Northeastern), Cedric Fournet & Nik Swamy (MSR)
  - **Amal Ahmed** coming to Paris for 1 year sabbatical (from 09/2017)
- **Secure compilation meetings (very informal)**
  - 1st at INRIA Paris on August 2016
  - 2nd in Paris on 15(?) January 2017 ... maybe at UPMC
  - **build larger research community, identify open problems, bring together communities** (hardware, systems, security, languages, verification, ...)

Questions for Gallium

- What do you think? Is this plan outrageous?
- Would CompCert be a good base for some of this?
- Is there any plan for a RISC-V backend for CompCert?
- Is anyone from Gallium interested in working on secure compilation?