SoK: Automated Kernel Vulnerability Discovery and Exploit Generation

Anil Kurmus, **Andrea Mambretti**, Alessandro Sorniotti

IBM Research Europe – Zurich

Vincent Lenders, Damian Pfammatter, Bernhard Tellenbach

Armasuisse - Cyber Defense Campus

WOOT 2025

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Once upon a time...

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Once upon a time...

UNIVERSITY OF OXFORD
COMPUTING LABORATORY

MSc COMPUTER SCIENCE DISSERTATION

Automatic Generation of Control Flow Hijacking Exploits for Software Vulnerabilities

---

Author:
Sean HEELAN

Supervisor:
Dr. Daniel KROENING

2009

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Once upon a time...

2011

AEG: Automatic Exploit Generation

Thanassis Avgerinos, Sang Kil Cha, Brent Lim Tze Hao and David Brumley
Carnegie Mellon University, Pittsburgh, PA
{thanassis, sangkilc, brentlim, dbrumley}@cmu.edu

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Once upon a time…

2016

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Darpa - Cyber Grand Challenge

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Contributions:

First big push towards full end-2-end AEG

Considerably advanced static and dynamic analyses

Modern opensource tools (e.g., angr, S2E)

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Simplified OS & Architecture (e.g., 7 syscalls)

Small size software

Binary code only

Proof-of-vulnerability only (e.g., IP control)

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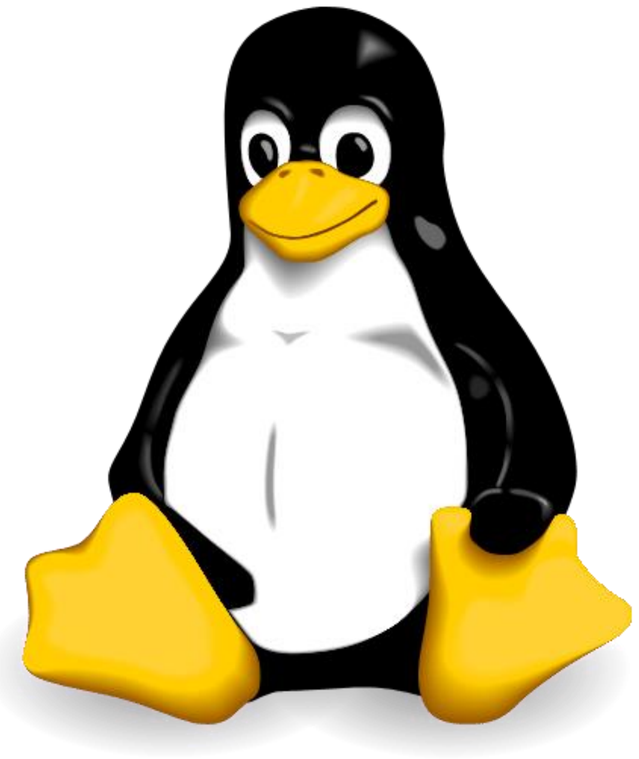
Small size software

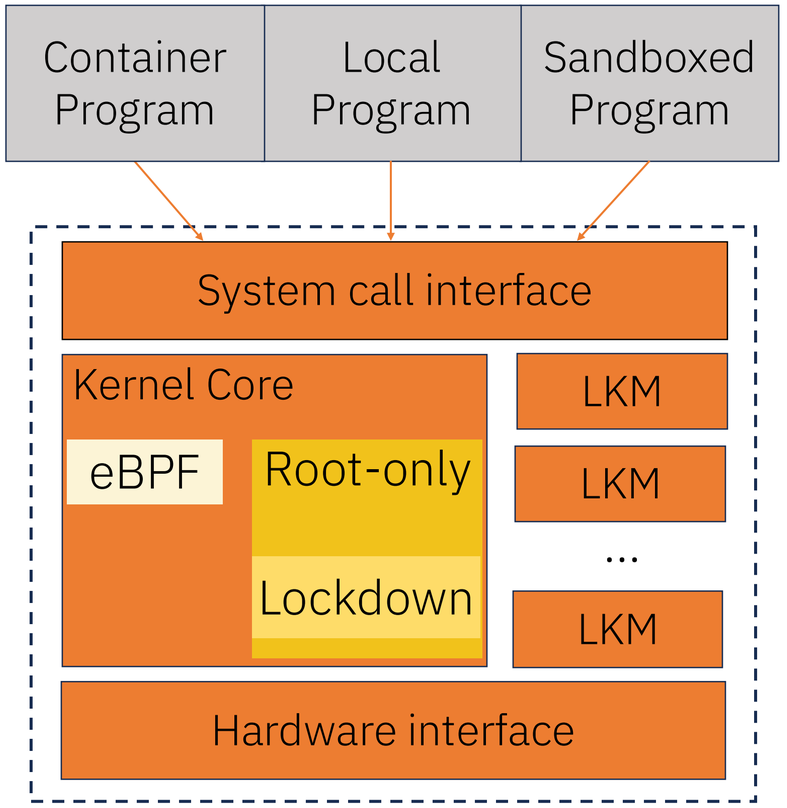
Binary code only

Proof-of-vulnerability only (e.g., IP control)

~10 years to move it to the next level

The ultimate target





Attacker

Attack surface

Running Kernel

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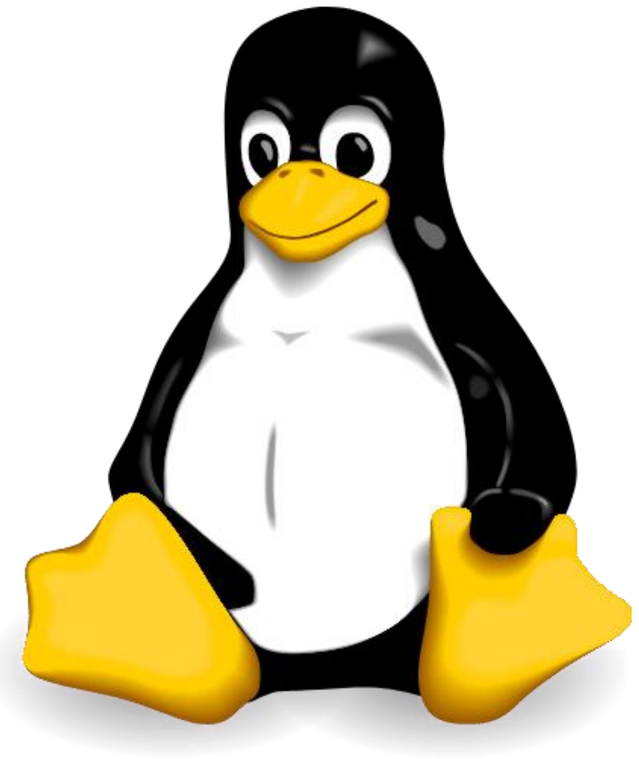
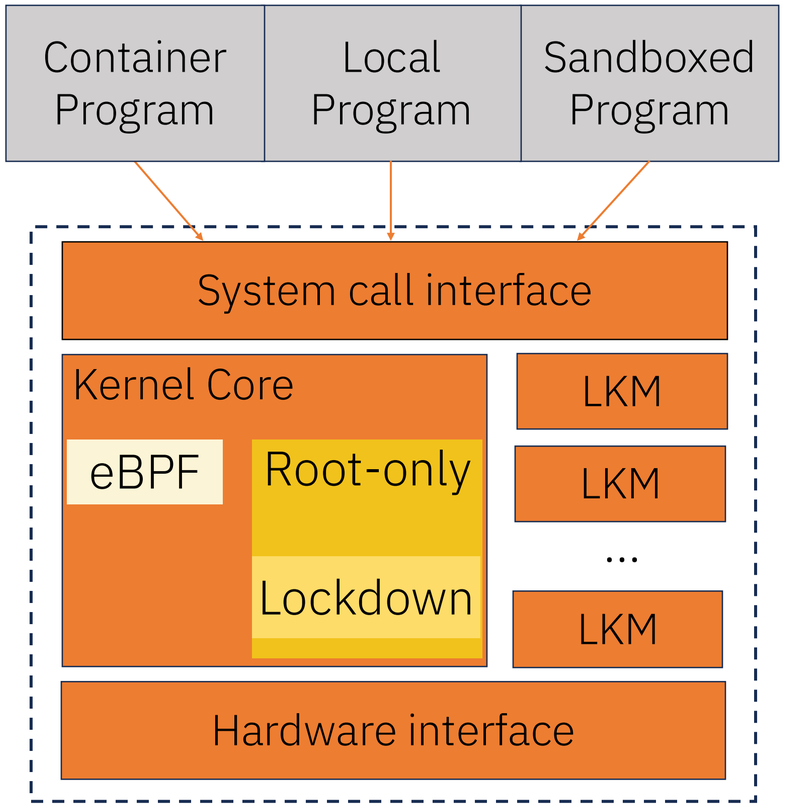
The ultimate target





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High Privilege

Large attack surface

Widely available and used

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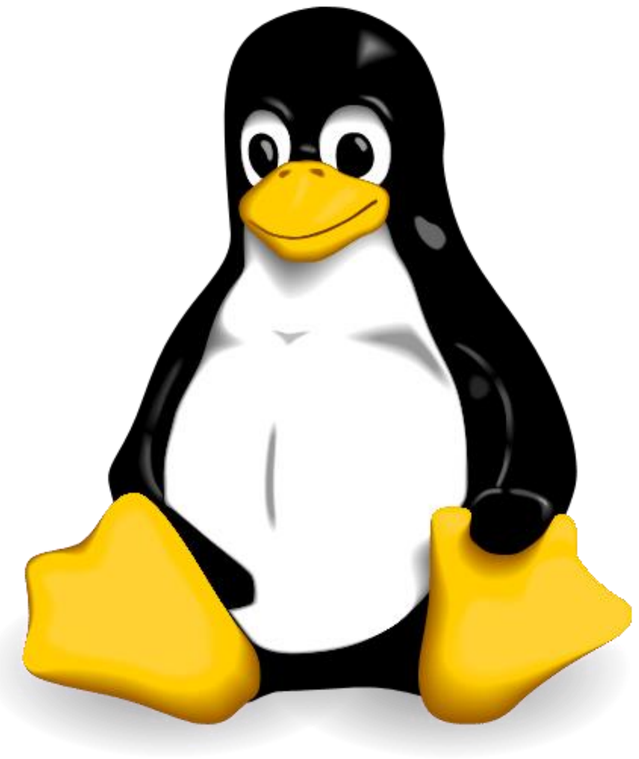
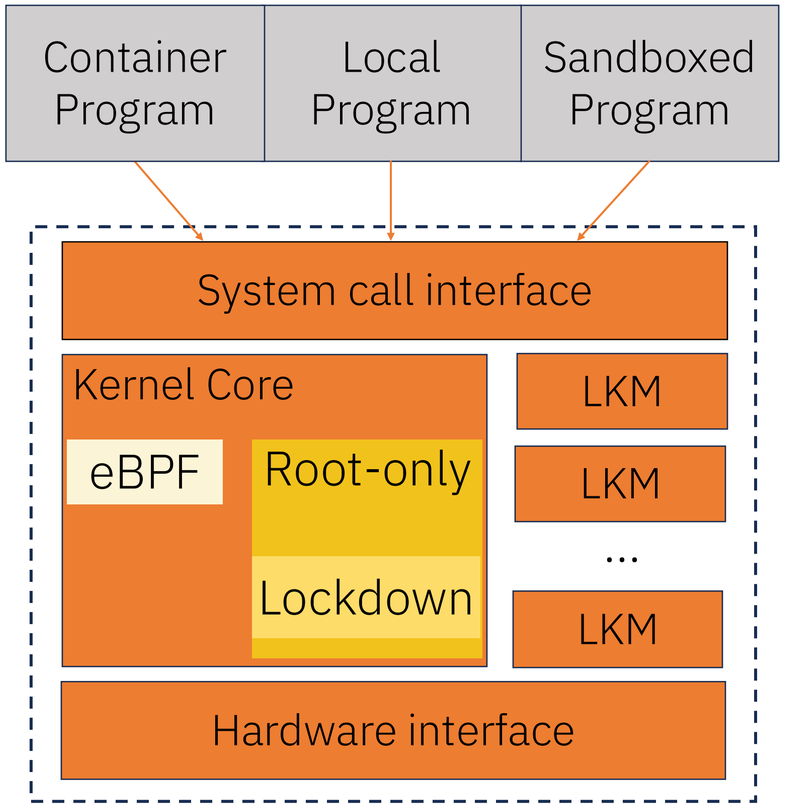
The ultimate target





Attacker

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Running Kernel

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Widely available and used

40 Millions LoC

Several threat models

Several attacks/mitigations

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Threat models

Local

Local/User sandbox

Local/Container

Remote

Kernel sandbox (eBPF)

Lockdown

Physical

Vulnerability classes

PRECURSOR: might lead to a serious consequence only through a base vulnerability

HELPER: might only lead to an attacker achieving its goal in combination with another vulnerability

BASE: potentially, it allows attackers to directly reach the goal

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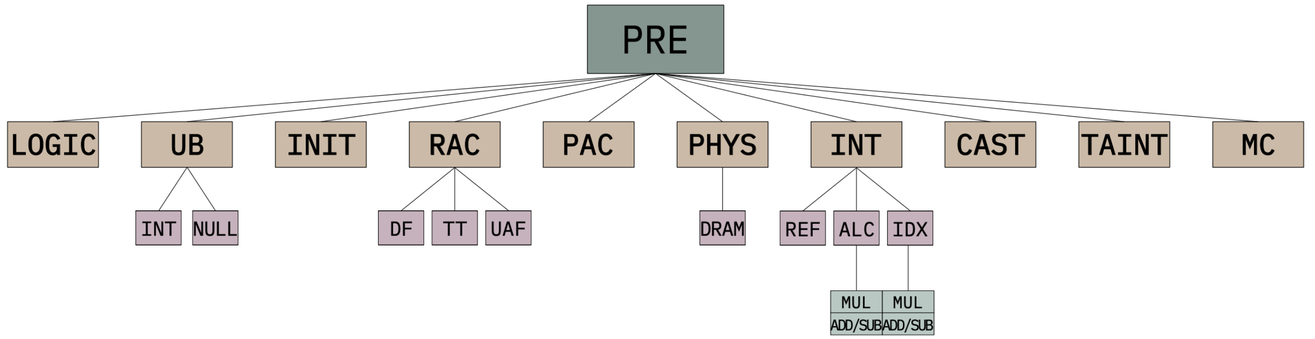

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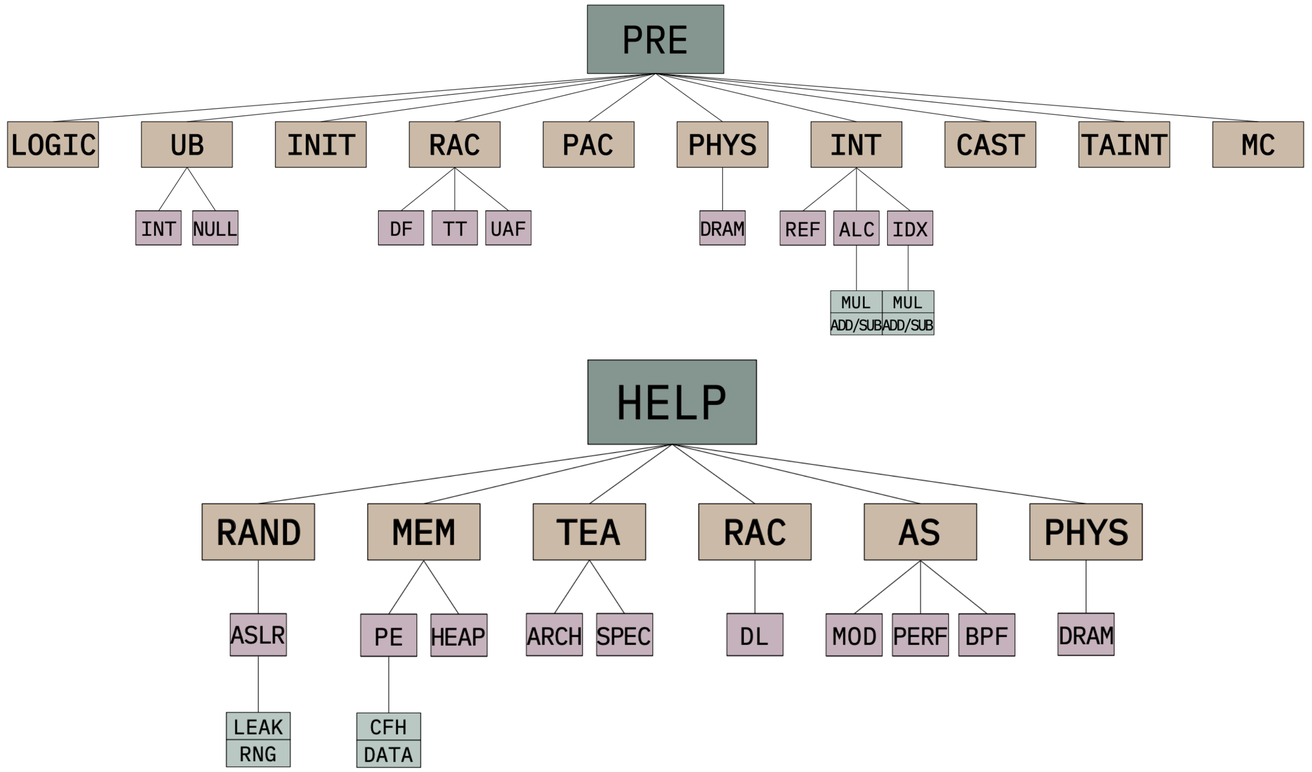

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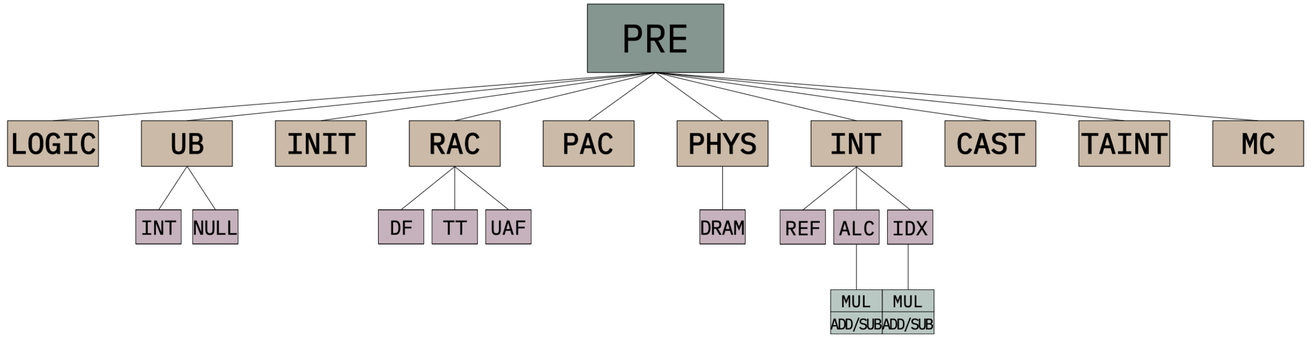

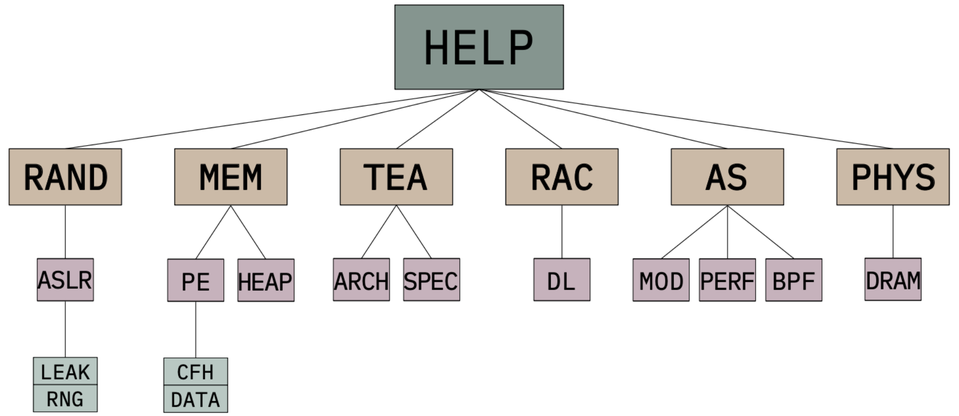

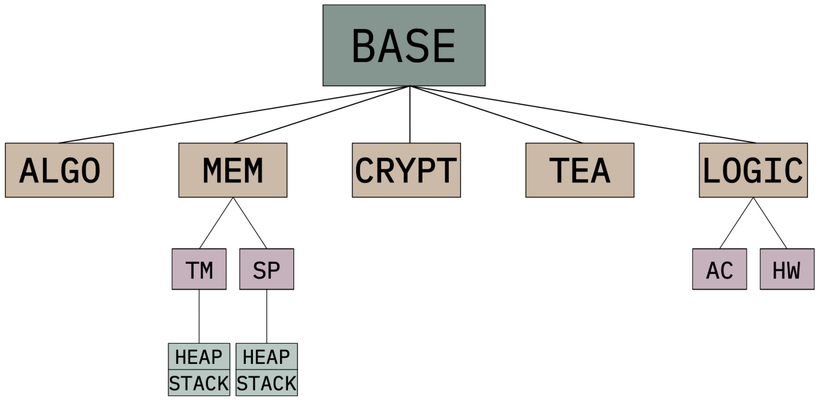

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Let’s now consider CVE-2021-4083

TREAD 1

```
init_skb()



fd = acquire_fd() {

/* window of 12 insts
between getting fd and
refcnt++ */

}



recvmsg(fd)
```

USD GC

```
if (refcnt == my_refcnt){

  /* I own skb */

...

  delete(skb)

  /* without locking */

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https://project-zero.issues.chromium.org/issues/42451370

IBM

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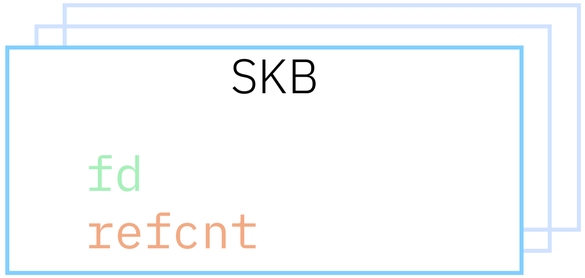

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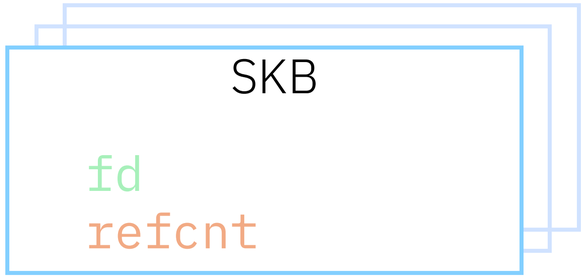

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SKB

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fd
refcnt
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PRE-RAC

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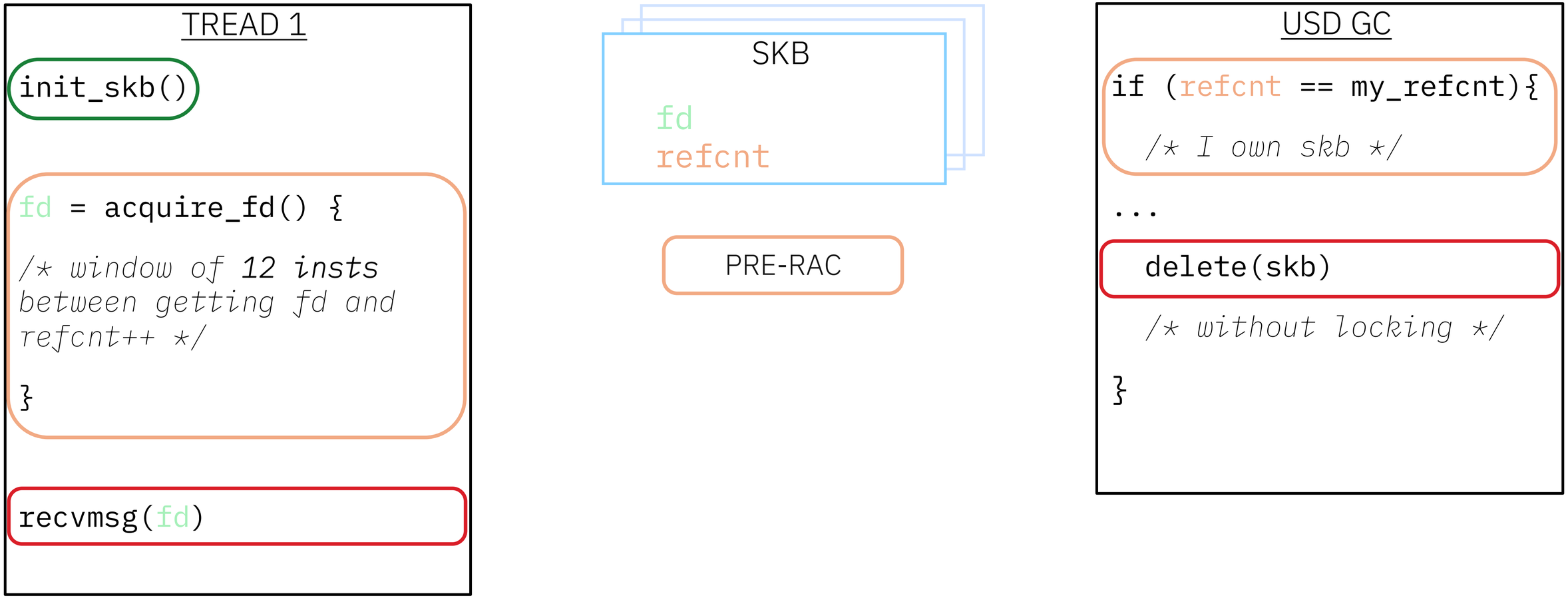

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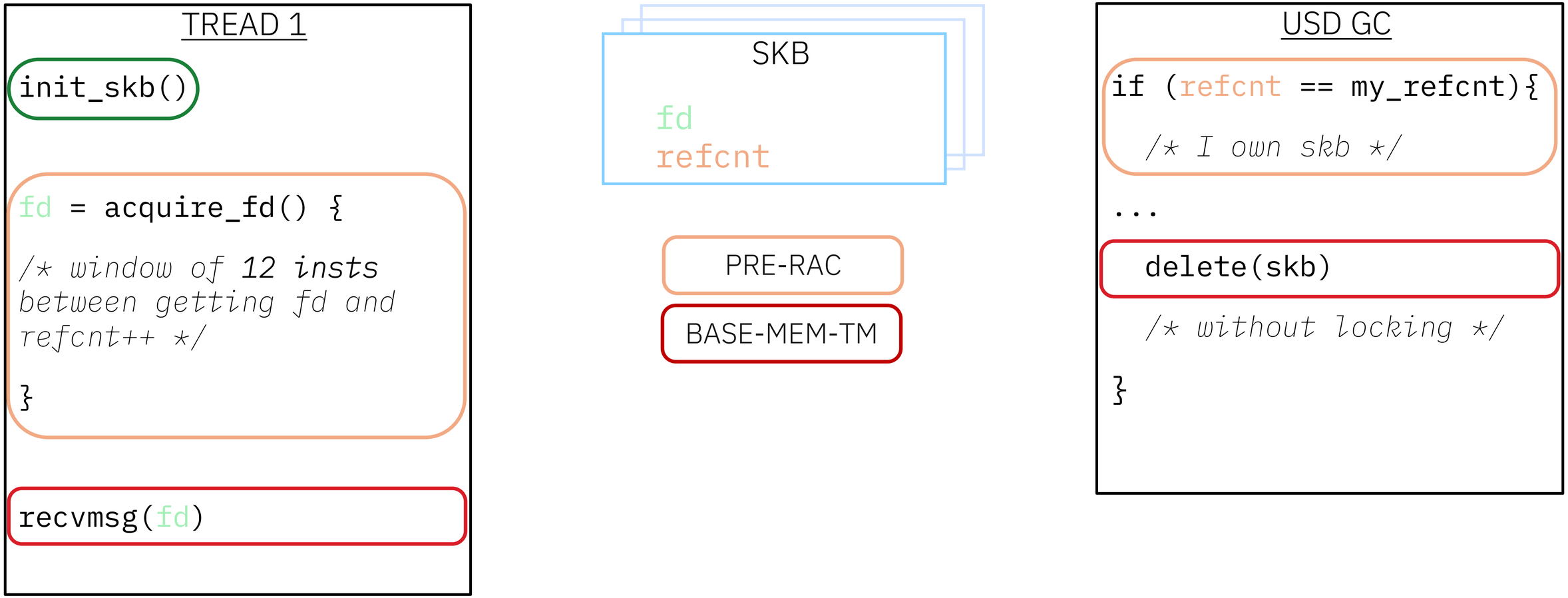

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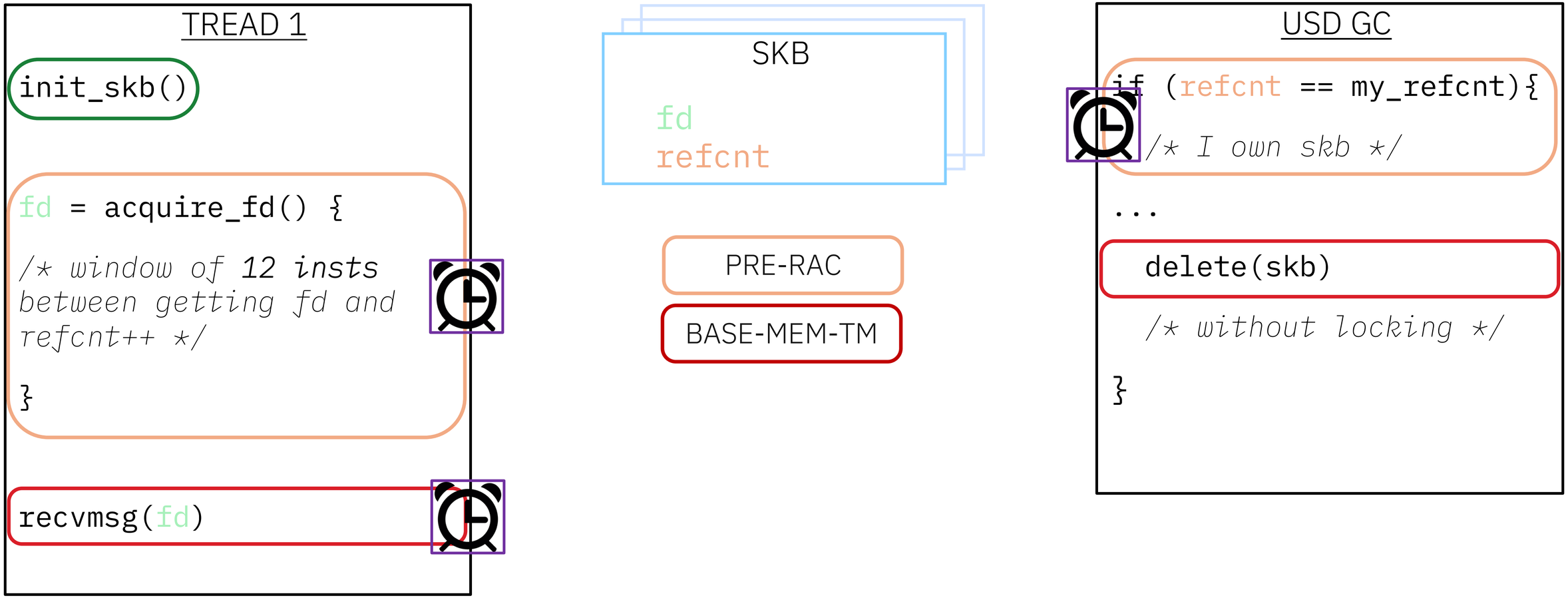

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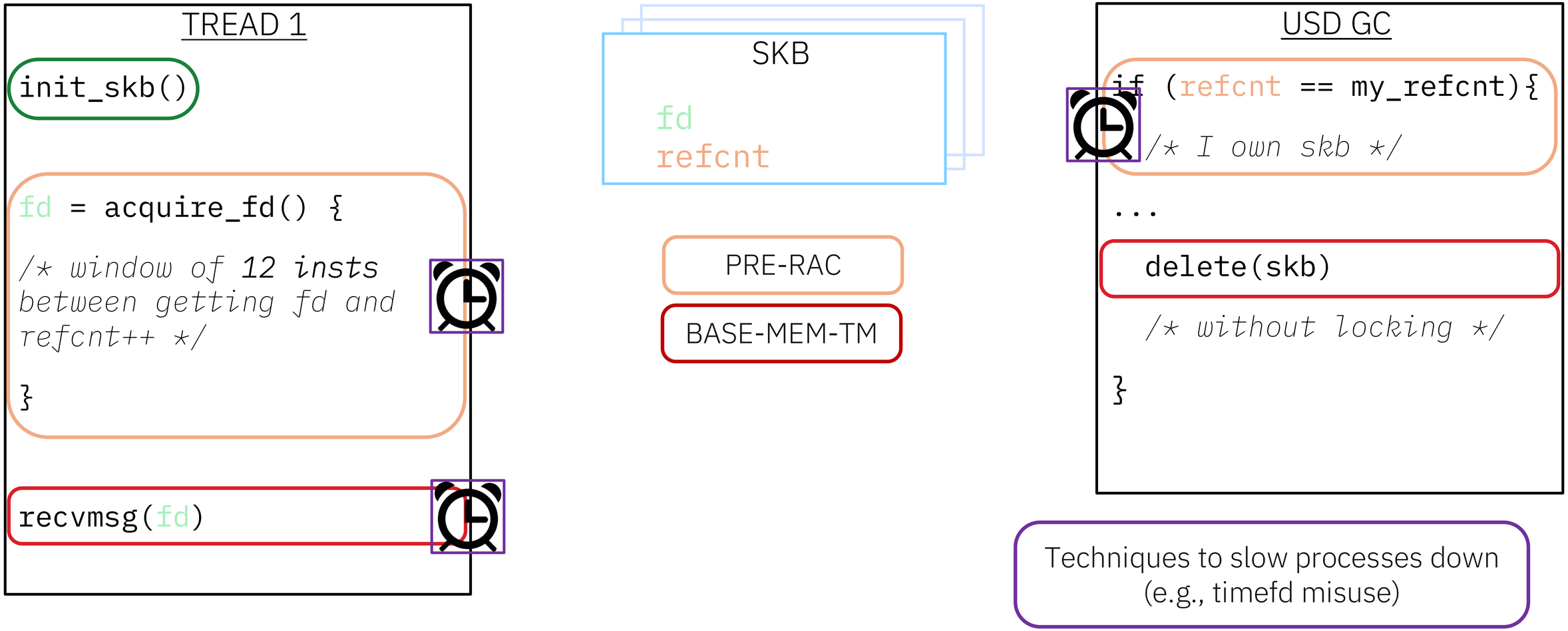

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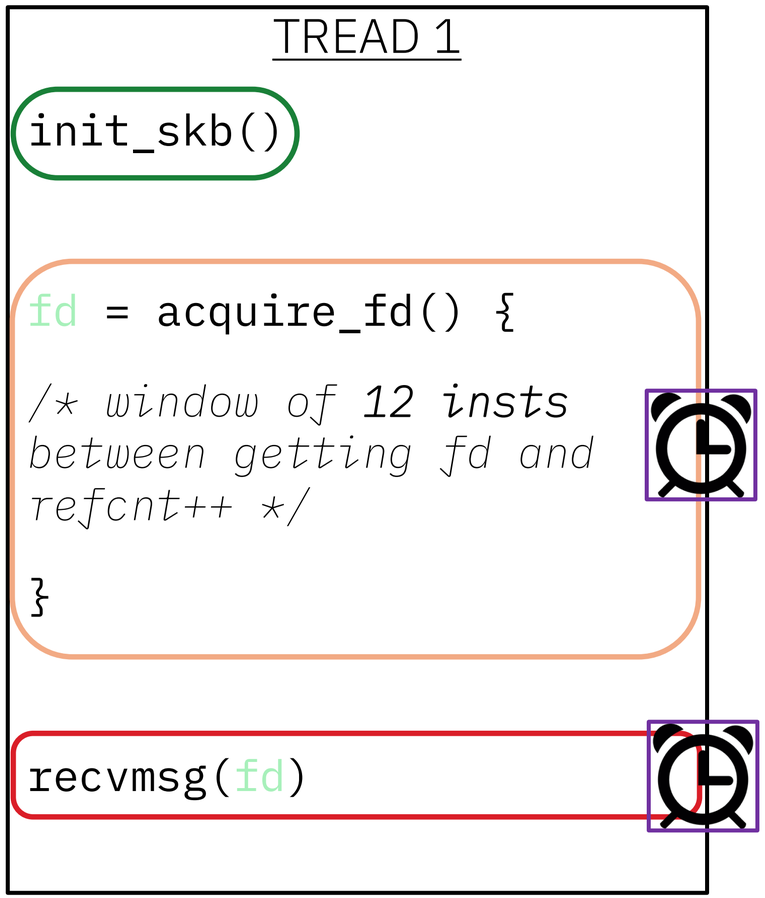

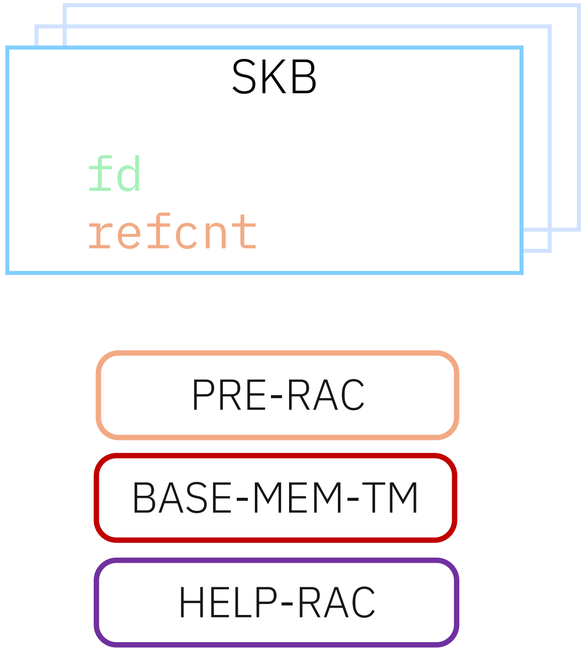

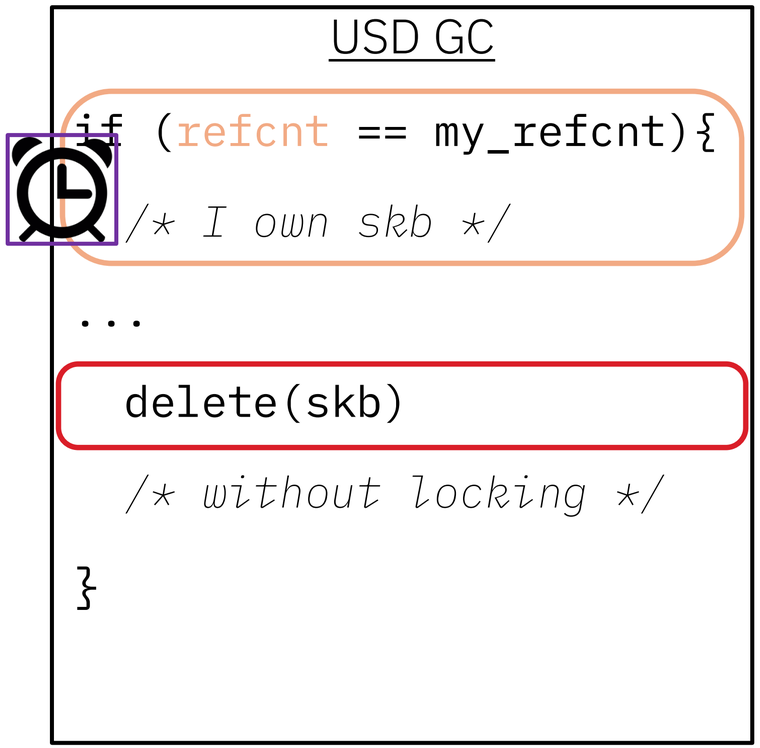

Techniques to slow processes down (e.g., timefd misuse)

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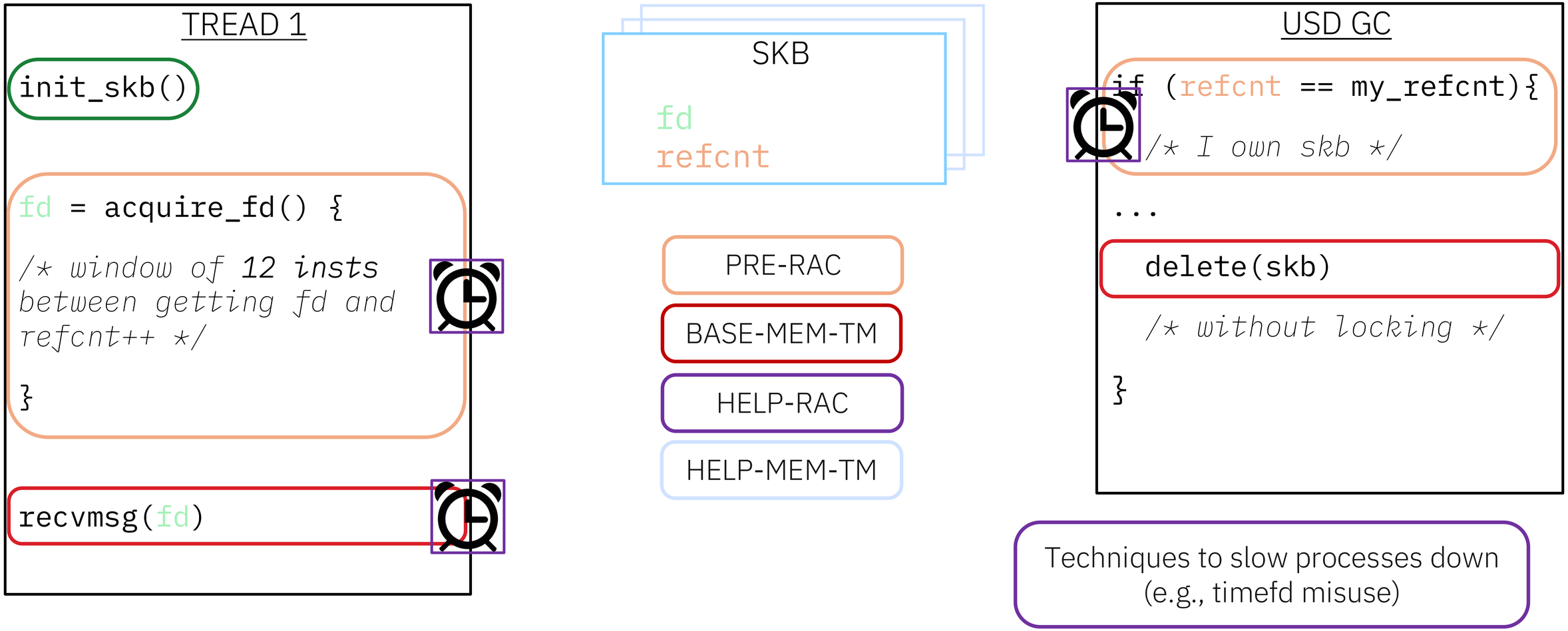

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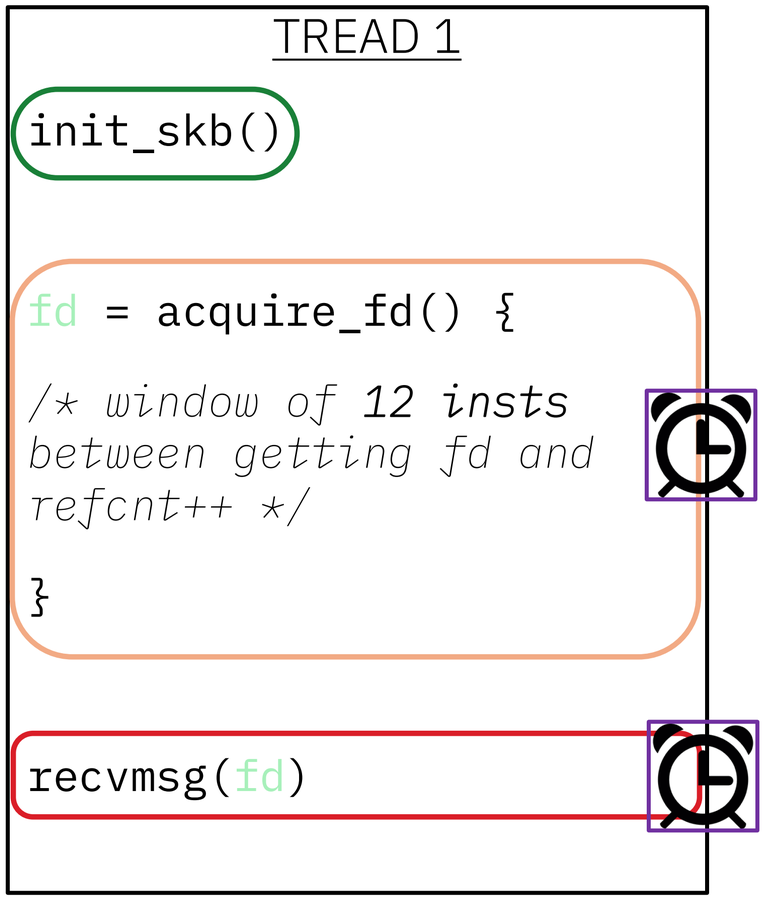
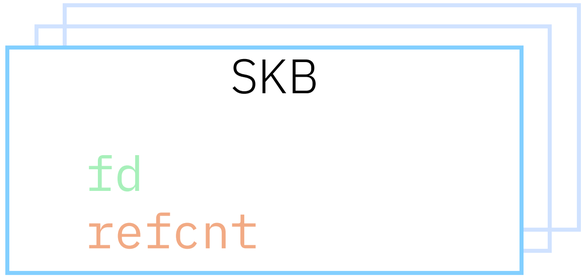
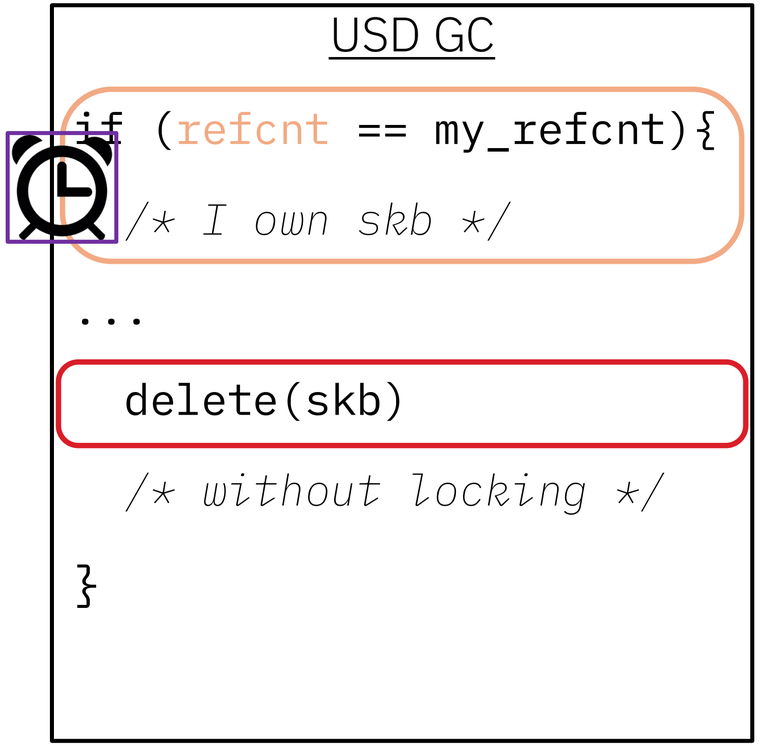




- PRE-RAC
- BASE-MEM-TM
- HELP-RAC
- HELP-MEM-TM
- HELP-MEM-ASLR



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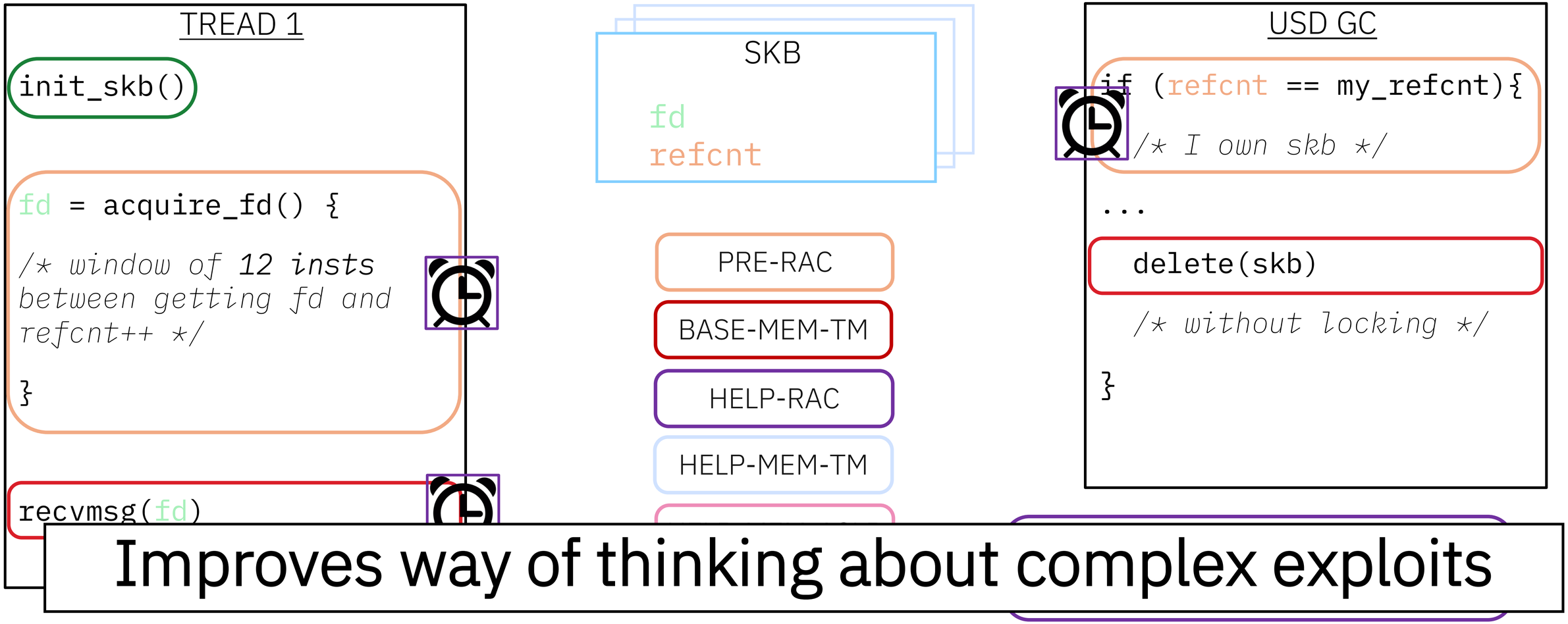

Improves way of thinking about complex exploits

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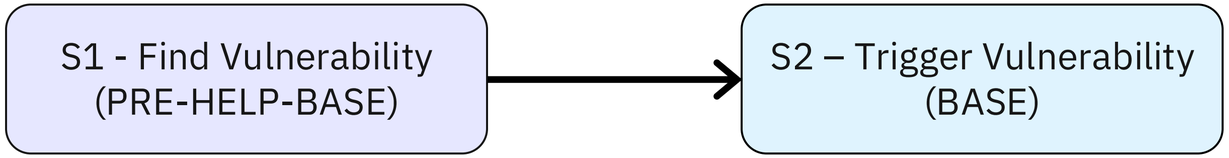
Exploitation Steps

Exploitation Steps

S1 - Find Vulnerability
(PRE-HELP-BASE)

Exploitation Steps



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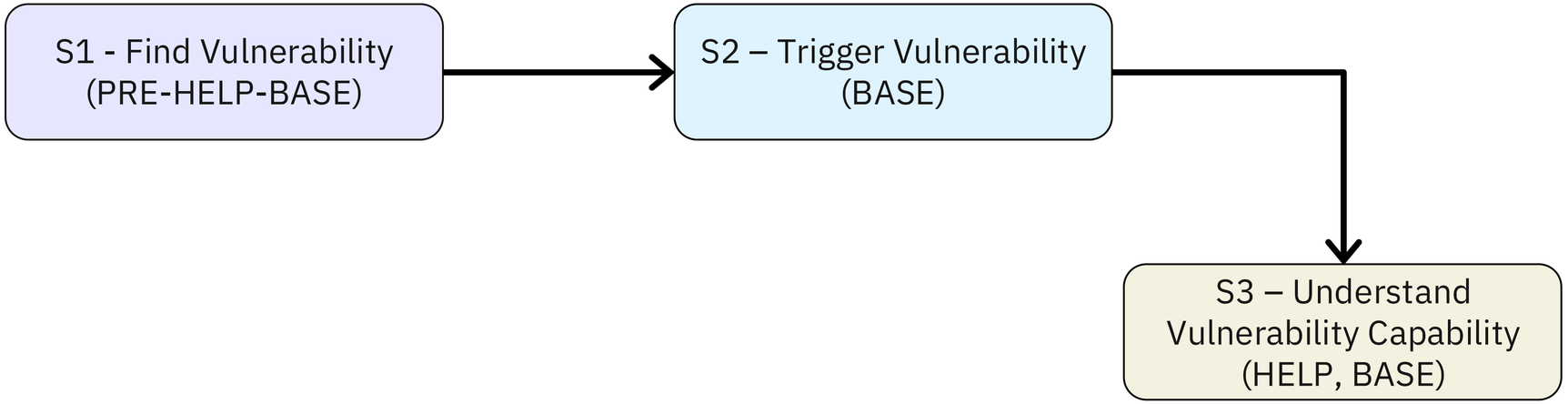

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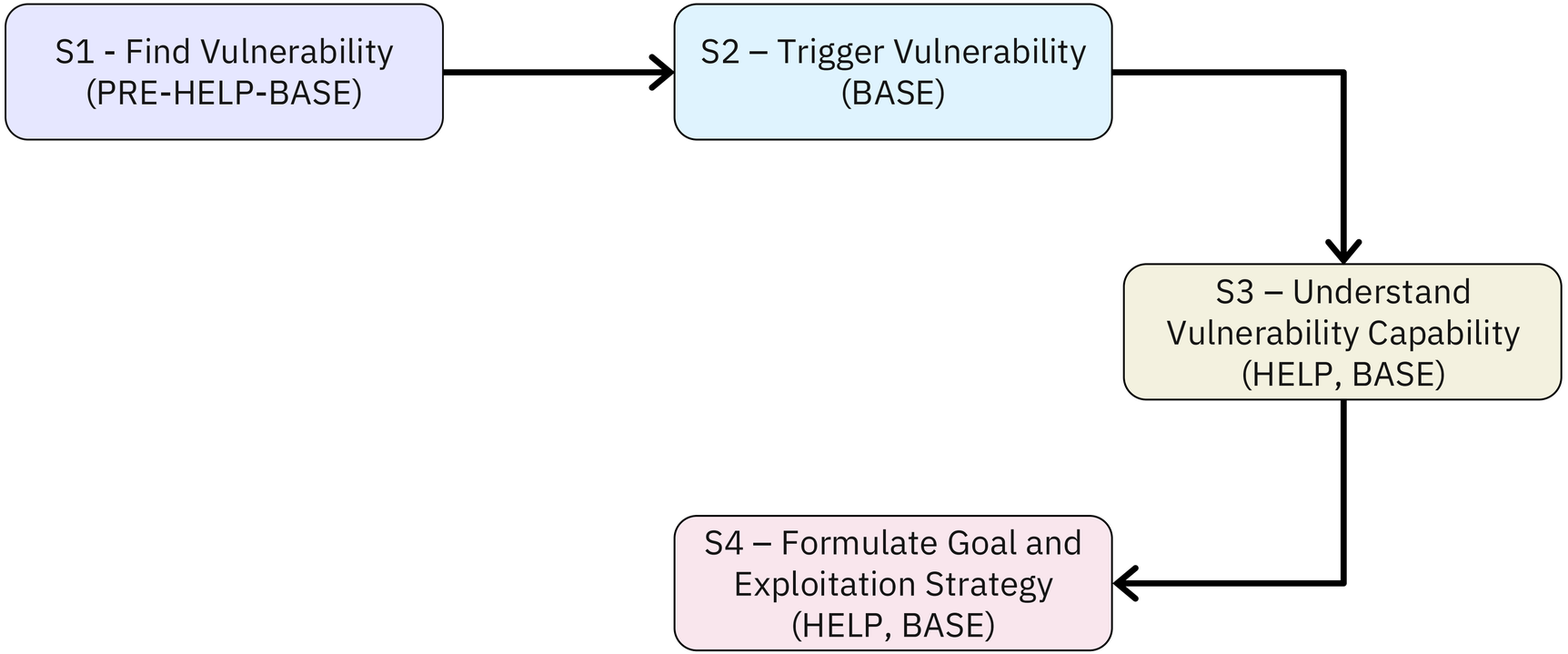

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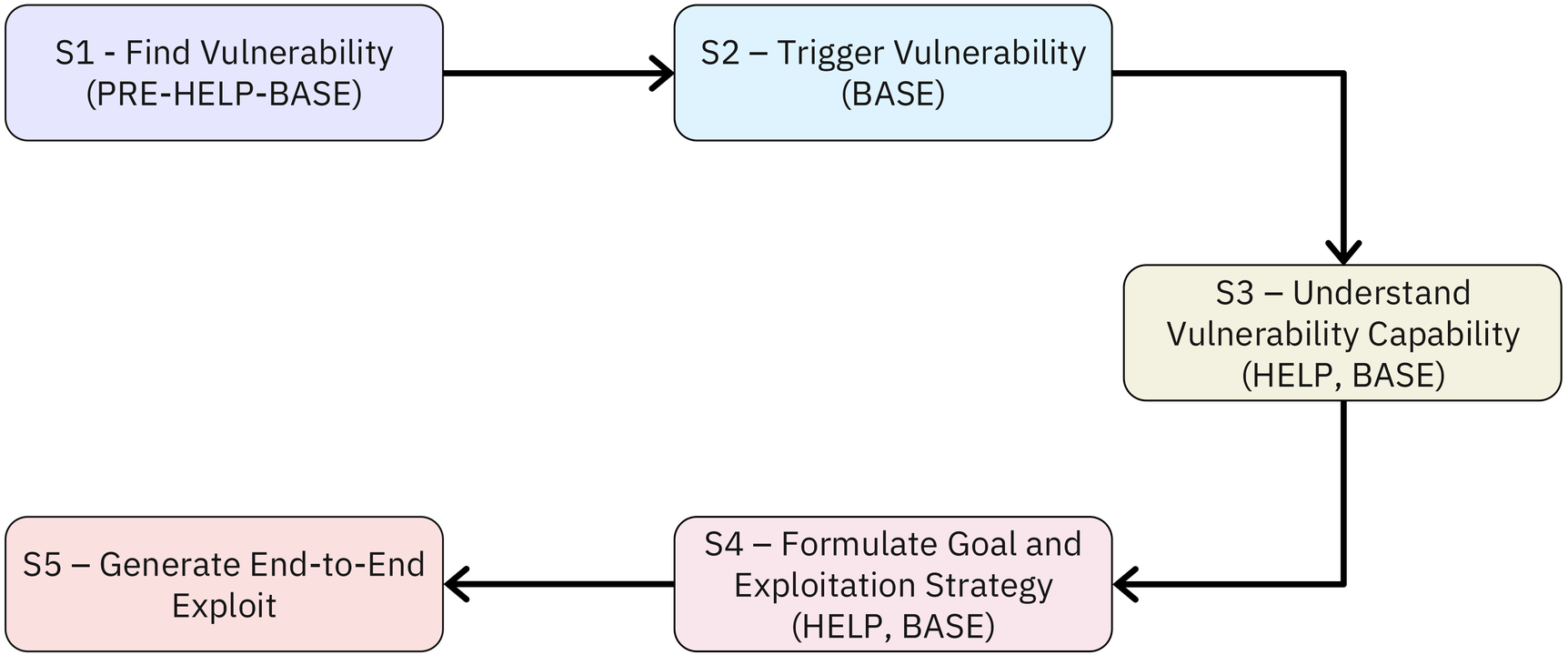

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SoK – methodologies & statistics

First: **paper from top tier venues** from 2013 to 2023.

Second: **collected cited work** not included in first selection.

Filtered for **new techniques** or **automation** of some steps of **kernel exploitation**

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41 TOTAL

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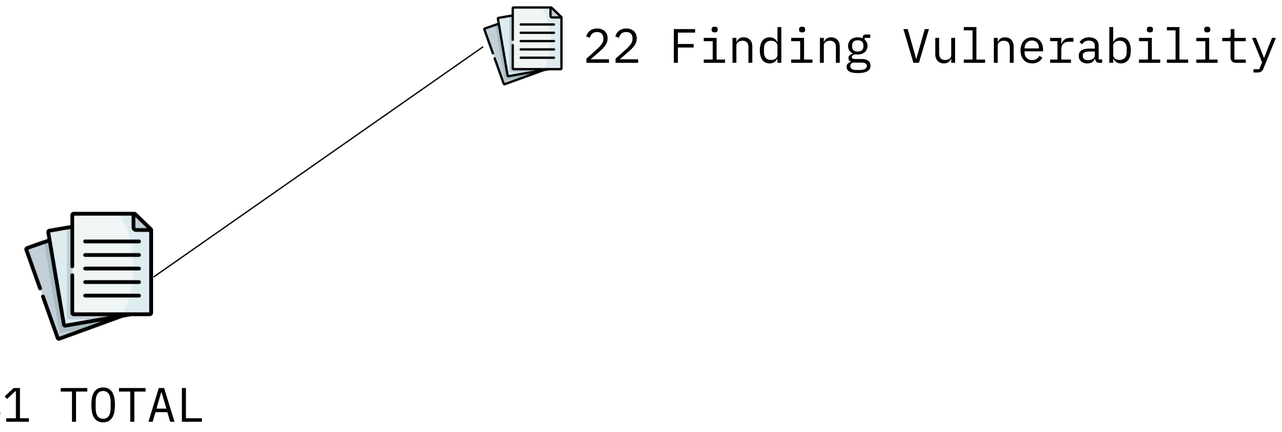

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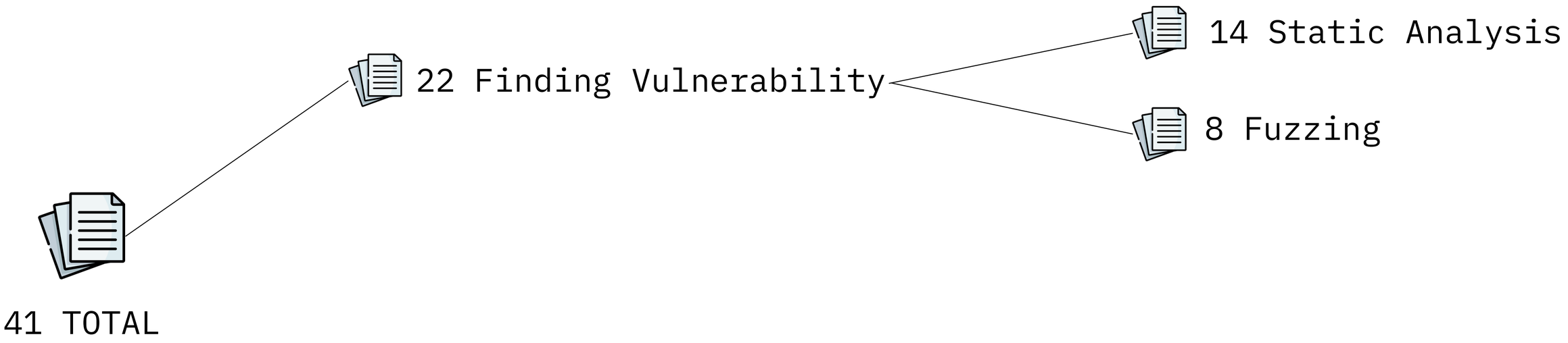

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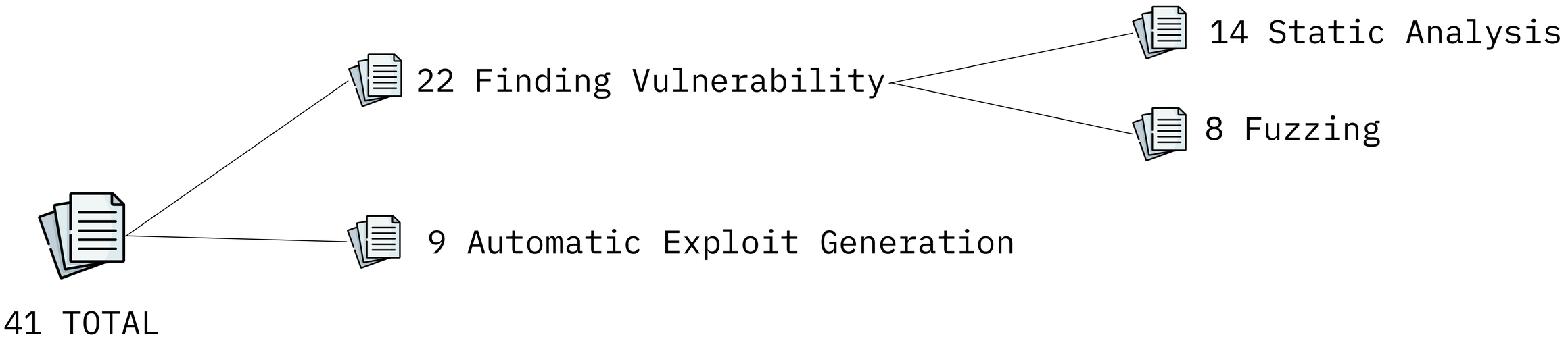

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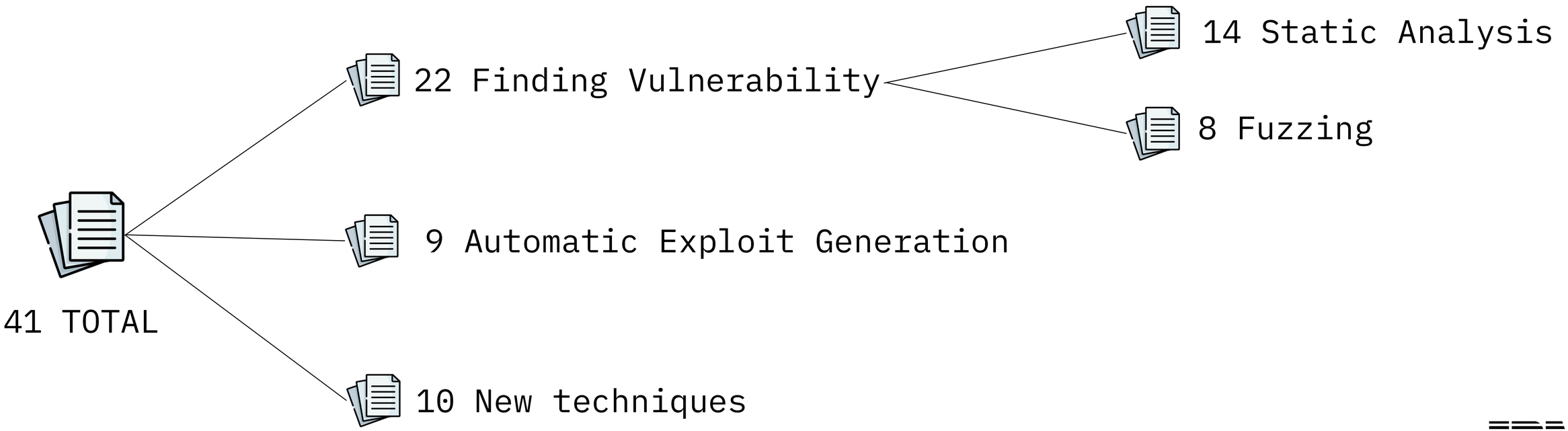

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Open problems – Attacker Model and Goals

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Most works are either threat model agnostic or focus solely to the local attacker scenario.

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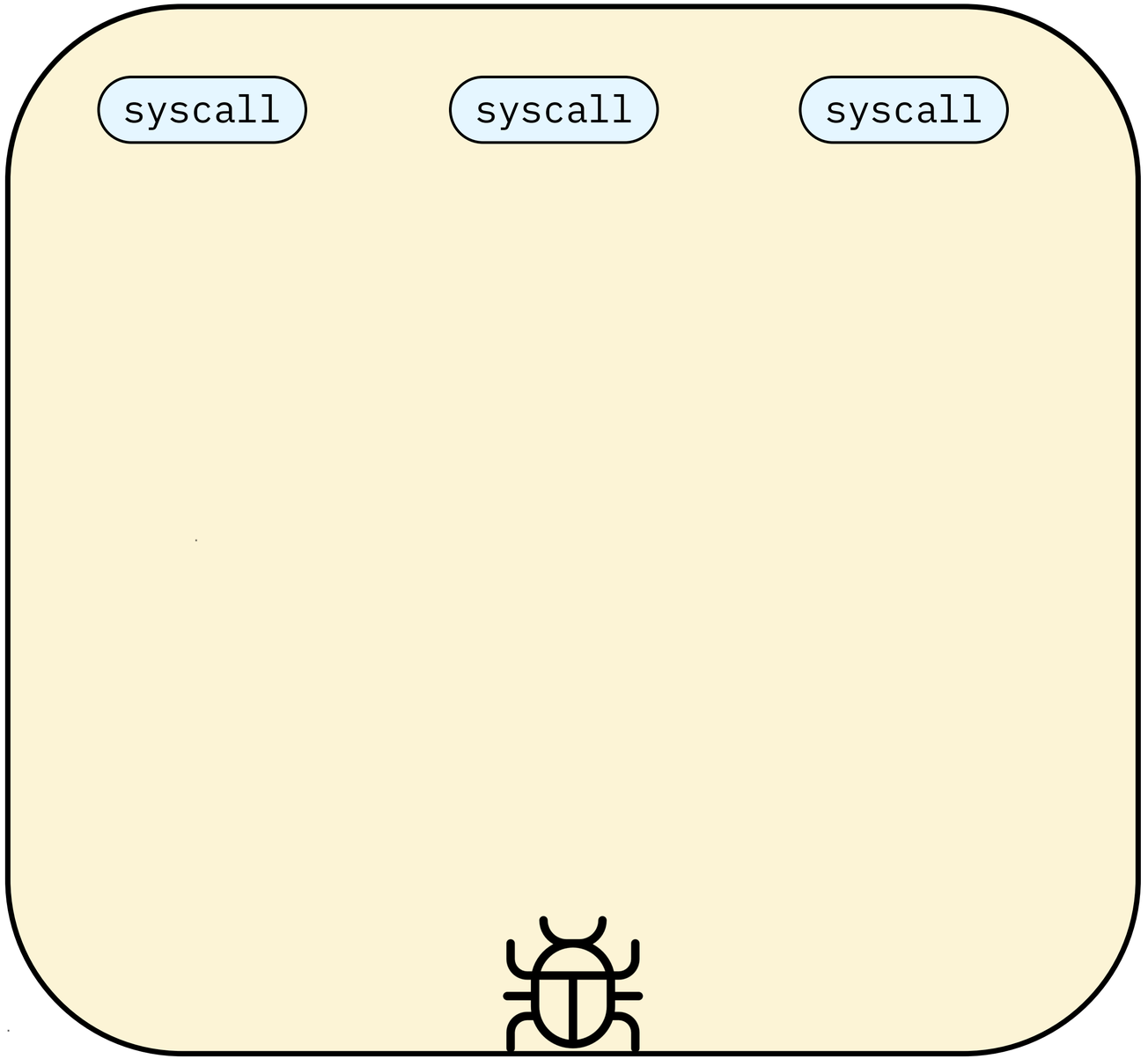
Attacker goals considered are only to PE or IL. DoS is tackled by only one paper

Open problems – Full Exploitability Assessment



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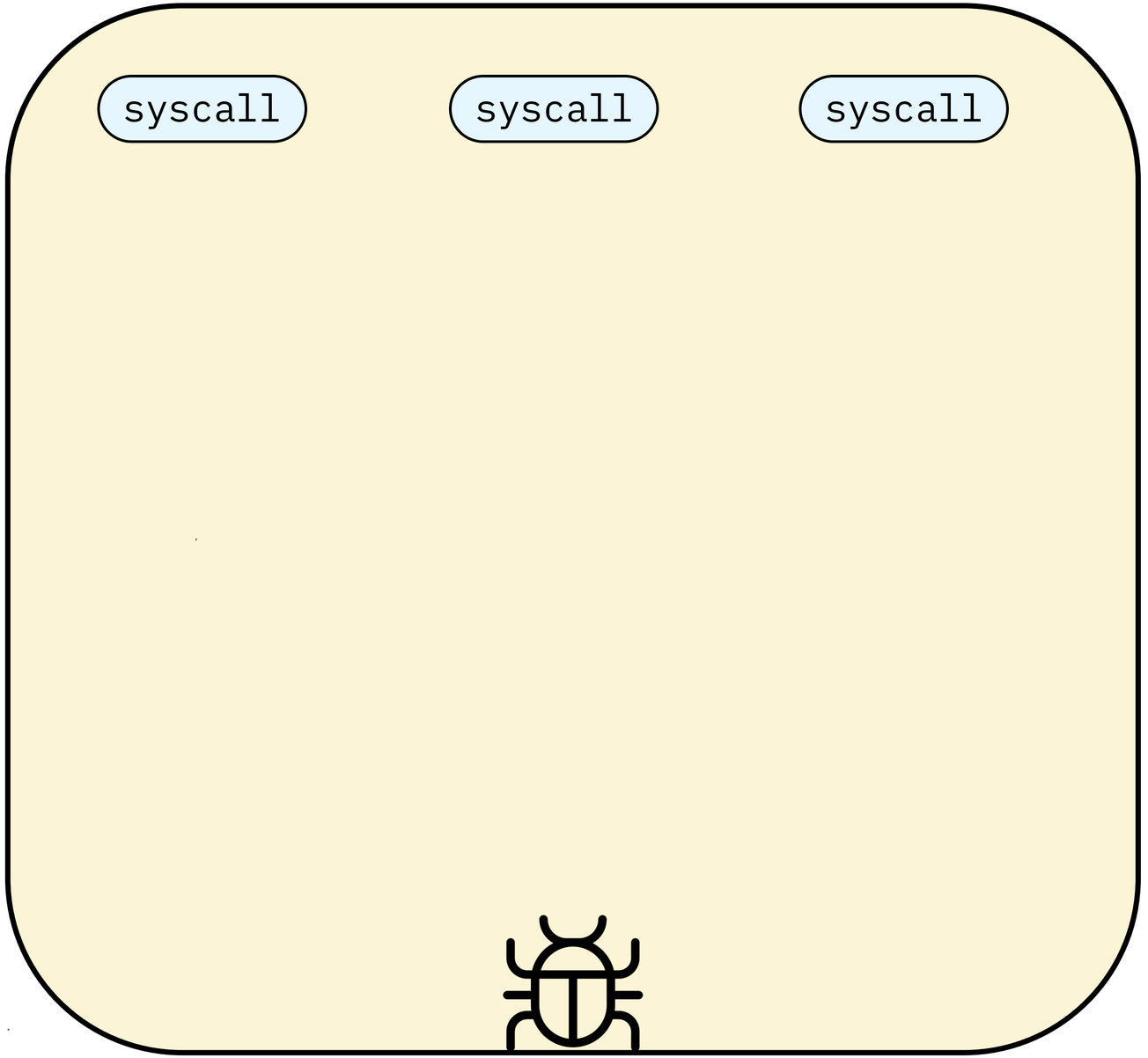

static analysis

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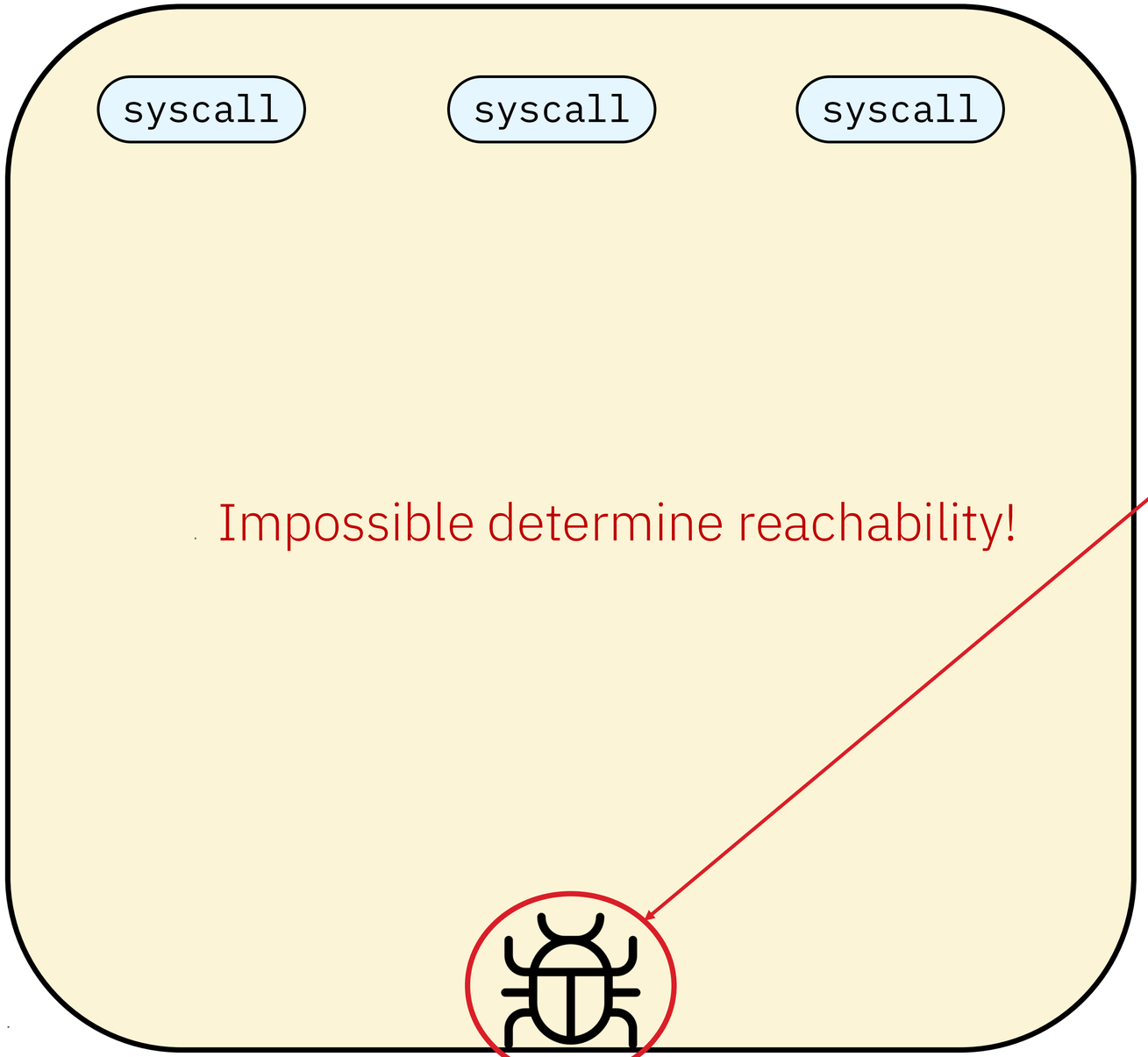

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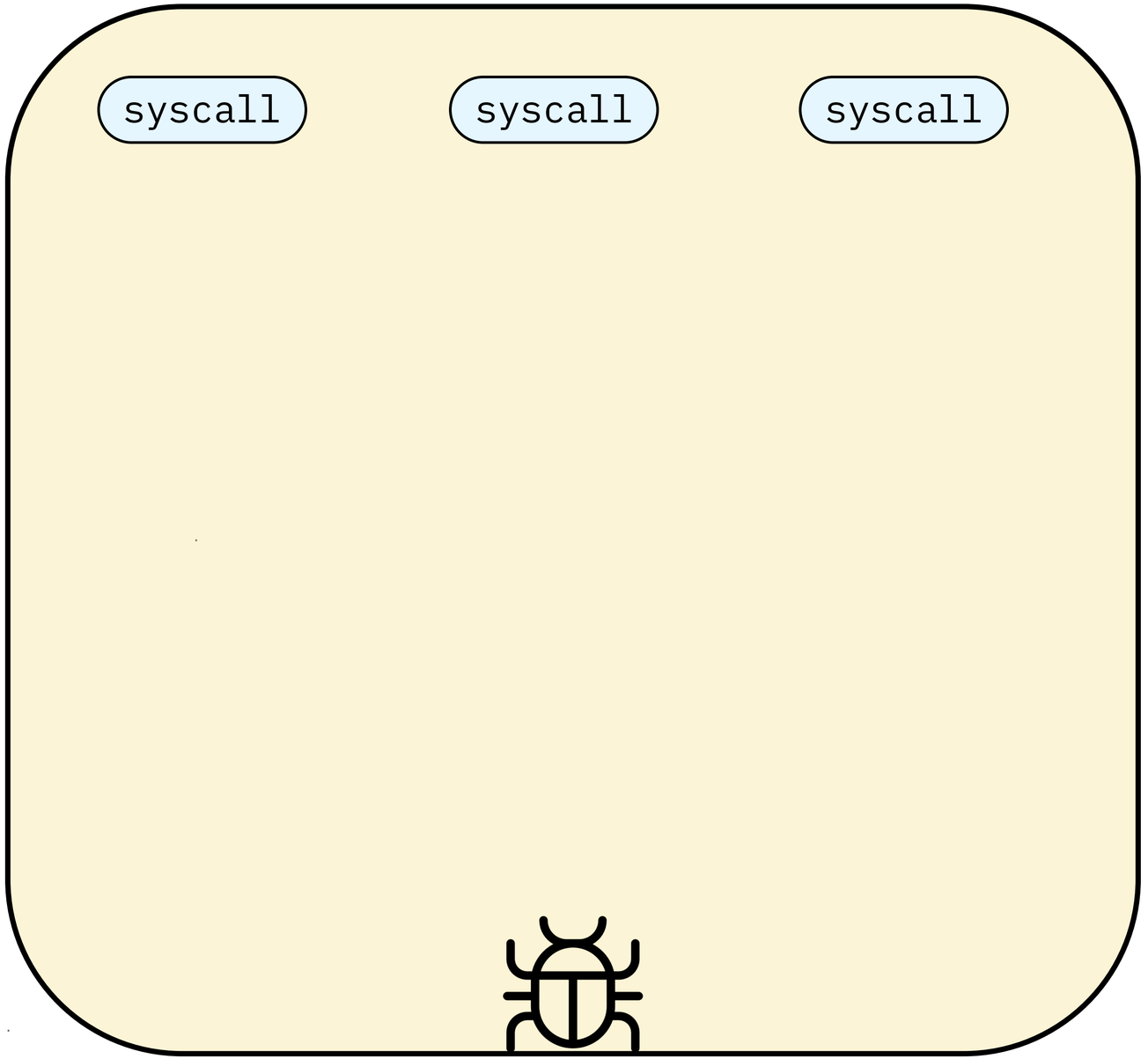

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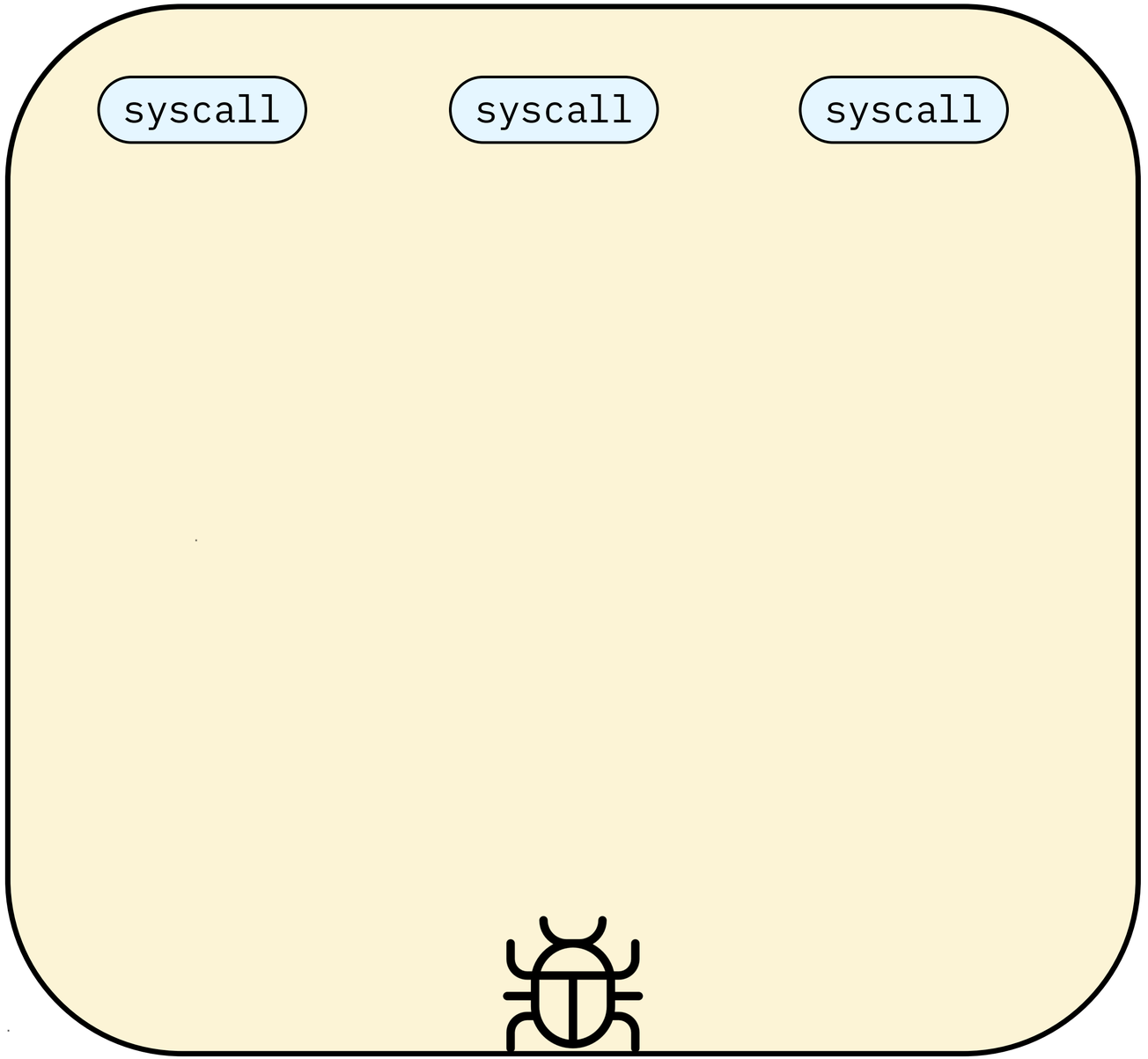

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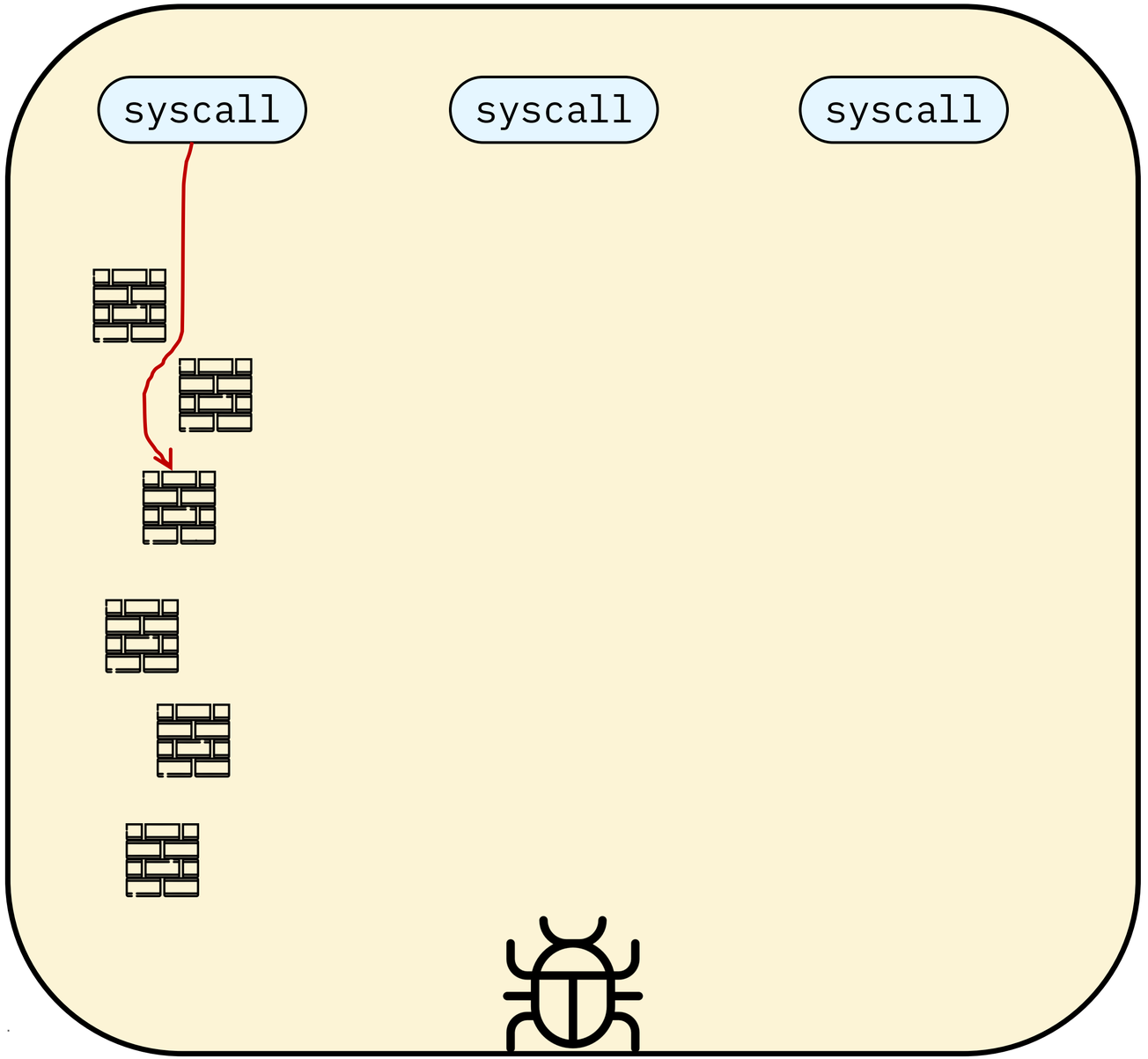

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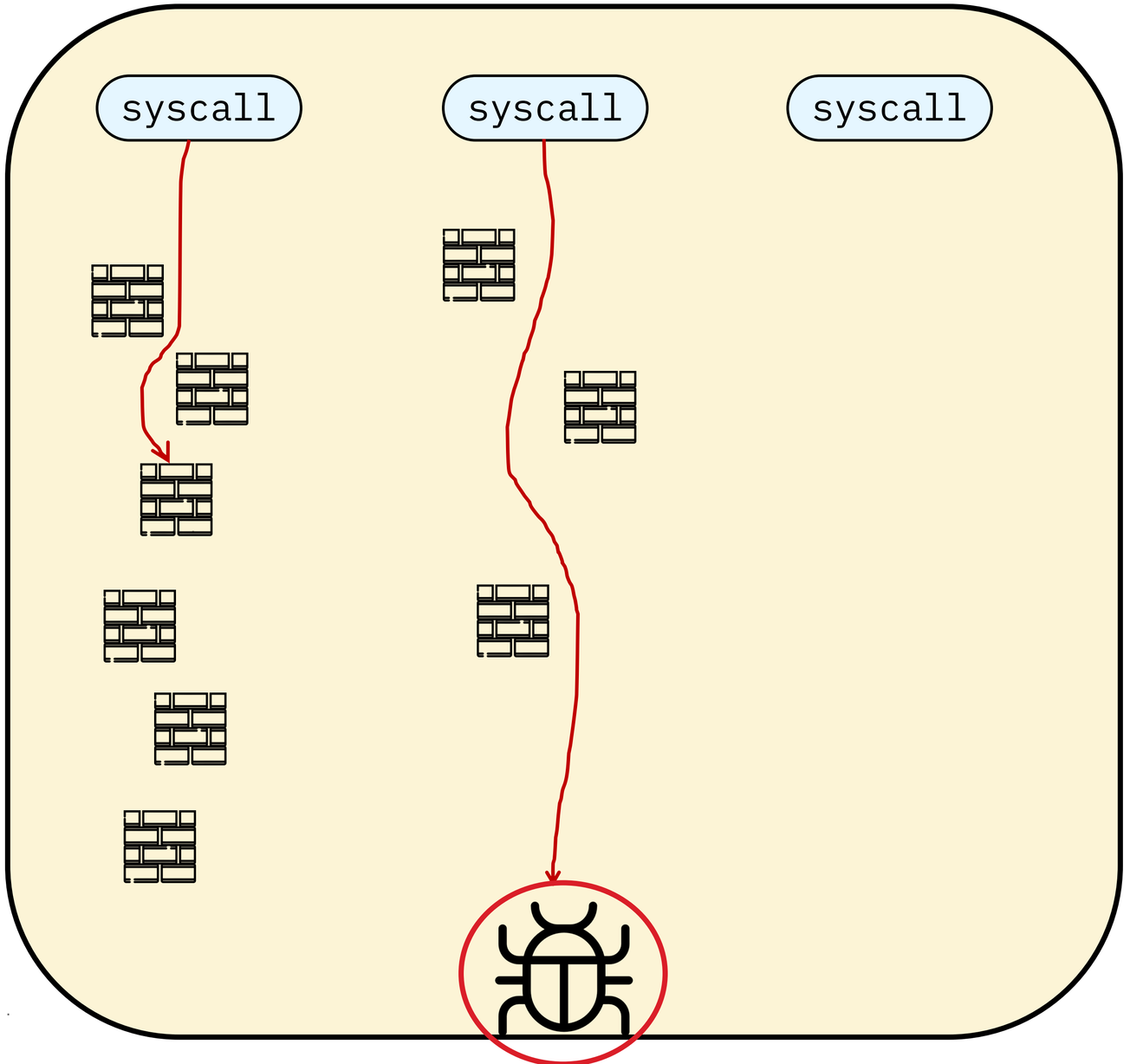

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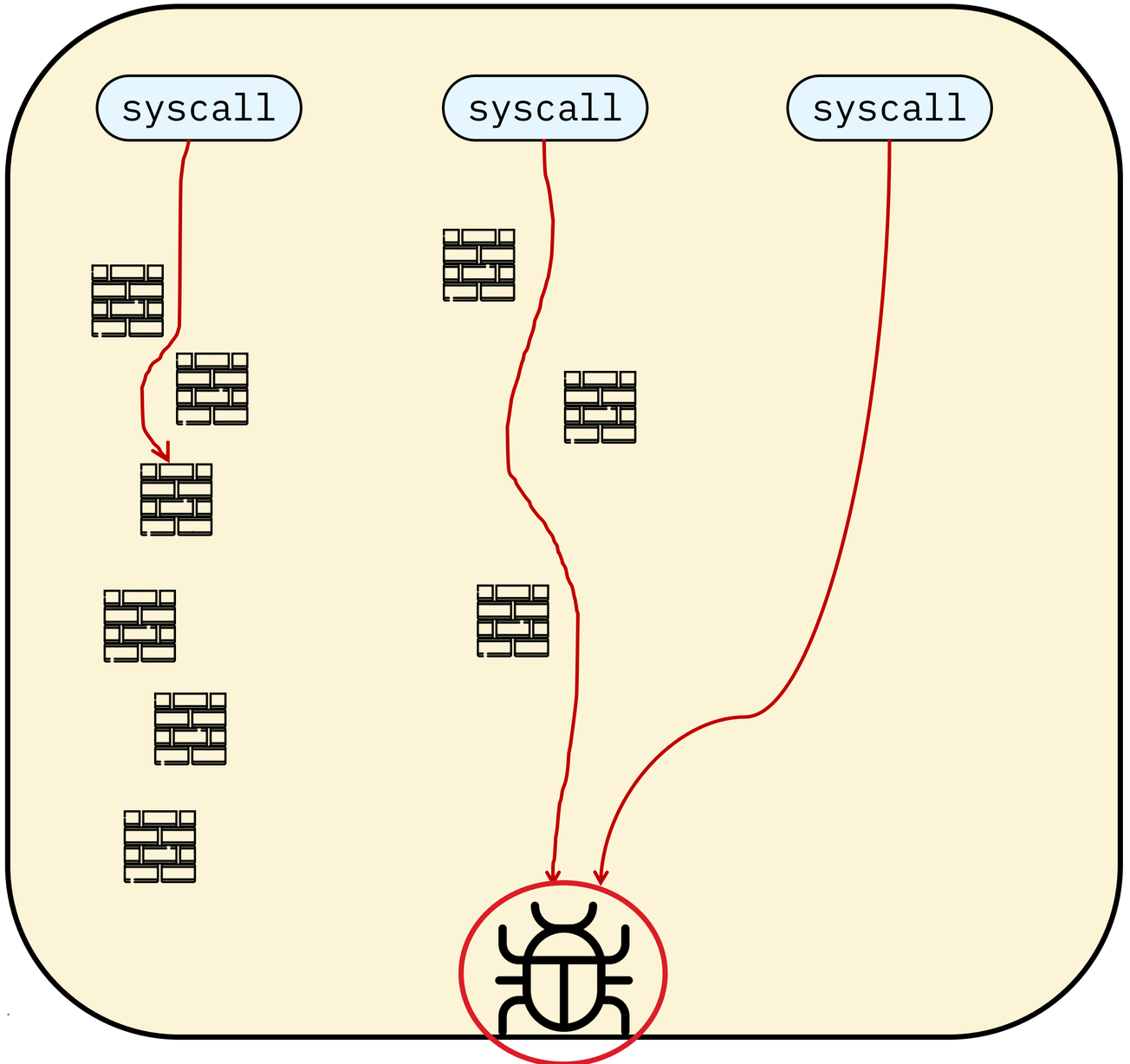
Open problems – Full Exploitability Assessment

dynamic analysis



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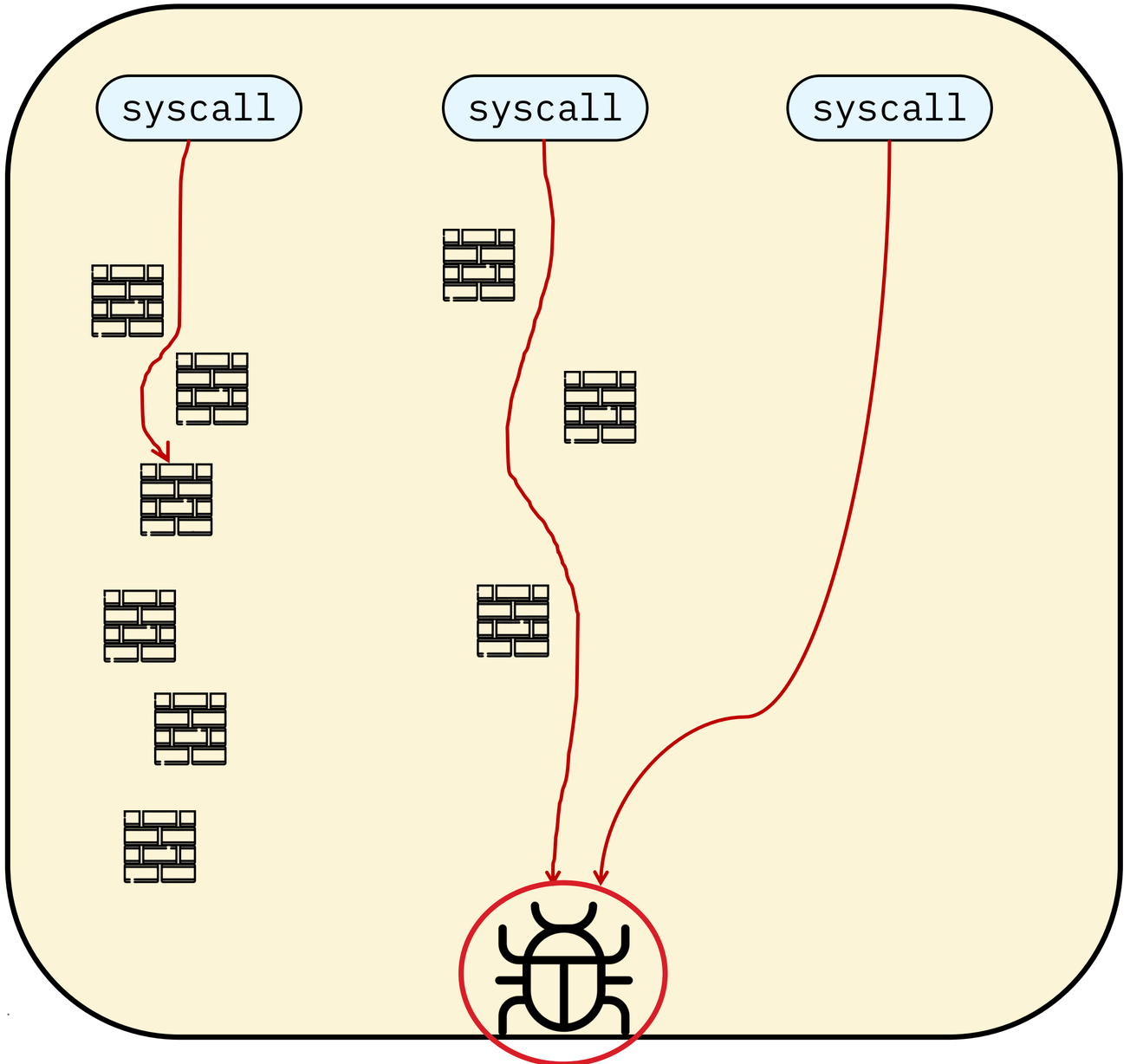

Only GREBE & SyzScope explore multiple/all paths to the same bug.

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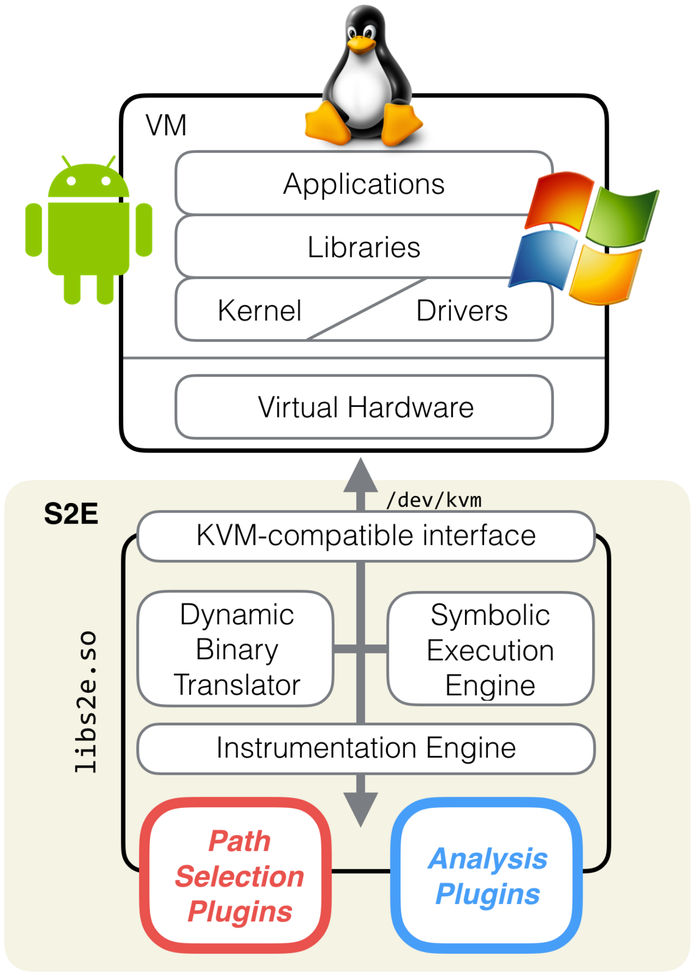
Open problems – Portability

Let’s consider the widely used S^{2}E as an example



Depends on:

1. Qemu v3.0.0 (mainline is at v10)
2. LLVM lifter
3. Klee
4. Instrumented kernel (version 4.9.3 until last year)
5. Custom KVM implementation

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Image source: https://s2e.systems/

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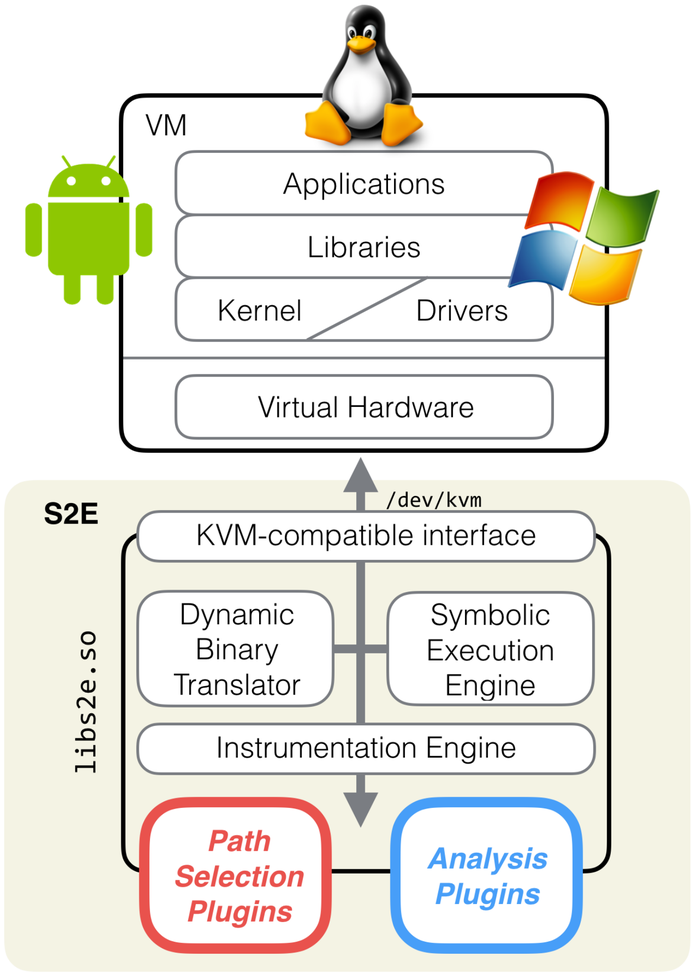

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Open problems – Reproducibility

Reproducing and comparing with previous work is hard and requires expert knowledge

Each paper select their favorite set of bugs and kernel version

The community could agree on one research Linux version and bug dataset

The known bugs could be ported to the supported kernel automatically (difficult!)

Open problems – Tool reuse

We found that Syzkaller, LLVM, S2E and angr are overall highly used - kudos!

However, papers using these tools re-implemented within them similar features which are never merged into the tool mainline

Often, no code is provided

Methodologies from different papers often cannot be combined due to incompatible or brittle codebases

Conclusions - Status Kernel AEG

No work has yet achieved full AEG for the kernel at scale.

Exploitation steps are often tackled in isolation.

Focus is given to only the most prominent threat model and attacker goals.

Very limited re-use of state of the art beyond major analysis framework.