ASPLOS 2023

KIT: Testing OS-Level Virtualization for Functional Interference Bugs

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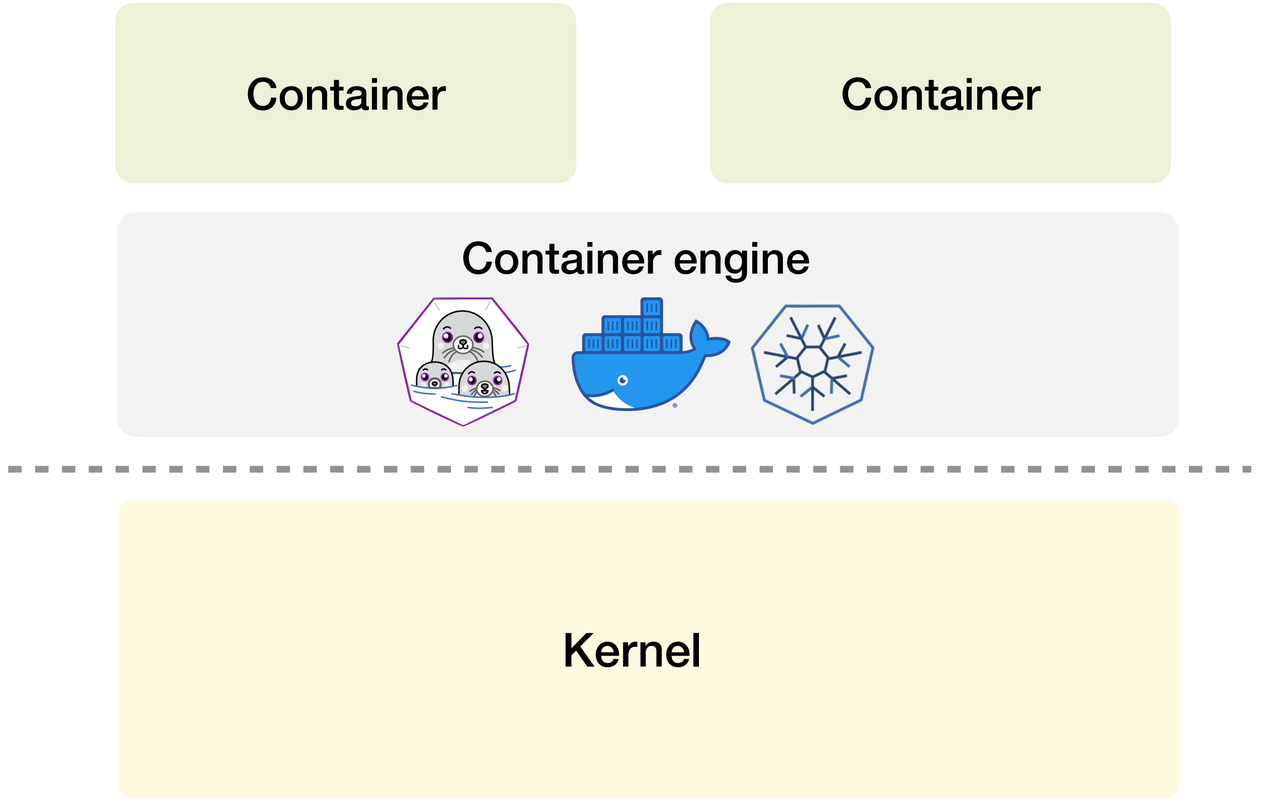
RELIABLE & SECURE SYSTEMS

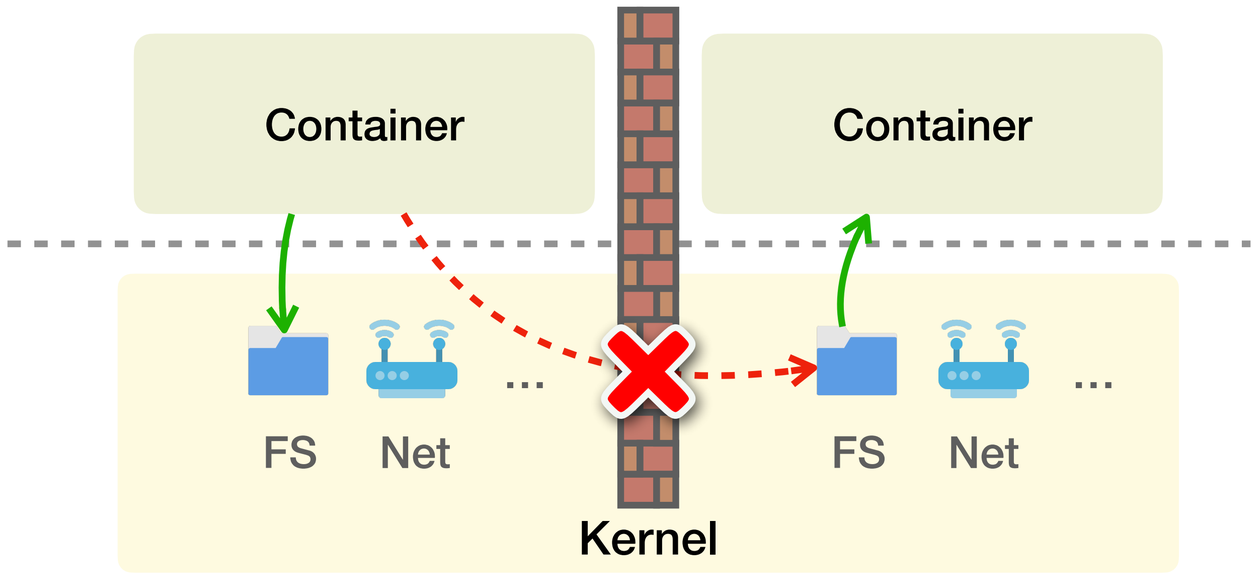
Containers are widely deployed

In 2022,
79% of organizations use containers in production,
with 44% using them for most or all production applications.

Containers efficiently and securely share the same kernel

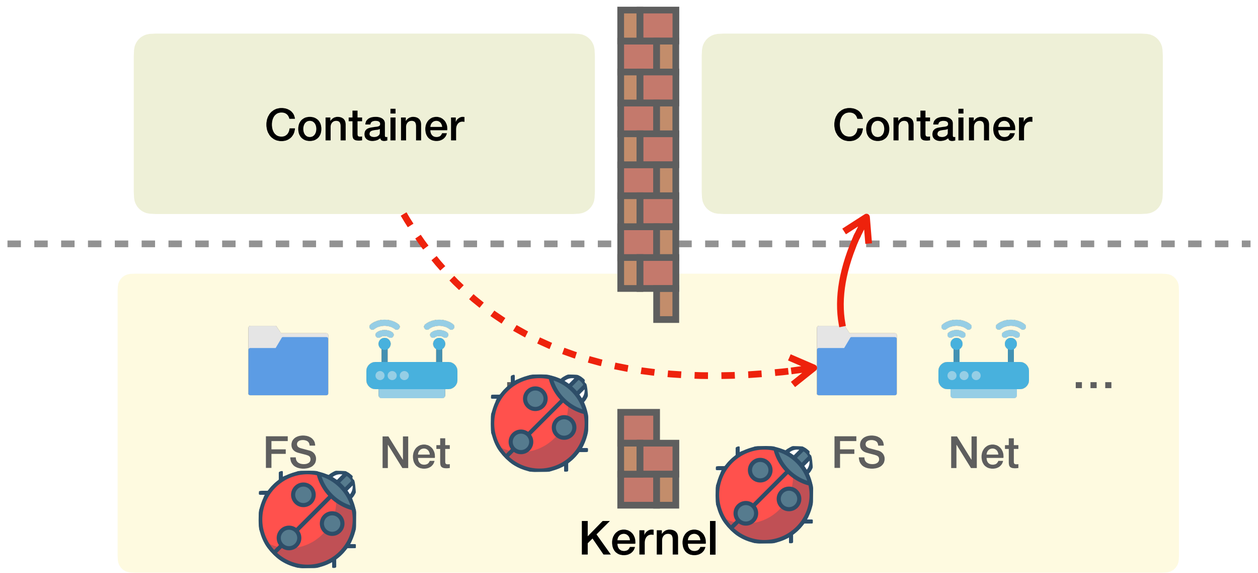


Kernel is responsible for isolating containers



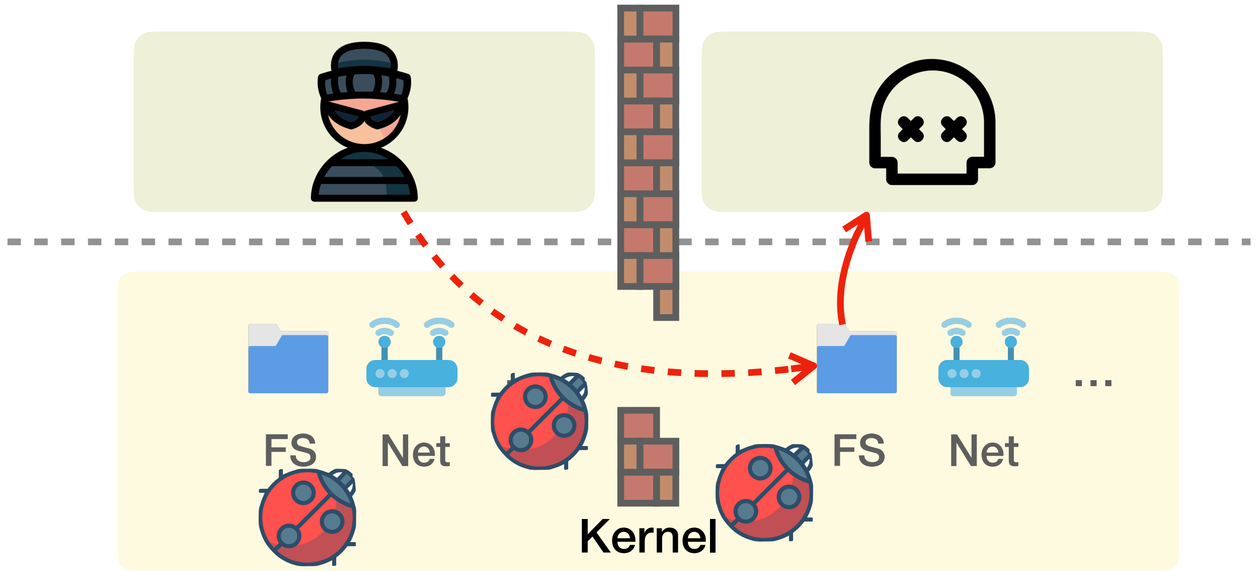
Kernel isolates resources for containers

This ‘wall’ has holes



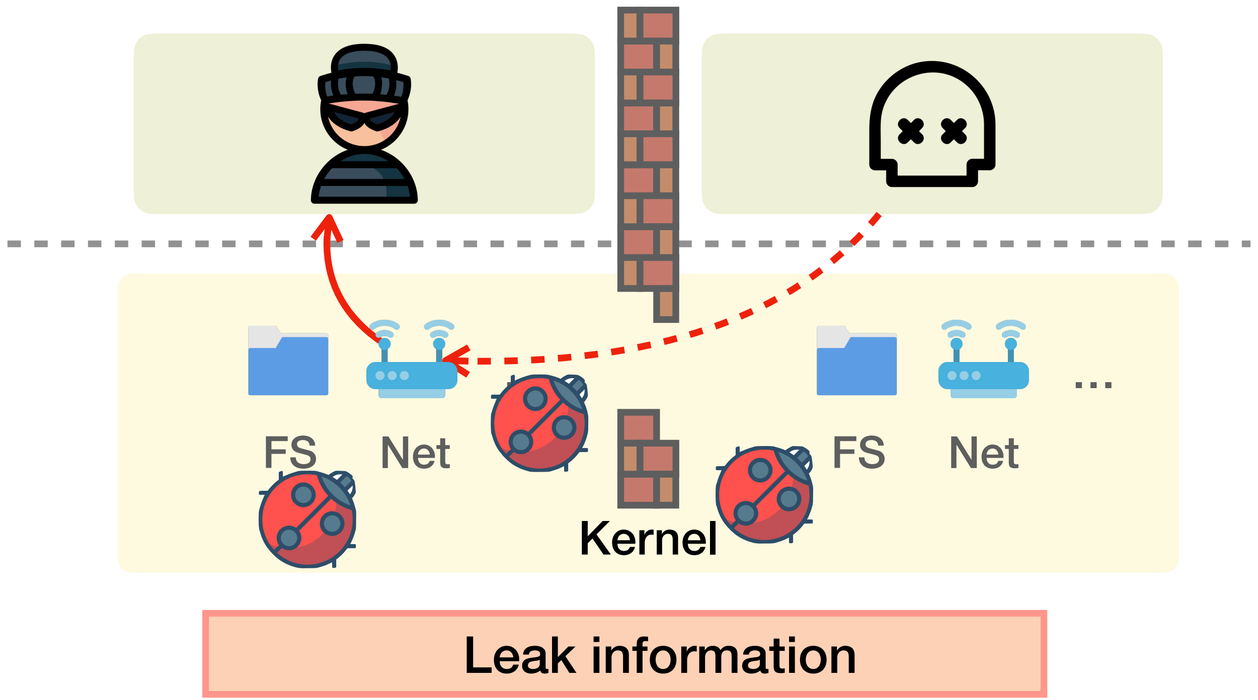
Functional interference bug:
A container affects other containers’ system call results (functionality)

Functional interference bugs are harmful

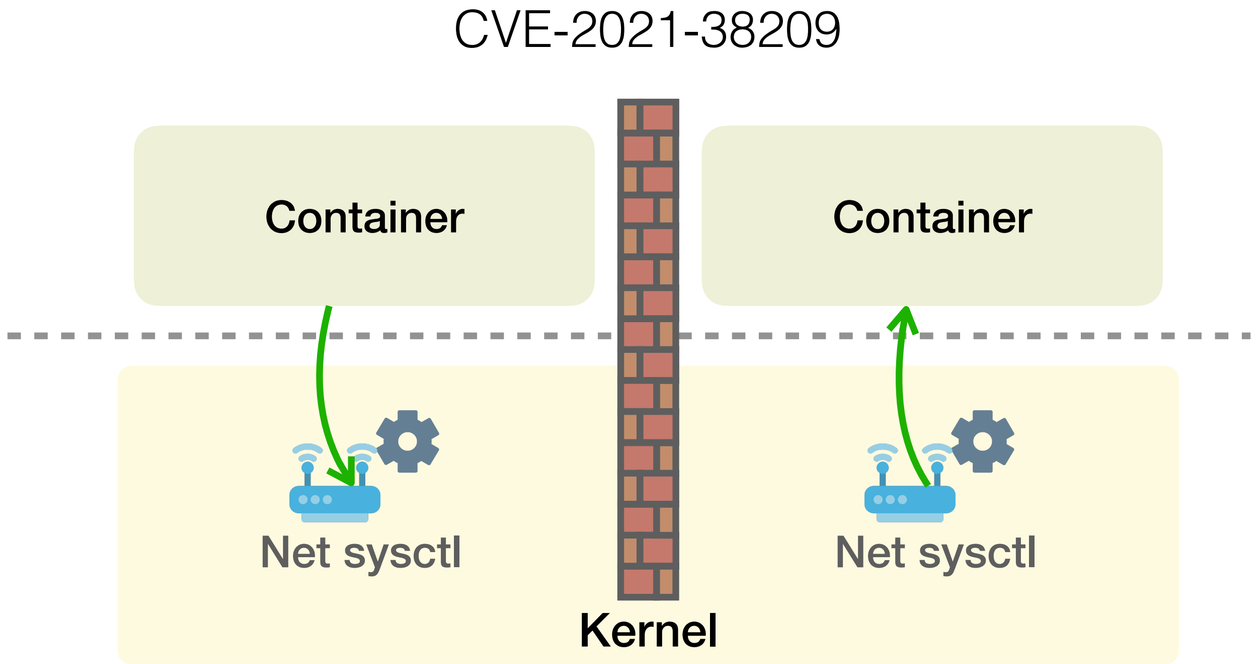


Integrity violation (data corruption) or cause denial of service

Functional interference bugs are harmful

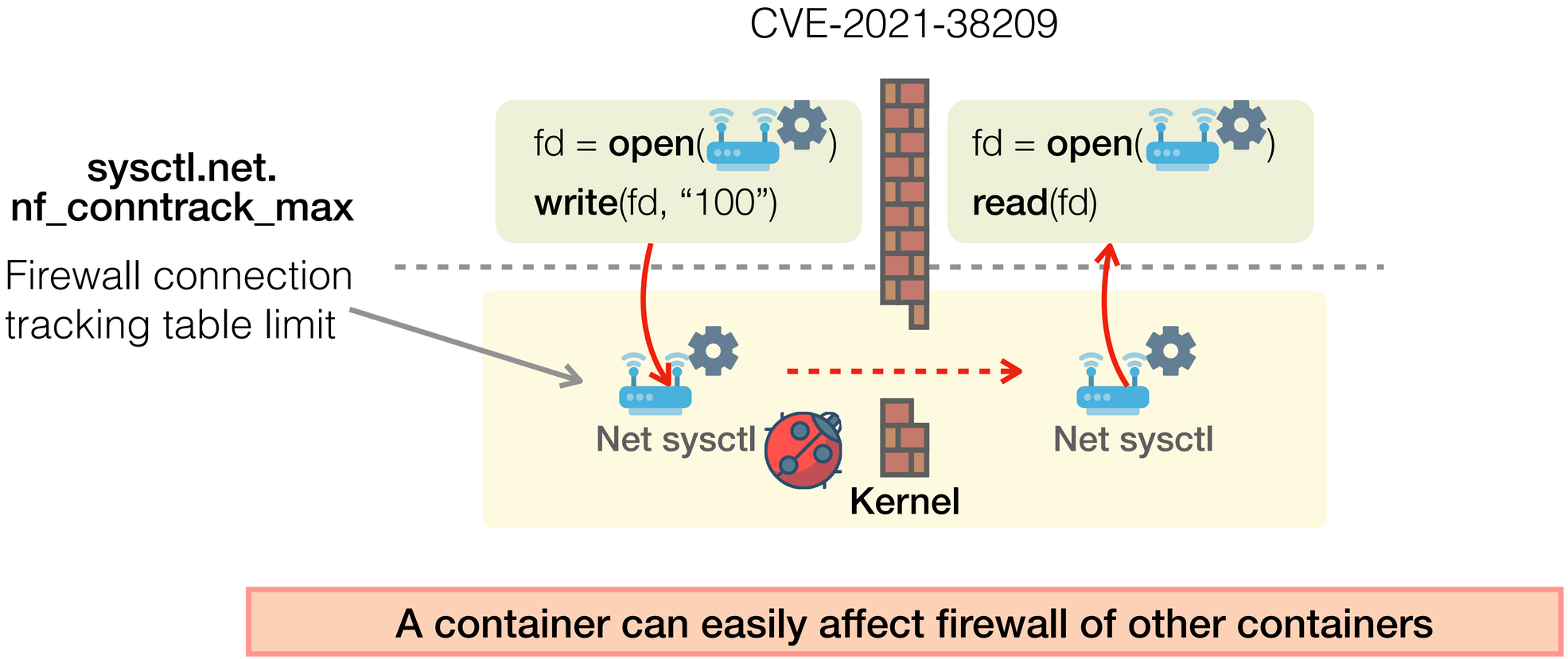


A functional interference bug in Linux namespaces



Network sysctls should be isolated by namespaces

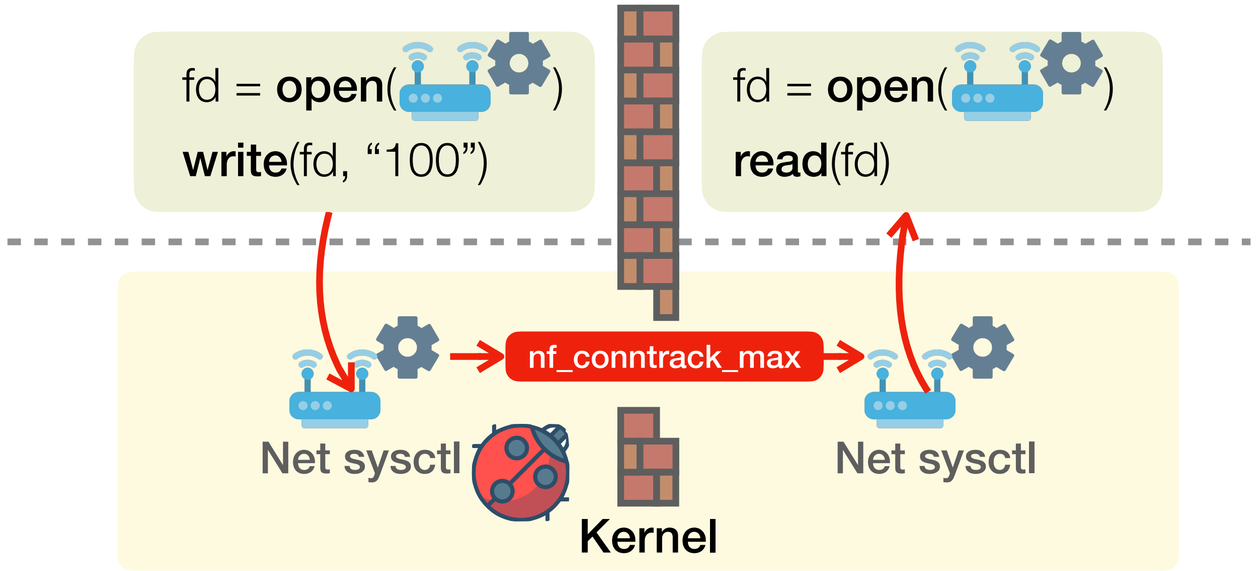
A functional interference bug in Linux namespaces



A container can easily affect firewall of other containers

A functional interference bug in Linux namespaces

CVE-2021-38209



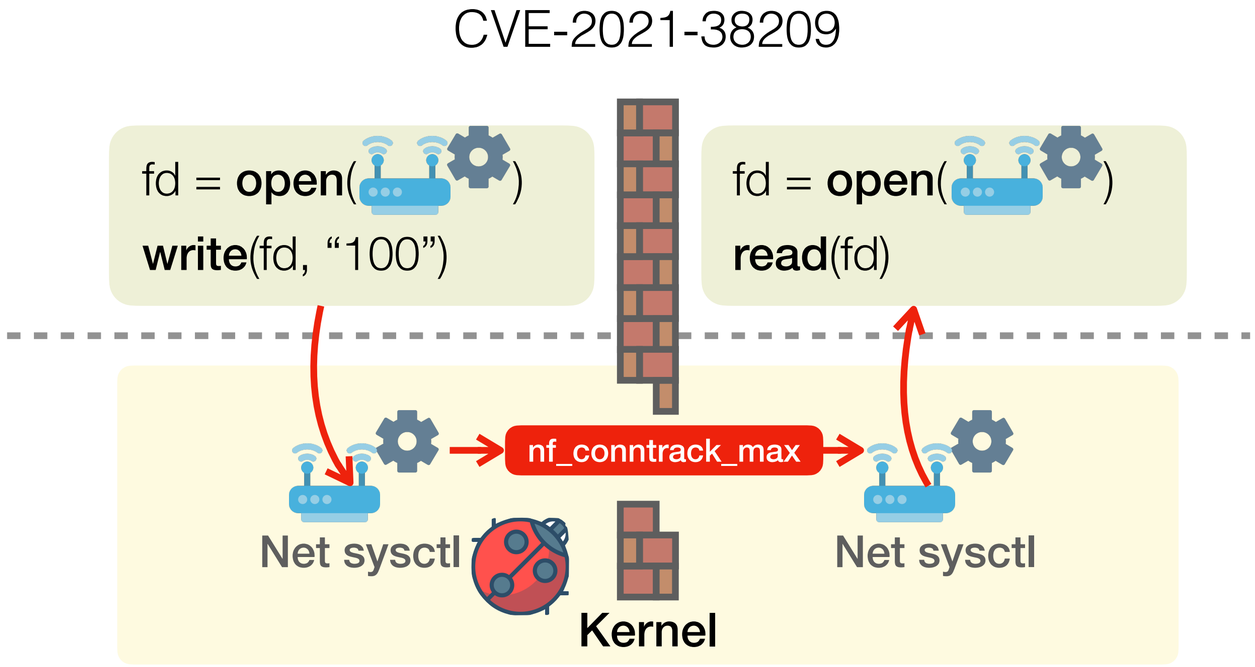
Root cause: share the same global variable

Functional interference bugs are usually semantic bugs

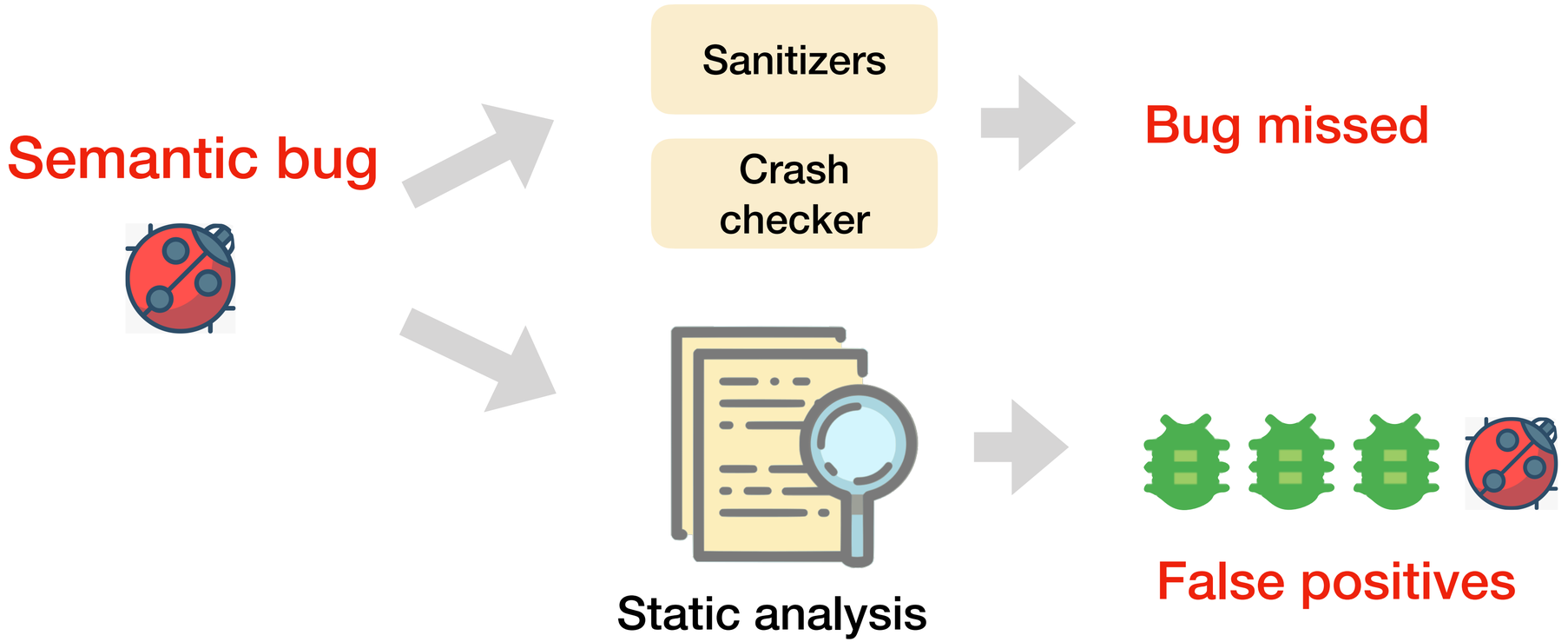
Semantic bug

Do not cause crashes

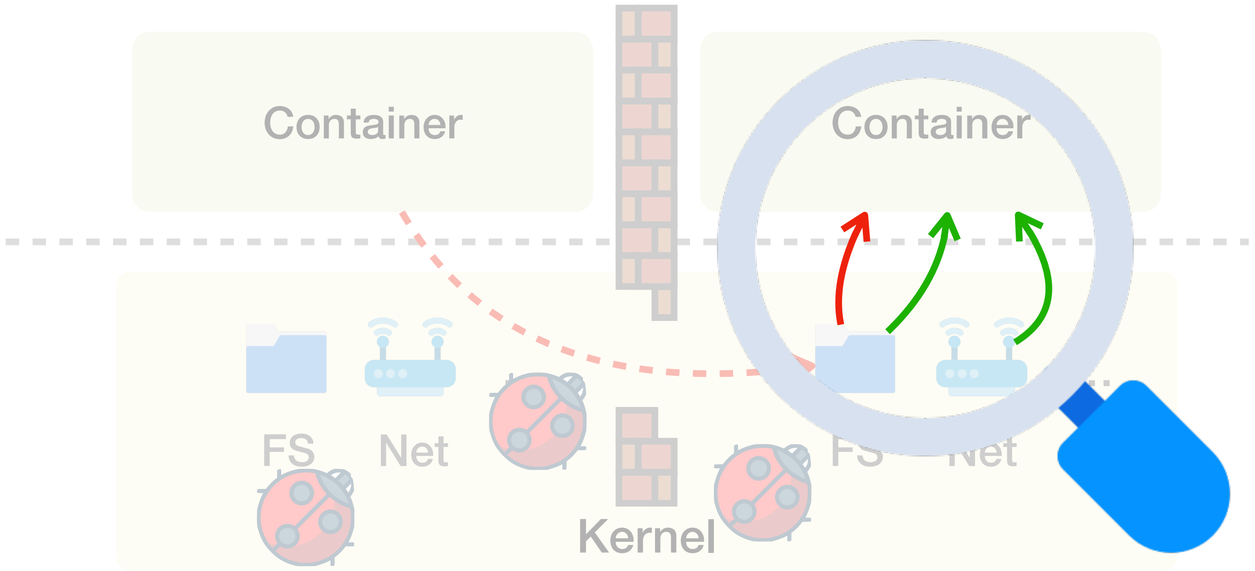
Do not involve memory errors or data races



Challenge: detect semantic functional interference bugs

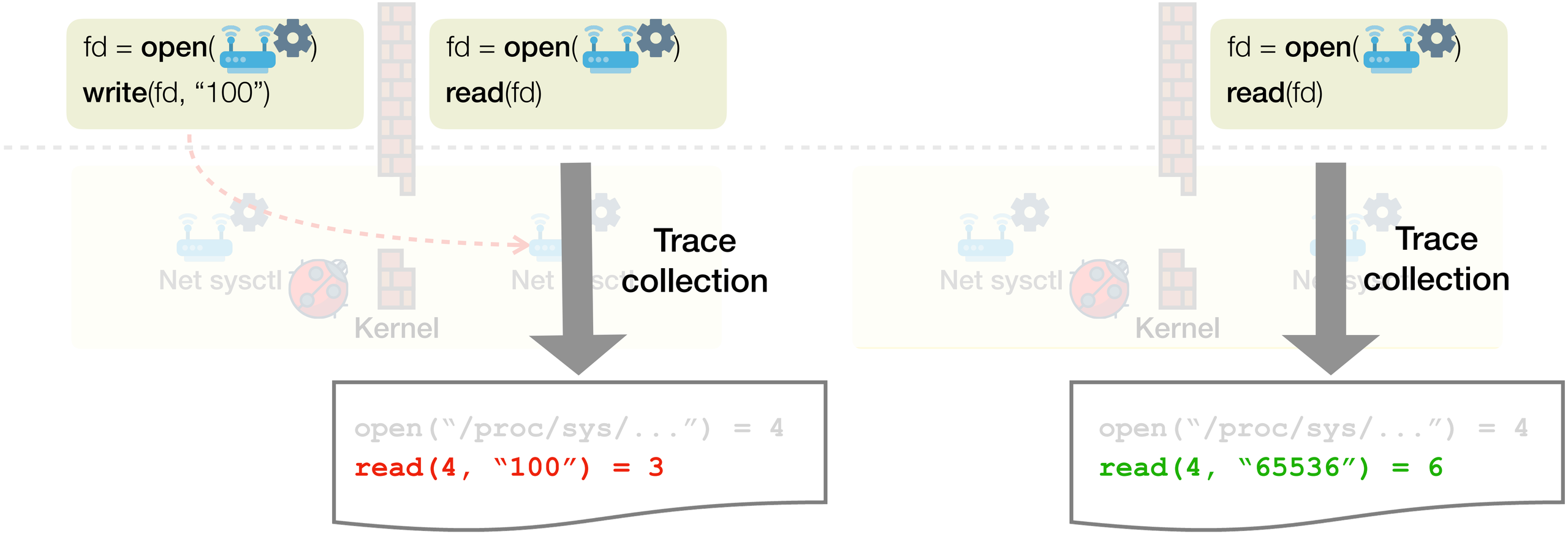


Goal: check system call results for correct isolation

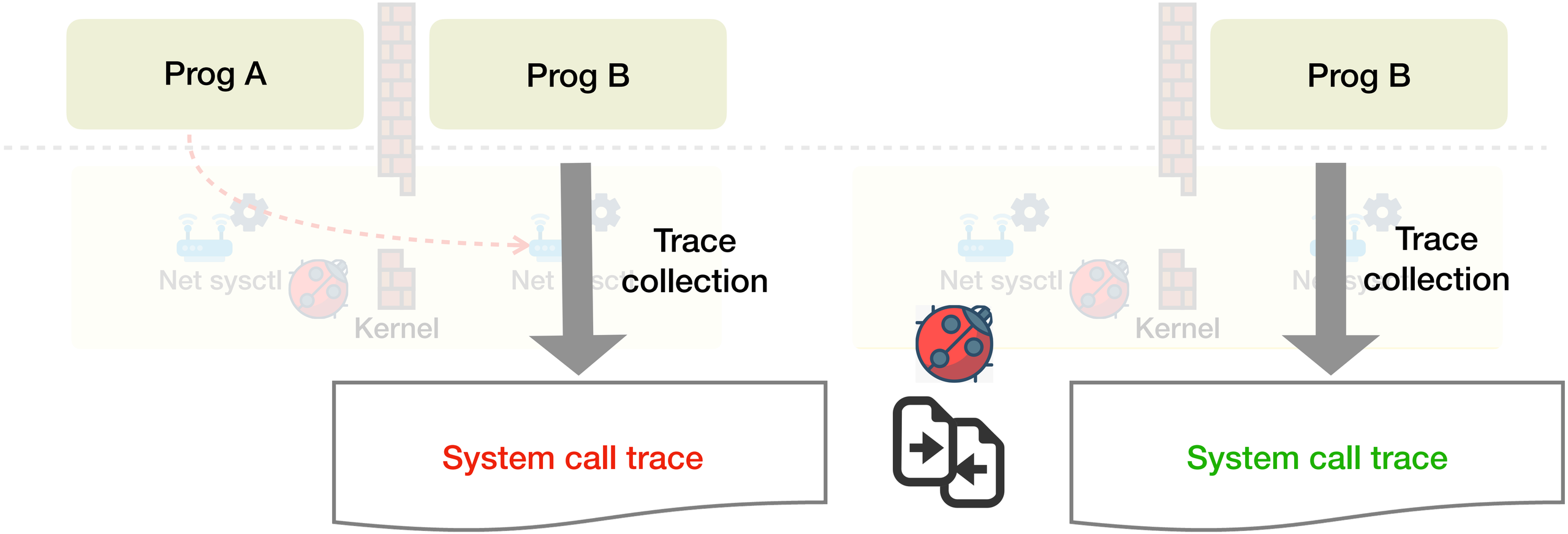


- Detect semantic bug
- Simplify analysis

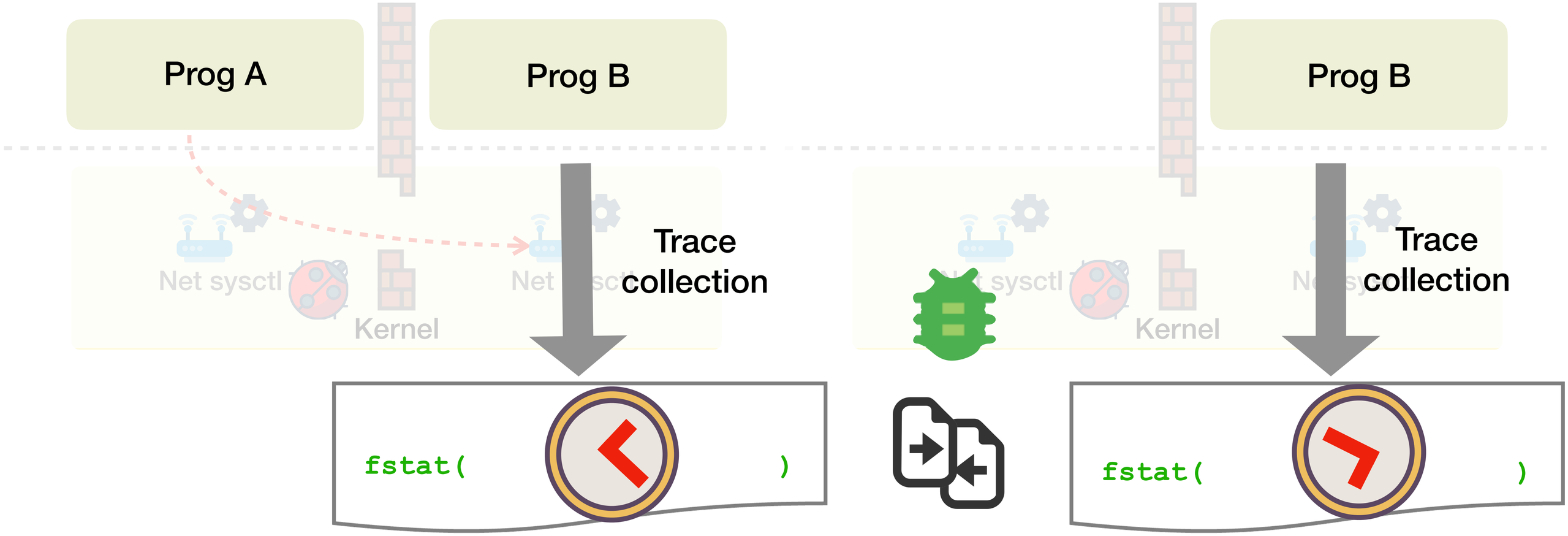
Observation: affected results usually change



Approach: compare system call trace across executions

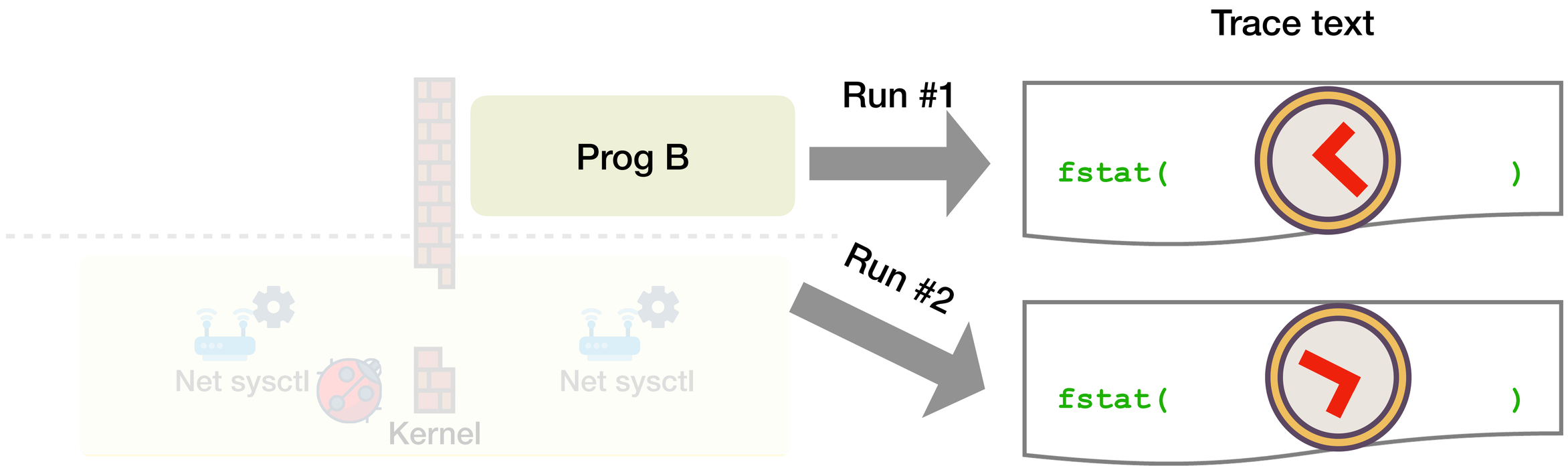


Exception I: Non-deterministic system call results



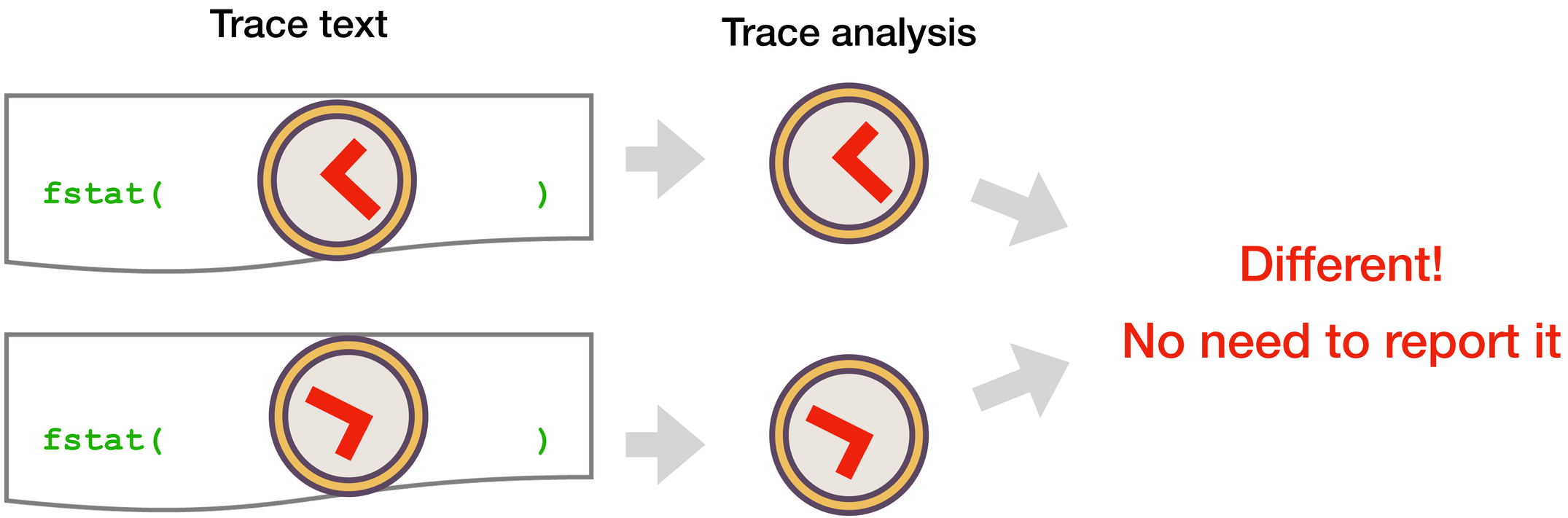
Non-determinism can also cause traces to be different and should be filtered

Filter non-deterministic system call results

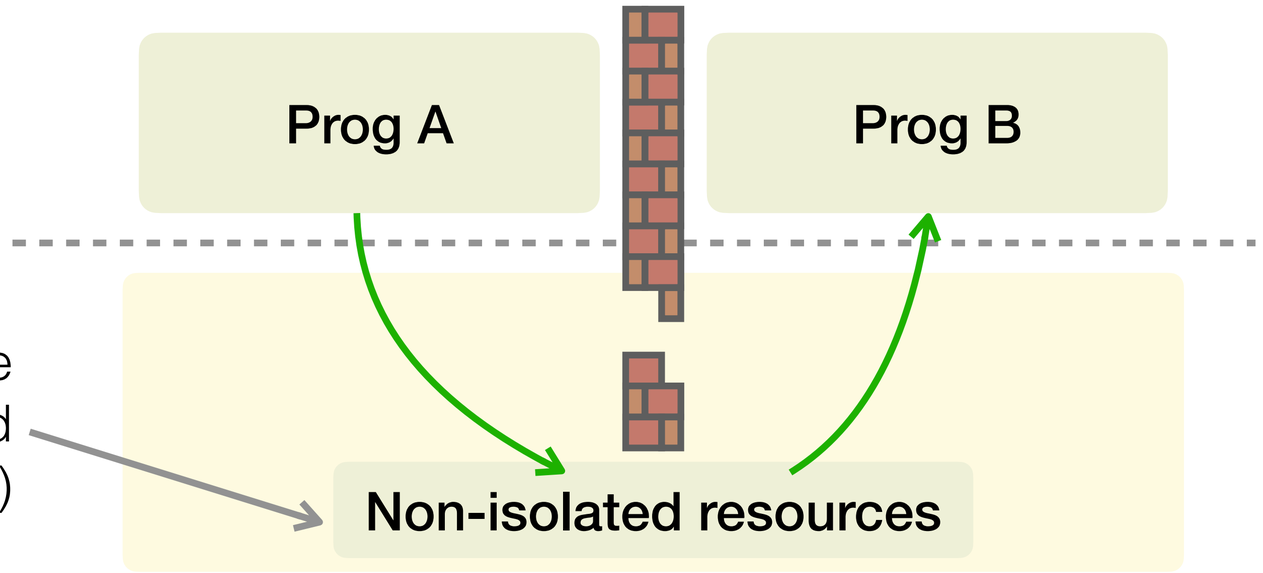


Non-determinism can be identified by running multiple times

Filter non-deterministic system call results



Exception II: non-isolated kernel resources



Some resources are deliberately not isolated (e.g., some files in /proc)

System calls on non-isolated kernel resources can interfere

Expected behavior, not bugs

Filter system call results on non-isolated kernel resources

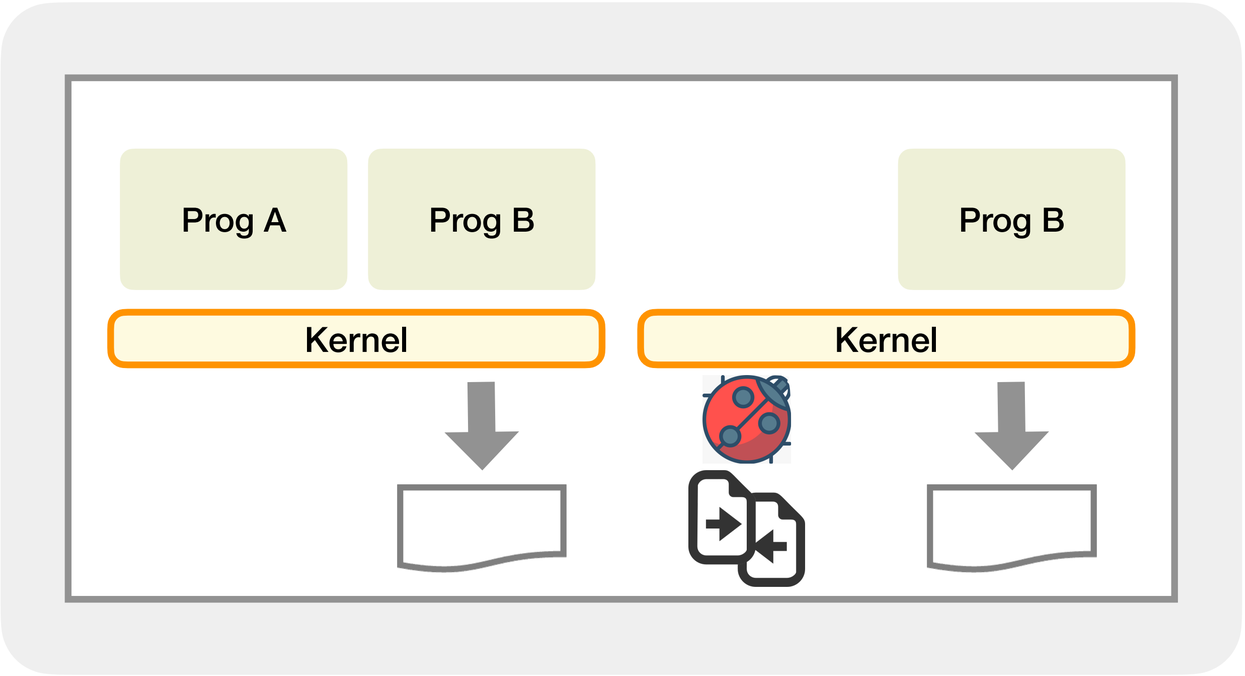
1. Container configuration

Limit accesses to
non-isolated resources

2. Isolated resource
specification

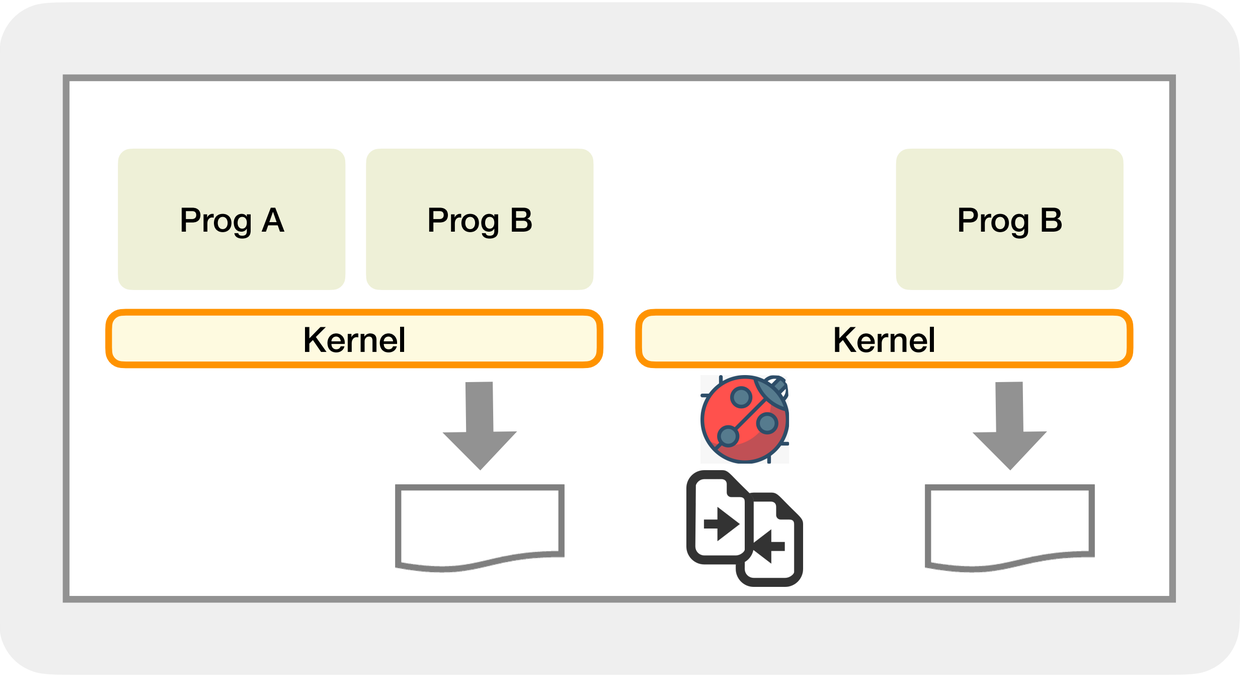
Progressively refine the
specification to check the
isolation on given resources

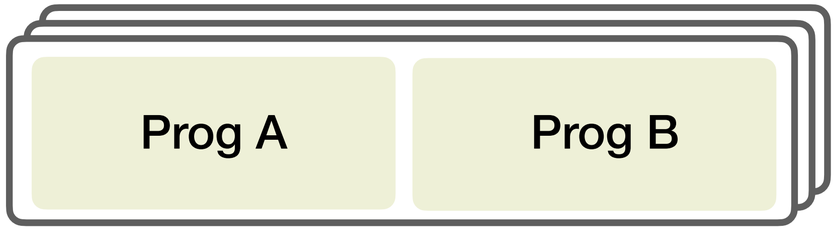
Previous: detect functional interference bugs



How to detect functional interference bugs?

Next: trigger functional interference bugs

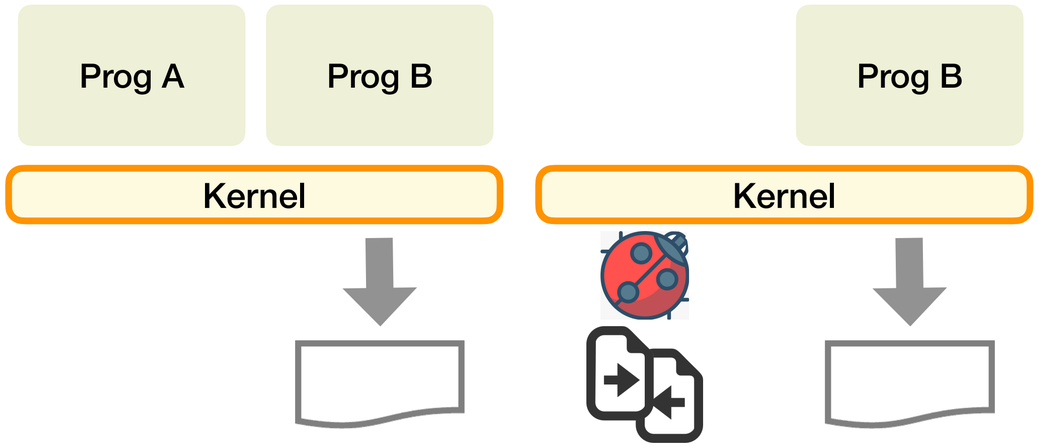


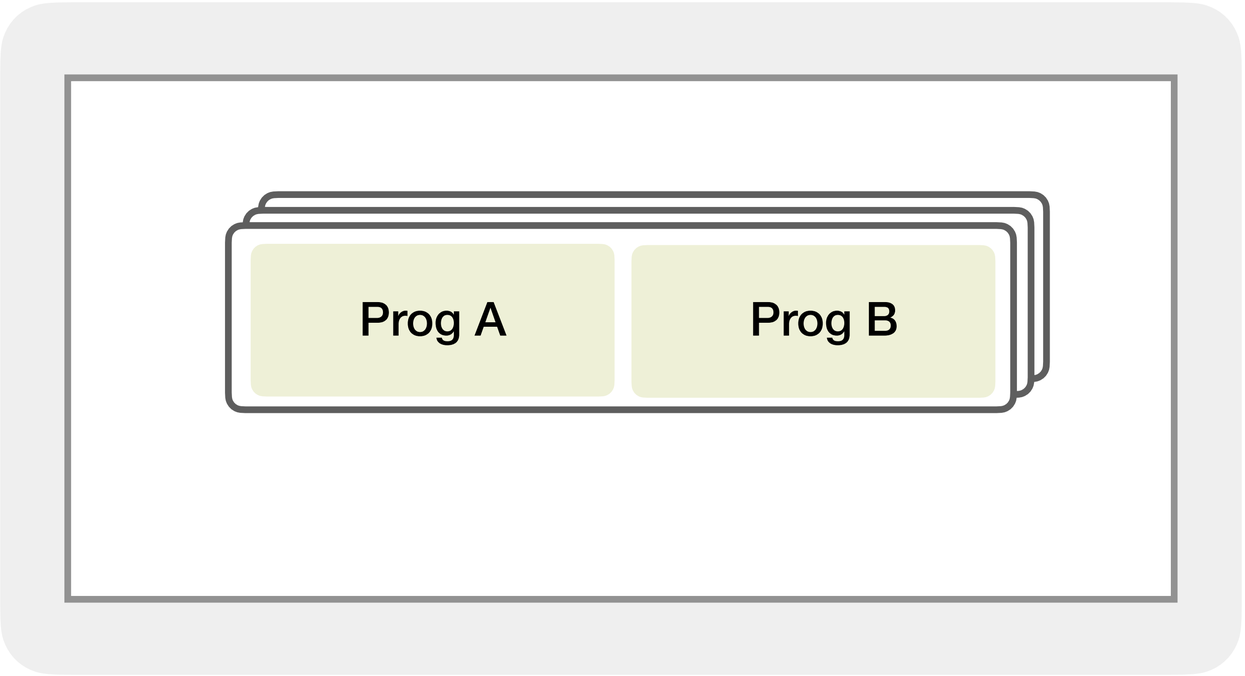


How to detect functional interference bugs?

How to generate effective test cases?

Next: trigger functional interference bugs

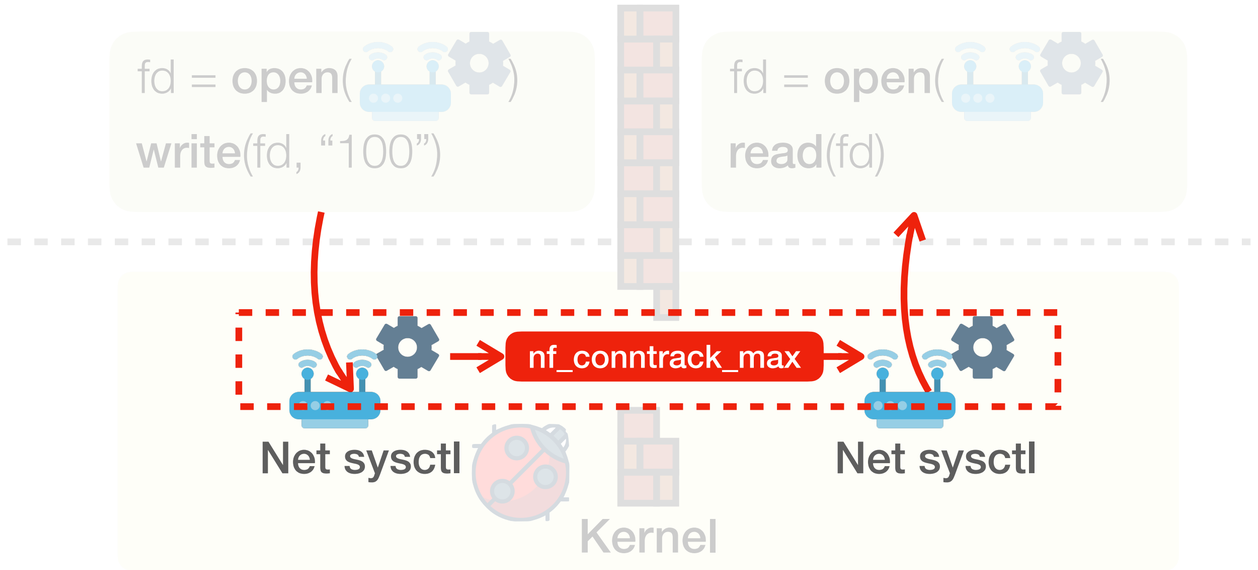




How to detect functional interference bugs?

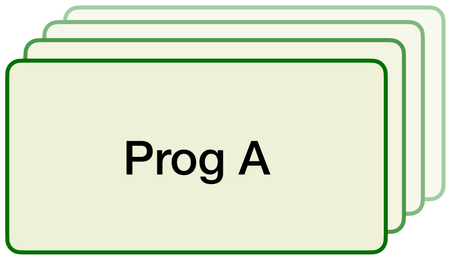
How to generate effective test cases?

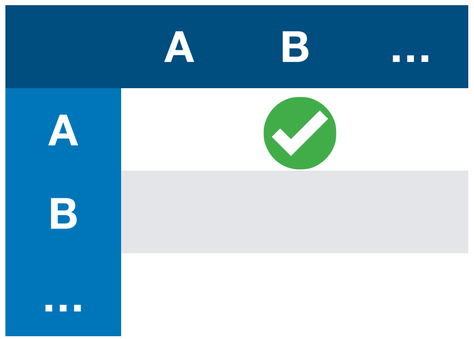
What makes a test case effective?

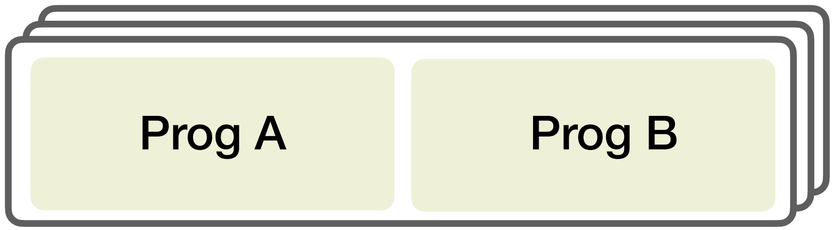


Functional interference bugs require kernel data flows

Generates test cases with inter-container kernel data flows







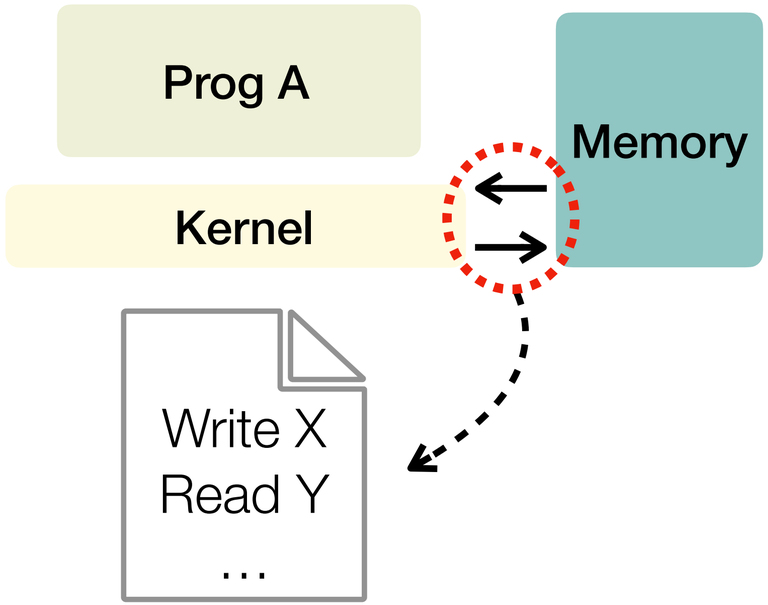
Input:
Programs

Predict inter-container kernel data flows

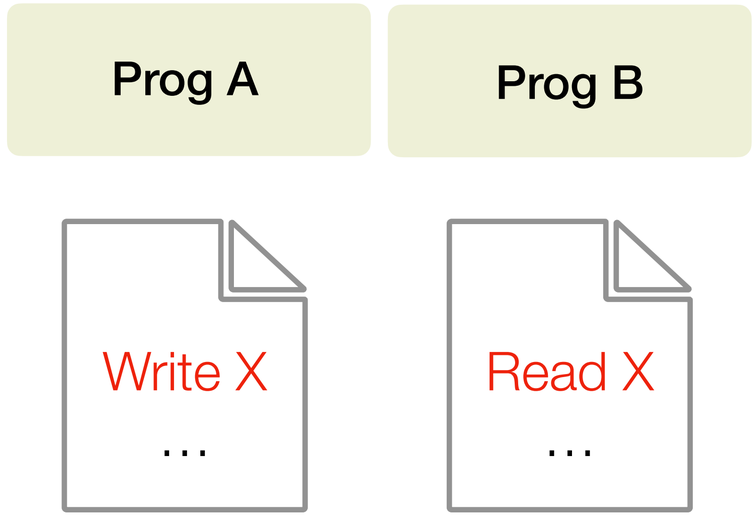
Output:
Program pairs

How?

Predict by analyzing kernel memory traces



1. Profile kernel memory address accessed from each program



2. Predict kernel inter-container data flow if two programs access same memory

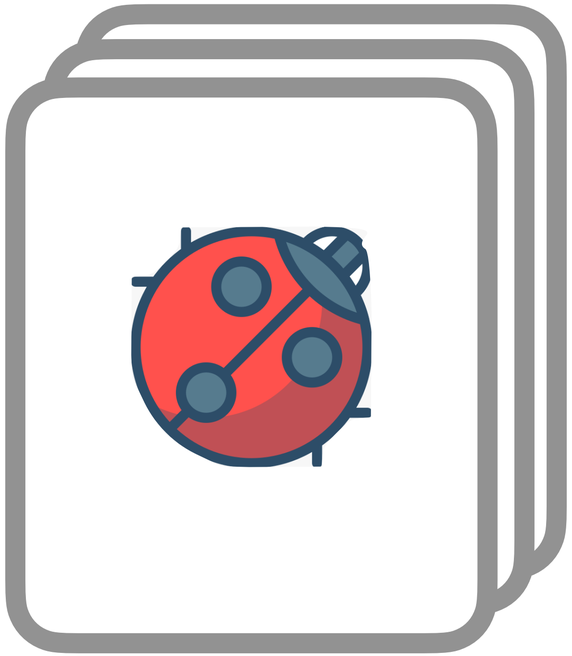
Implementation

KIT is implemented in 8K LOC

We wrote a (partial) namespace specification

Support clustering similar test reports to reduce analysis effort

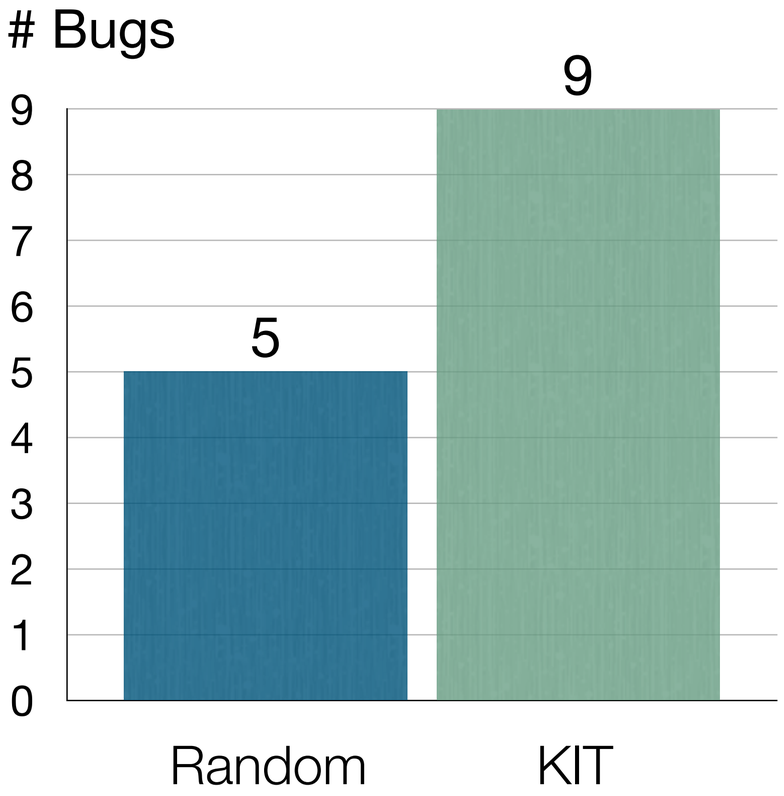
Evaluation: bug detection

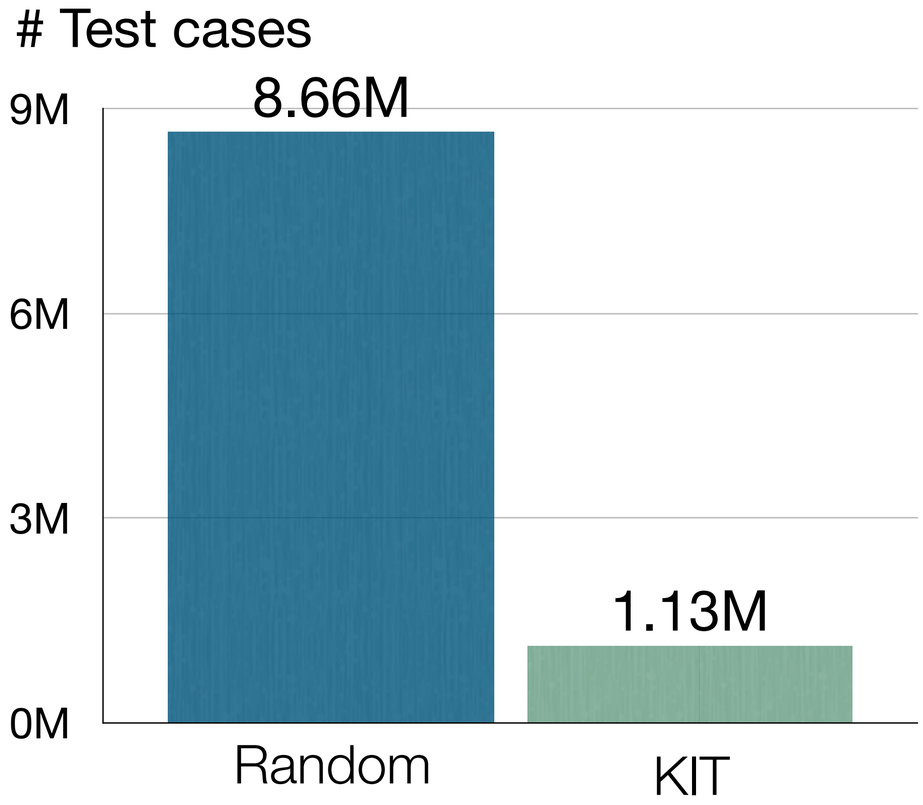


KIT found 9 bugs in Linux kernel 5.13

Disabling network fast path, leaking network statistics, resource contention…

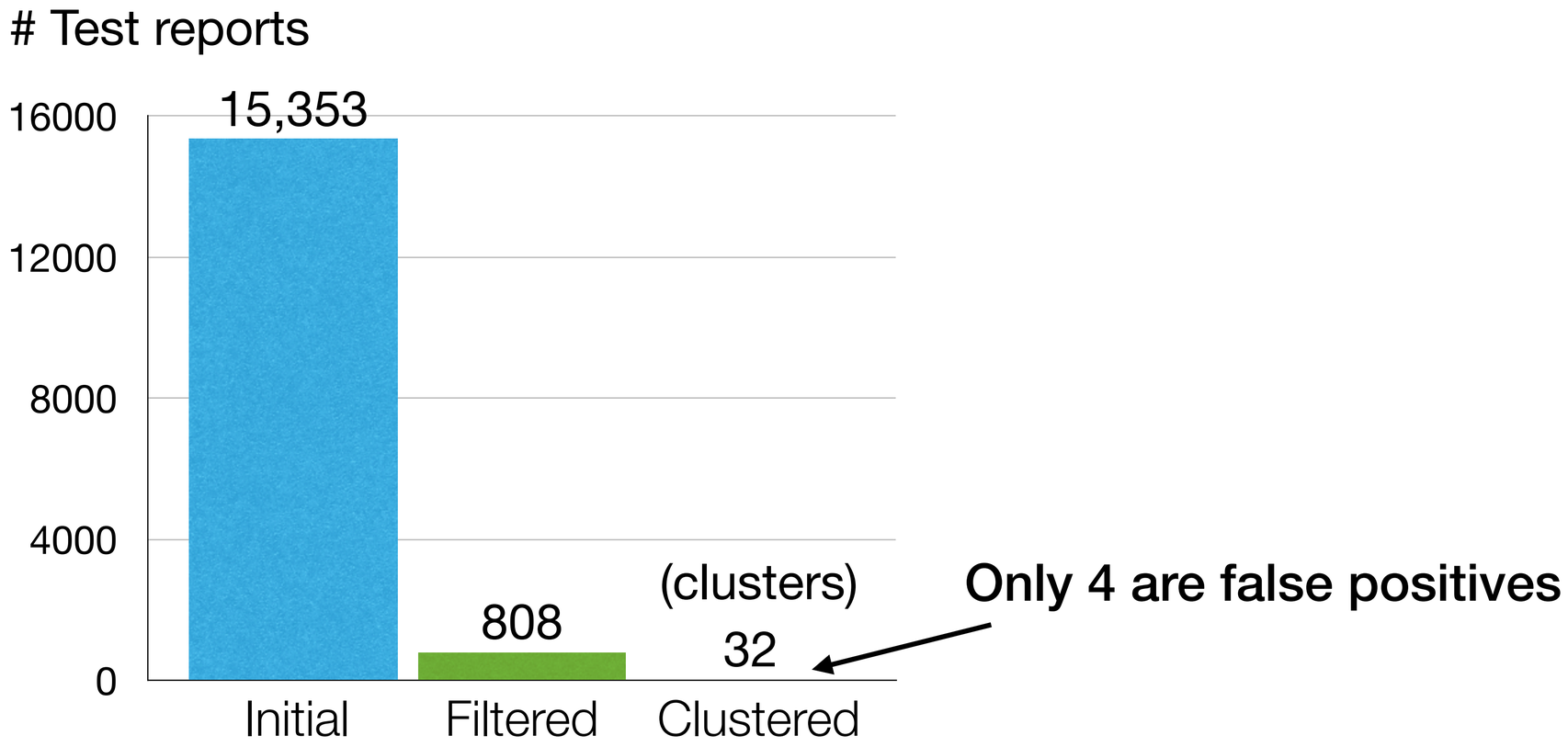
Evaluation: test case generation





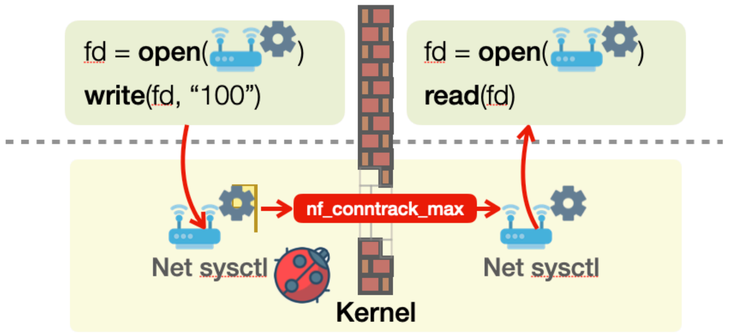
KIT found 2X bugs than random while using 1/8 test cases

Evaluation: result filtering and report clustering effectiveness

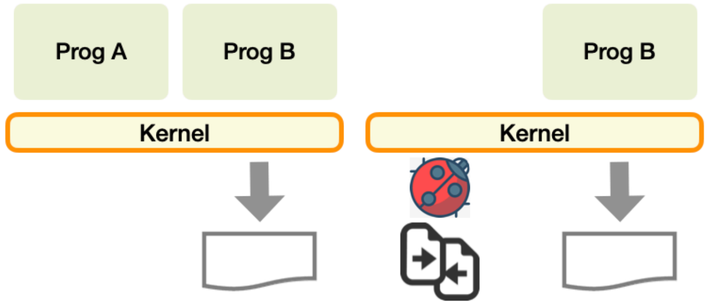


Filtering and clustering significantly reduce analysis effort

Conclusion



OS-level virtualization suffers from functional interference bugs



KIT detects functional interference bugs by analyzing syscall traces

KIT finds new functional interference bugs in Linux namespaces

KIT artifact: https://github.com/rssys/kit-artifact