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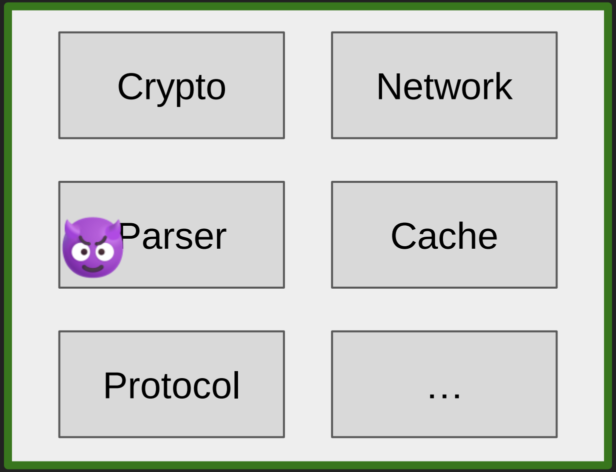
Endokernel: A Thread Safe Monitor for Lightweight Subprocess Isolation

Fangfei Yang, Bumjin Im, Weijie Huang, Kelly Kaoudis, Anjo Vahldiek-Oberwagner, Chia-Che Tsai, Nathan Dautenhahn

Process provide isolation but when exploited enable access to the entire runtime

- Compartmentalize the application to improve security
- Fast, fine-grained and high-performance isolation with hardware assistance
- Monitors are used to manage the user space isolation by previous work



NGINX

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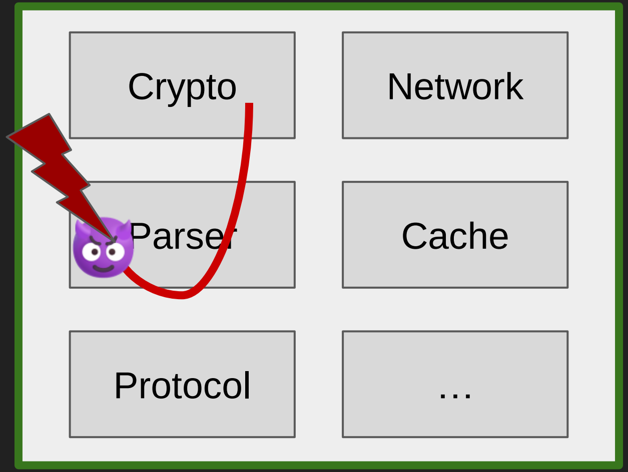

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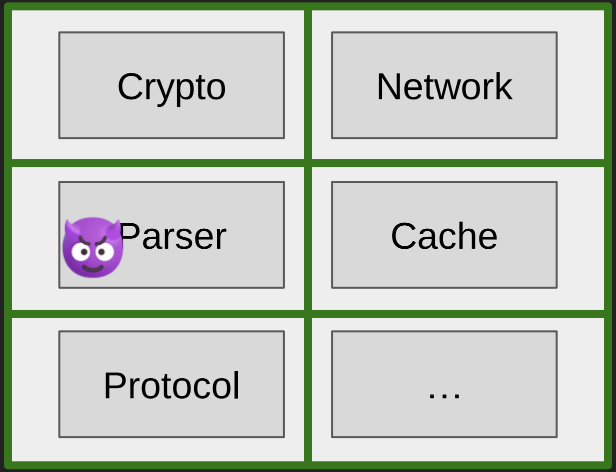


Crypto

Network

Parser

Cache

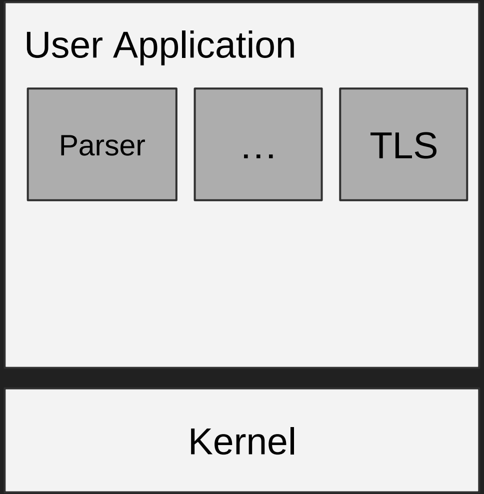
Protocol

…

NGINX

Privilege Separation with In-process Secure Monitor

- Kernel **unaware** of isolation policy and violate the policy
  - Filtering syscalls to ensure the kernel doesn't break the isolation policy in user space
- Monitor determines whether the system call is legitimate
- BUT, making the right policy decisions in **multithreading** is harder than you think
- **=>** "Secure" Monitor is **NOT** actually secure



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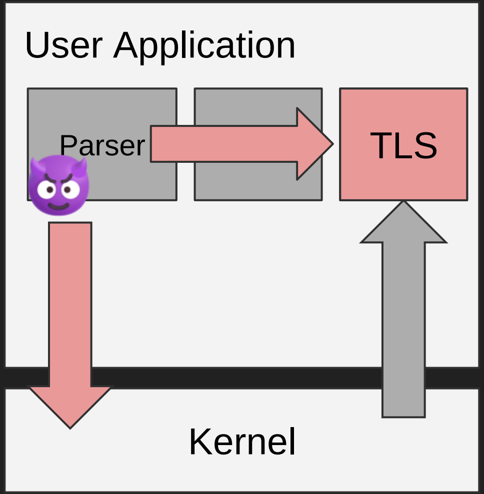

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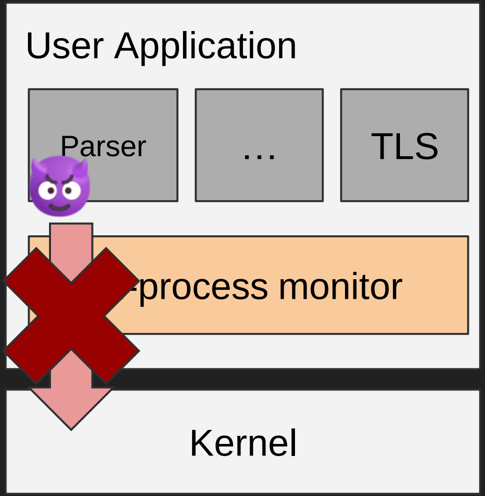
User Application
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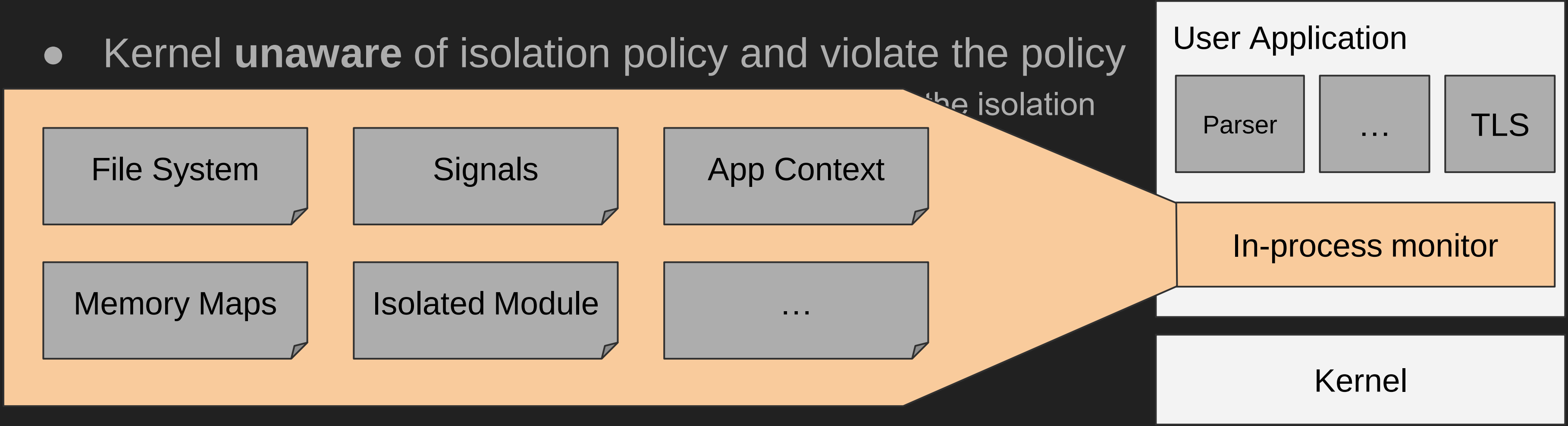
File System
Signals
App Context
Memory Maps
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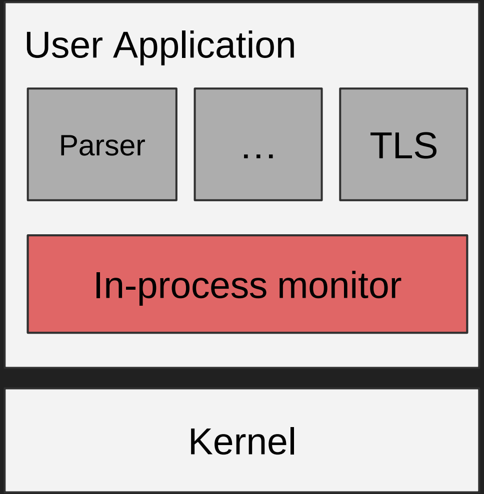

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Existing Works Fails to Secure Multi-threaded Monitor

- Monitor needs **truth** about the system to make right decision
  - Which memory address belongs to whom? Is this file descriptor valid? …
- System states **changed** via syscalls and signals: easy if only **one** thread
- Gap: changes in state and updates in the monitor are **never synchronized**
  - The kernel maintains its internal consistency but not for the in-process monitor
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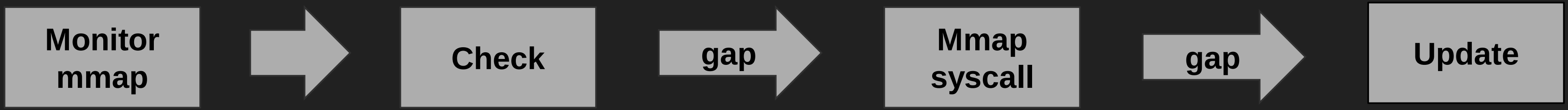

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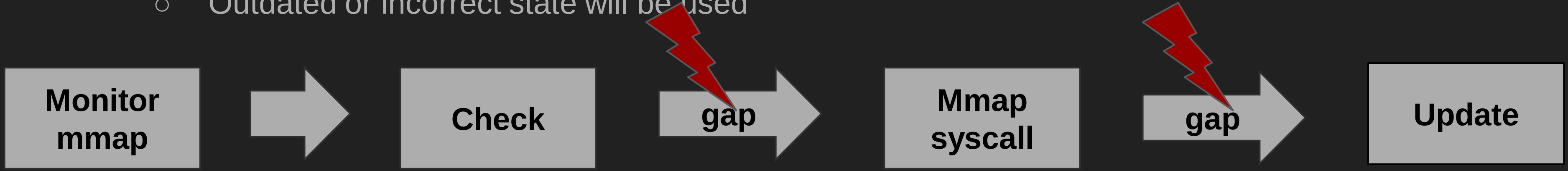

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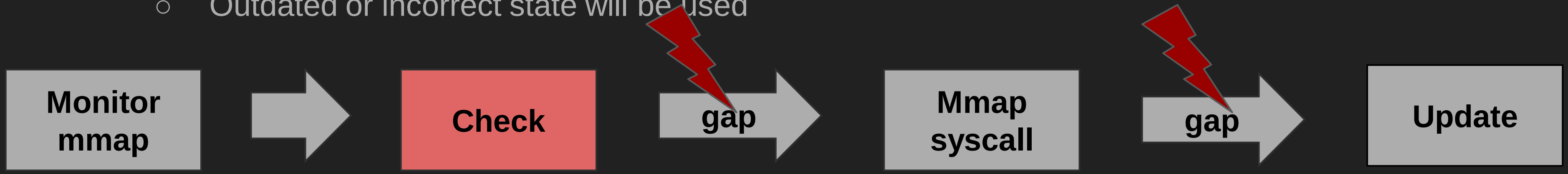

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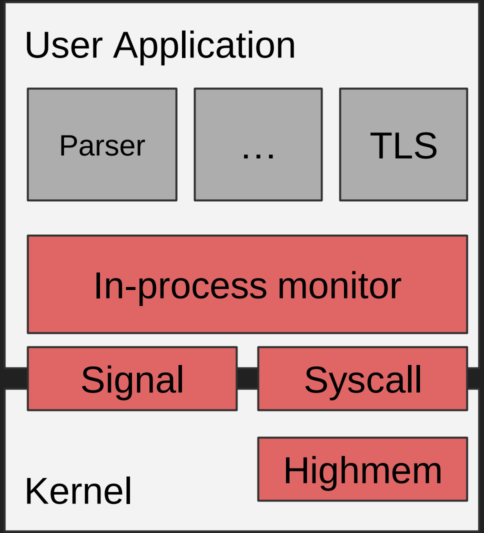
Endokernel Design

Challenge: The kernel does not cooperate with the monitor

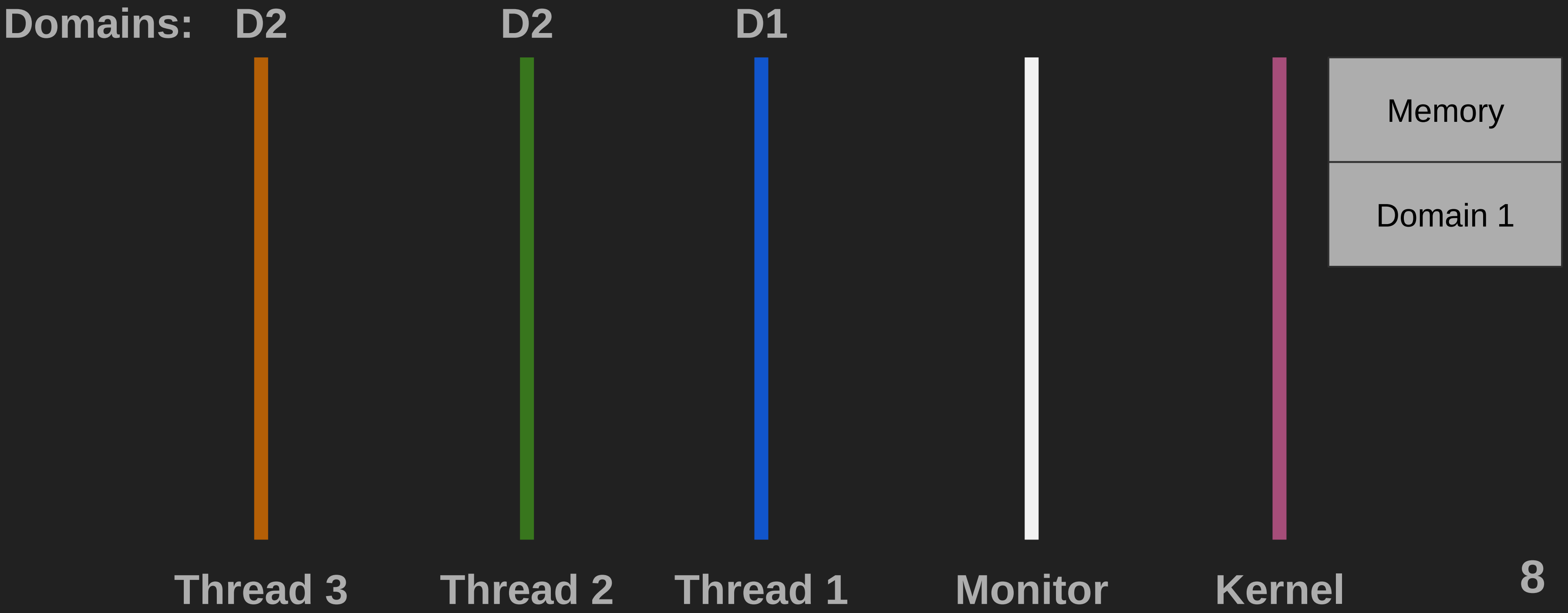
- General Syscalls: memory metadata, file descriptors
  - open/read/write/mmap/mprotect/…
  - States change before/after syscalls
- Signals: Kernel-involved context switches
  - Signal delivery and sigreturn can alter control flow and privilege
- Highmem: access physical memory and bypass checks
  - Hidden, complex, delayed and overlooked
  - Requires case-by-case analysis and solutions



Endokernel – Build a thread-safe monitor!

General Syscalls: Monitor/Kernel Synchronization

- Assume D1 owns a secret memory region, and D2 wants to steal it



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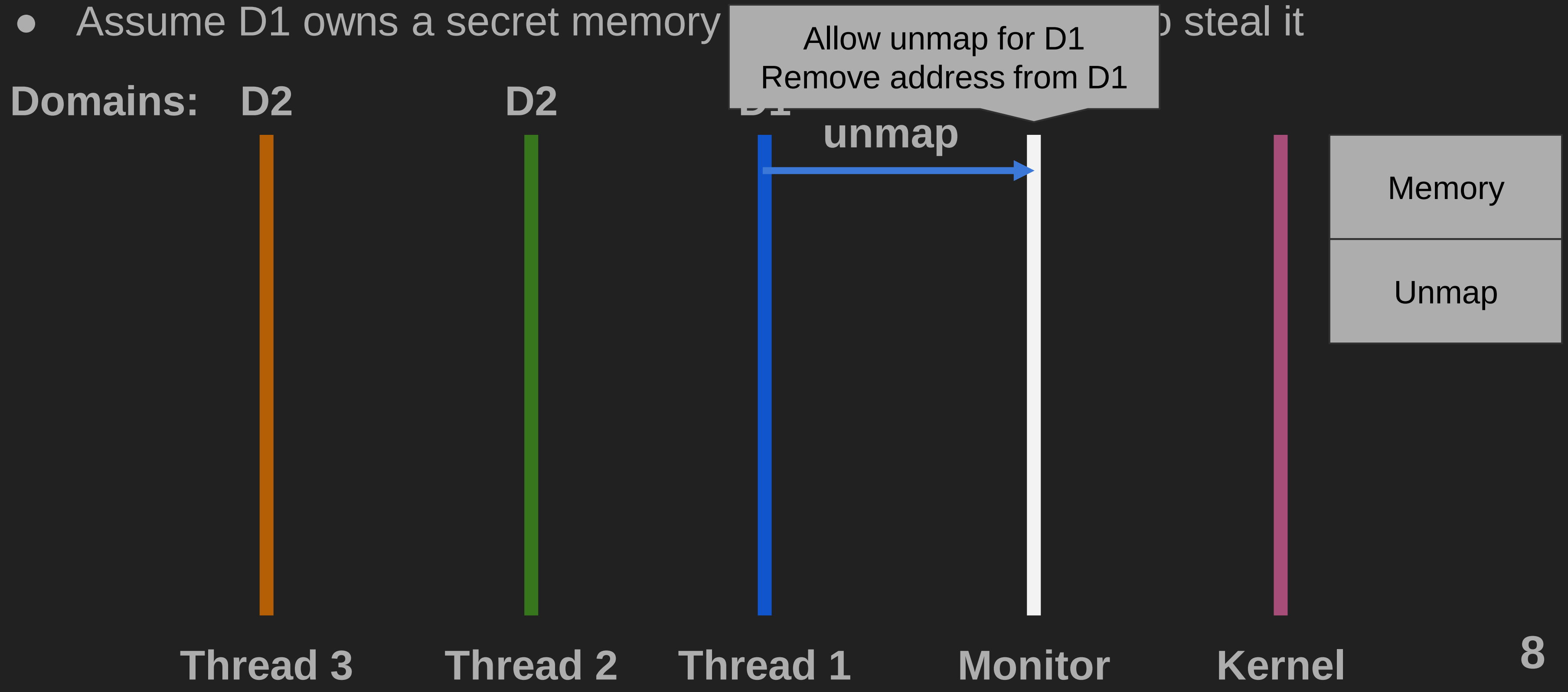

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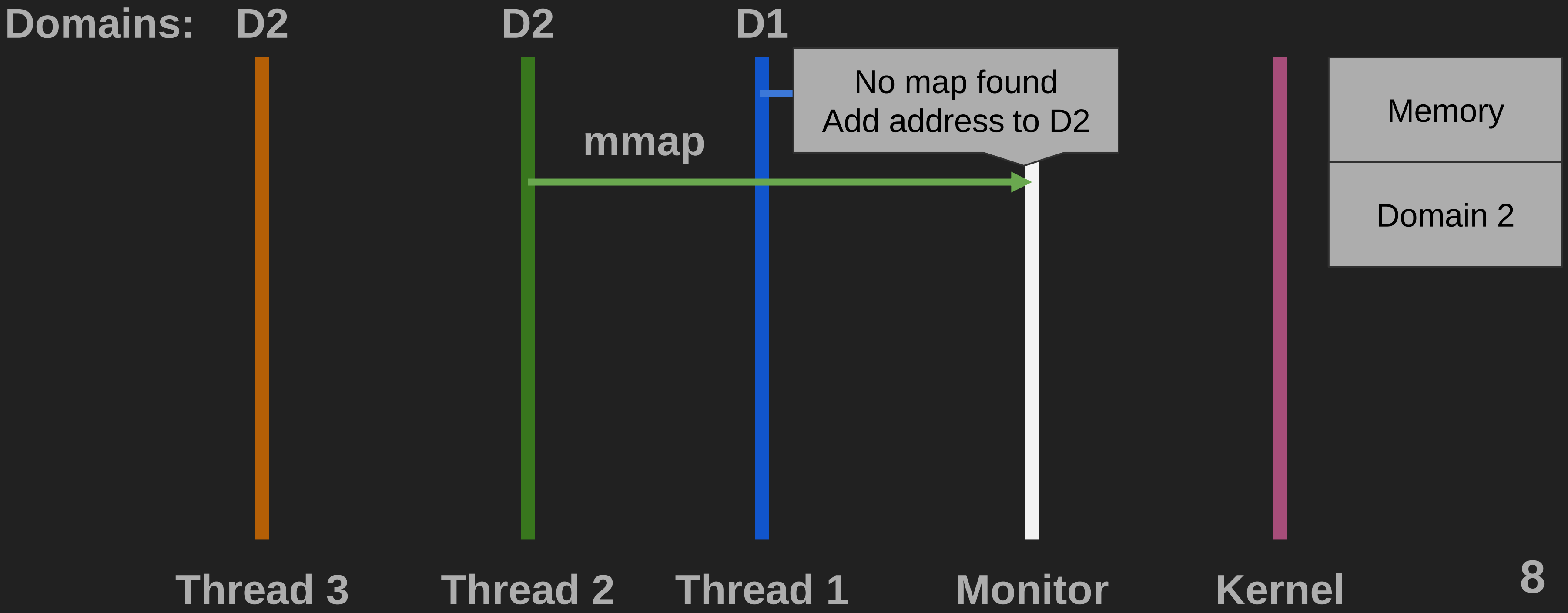

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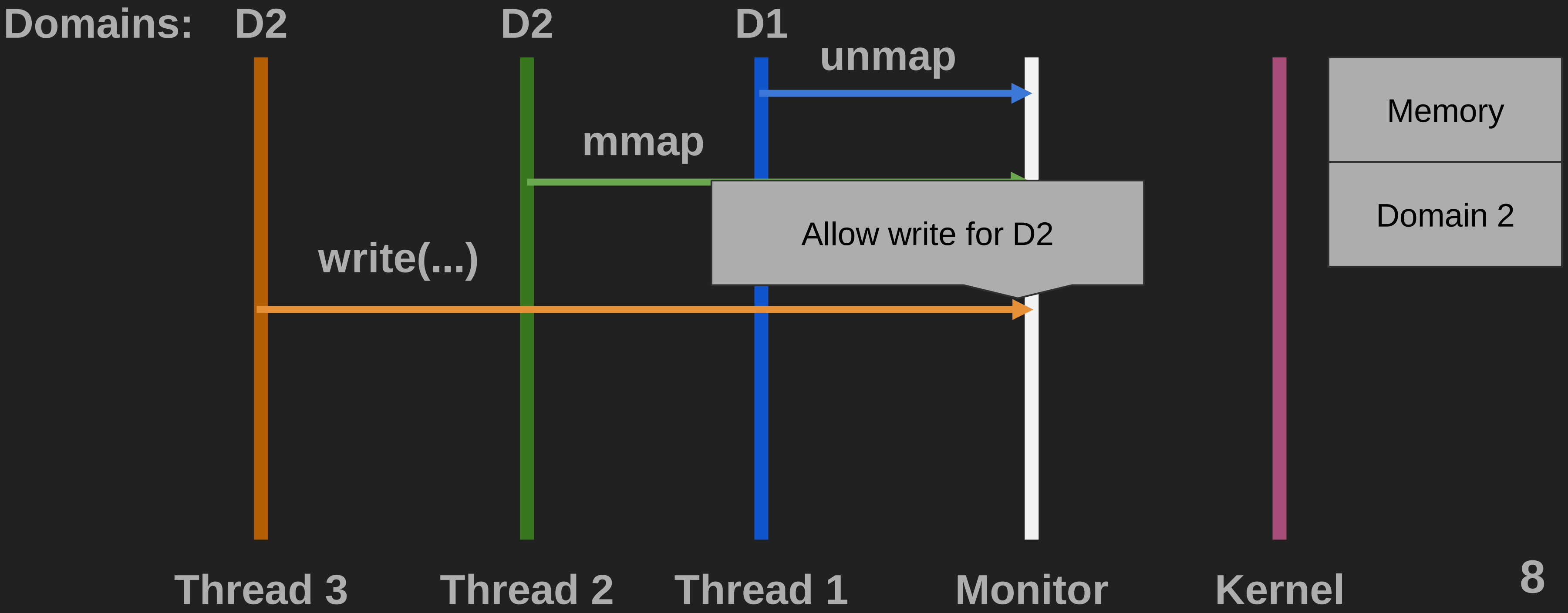

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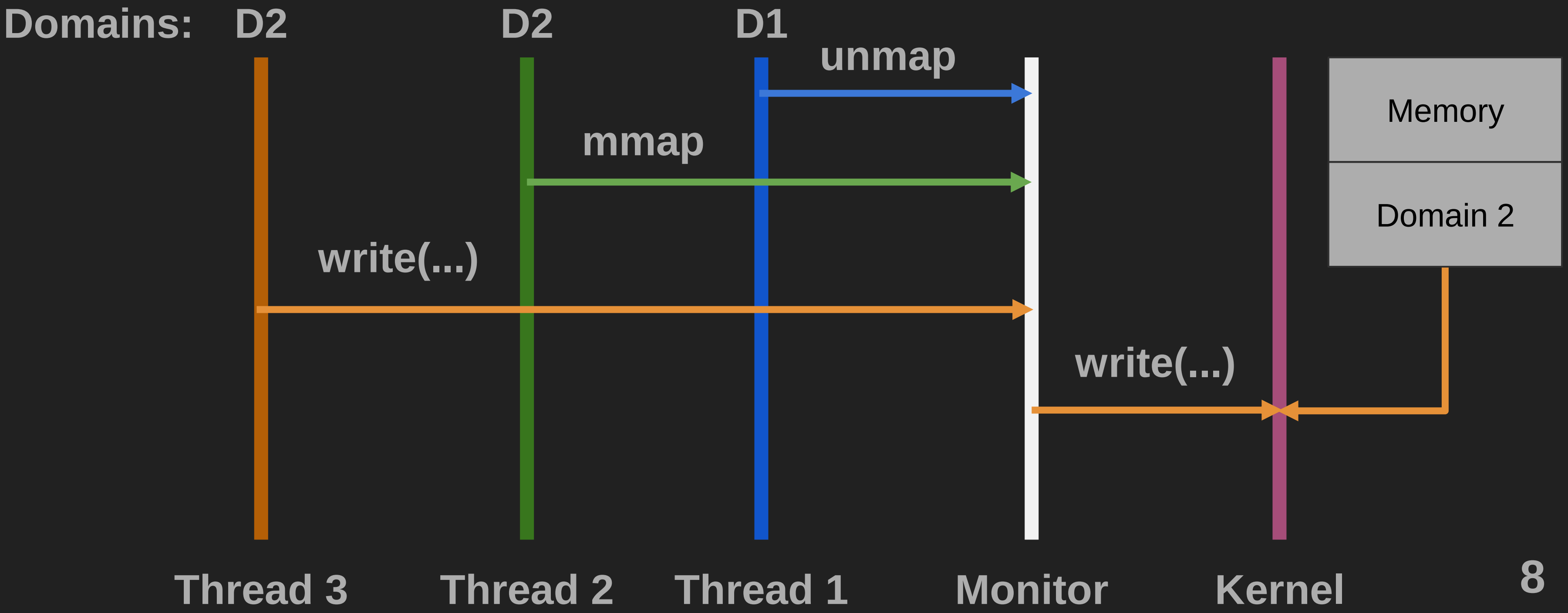

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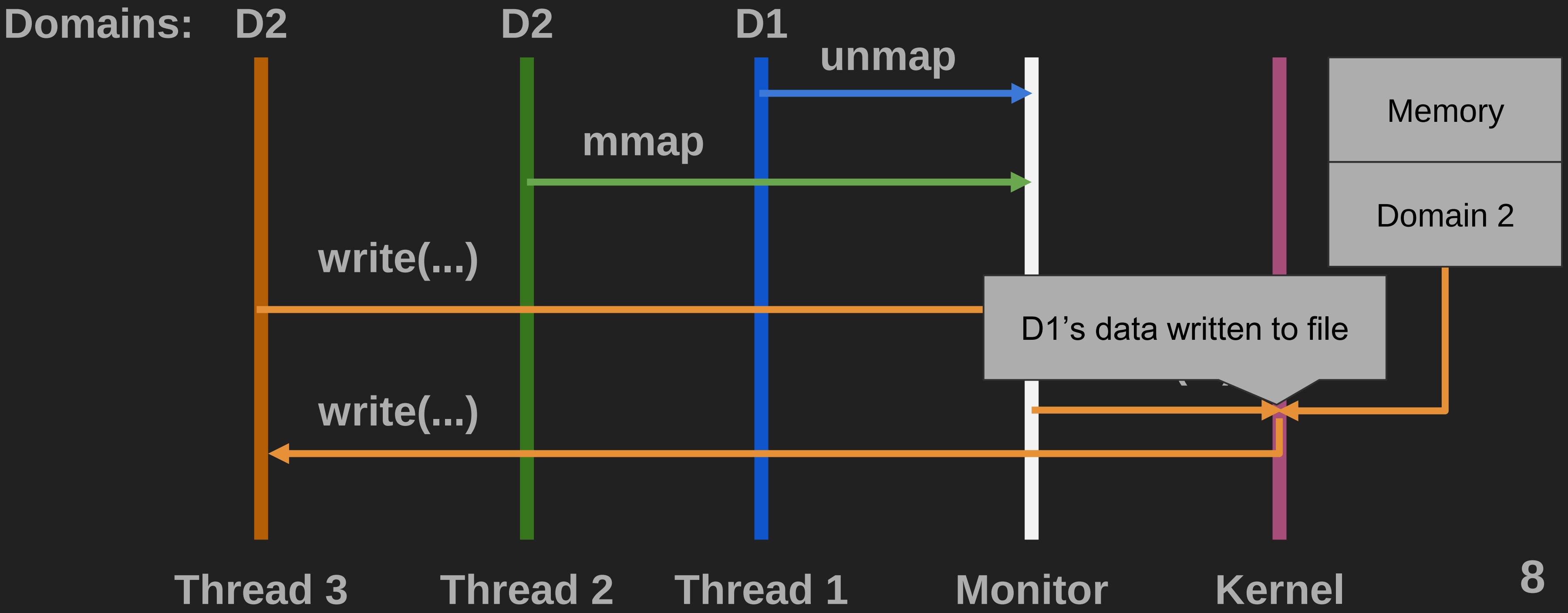

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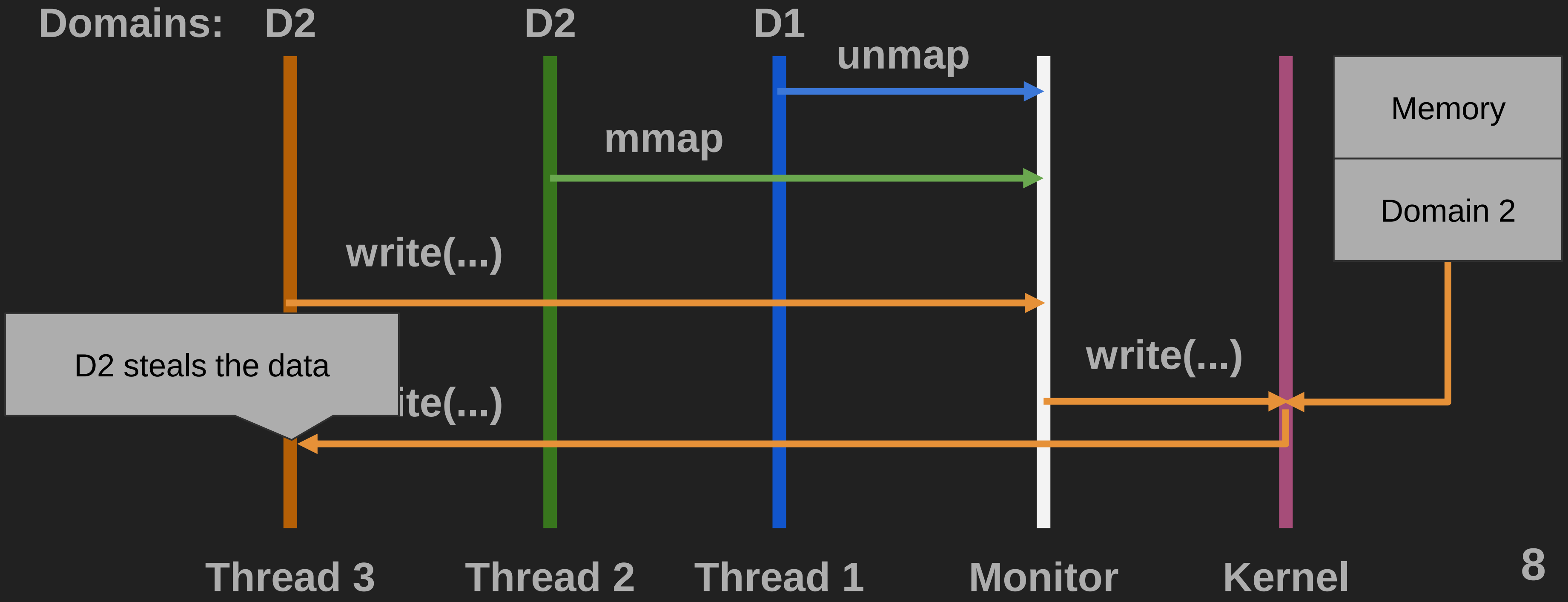


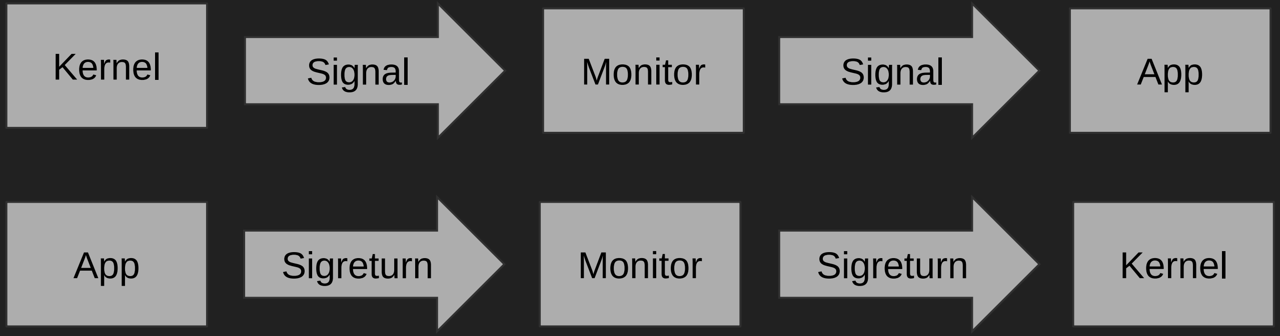
Solution: Weak Metadata Synchronization

- Tolerate inconsistencies before and after system calls; ensure they **only lead to inspection failures**
- Mark pages involved in system calls; block other calls that would change their properties while the memory is in use
- Allow concurrent invocation of system calls if they don't alter page properties
- Ensure **correct decisions** are made, even with Kernel-Endokernel inconsistencies, without violating policy.

Desynchronization **never** violates security policies

Signal: Intermediate States Exposed by Sigreturn

- Signal delivery and return are meant to switch contexts
- Different contexts have different permissions defined by the policy
- Unfortunately, the kernel cannot correctly handle these permissions, and can break the policy during context switches


Kernel
Signal
Monitor
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App

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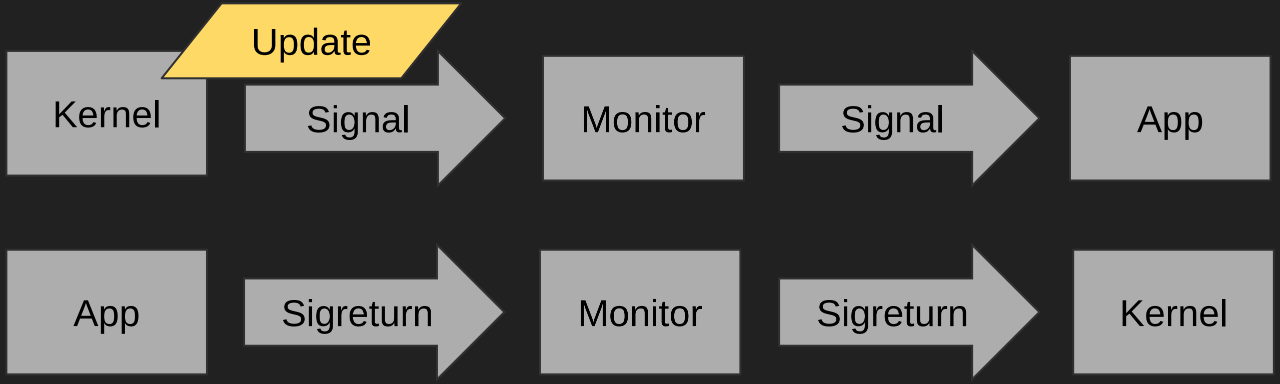

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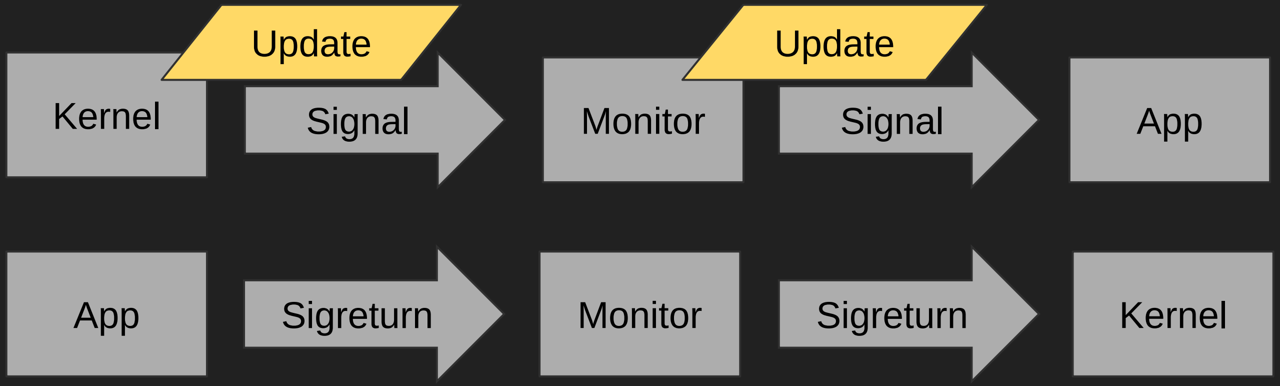

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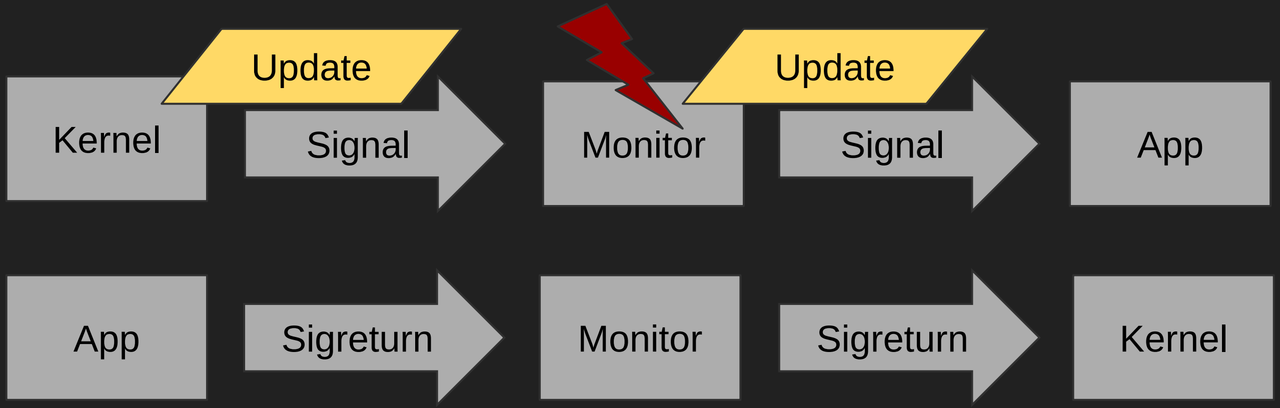

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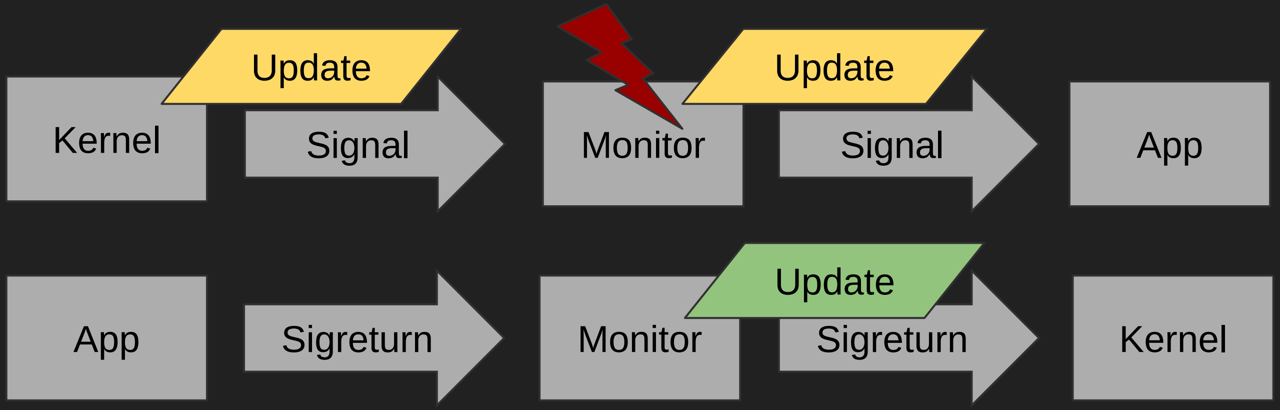

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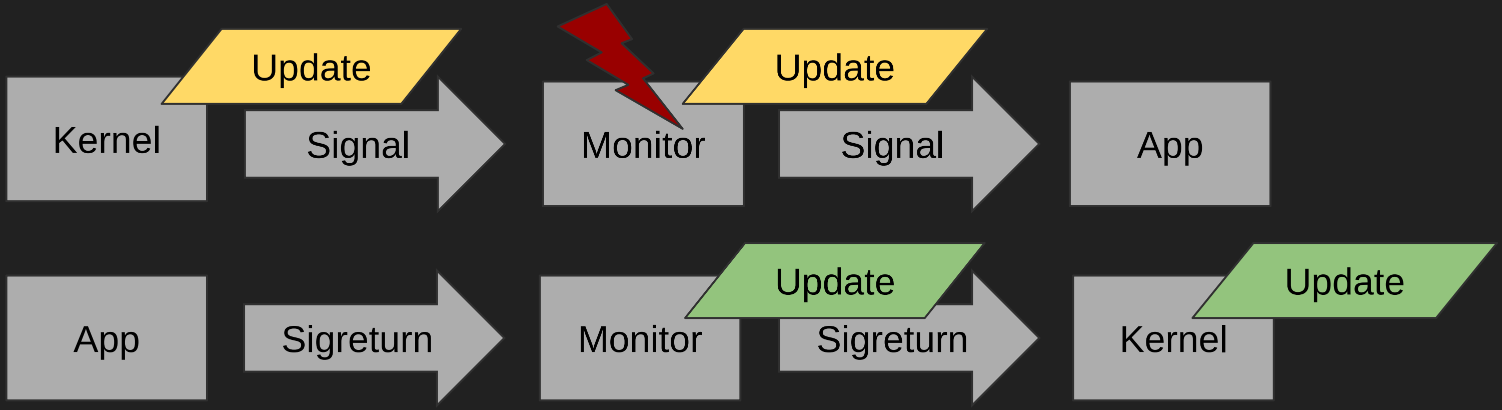

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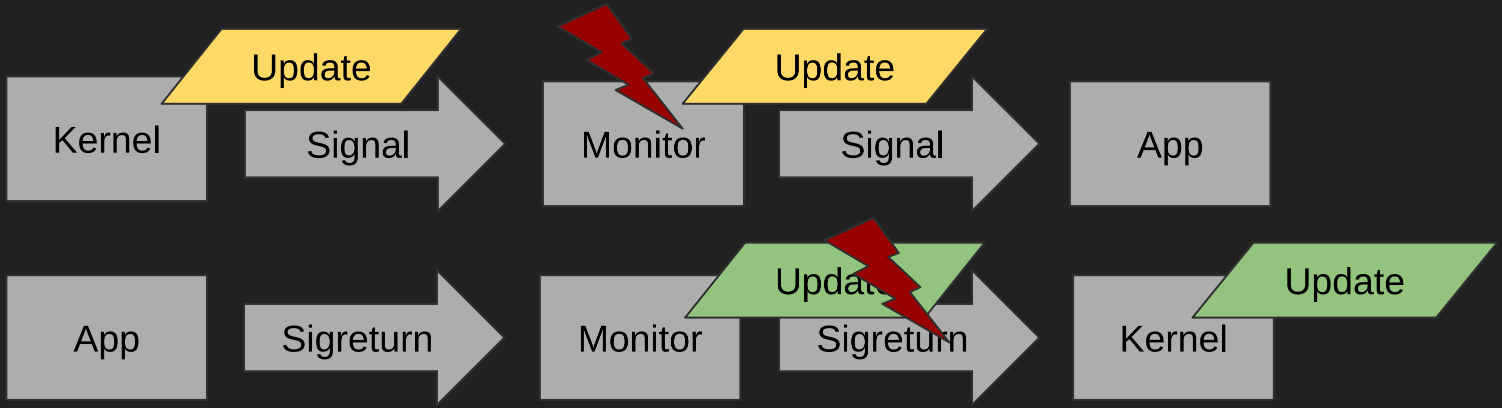

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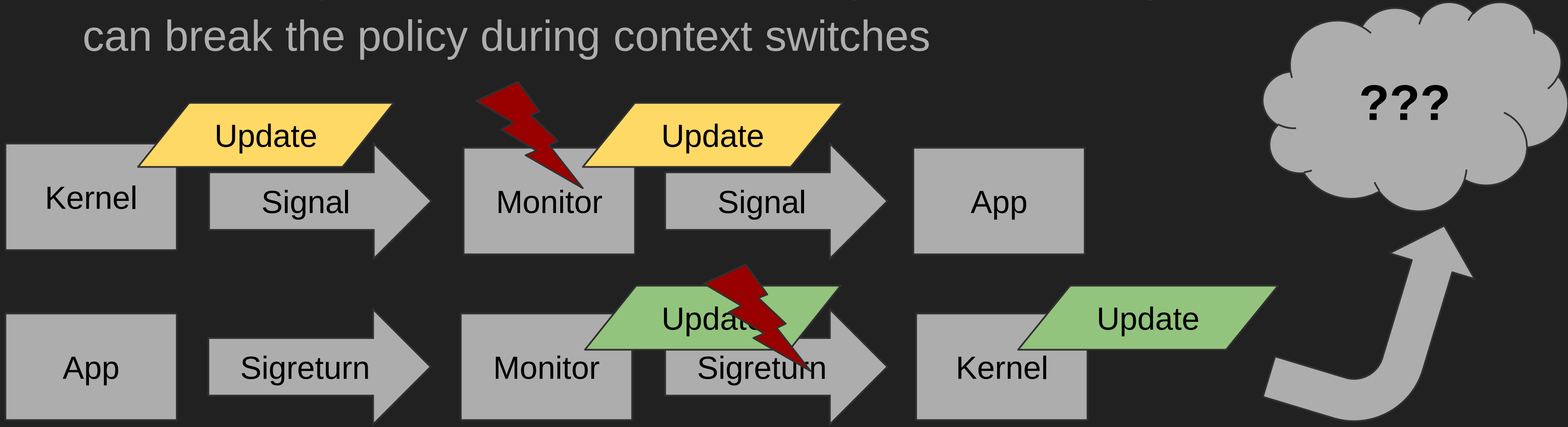
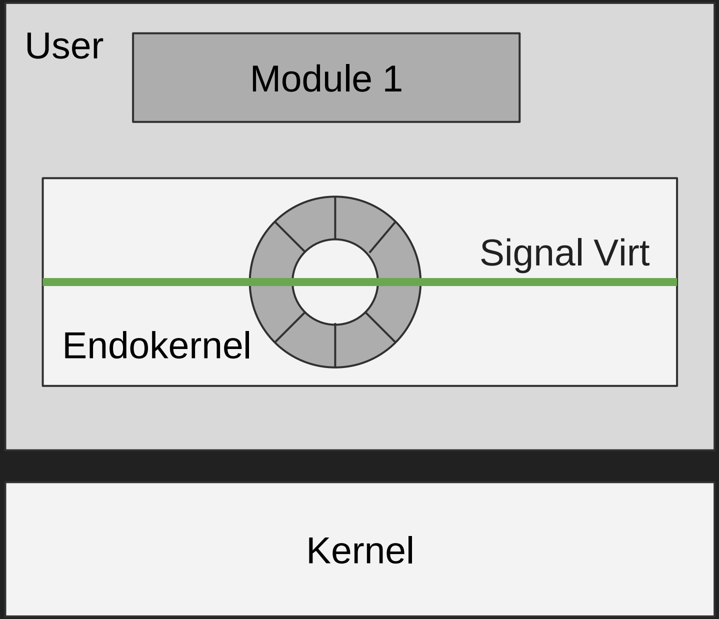


Solution: Fully Virtualized Signal

- Endokernel acts as a **middleware**
- Endokernel receives signals from the kernel
  - Stores signals in a pending queue
  - Returns control to the kernel with sigreturn
- Endokernel delivers signals to the user
  - Creates a new sigcontext and sigframe.
  - Simulates the user's sigreturn syscall



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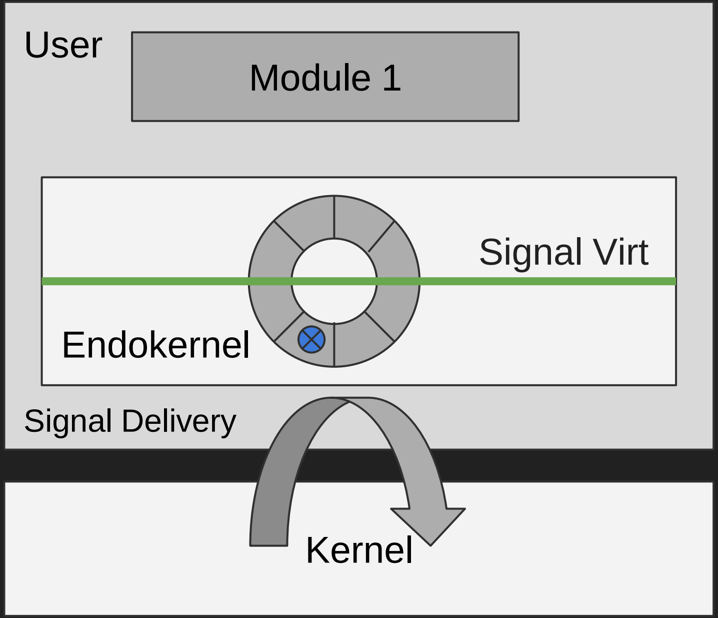

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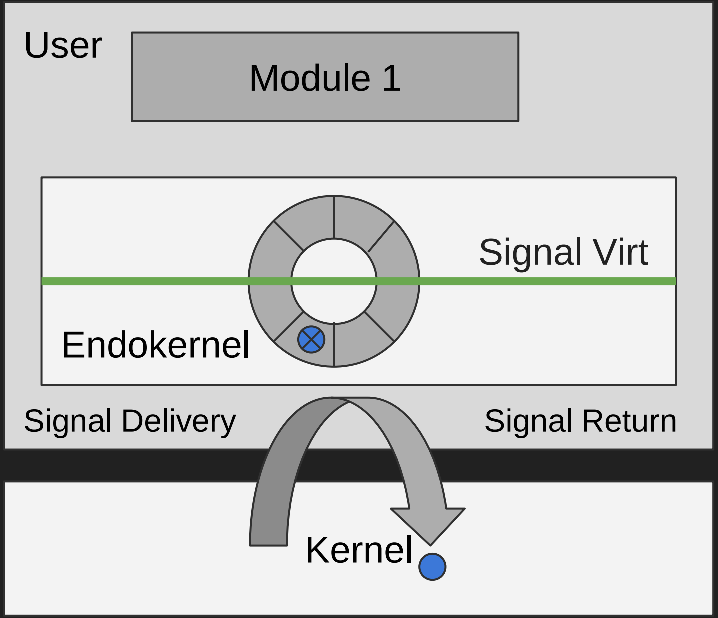

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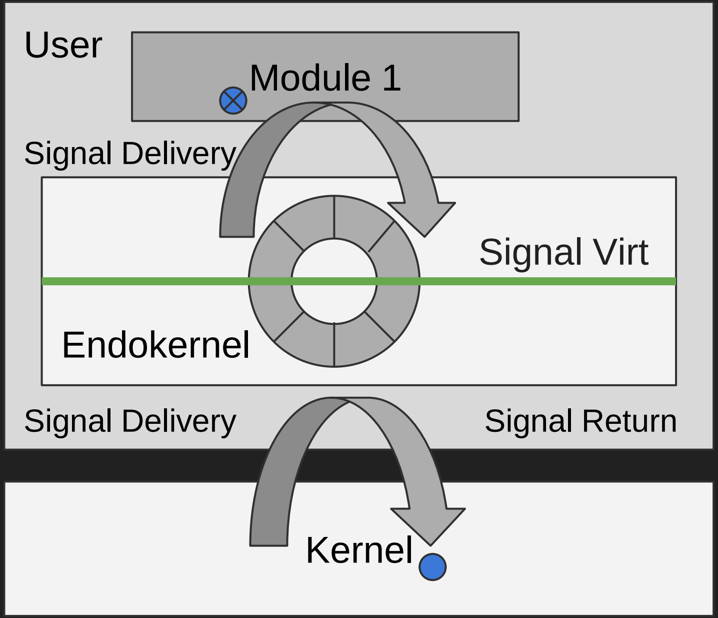

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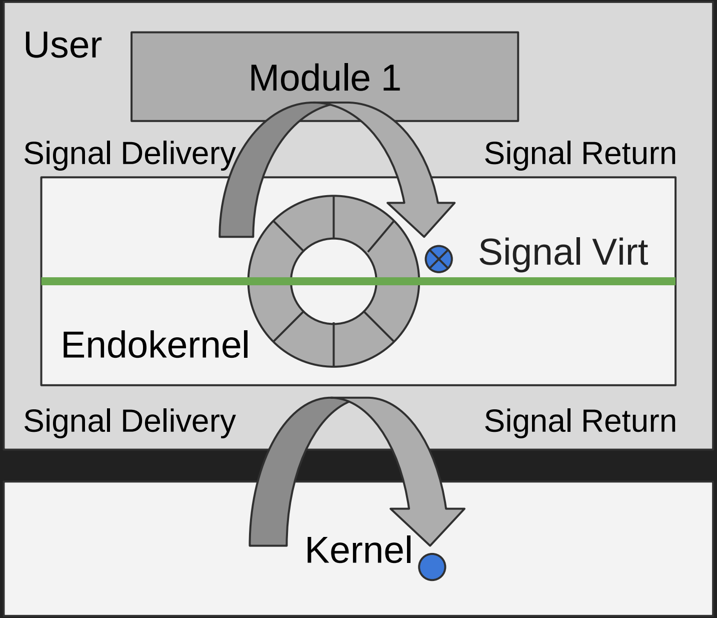

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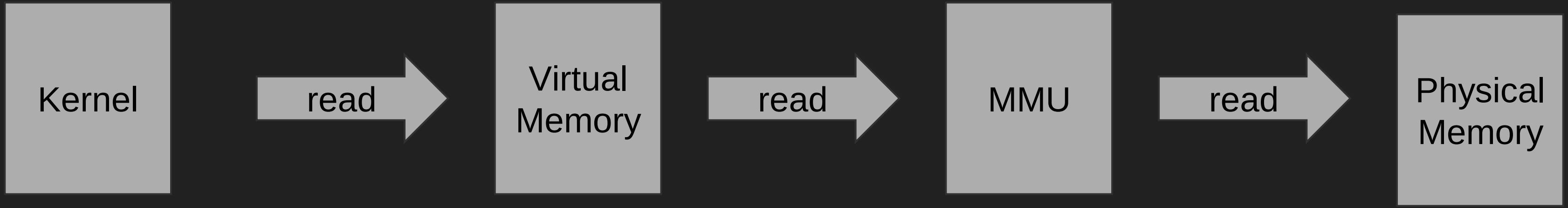
Highmem: Bypass Pattern and Delayed Memory Access

- Various triggering mechanisms
  - /sys/kernel/tracing/user_events_data
  - Process_vm_readv, Sendmsg with MSG_ZEROCOPY
- Access physical pages with high memory and bypass permission check
  - Some code paths checked
    - __get_user_pages -> check_vma_flags -> arch_vma_access_permitted
  - Nonetheless, sendmsg delayed the memory access
  - The MMU may change after the check



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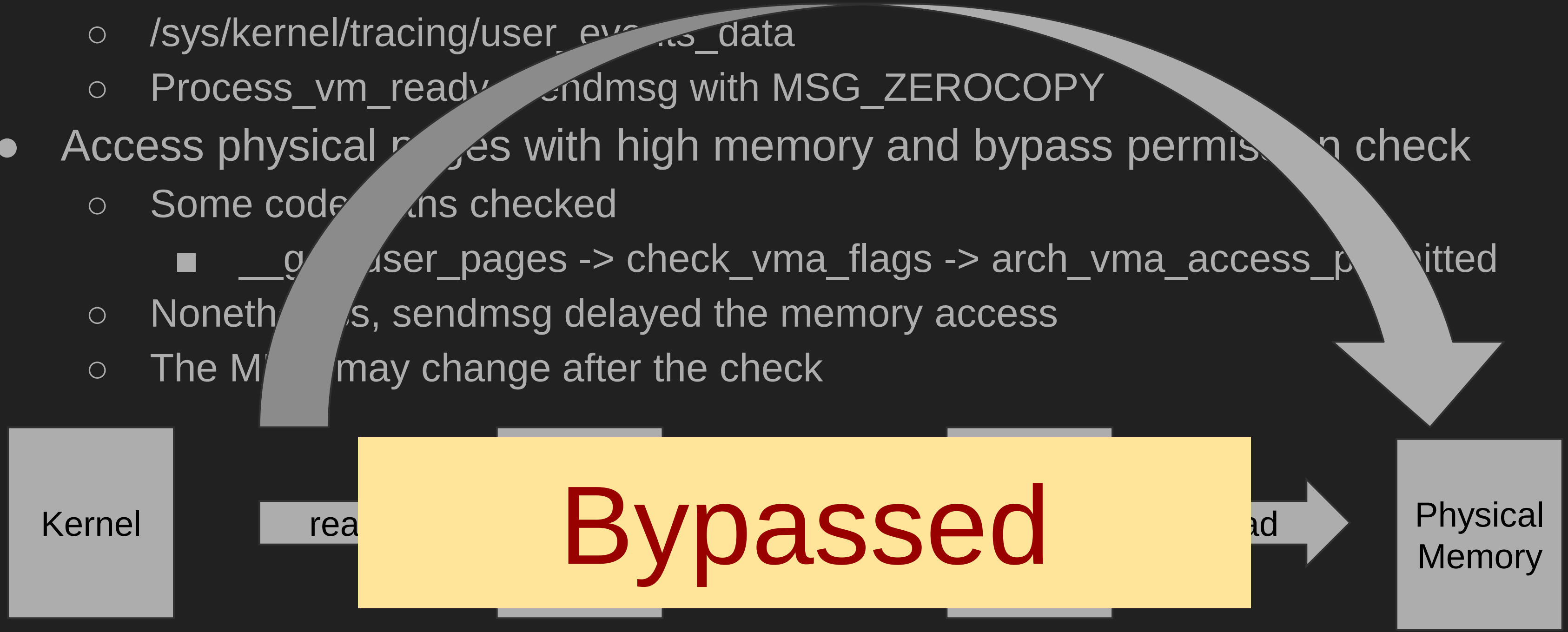

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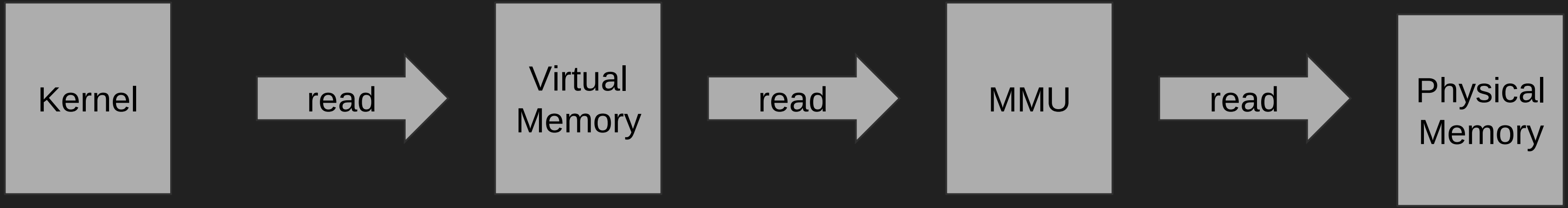


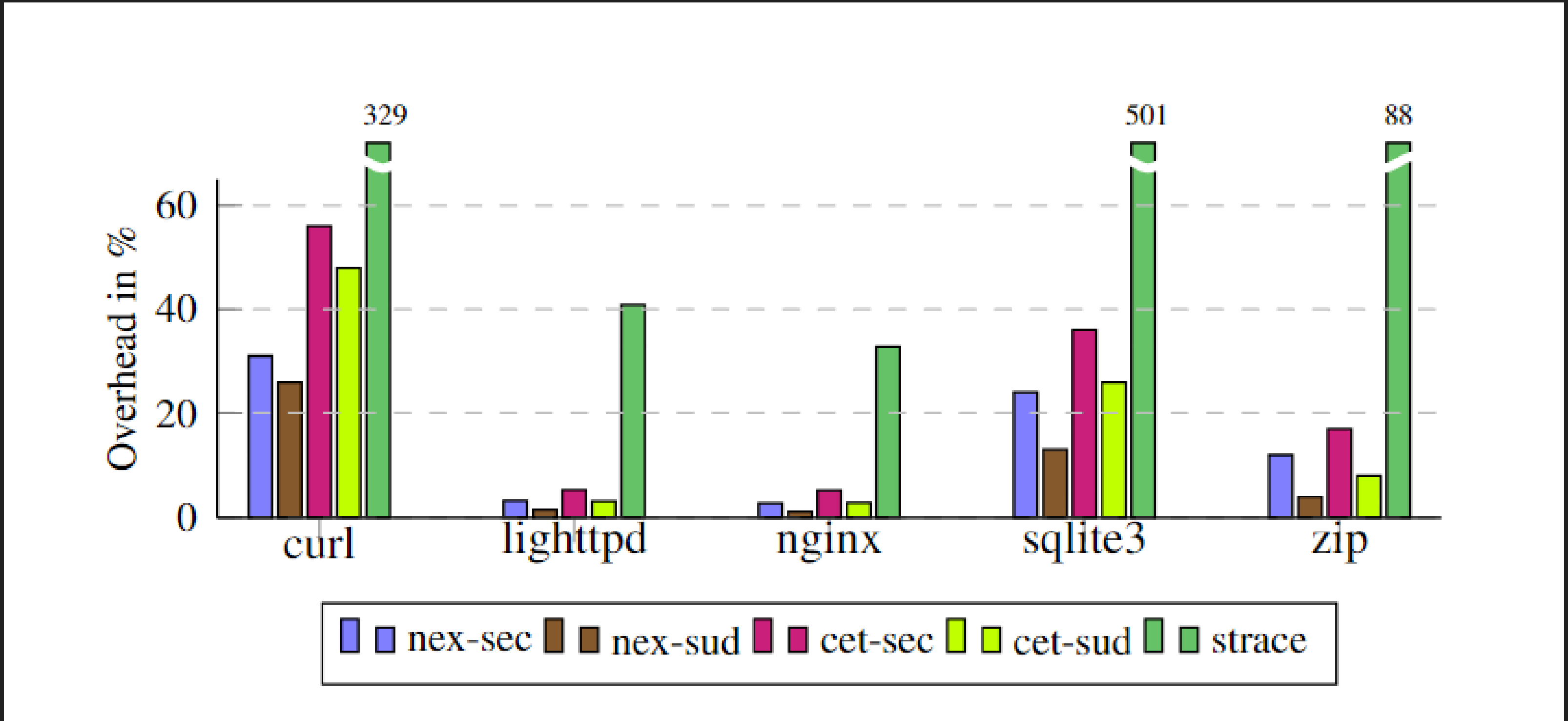
Solution: Extra Policy with Syscalls Analysis

- Traced the syscalls in the kernel that use certain APIs most of which are related to driver and ioctl
- Restrictions need to be applied based on specific use cases
  - For example, adding extra policies to prohibit the use of zero copy or prevent the memory from being unmapped
- Kernel features that improve efficiency can make in-process monitoring more challenging

Identified **patterns**, allowing for case-by-case analysis

Evaluation

Virtualization Cost with Different Callgate Mechanism



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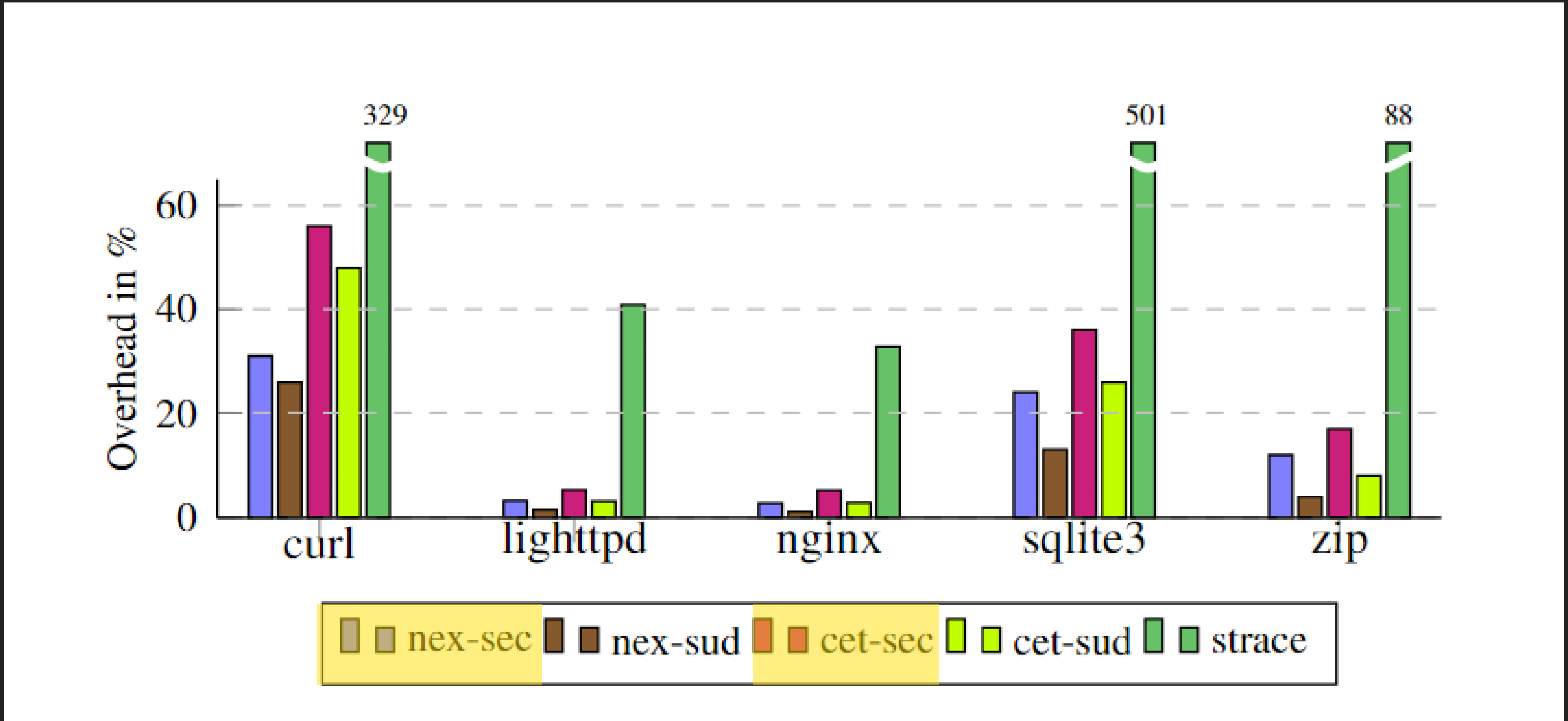

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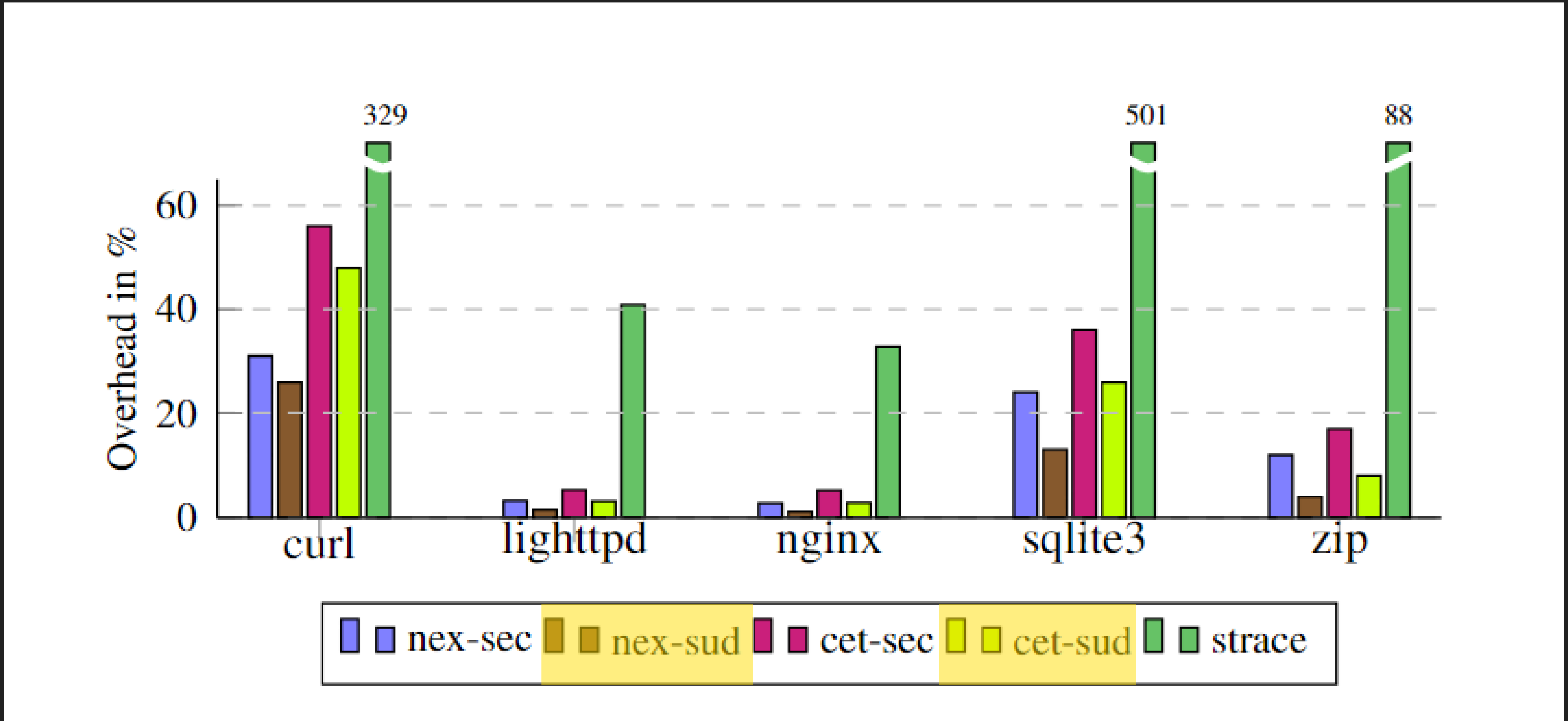

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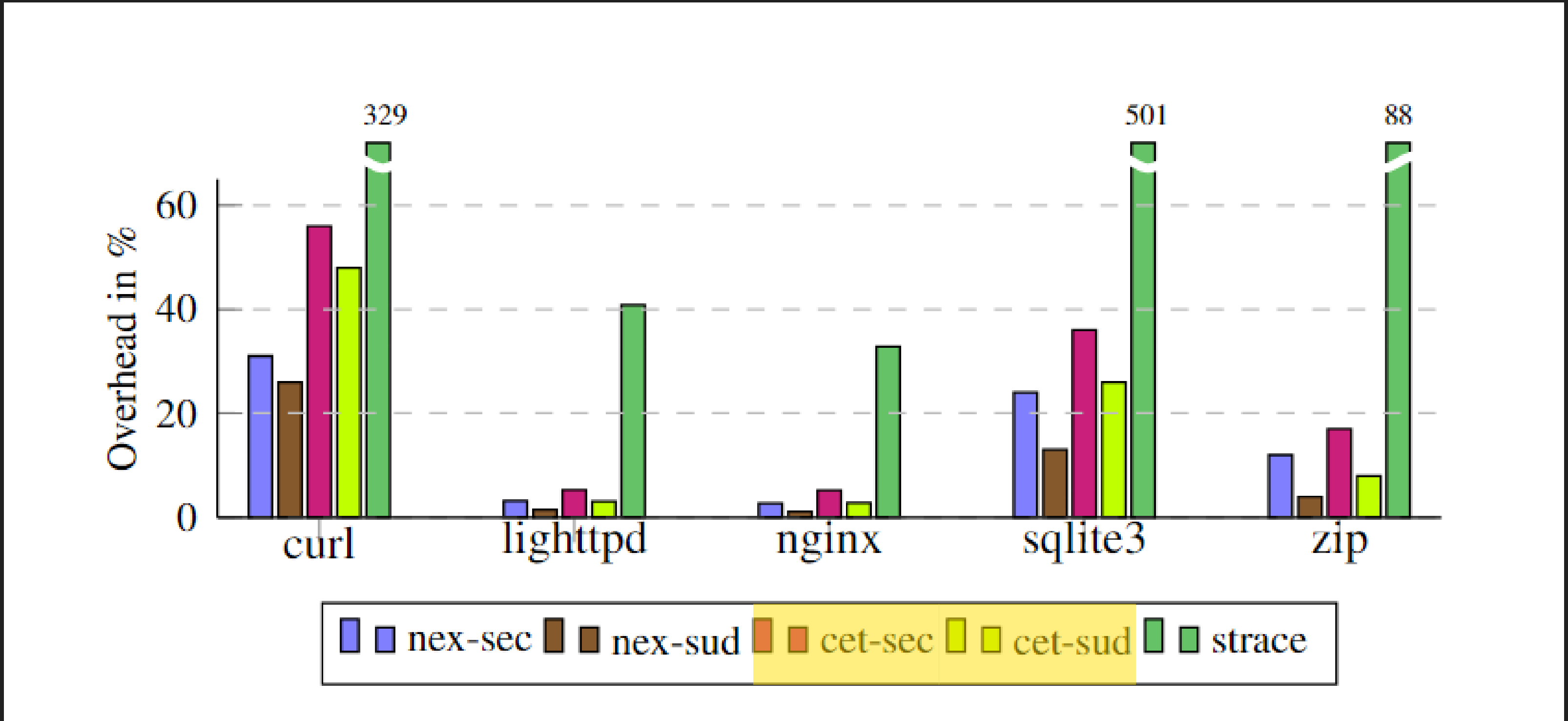

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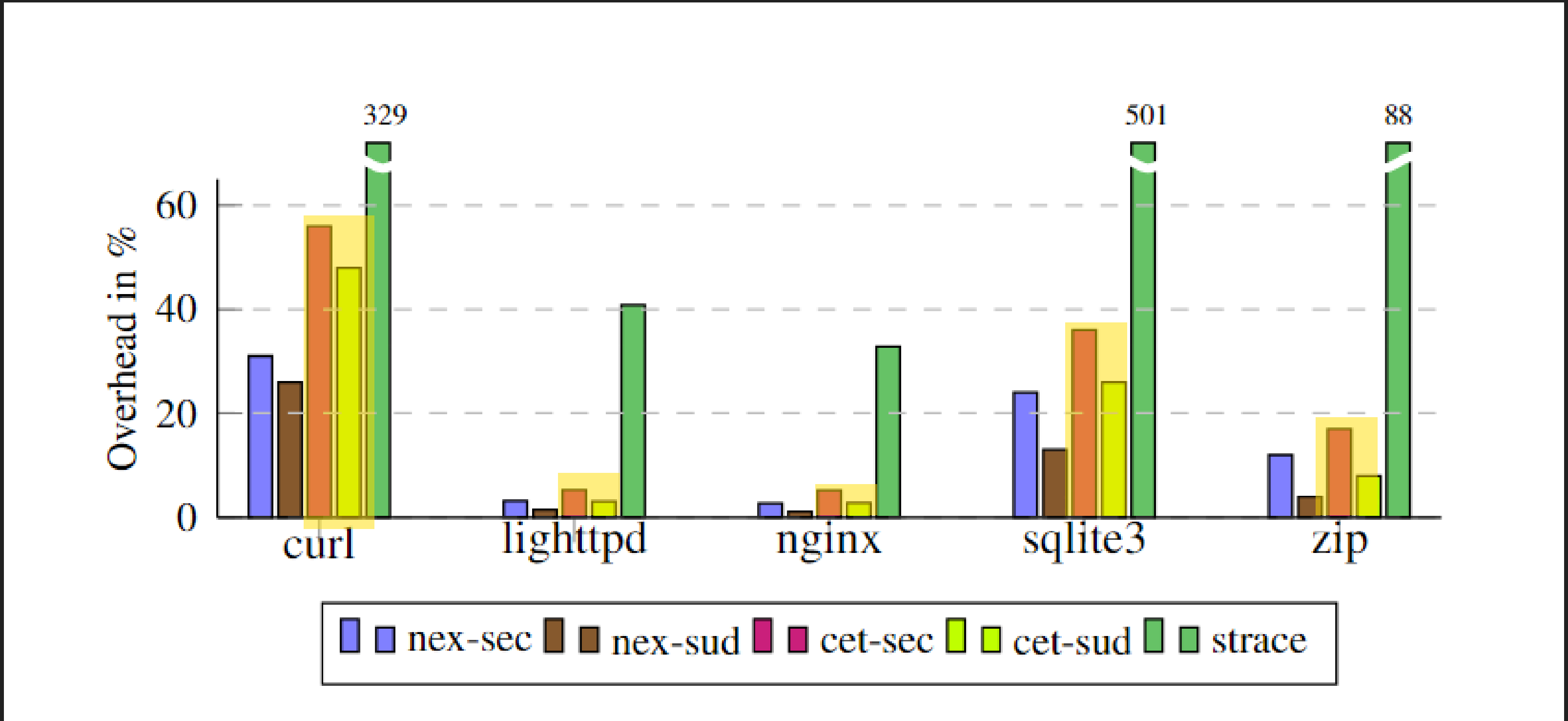

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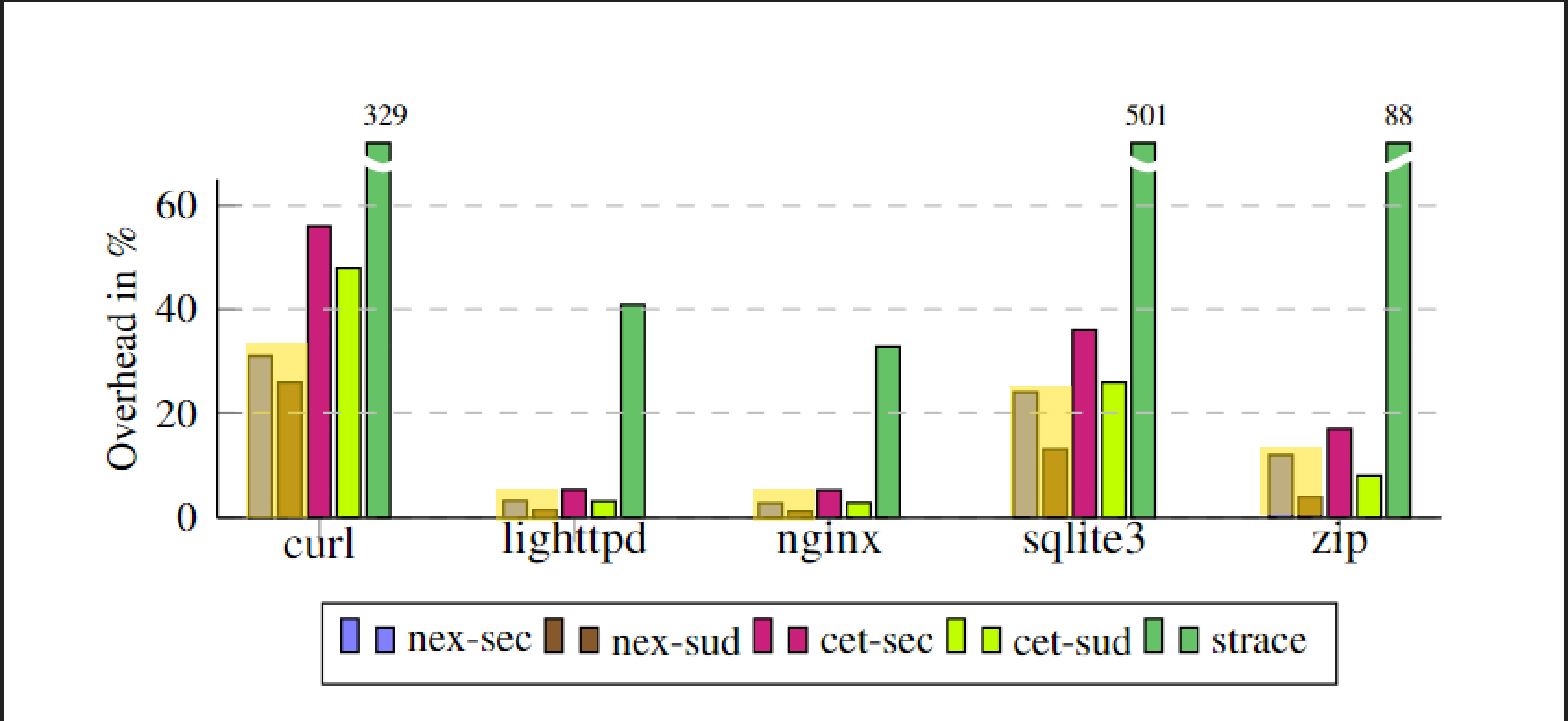

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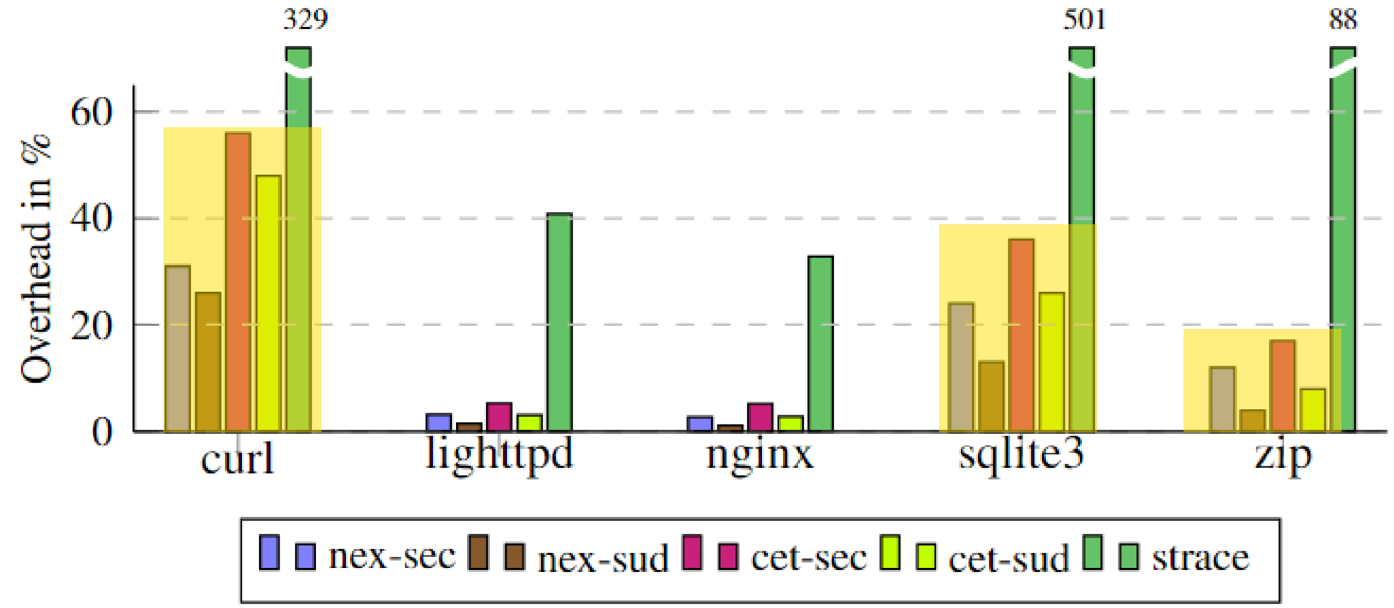

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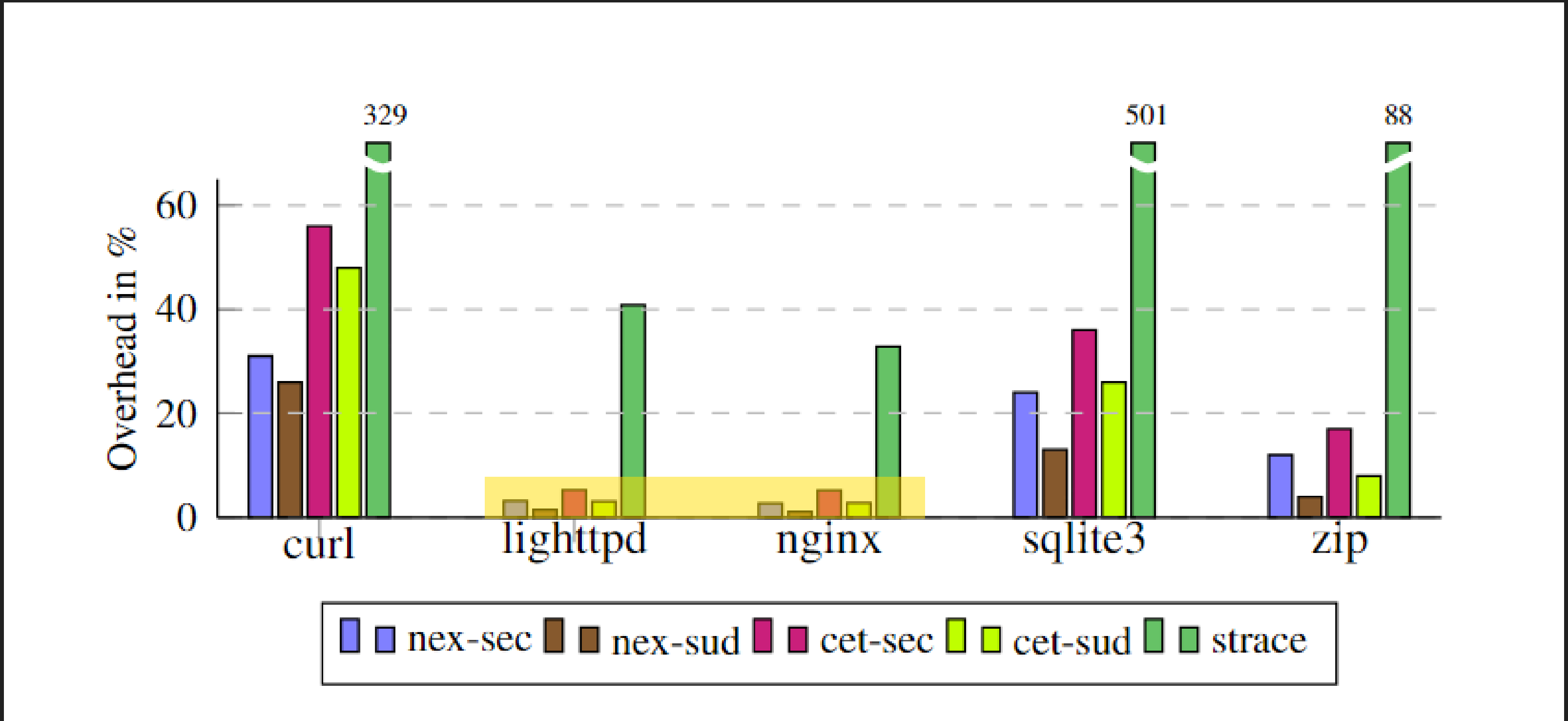

Thread Scalability: Near Consistent Overhead with More Thread

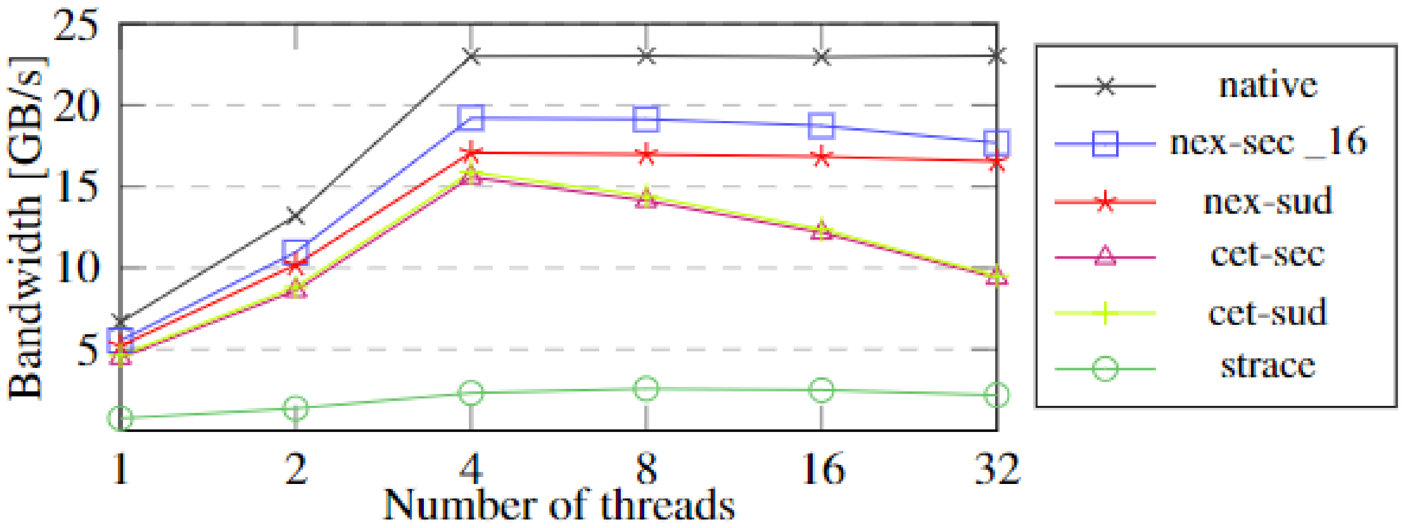

Figure 6: Random read bandwidth for diff. numbers of threads measured with `sysbench`. Std. dev. below 0.7%.

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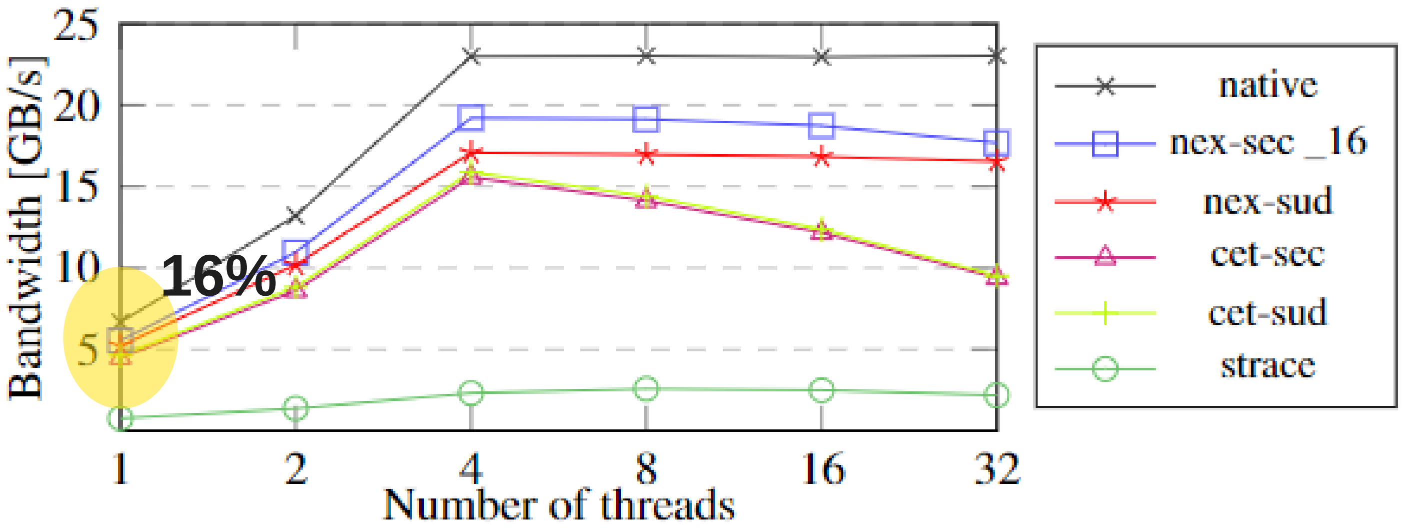

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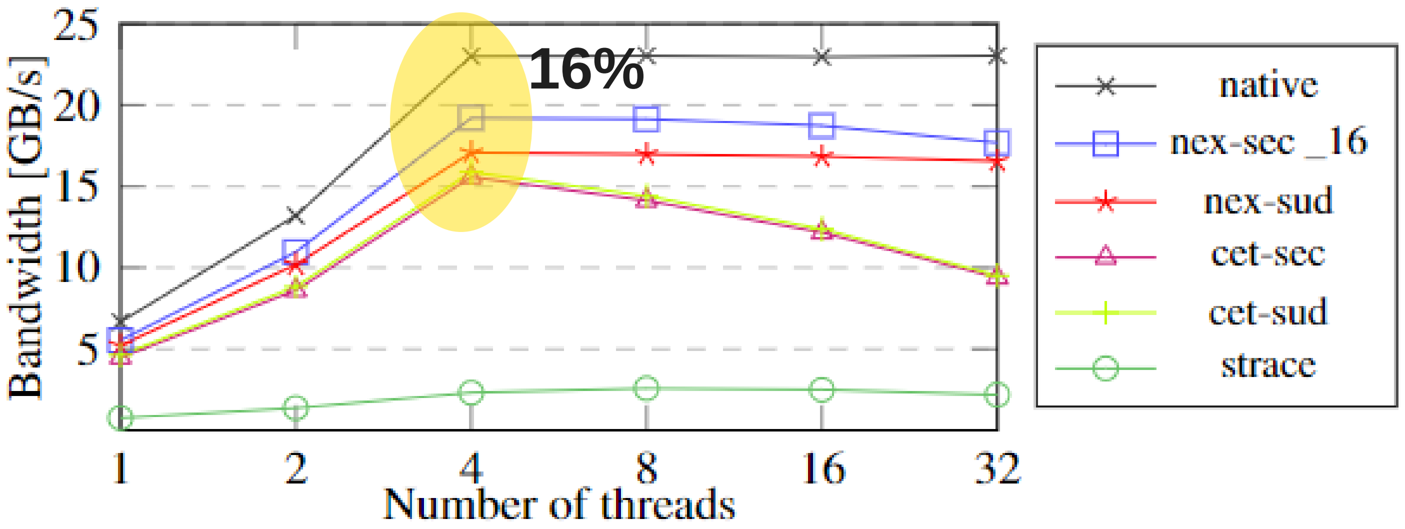
Thread Scalability: Near Consistent Overhead with More Thread



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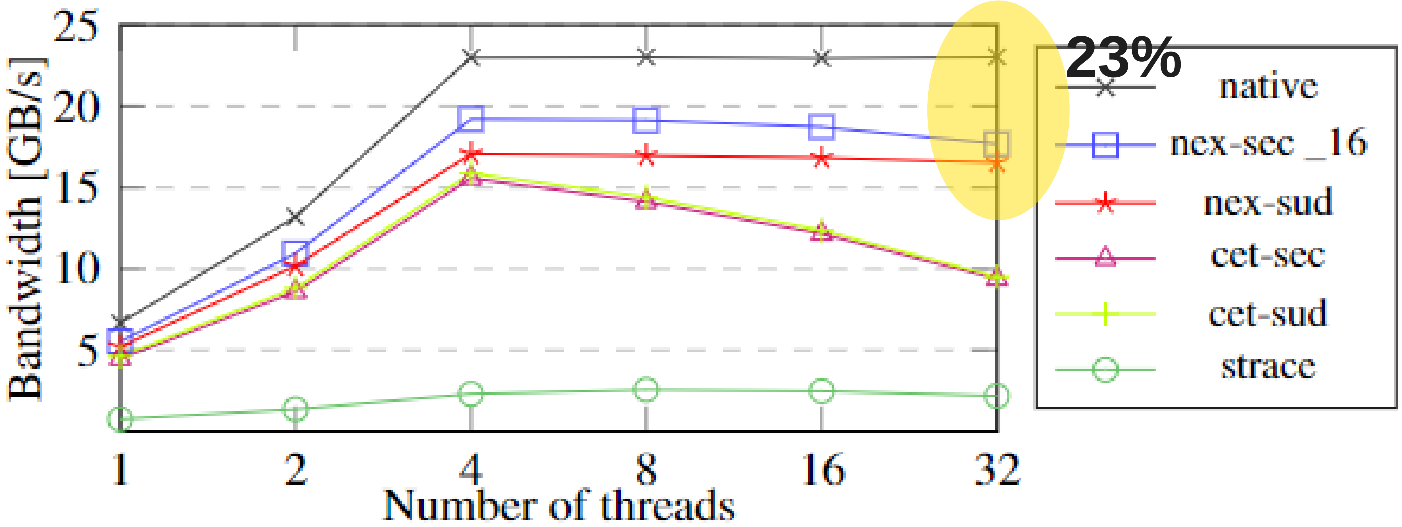

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Compatibility Test for the Signal and Multithreading

- Linux Test Project (LTP) provides regression and conformance to the kernel
- The Endokernel passed **95.95%** of the LTP test cases
- The failed cases are not related to thread or signal compatibility
  - Security-related
  - Kernel Side-Effect
  - Endokernel as a secondary loading
  - Memory Layout

Takeaways

- For an in-process monitor, thread safety is **not** as simple as just adding locks
- Weak Metadata Synchronization
  - Conservative monitor state updates to achieve safe results even in cases of unsynchronized operations
- Signals Virtualization
  - Complete virtualization of signal behavior within the monitor to avoid synchronization with the kernel
- High Memory Access Bypass
  - Locating these patterns through source code analysis, enabling for case-by-case examination
- <5.5% overhead on nginx and lighttpd; ~30% overhead on curl with nex-sud
- ~23% overhead with increasing thread count
- Passes 95% of LTP tests with insignificant failed cases
- Source code: https://github.com/endokernel/test/
- Q&A