LITESHIELD: Secure Containers via Lightweight, Composable Userspace µKernel Services

USENIX ATC'25

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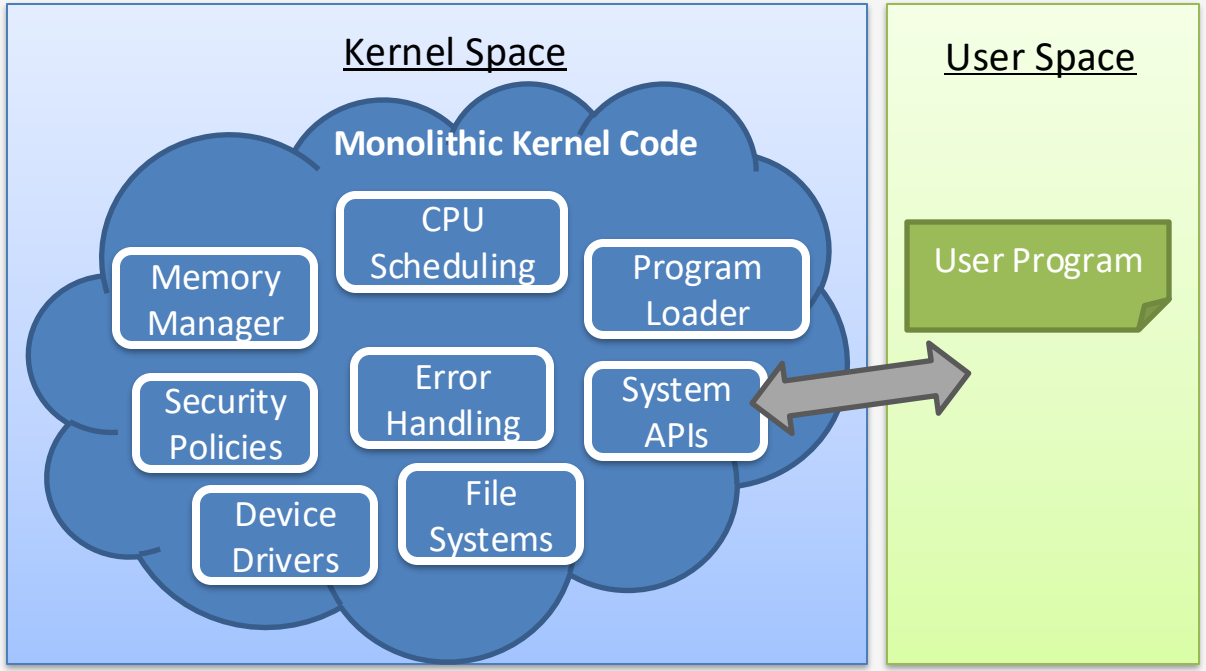
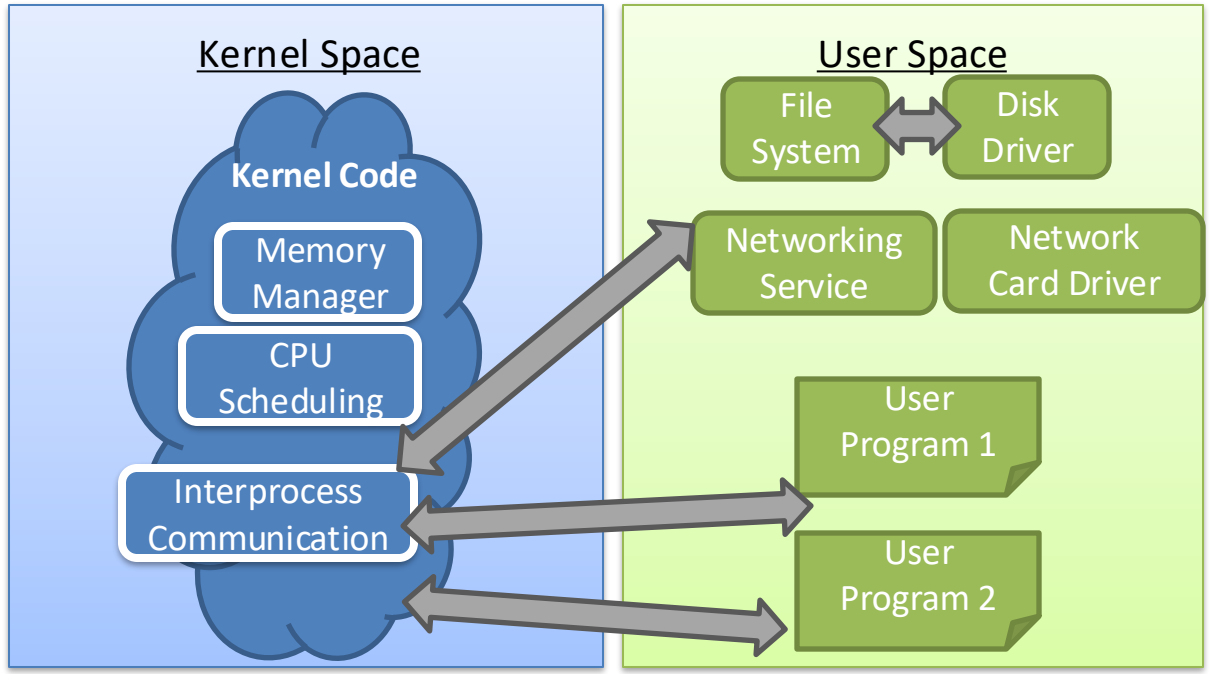
Microkernel vs. Monolithic Kernel

Secure applications running atop monolithic kernels with the microkernel concepts





Monolithic Kernels:

Huge code base – hard to make it secure

Many features – easy to develop programs

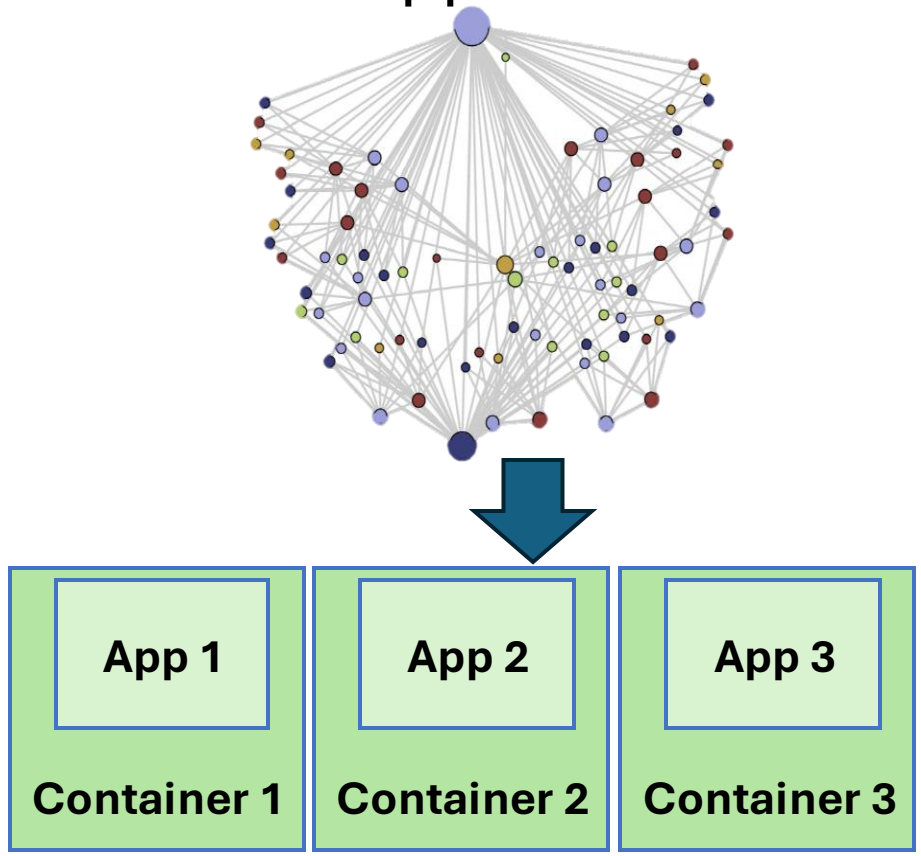
Microkernels:

Small code base – formally verified (e.g., seL4)

Few features – hard to develop user programs

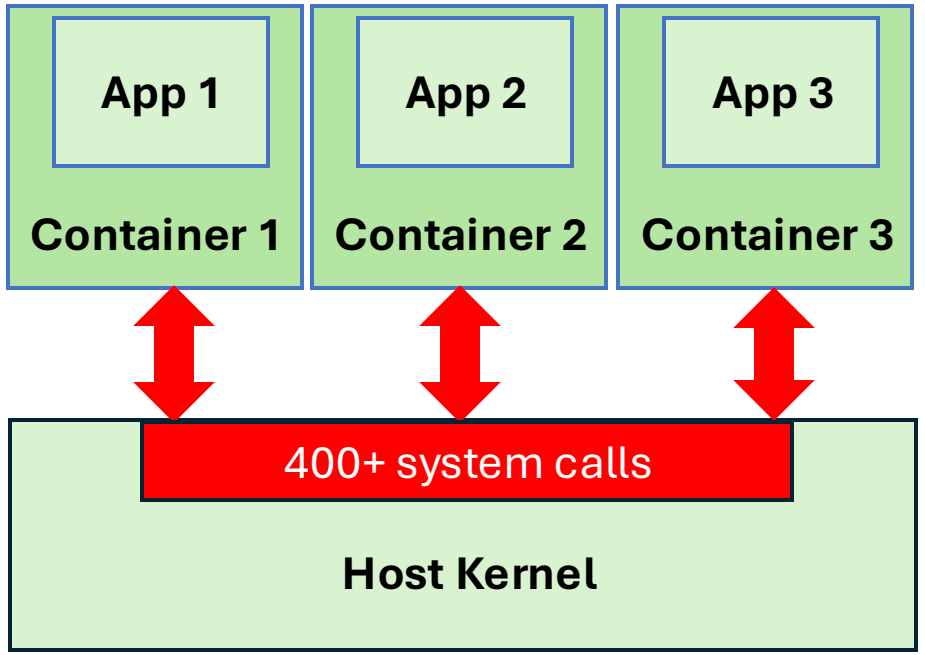
Research Background

- Most modern applications leverage a **microservices** architecture
  - An application consists of numerous small, interconnected components that collectively operate as a unified application.
  - Many benefits include straightforward **horizontal scaling**, **flexibility in deployment**, and **fault tolerance through redundancy**.
  - To deploy these microservices, containers are commonly used, as they are lightweight, and easy to provision on demand



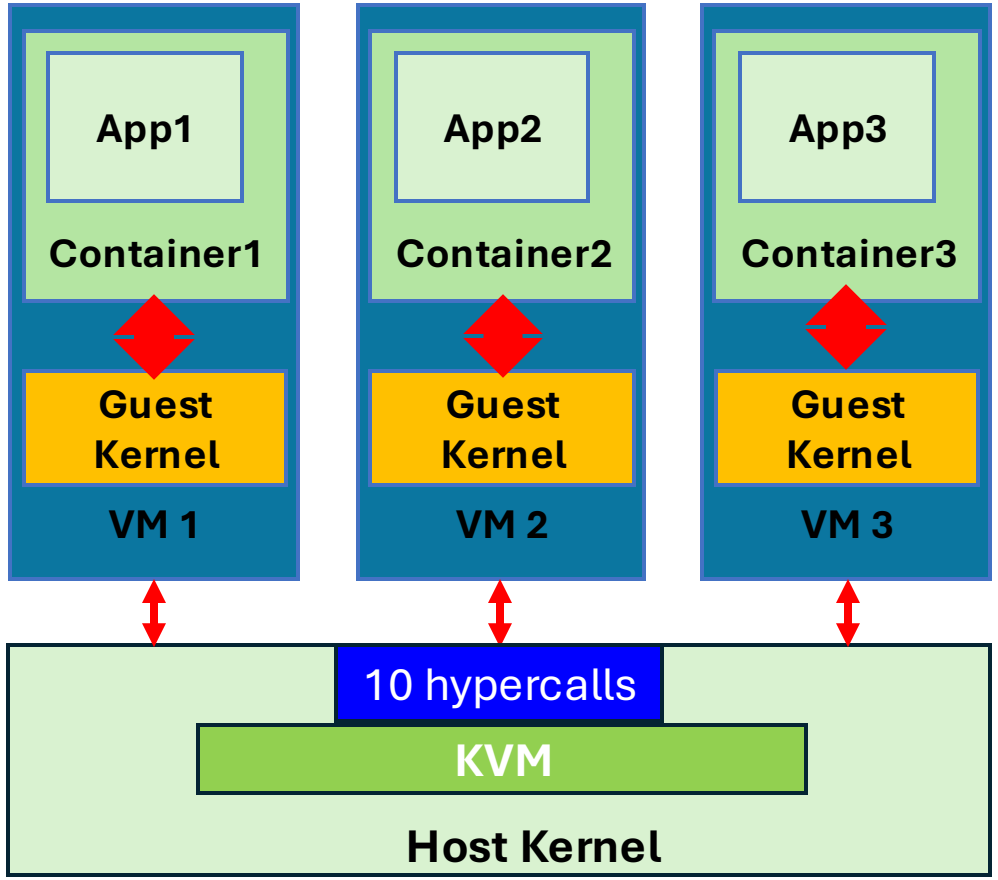
Isolation Problem

- While containers incur less overhead when compared to other isolation mechanisms, e.g. Virtual Machines (VM), they provide **weaker secure isolation**
- The main reason lies in the **large attack surface** between a container and the host kernel (e.g., 400+ system calls)
- Any kernel-related vulnerabilities, exploited via the large attack surface, could break the isolation layer

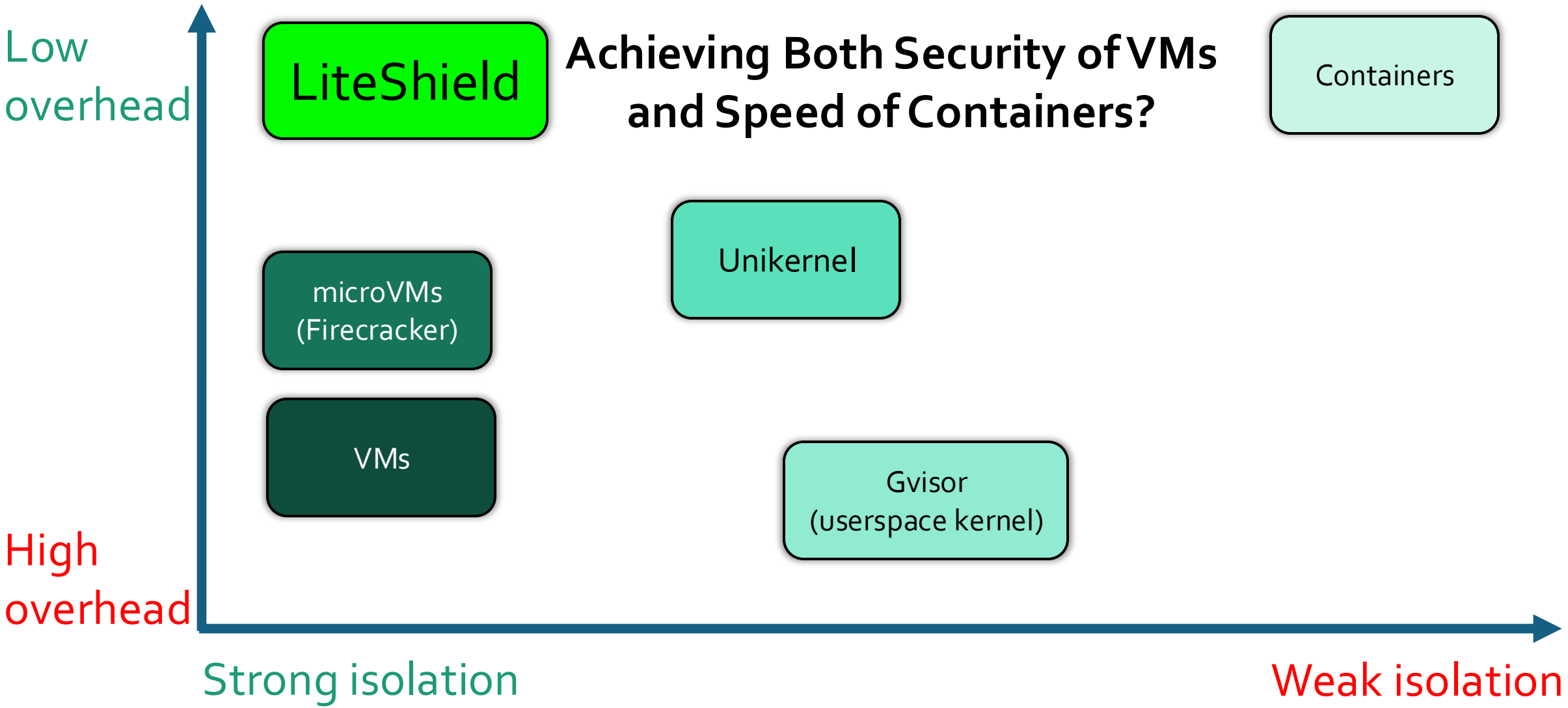


State-of-the-art: VM-based Secure Containers

- The current practical solution to provide **strong isolation** in the public cloud is to **run containers inside a VM** like KVM to separate clients from each other
- This provides a **secure isolation** layer, at the cost of the **high overhead** of running an entire guest OS for both high CPU utilization, large memory footprint, and long I/O latency



Isolation vs. Performance



Key Idea: Userspace Microkernel Architecture

- Decouple guest applications from their guest kernels
- Guest kernel runs as a set of userspace microkernel (**μKernel**) services

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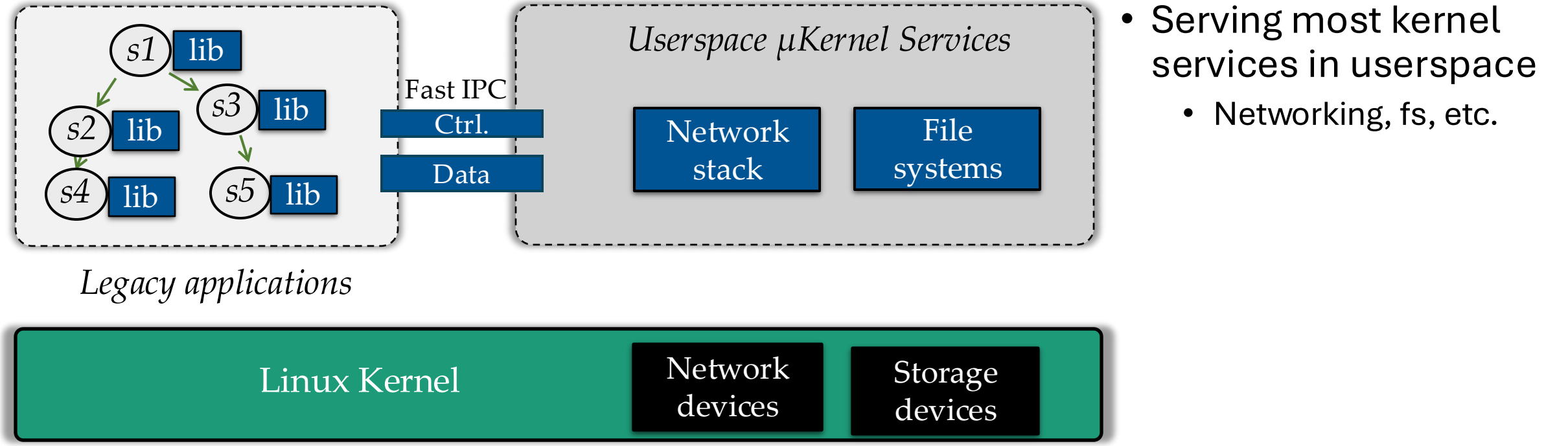

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  - Networking, fs, etc.

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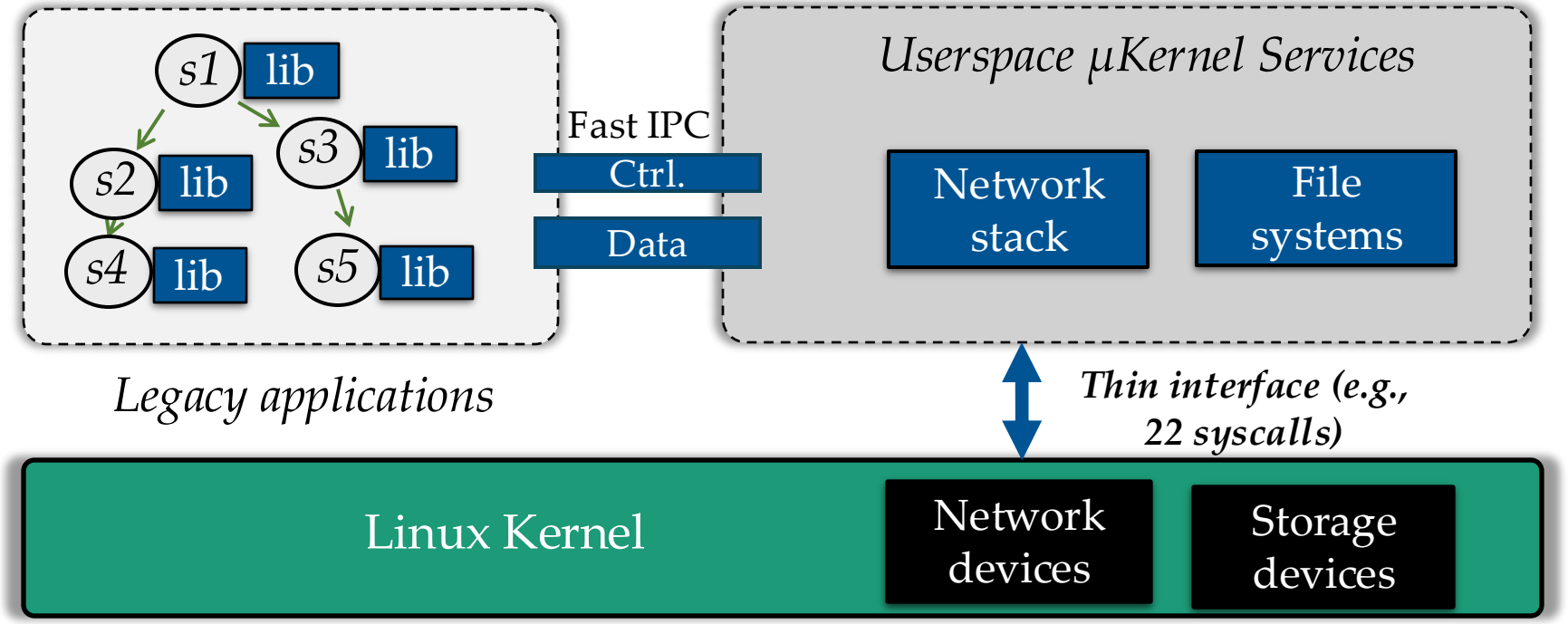

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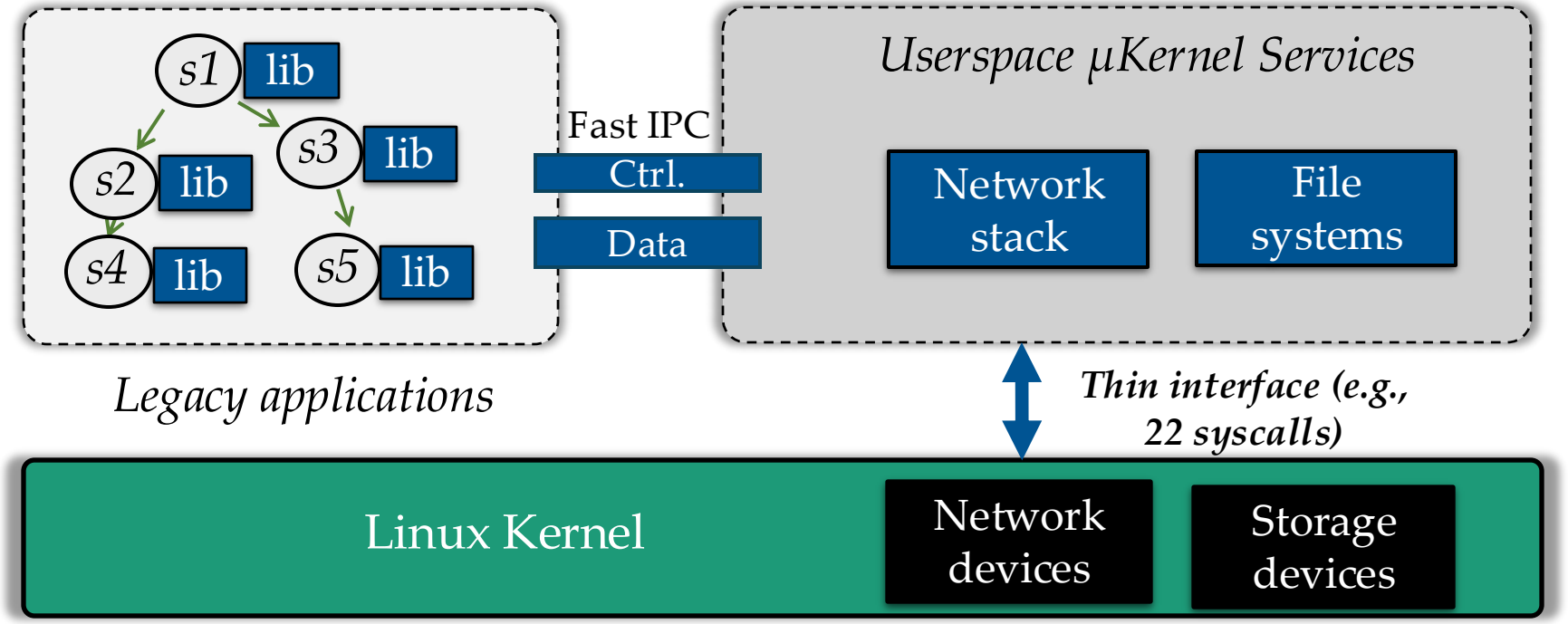

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  - High performance

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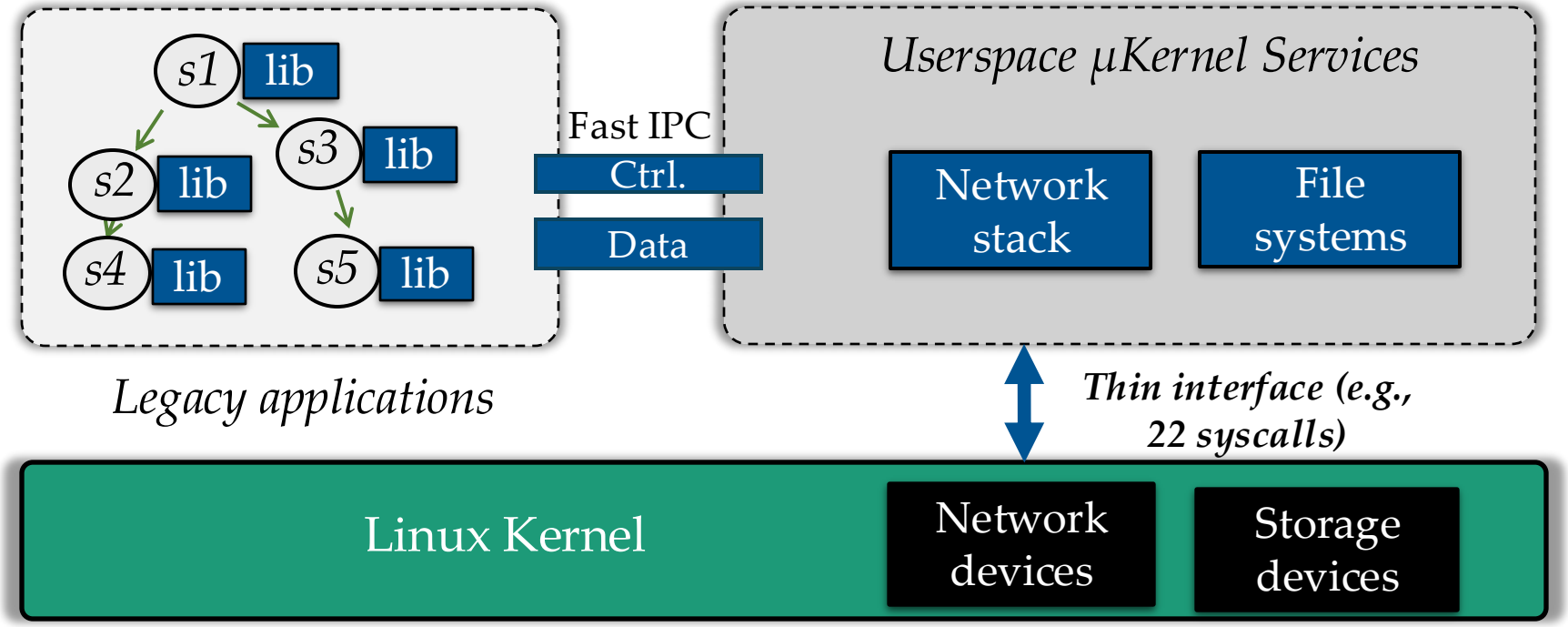

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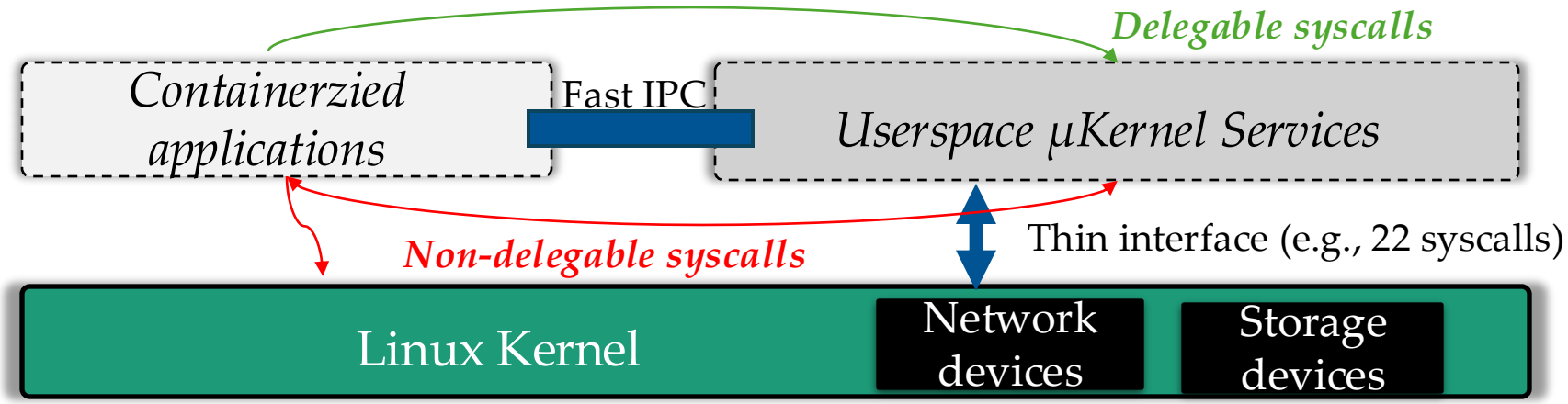
The **more** we can accomplish in **userspace**, the **less** that we must do in **kernel** space

Key Challenge - 1

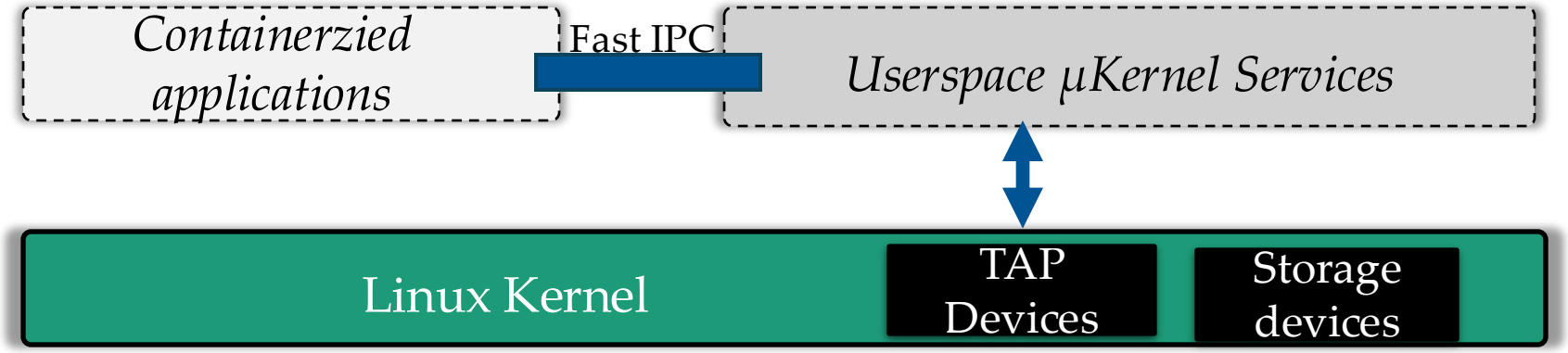
- **No-delegable syscalls:** some syscalls cannot be completely implemented in userspace
  - Must execute **under the same address** space of the guest applications
    - Limited by the Linux kernel's implementation
    - E.g., memory or process management
- **Solution**:
  - Allowed but monitored → use ptrace to enforce correctness



Delegable (140+)	Non-delegable (28)
read	mmap
write	execve
open	fork
close	clone
fstat	exit
accept	kill
…	…

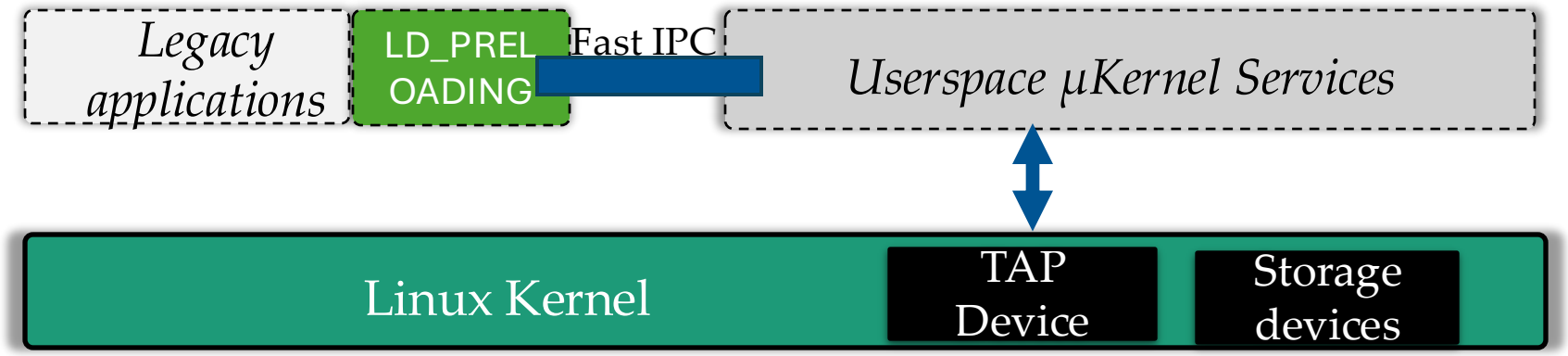
Key Challenge - 2

- **Complete kernel-bypass:** userspace kernel-bypass solutions completely bypass kernel
  - I.e., **no sharing**, each app needs its own NIC
    - Not scalable, infeasible in cloud environments
- **Solution**:
  - Partial kernel bypass: use userspace bypass solutions with emulated devices
    - E.g., use a TAP device as a NIC for DPDK
    - Still benefit from reduced interface (e.g., packet processing in userspace) with **minimal host kernel involvement**



Key Challenge - 3

- **Supporting legacy apps:** traditional Linux apps use syscalls
  - Rewriting apps would require large effort
- **Solution**:
  - LD_PRELOADing: use a preloaded library to intercept requests at syscall granularity



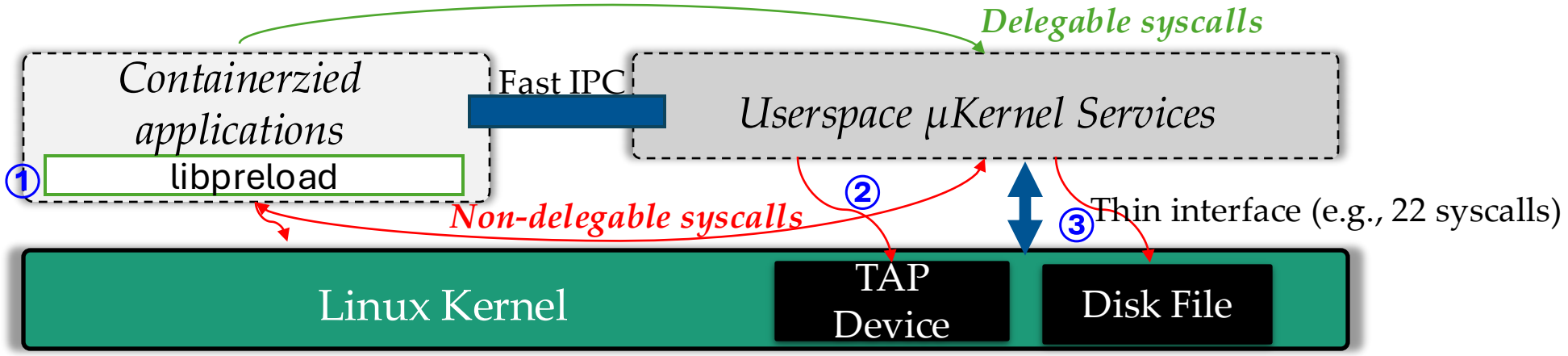
Implementation

① Shared memory IPC calls used to replace traditional syscalls for guest apps using LD_PRELOADING

② A userspace **networking stack** with **DPDK support**

- Based on an existing solution – fstack

③ Userspace **storage stack** with ext2 support backed by a memory-maped file

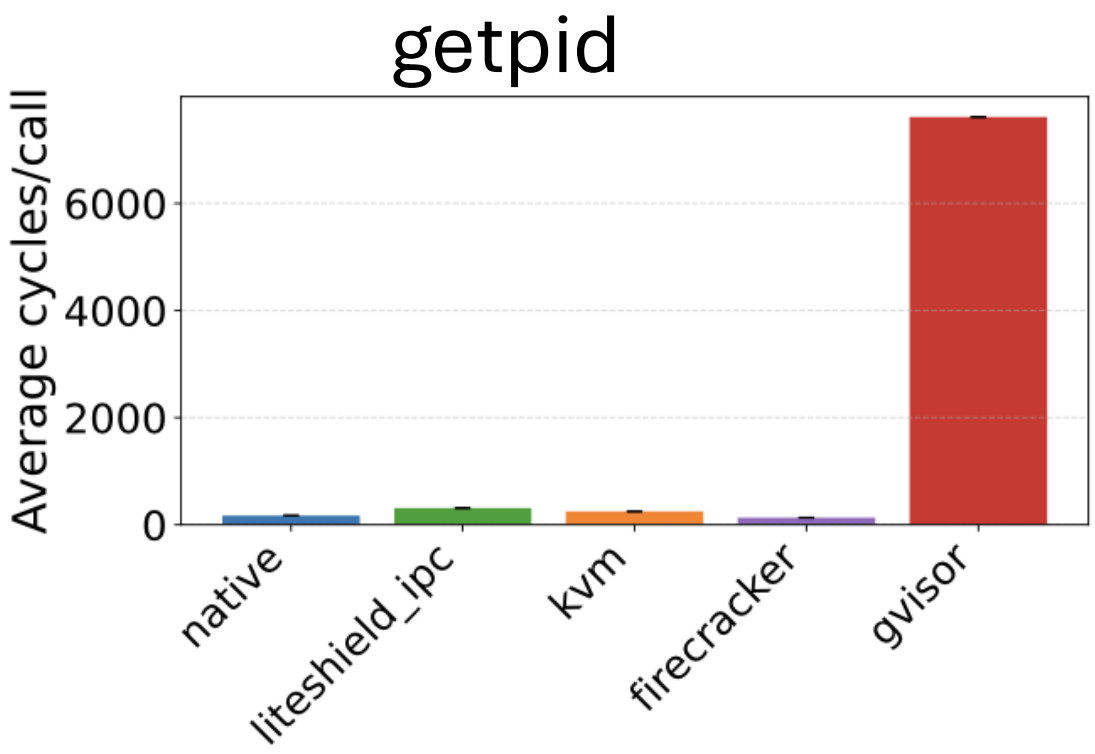


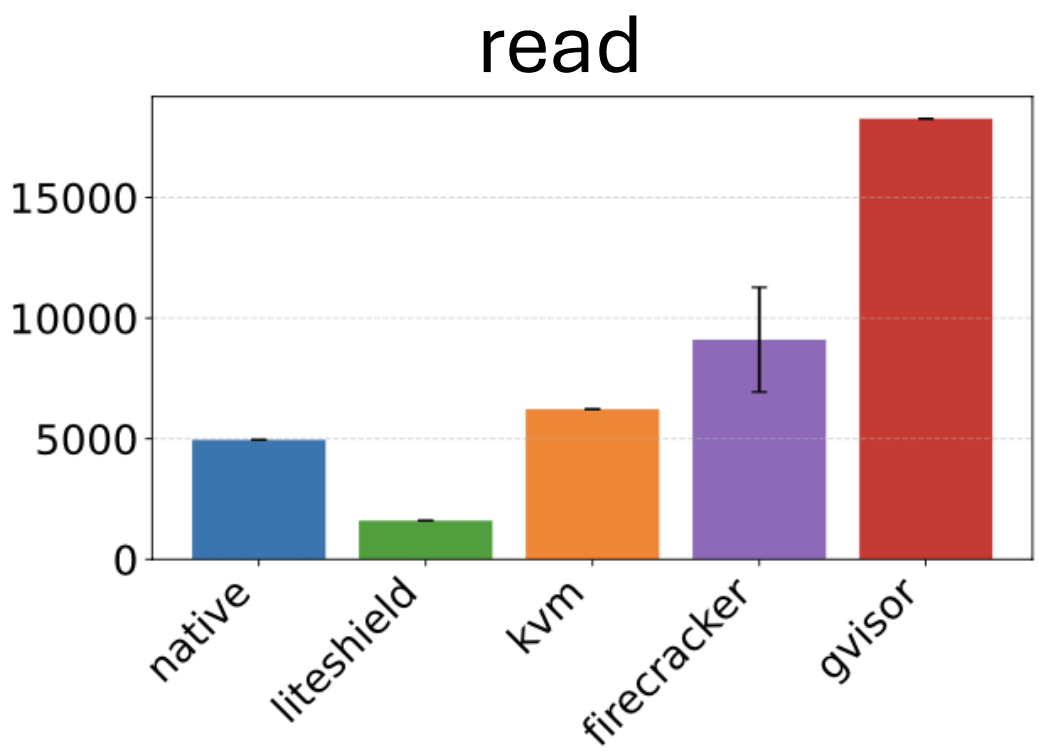
Evaluation

- **~7,000** lines of code for **core services**
- Reduced interface from **400+** to **22**
- **Testbed**
  - **Kernel**: Linux 5.15
  - **CPU**: Intel Xeon Gold 6430 (Hyperthreading disabled)
  - **Memory**: 96GB DDR5 RAM
  - **Disk**: Micron 7450 NVMe SSD (ext4)
- **Baselines** for comparison:
  - Docker containers
  - KVM-based VM
  - Firecracker: a microVM
  - gVisor: a userspace VM

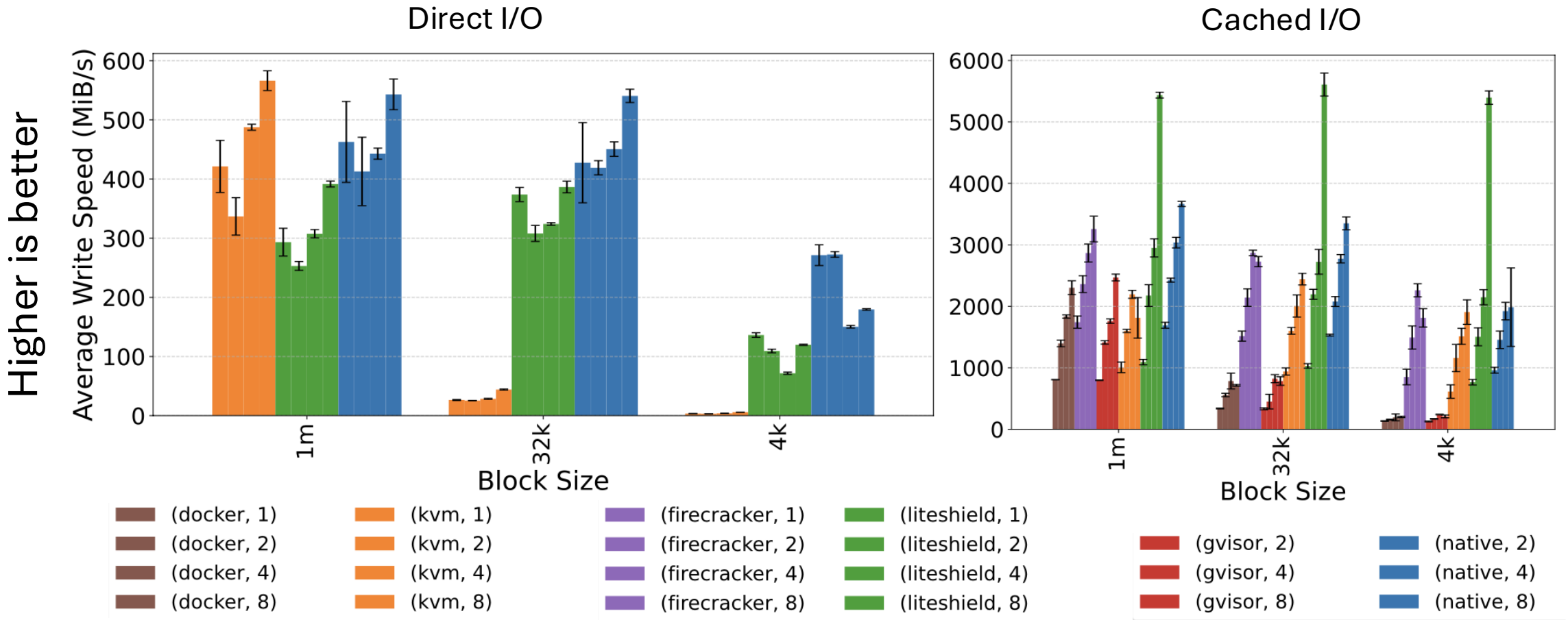
Evaluation: Syscall latency comparison

Lower is better





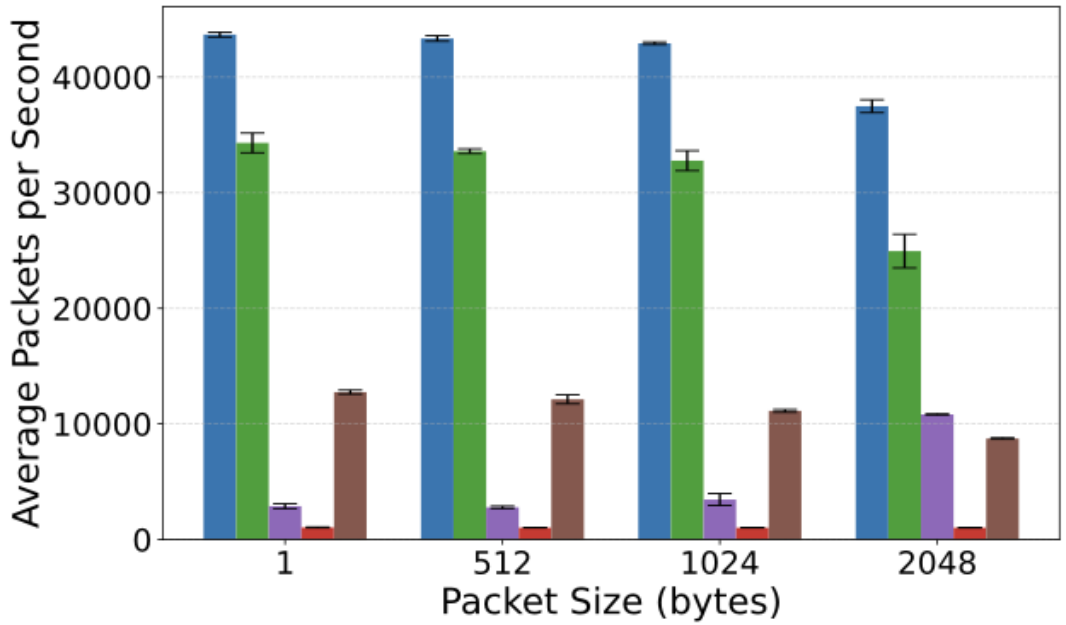
Evaluation: Disk I/O with FIO



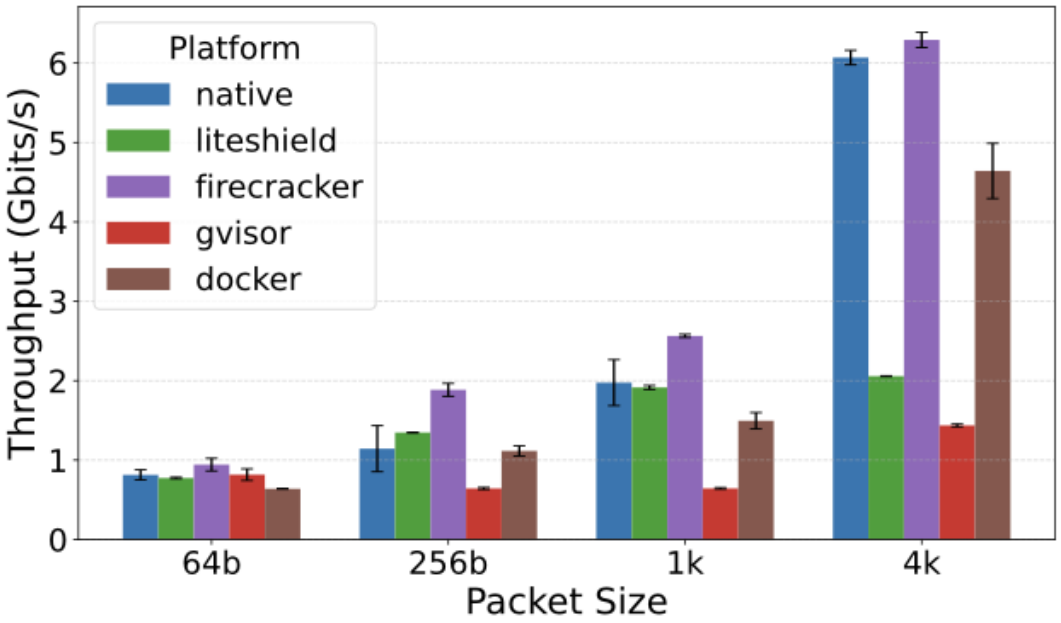
Performance comparisons for writing a 4GB file with various threads and block sizes

Evaluation: Networking Performance

Higher is better



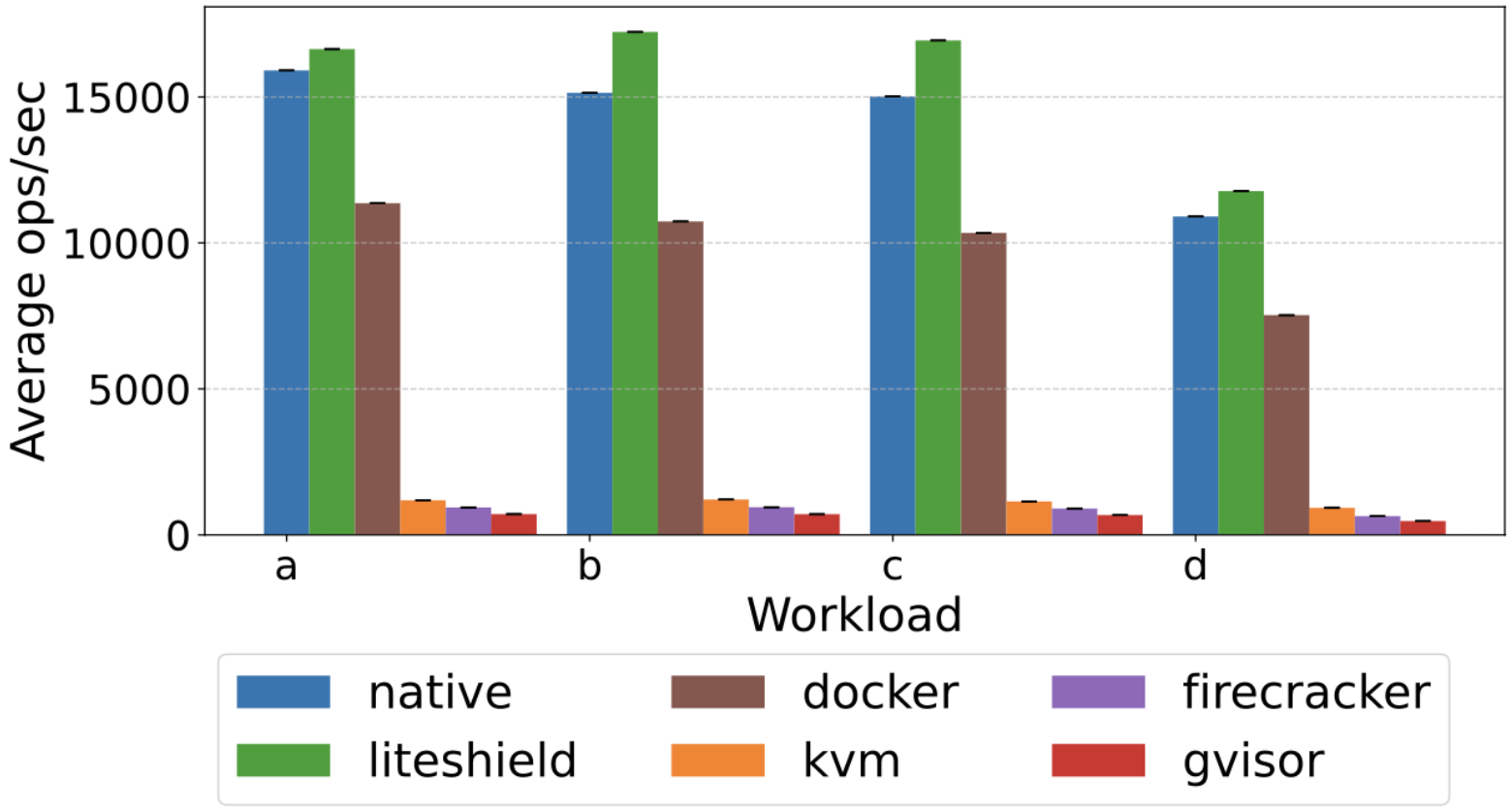
(a) UDP.



(b) TCP.

Evaluation: YCSB on Redis

Higher is better



A	B	C	D
50%/50% Read/Update	95%/5% Read/Update	95%/5% Read/Insert	50%/50% Read/Read-Modify-Write

Summary

- In this talk, we presented **LITESHIELD**, a secure container solution
  - Reduces host-guest interface from **400+** syscalls to **22** by moving kernel services to userspace
  - Replaces traditional syscalls with fast IPC calls
    - Using LD_PRELOAD techniques
  - Uses lightweight kernel abstractions (e.g. TAP) to allow **sharing**
  - Runs legacy apps with **no porting required**

- Evaluation shows that LITESHIELD has comparable performance to the baseline (containers) and is generally faster than VM-based solutions

Thank you!

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