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Tradeoffs for Virtualization Mechanisms

Lectures on Distributed Operating Systems (SS’25)

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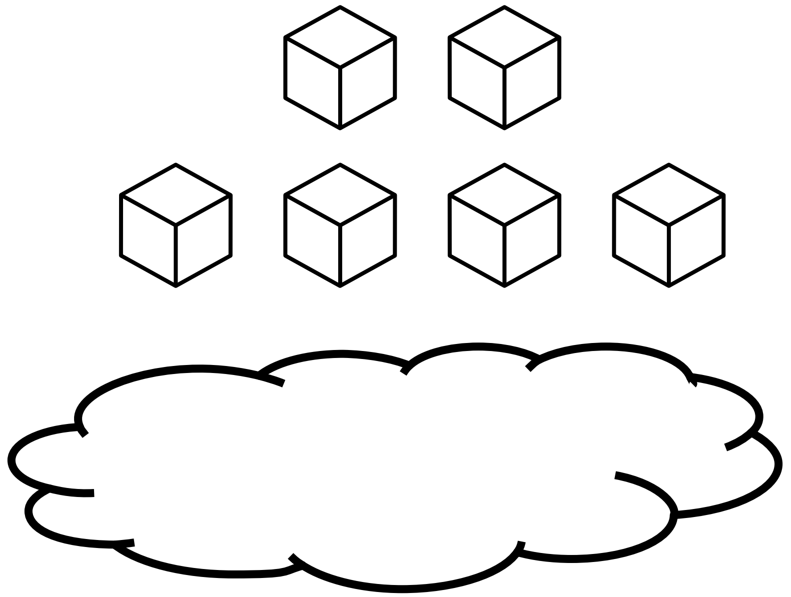
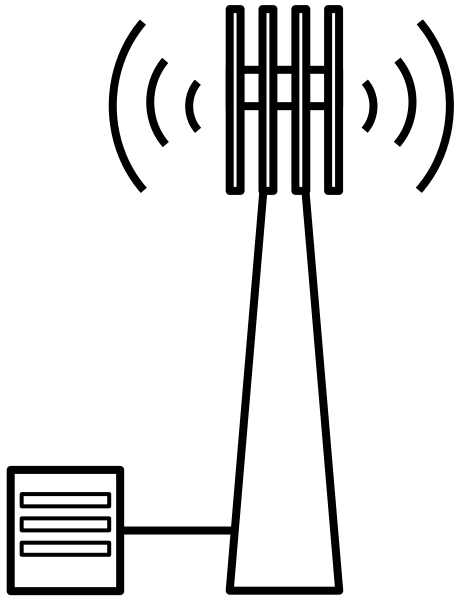
Recap: Public Clouds

- Large-scale systems that run applications on behalf of *untrusted* users





- Outsourcing to cloud providers often due to (alleged) economic benefits

Requirements in Cloud Computing

- Users want their applications to run reliably.
  - Data protection (confidentiality / integrity), availability
  - Do not depend on third parties in any form

- Users want performance close to that of native deployment.
  - Get resources that you pay for

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  - If possible, customers should share physical hardware
  - Function as a service (FaaS) / serverless instead of static instances
  - Requires highly dynamic systems

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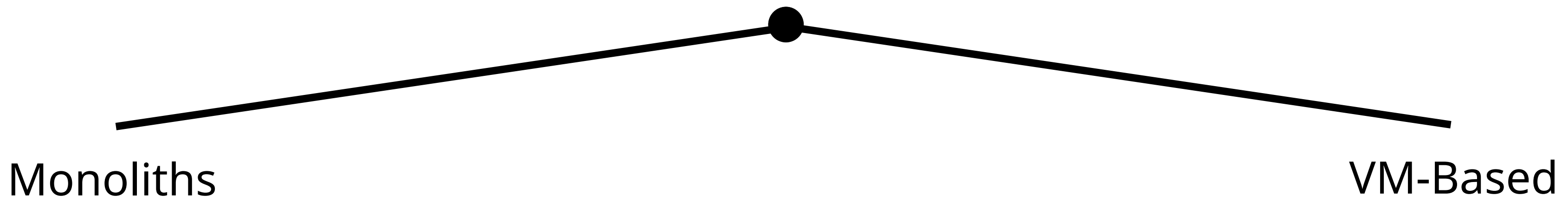
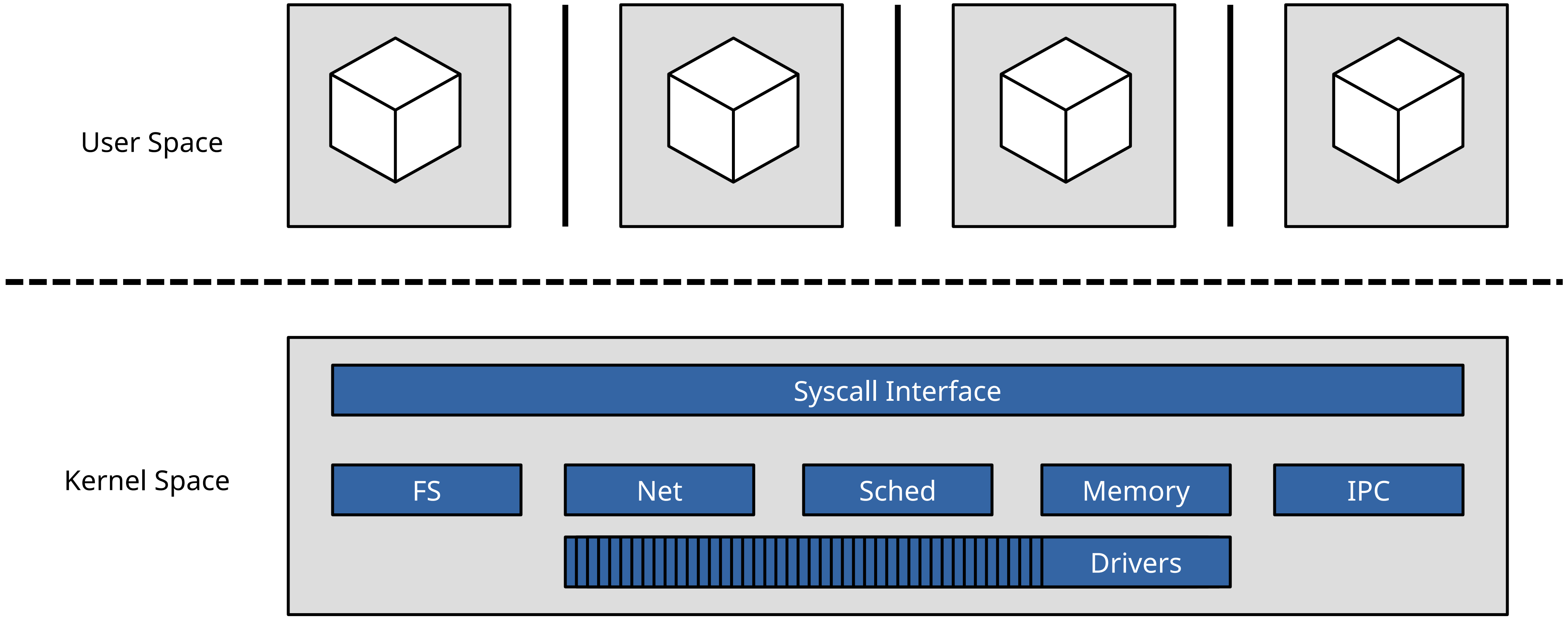
Isolating Cloud Applications – A Naive Approach

Hardening Operating Systems for the Cloud



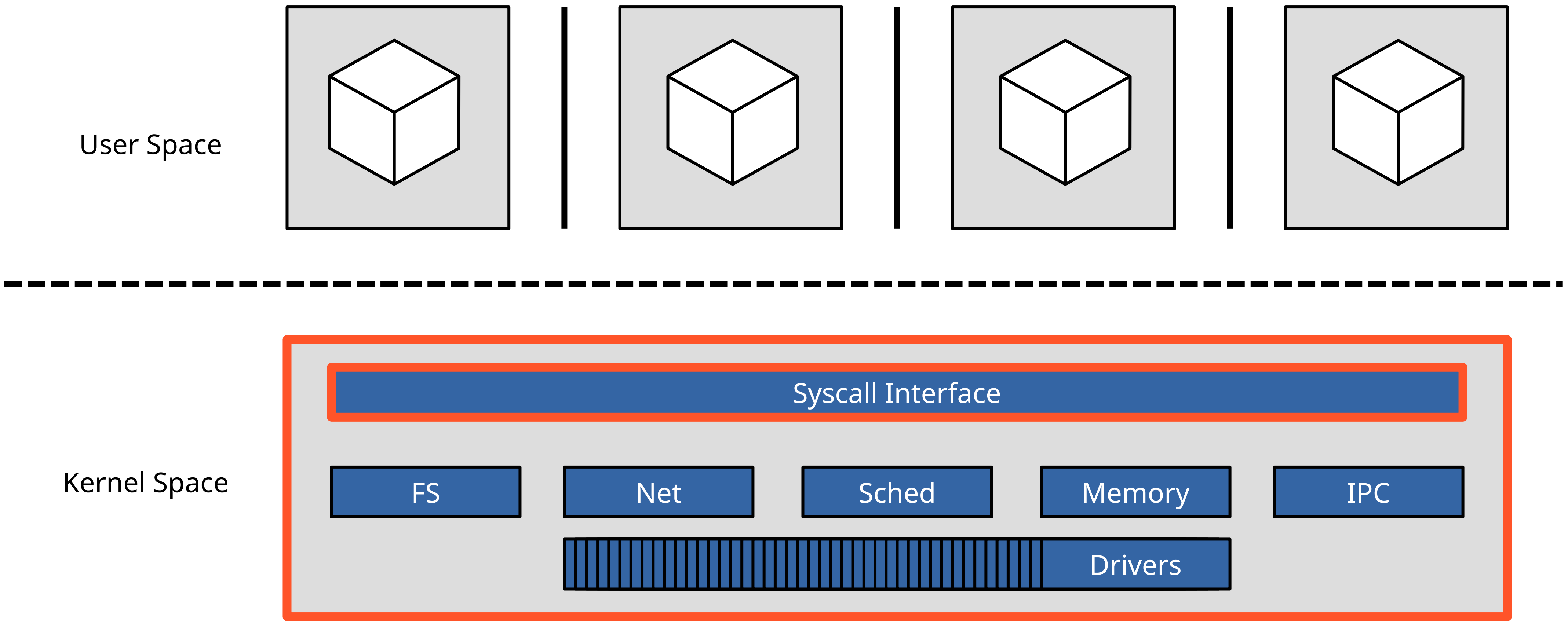
Cloud Servers from a Systems Perspective

- Dominated by Linux, a monolithic OS design



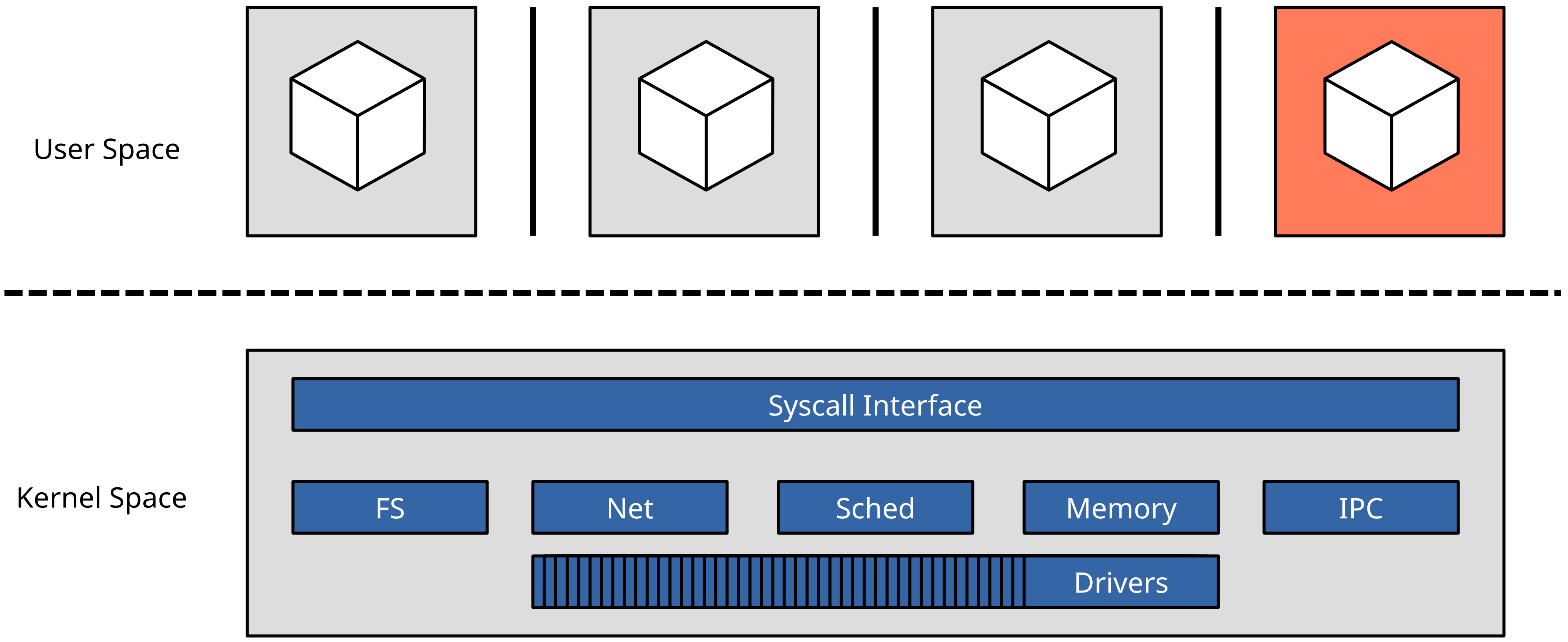
Cloud Servers from a Systems Perspective

- Monolithic OS: large API, large trusted computing base (TCB)



Cloud Servers from a Systems Perspective

- Monolithic architectures are prone to privilege escalation



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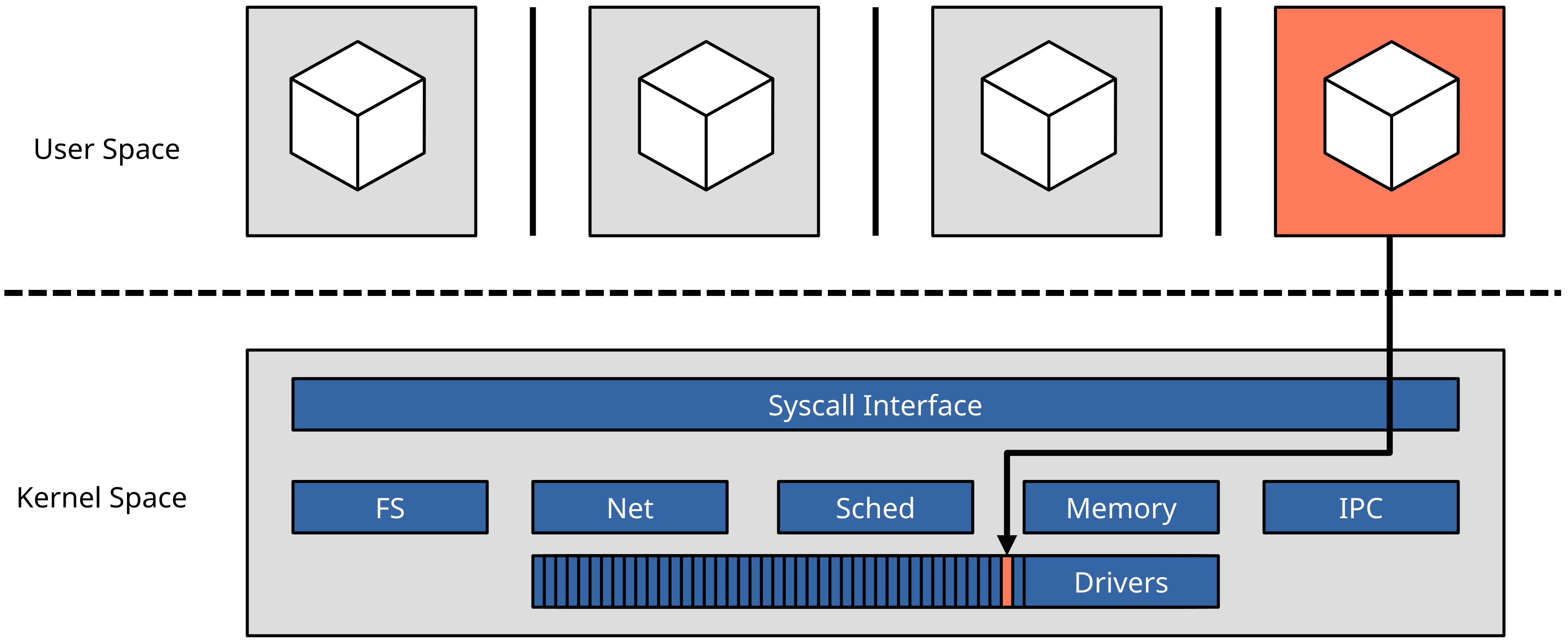

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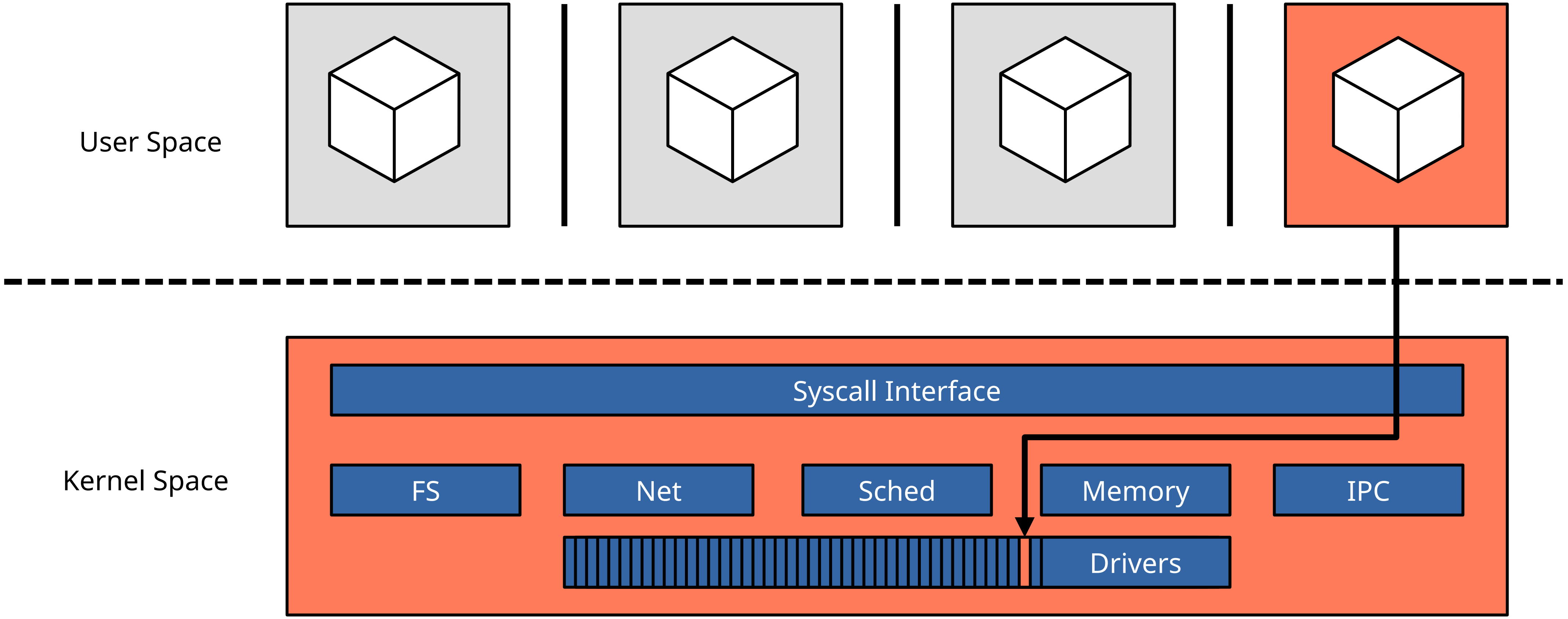

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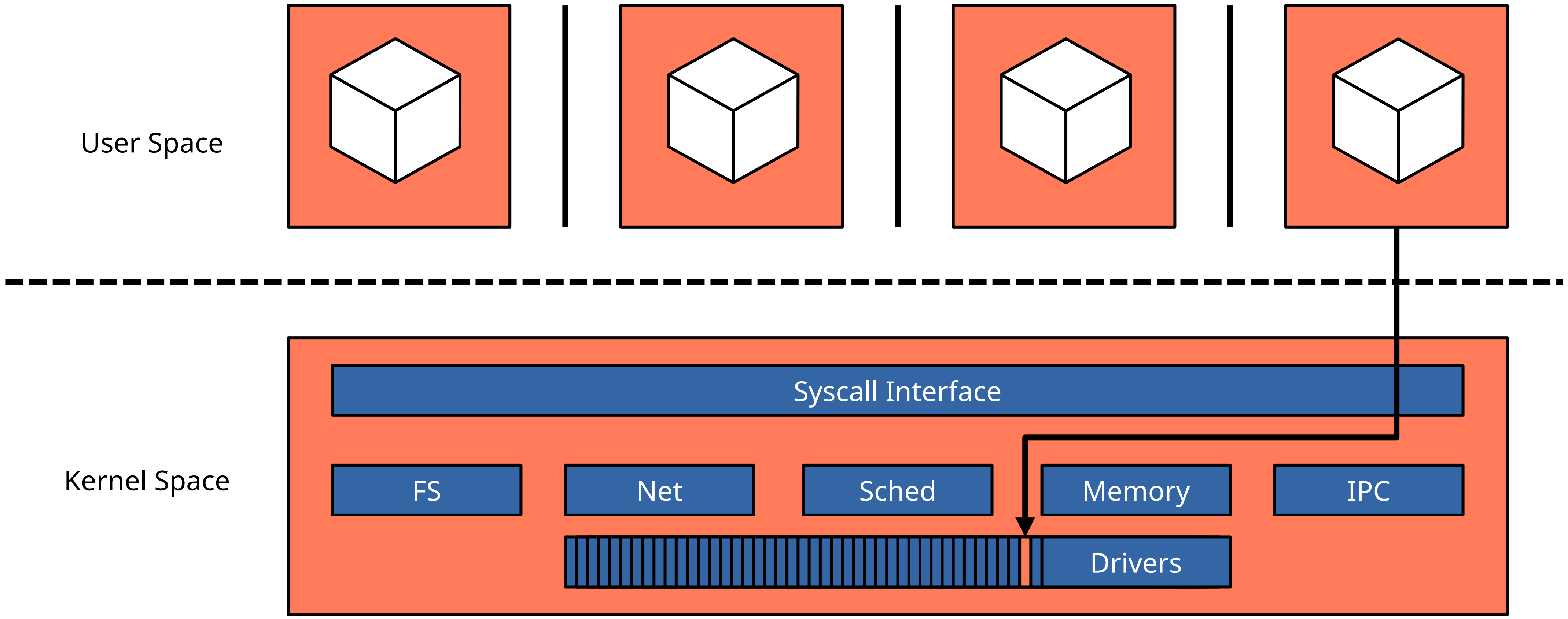
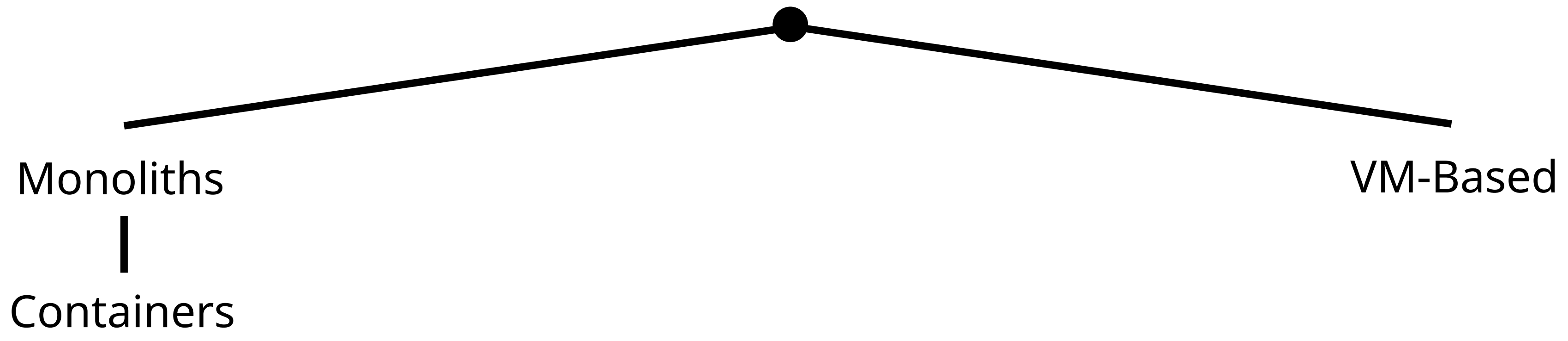


Why Is Process-Based Isolation on a Monolith Not Optimal?

- Architectural weaknesses
  - No restriction of accessible kernel API (*ambient authority*)
- Insufficient means for enforcing resource limits
  - If applicable, `rlimit` too coarse-grained
- Processes share several global “namespaces”
  - E.g., process IDs, network devices, view on file system, …
- But: Excellent performance on standard hardware, compatible, easy to use

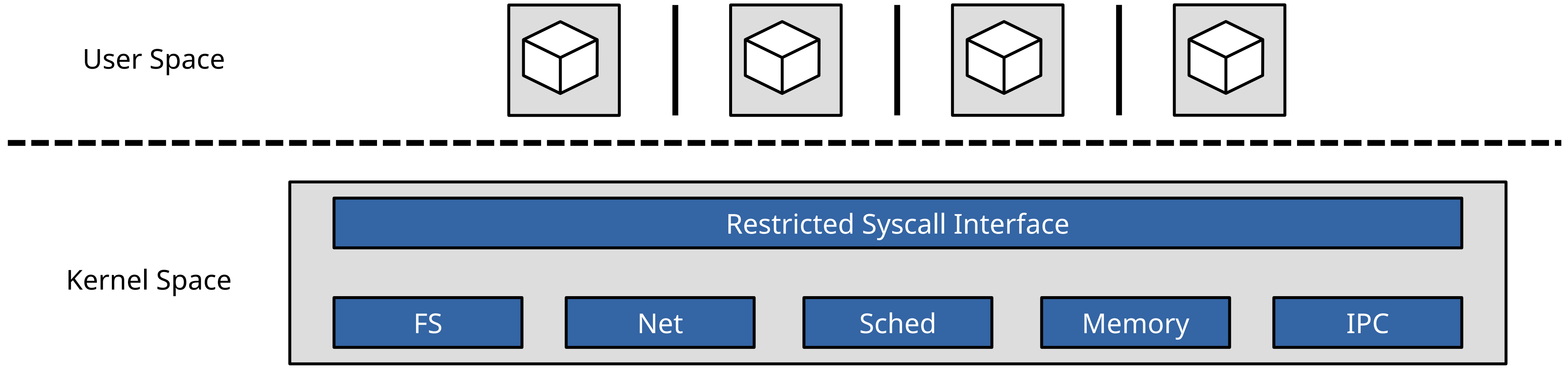
Isolating Cloud Workloads in Containers

Hardening Operating Systems for The Cloud



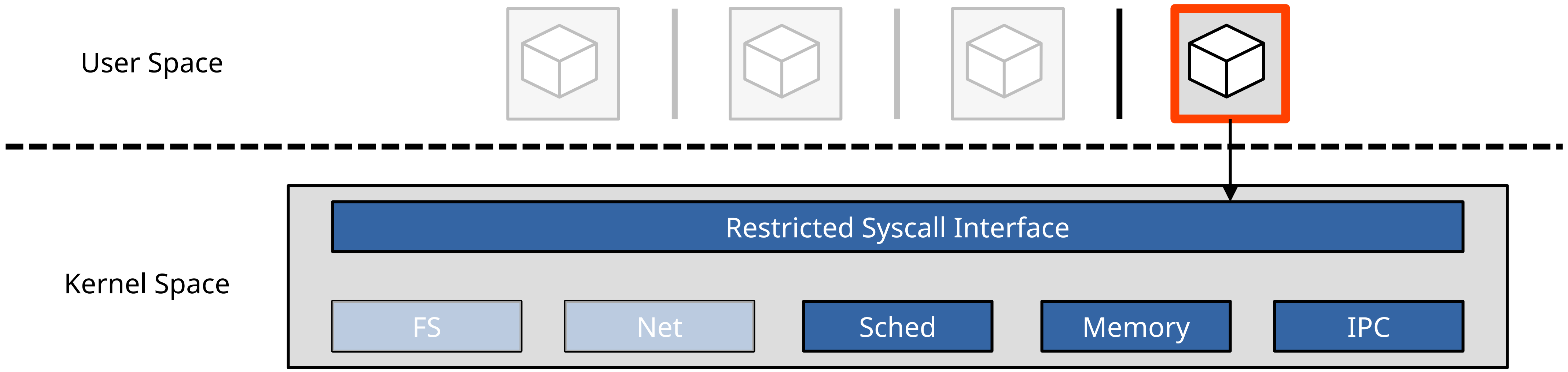
Containers

- Lightweight virtualization (BSD Jails [KW00], Solaris Zones [TC04], Linux [FF+15])
- Increase isolation level of groups of processes using in-kernel facilities
  - Comes with an entire ecosystem for deployment
  - Intuition: Provide separated userland instances on top of a shared kernel
  - No application modification and / or awareness needed, run images as-is



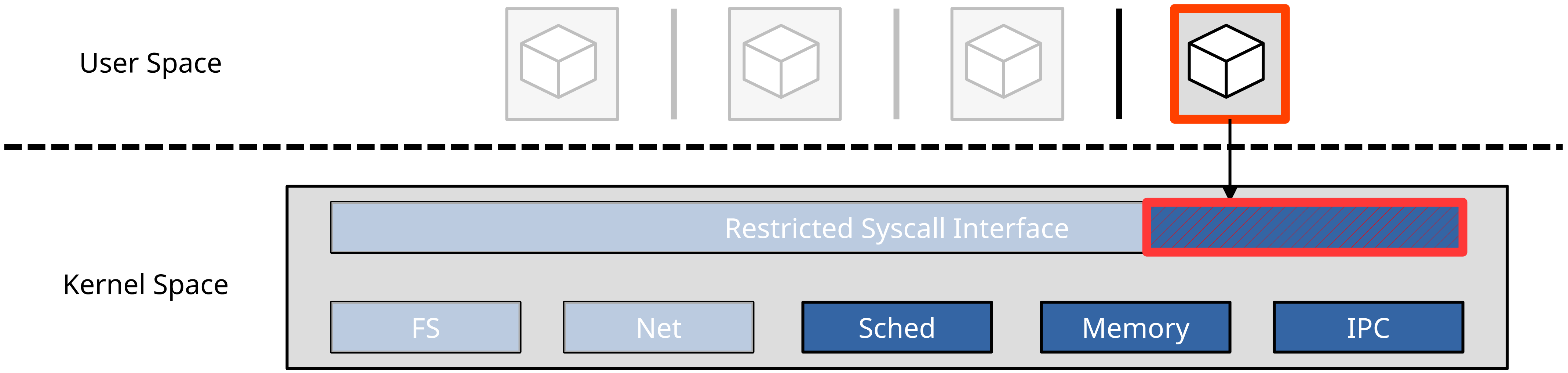
Linux Containers – Namespaces

- Restrict visibility of system components inside a container
- Used to virtualize a variety of kernel abstractions shared by stock processes
  - PIDs, mount points, network interfaces, IPC channels, …
- Often additional restrictions for visibility of file system subtrees (`chroot`, …)



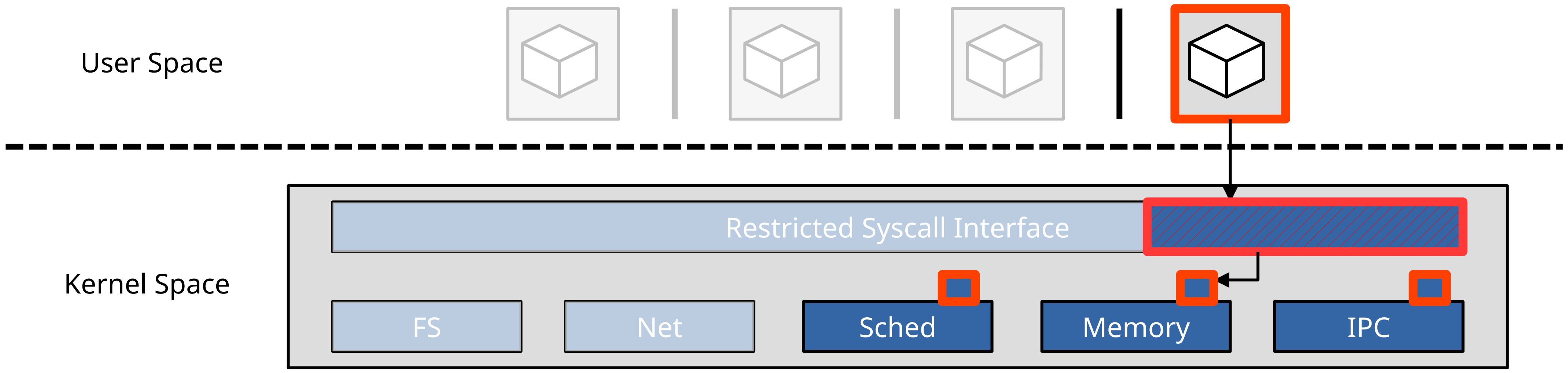
Linux Containers – Seccomp-BPF

- Enables administrator to limit execution of system calls
  - Inject BPF programs interpreted at certain probe points in the kernel
  - Possible to load / unload BPF programs at runtime
  - Also enables restriction of valid parameter range for system calls



Linux Containers – Cgroups

- Unified framework for resource restriction and accounting
  - CPU time / share, memory budgets, network bandwidth, …
  - Hierarchical organization possible → Pass fraction of own budget to other process
  - Offers priorities (e.g., differentiate between different customers)



Containers – Additional Benefits

- Execution inside virtual machines for performance reasons [SS+19]
  - Deploy customized system services per containerized application
- Implementation of Linux features in userspace container runtime [YZ+19]
  - Idea: Reduction of API used by the container
  - gVisor widely applied by Google
- Adding and removing container parts on demand [TB+18]
  - Reduce TCB inside containers

Hardening Containers

Everything Secure Now?

- Various approaches for further hardening container mechanisms
  - Automatic generation of system call filters [CW+21]
  - Transparent change of kernel substrate the containers run on [NS+23]
  - …

Everything Secure Now?

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  - Automatic generation of system call filters [CW+21]
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- The complexity of container mechanisms remains.
  - Various CVEs (e.g., CVE-2018-18955 for namespaces, CVE-2022-0492 for cgroups)
  - Executing user-provided code in kernel dangerous [HG+23]
  - Huge TCB for confidentiality, integrity, and availability

Running Containers Inside TEEs

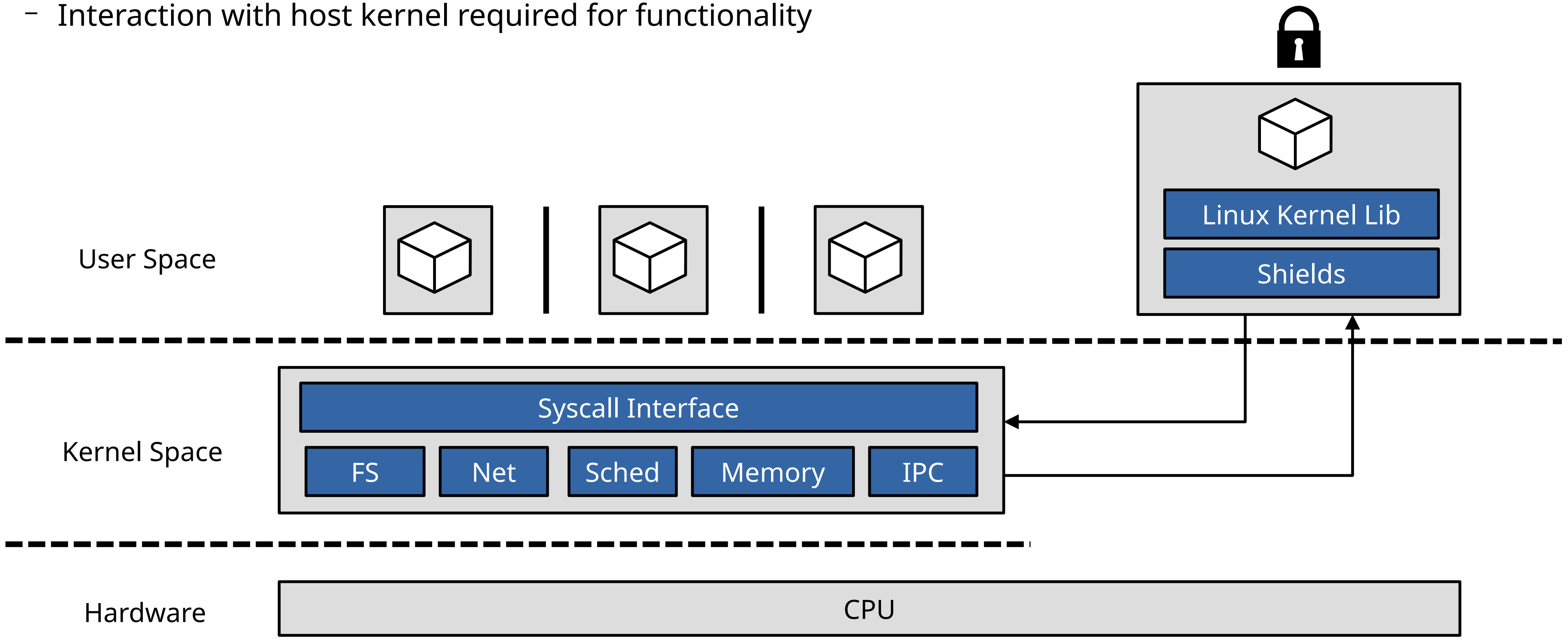
- SCONE: Trusted execution environment (TEE) to shield container [AT+16]
  - Based on Intel SGX
  - Idea: Let hardware provide secure compartments for executing applications

- SGX provides extensive security guarantees ($\rightarrow$ see lecture on trusted execution)
  - Enclaves provide encrypted execution of applications in ring 3 (user space)
  - Enclave set up by OS, inaccessible from any software after initialization (including SMM and DMA)
  - OS, BIOS, firmware are *not* a part of a container’s TCB
  - Only need to trust CPU vendor (for attestation)

- TEEs like SGX can incur significant performance overhead

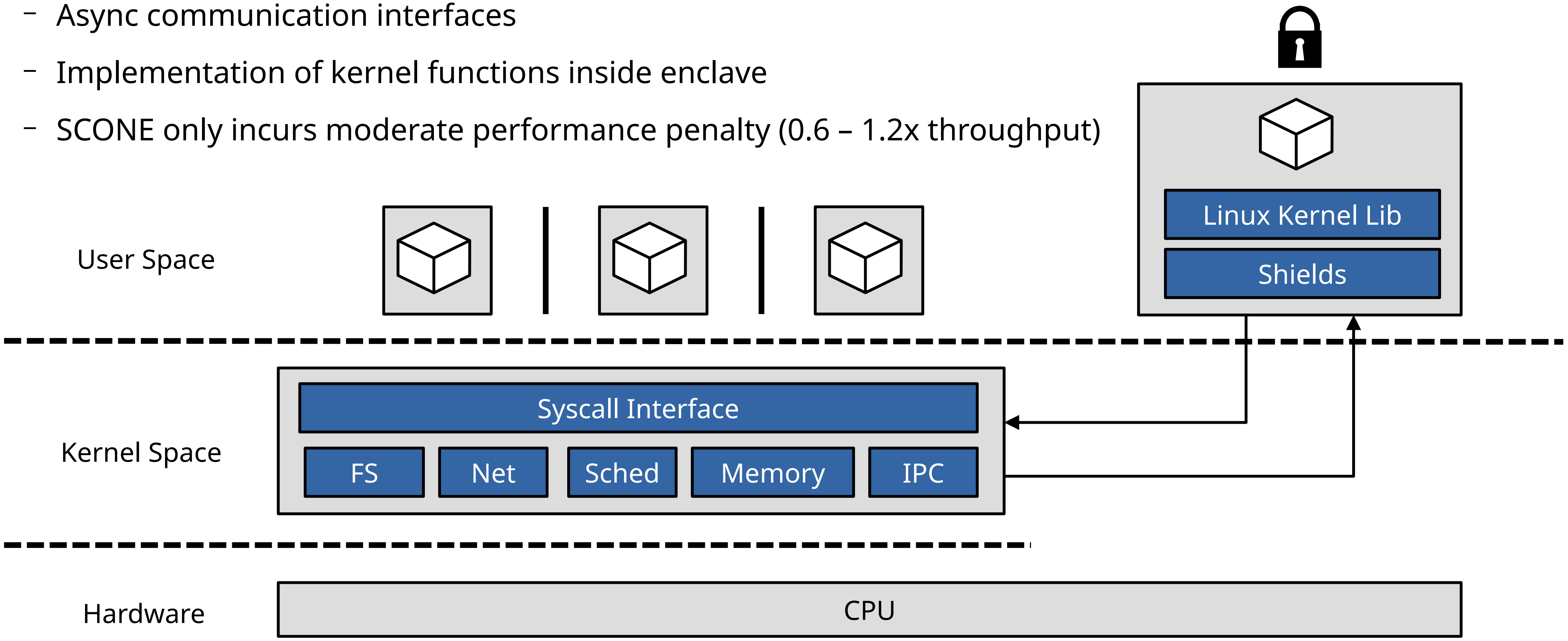
Running Containers Inside TEEs

- Container in TEE runs isolated from the rest of the system
  - Interaction with host kernel required for functionality



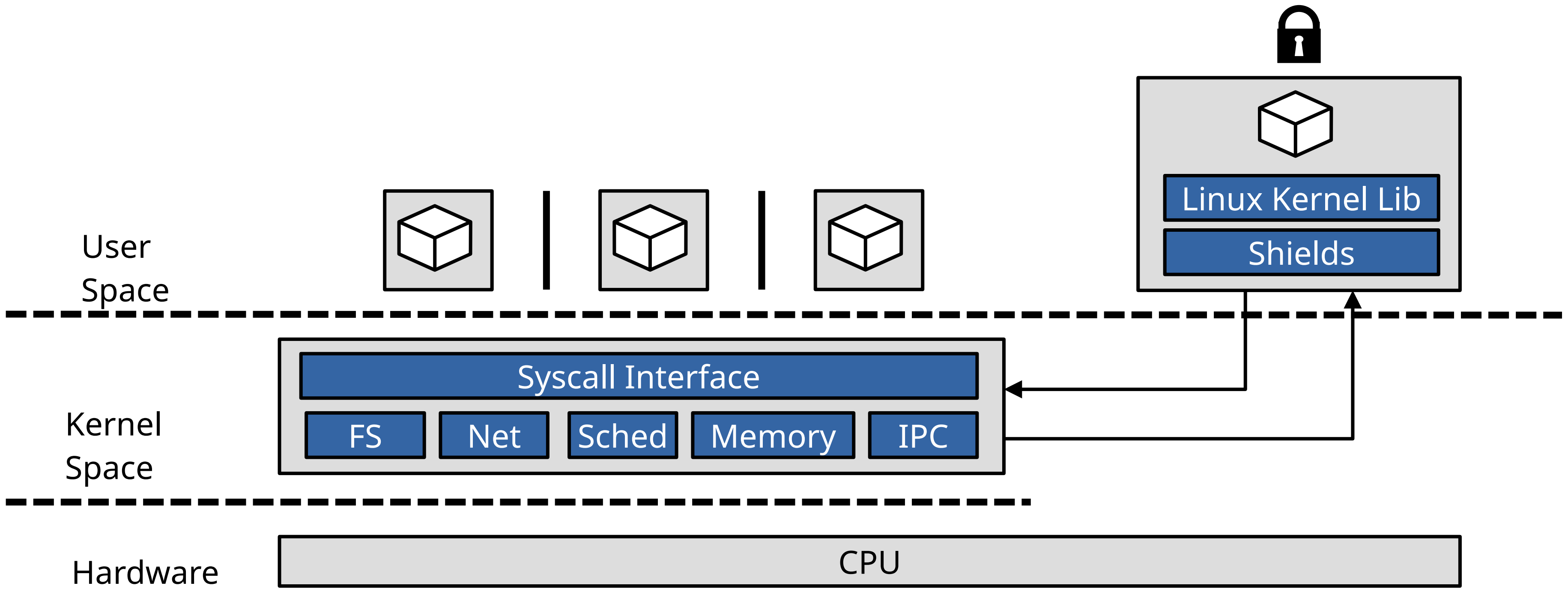
Running Containers Inside TEEs

- SCONE applies optimizations to reduce SGX overhead
  - Async communication interfaces
  - Implementation of kernel functions inside enclave
  - SCONE only incurs moderate performance penalty (0.6 – 1.2x throughput)



Running Containers Inside TEEs

- What are the security implications of TEEs?



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- What are the security implications of TEEs?
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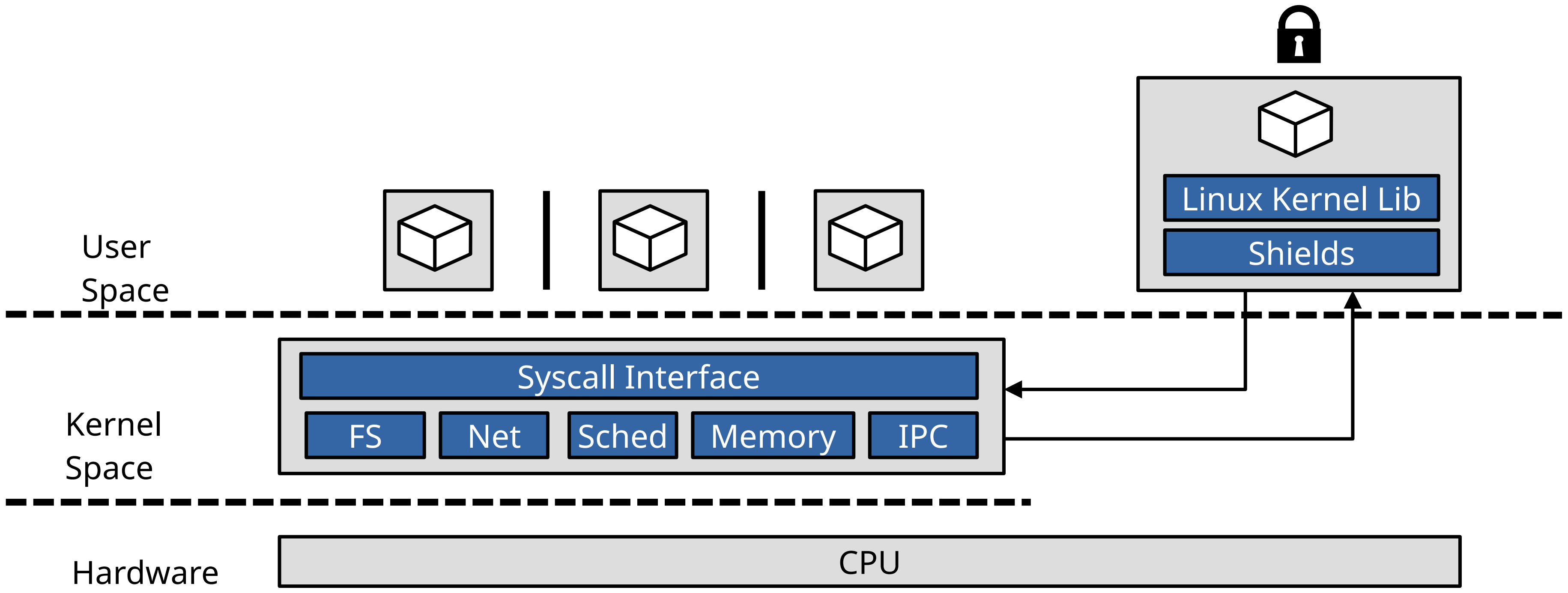
  - Complexity moved from soft- to hardware
  - Effective TCB?



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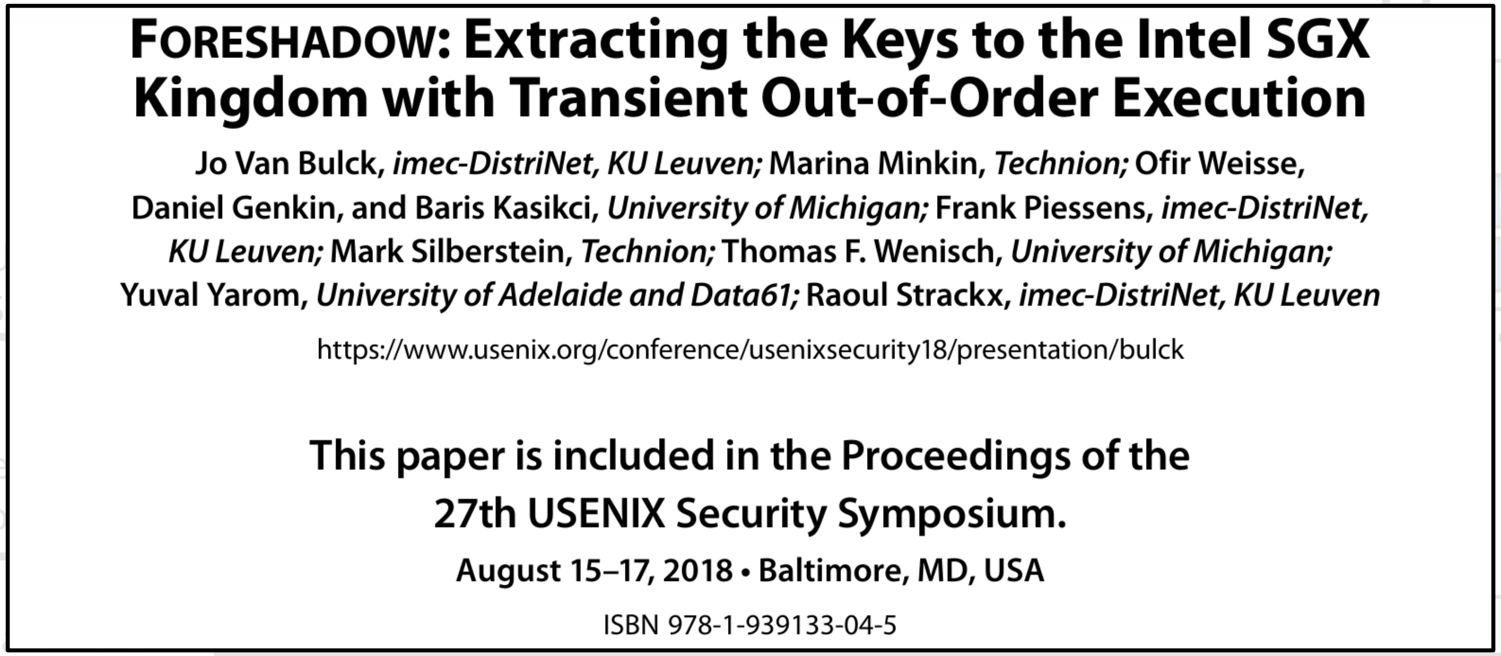

FORESHADOW: Extracting the Keys to the Intel SGX Kingdom with Transient Out-of-Order Execution

Jo Van Bulck, *imec-DistriNet, KU Leuven;* Marina Minkin, *Technion;* Ofir Weisse, Daniel Genkin, and Baris Kasikci, *University of Michigan;* Frank Piessens, *imec-DistriNet, KU Leuven;* Mark Silberstein, *Technion;* Thomas F. Wenisch, *University of Michigan;* Yuval Yarom, *University of Adelaide and Data61;* Raoul Strackx, *imec-DistriNet, KU Leuven*

https://www.usenix.org/conference/usenixsecurity18/presentation/bulck

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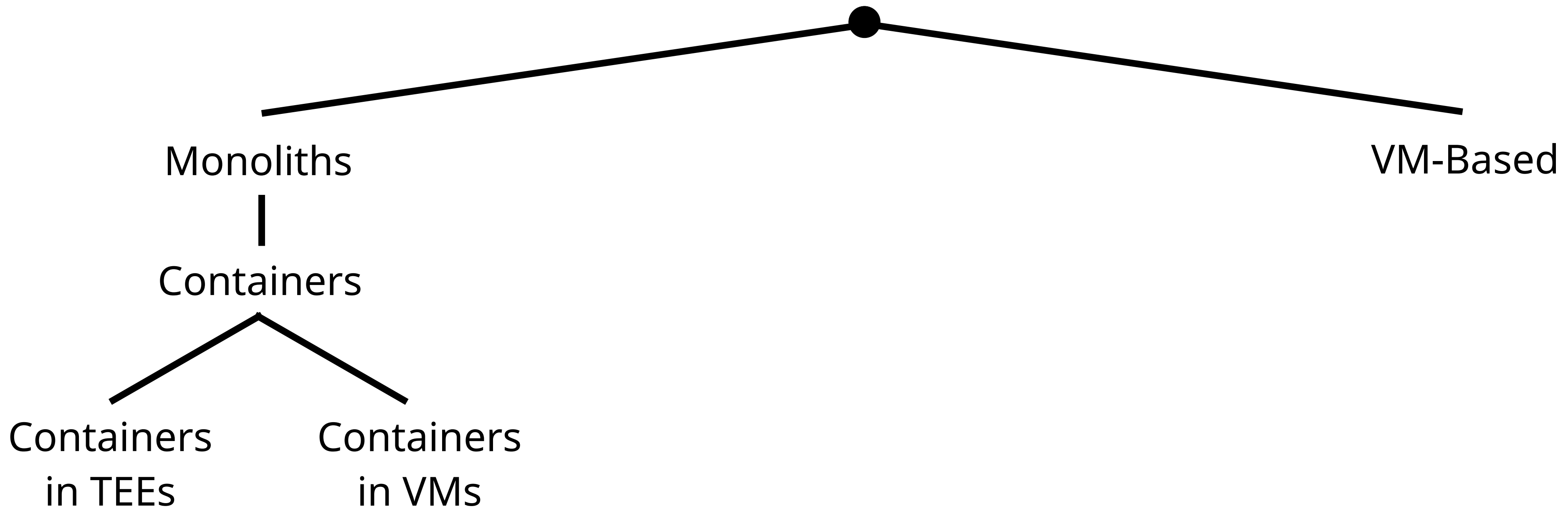
Hardening Operating Systems For The Cloud



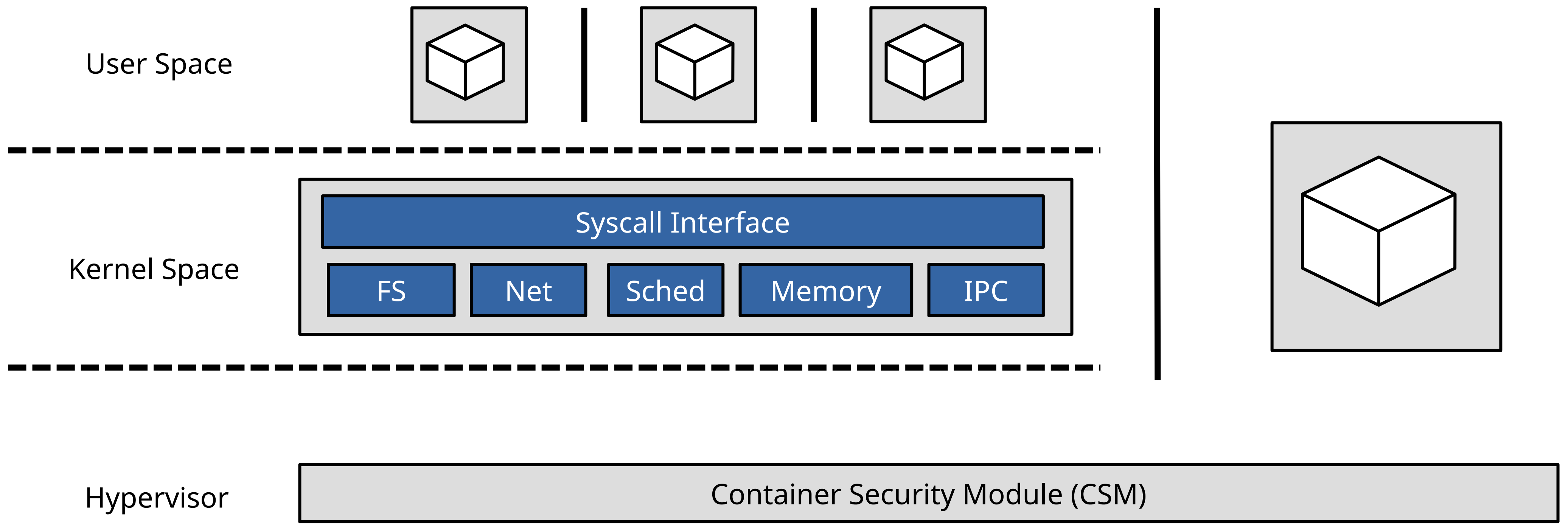
Running Containers as Virtual Machines

- Simpler hardware, yet strong isolation possible (BlackBox [VN22])
  - Runs on standard virtualization hardware

- Run containers on top of a *container security module* (CSM)
  - Linux VM with drivers etc. running beside application containers
  - CSM shields application containers
  - Applications should not have to trust function donor VM

Running Containers as Virtual Machines

- Simple hardware, yet strong isolation possible (BlackBox [VN22])
  - Only needs to trust CSM for security, integrity (~10k LoC)
  - Moderate performance overhead compared to native containers



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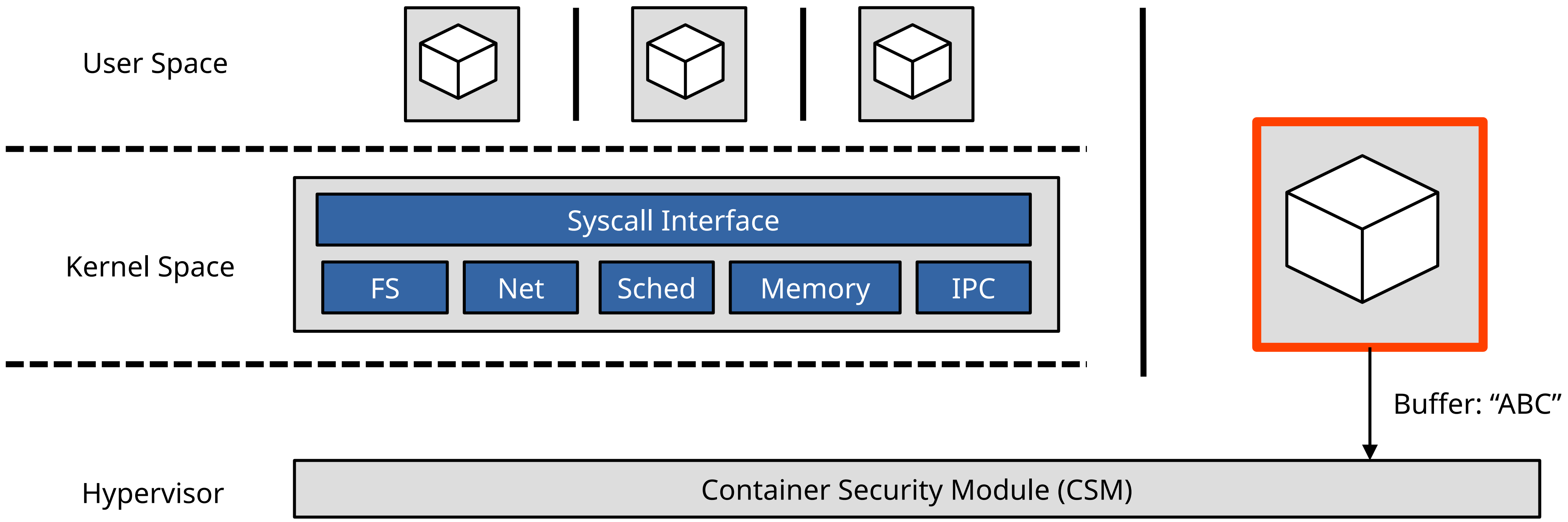

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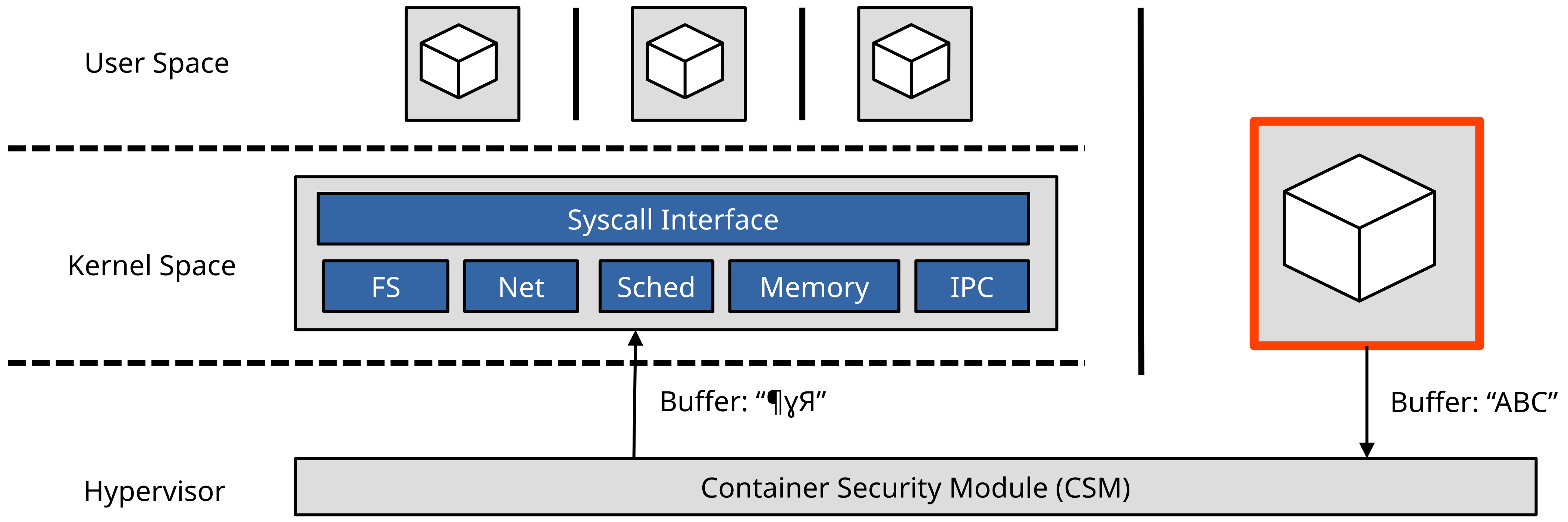
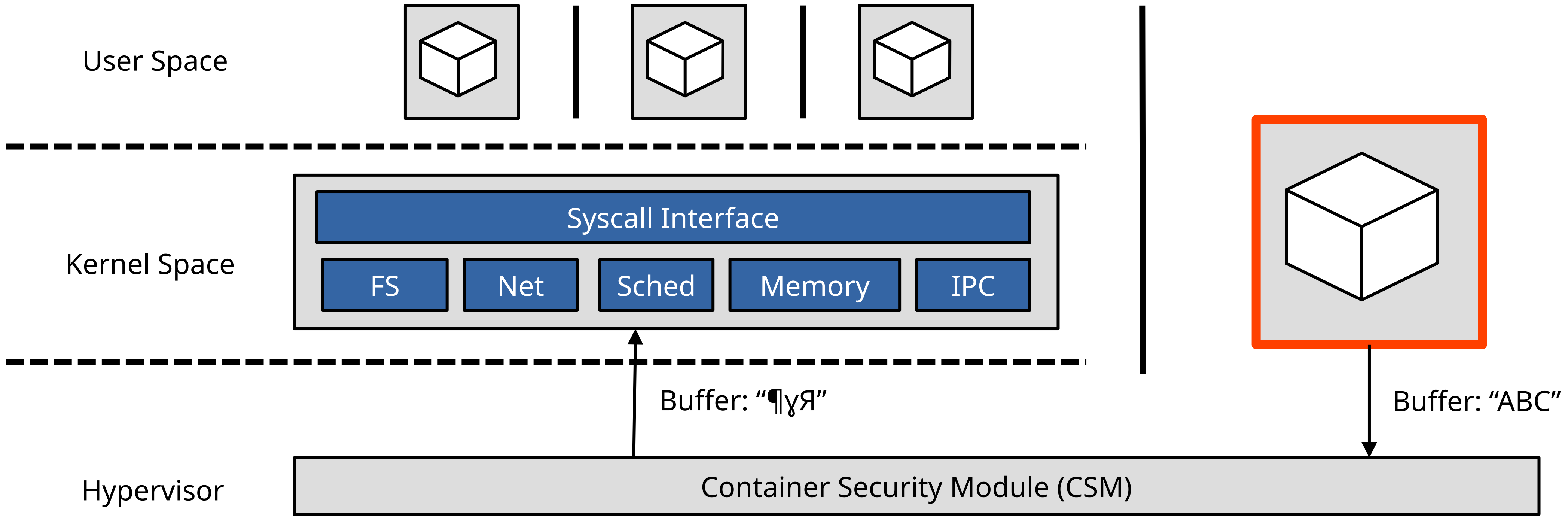


Running Containers as Virtual Machines

- Simple hardware, yet strong isolation possible (BlackBox [VN22])
  - What about the TCB size regarding availability?



Lightweight Virtual Machines

Virtual Machines in Dynamic Cloud Settings

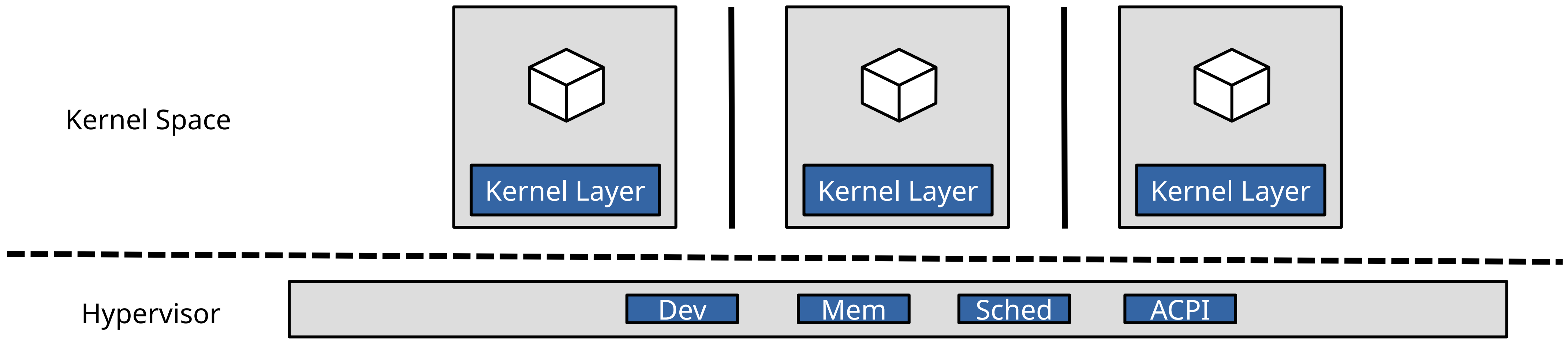
- Strong isolation between VMs
  - Hypervisor has a smaller interface to provide than an OS kernel
  - Hardware acceleration is wide-spread, also for many devices (SR-IOV [YY+08])

- Performance overhead cannot be avoided.
  - Nested paging
  - Device emulation

- Load complete kernel, startup considered slow [ML+17]
  - Partially caused by device initialization
  - Cost for being able to run arbitrary operating systems

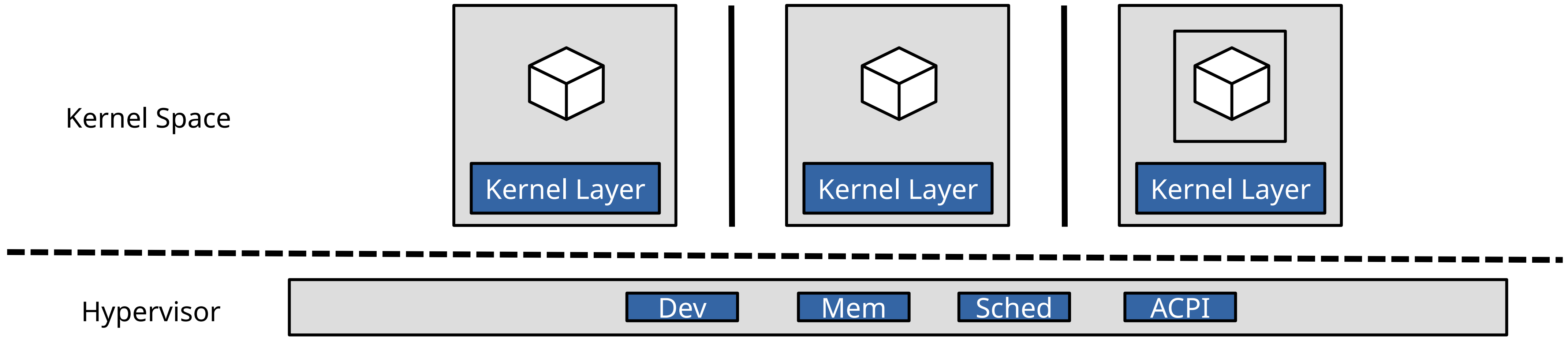
Lightweight Virtual Machines

- Reduce VM startup overhead, but retain isolation (e.g. LightVM [ML+17])
  - Remove unused devices etc.
  - Boot time as low as a couple of milliseconds
- Dedicated hypervisors offering tight feature set
  - E.g., Firecracker [AB+20] (used by AWS)



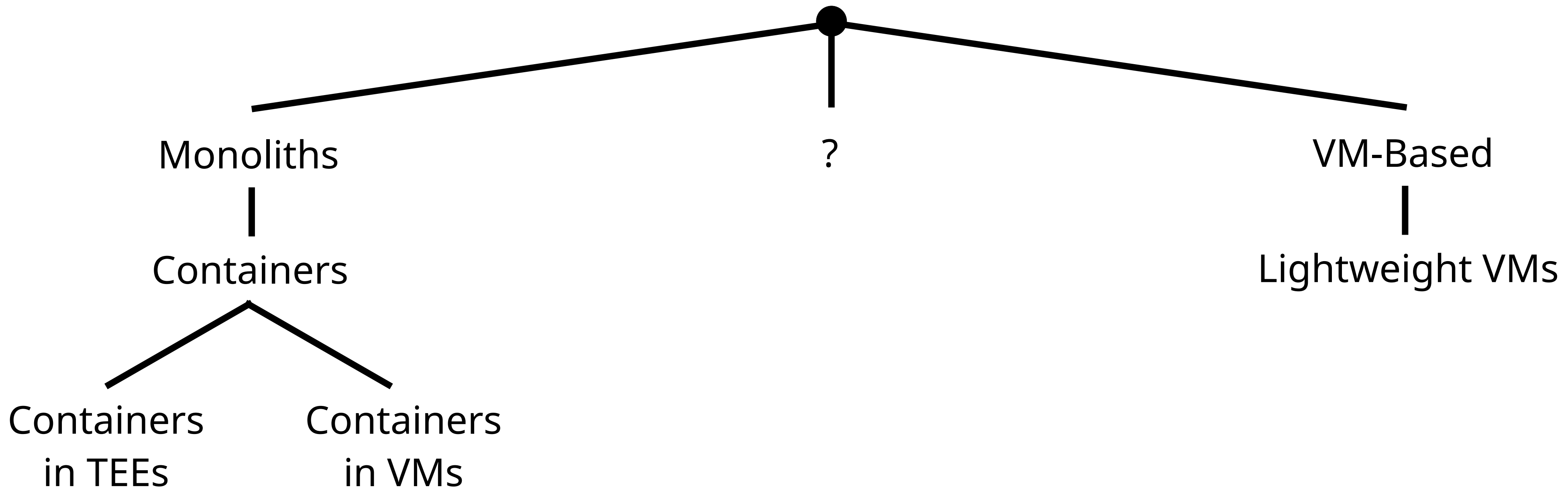
Lightweight Virtual Machines

- Flavor I: Unikernel guests (e.g., Unikraft [KB+21])
  - Performance and TCB advantages possible
- Flavor II: Containers inside lightweight VM (e.g., Kata containers [KC24])
  - Second layer of defense, used with Alibaba Cloud [LC+22]



Current Research: Microkernels as Data Center Substrate

Hardening Operating Systems for the Cloud



Containers on Microkernels

- General idea of microkernels: Minimize code running in kernel mode
  - Drivers, file systems, network etc. implemented in user space
  - Only requires basic CPU architecture (standard virtual memory and threads)

- Modern microkernels use capabilities for access control
  - Processes can only access resources for that they have been granted permission explicitly
  - No ambient authority

- Inter process communication (IPC) important for performance
  - Microkernels by design have performance disadvantages compared to monoliths

Till Miemietz, Viktor Reusch, Matthias Hille, Max Kurze, Adam Lackorzynski, Michael Roitzsch, Hermann Härtig: A Perfect Fit? - Towards Containers on Microkernels. WOC@Middleware 2024

Containers on Microkernels

- What if we used an OS with proper process isolation to begin with?
  - Capability-based access control
  - Small TCB for confidentiality, integrity, **and** availability

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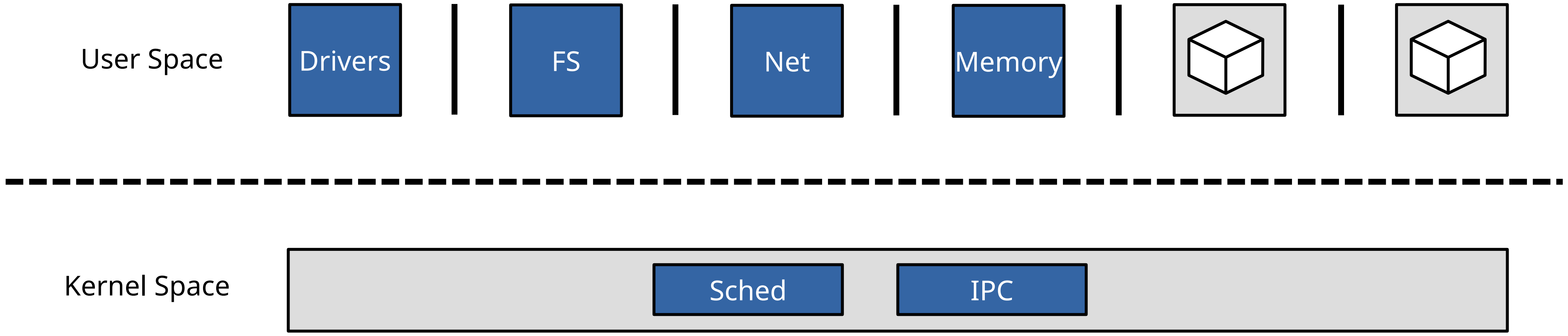

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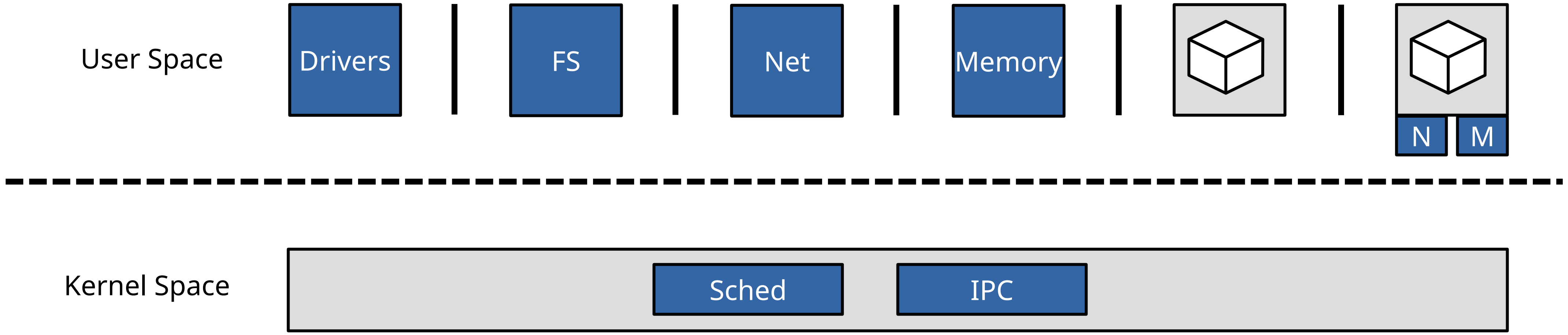

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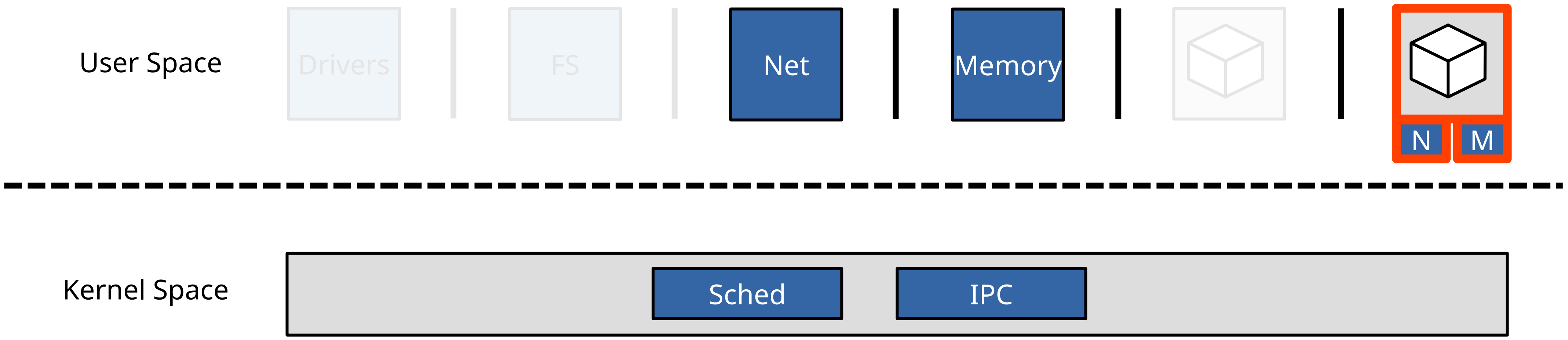

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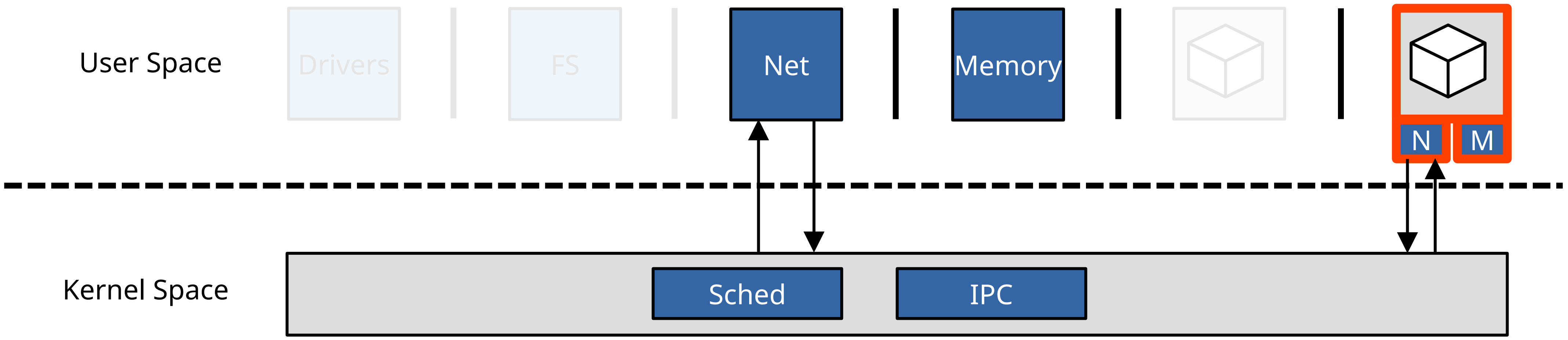
Containers on Microkernels

- What if we used an OS with proper process isolation to begin with?
  - Capability-based access control
  - Small TCB for confidentiality, integrity, **and** availability
  - Interaction with system services more expensive



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Containers on Microkernels

- Visibility restrictions
  - Integrated in capability system
  - Namespace abstraction also exists on L4Re

- Interface restrictions: Containers can only access a minimal interface by design
  - There is no ambient authority.

- Resource restrictions
  - Tied to capability
  - To be implemented by individual service

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Does It Work in Practice?

- Simplicity reduces attack surface by orders of magnitude

- What about performance?

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Does It Work in Practice?

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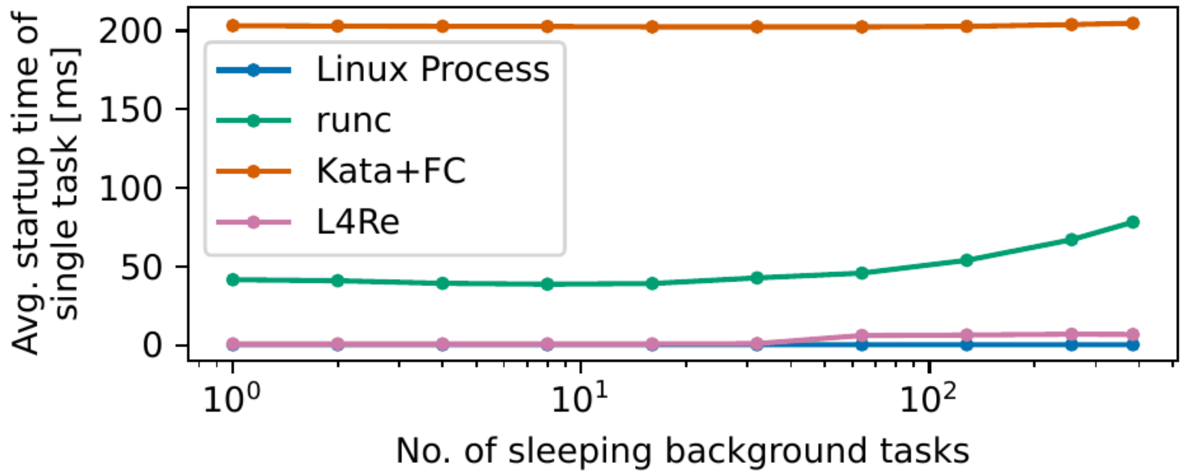
- Starting a single container



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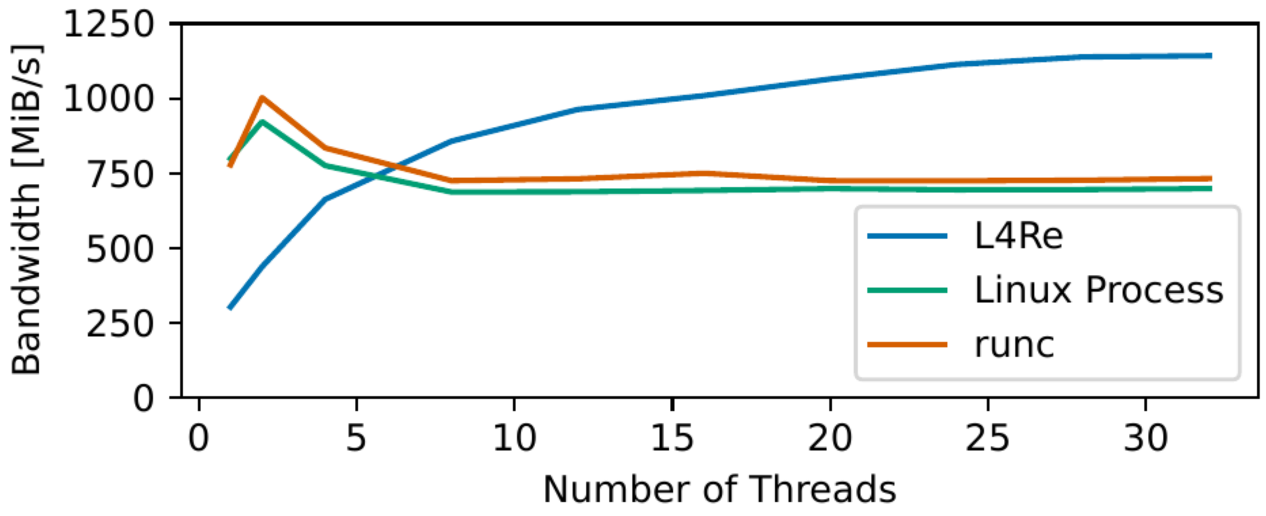

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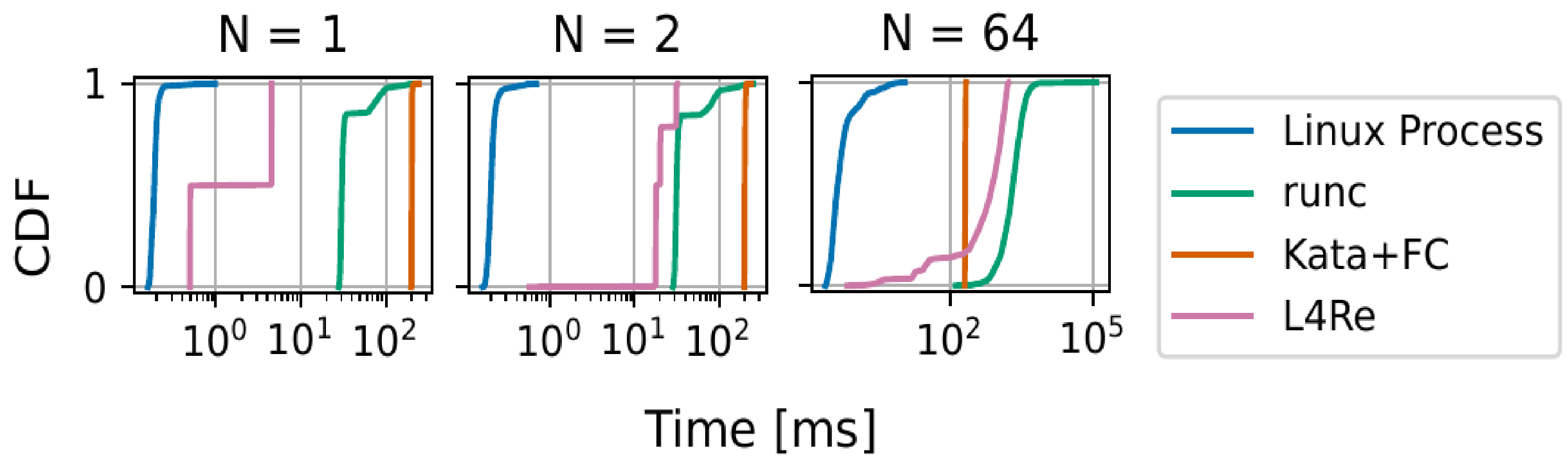
- Parallel container startup



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Summary: Mechanisms for Isolating Cloud Applications

Approach	Isolation	Small TCB	Low Overhead	Scalability	Compatibility
Monolith	X	X	✓	✓	✓

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Microkernel	✓	✓	?	?	?

Summary

- Current isolation mechanisms in dynamic cloud settings complex
  - Requirements: Strong isolation between clients, fast startup, good performance
  - Large attack surface hard to avoid with standard system design

- Capability-based microkernels with strong built-in isolation
  - Container isolation is conceptually simple on a microkernel

- Simplicity is key for building secure systems
  - Holds for both software and hardware
  - Modularity to have the choice of including complex, high-performance implementations in TCB

References for Further Reading I

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