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Libservices: Dynamic Storage Provisioning for Multitenant I/O Isolation

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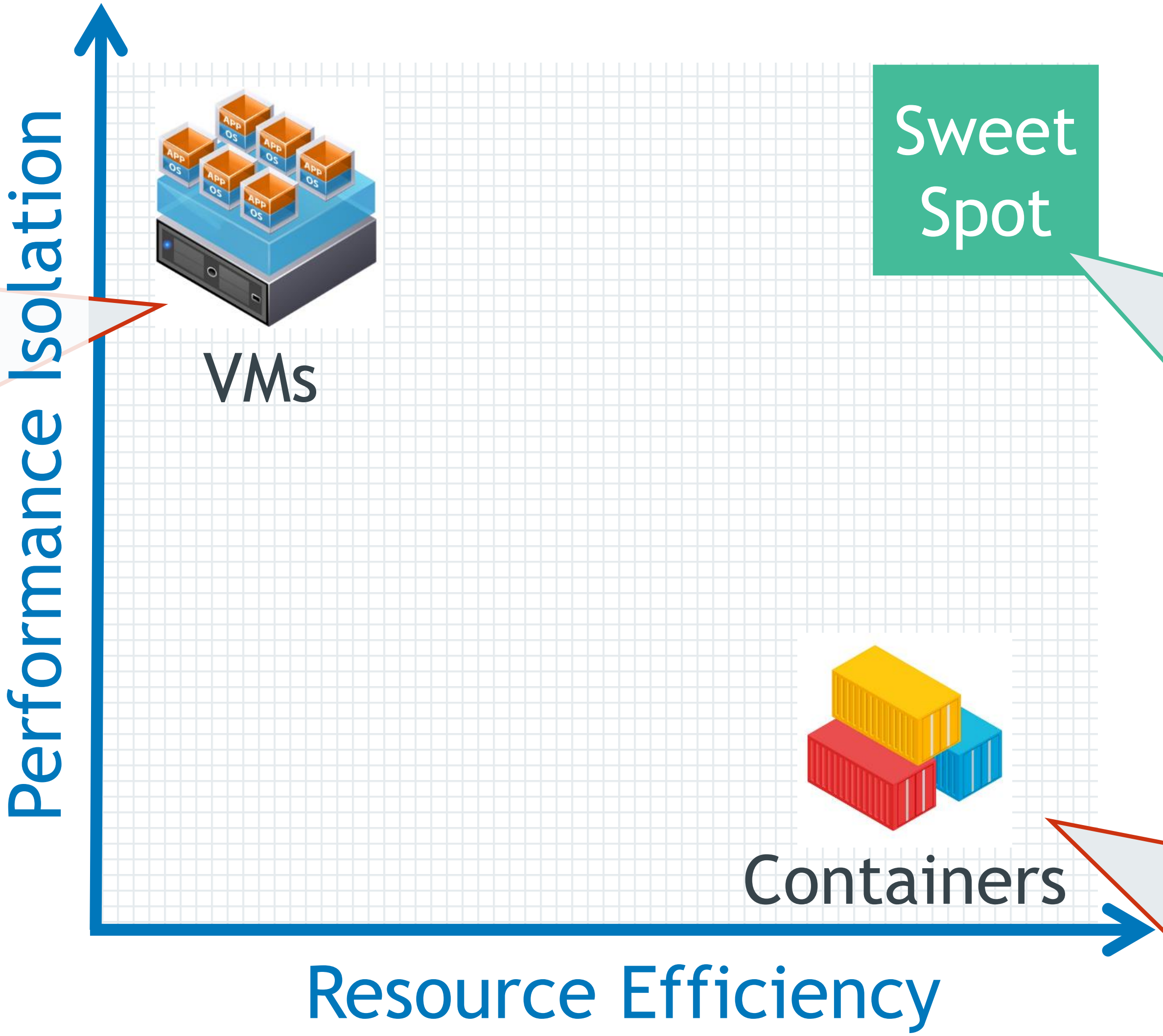
Isolation or Efficiency?

High overhead
High footprint
Static resources
Strong isolation



Low overhead
Low footprint
Adaptive resources
Strong isolation

Low overhead
Low footprint
Adaptive resources
Weak isolation

Serving Data-Intensive Applications

User facing; Processing vast amounts of data; Variable demands

- E.g., Key-value stores, interactive applications, real-time big data

Predictable performance

- Latency-sensitive
- Strict Service-Level Objectives (tail latency)

Sensitive to interference

- Tail latency increases with load

How to achieve high resource efficiency?

- Dynamic resource allocation
- Workload collocation

Container Resource Isolation

Limit the container resource view and usage

- Private resources: assigned exclusively to tenants
- Shared resources: limit enforcement, accounting
- Isolation: A tenant should only consume its assigned resources

Namespaces: Isolate resource names

- **Process:** Process IDs
- **Mount:** Mount Points
- **IPC:** SysV IPC, Message Queues
- **User:** User and Group IDs
- **Net:** Net Devices, stacks, ports

Cgroups: Isolate resource usage

- **CPU:** CPU, Cpuset controllers
- **Memory:** Memory controller
- **I/O:** IO Controller
- **Network:** net_cls (class), net_prio (priority) controllers

Multitenancy Setup

Tenant

- 1 Container
- 2 CPUs (Cgroups v1), 8GB RAM (Cgroups v2)

Container Host

- Up to 32 tenants

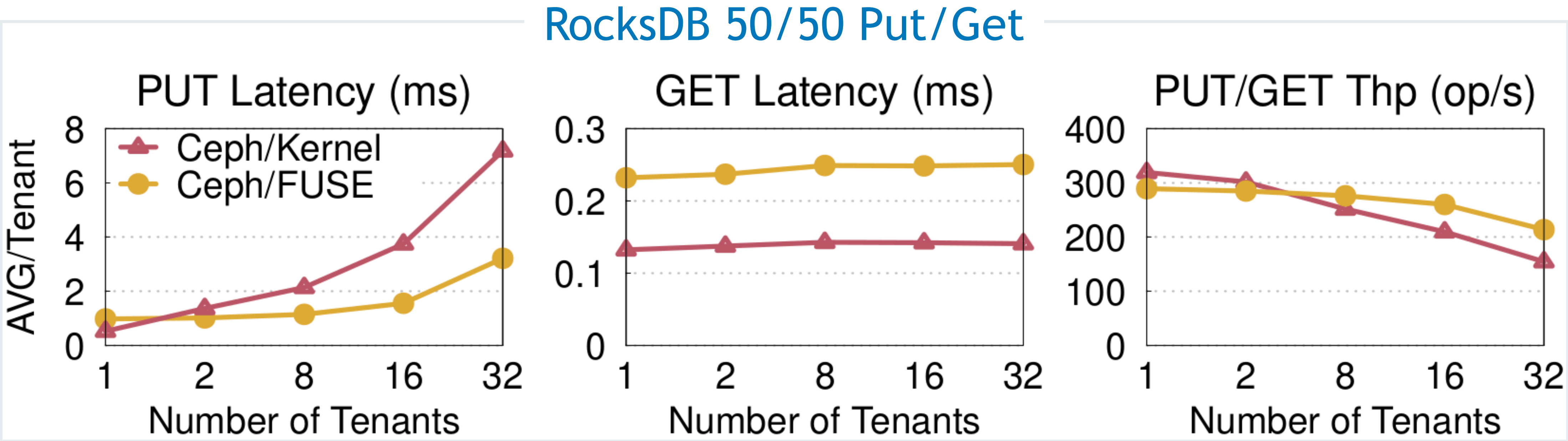
Container Application

- RocksDB

Shared Storage Cluster

- Ceph
- Per container root directory trees

Motivation: Collocated I/O Contention



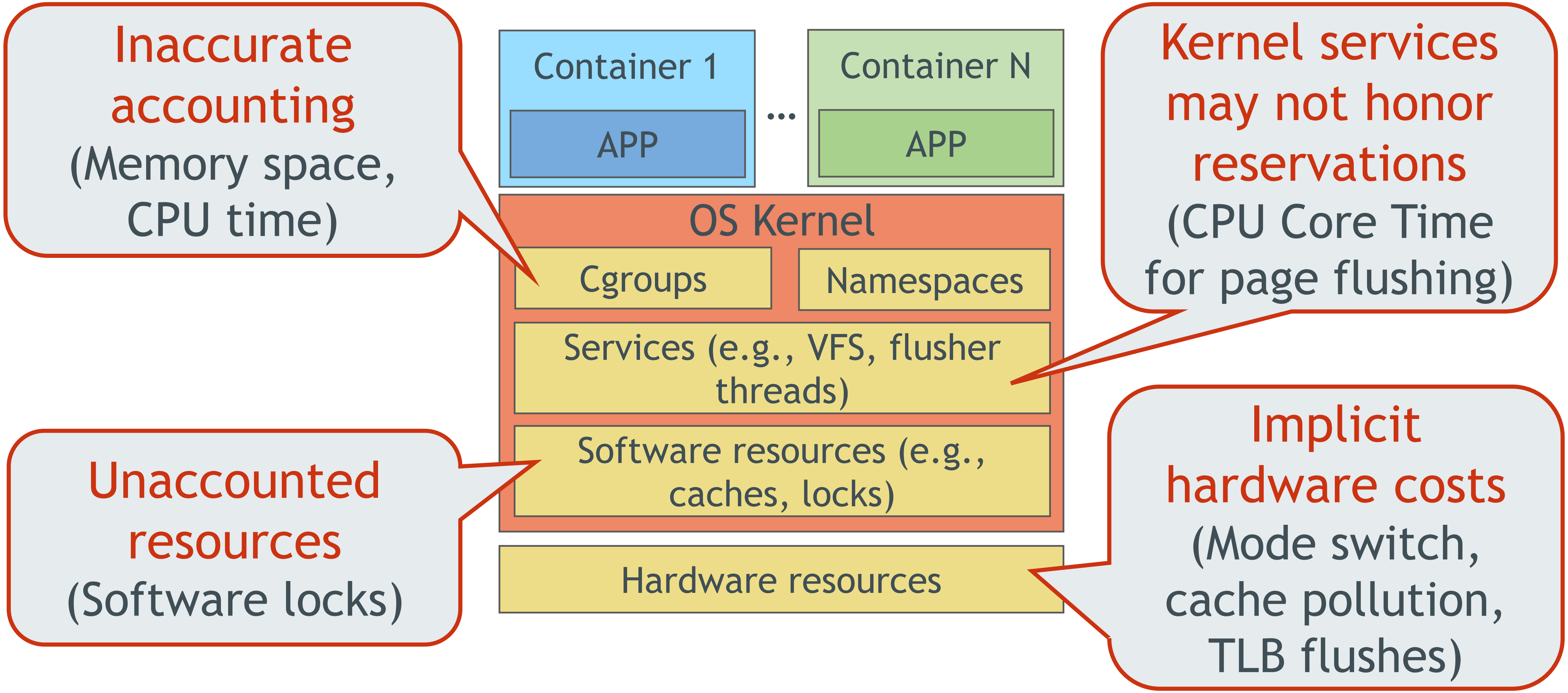
Outcome

- Workload collocation: severe performance variability & slow down

Reasons

- Contention on shared kernel data structures (locks)
- Kernel dirty page flushers running on arbitrary cores

I/O Multitenancy Issues



Existing Solutions

Kernel structure partitioning

- Performance overheads from static partitioning
- High engineering effort to refactor the entire kernel
- E.g., IceFS (OSDI ‘14), Multilanes (FAST ‘14)

Dynamic resource allocation

- Hardware resources only (e.g., CPU, RAM)
- No guarantee for fair allocation of system services (page flushing)
- E.g., PARTIES (ASPLOS ‘19)

Lightweight hardware virtualization

- Virtualization overheads, static resource allocations
- E.g., LightVM (SOSP ‘17), X-Containers (ASPLOS ’19)

The libservices unified framework

Goals

- Isolation: Tenant resource utilization limited by reservations
- Elasticity: Dynamic resource allocation
- Efficiency: Low virtualization cost
- Compatibility: Unmodified applications

libservices

- User-level storage functions derived from existing I/O libraries
- Build complex filesystem services for the client and server

Key concepts

- Same design pattern at client and server
- Dynamic provisioning of storage systems per tenant
- User-level storage services over reserved resources

Dynamic Storage Provisioning

Storage System

- Client-Server Architecture

Application Filesystem

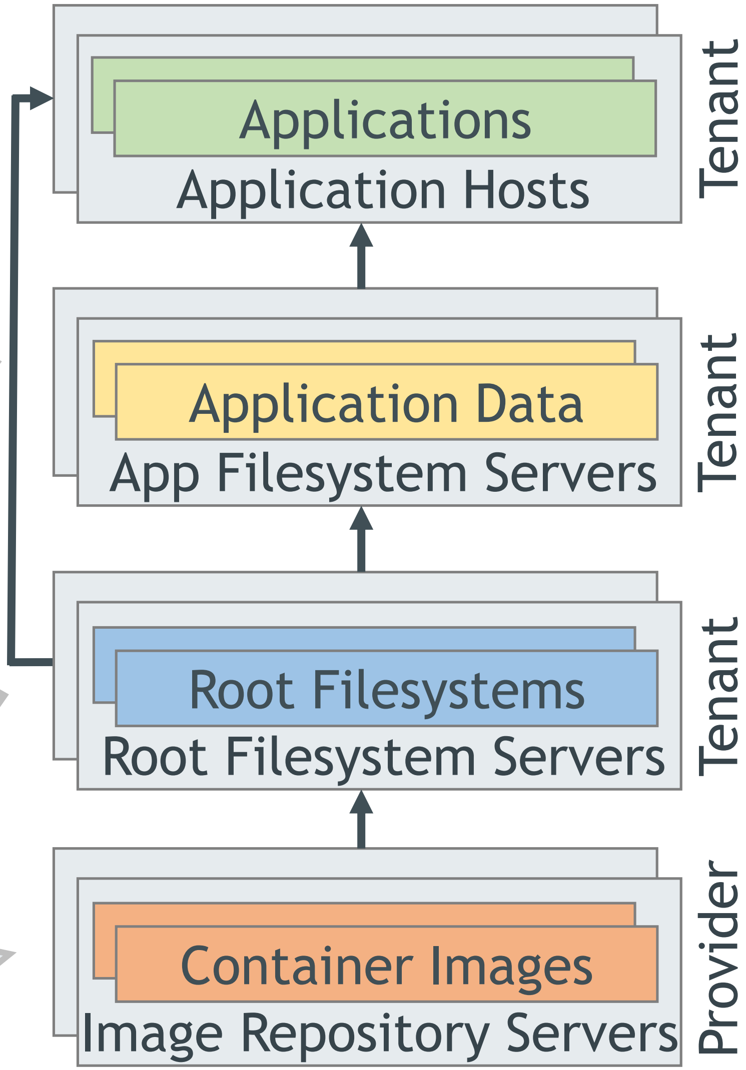
- Stores application data
- Serves tenant applications

Root Filesystem

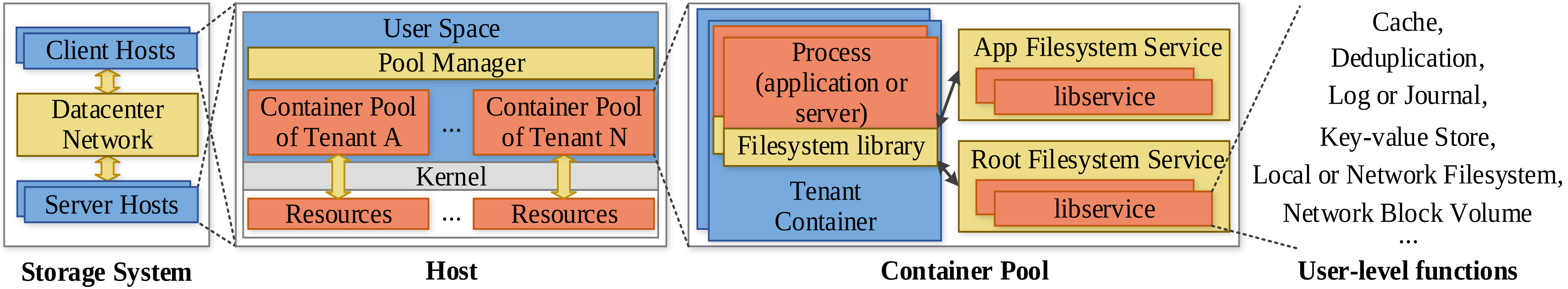
- Stores container root filesystems
- Serves Application containers & Application Filesystem servers

Image Repository

- Stores and distributes container images



User-level Storage Framework



Container Pool

- Collection of Containers
- Per tenant / machine

Pool Manager

- Manages pool resources
- Per machine

Filesystem Service

- Collection of user-level I/O services per tenant

Filesystem Library

- Storage access to applications at user level

Libservice

Standalone user-level storage function, e.g.,

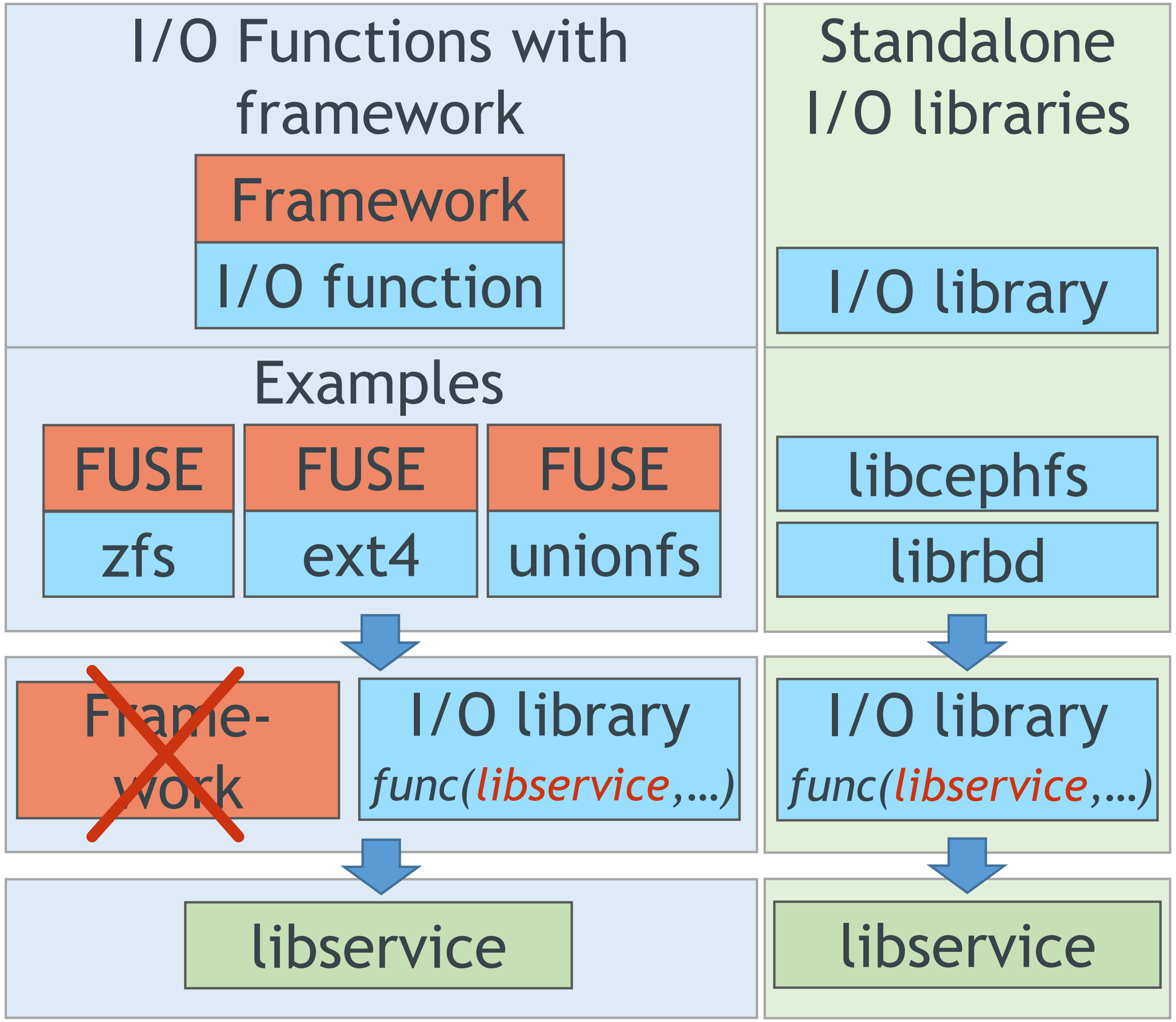
- Network filesystem client
- Local filesystem
- Block Volume
- Cache
- Deduplication
- Log
- Key-Value store

Filesystem Service

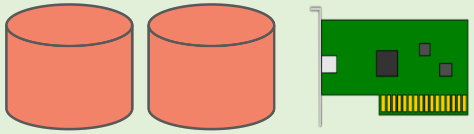
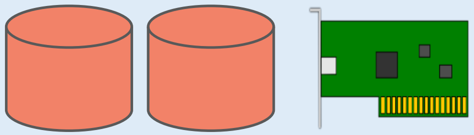
- Stack or tree of libservices
- Requests pass through libservices from top to bottom

Building Libservices

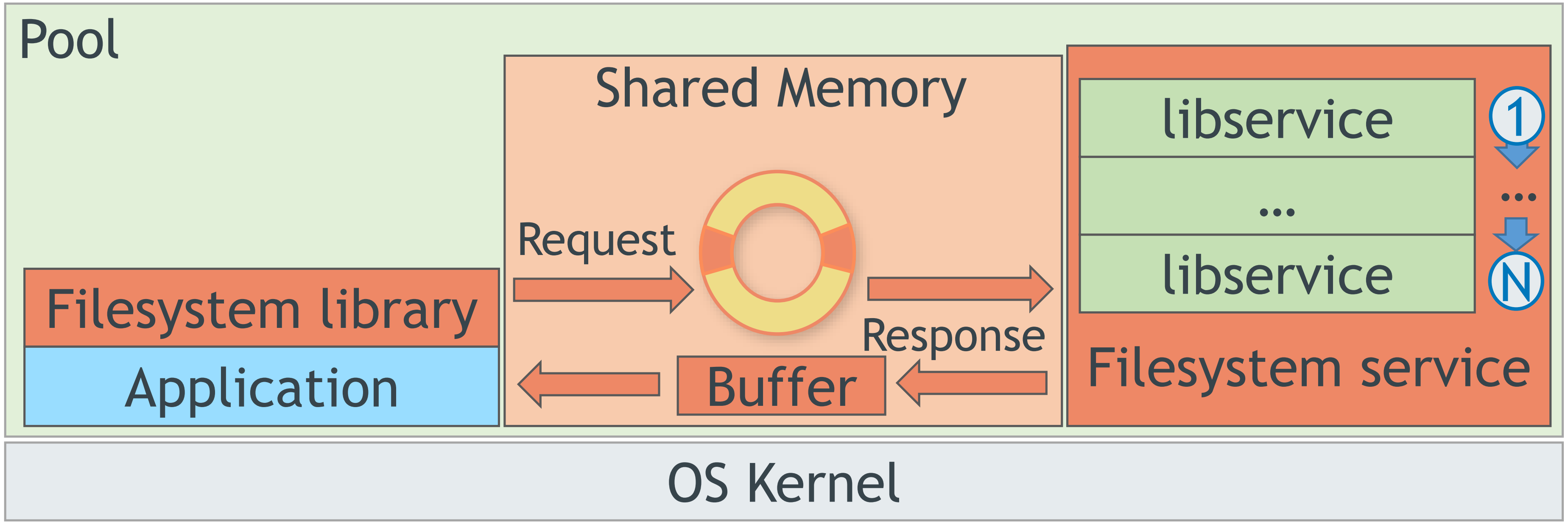
1. Use existing I/O component
   - I/O function & framework
   - Standalone I/O library
2. Create standalone library
   - Separate I/O function from framework, global deps
3. Port I/O library to libservice interface
   - Libservice object first parameter to I/O functions



Libservice Functions

Client	Server
Serves applications, pool managers, orchestration systems	Stores data and metadata on local storage devices
Union — File deduplication Cache — Data/metadata Caching Local Filesystem, Network Block Volume, Network Filesystem — Remote storage access	Log or Journal — Crash recovery Key-value Store — Metadata storage Cache — Data/metadata caching Deduplication — Block deduplication Local filesystem — Persistent storage
 Local storage and network devices	 Local storage and network devices

Interprocess Communication



User level

- Minimize mode switches & CPU cache stalls

Per pool shared memory

- Circular queues for requests
- Shared buffers for responses

Resources and Devices

Resource reservation

- Guarantee resource limits (CPU, RAM, Net, I/O)

Resource management

- Resource tracking and process accounting
- Dynamic resource allocation based on reservations & utilization

Device management

- Protected operation of local devices

Our approach

- Kernel Cgroups for accounting of user-level processes
- Possible to manage the network & storage devices at user level

Example Storage Systems

Root Filesystem (boot application & storage containers)

- Client: Network FS with cache (CephFS); Union FS (AUFS)
- Server: Local journaled FS (ext4); Key-value store (RocksDB)

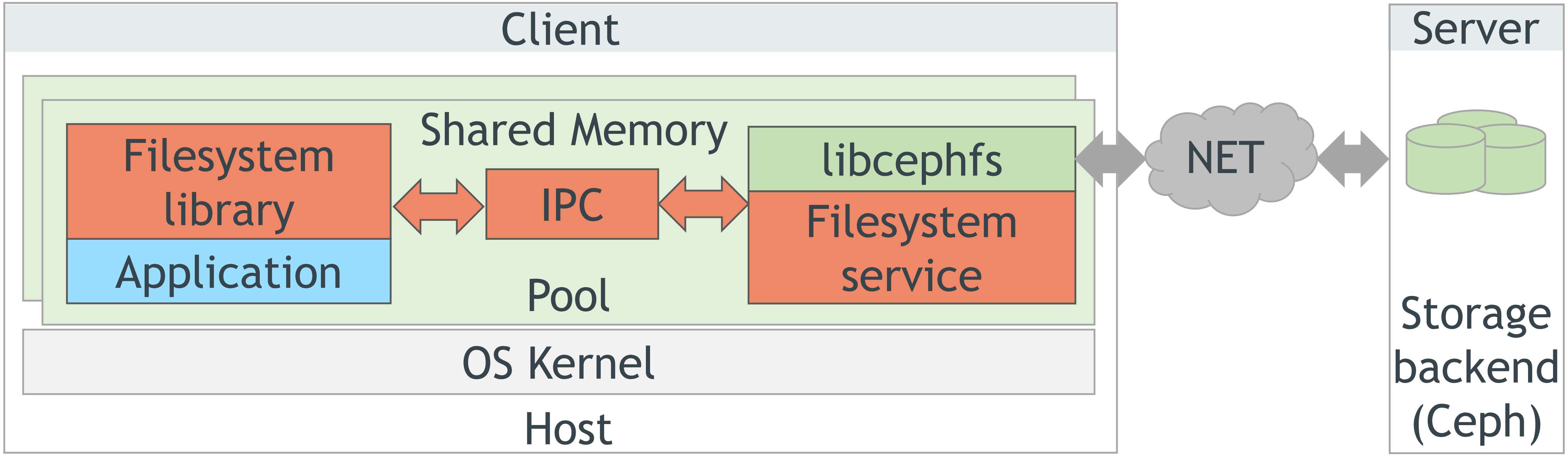
Application Filesystem (serve applications)

- Client: Network FS with cache (CephFS)
- Server: Local journaled FS (ext4); Key-value store (RocksDB)

Container Image Storage (image repository)

- Client: Network FS with cache (NFS)
- Server: Local FS with cache & deduplication (ZFS)

Early Prototype: Client per tenant



Provision the client side of the root filesystem storage system

- Filesystem service: libcephfs libservice (network client and cache)
- Filesystem library: preloaded to applications (LD_PRELOAD)
- IPC: User-level shared-memory

Test Setup

2 Servers

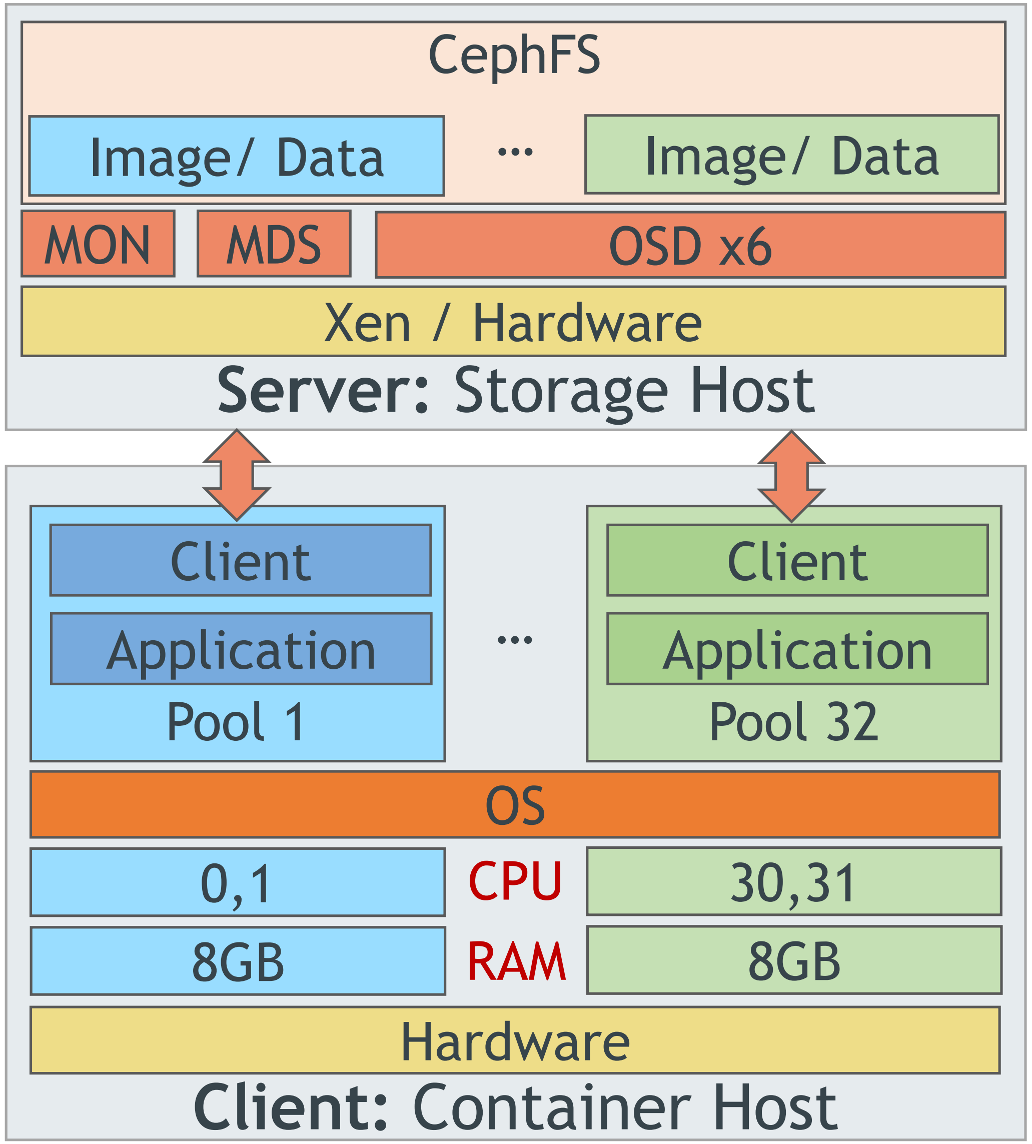
- 64 Cores, 256GB RAM
- 2 x 10Gbps Ethernet
- Linux v5.4.0

Shared CephFS

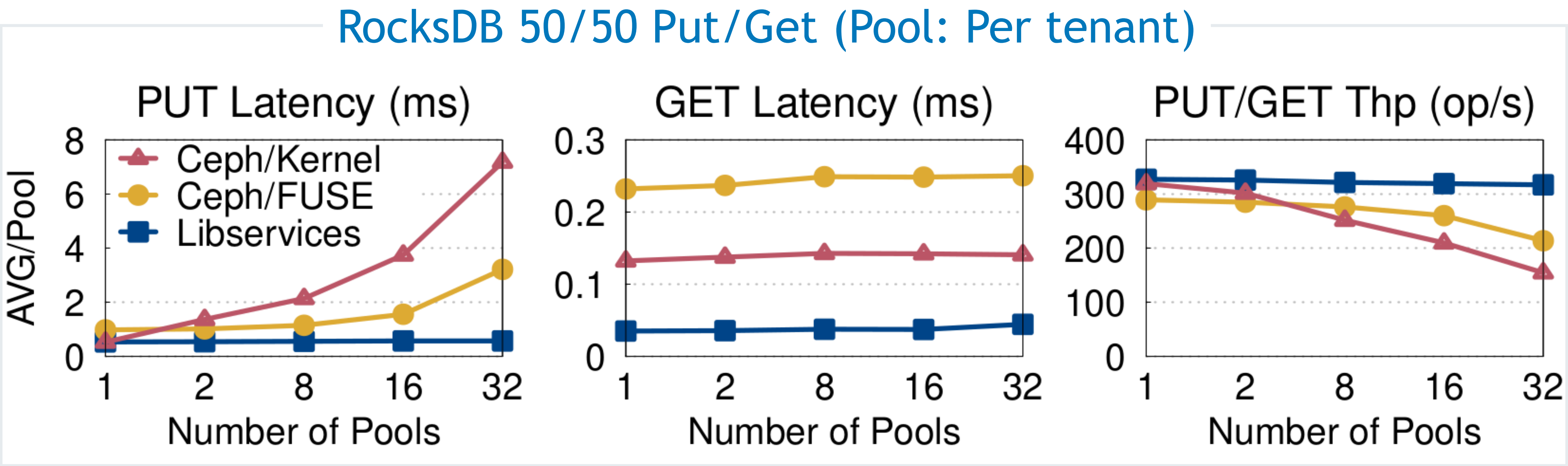
- 6 OSDs (2 CPUs, 8GB RAM, 24GB Ramdisk for fast storage)
- 1 MDS, 1 MON (2 CPUs, 8GB RAM)

Container Pool

- 1 Container
- 2 CPUs (Cgroup v1 - cpuset)
- 8 GB RAM (Cgroup v2 - memory)



I/O Workload Collocation



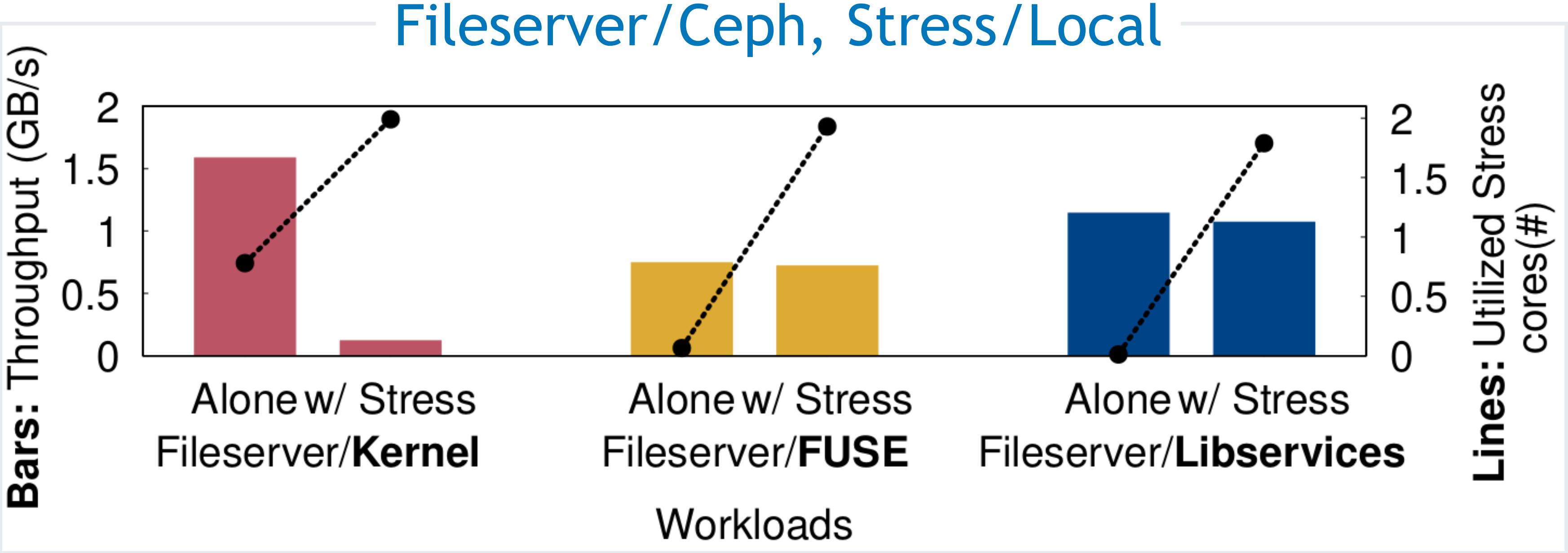
Libservices achieve faster I/O response & stable performance

- **Put latency (longer)** FUSE: up to 5.6x, Kernel: up to 12.6x
- **Get latency (longer)** FUSE: up to 3.9x, Kernel: up to 6.7x
- **Throughput (slowdown)** FUSE: up to 1.5x, Kernel: up to 2.1x

Contention Sensitivity

2 Containers of

- 2 Cores
- 8GB RAM
- Fileserver or Stress with rand I/O



Outcome

- Kernel client sensitive to contention
- Throughput drops up to 12.9x when collocated with Stress

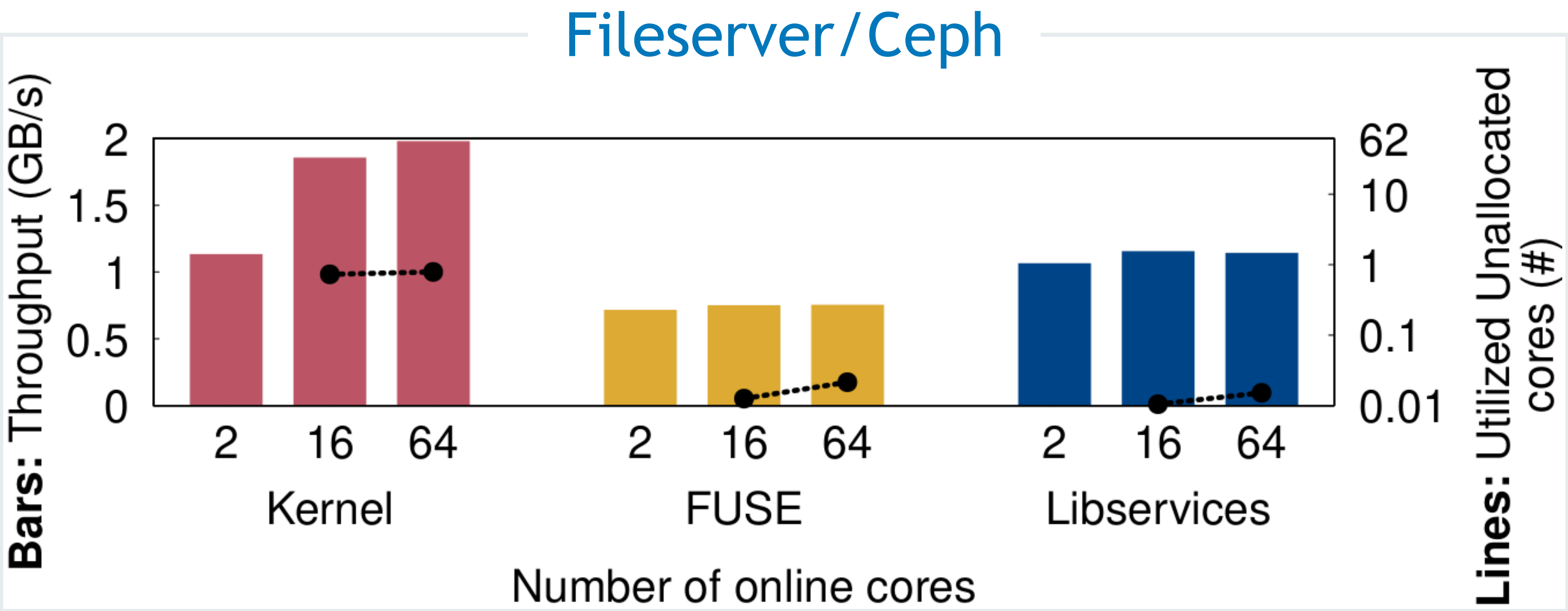
Reason

- Kernel I/O utilizes all cores (dirty page flushing)

Violation of Resource Limits

1 Container of

- 2 Cores
- 8GB RAM
- Fileserver



Outcome

- The Kernel client increases performance up to 75% because it utilizes unallocated cores
- Kernel flusher threads run on non allocated cores

Conclusions & Future Work

The Problem: Performance variability from shared Kernel I/O

- Lack of accounting; Aggressive resource utilization

Our Solution: Libservices Framework

- Performance isolation combined with high efficiency
- I/O performance isolation by handling container I/O at user level
- Same design pattern for the client and server of a storage system
- Dynamic provisioning of container storage systems

Future Work

- Dynamic readjustment of allocated resources (e.g., memory)
- Network and storage device management at user level
- Resource scheduling services at user level (e.g., Cgroups)