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Scale and Performance in a Filesystem Semi-Microkernel

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University of Wisconsin – Madison
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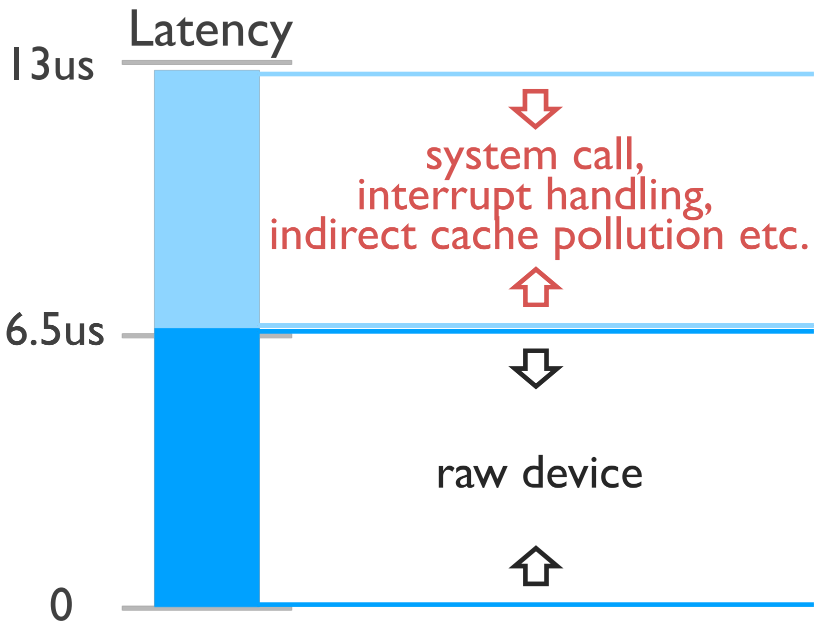
HW is Fast – but SW Appears Slow

How to close the HW-SW performance gap in storage stack?

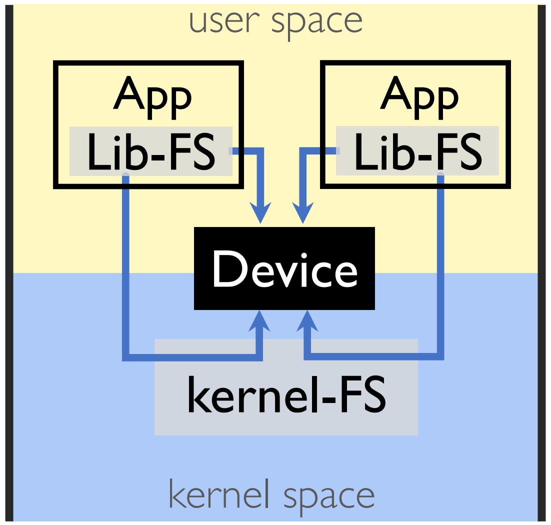


Barroso *et. al*, Attack of the Killer Microseconds, 2017

Existing Solutions

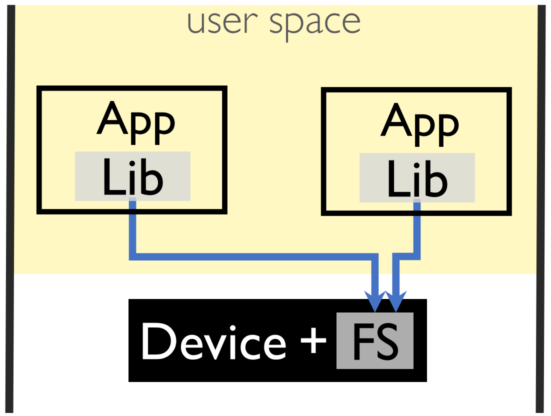
Libraries directly access the device

- E.g., Strata (SOSP-17), SplitFS (SOSP-19)
- Complicate the device access isolation and sharing



Move Filesystems to the device

- E.g., DevFS (FAST-18), CrossFS (OSDI-20)
- "Smarter-HW" assumption and unknown HW constraints



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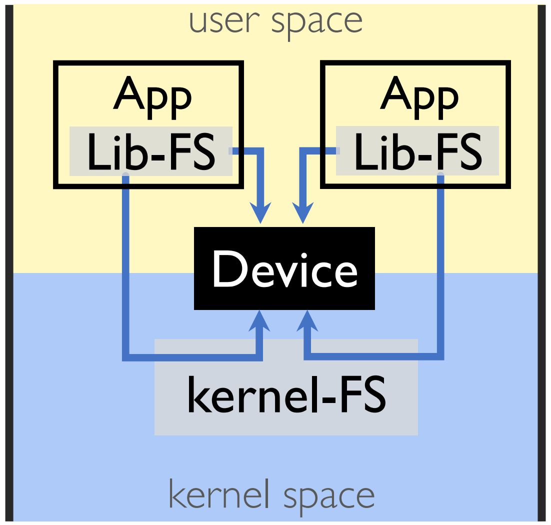

Centralized IO multiplexing; simpler isolation and sharing

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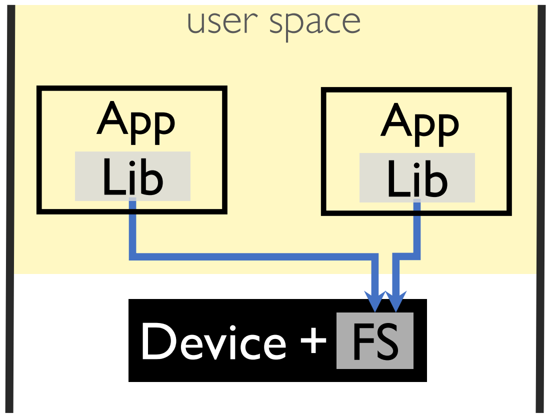
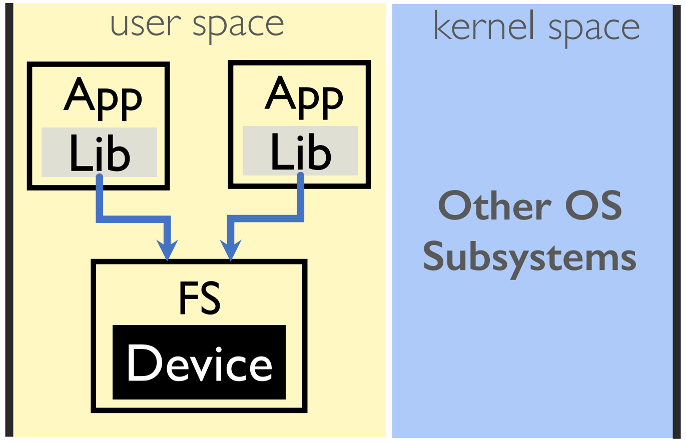


Realistic Assumption: Ultra-fast Devices and NVMe protocol

Our Approach: Filesystem Semi-Microkernel

What is a "Semi-Microkernel"?

- An OS subsystem that runs as a user-level process
- Works in tandem with the monolithic kernel



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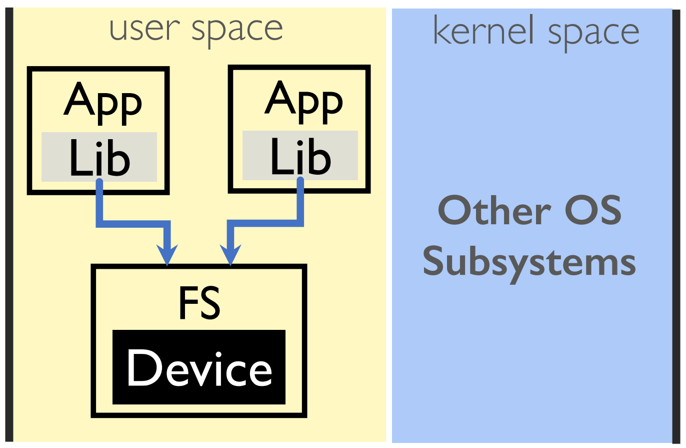

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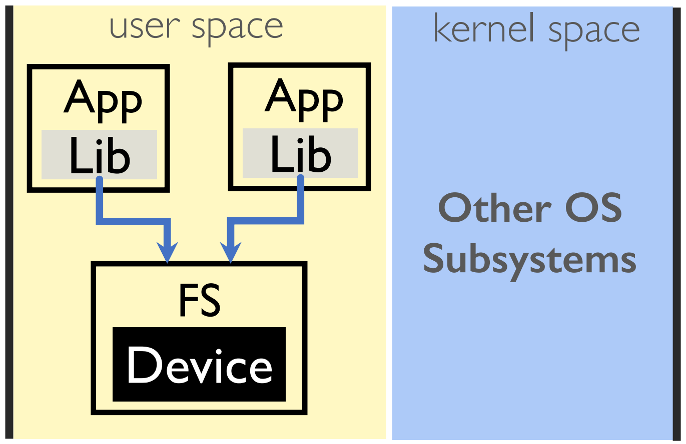
Prior networking semi-microkernels

- Snap (SOSP-19), TAS (Eurosys-19)

Possible for storage now

- User-level device drivers

Benefits of Filesystem Semi-Microkernels



Development and Deployment Velocity

- Developing tools and libraries for "application" code
- Rapidly adopt hardware and tailor for applications

Performance

- Optimize for device access (avoid the kernel SW overhead)
- Scale filesystem independently from applications

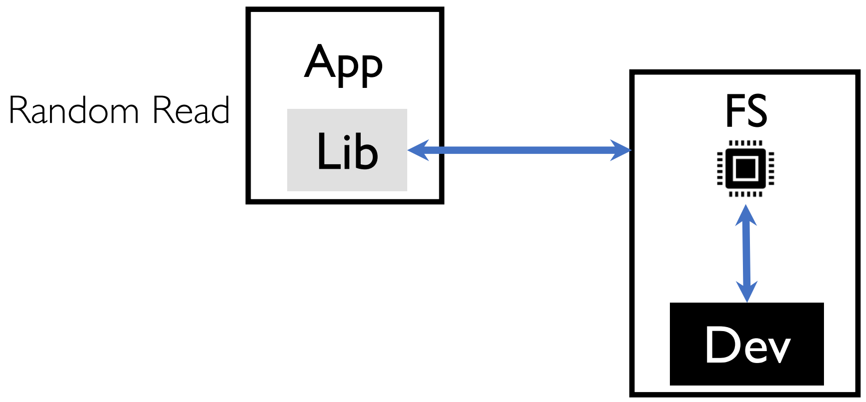
Simplify the sharing and permission

- Untrusted applications cannot access the device

Challenges

Base Performance

- Inter-process communication
- Device access



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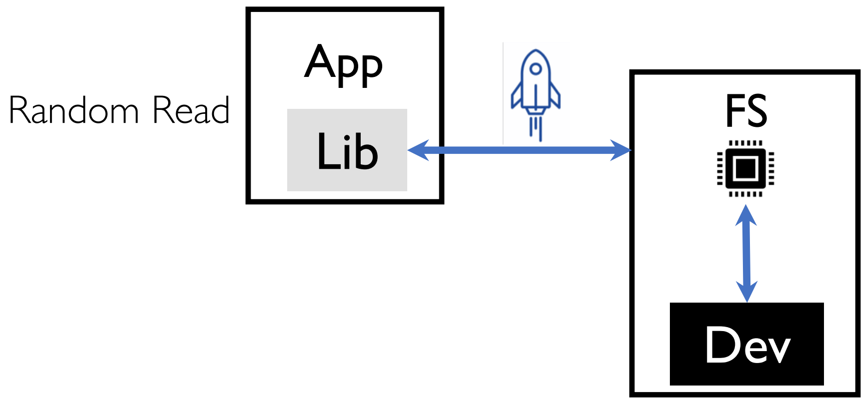

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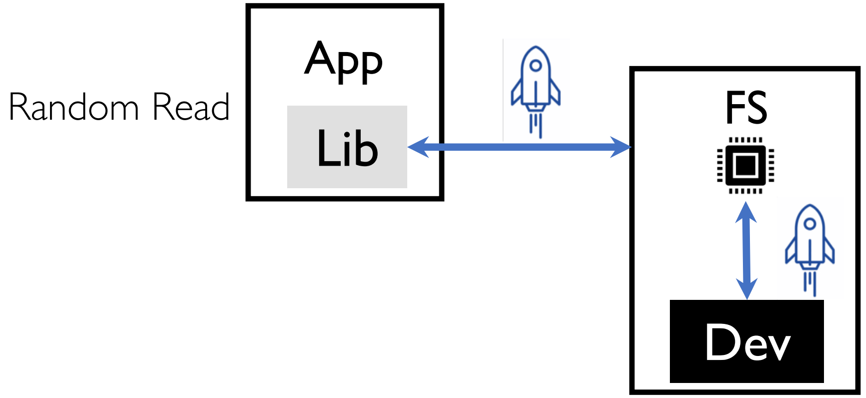

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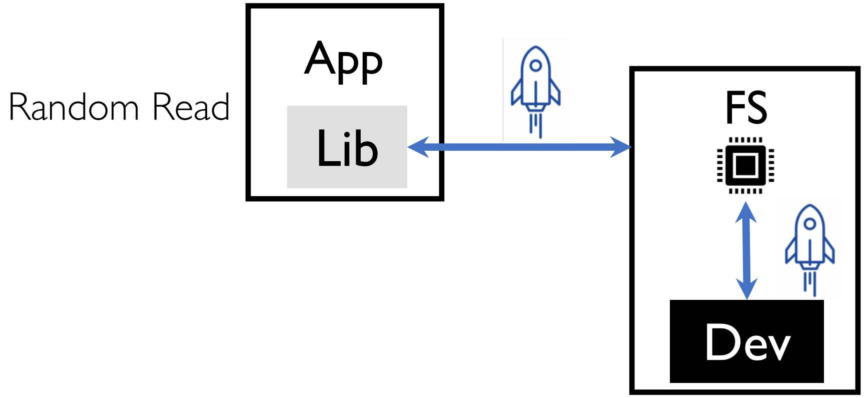

Base Performance

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Scales up and down

- Dynamic and heterogeneous application demand
- Invests just-right amount CPU
  - Fully utilize the devices
  - Keep up with the apps

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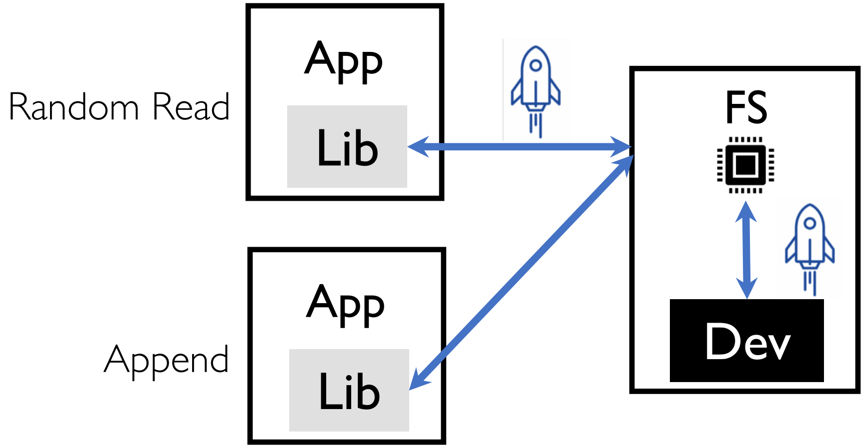

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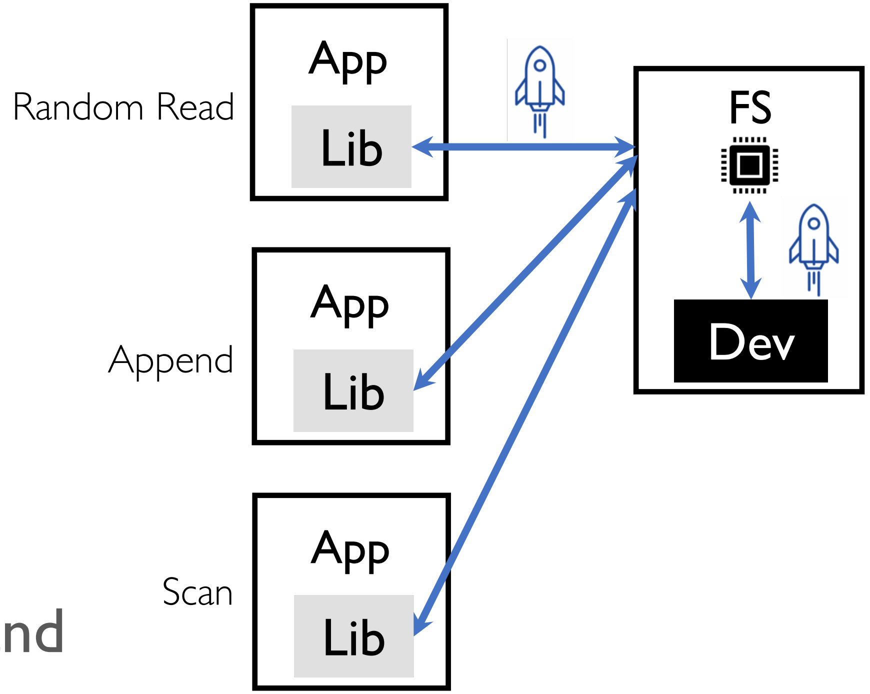

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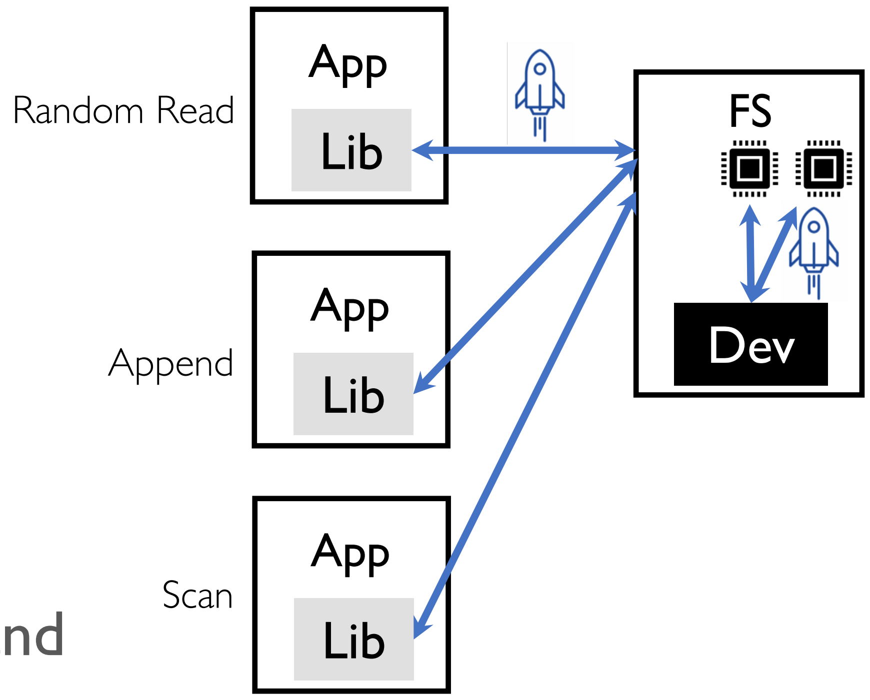

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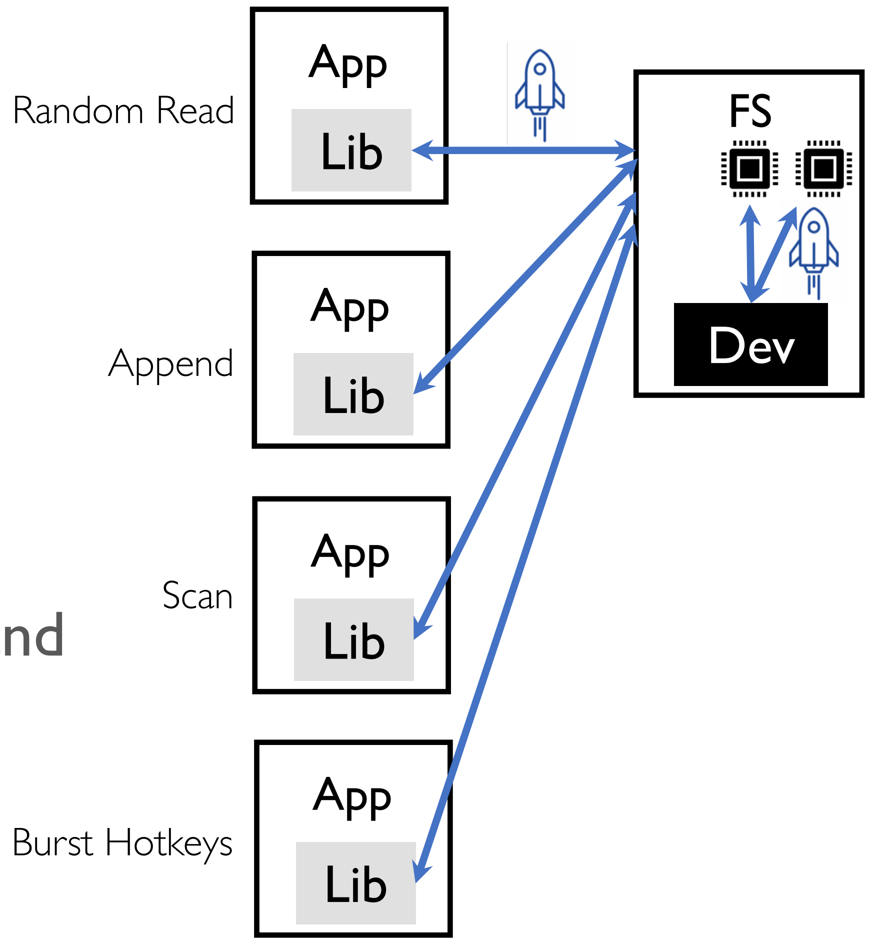

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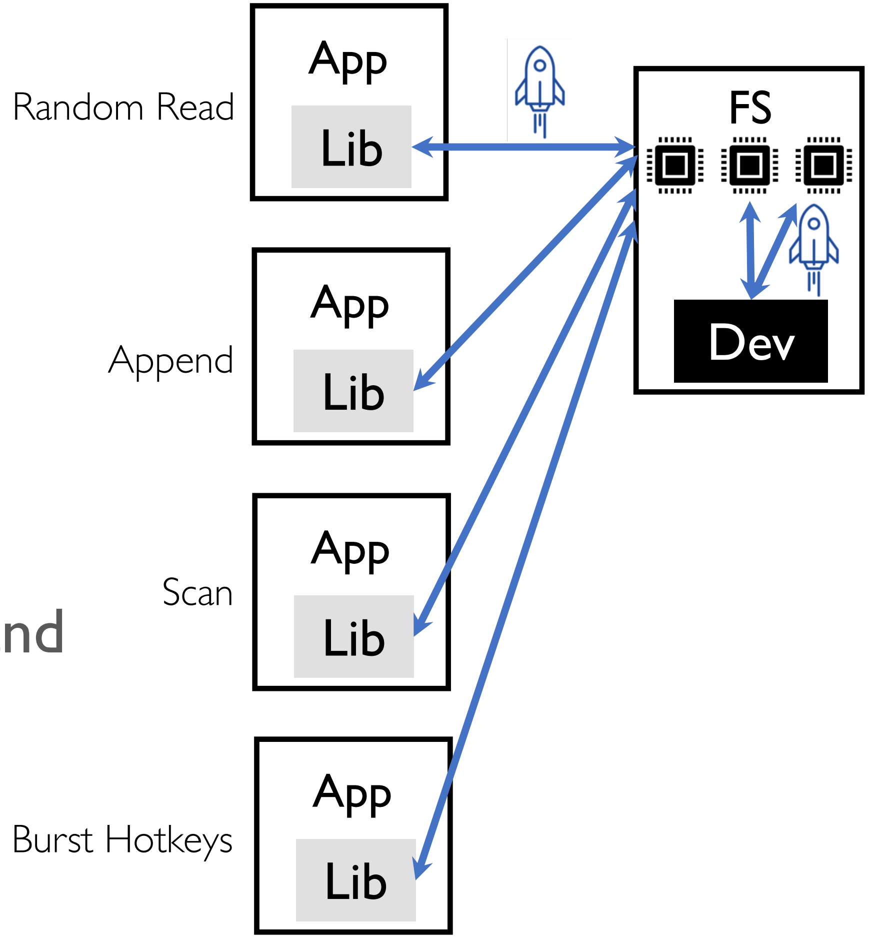

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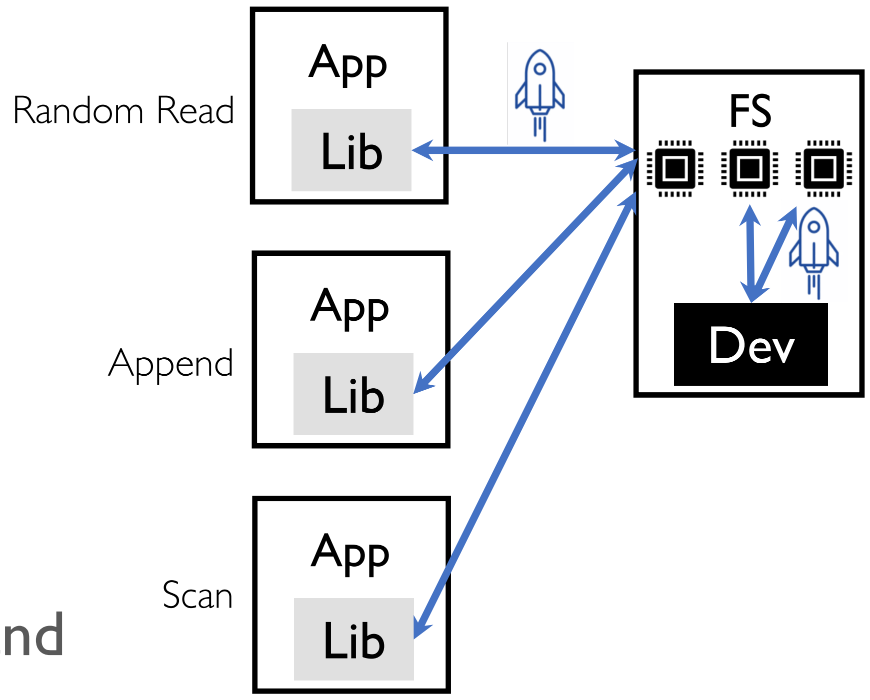

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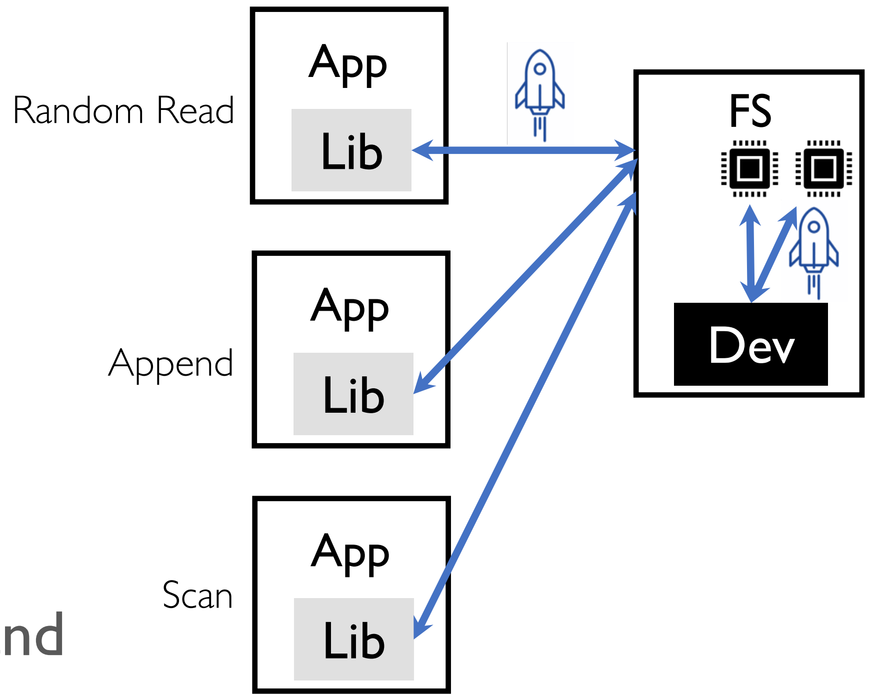

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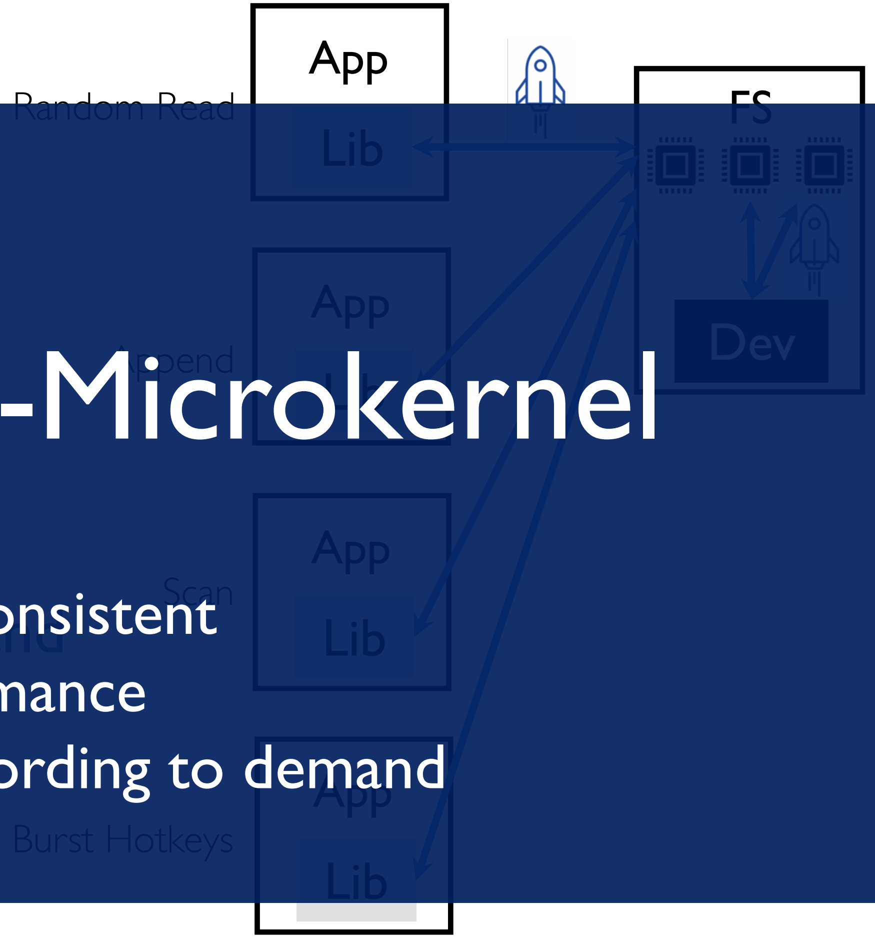
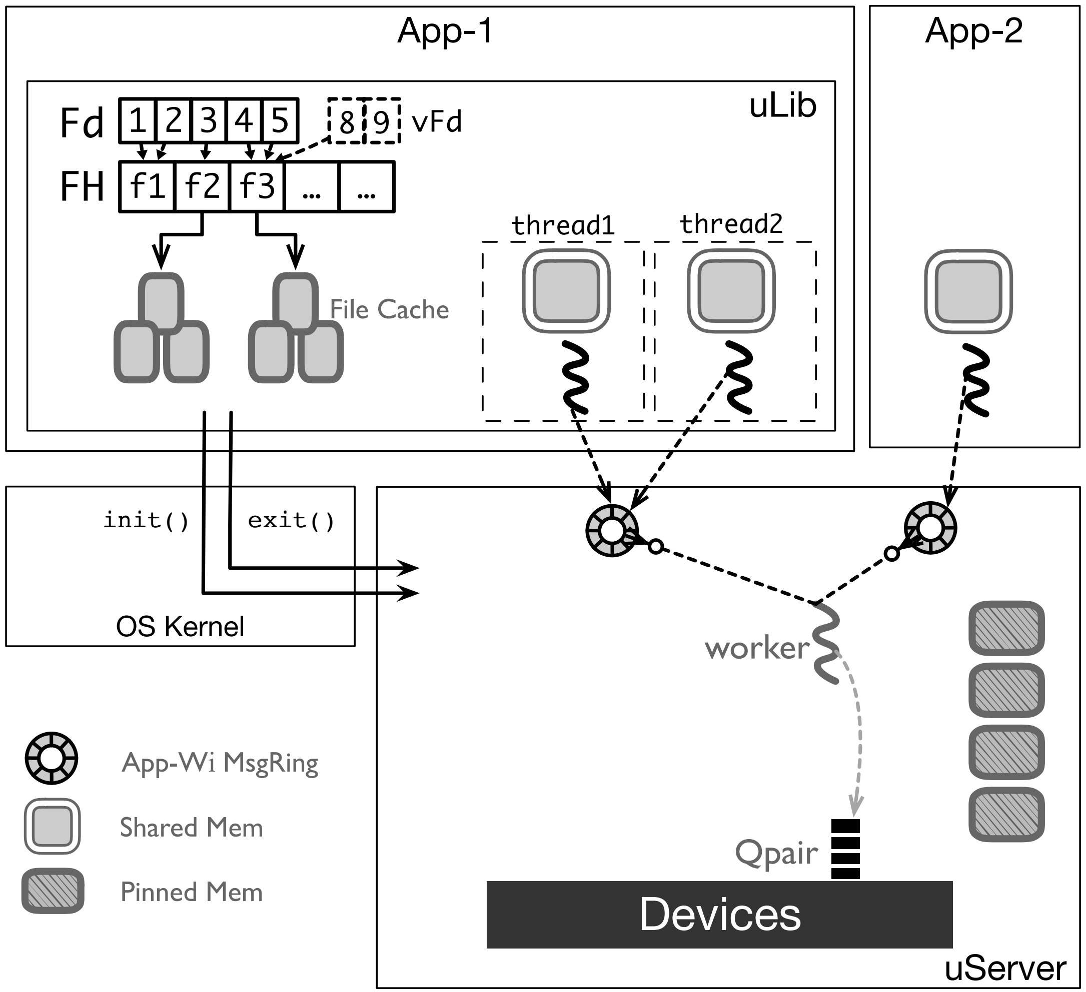


uFS: A Filesystem Semi-Microkernel

Fully functional and crash consistent
Offers good base performance
Dynamically scales up and down according to demand

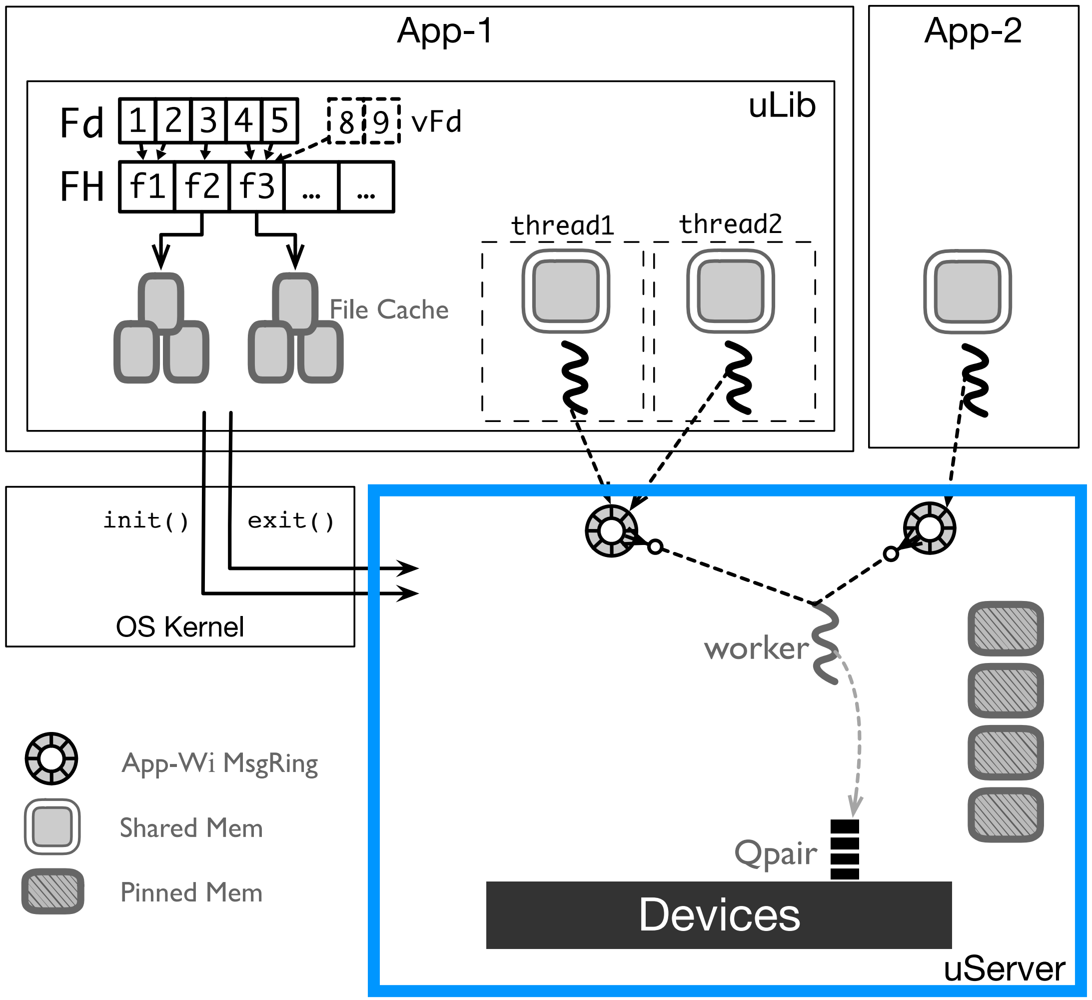
uFS Architecture



uFS Architecture

uServer

- Directly access the device via NVMe commands
- Non-blocking: device polling
- Manage pinned memory as block buffer cache



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- POSIX-API
- App-integrated file cache (lease-based)
- Open-lease management (vFd)

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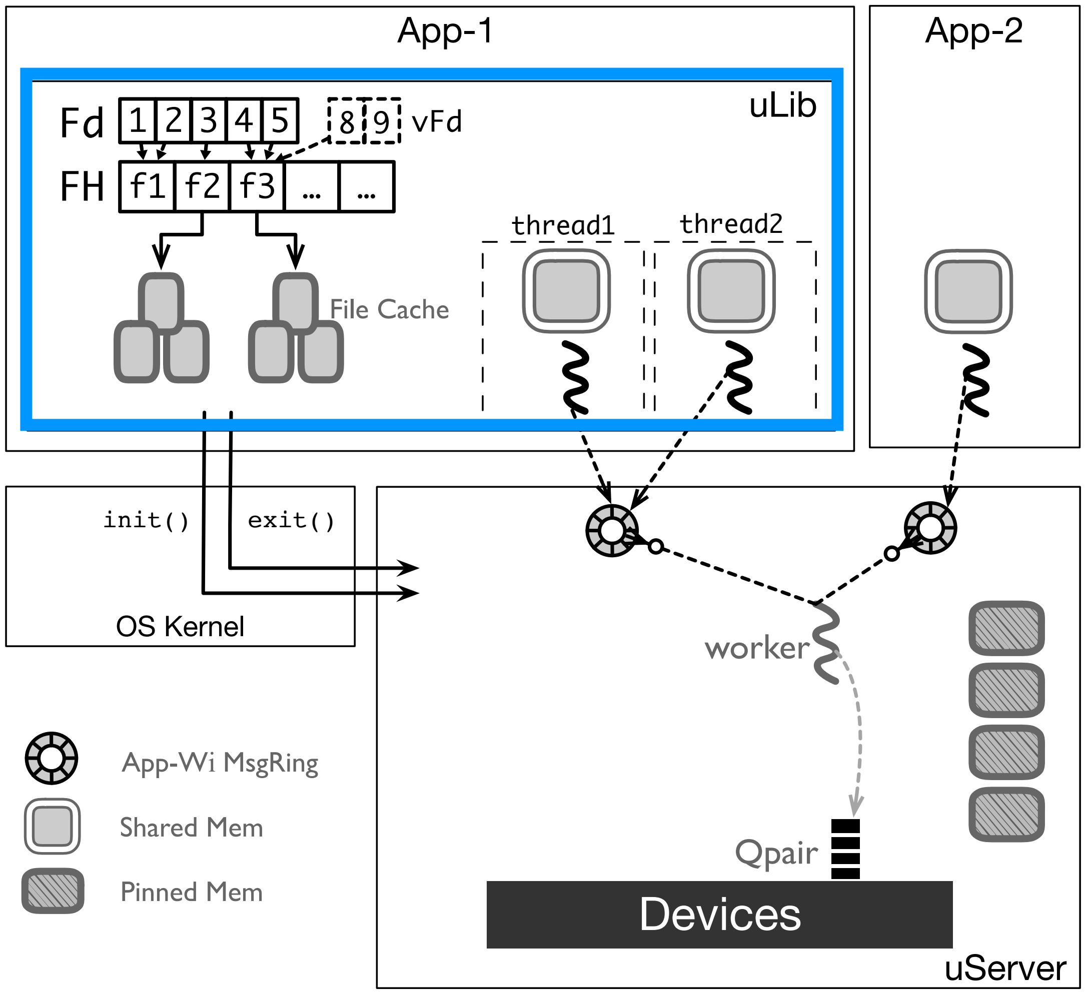

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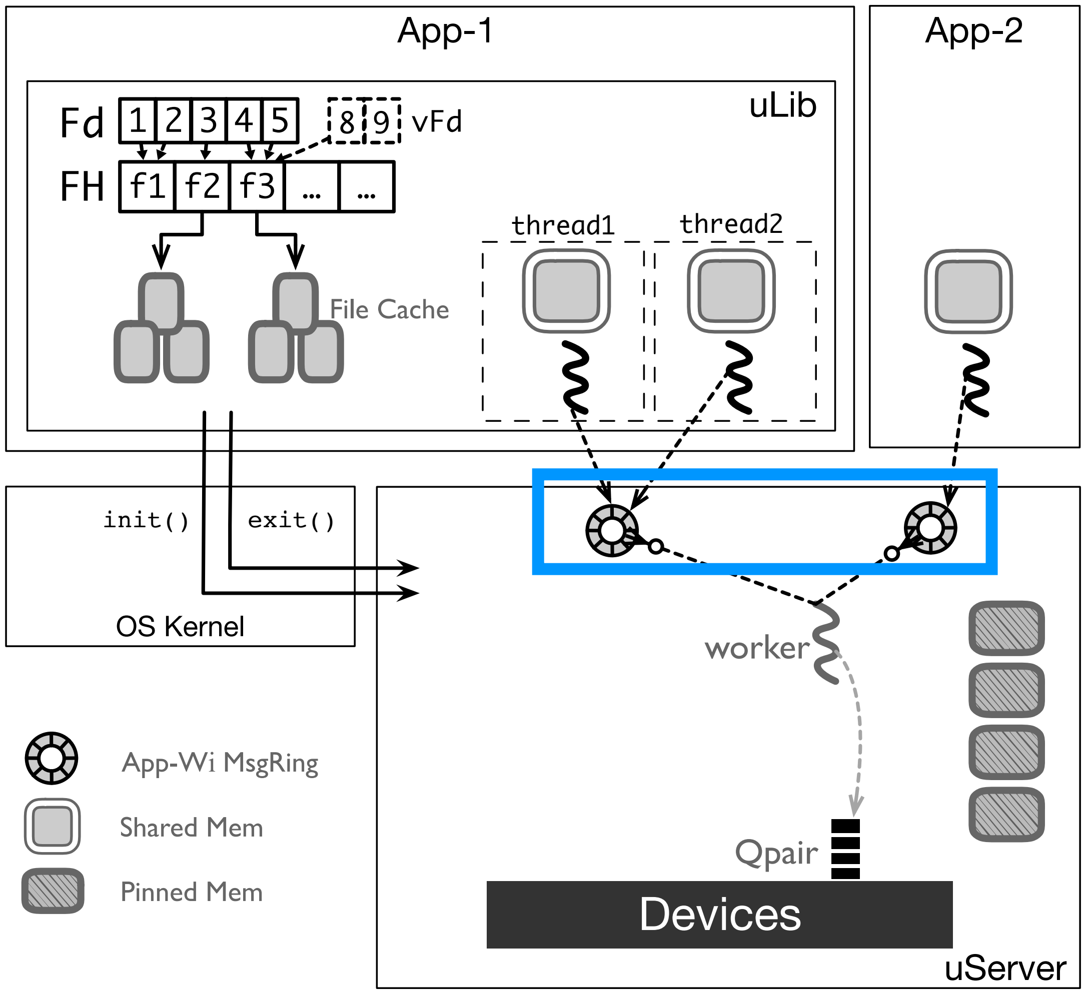
uLib ⟷ uServer

- Shared-mem IPC (cache-line-size message)



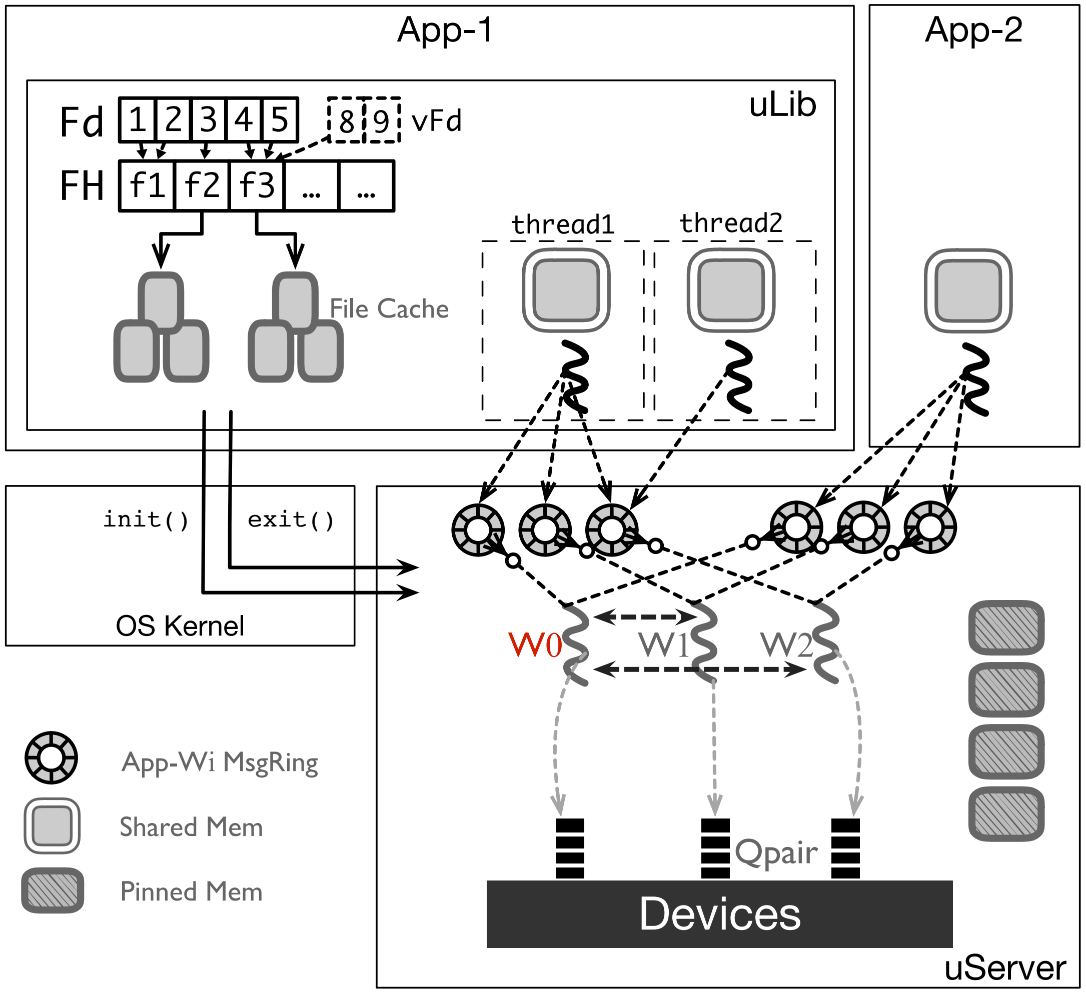
uFS Architecture

uServer: single worker is not enough

- More computing power to saturate device
- In-mem op capacity limited by one core

uServer – multiple workers

- Scalable by design: avoid sharing



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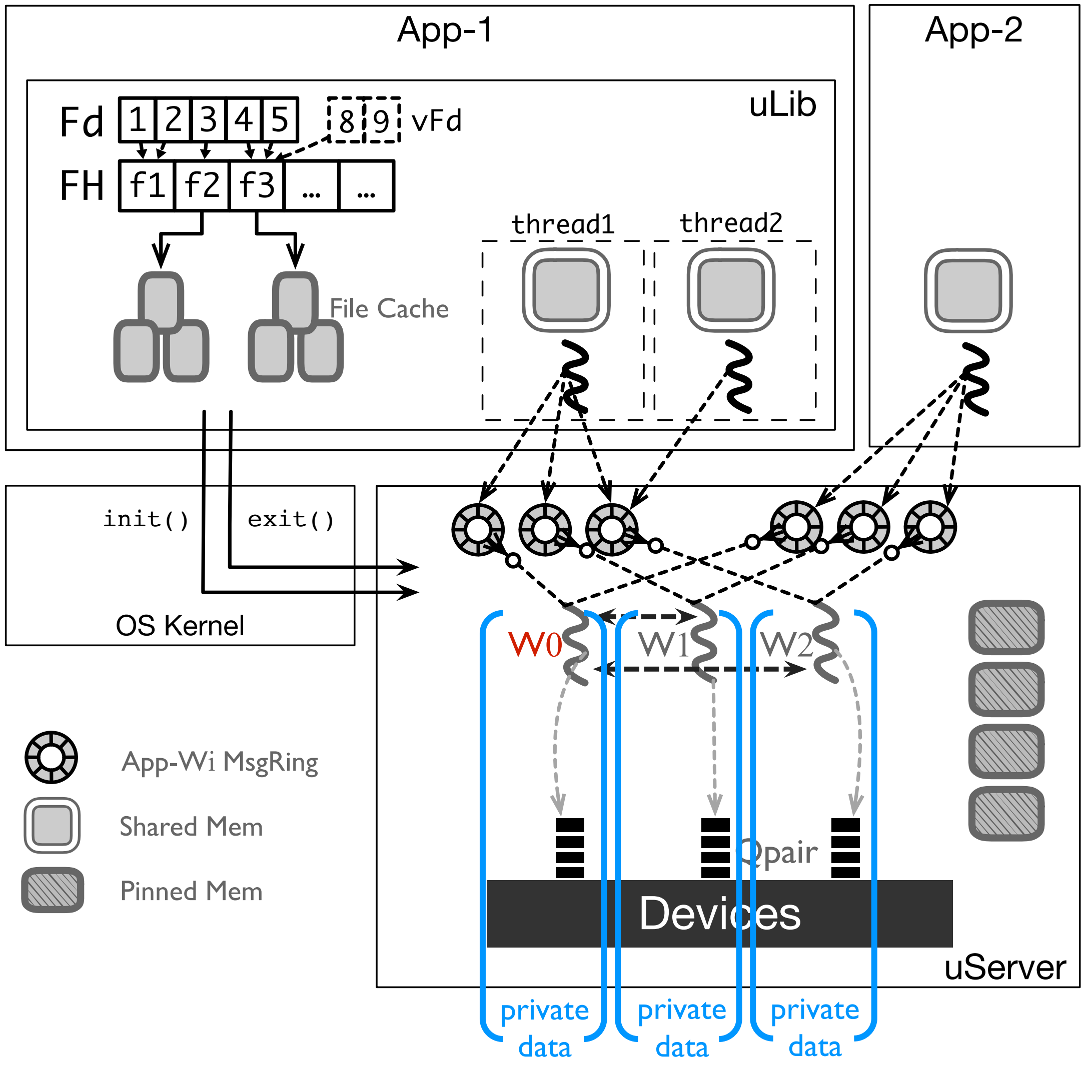

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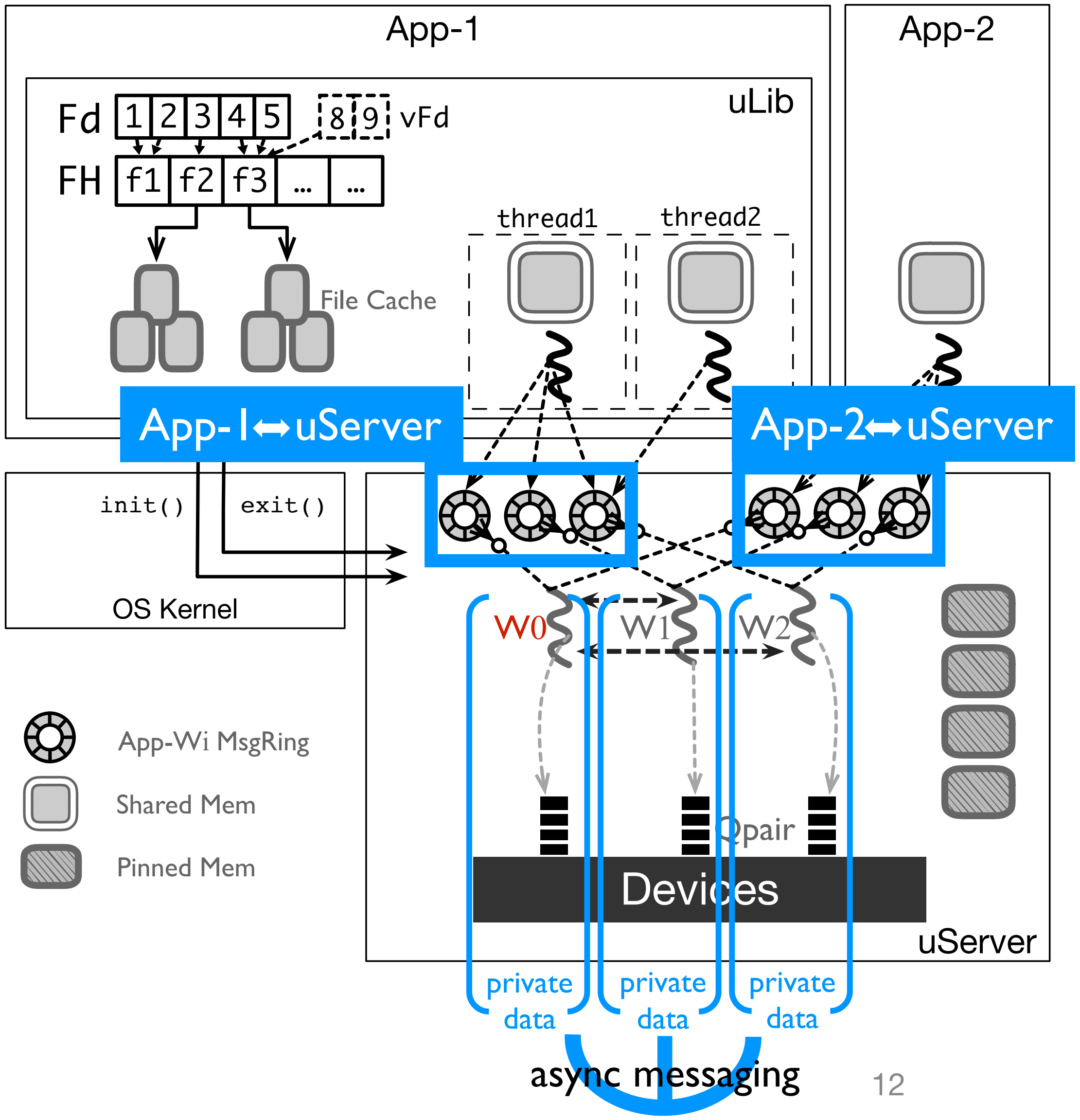
  - HW qpair to submit device requests
- Each App-W_{i} has separate message ring
  - Threads in one app will share the ring



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Dynamic Load Management

- Load balancing
- Core allocation

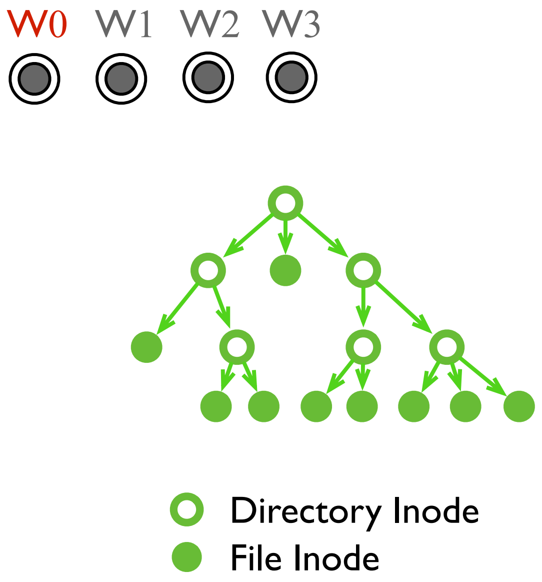
Runtime Inode Ownership

Each group of inodes is exclusively accessed by one worker

- No need for synchronization

Decouple the namespace and the ownership

- Inodes in one directory can be owned by two workers



Asymmetric Workers

- A primary worker (W0)
  - Owns all the directory inodes: handle all the directory ops
  - Default owner of all the file inodes
  - Coordinates the inode reassignment protocol through message passing
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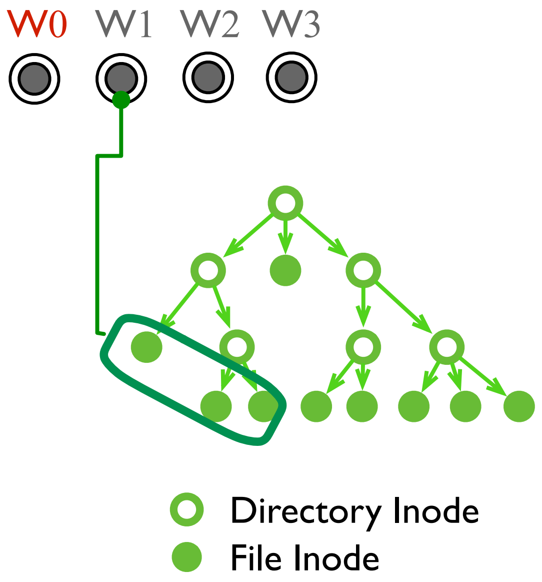

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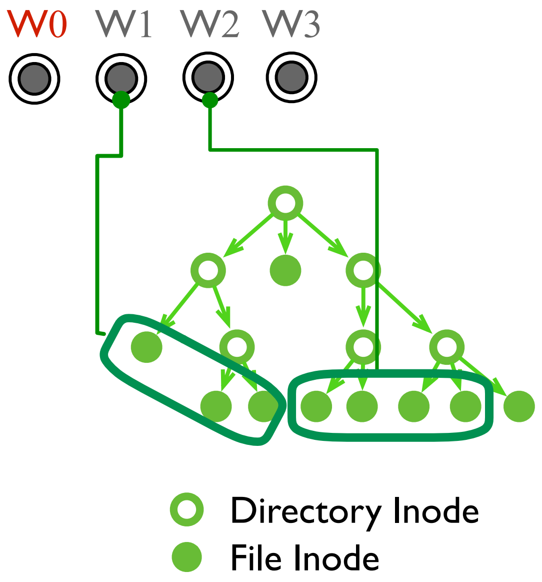

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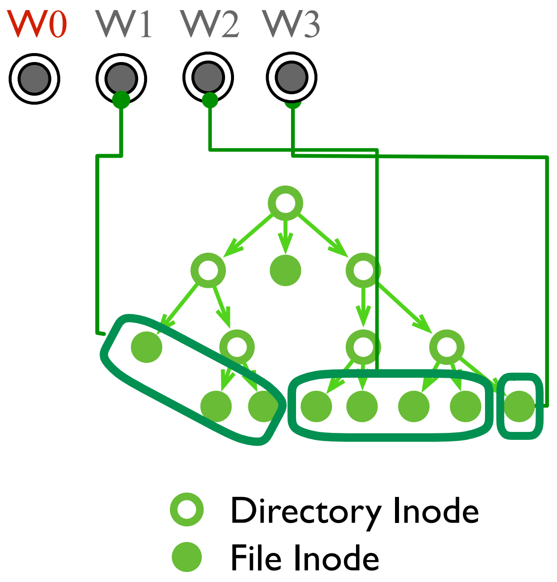

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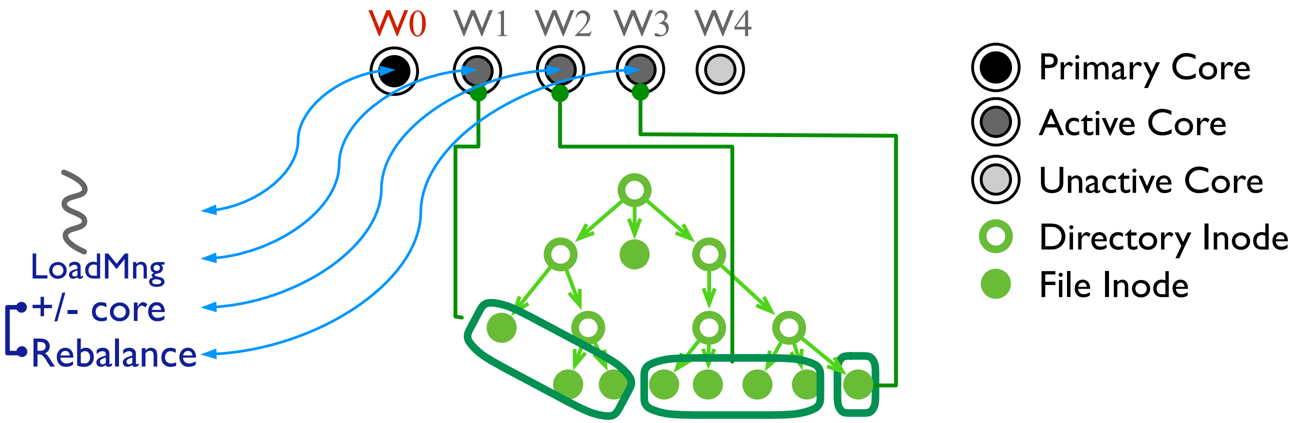
Dynamic Load Management

Separate load managing thread (LoadMng)

- Periodically gathers load stats from each worker (a monitoring window)
- Decides per-worker [load goal] ➡ Informs each worker the desired goal to achieve
- Decides number of cores ➡ (De)activates cores

Worker invokes inode reassignment

- Tracks per-inode stats
- Given [load goal], decides which groups of inodes to be re-assigned



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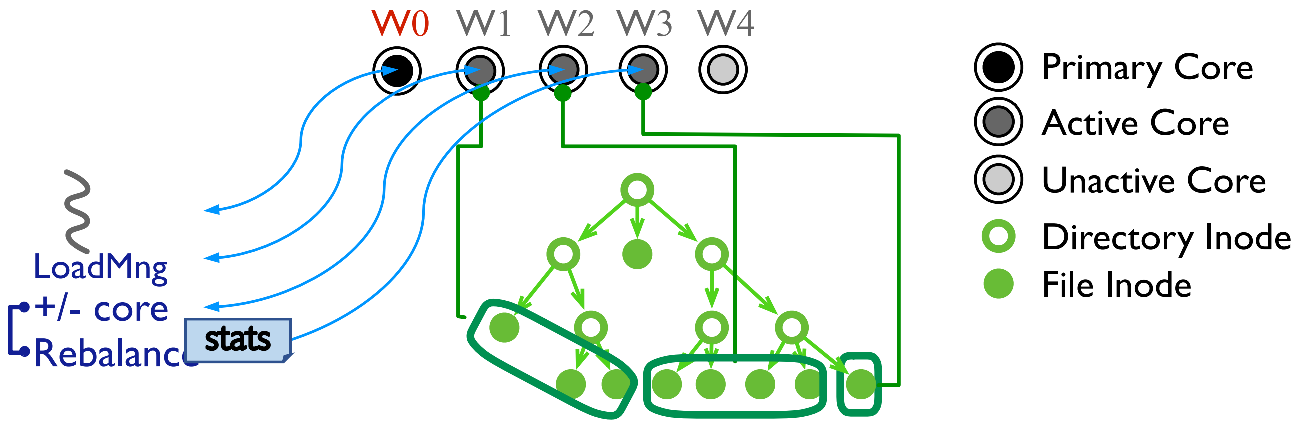

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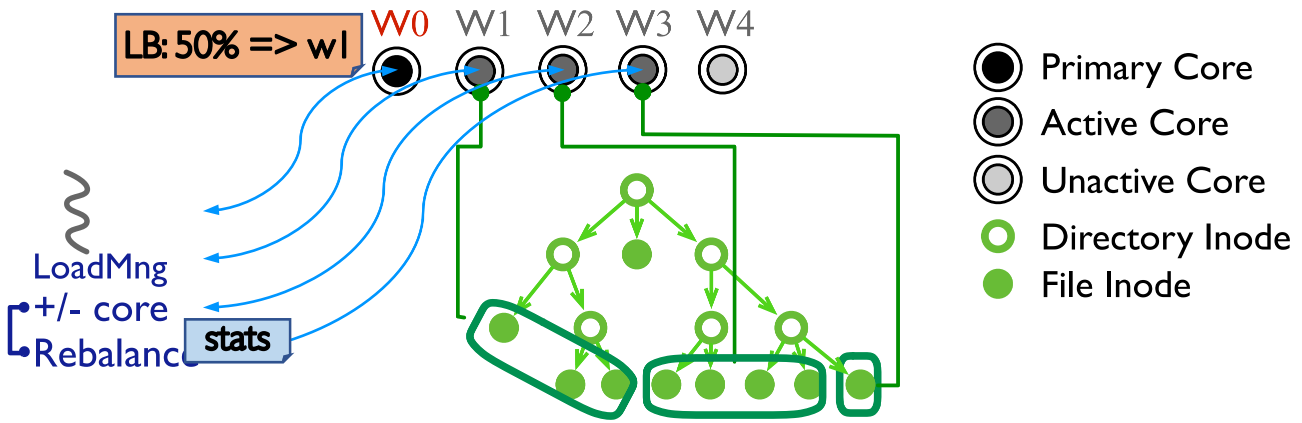

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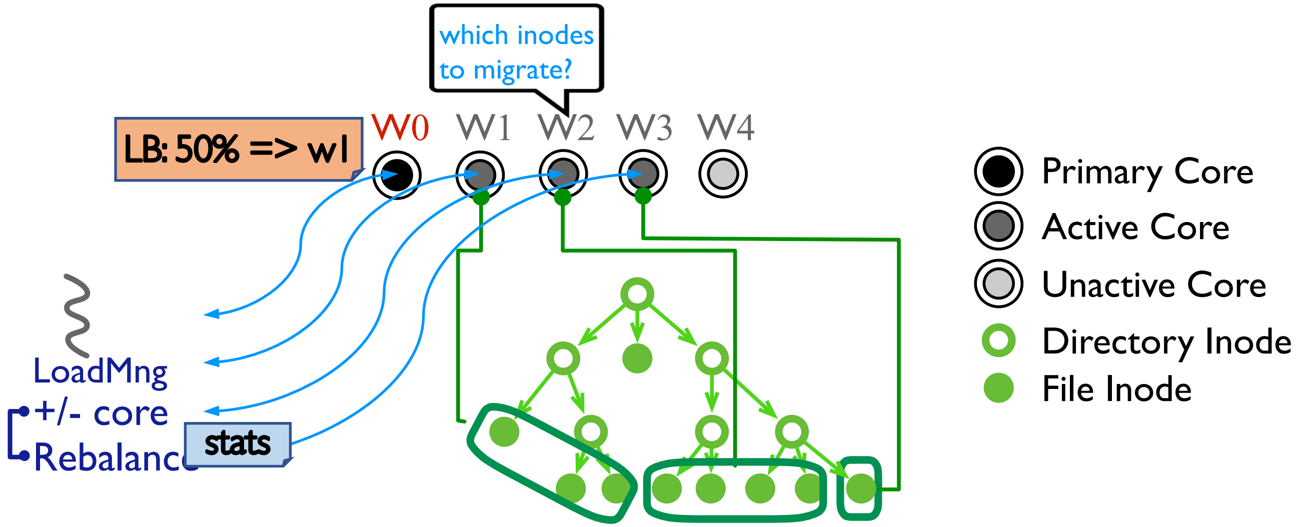


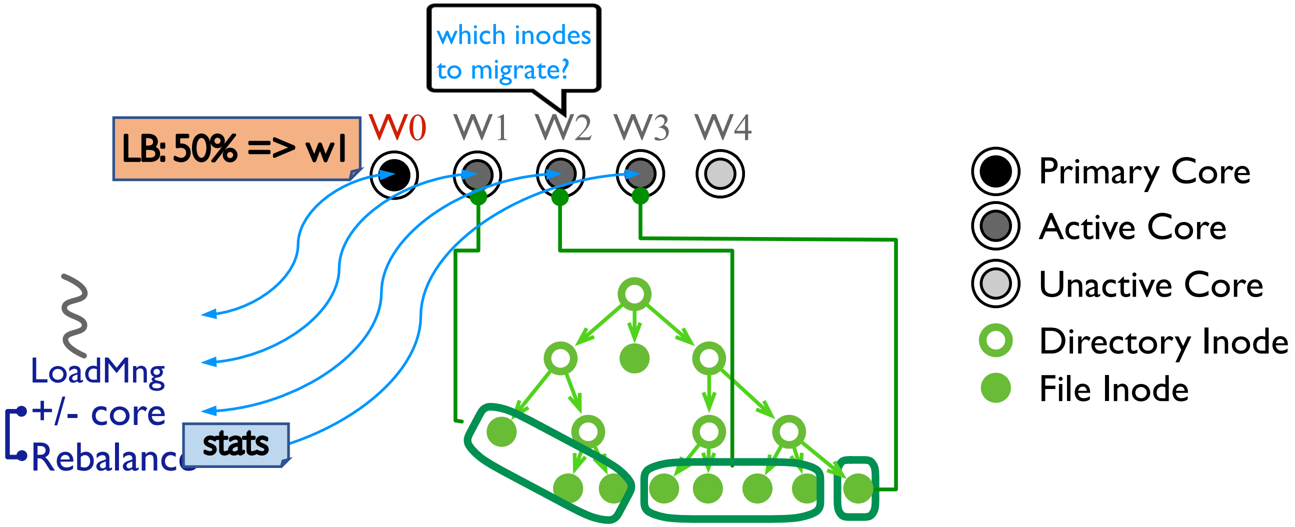
Dynamic Load Management: Algorithms

Load balancing

- Towards minimizing congestion on each core

Core allocation

- Meets a per-core CPU utilization goal
- Answer the "what if" questions by algorithmically emulating the load balancing results
  - Load balancing as a black-box
  - What if [add one core | no change | remove one core]



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uFS offers good single-threaded base performance

uFS performs well as a multi-threaded microkernel

uFS dynamically scales to match demand

- Load Balancing Experiments
- Core Allocation Experiments

uFS performs and scales well with real applications

- LevelDB and YCSB workloads

Platform

- Intel Optane 905P SSD; Intel(R) Xeon(R) Gold 5218R CPU
- Linux 5.4, SPDK 18.04

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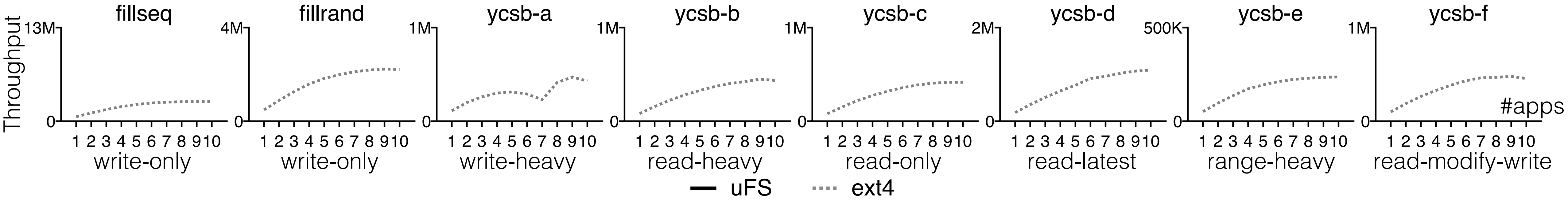

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uFS will allocate different number of cores for various workloads

Giving more cores (>10) to ext4 does not help much for performance

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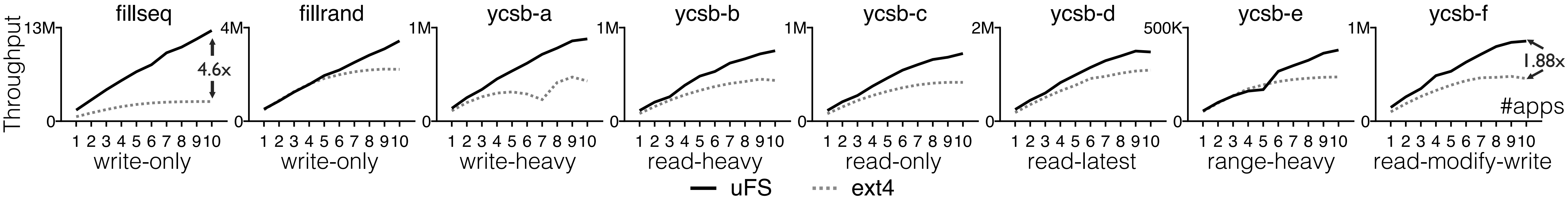

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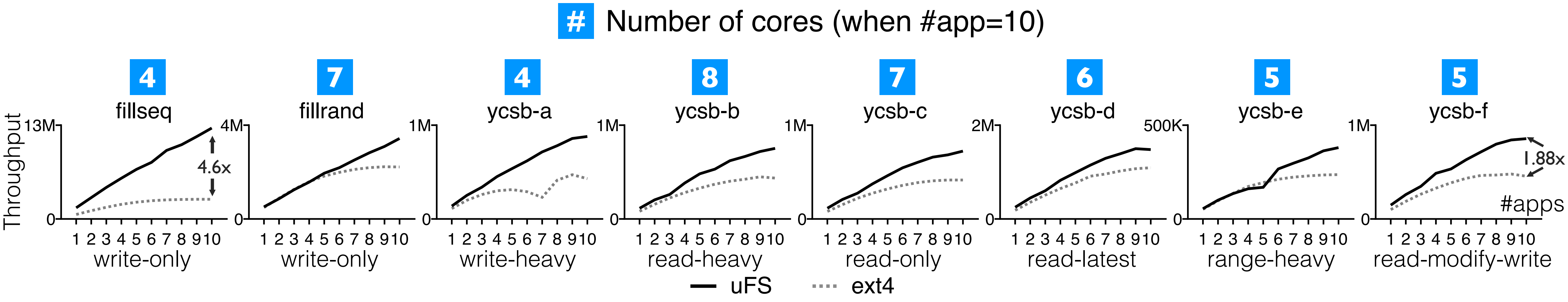

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  - Outperforms ext4 under LevelDB workloads by 1.22x to 4.6x
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Filesystem Semi-Microkernel Approach

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- Has all the benefits of user-level development

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Questions?