Scale and Performance in a Filesystem Semi-Microkernel

李缙、徐宇鸣

Outline

- **Background**
- **uFS Design**
- **Evaluation**
- **Conclusion**

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  - **notable overhead to trapping in and out of the kernel**
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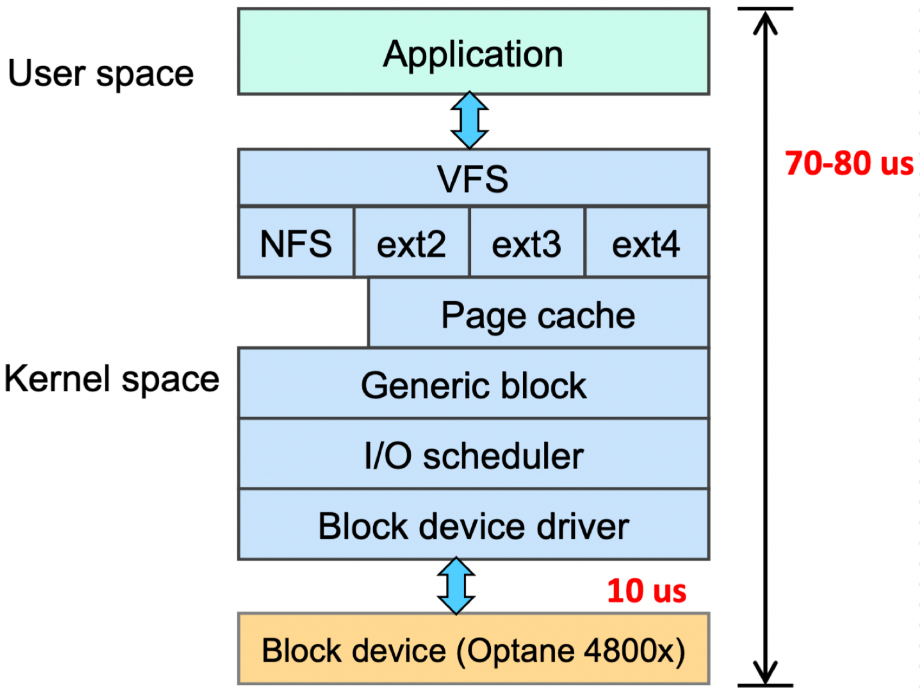

Linux I/O Stack

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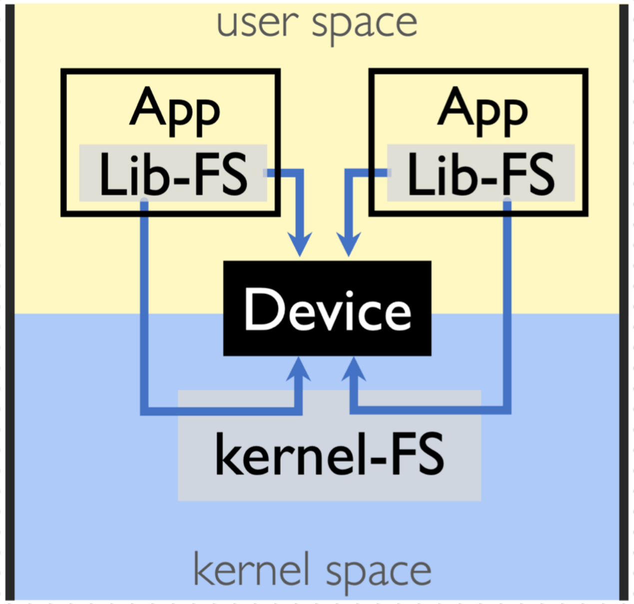

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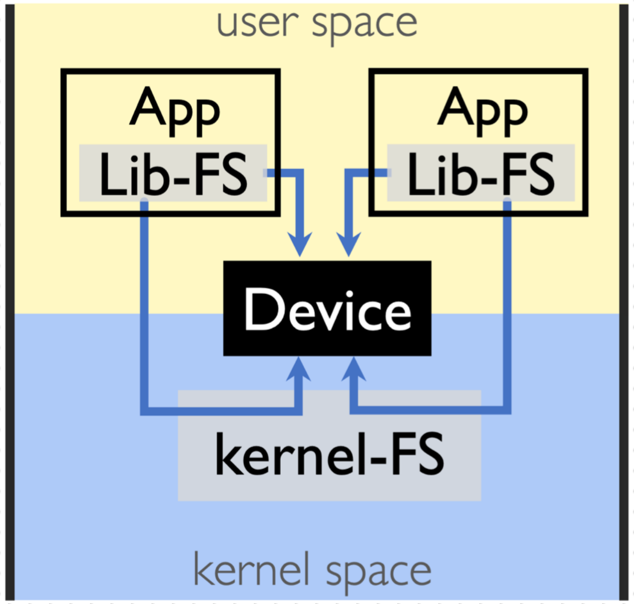

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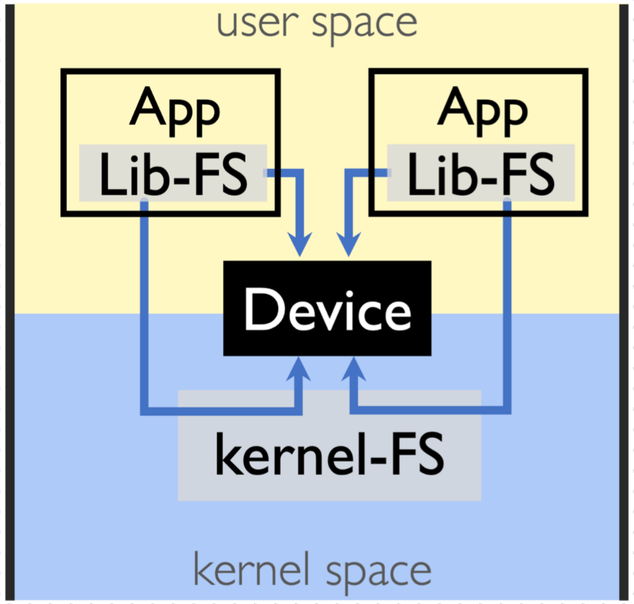
  - **Conclusion**
    - **Centralized IO multiplexing**
    - **Simpler isolation and sharing**



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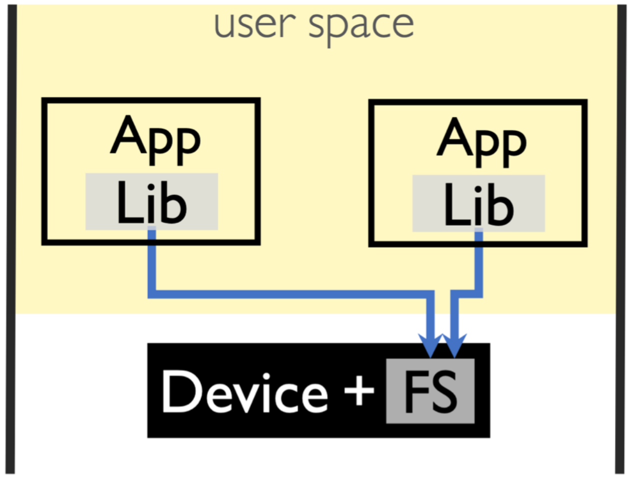

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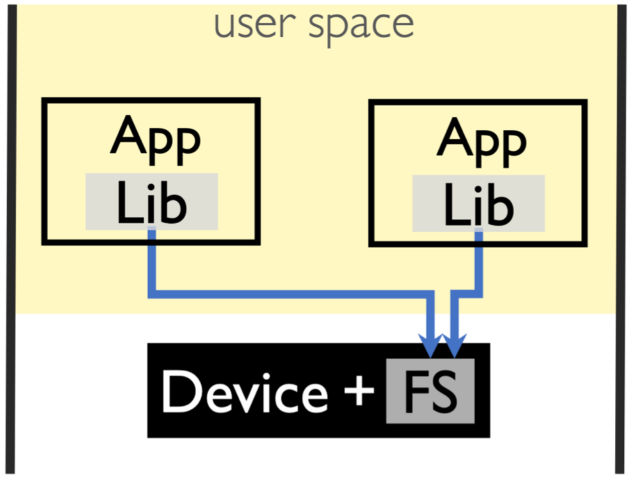
    - **Unknown HW constraints**



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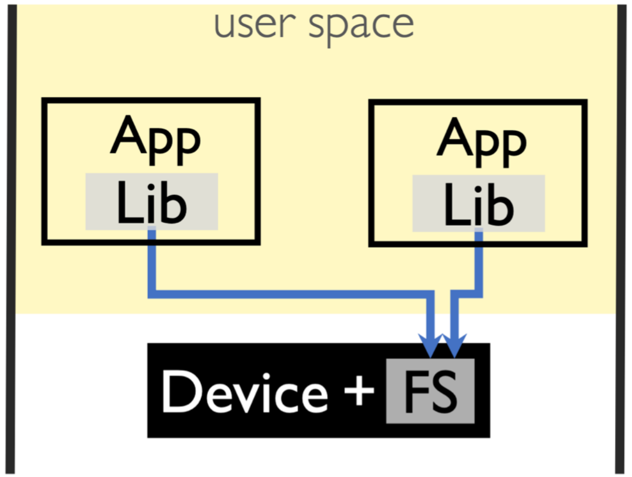
  - Conclusion
    - Realistic Assumption
    - Ultra-fast Devices and NVMe protocol



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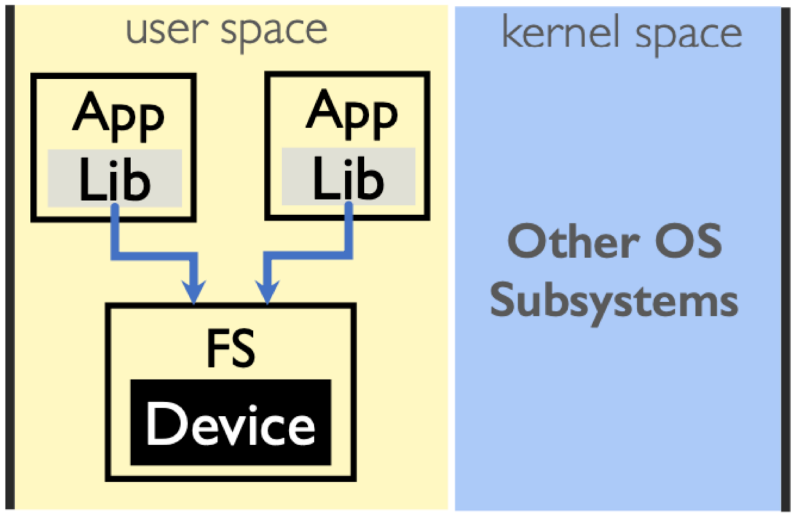
- **Possible solution:**
  - **Semi-Microkernel**
    - **Or “filesystem as a process”(HotStorage-19)**



Background

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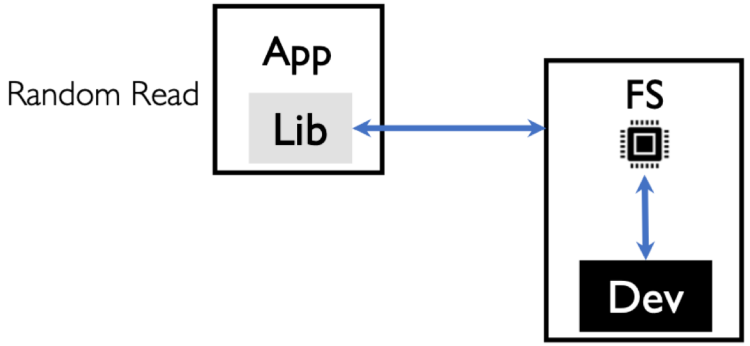
- **Semi-Microkernel**
  - **An OS subsystem that runs as a user-level process**
  - **Works in tandem with monolithic kernel**
- **Benefits of Semi-Microkernel**
  - **Code velocity**
    - **Quickly develop, modify, and deploy system software**
    - **Application-level debugging and testing**
  - **Performance**
    - **Scale subsystem independently from applications**
    - **Avoid extra kernel overhead**

Background

- Semi-Microkernel
  - An OS subsystem that runs as a user-level process
  - Works in tandem with monolithic kernel
- Prior semi-microkernel
  - Focus on networking
    - Snap(SOSP-19), TAS(Eurosys-19)
- Possible for storage now
  - User-level device driver(SPDK)

Background

- **Challenge**
  - **Base Performance**
    - **Inter-process communication & device access**



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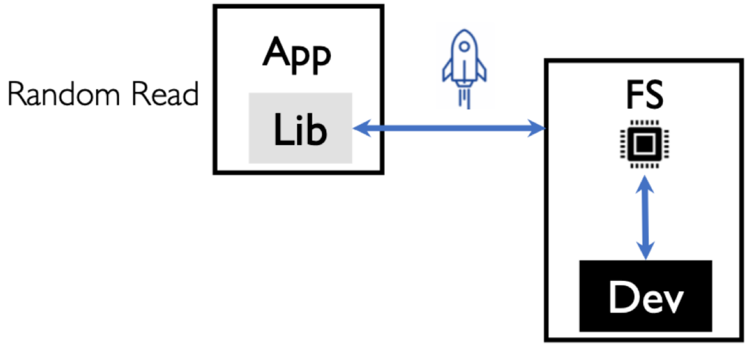

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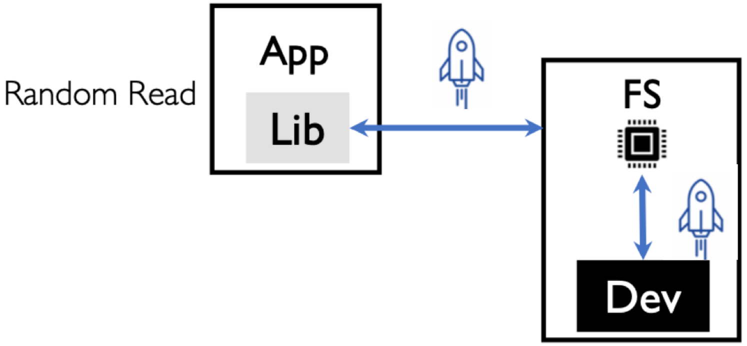

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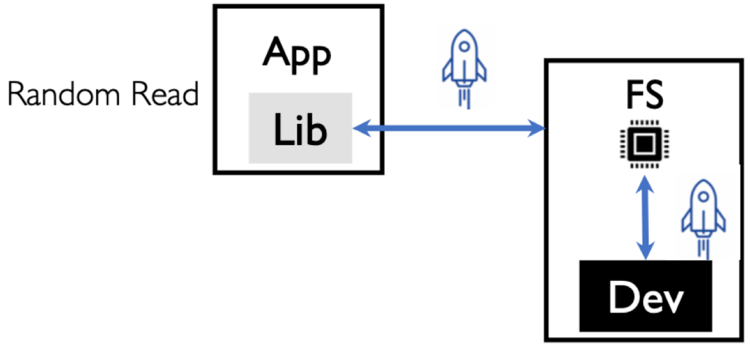

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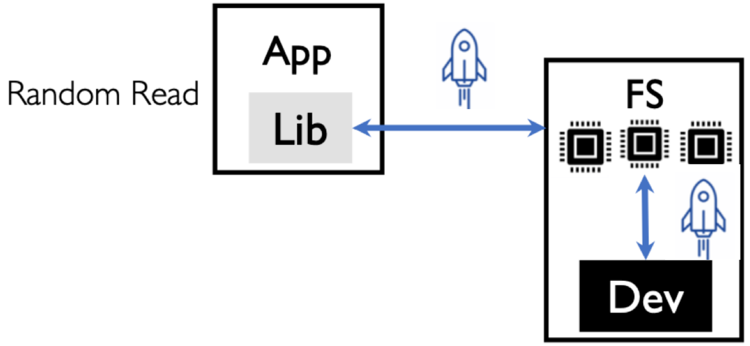

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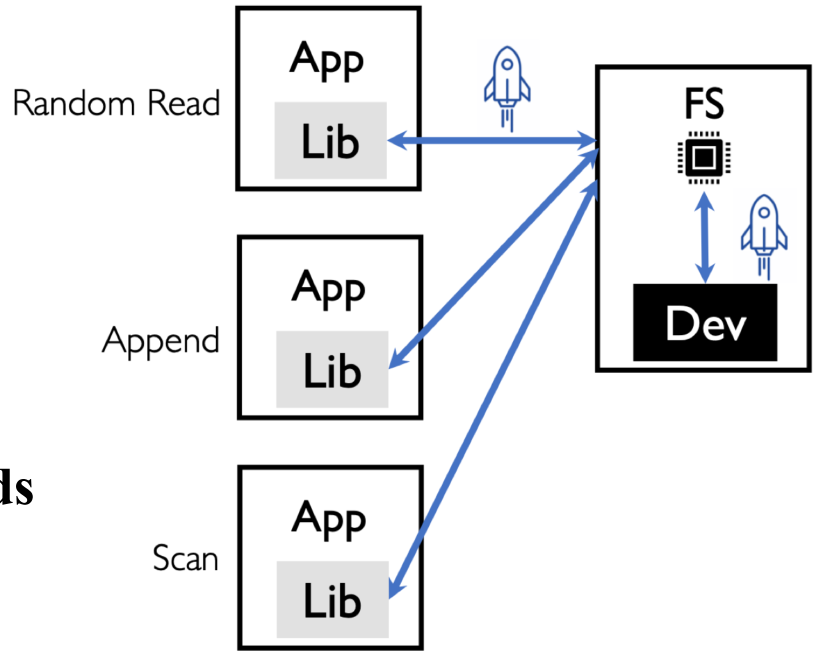

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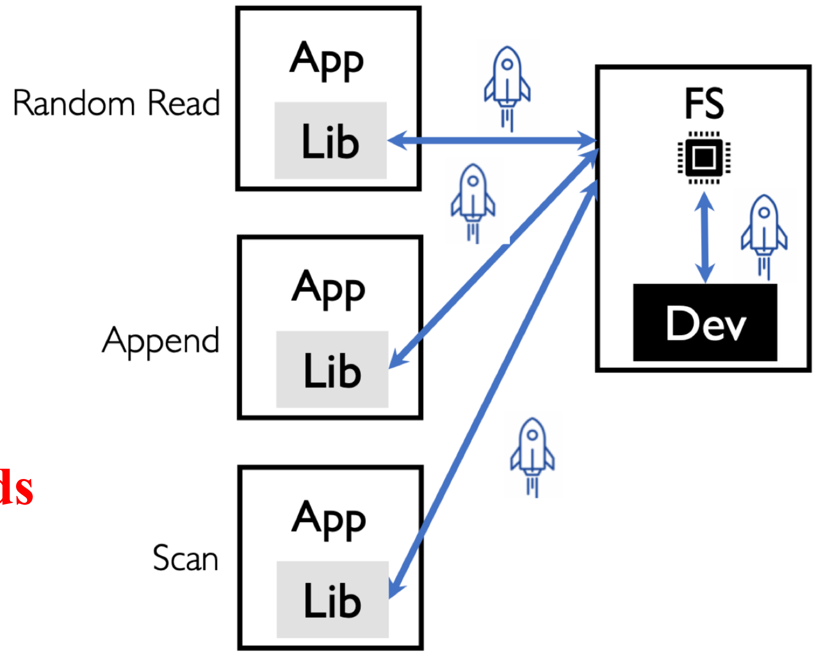

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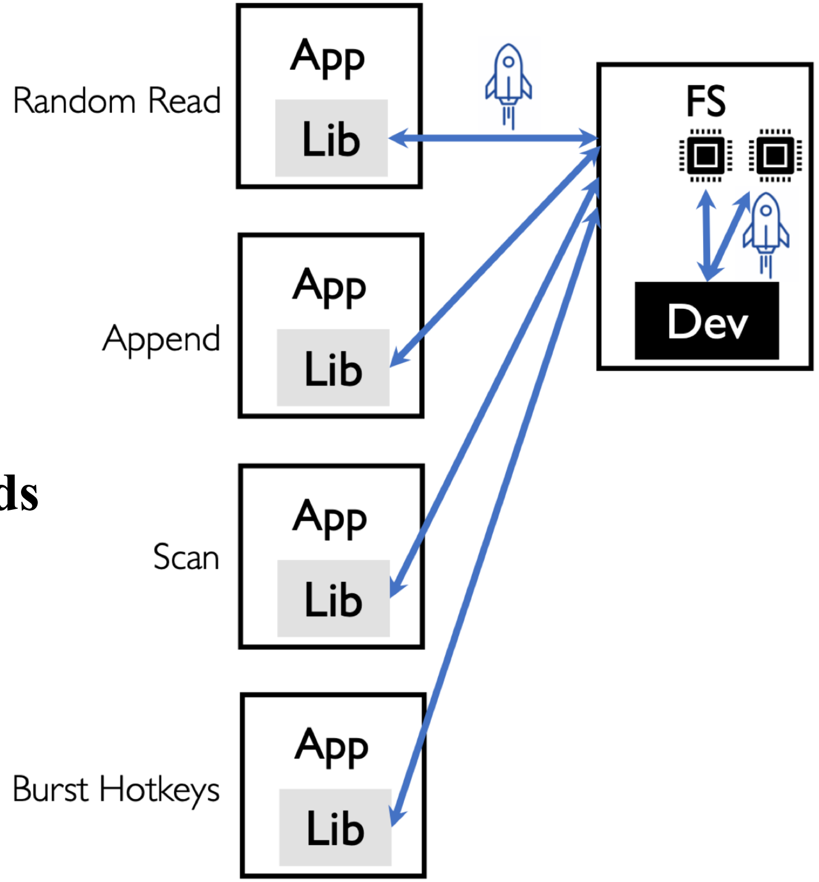

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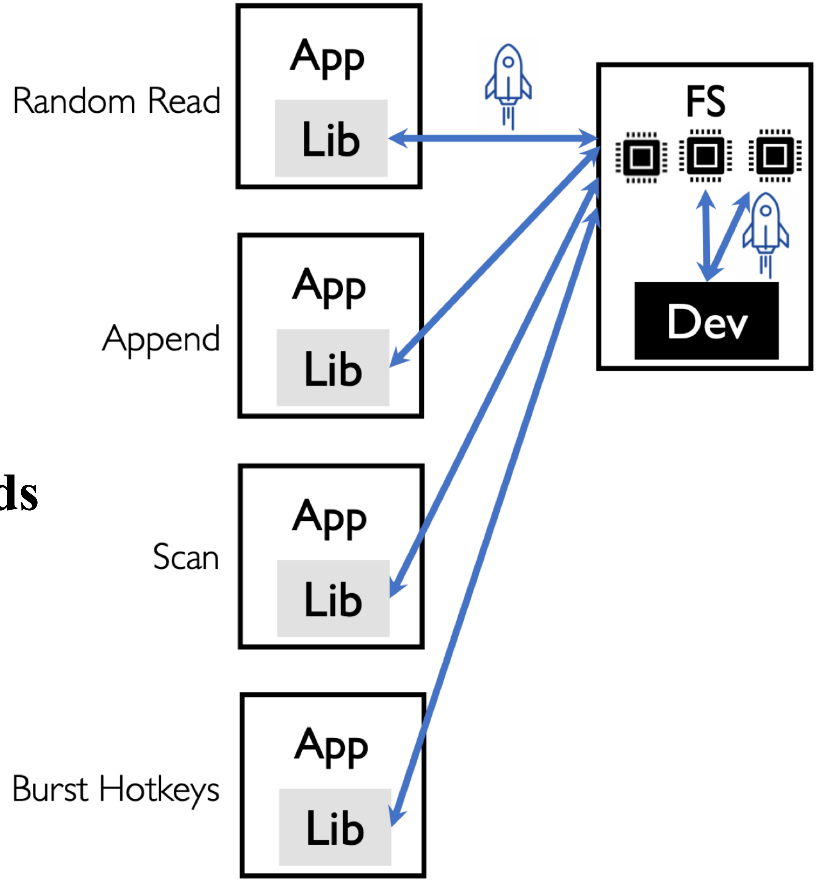

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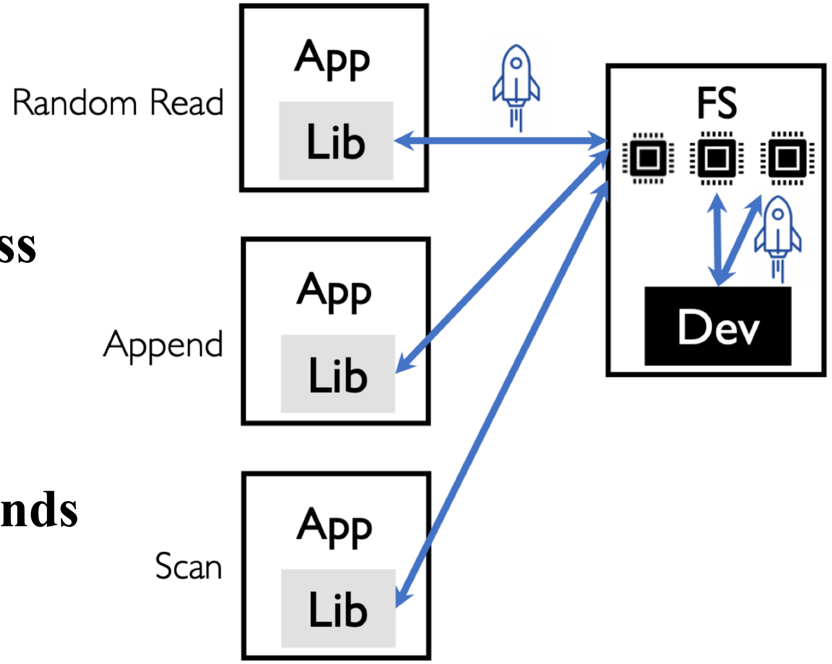

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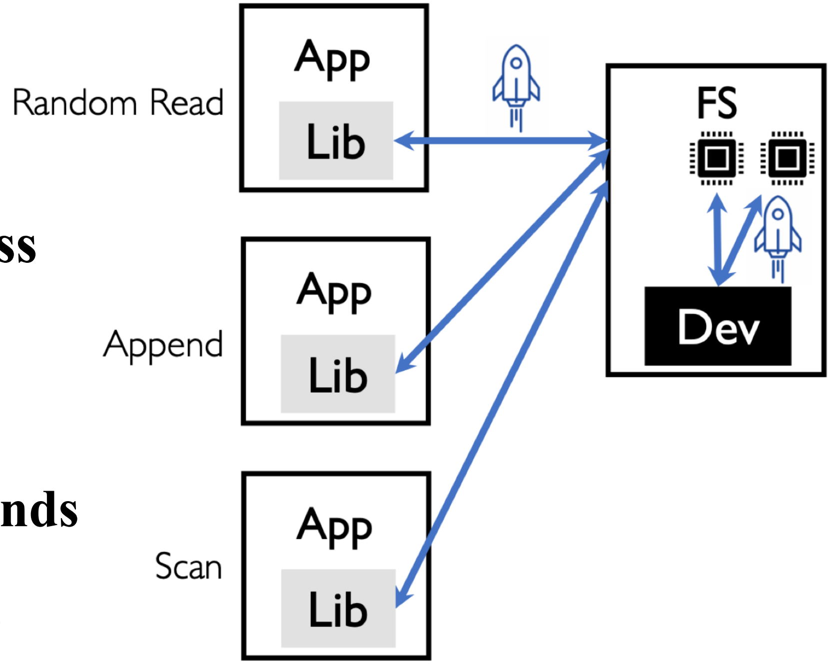

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- Background
- **uFS Design**
- Evaluation
- Concusion

uFS Design

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- **Single-Threaded uServer**
- **Multi-Threaded uServer**
- **Dynamic Load Management**
- **Employ Non-blocking Shared Structures Judiciously**

uFS Design

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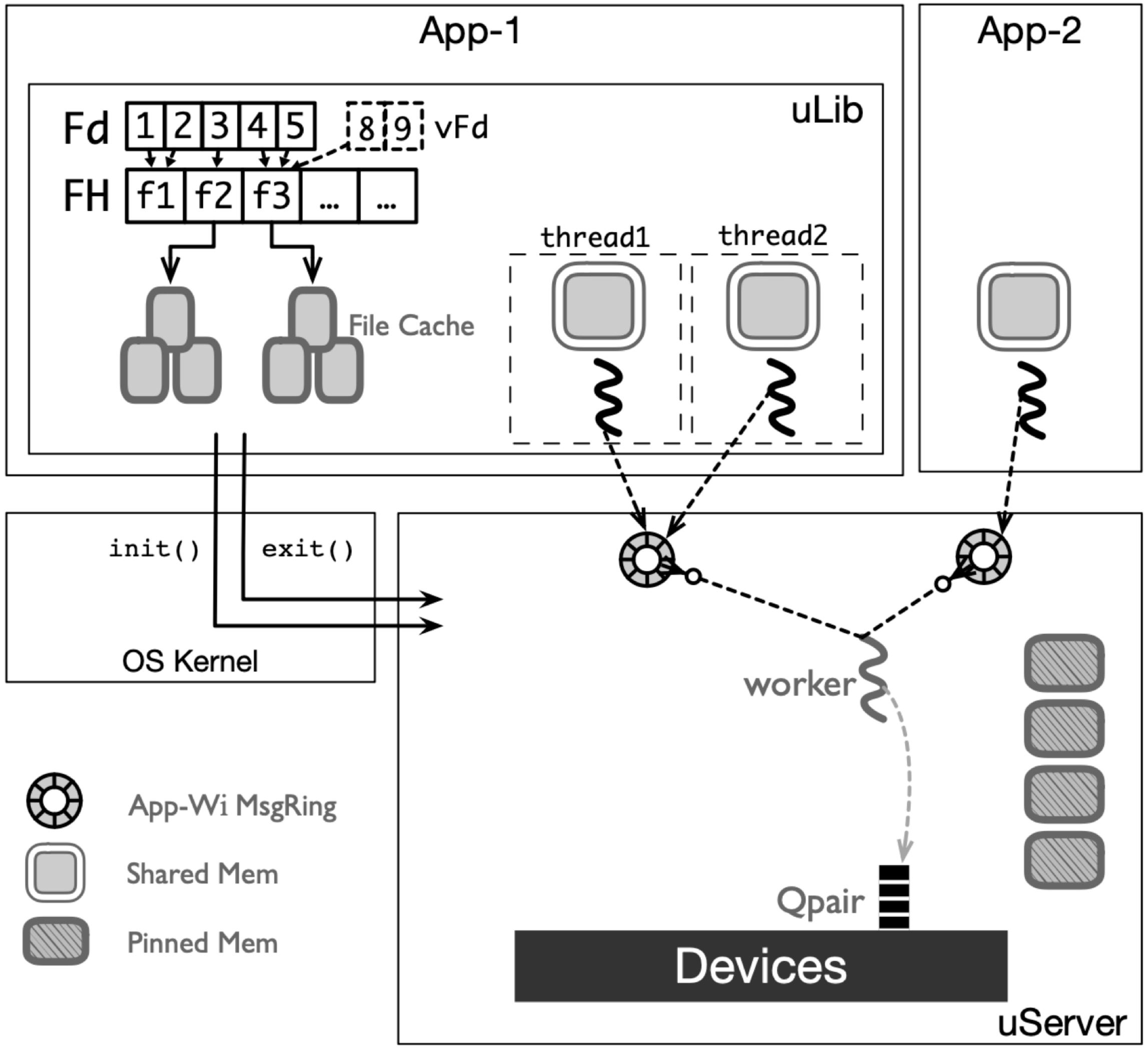
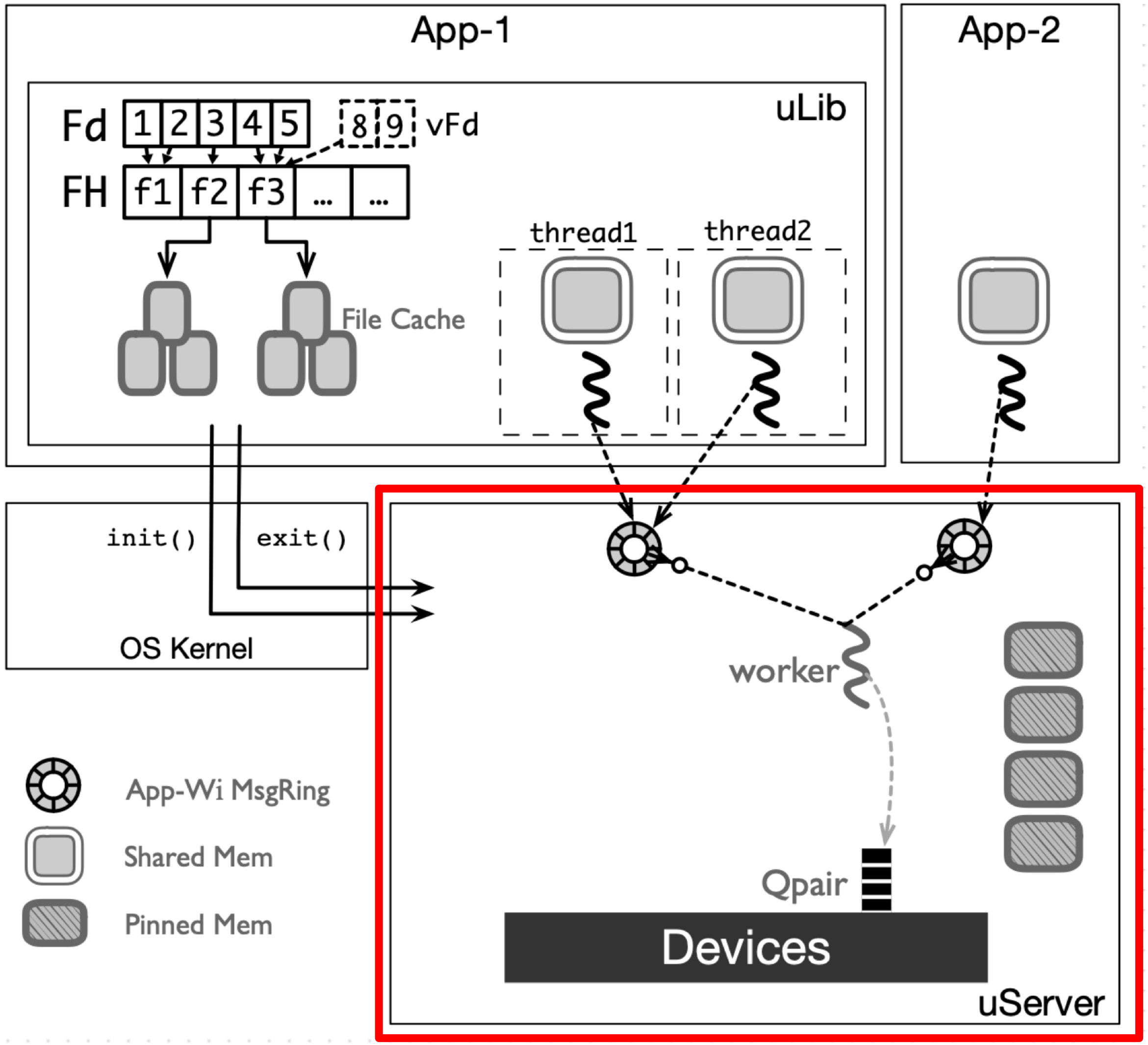
uFS Design

- **Single-Threaded uServer**



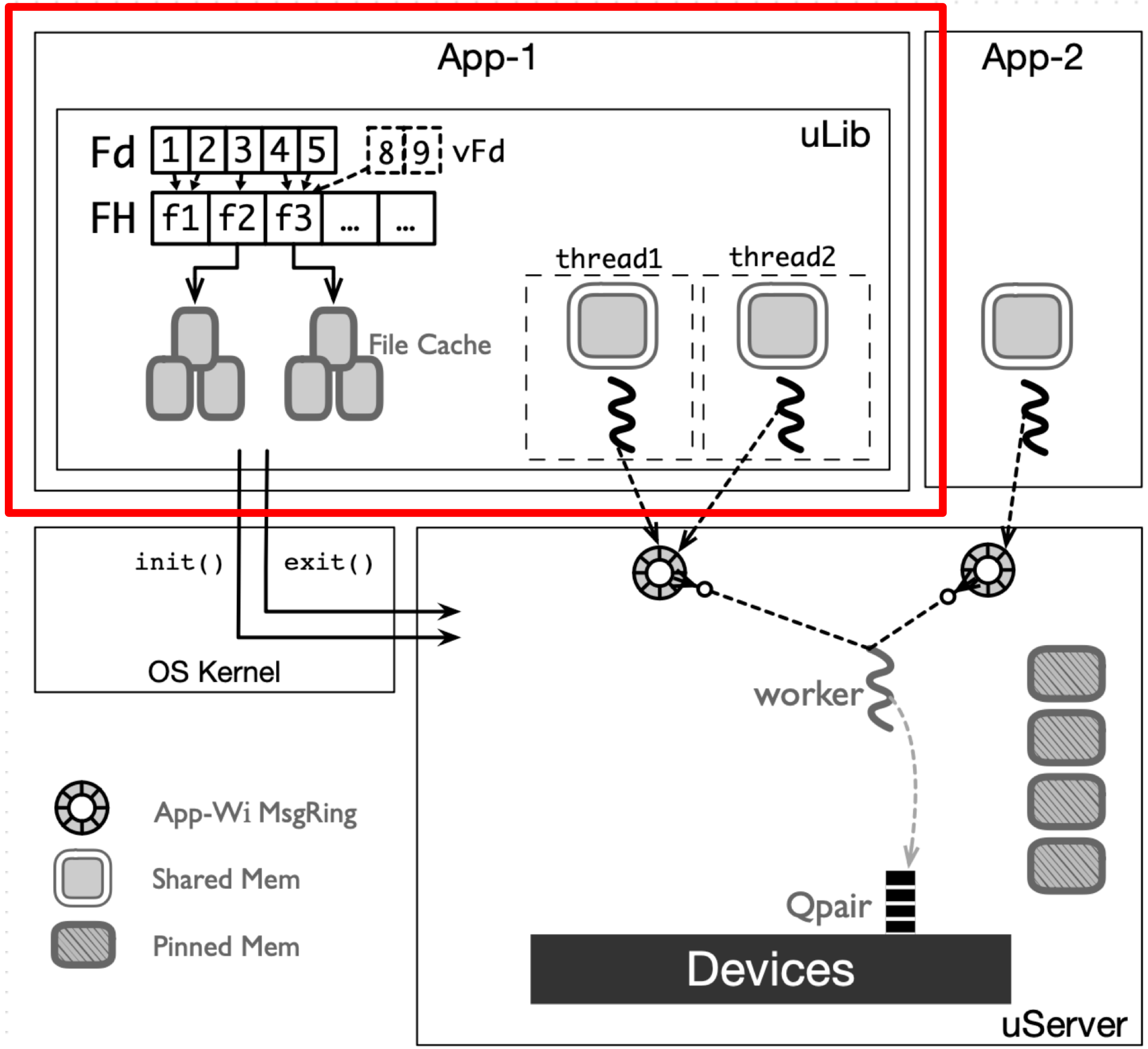
uFS Design

- **Single-Threaded uServer**
  - **uServer**
    - **Directly accesses the device via SPDK**
    - **Non-blocking polling**
    - **Pinned memory as block buffer cache**



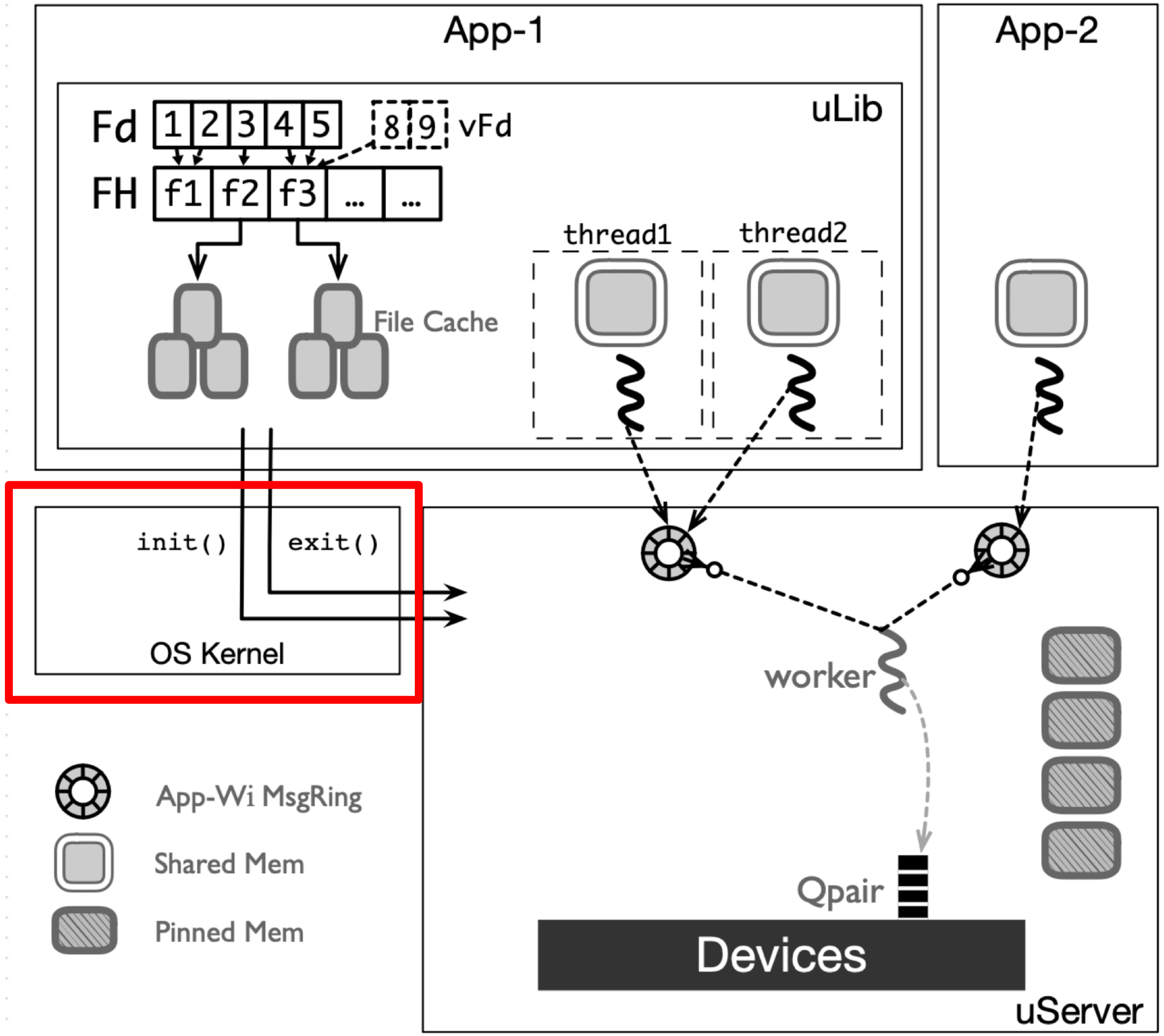
uFS Design

- Single-Threaded uServer
  - uLib
    - POSIX-API
    - App-integrated file cache (lease-based)
    - Open-lease management



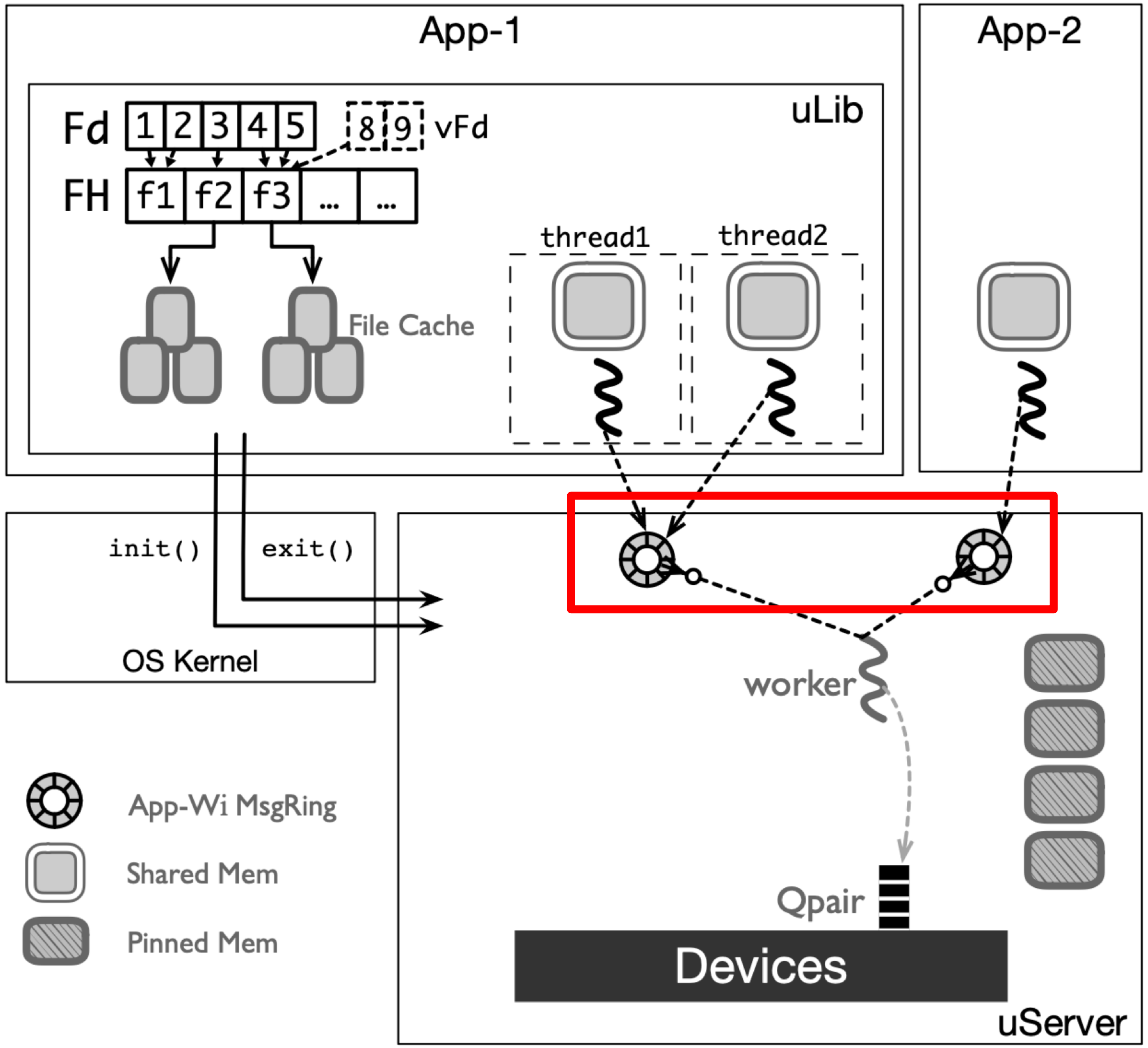
uFS Design

- **Single-Threaded uServer**
  - **The OS kernel only involves for initial authentication (fs_init)**



uFS Design

- Single-Threaded uServer
  - Inter-process communication
    - Control: shared-mem IPC
      - Cache-line-size message



uFS Design

- Single-Threaded uServer
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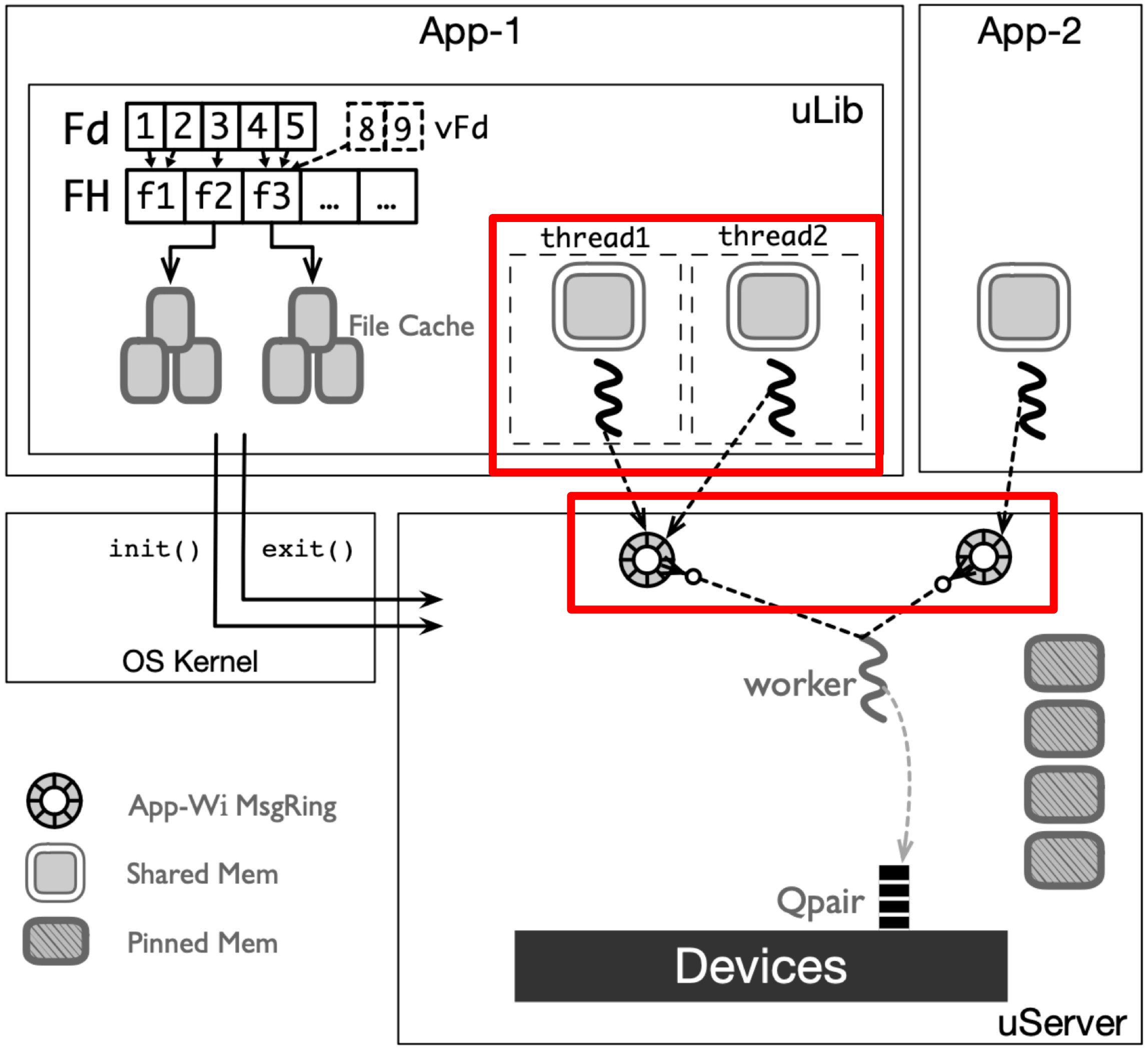
      - Cache-line-size message
    - Data: customized malloc in uLib
      - uLib shares pages with uServer

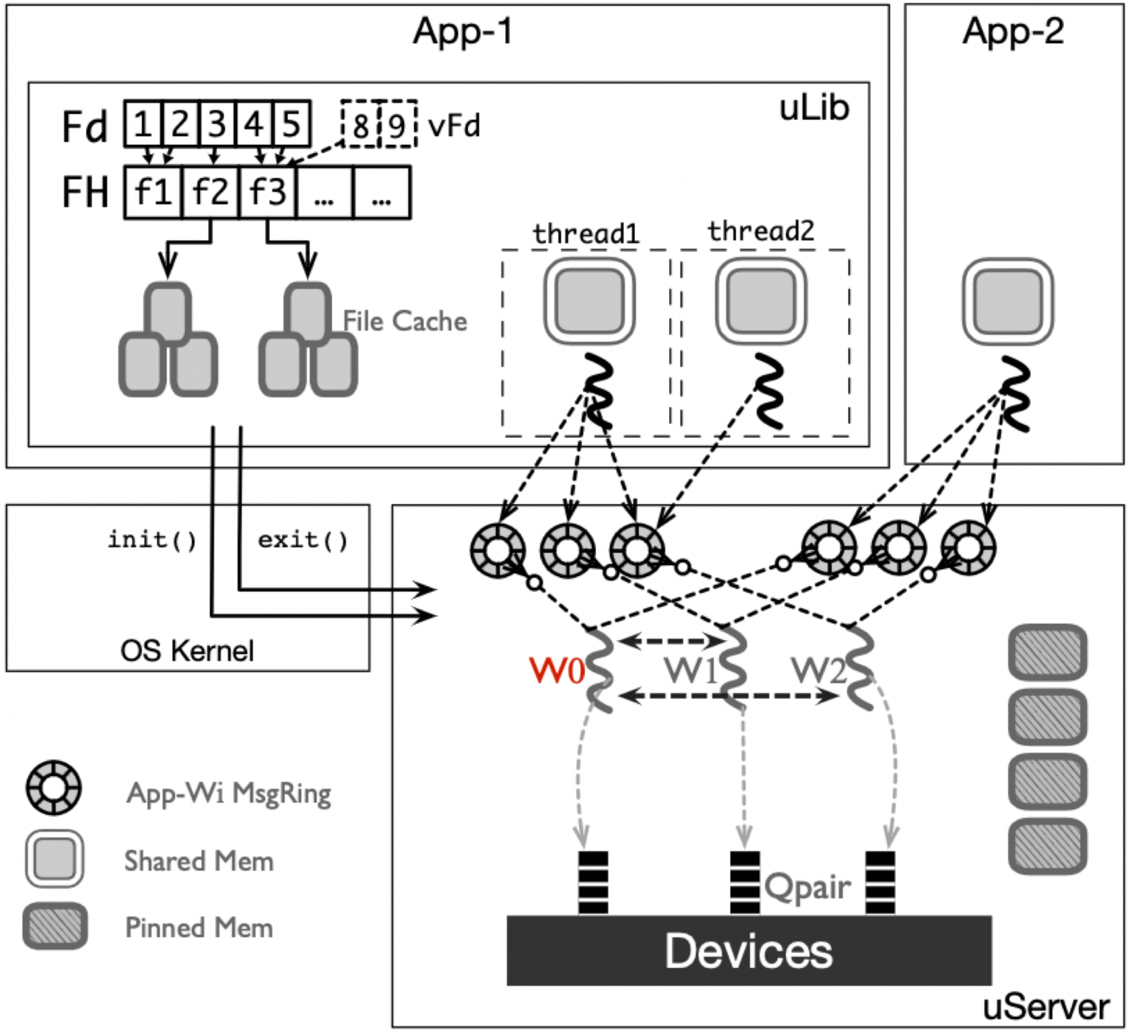


uFS Design

- Single-Threaded uServer
- **Multi-Threaded uServer**
- Dynamic Load Management
- Employ Non-blocking Shared Structures Judiciously

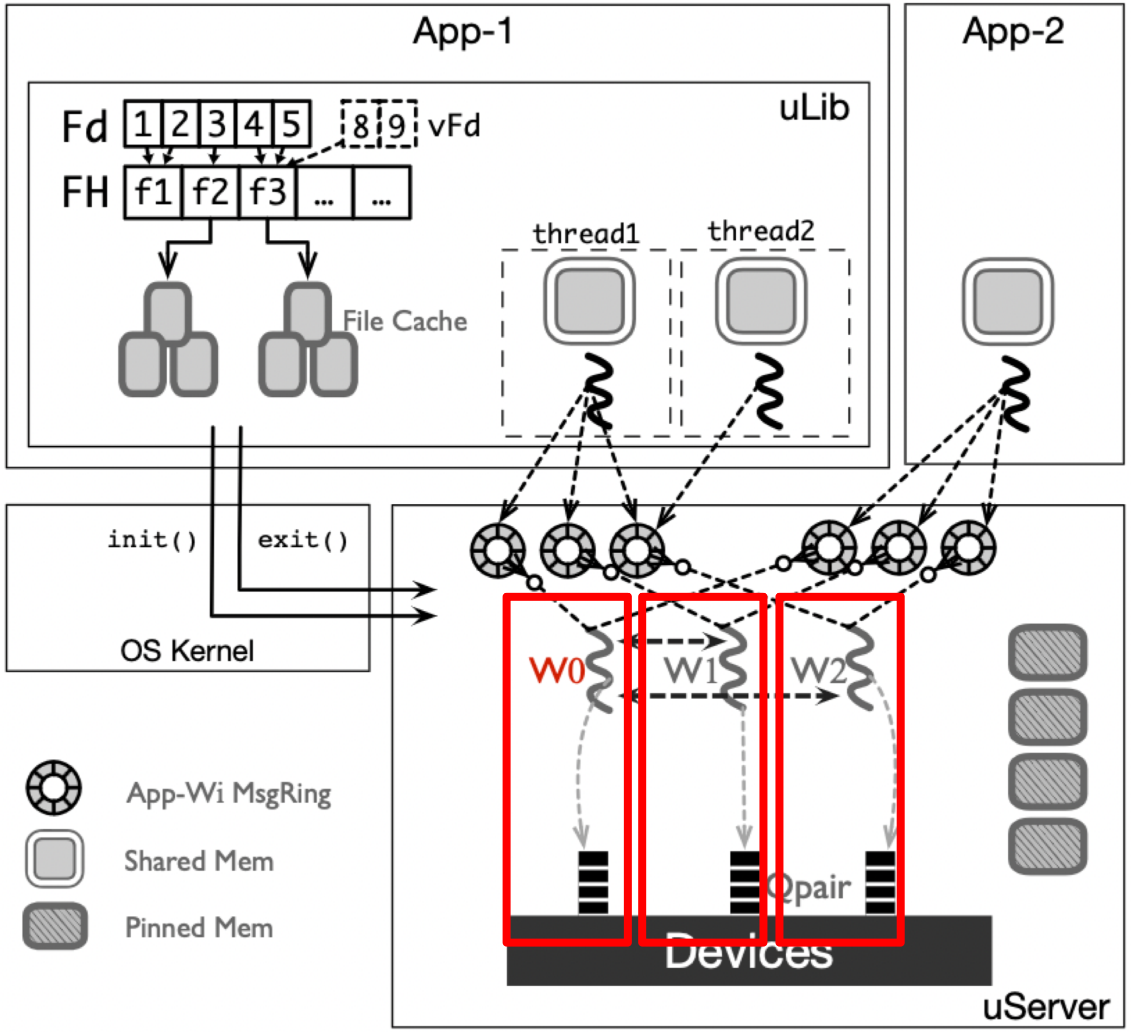
uFS Design

- **Multi-Threaded uServer**
  - **Utilize the full bandwidth of current I/O devices**
  - **More computation resource**



uFS Design

- **Multi-Threaded uServer**
  - **Scalable by design: sharing nothing**
  - **Each worker has several private data structure**
    - **Device requests qpair**



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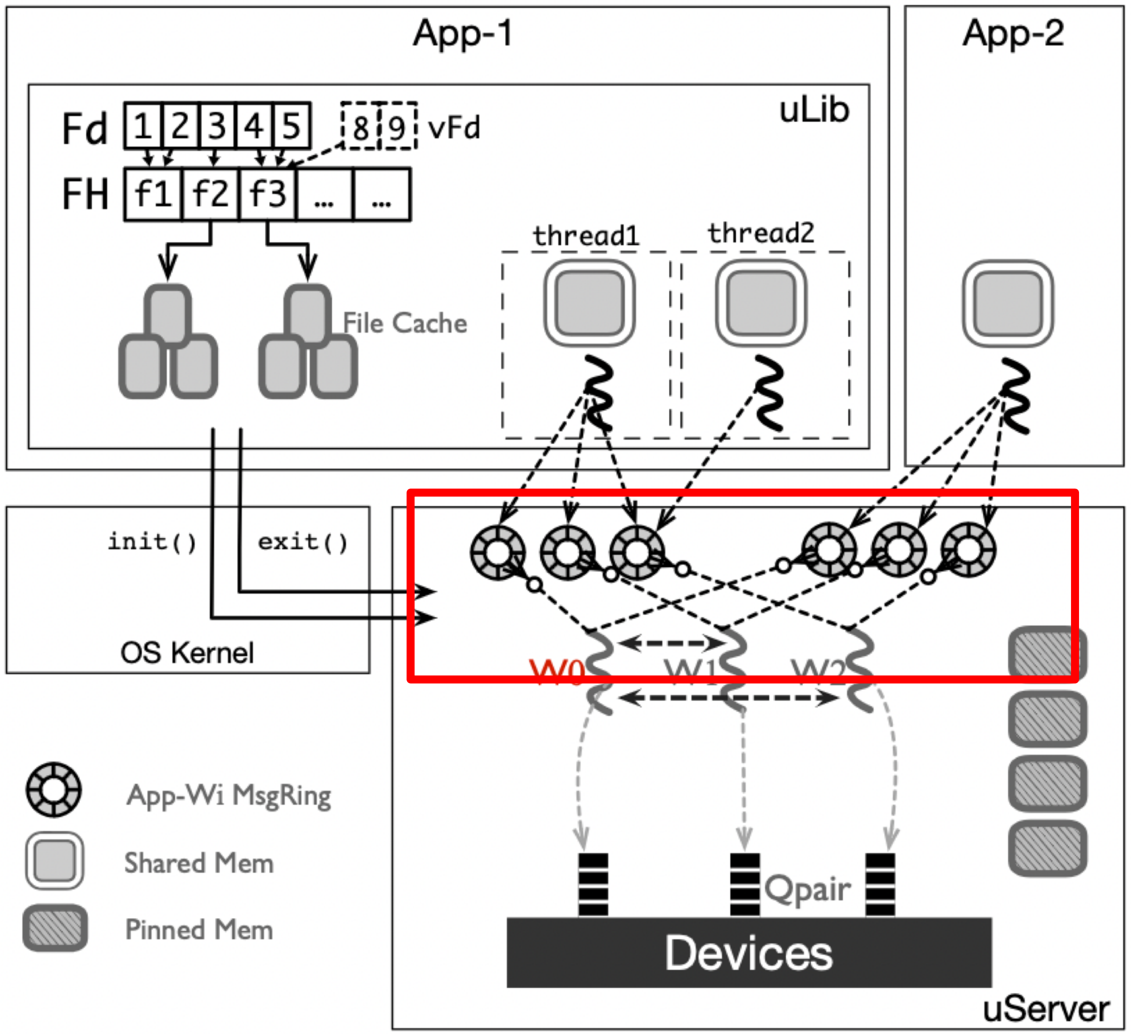

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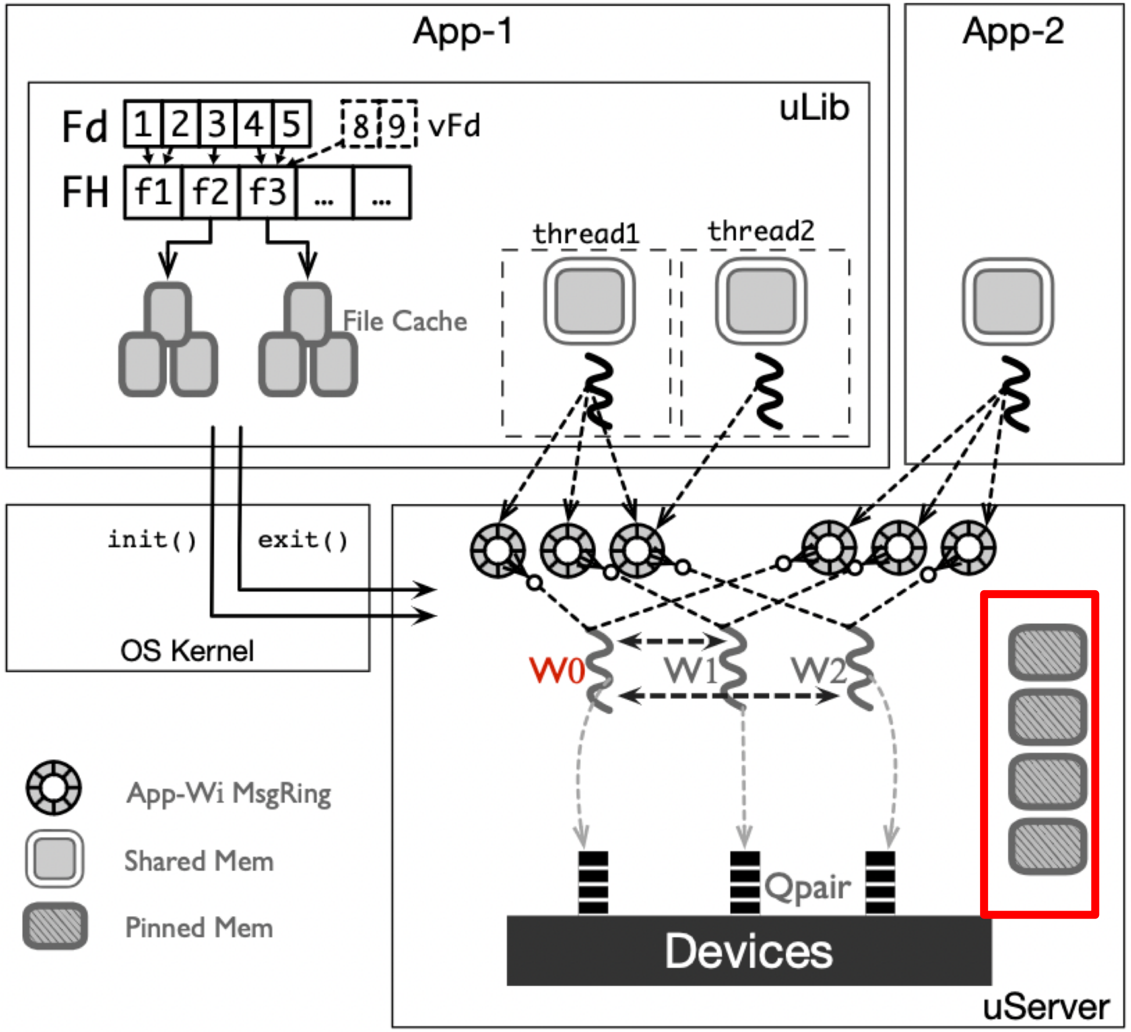

uFS Design

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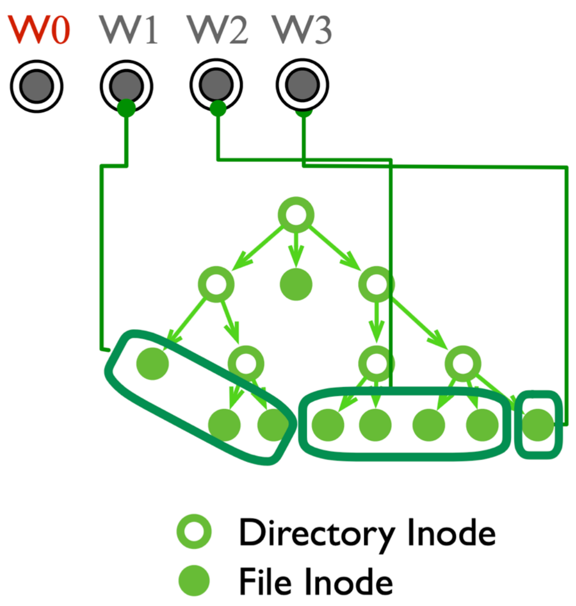
- **Multi-Threaded uServer**
  - **Data parallelism for scalability**
    - **Shared-nothing architecture**
    - **Divide filesystem states and data into threads**
    - **minimizes the sharing of in-memory data structures across cores**

Runtime Inode Ownership

Employ Non-blocking Shared Structures Judiciously

uFS Design

- Multi-Threaded uServer
  - Runtime Inode Ownership
    - Each group of inodes is exclusively accessed by one worker
      - No need for synchronization
      - Pre-assign data bitmap to each worker for data allocation



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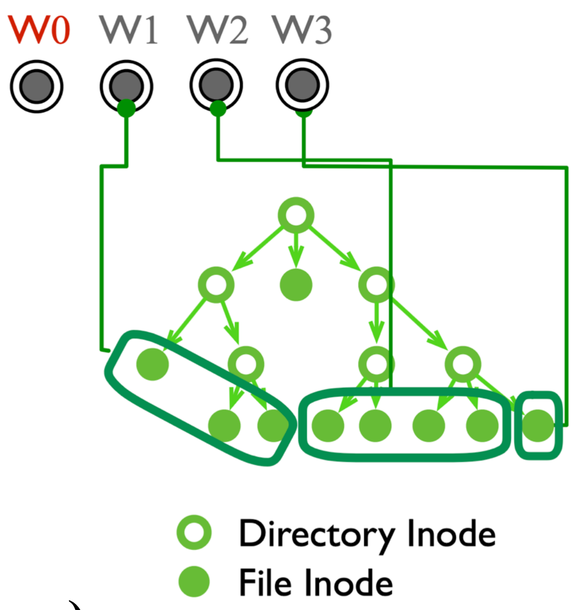
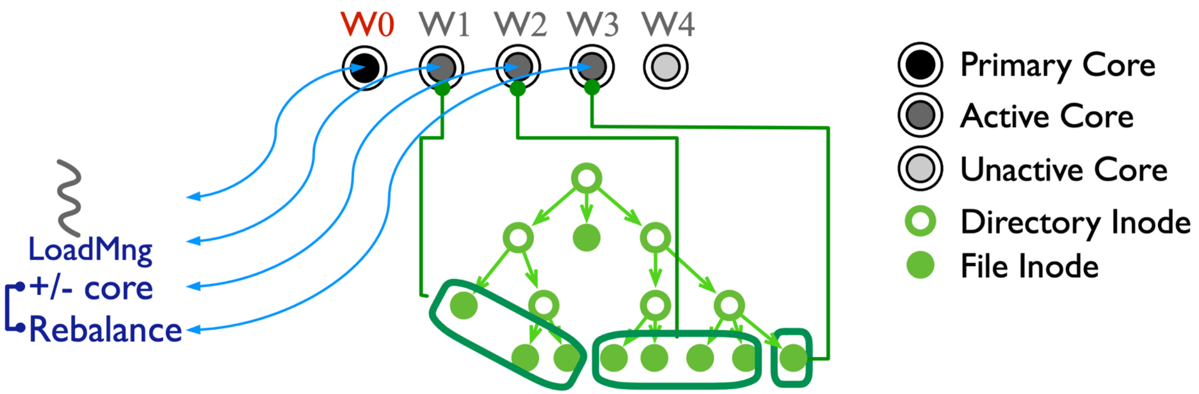
    - **Asymmetric Workers**
      - **Primary(W0)**
        - **Own and handles metadata workload (directory operations)**
        - **Coordinates with the workers**
      - **Worker**
        - **File operations**



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
  - Decides number of cores → Activate/Deactivate 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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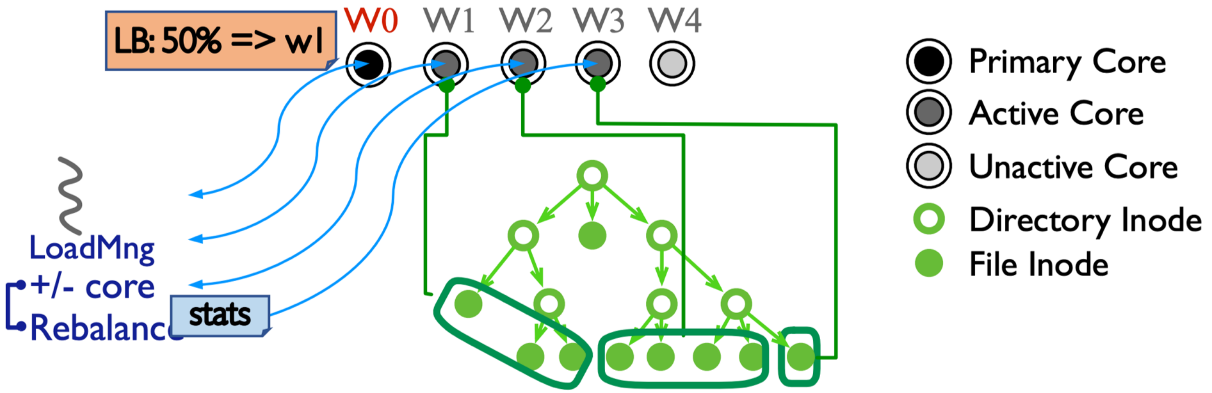

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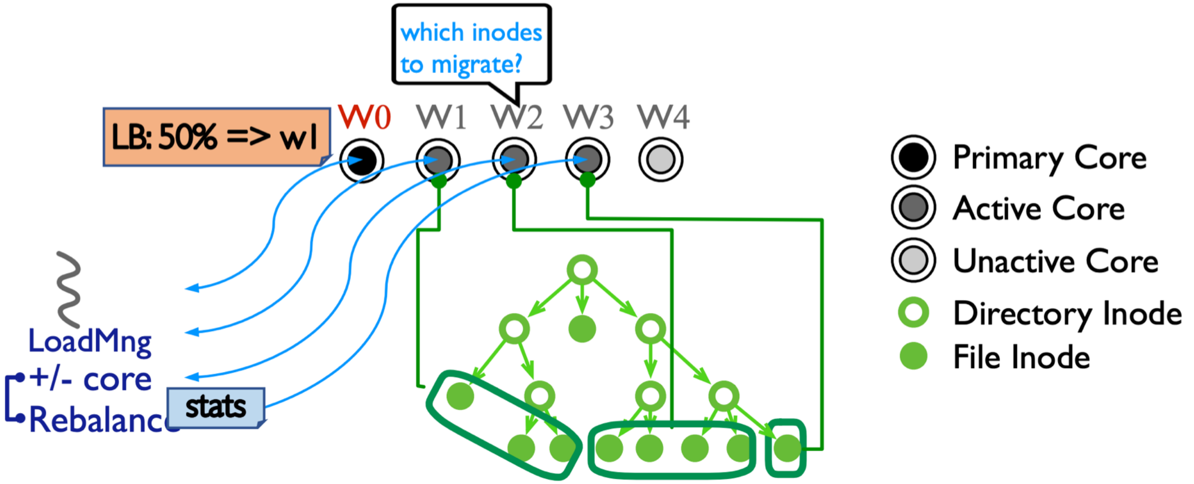
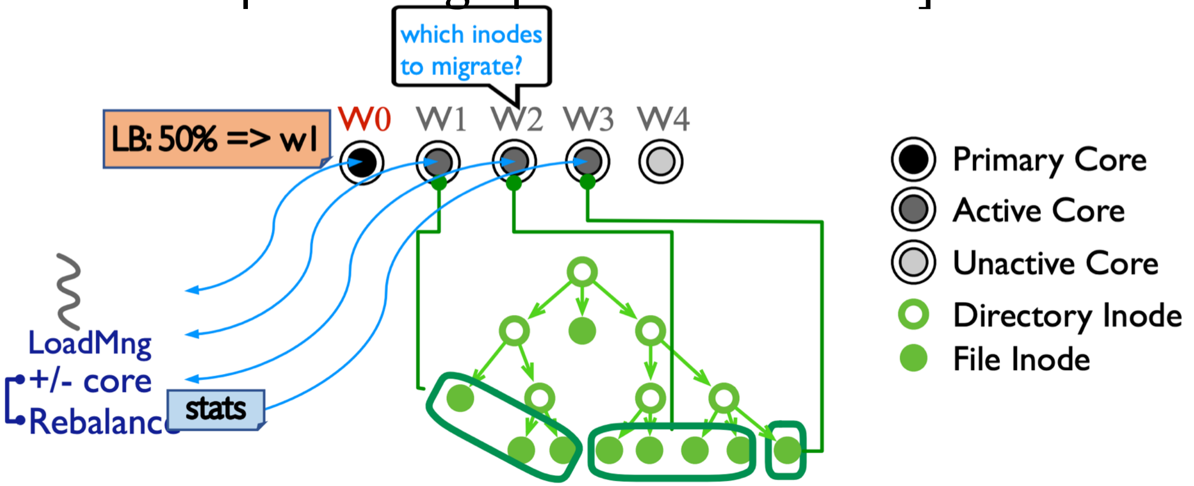


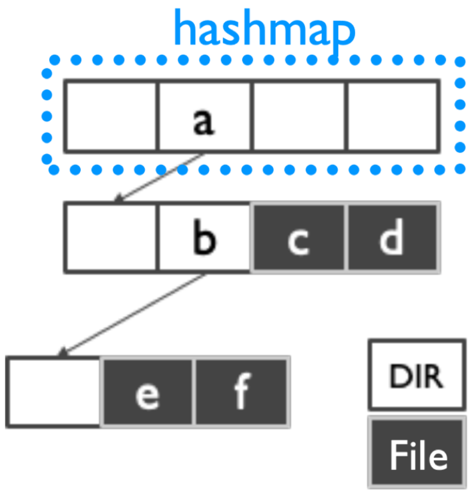
Dynamic Load Algorithms

- 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]



Employ Non-blocking Shared Structures Judiciously

- Dentry Cache and Permission Checking
  - Recursive HashMap
  - Only the primary worker can update and all can read
  - Leverage industrial-quality lock-free data structures



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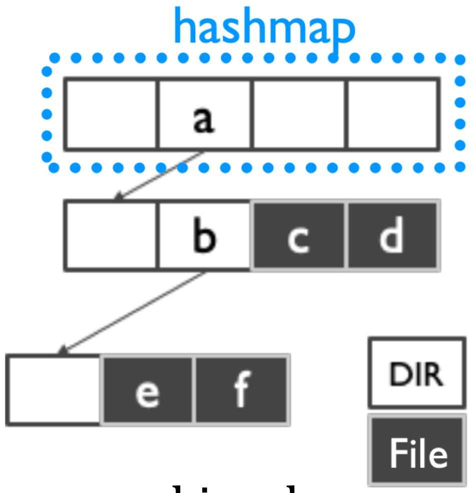
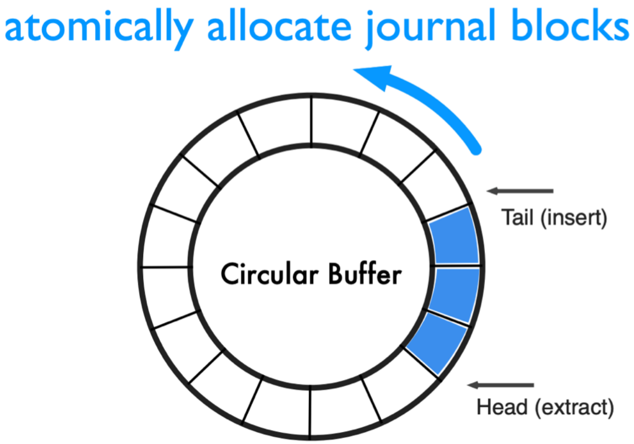


- Global Logic Journal that allows maximal parallelism
  - Each worker can initialize journal transactions independently for owned inodes
  - Negligible overhead added
    - Recording logic modification is lightweight
    - Minimal critical section when reserving journal blocks



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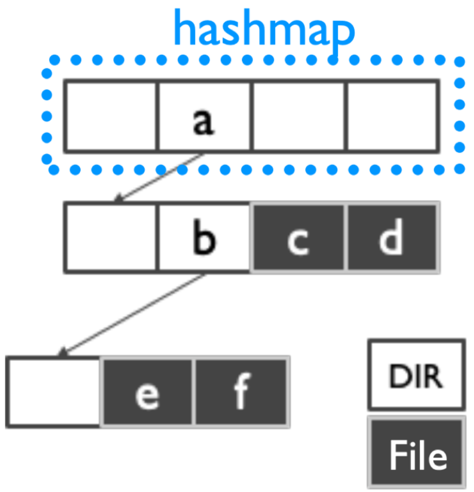
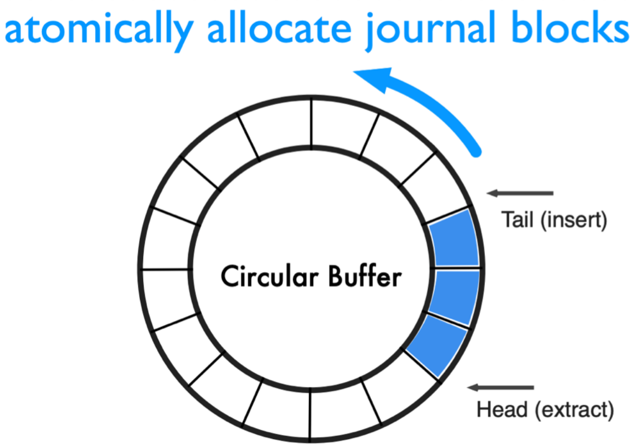
Evaluation

- uFS offers good single-threaded base performance
- uFS performs well as a multi-threaded micro-kernel
- 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® Xeon® Gold 5218R CPU
  - Linux 5.4, SPDK 18.04





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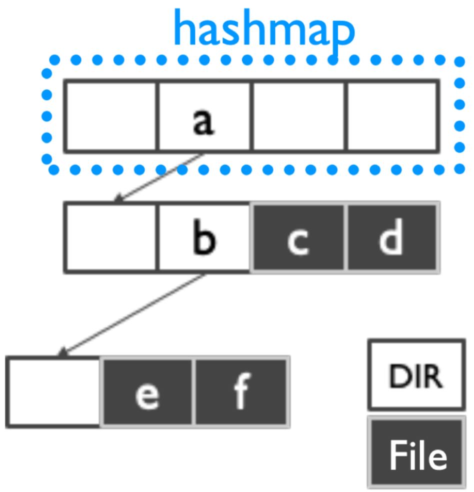
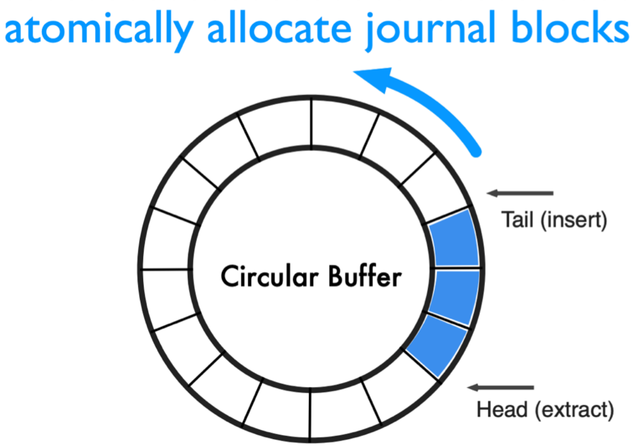
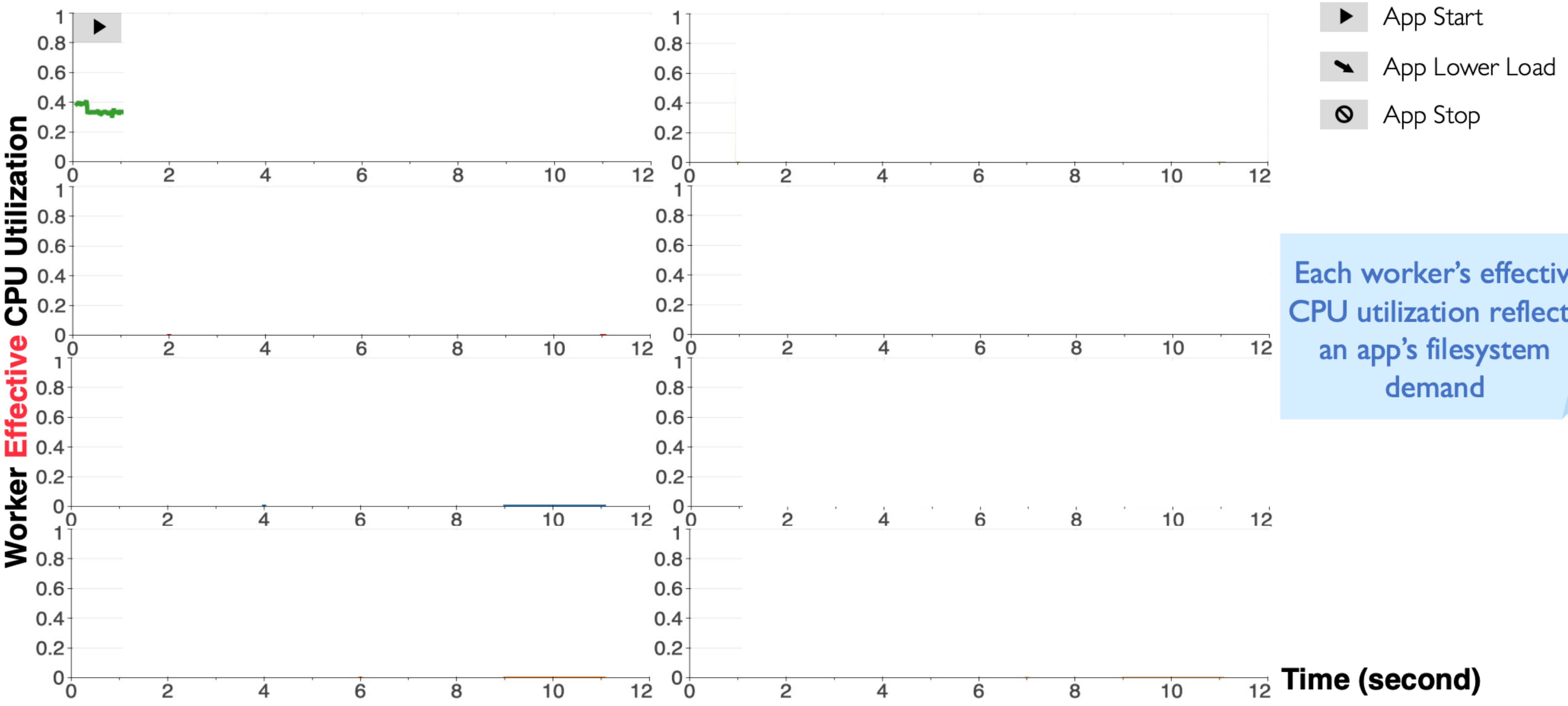




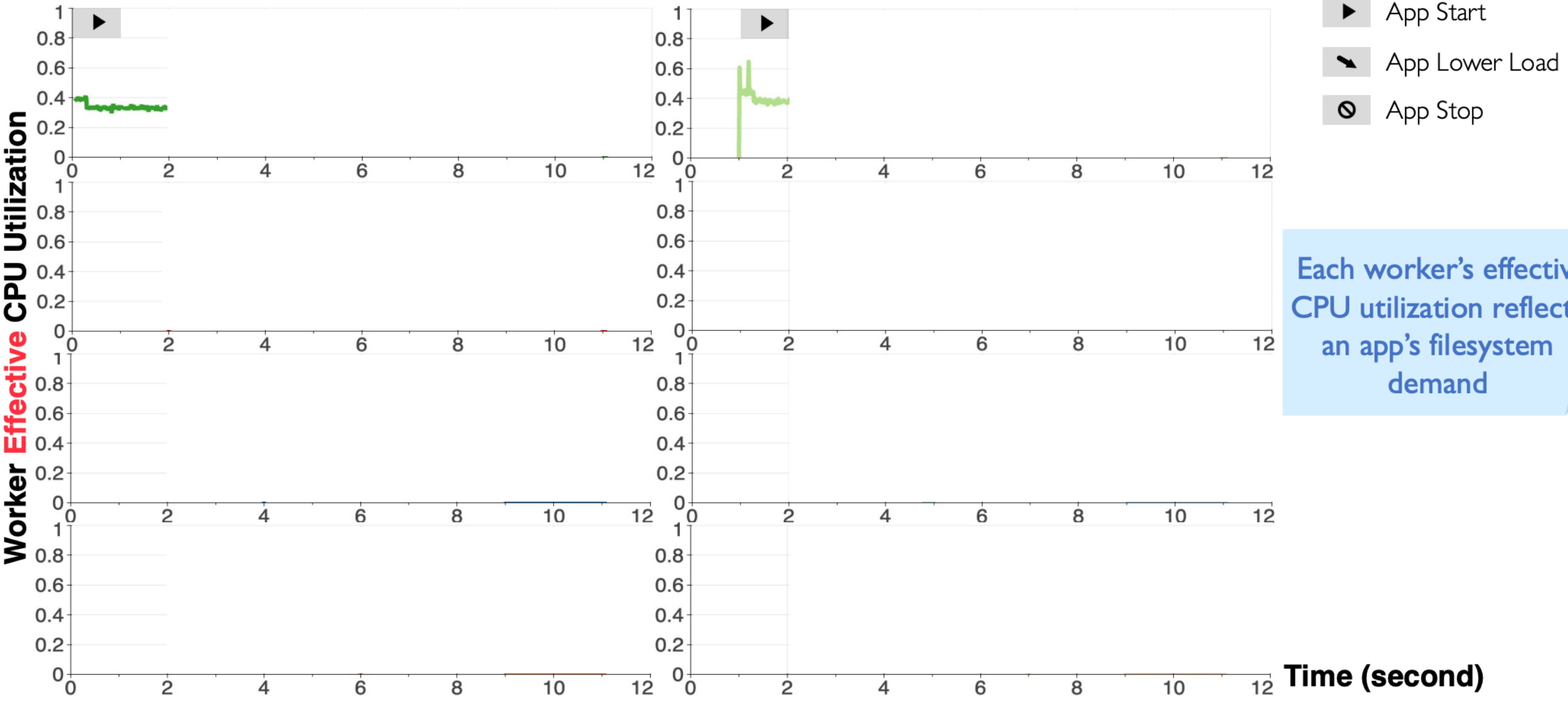
Core Allocation Experiments



Each worker's effective CPU utilization reflects an app's filesystem demand

Core Allocation Experiments

USTC, CHINA ADSLAB



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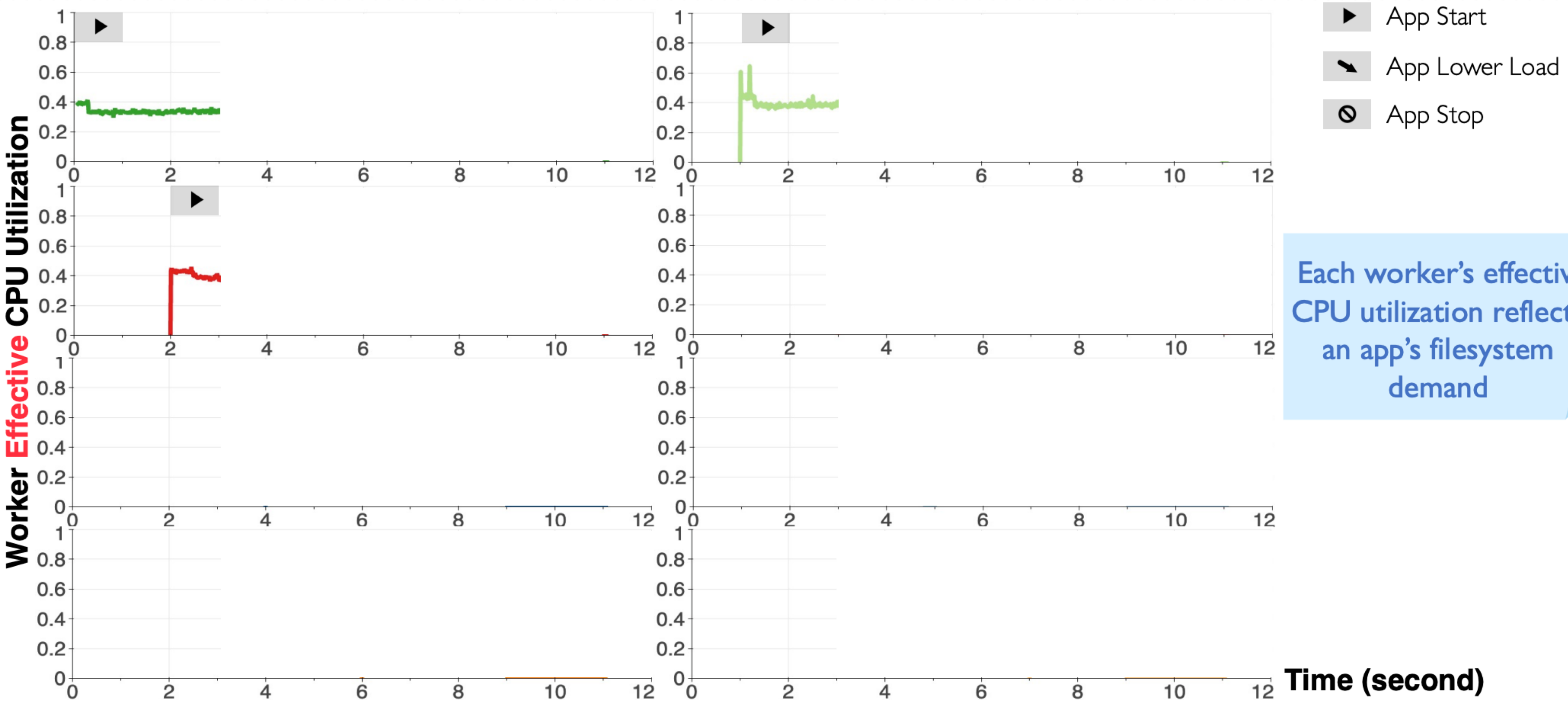

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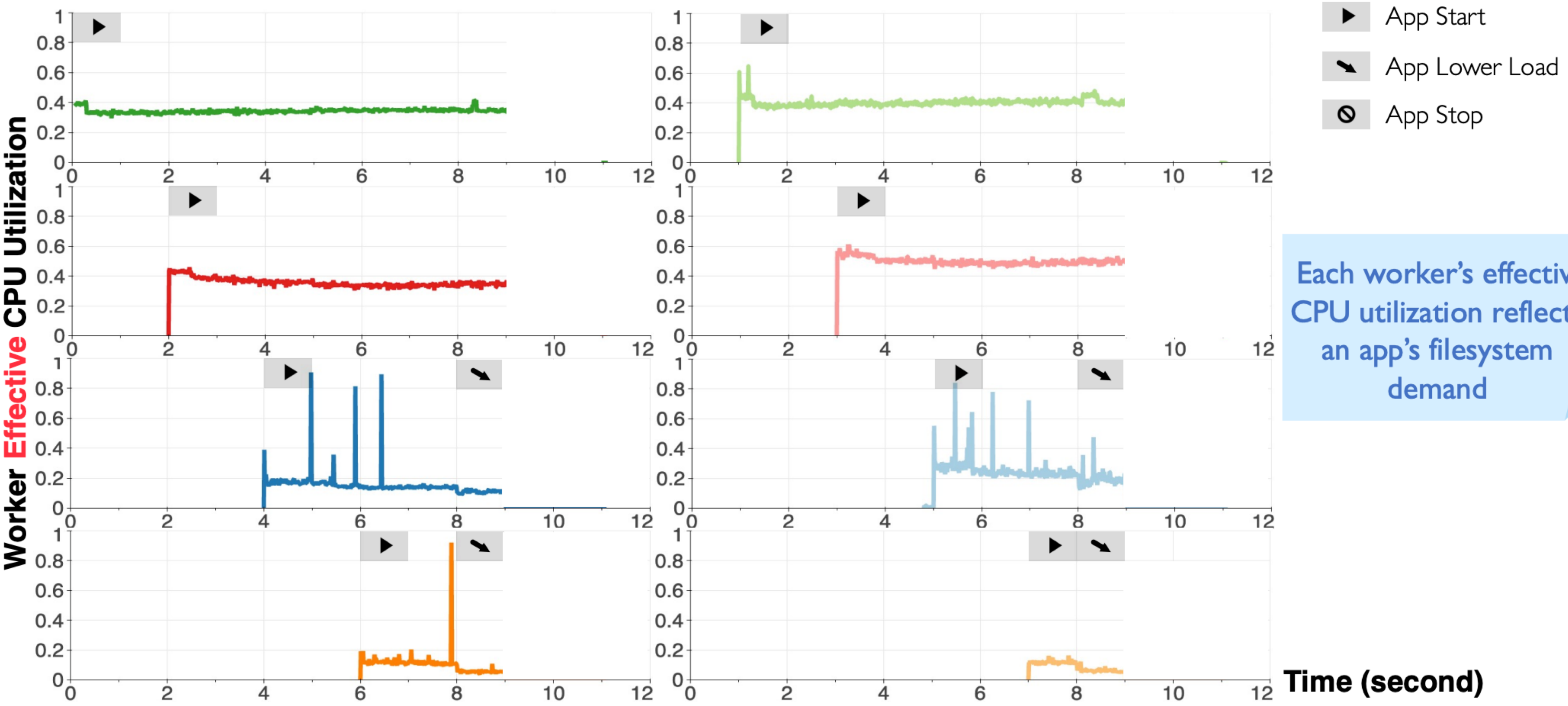

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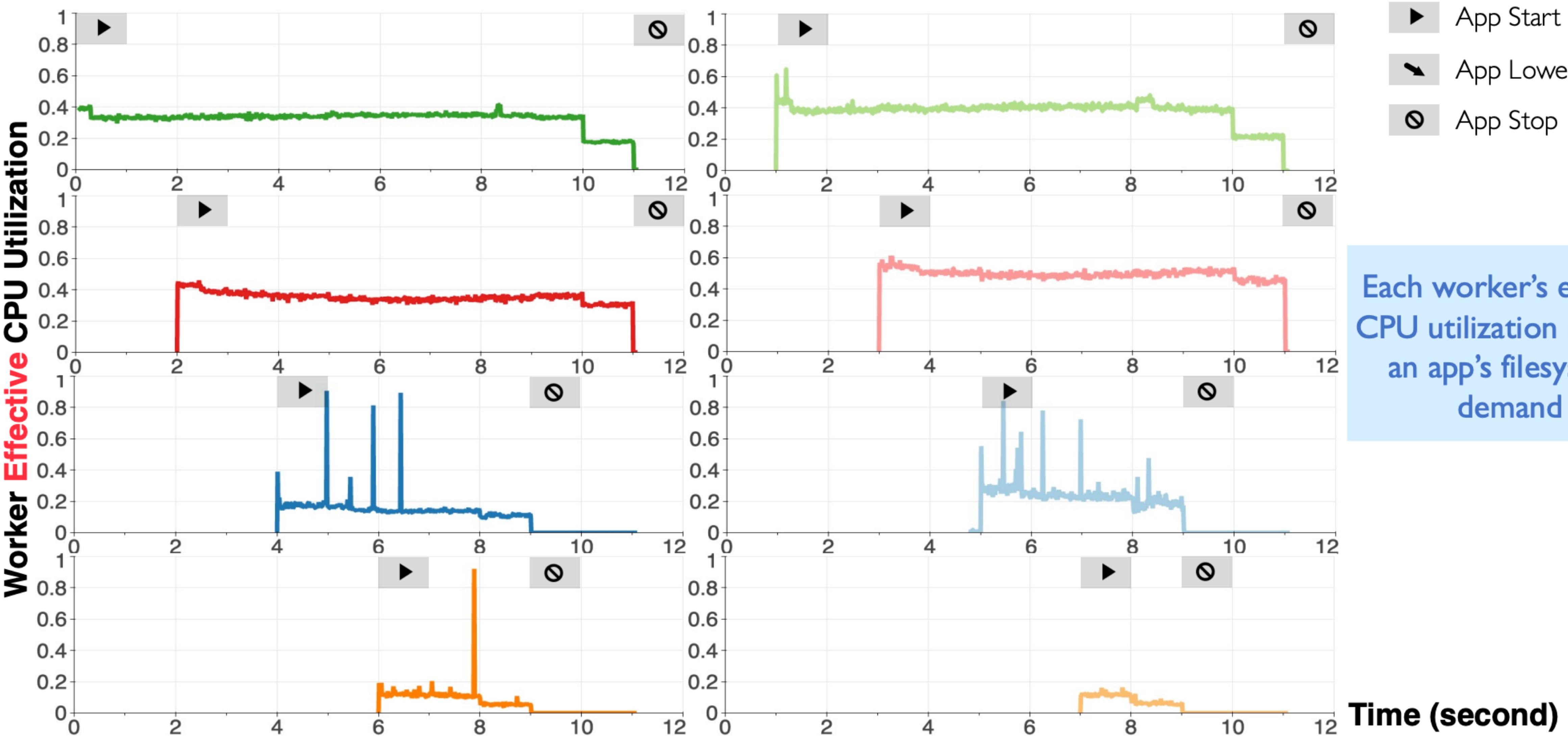

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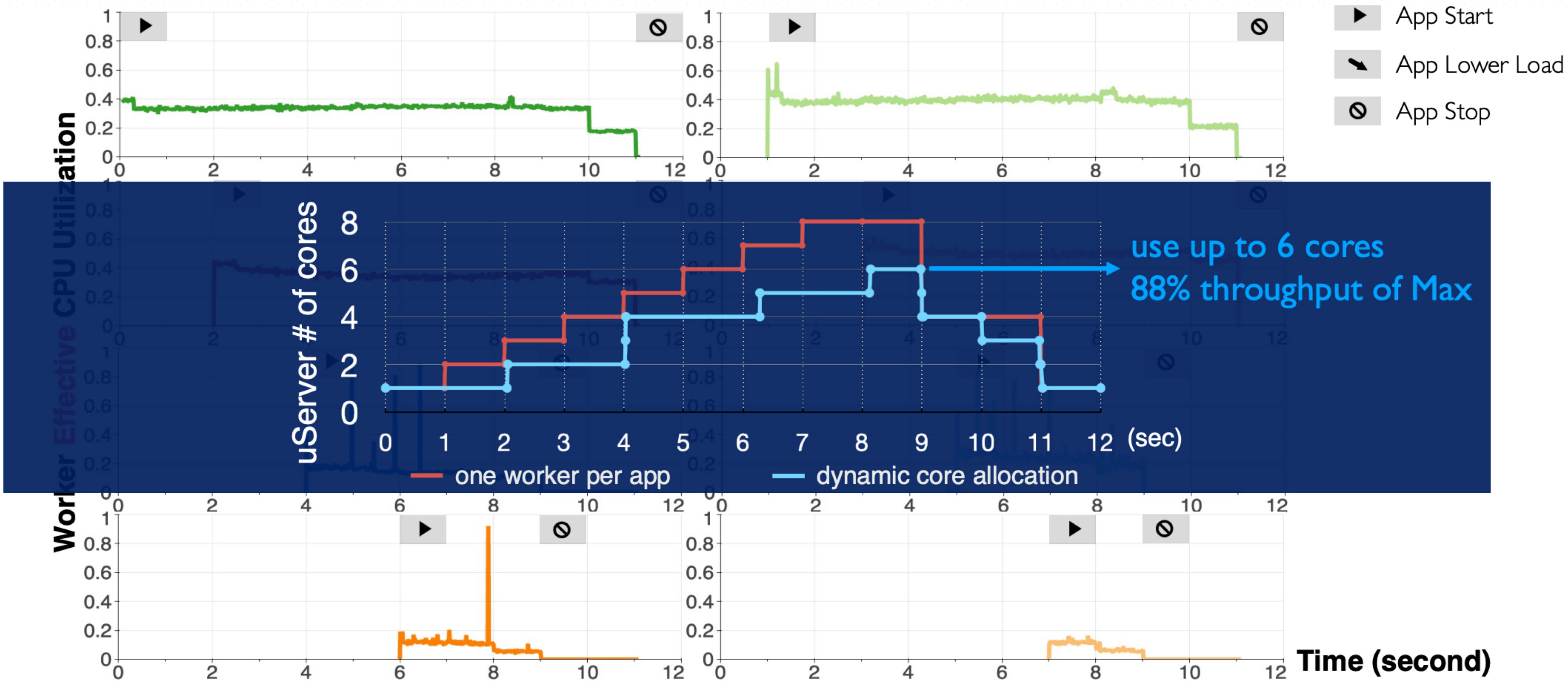
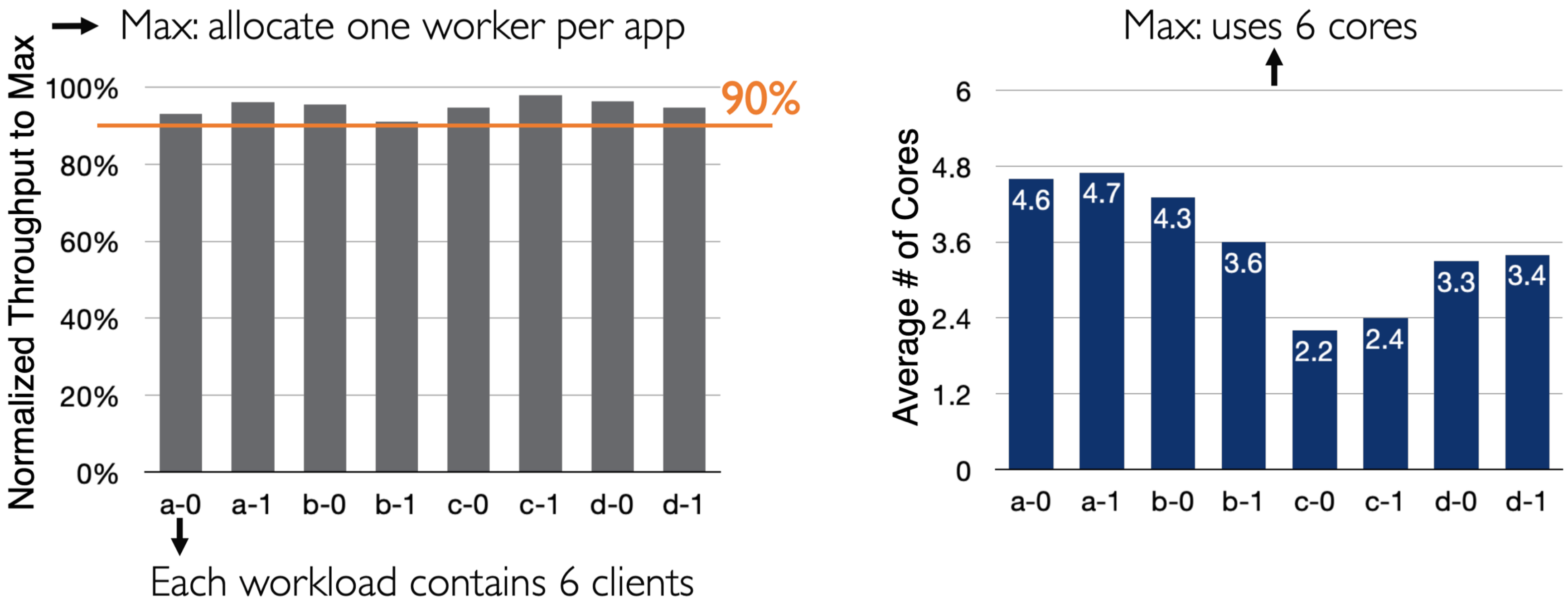


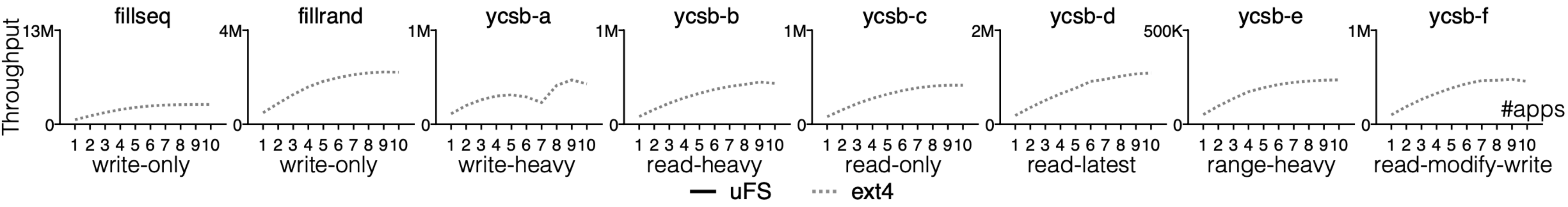
Core Allocation Experiments

8 workloads: each changes one factor by N steps along the time

- Factor example: think-time, data screw degree, request size
- uFS delivers between 91% to 98% throughput of Max
- uFS controls number of cores as needed



LevelDB: uFS with Real Apps



- uFS can scale much better than ext4
- uFS will allocate different number of cores for various workloads
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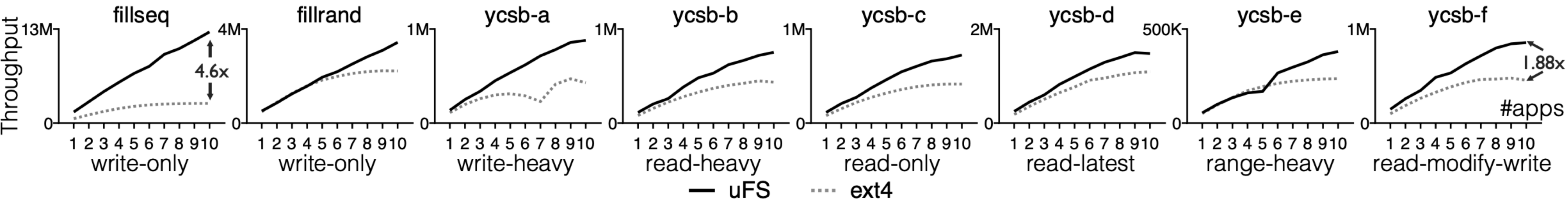

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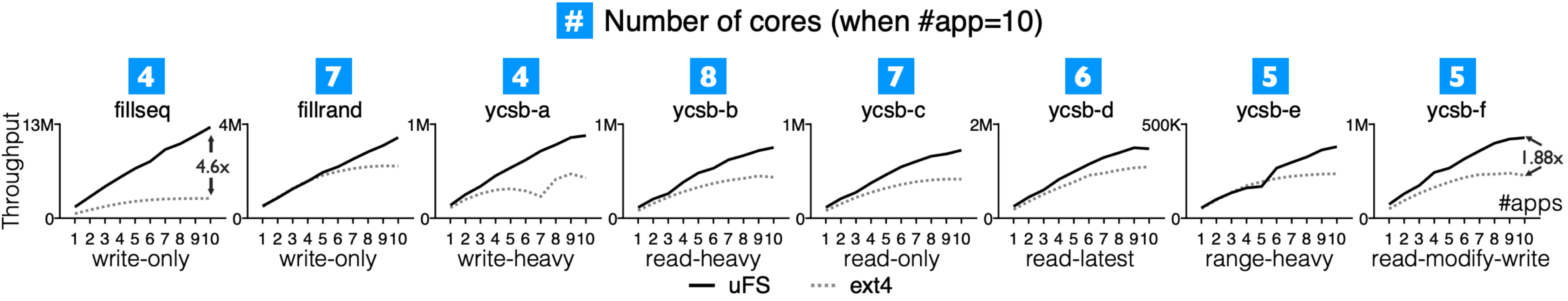

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Outline

- Background
- uFS Design
- Evaluation
- **Conclusion**

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- **Filesystem Semi-Microkernel Approach**
  - Performs and scales well under various workloads
  - Has all the benefits of user-level development

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