The Storage Hierarchy is Not a Hierarchy: Optimizing Caching on Modern Devices with Orthus

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Storage Hierarchy

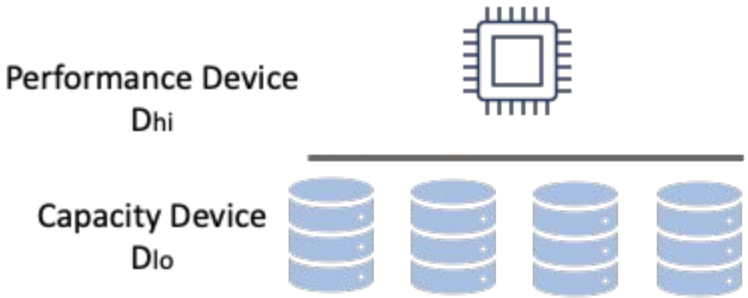
- Long been central to system designs

"Ideally one would desire an indefinitely large memory capacity ... It does not seem possible to achieve such a capacity. We are therefore forced to recognize the possibility of constructing a hierarchy of memories ..."

--- "**Preliminary Discussion of the Logical Design of an Electronic Computing Instrument**" (1946),
by Burks, Goldstine, and von Neumann.

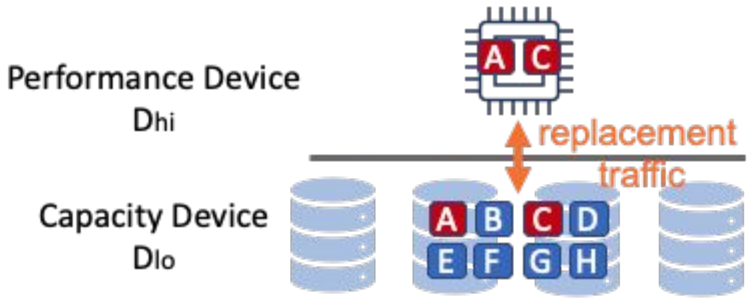
Storage Hierarchy

- Simplified two-layer hierarchy
  - **Performance Device:** fast, expensive, small
  - **Capacity Device:** slow, cheap, large



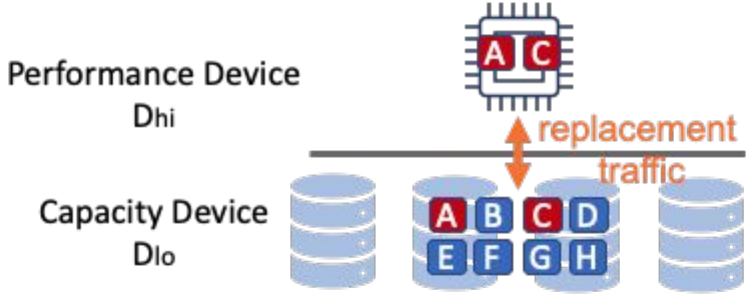
Caching

- Replicating popular items in **Performance Device**



Caching Wisdom: Maximizing Hit Rates

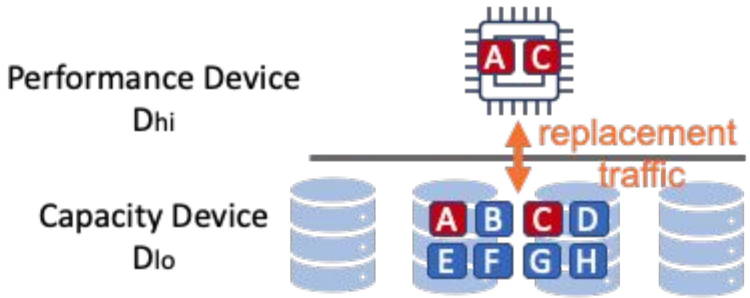
- Strives to direct most accesses to **Performance Device**



Caching Wisdom: Maximizing Hit Rates

- Strives to direct most accesses to **Performance Device**

- Caching delivers ~**Performance Device** speed along with **Capacity Device** capacity
- Traditionally, very good!
  - **Performance:** Performance Device >> Capacity device
  - E.g. DRAM vs. HDD (100x differences)



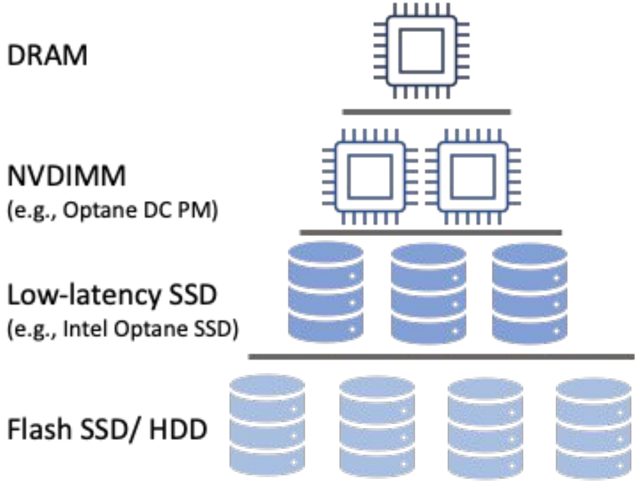
Problem: Caching is Insufficient in Modern Storage Hierarchies

- **Insight**:

  the assumption (Performance device >> Capacity device) is broken

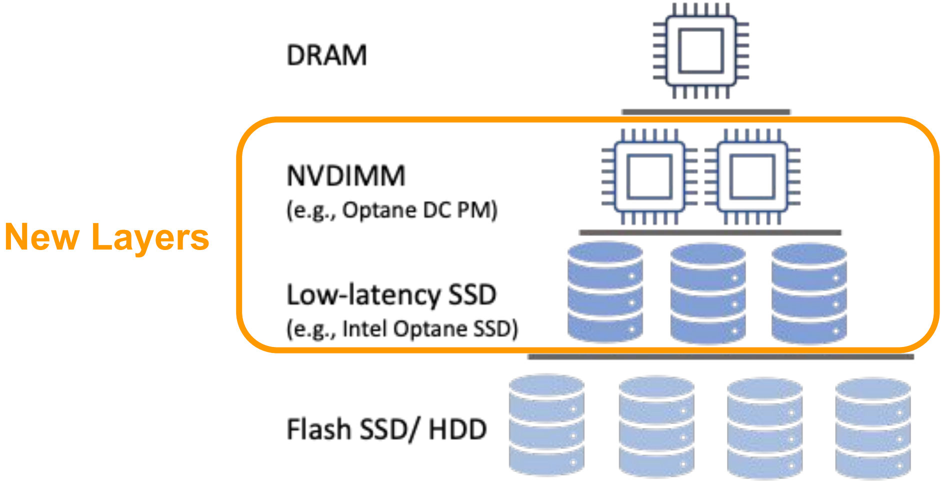
The Modern Storage Hierarchies

- Non-Volatile Memory-based devices are filling the performance gap



The Modern Storage Hierarchies

- Non-Volatile Memory-based devices are filling the performance gap
  - NVDIMM (300ns, ~7GB/s)
  - Low-latency SSD (10us, ~3GB/s)



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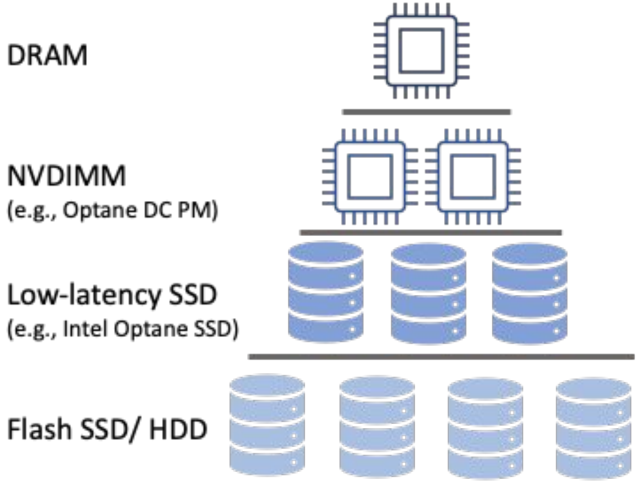

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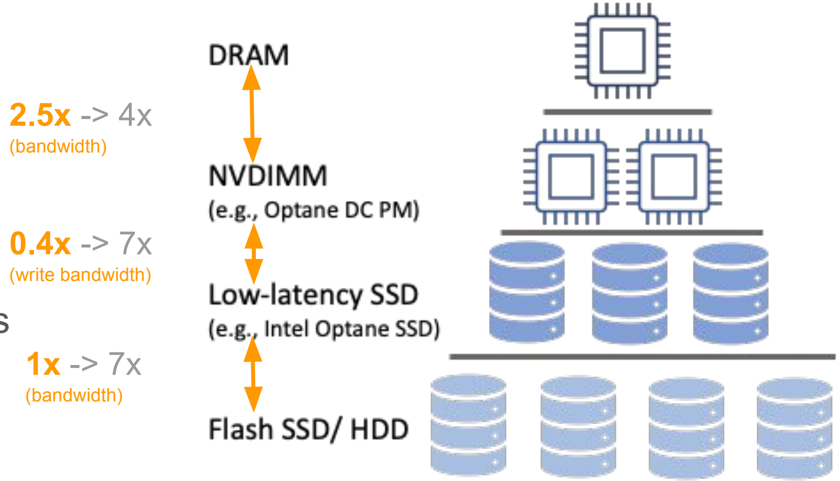

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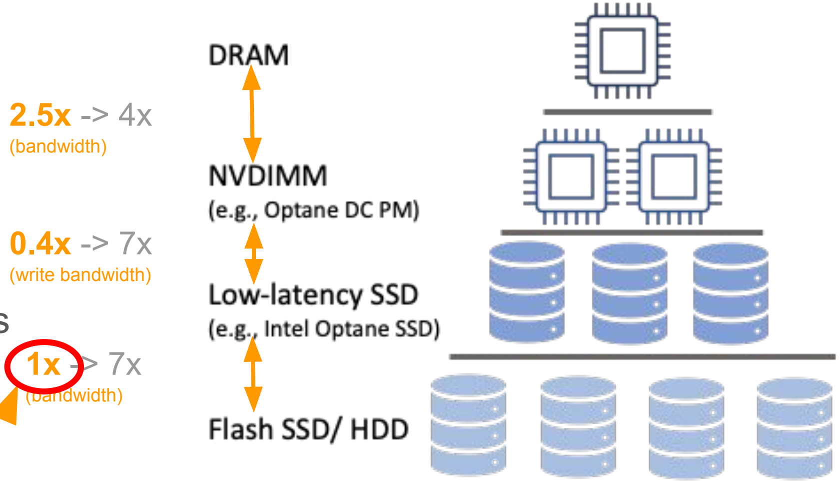
- The differences between today’s neighboring layers are less clear and even overlapping (depending on workloads)
- E.g., serving reads with high parallelism, Optane SSD ~ Flash SSD, caching leaves huge performance available in Flash SSD **unexploited**



It’s imperative to rethink how modern hierarchies should be managed.

Our Approach:
Non-Hierarchical Caching (NHC)

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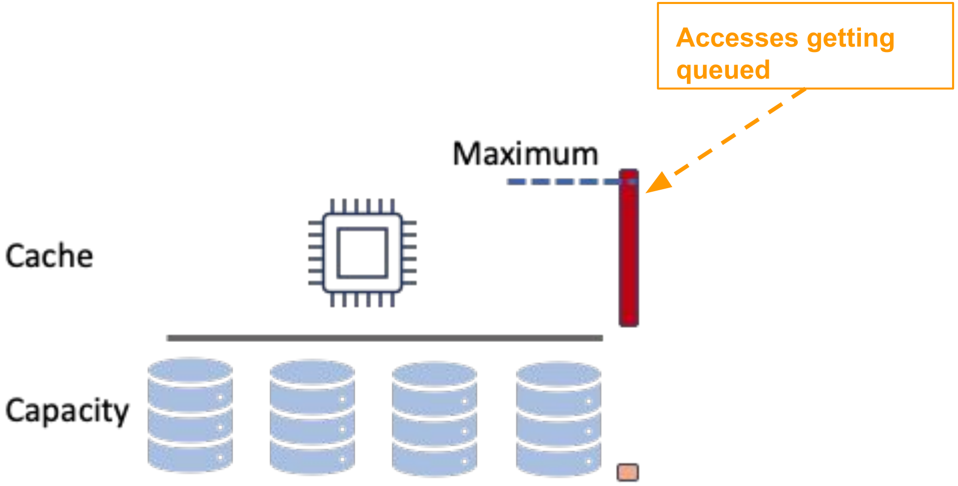
- Key idea: augmenting caching with dynamic load **admission** and request **offloading**

Augmenting Caching with Dynamic Load Admission and Request offloading

- **Intuition:** we should avoid **excess load** to cache device when it is **saturated**



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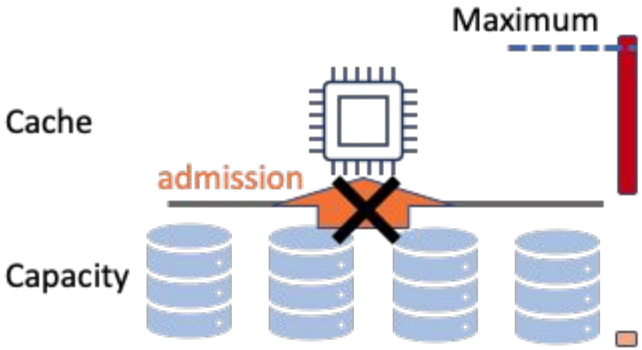
  - Data admission to further improve hit rate



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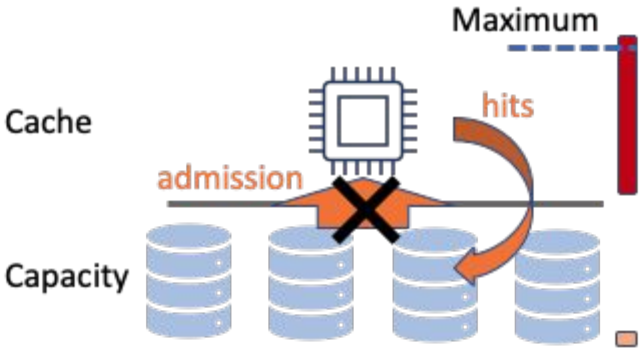
- **Excess load examples:**
  - Data admission to further improve hit rate
  - Too many cache hits



Design: Non-Hierarchical Caching

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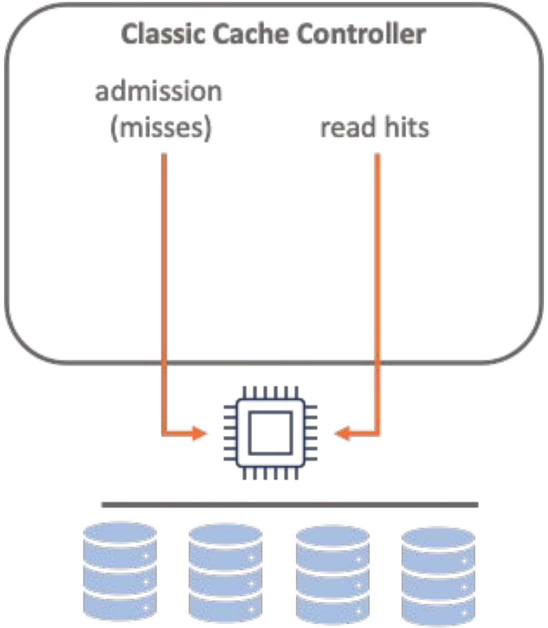
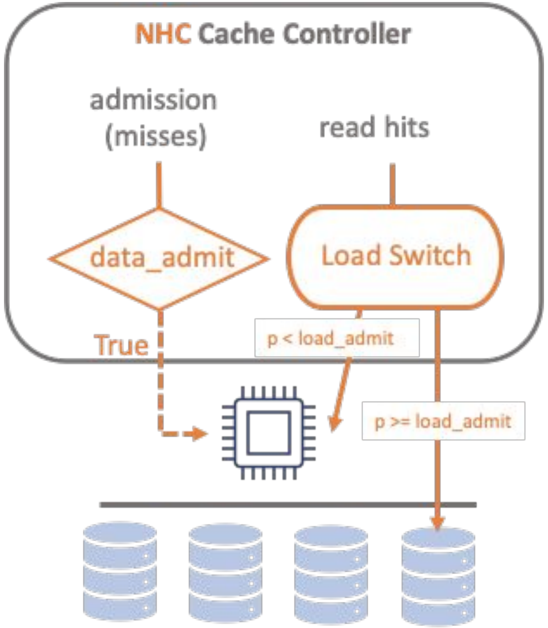
- Enable offloading: **tunable caching behaviors**
  - Classic caching is (data_admit = true, load_admit_ratio = 100%)





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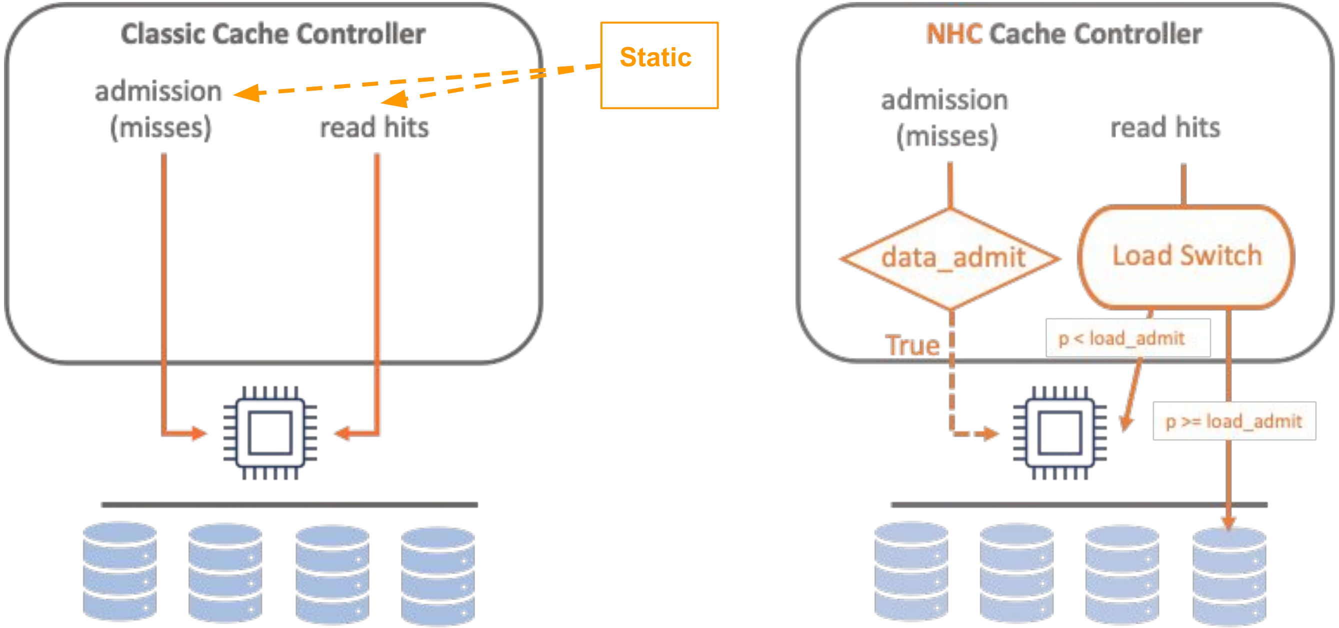

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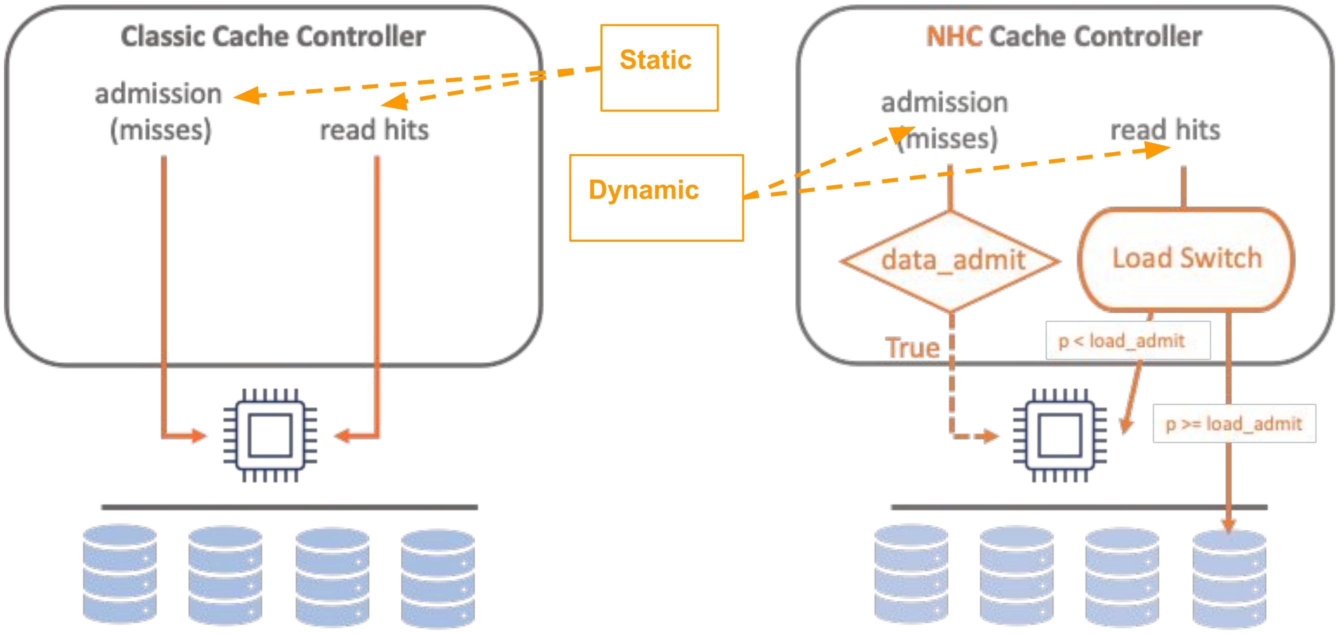

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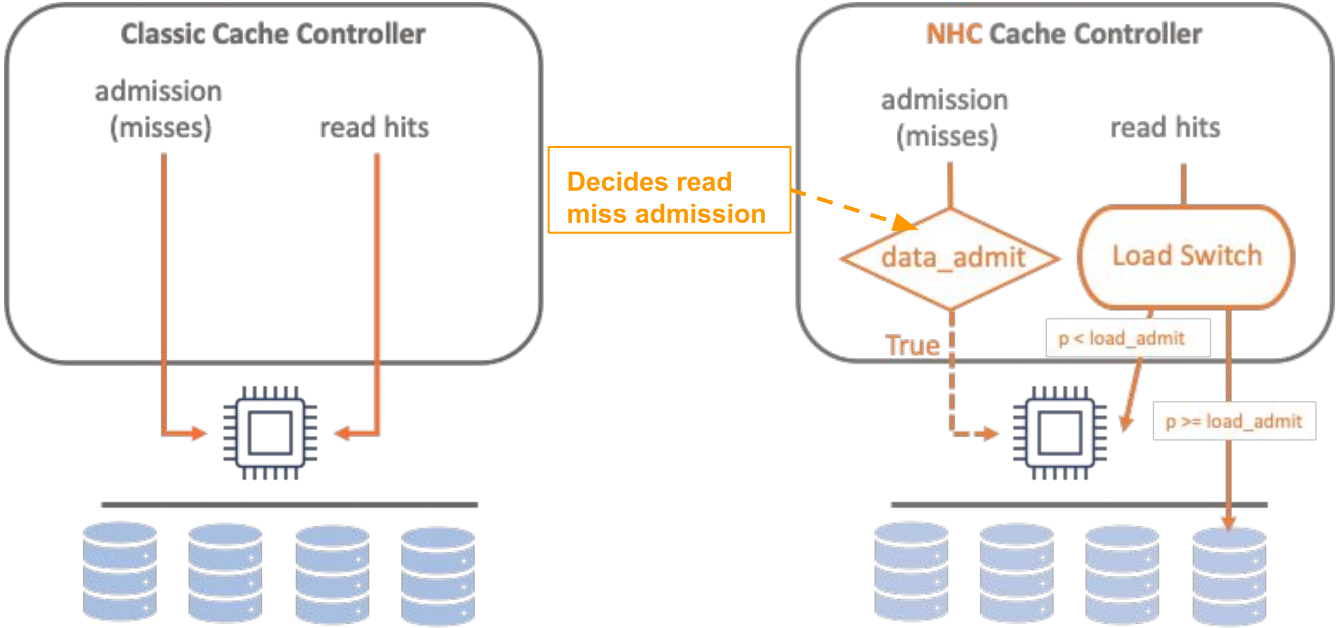

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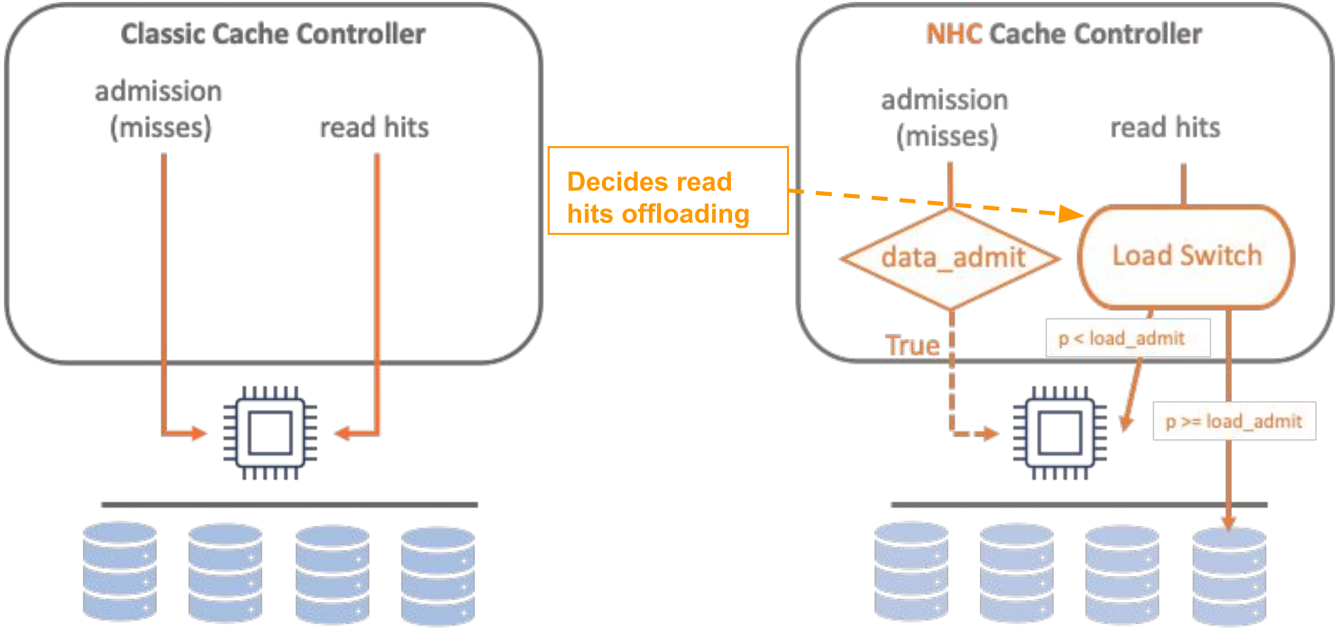
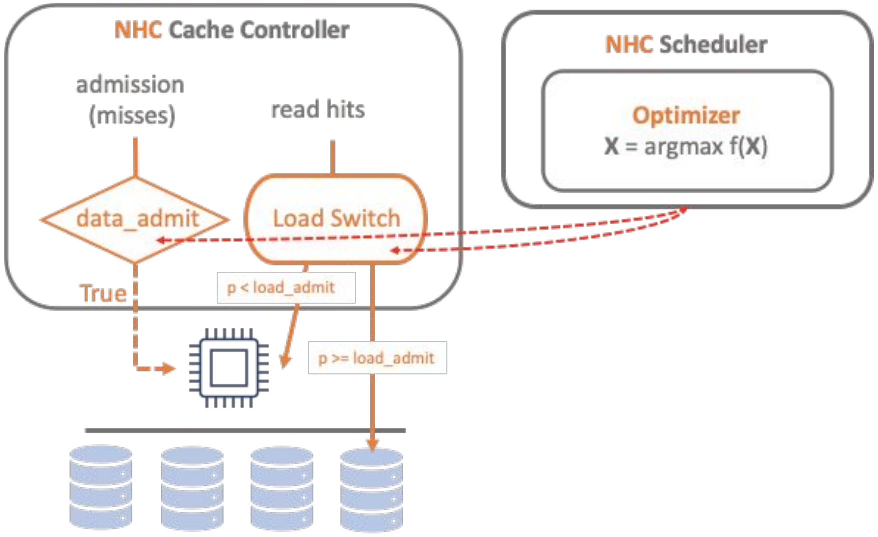


How much load to offload?

- **Observation**: different hierarchies, different workloads desire different split of load to devices (for best performance)
- Handle complexities: **feedback-based cache scheduler**

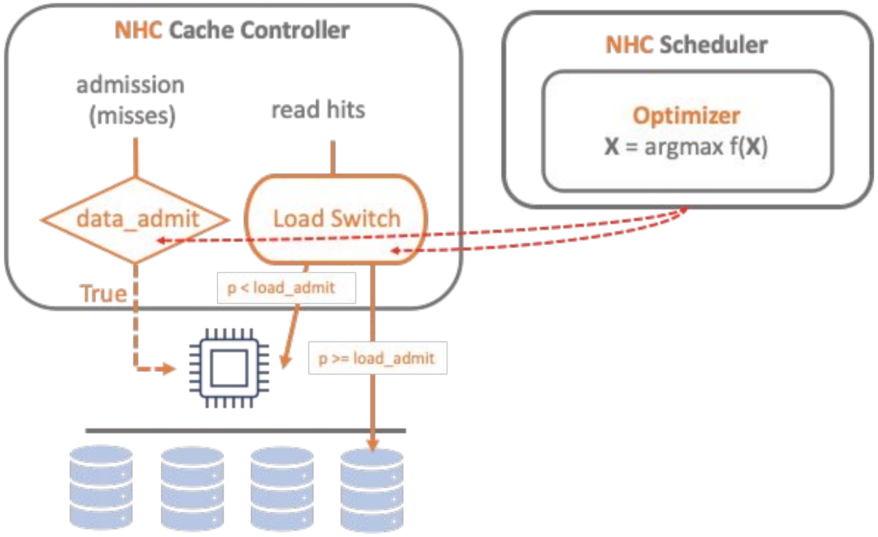
Design: Non-Hierarchical Caching

- feedback-based cache scheduler
  - Adjust tuning knobs (e.g., data_admit flag, load_admit ratio)



Design: Non-Hierarchical Caching

- feedback-based cache scheduler
    - **Optimize a target performance metric**
    - Target metric: user/device; throughput/ latency/ tail latency
        - **f(X):** a function to measure/compute the target metric



Example NHC Scheduling States

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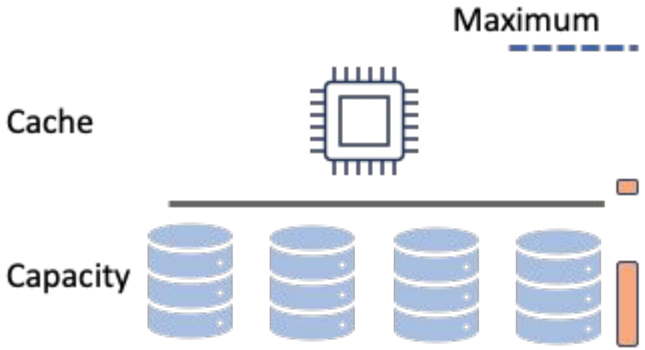
- State 1: begin with classic caching



Example NHC Scheduling States

- State 1: begin with classic caching
  - Ends when hit rate becomes “stable”

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- State 2: adjust load between devices

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- **State 2: adjust load between devices**
  - Turn off data admission for read misses
  - Start to tune load admit ratio (base point 100%)

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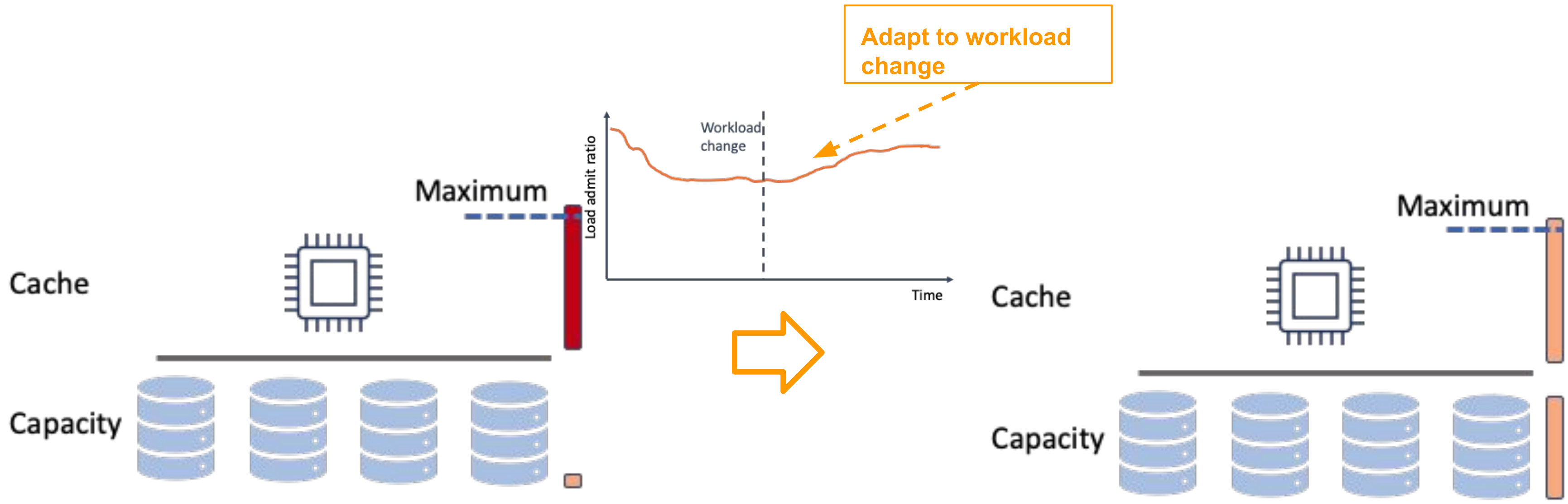
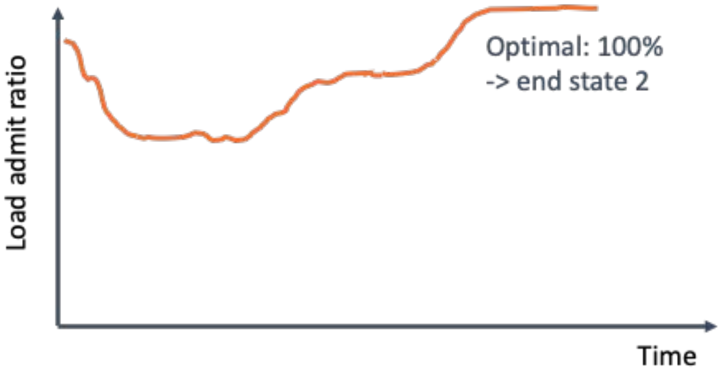


Example NHC Scheduling States

- **State 2: adjust load between devices**
  - **End state 2 when: -> back to State 1 (classic caching)**
    - Workload hit rate significantly changed
    - Find 100% load admit rate is always optimal



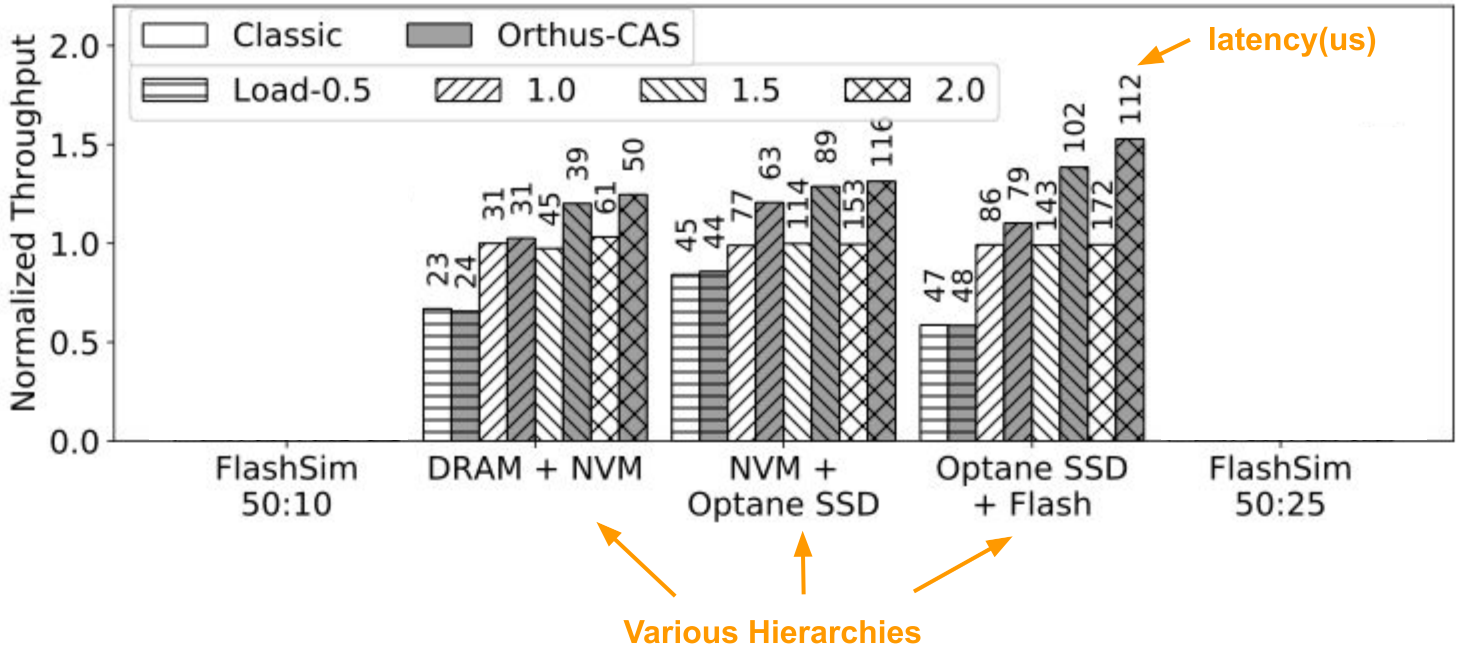
NHC - Key Properties

- Compatible with all classic caching implementations/ policies
- Require no prior knowledge of devices and workloads
- Robust to dynamic workloads

Implementation

- **Implementation (Orthus):**
  - **Orthus-CAS:** block-layer caching kernel module, based on Intel Open CAS framework
  - **Orthus-KV:** user-level caching layer for Wisckey [FAST' 16] (a LSM-tree based K/V store)
- **Supported target metrics:**
  - Throught
  - Avg. latency
  - P99 latency
- **Evaluated hierarchies:**
  - DRAM/Optane DC PM
  - Optane DC PM/Optane SSD
  - Optane SSD/Flash SSD

Ability to utilize capacity device performance



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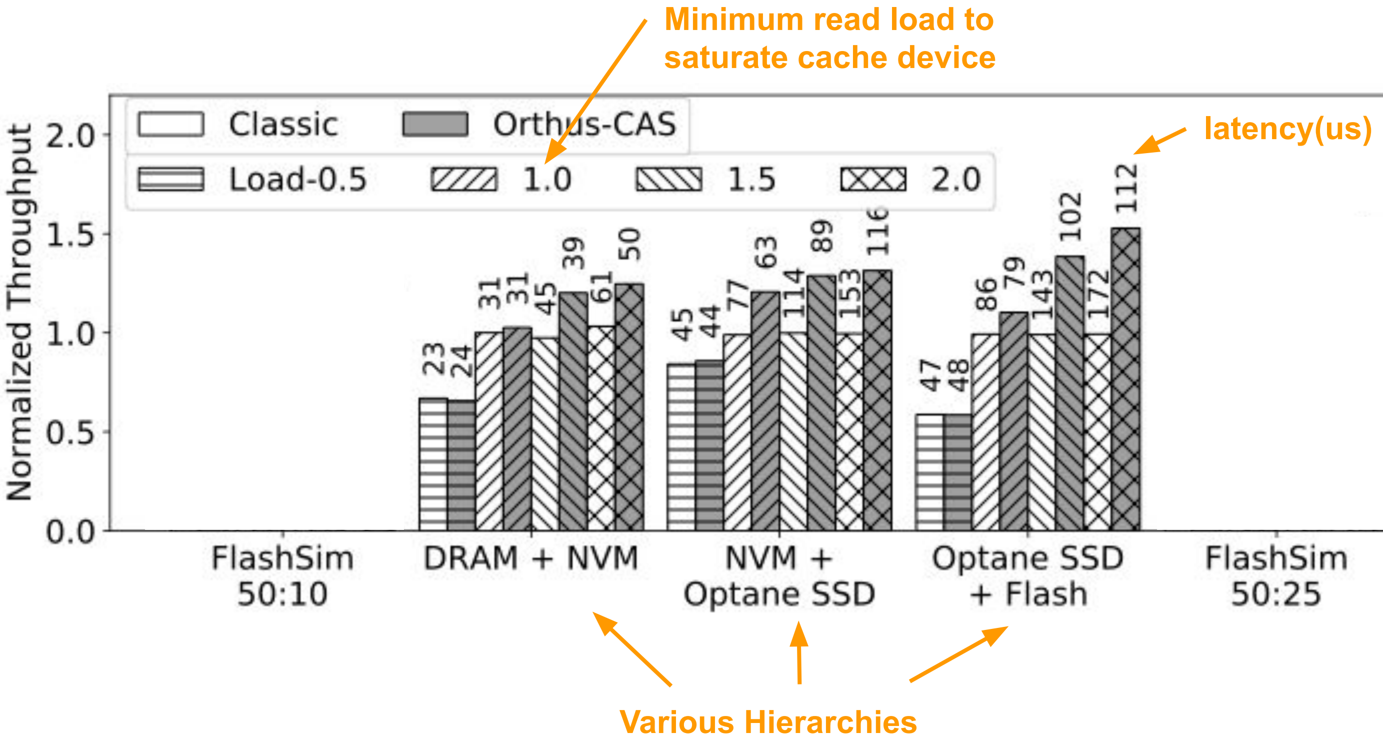

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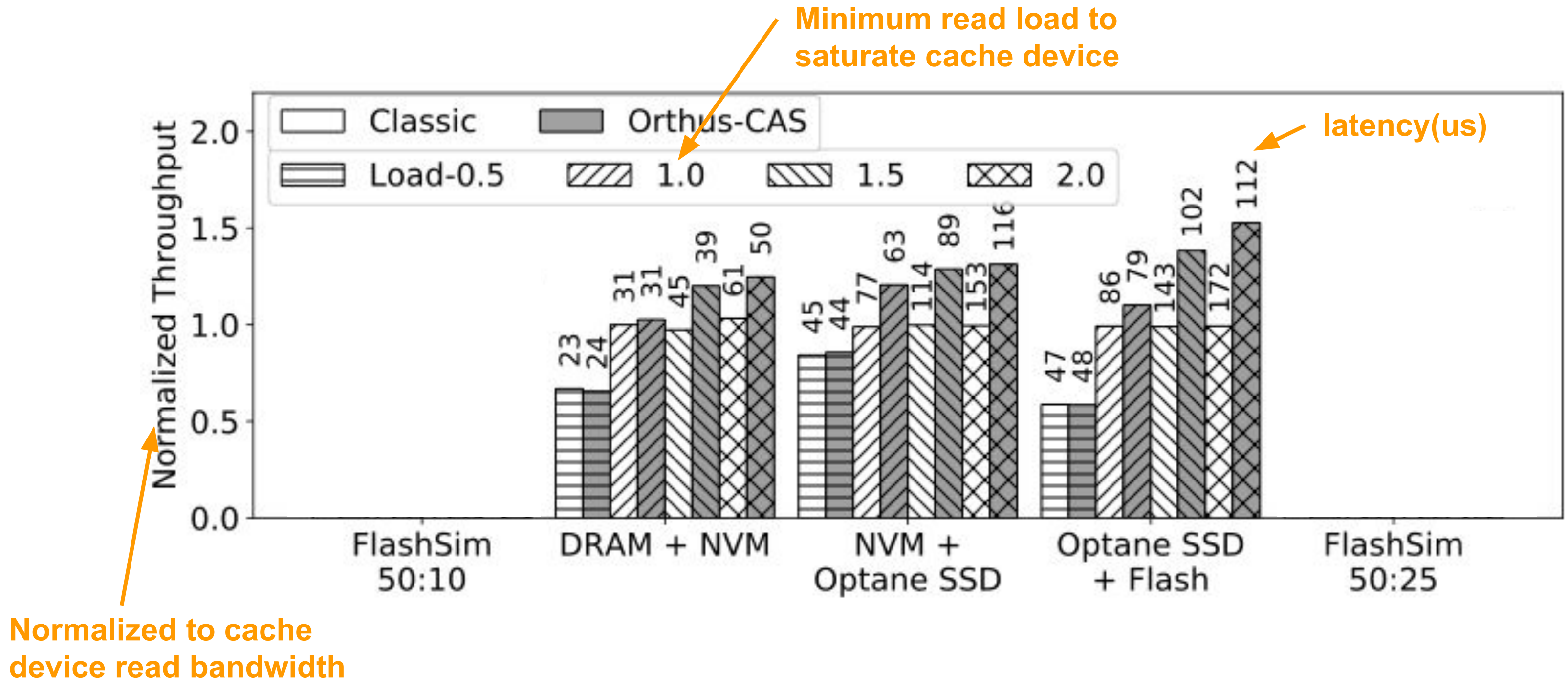

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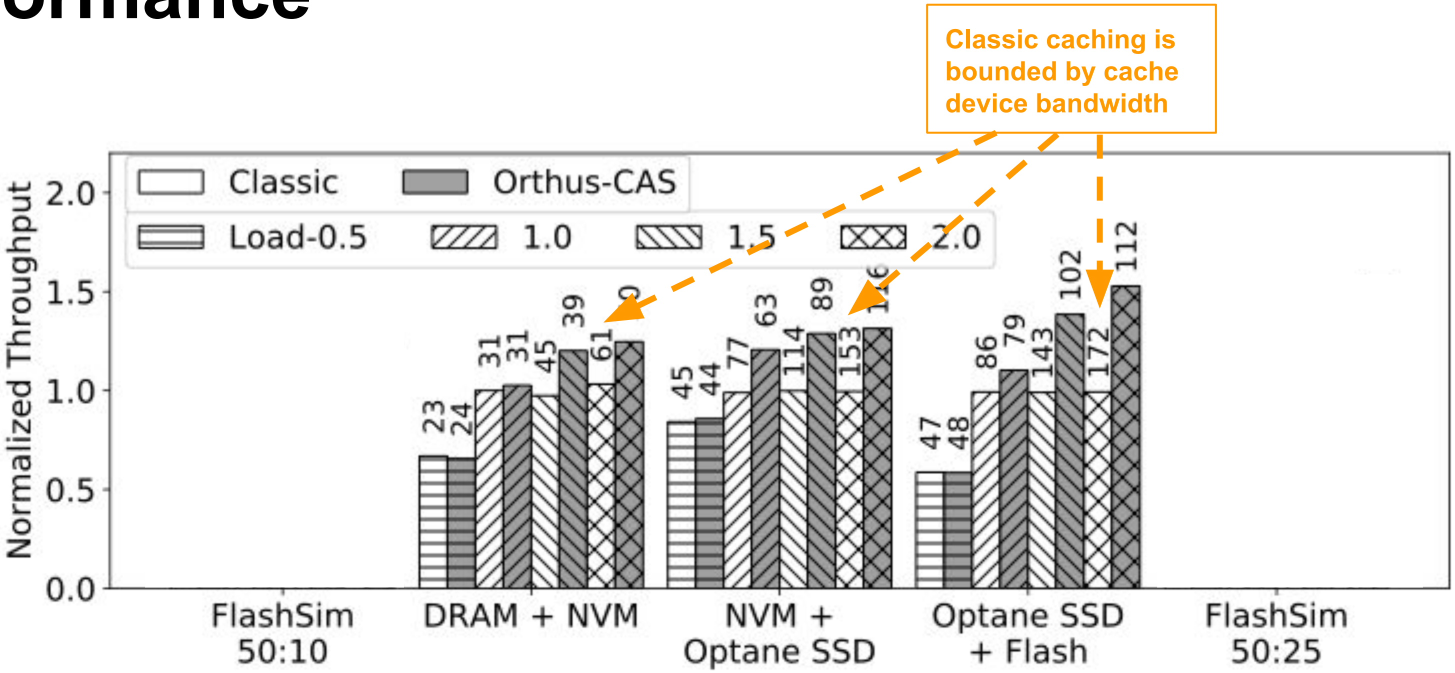

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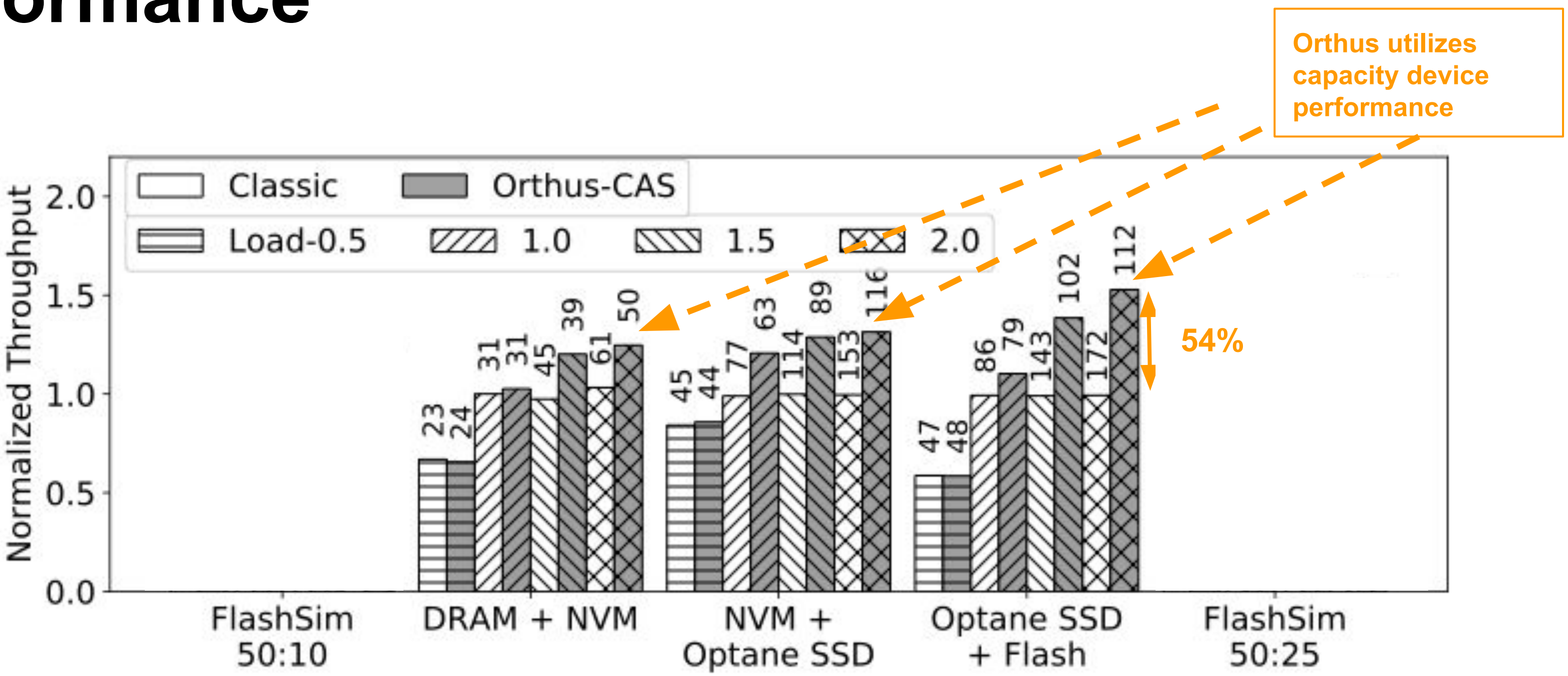

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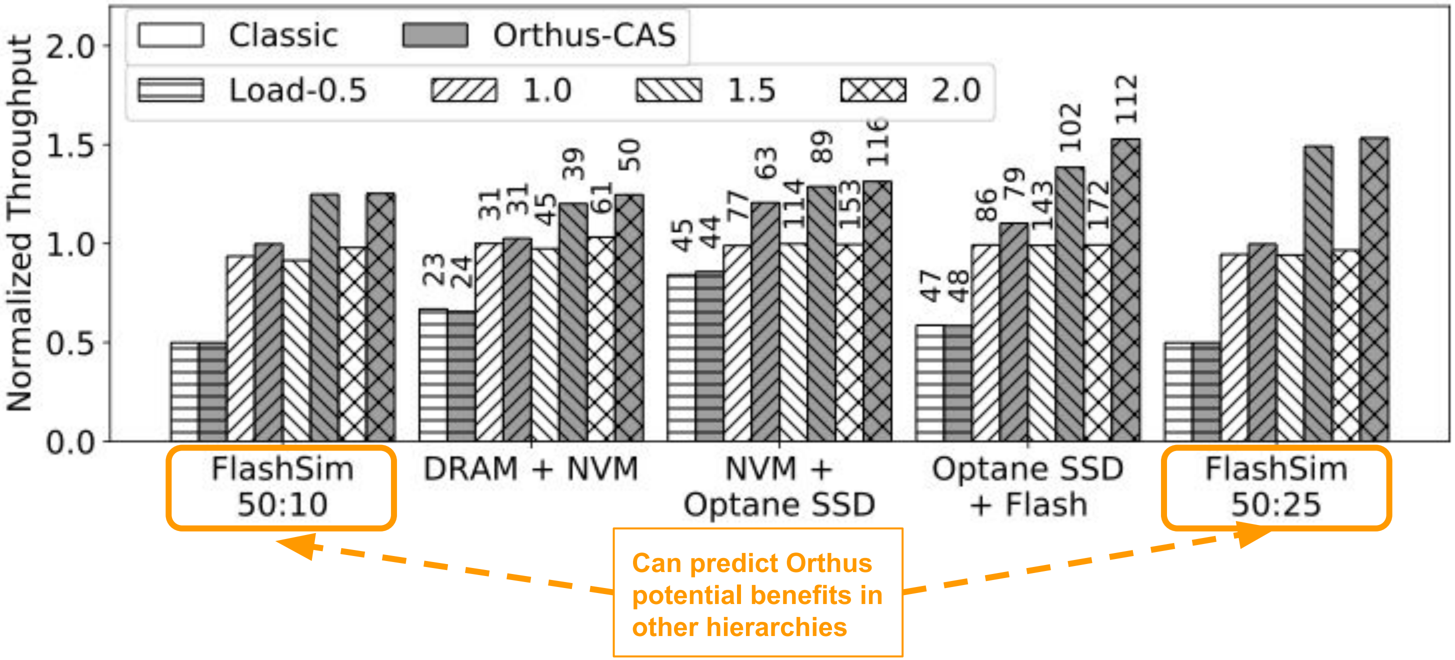

Other Experiments in the Paper

- Orthus improves with various caching **policies**
- Orthus optimizes different **target metrics** (e.g., tail latency)
- Orthus improves YCSB workloads
- Orthus improves **dynamic workloads**, such as Facebook ZippyDB workloads [FAST' 20]
- ...

Conclusion

- Evolving storage hierarchies have strong implications for caching
  - Quantitative comparisons across modern storage devices
  - Characterizing caching performance in both classic and modern hierarchies
- Orthus optimizes classic caching, by dynamic load admission and request offloading
  - Is compatible with all classic caching policies
  - Requires no prior knowledge of devices and workloads
  - Adapts to dynamic workloads

  - Can improve performance (throughput, tail latency) by up to 2X over classic caching in various storage hierarchies, under a range of realistic workloads

Thank you
&
Questions?

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