Daredevil: Rescue Your Flash Storage from Inflexible Kernel Storage Stack

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Yongqiang Xiong, Chenxiong Qian

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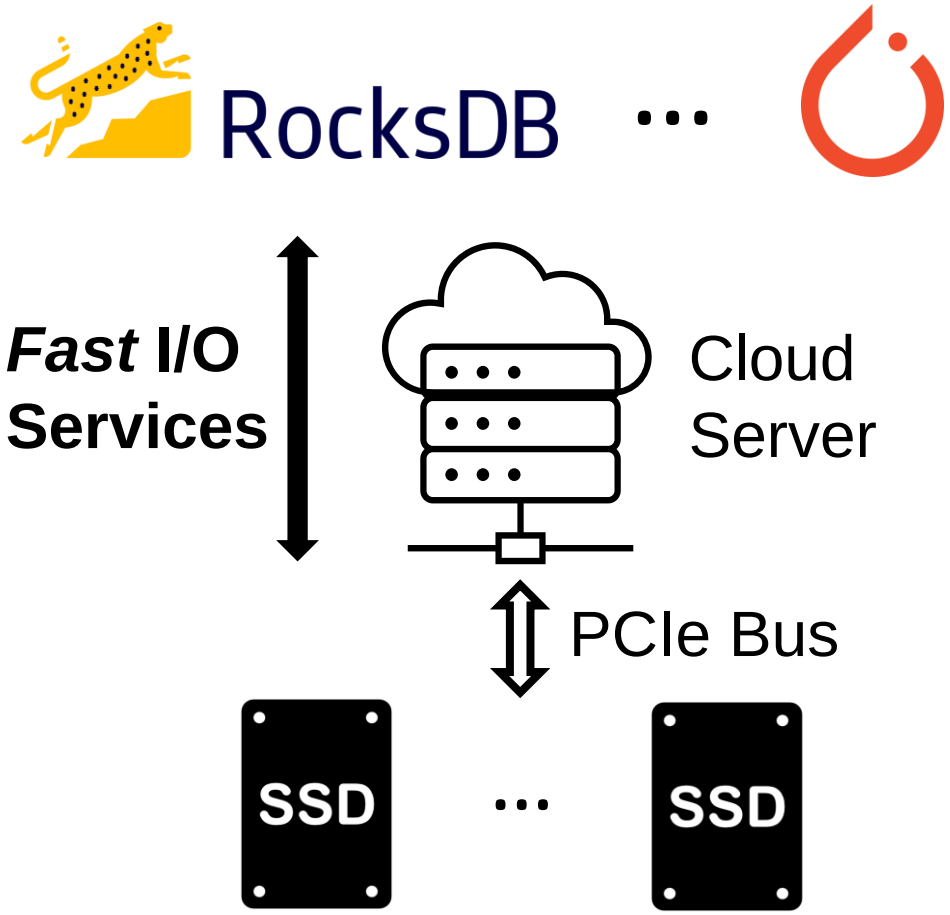
I/O Services: In the Face of Diversity



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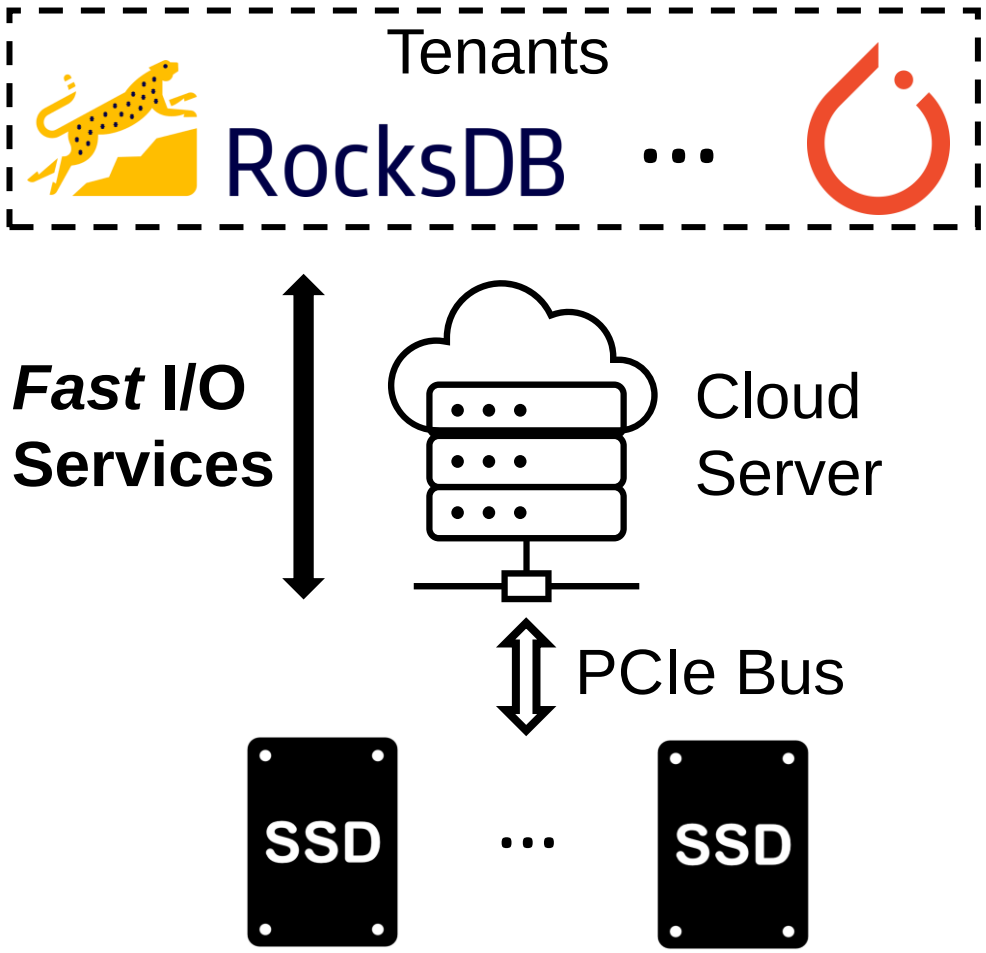

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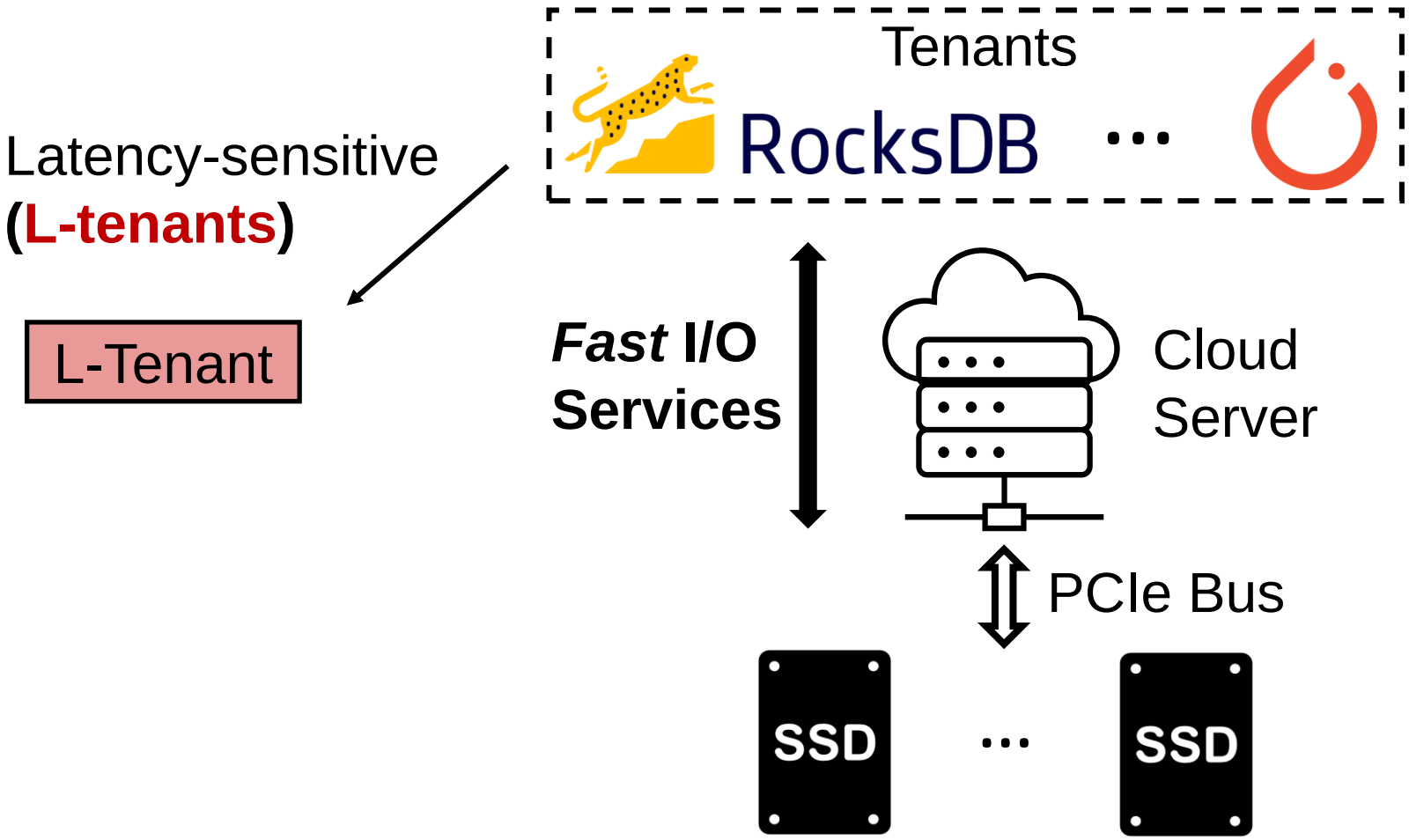

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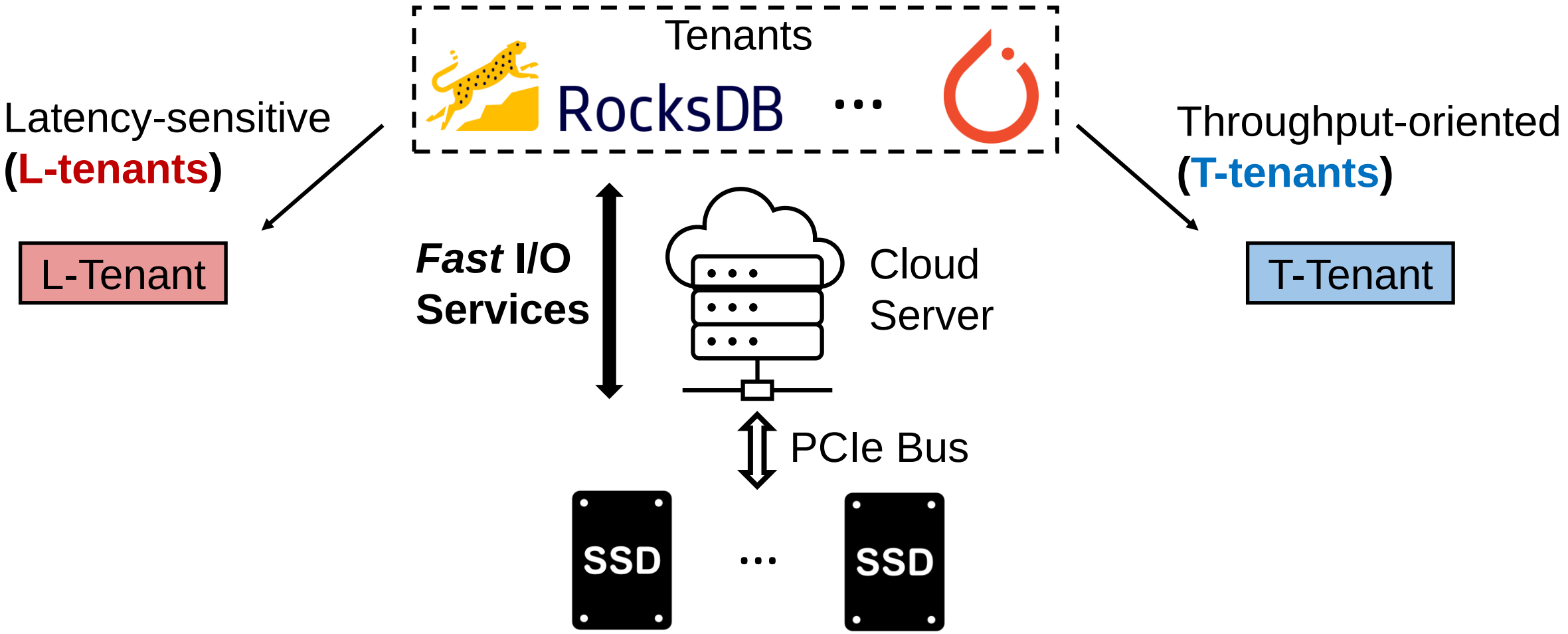

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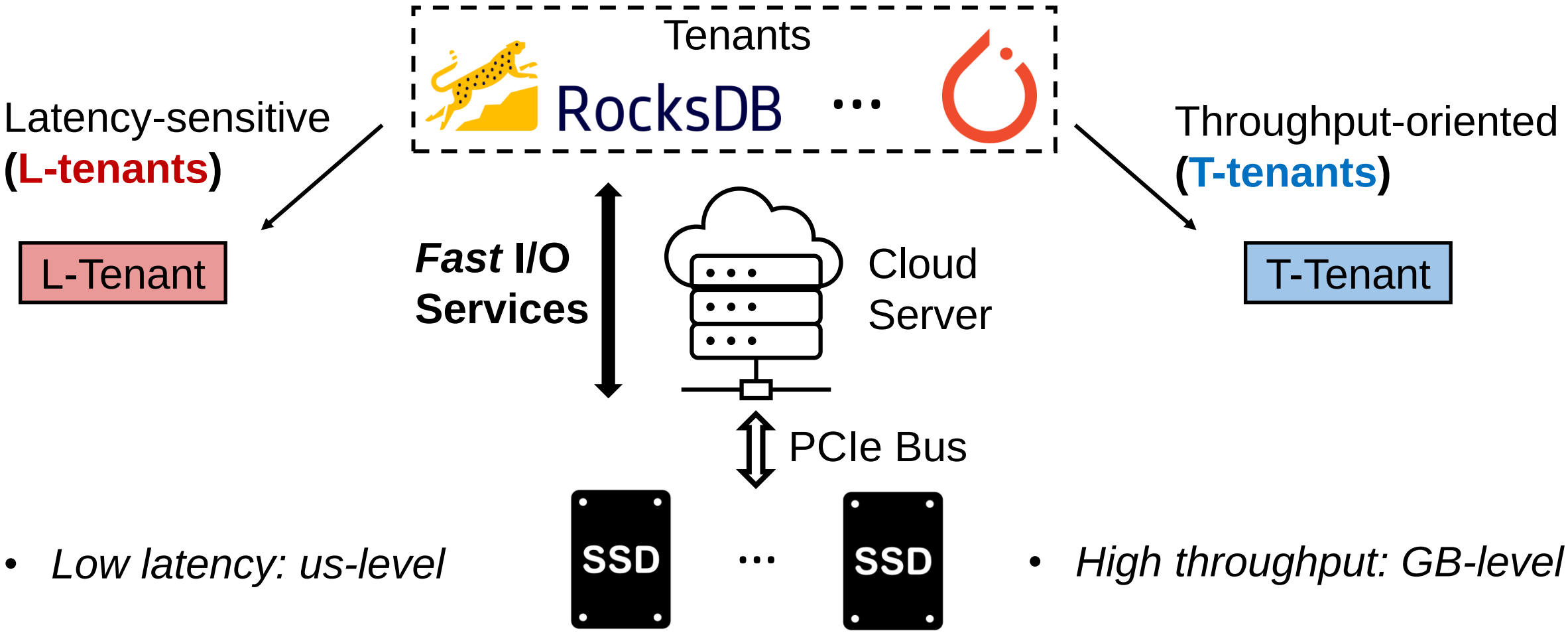

- *Low latency: us-level*
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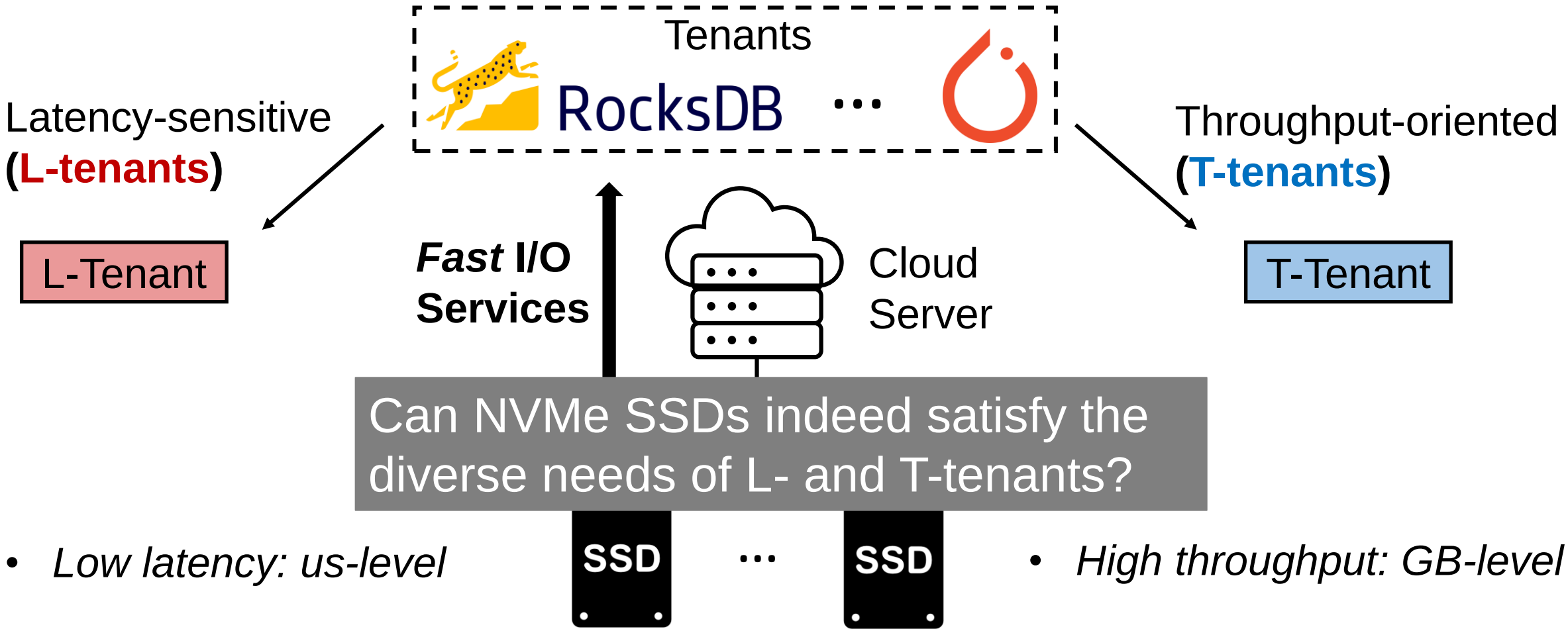

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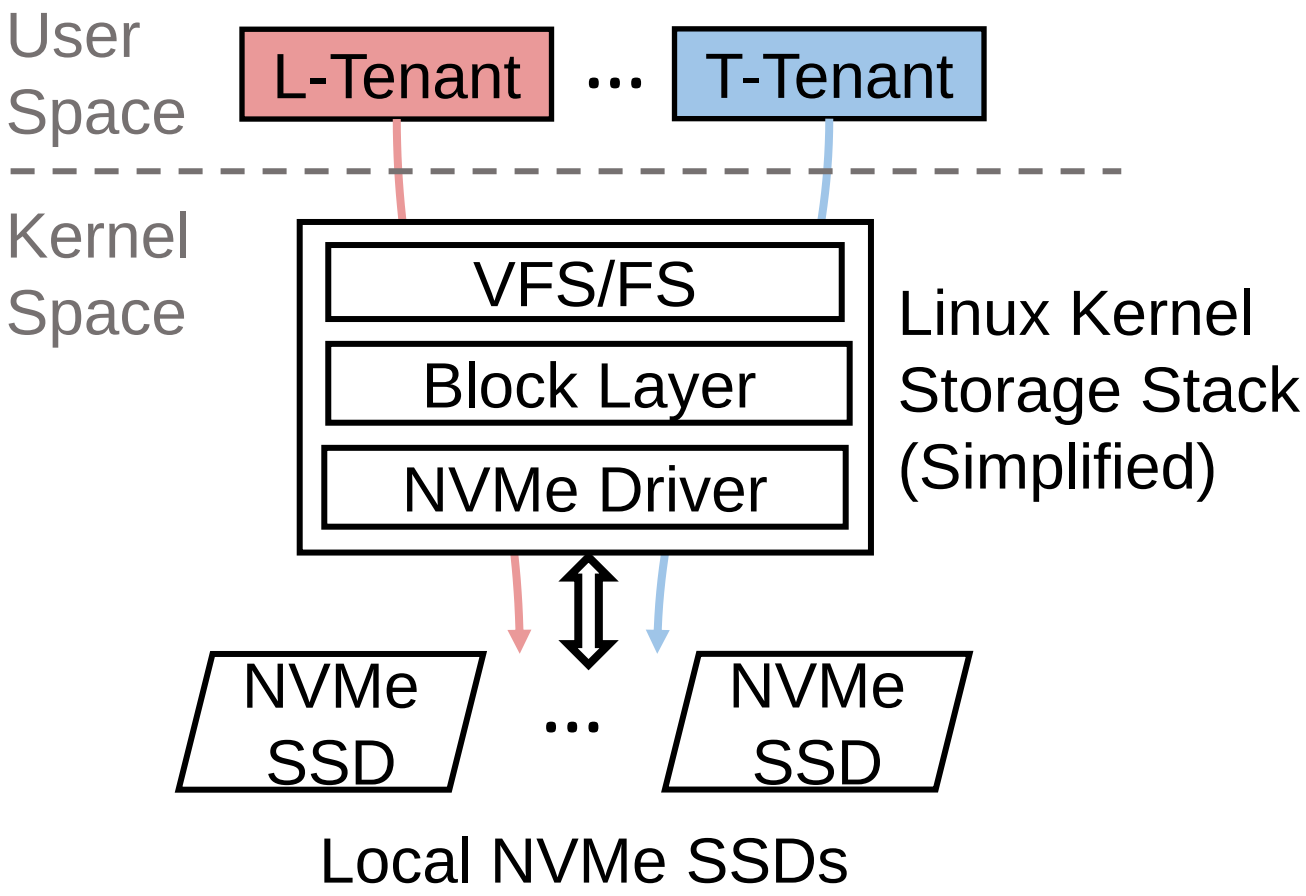

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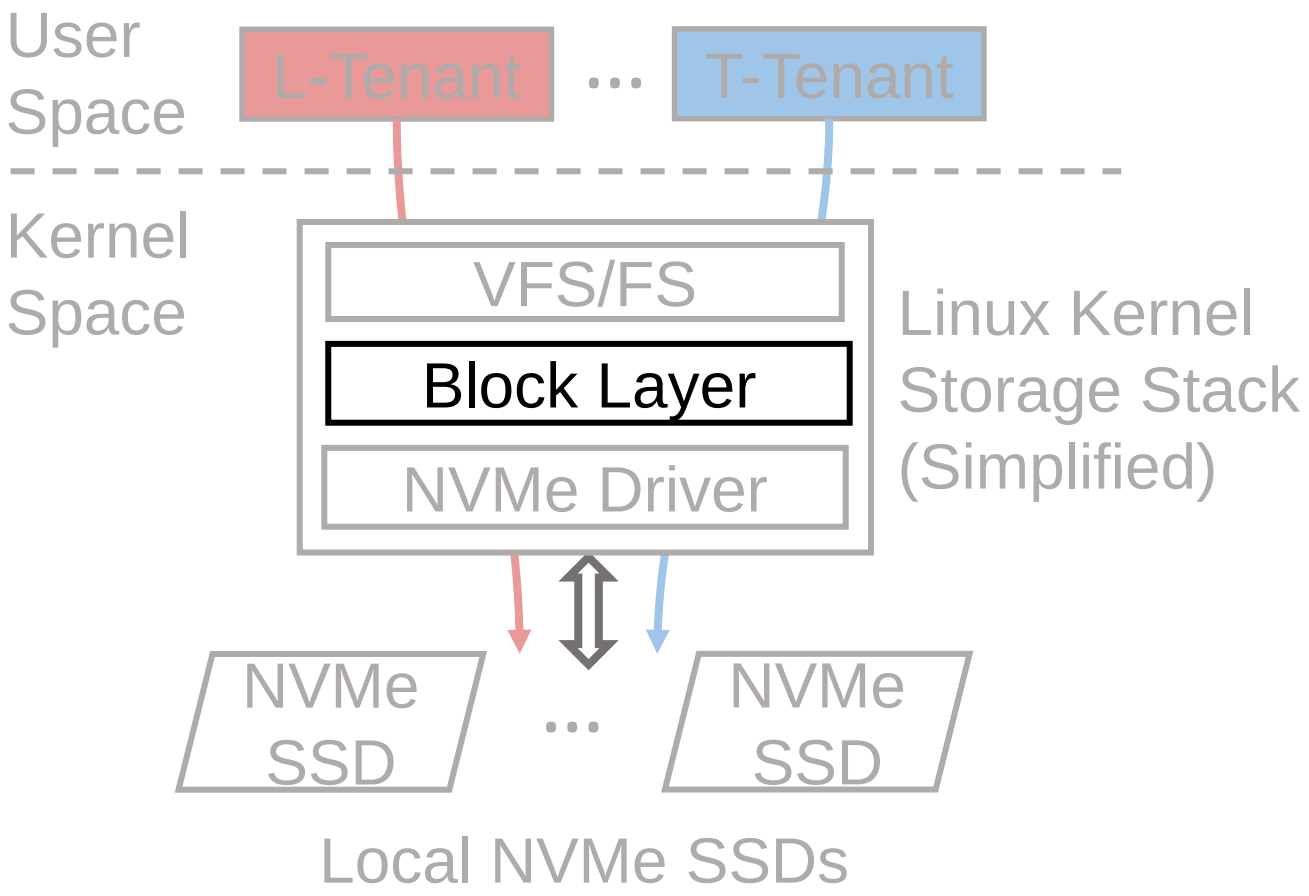

Block layer – Where generic I/O scheduling operations happen.

Kernel Storage Stack: *blk-mq* Structure

NVMe SSDs support multiple ***NVMe I/O queues (NQs)***

- Used for kernel-SSD I/O interactions
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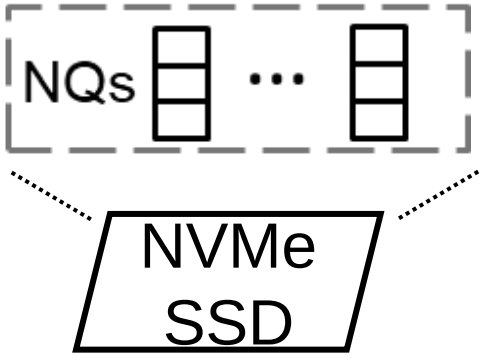

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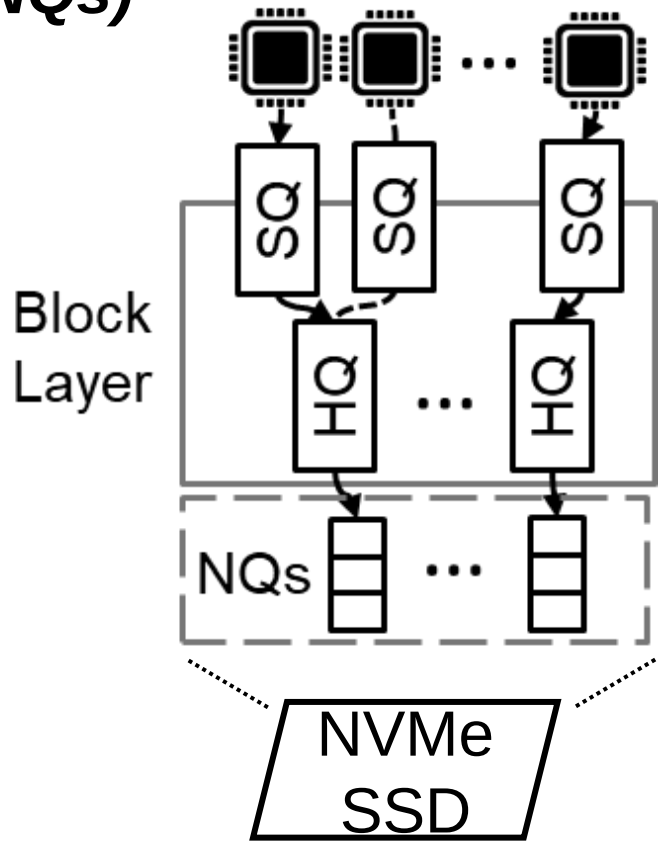

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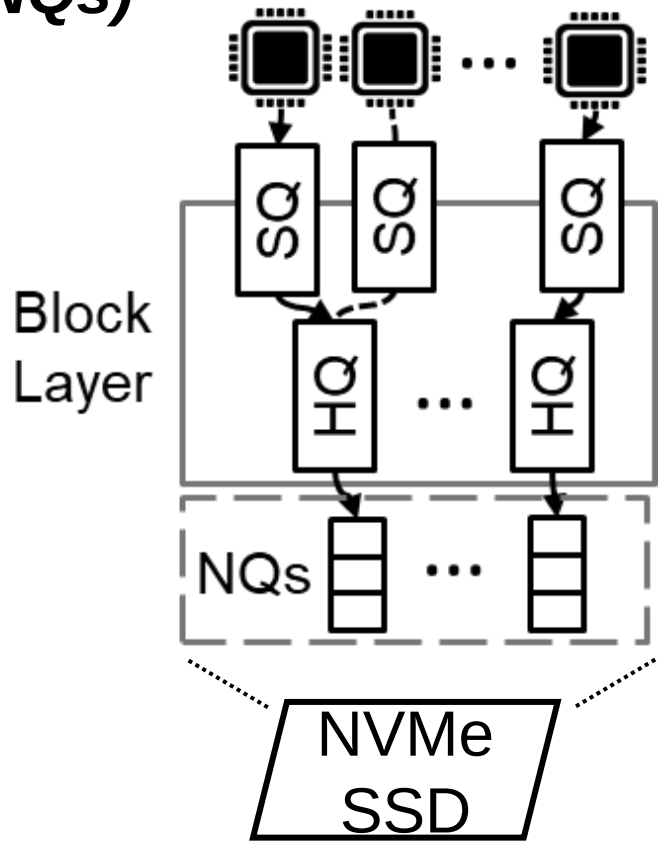

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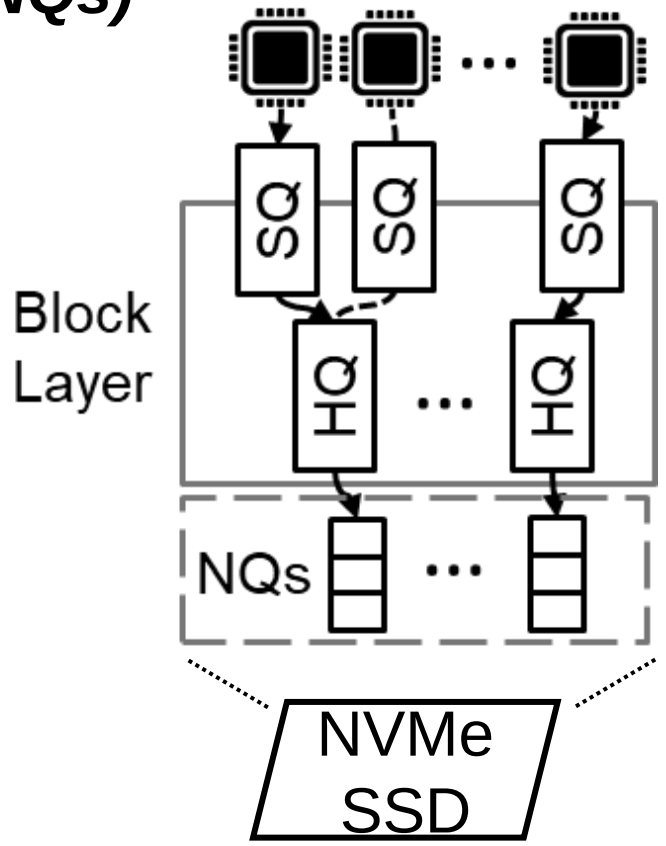

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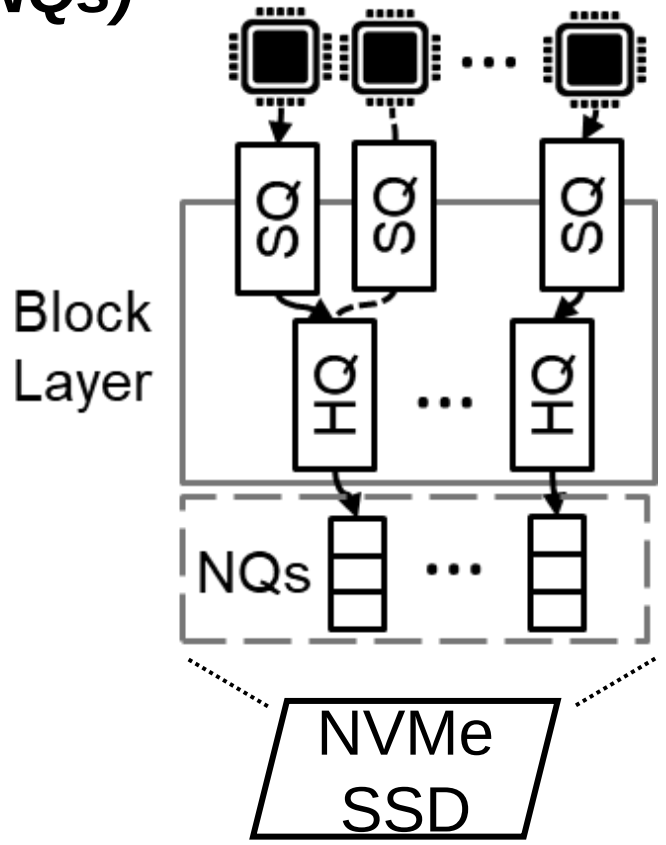

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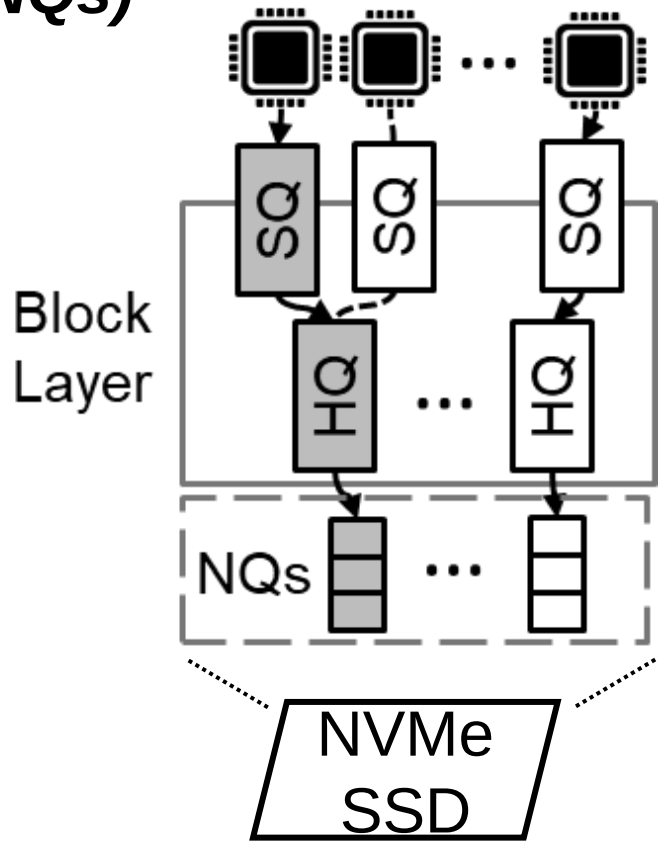

I/O flow: CPU core → SQ → HQ → NQ

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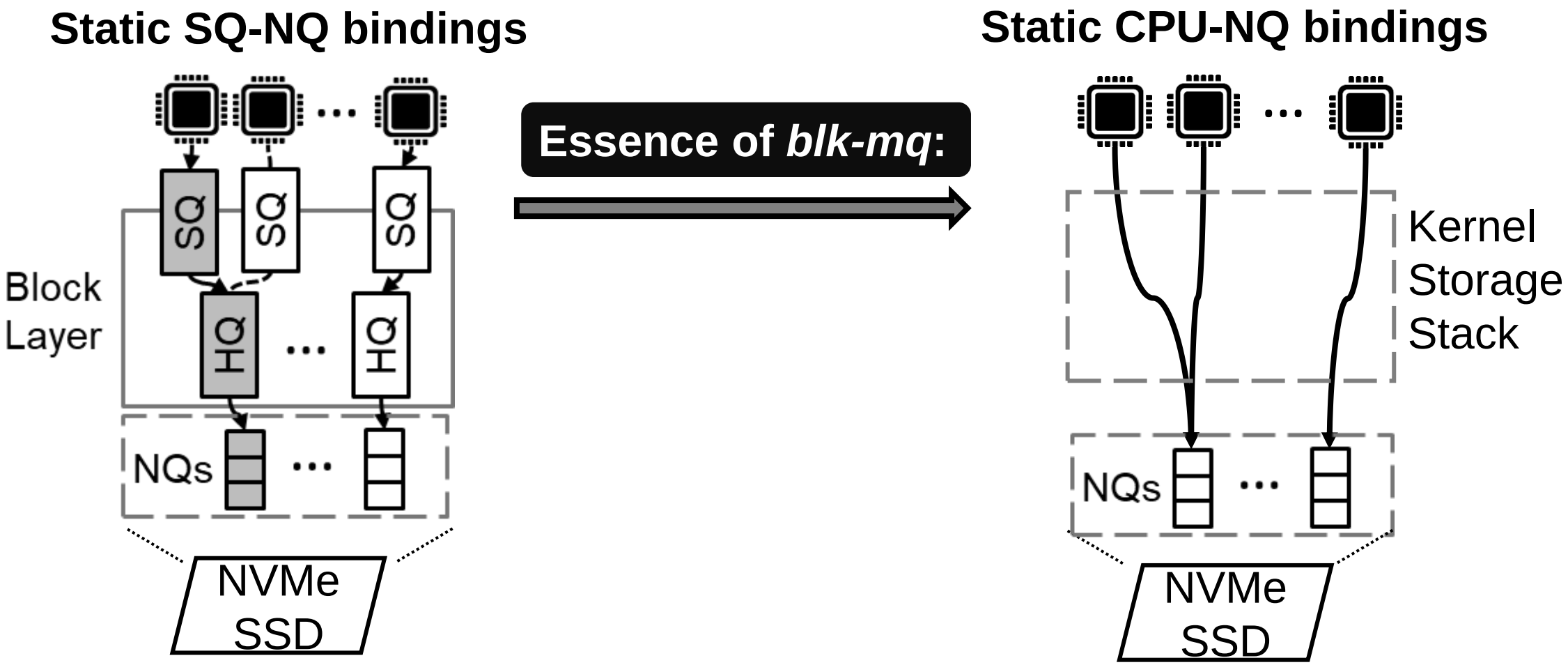

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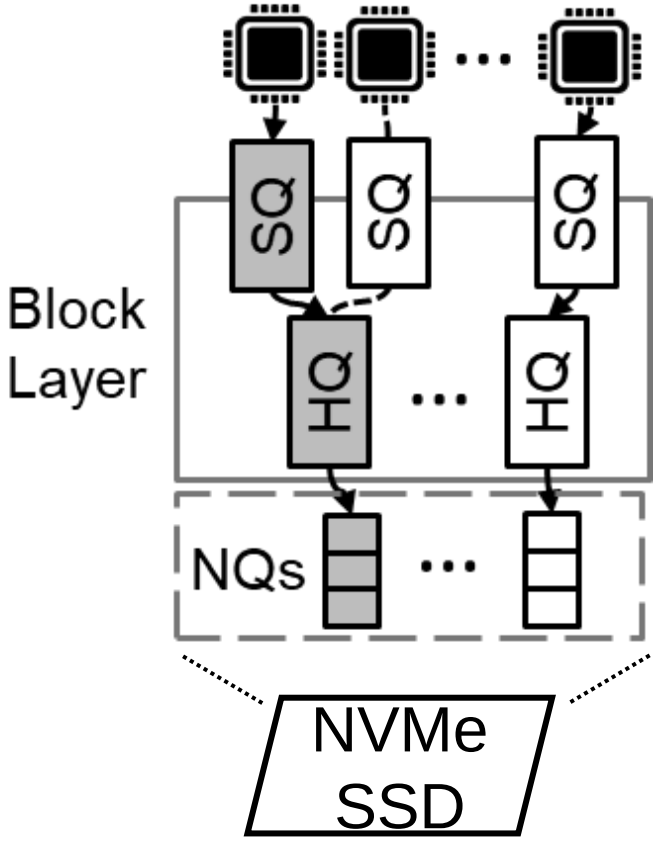

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- Parallelism/Concurrency

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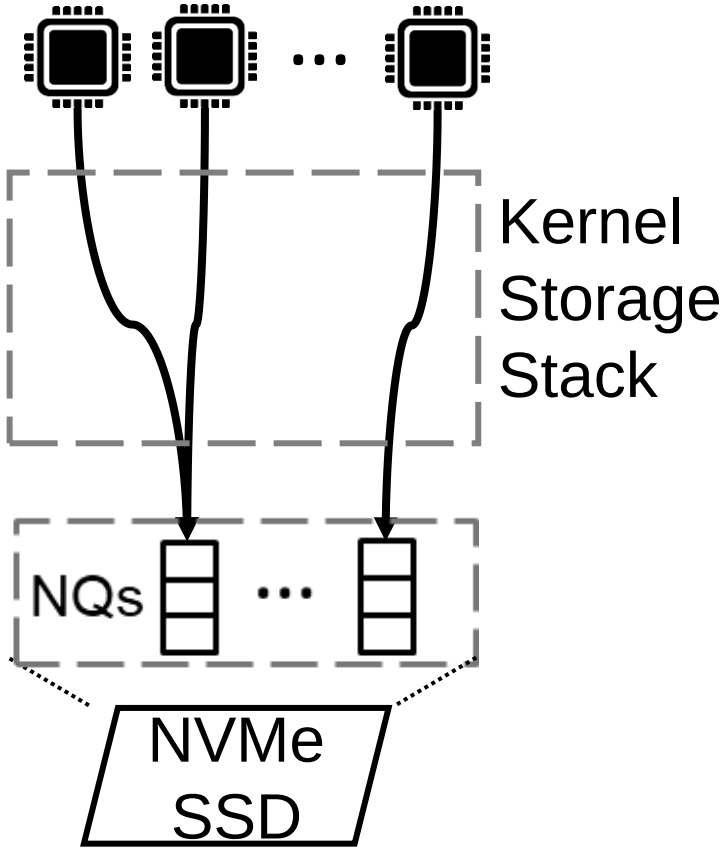

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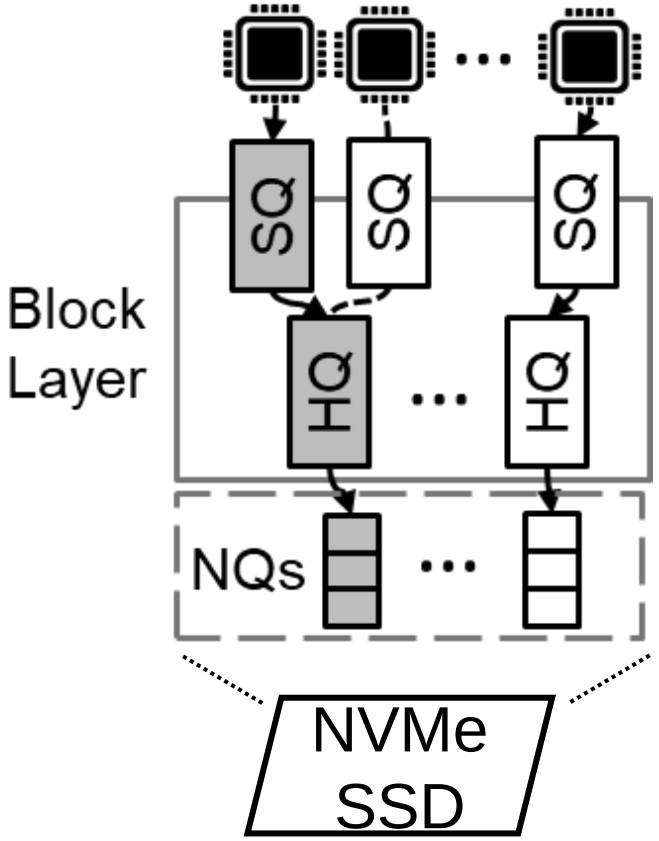

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- **But…! *Troublesome*** in cloud servers

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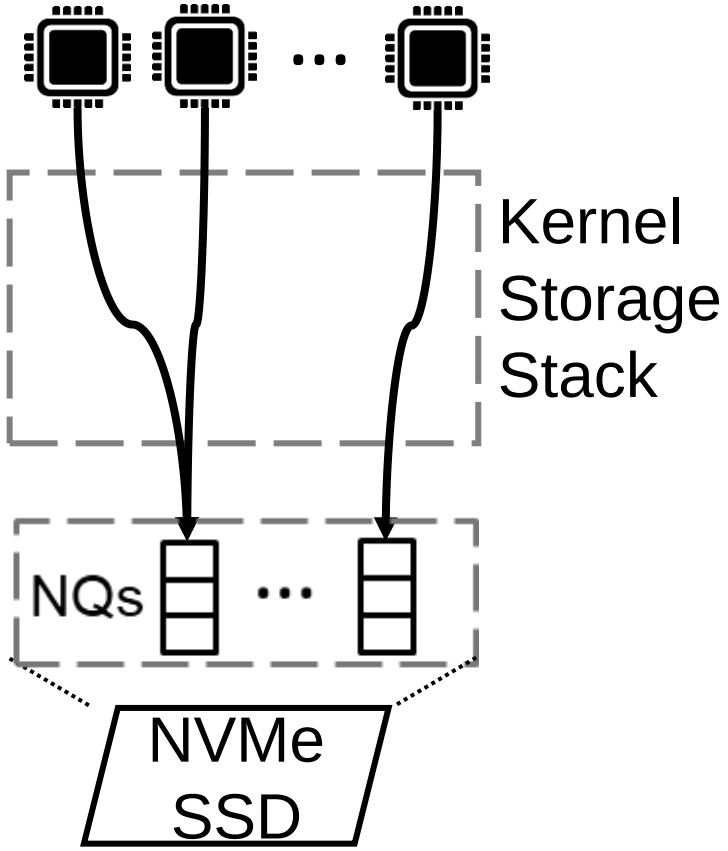
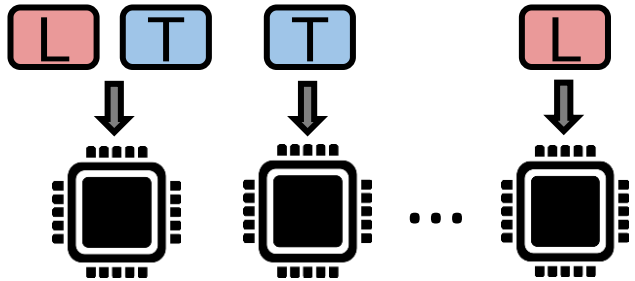


I/O Services: Within the *blk-mq* Structure

T : Throughput-oriented tenants (T-tenant)

L : Latency-sensitive tenants (L-tenant)

Common CPU **sharing among L- and T-tenants**.



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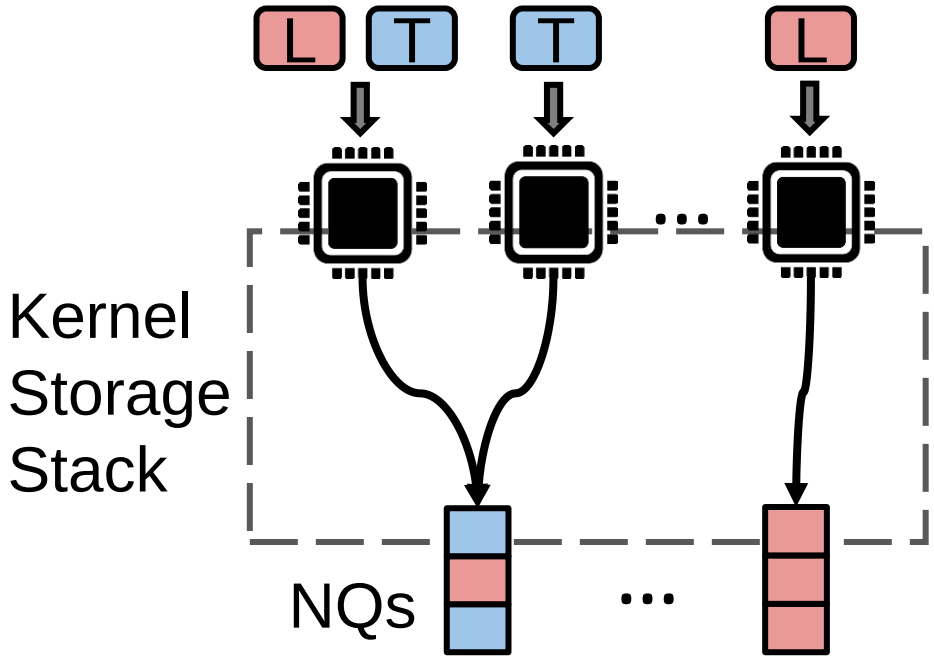

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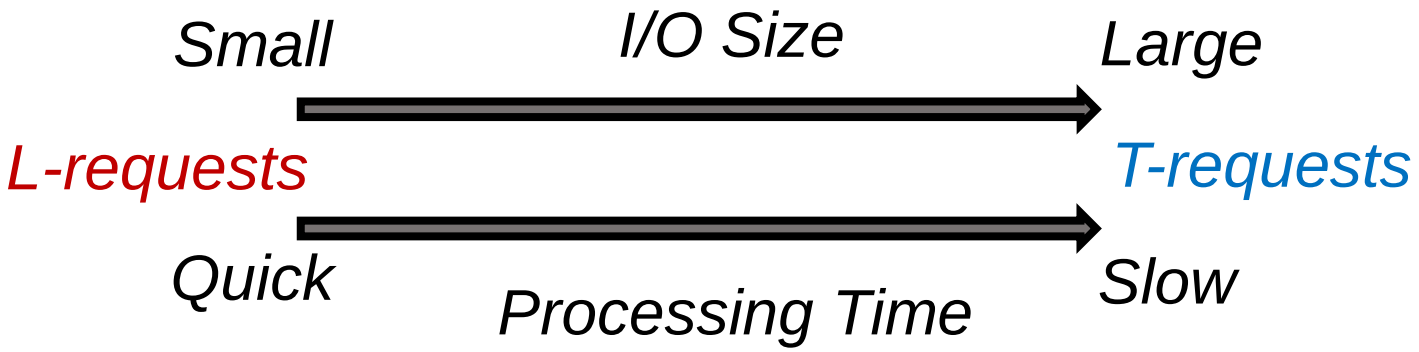

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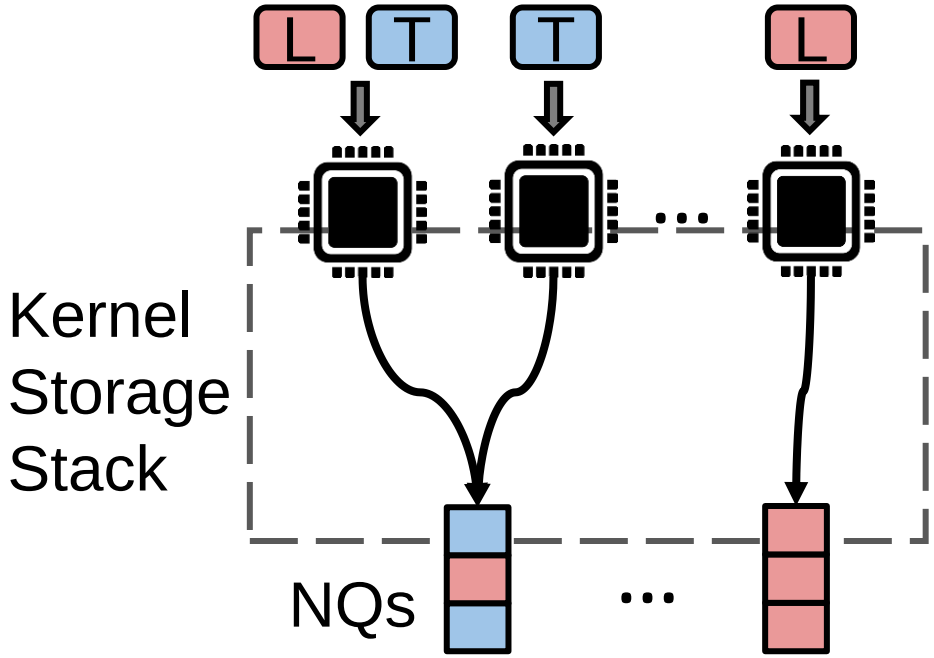

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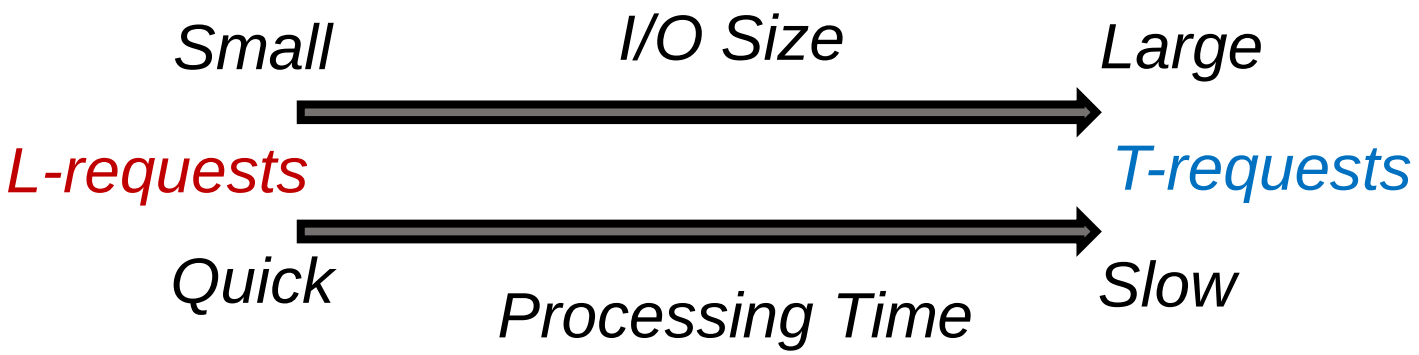

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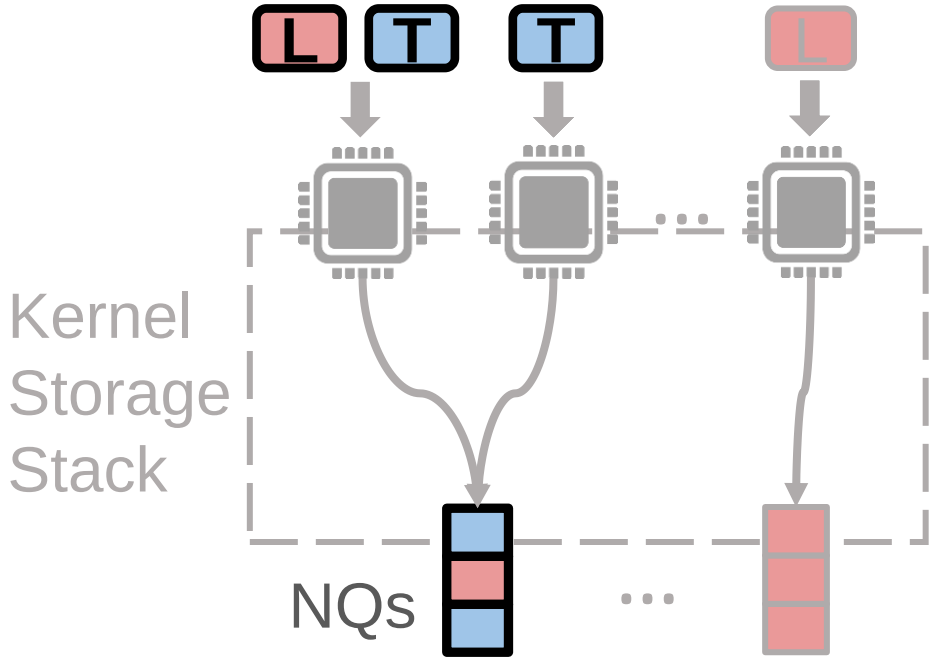

Head-of-line (HOL) blocking from T-requests!

I/O Services: Evidencing HOL Blocking

Experiment:

- w/ Interfere: L- and T-tenants served **within *the same NQs*.**
- w/o Interfere: L- and T-tenants served **by *separate NQs*.**

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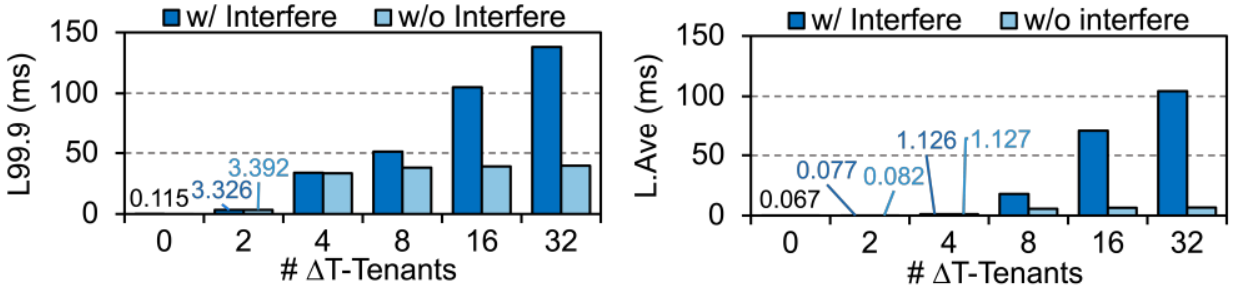

(a) L-tenant 99.9^{th} tail latency. **(b)** L-tenant average latency.

Figure 2. I/O latency of L-tenants with T-tenants interfering within the same NQs (*w/ Interfere*) and using separate NQs (*w/o Interfere*).

3x/15x increase in tail/average latency with HOL T-requests.

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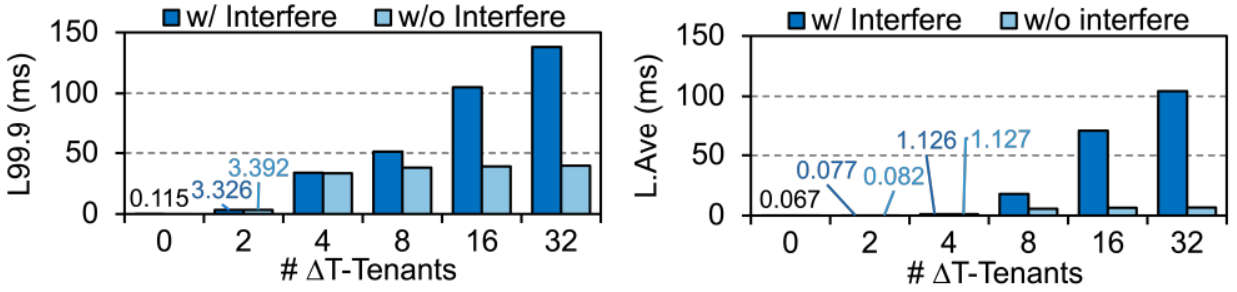

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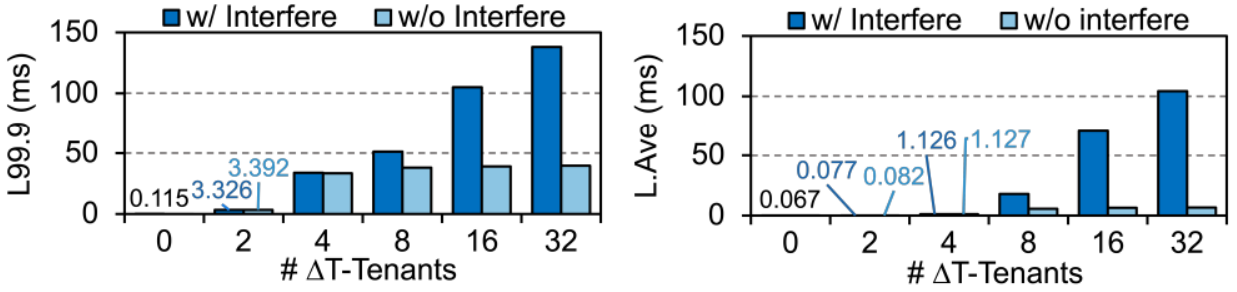

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How can we solve this issue within the kernel storage stack?

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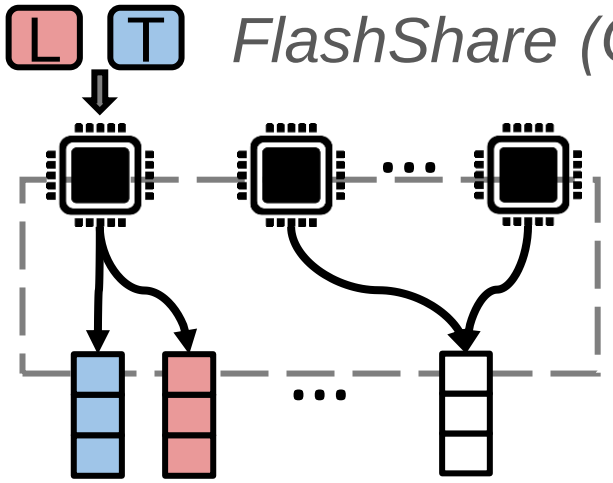

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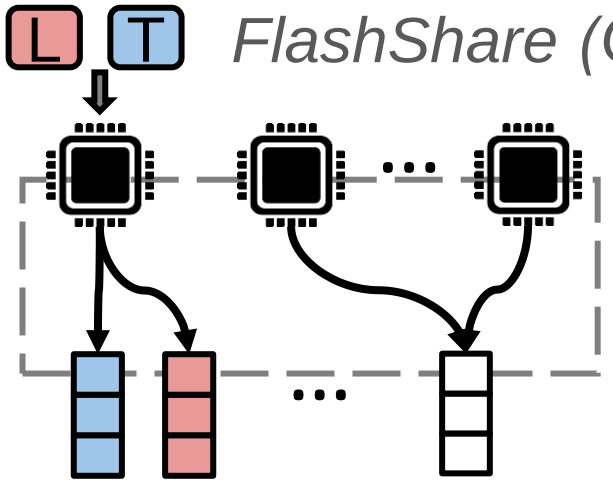

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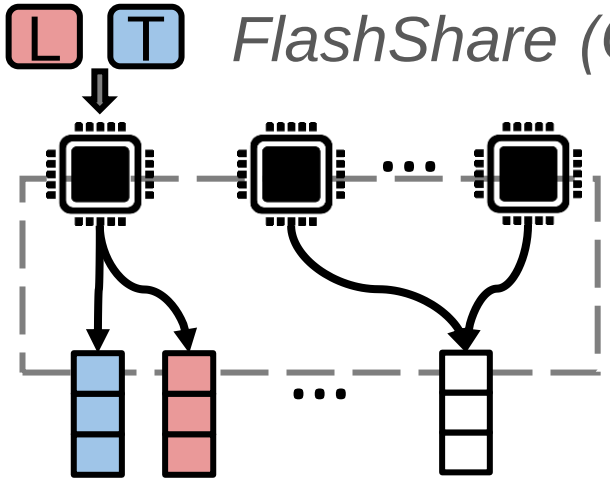

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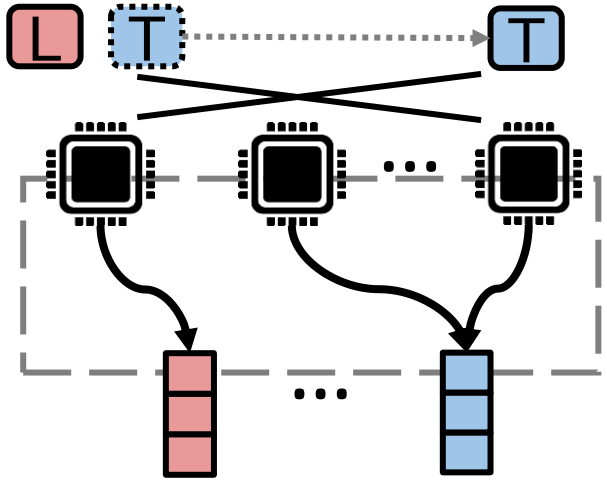

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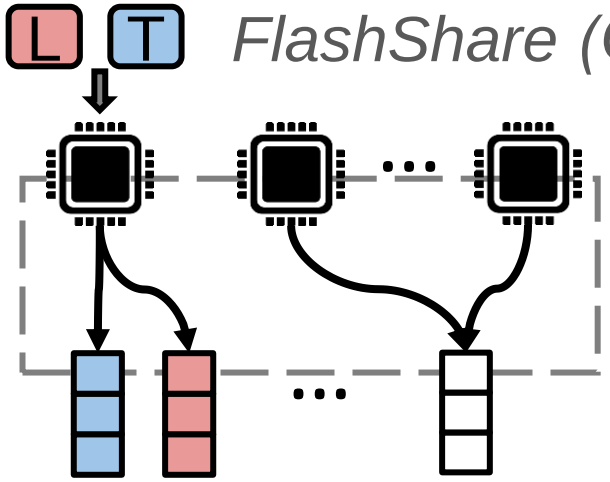

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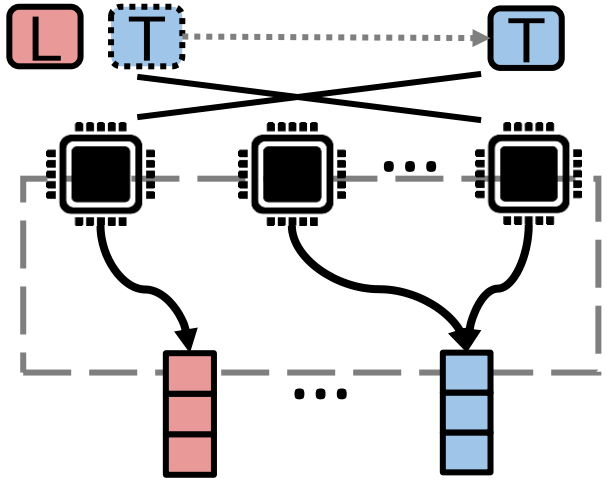

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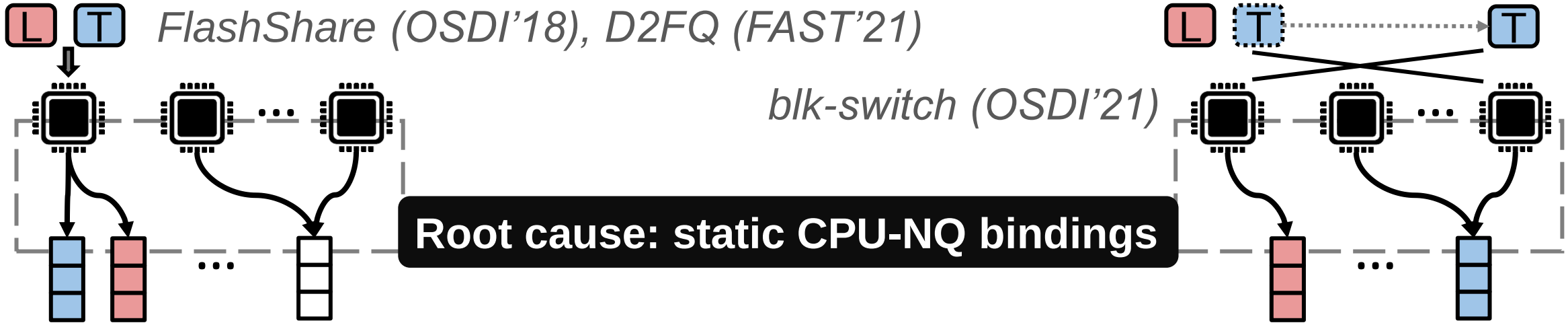

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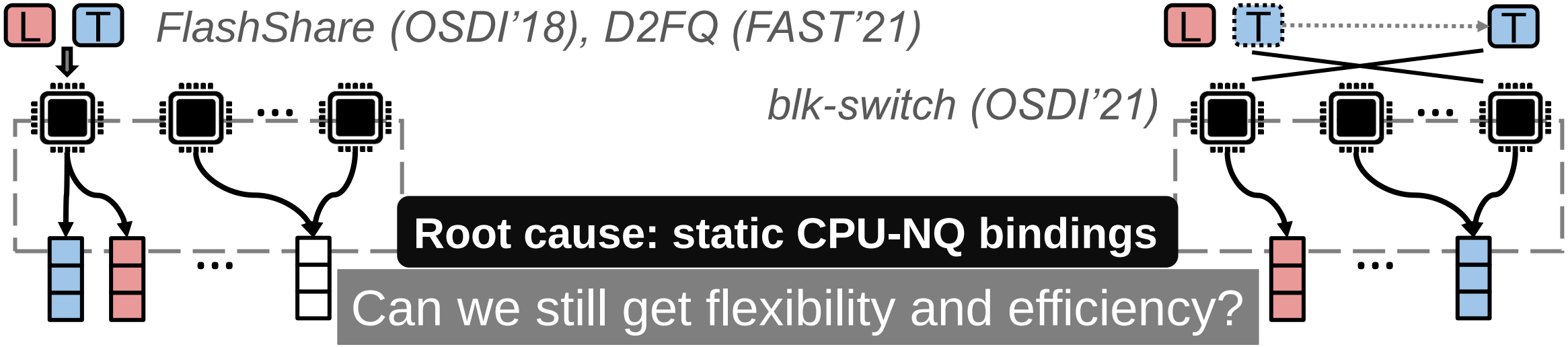

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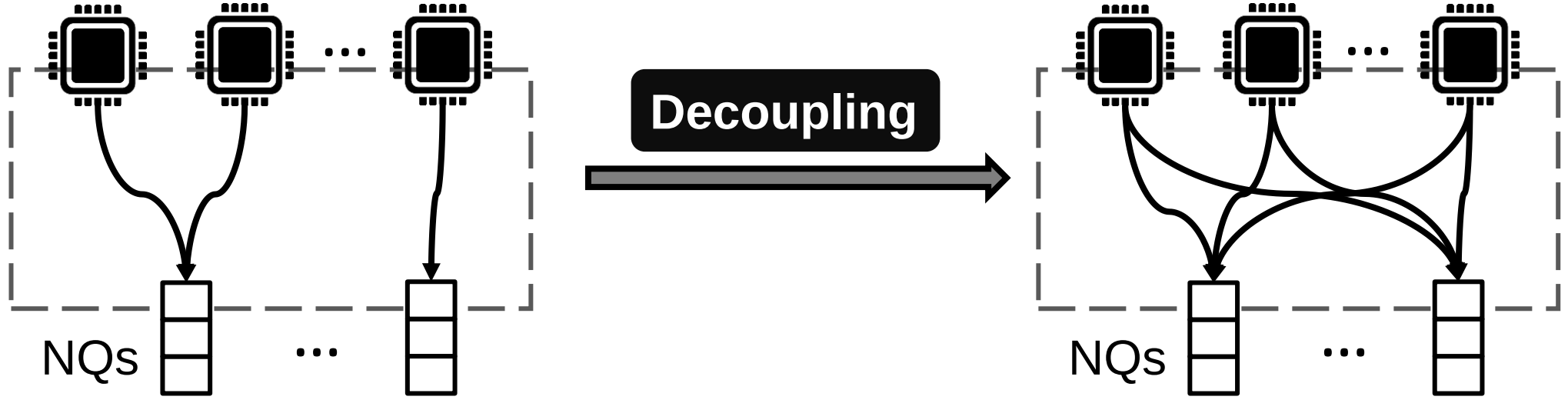

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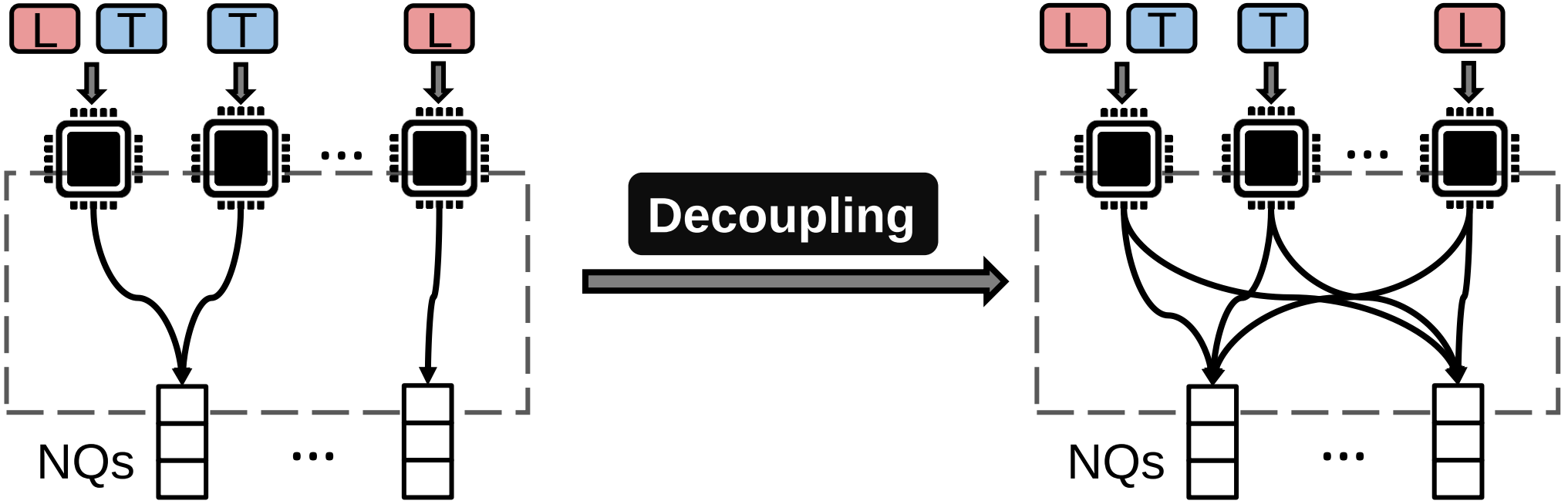

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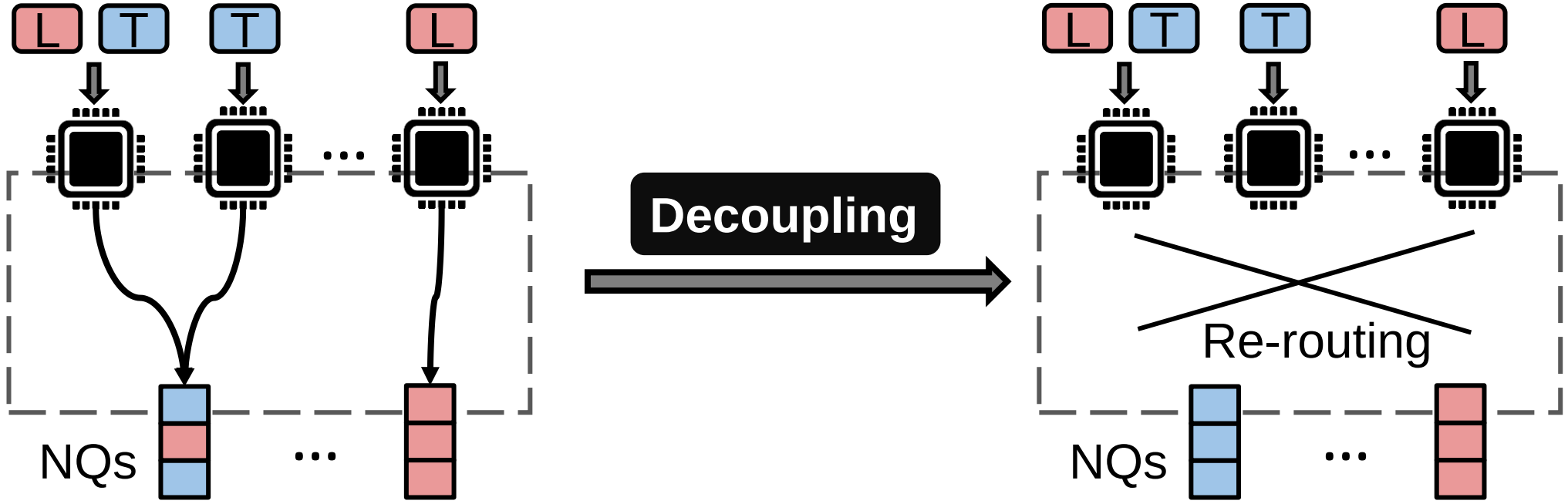

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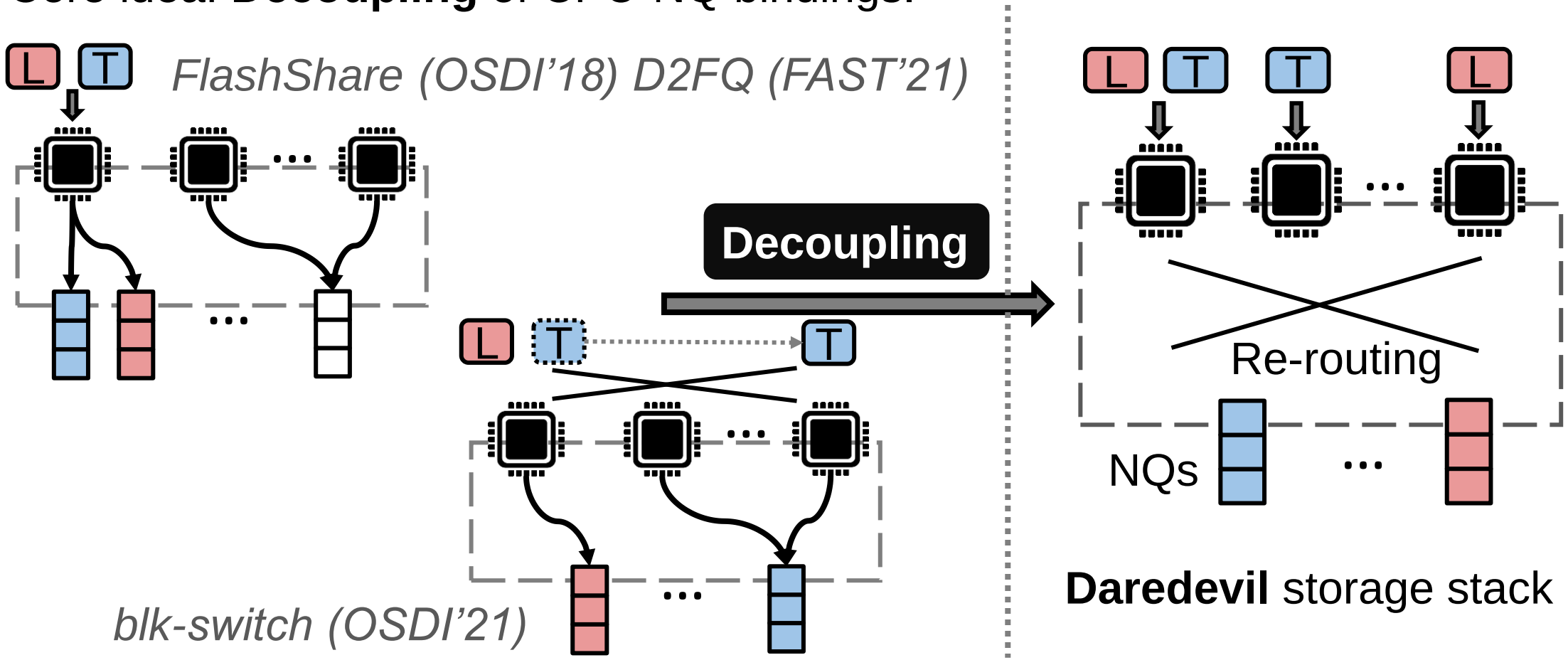

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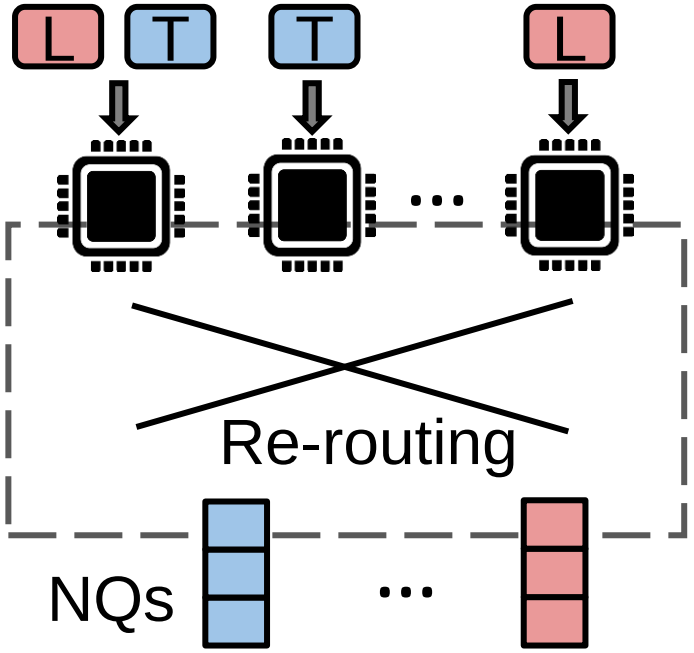
Core idea: **Decoupling** of CPU-NQ bindings.

- **Full-connectivity** between CPU cores and NQs.
- **Independent & flexible** policy for multi-tenancy control.
- **Full utilization** of NQs.



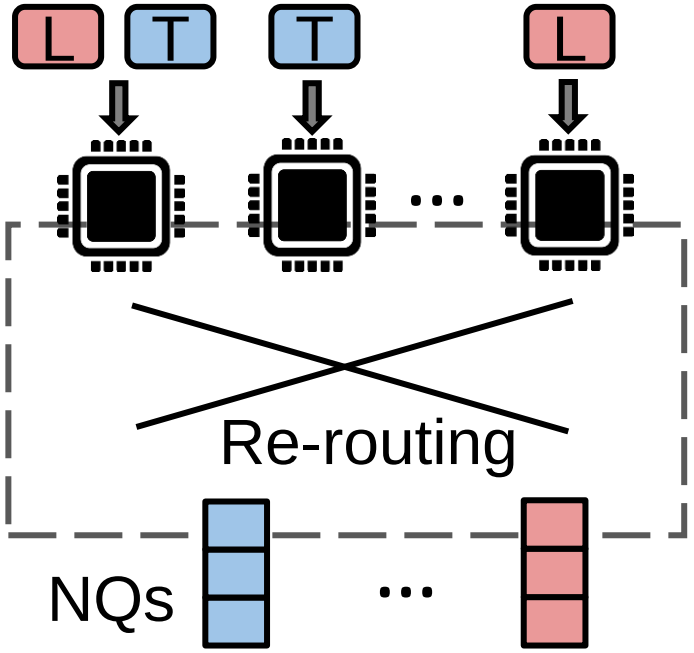
Daredevil storage stack

Daredevil: Here Comes the Rescue

Core idea: **Decoupling** of CPU-NQ bindings.

- **Full-connectivity** between CPU cores and NQs.
- **Independent & flexible** policy for multi-tenancy control.
- **Full utilization** of NQs.

But…At what cost?



Daredevil storage stack

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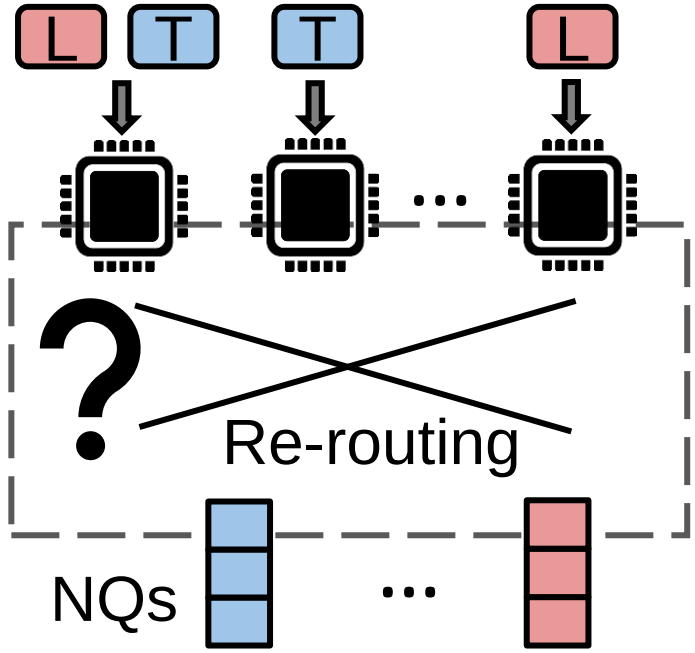
Challenge #1: Light-weight routing decisions for I/O requests.

Where should I/O requests go?



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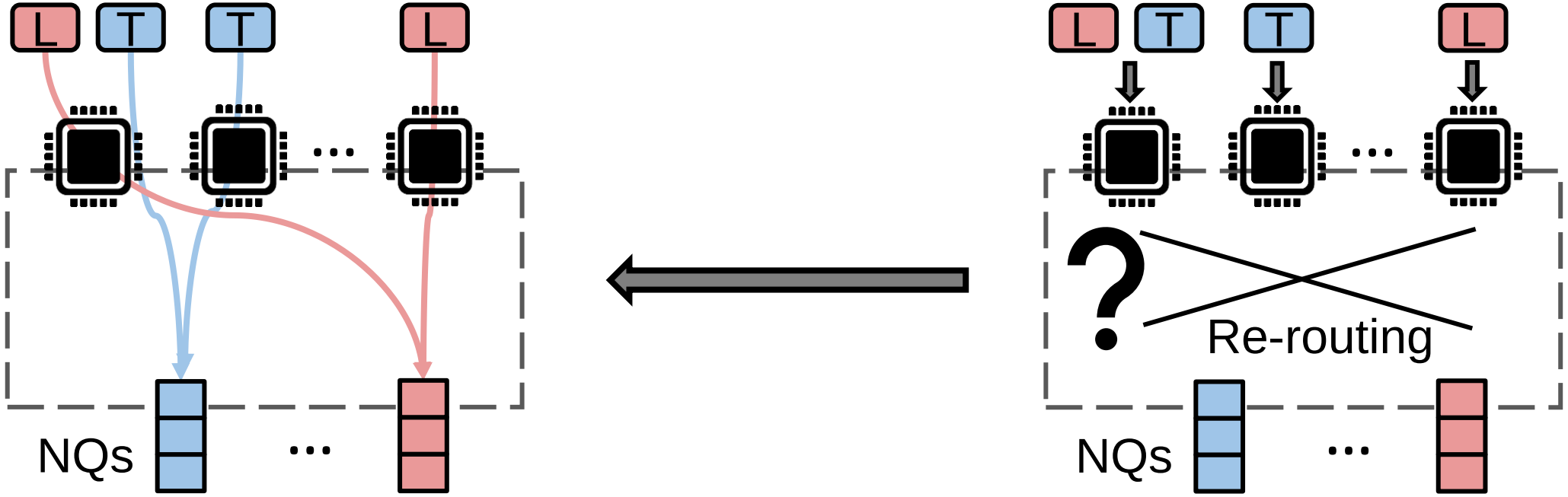
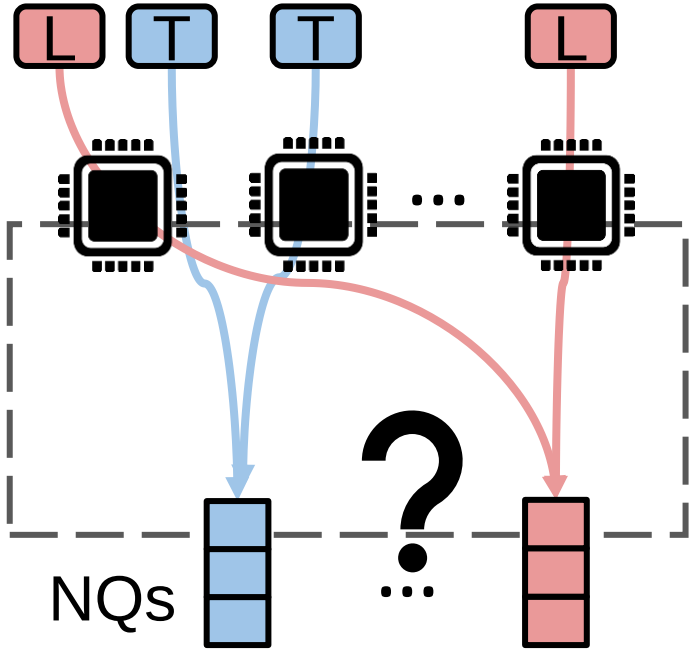


Solution #1: Tenant-based request routing.

Daredevil: Here Comes the Rescue

Challenge #2: Performance assurance for NQ-level separation.



How to ensure separation with guaranteed performance?

Daredevil: Here Comes the Rescue

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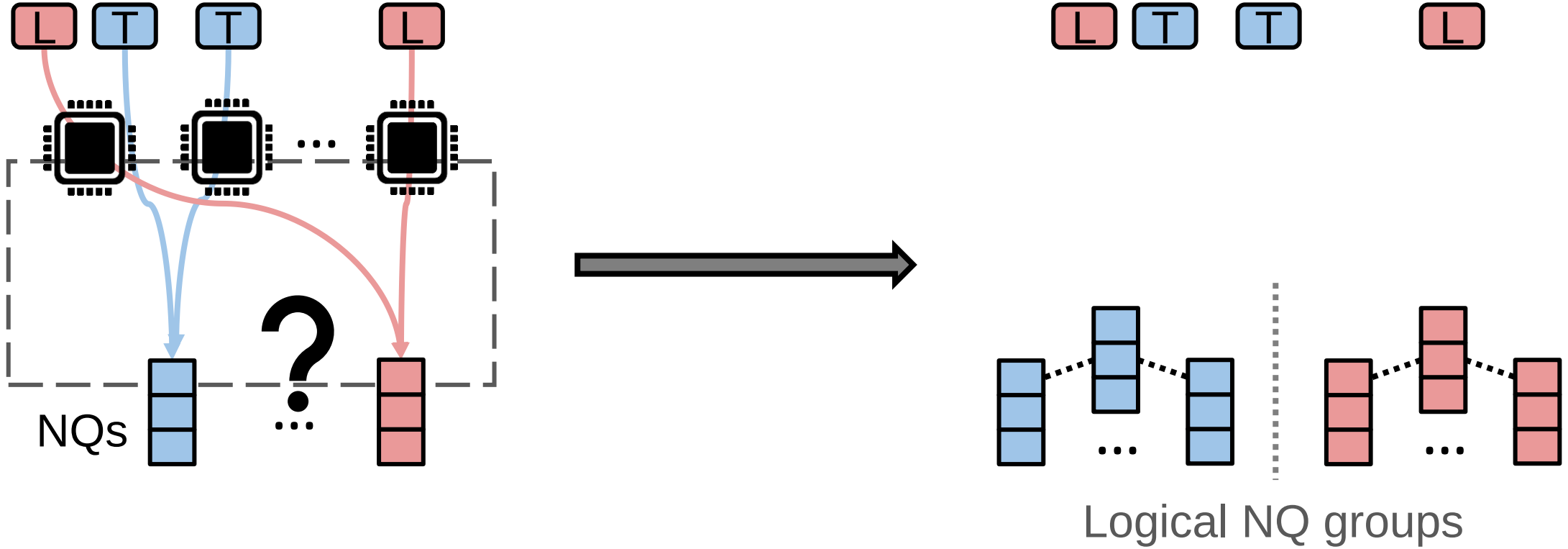

Solution #2: Heap-based performance-aware NQ scheduling.

Daredevil: Here Comes the Rescue

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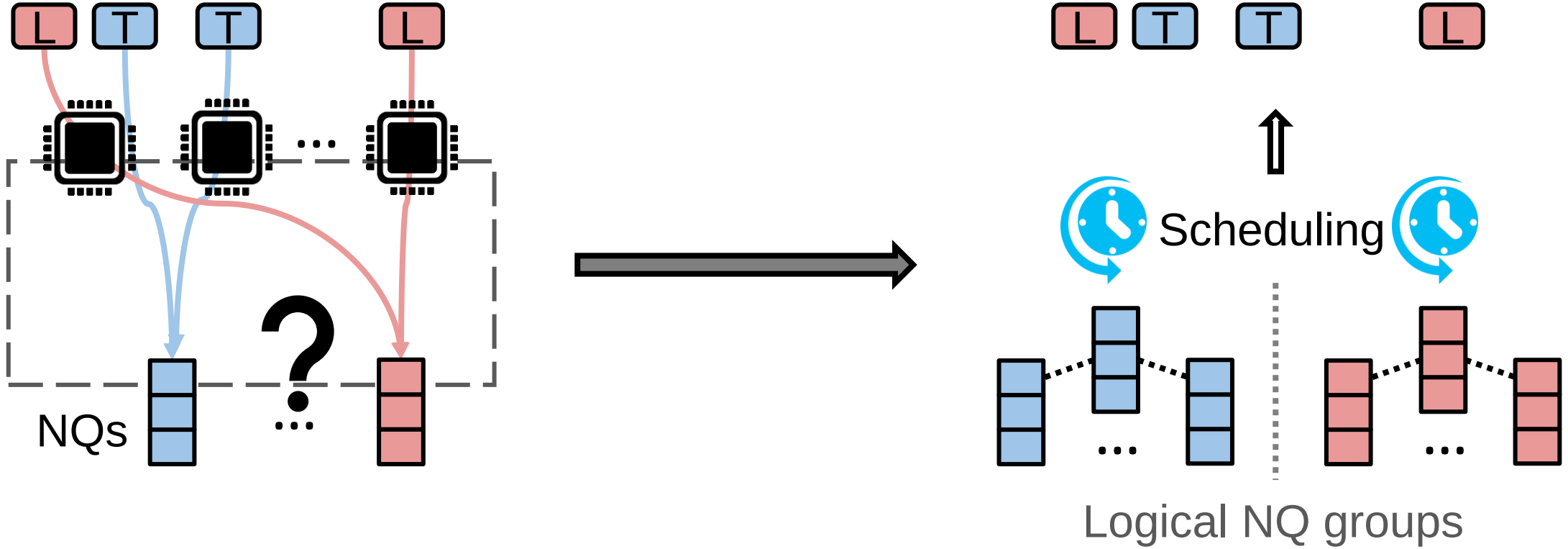

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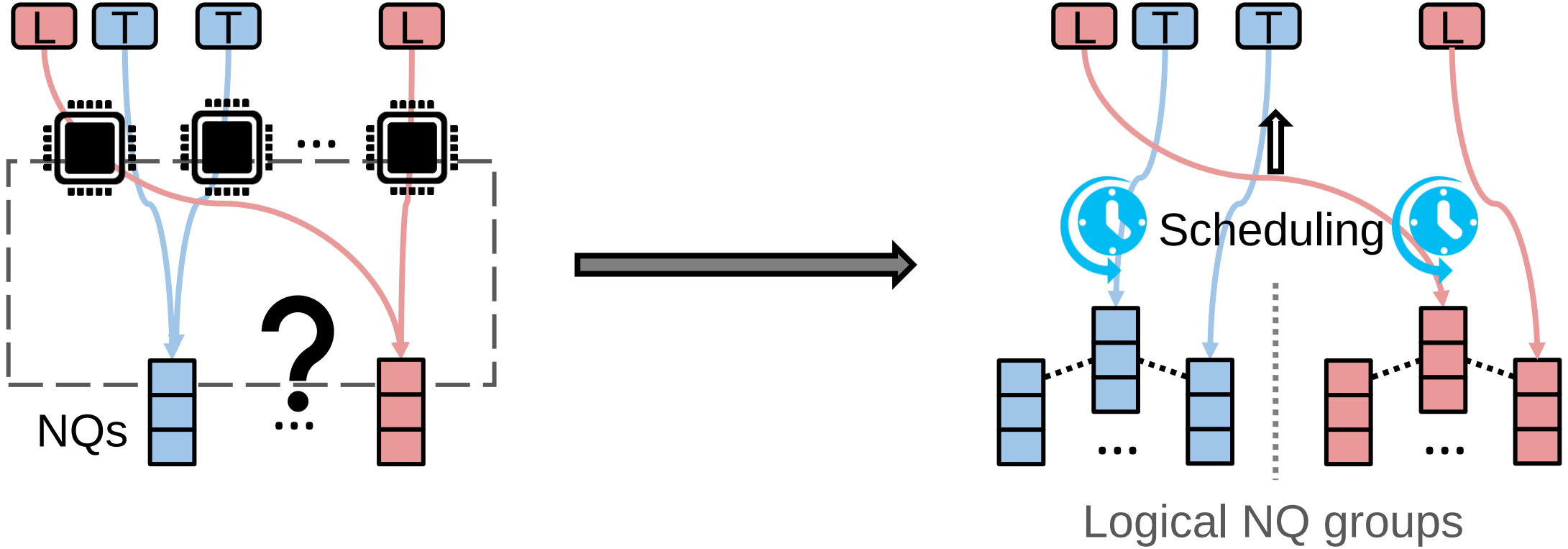


Solution #2: Heap-based performance-aware NQ scheduling.

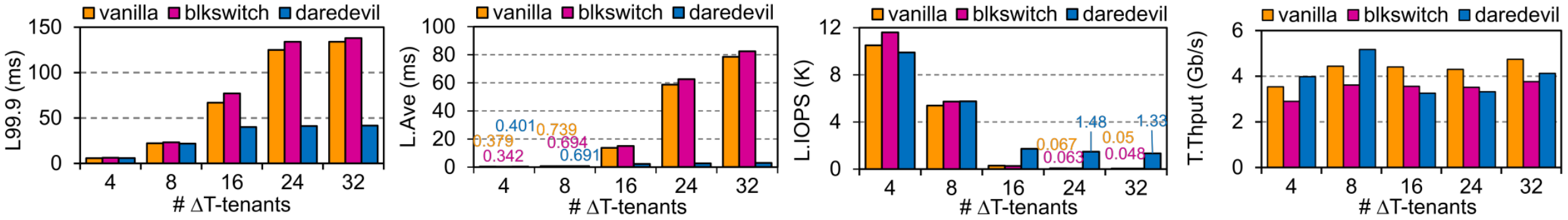
Daredevil: Here Comes the Rescue

Design & implementation details:

- Tenant & outlier cases identification
- Scheduling criteria
- Light-weight concurrent scheduling
- I/O service acceleration

Please refer to our paper for more details.

Evaluation: Efficient Multi-tenancy Support



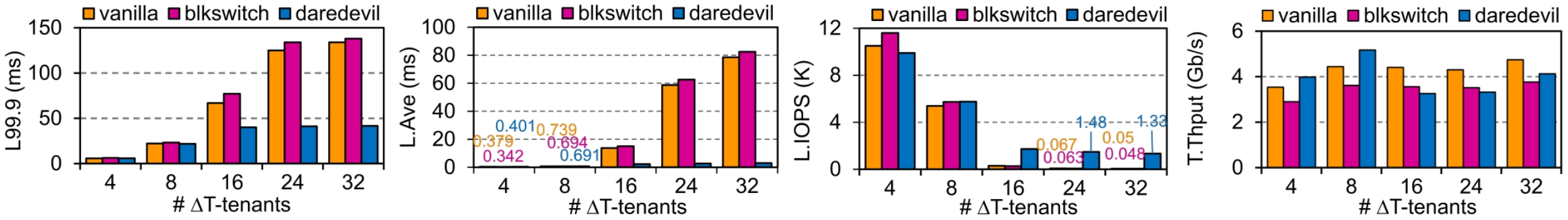
(a) L-tenant 99.9^{th} tail latency. **(b)** L-tenant average latency. **(c)** L-tenant I/O rate. **(d)** T-tenant throughput.

Figure 6. Performance results with increasing T-pressure in SV-M. DAREDEVIL maintains in-time responses for L-tenants even under extreme T-pressure, while the vanilla kernel and `blk-switch` significantly inflate the L-tenants' I/O latency.

Benchmark: FIO-based simulation for L- and T-tenants.

Evaluation: Efficient Multi-tenancy Support

***3x* & 27*x* reduction** in tail & ave latency.



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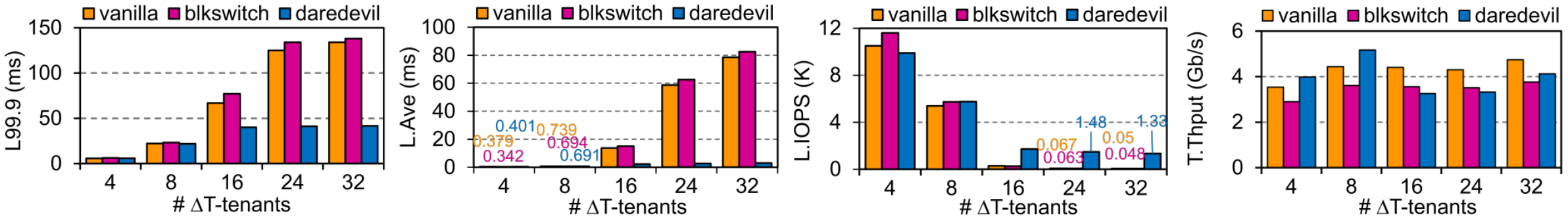

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Evaluation: Efficient Multi-tenancy Support

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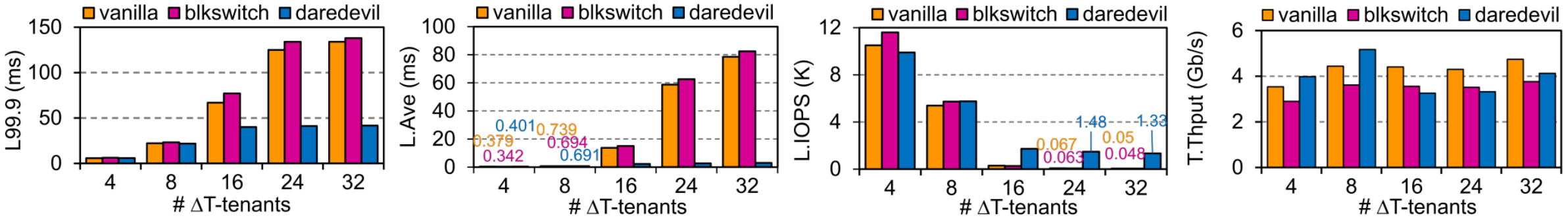

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Ablation of Daredevil: What contributions do its optimizations make?

- dare-base: only decoupling and round-robin request routing
- dare-sched: decoupling + NQ scheduling
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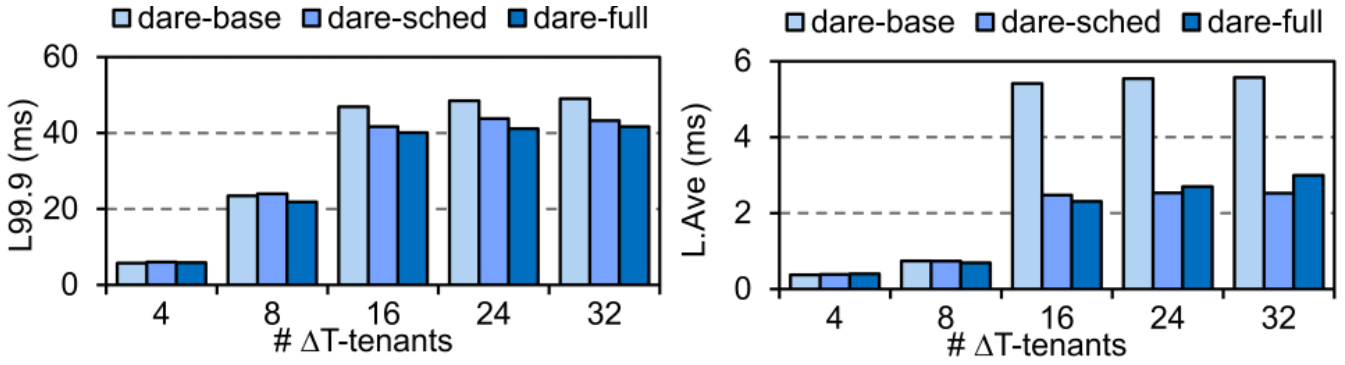

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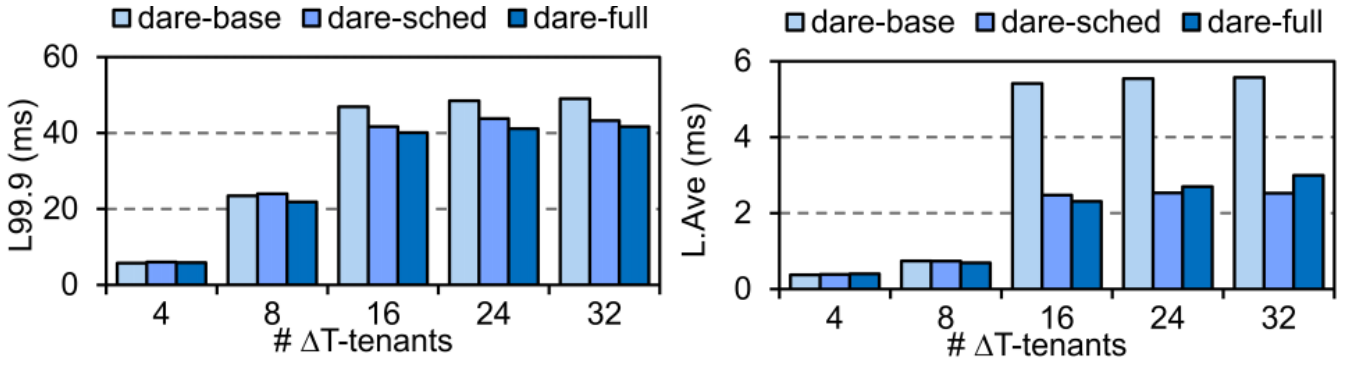

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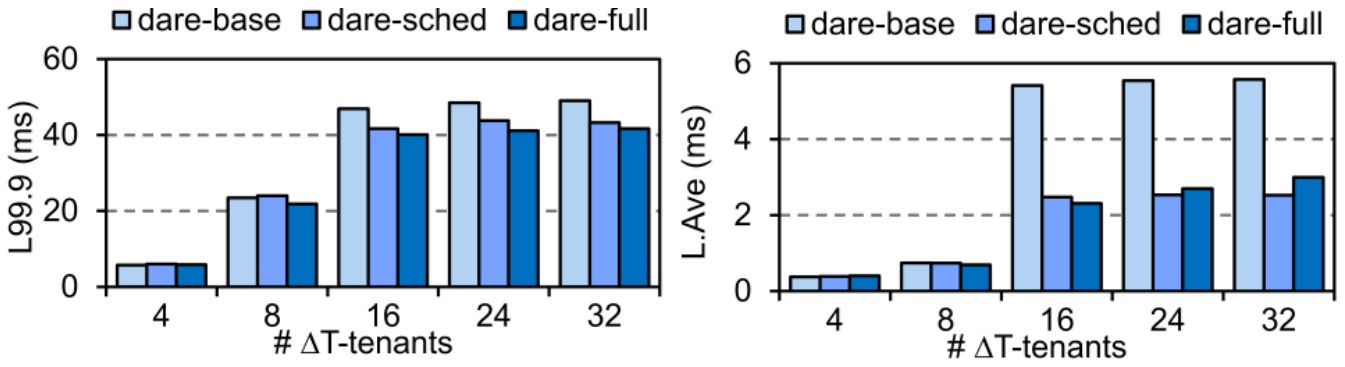

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- I/O service acceleration reduces tail latency.

Discussion

Compatibility with virtual machines (VMs)?

- Not yet: processes inside VMs are invisible to the host.

Beyond NVMe SSDs to new devices?

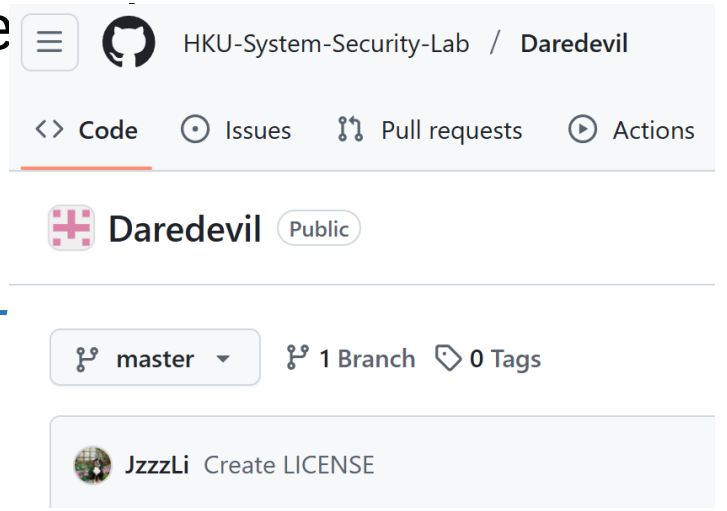
- Possible: the multi-queue feature is maintained for CXL/ZNS SSDs.

Future road after Daredevil:

- Finer-grained performance isolation/consideration with cgroups.
- More comprehensive maintenance with CPU core scheduling.

Conclusion

- Daredevil is a wild research prototype to challenge the static Linux kernel storage stack.
- It achieves *flexibility* and *efficiency* with higher performance multi-tenant I/O services.
- Open sourced at: *https://github.com/HKU-System-Security-Lab/Daredevil*



*Please contact **Junzhe Li** (jzzzli@connect.hku.hk) for any questions!*

Thank you!