Splinter: Bare-Metal Extensions for Multi-Tenant Low-Latency Storage

Chinmay Kulkarni, Sara Moore, Mazhar Naqvi, Tian Zhang, Robert Ricci, and Ryan Stutsman

University of Utah

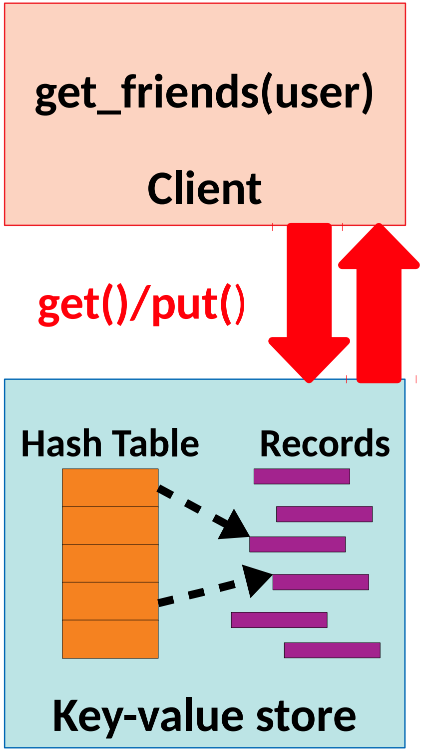
Introduction

- **Kernel-bypass** key-value stores offer **< 10µs** latency, **> Mops/s** throughput
  - Fast because they're just dumb?

- **Problem:** Leverage performance → **share** between tenants
- **Problem:** Apps require rich data models. Ex: Facebook's TAO
  - Implement using gets & puts? → **Data movement, client stalls**
  - Push code to key-value store? → **Isolation costs limit density**

- **Splinter: Multi-tenant** key-value store that code can be pushed to
  - Tenants push type- & memory-safe code written in **Rust** at runtime
  - **> 1000** tenants/server, **3.5 Million** ops/s, **9µs** median latency

Richer Data Models Come At A Price



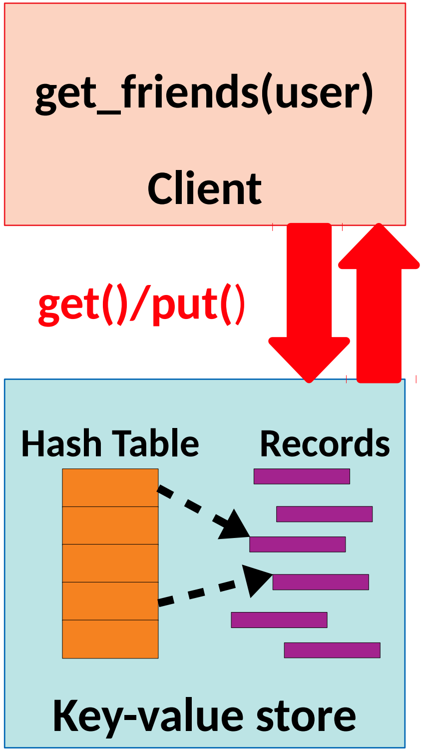
Apps require rich data models in addition to performance

- Ex: Social graphs, Decision trees etc.

Key-value stores trade-off data model for performance

- Simple get()’s & put()’s over key-value pairs

Richer Data Models Come At A Price



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Key-value stores trade-off data model for performance

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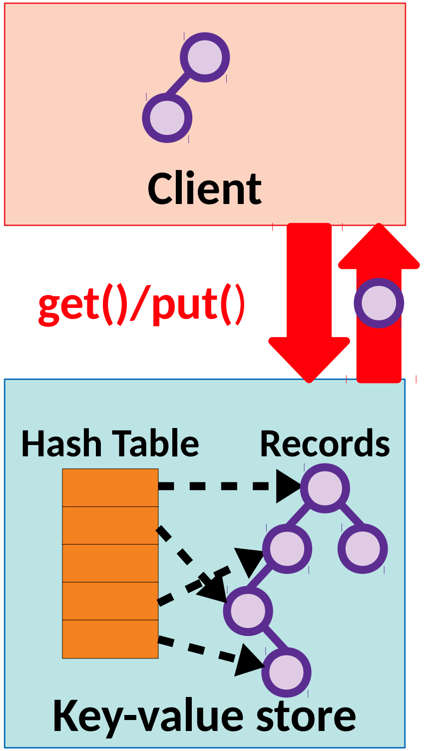
Thinner data model → Better performance
But do applications benefit?

Extra Round-Trips (RTTs) Hurt Latency & Utilization



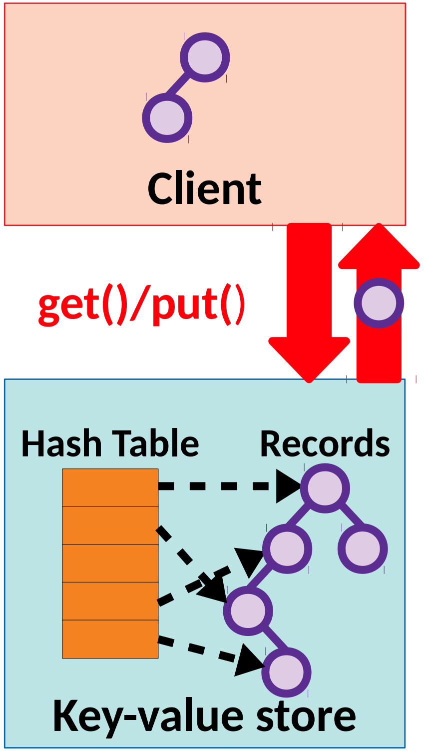
Example: Traverse tree with N nodes using gets

- One get() at each level of the tree → **O(log N) RTTs**
- Control flow depends on data → **Client stalls during get()**

Network RTTs, dispatch are the main bottleneck ~10µs

- 1.5µs inside the server

Extra Round-Trips (RTTs) Hurt Latency & Utilization



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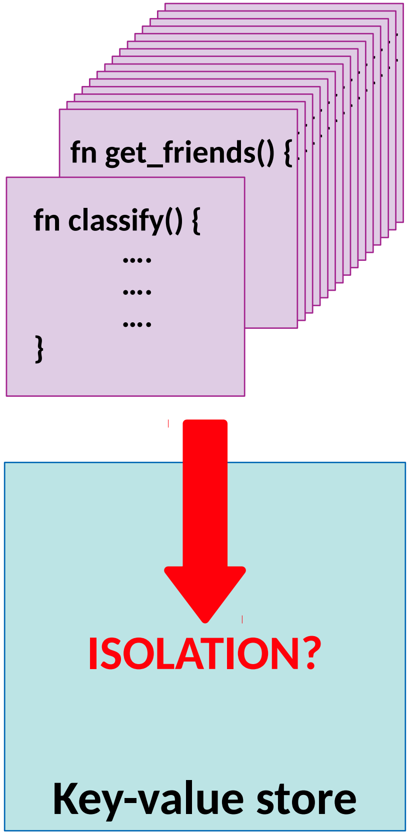
- 1.5µs inside the server

So push code to storage?

Why Not Push Compute To Storage?



RPC Processing Time ~1.5µs

Only native code will do

Context Switches ~1.5µs

Multi-tenancy → Need hardware isolation

What Do We Want From The Storage Layer?

Granularity of compute is steadily decreasing

Virtual machines → Containers → Lambdas

- **Extremely high tenant density**
  - Fine-grained resource allocation; 100s of CPU cycles, Kilobytes of memory

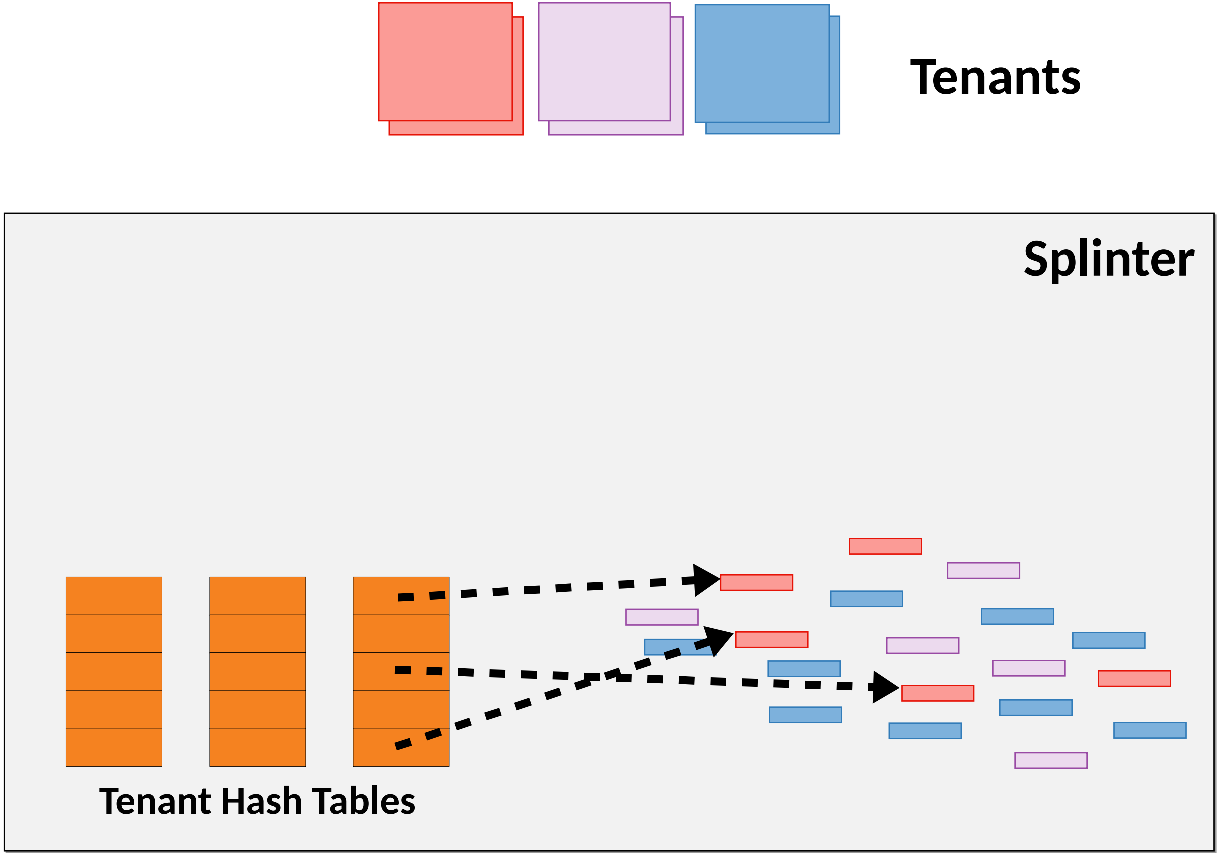
- **Allow tenants to extend data model at runtime**
  - Low overhead isolation between tenants & storage layer

Splinter: A Multi-Tenant Key-Value Store

- **Tenants can install and invoke extensions at runtime**
  - Extensions written in **Rust**
  - Rely on type and memory safety for isolation, avoids context switch

- **Implemented in ~9000 lines of Rust**
  - Supports two RPCs **→ install(ext_name) & invoke(ext_name)**
  - Also supports regular get() & put() RPCs **→ “Native” operations**

1000 Foot View Of Splinter



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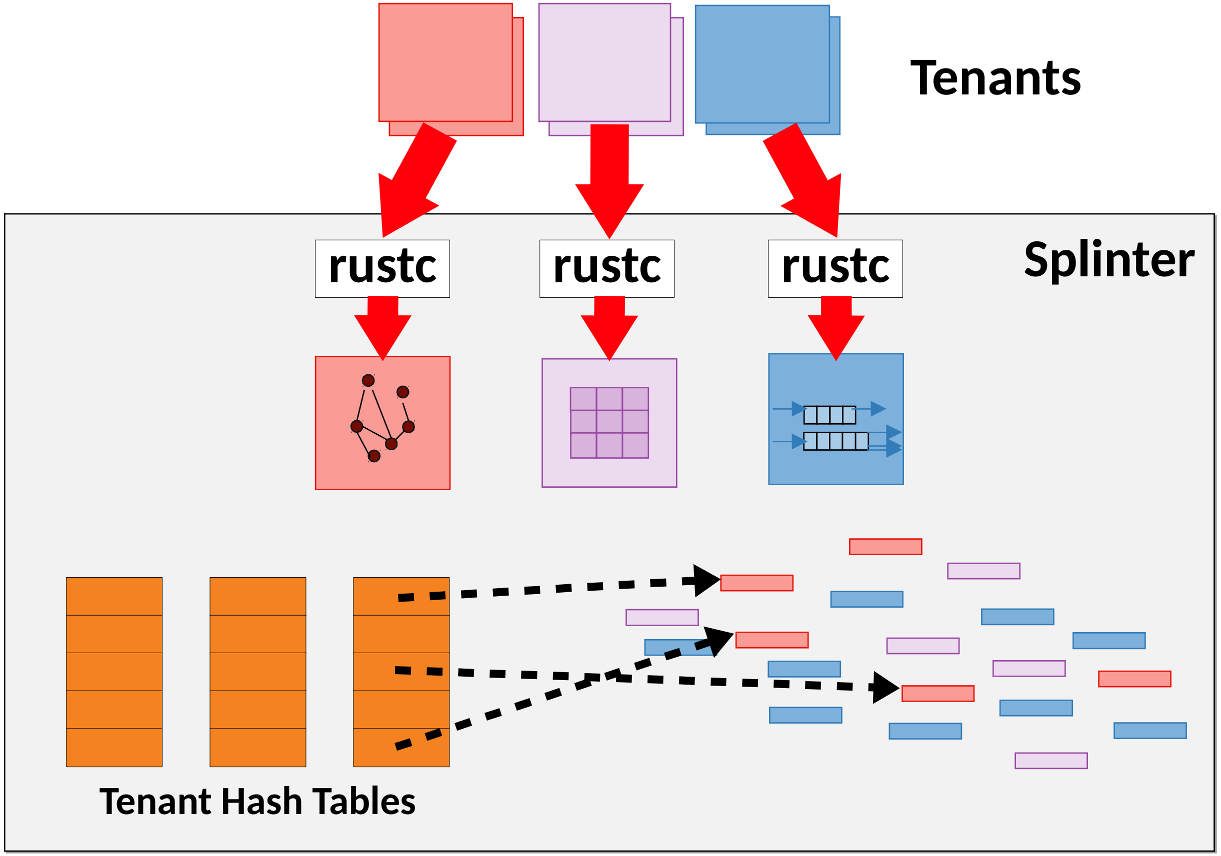
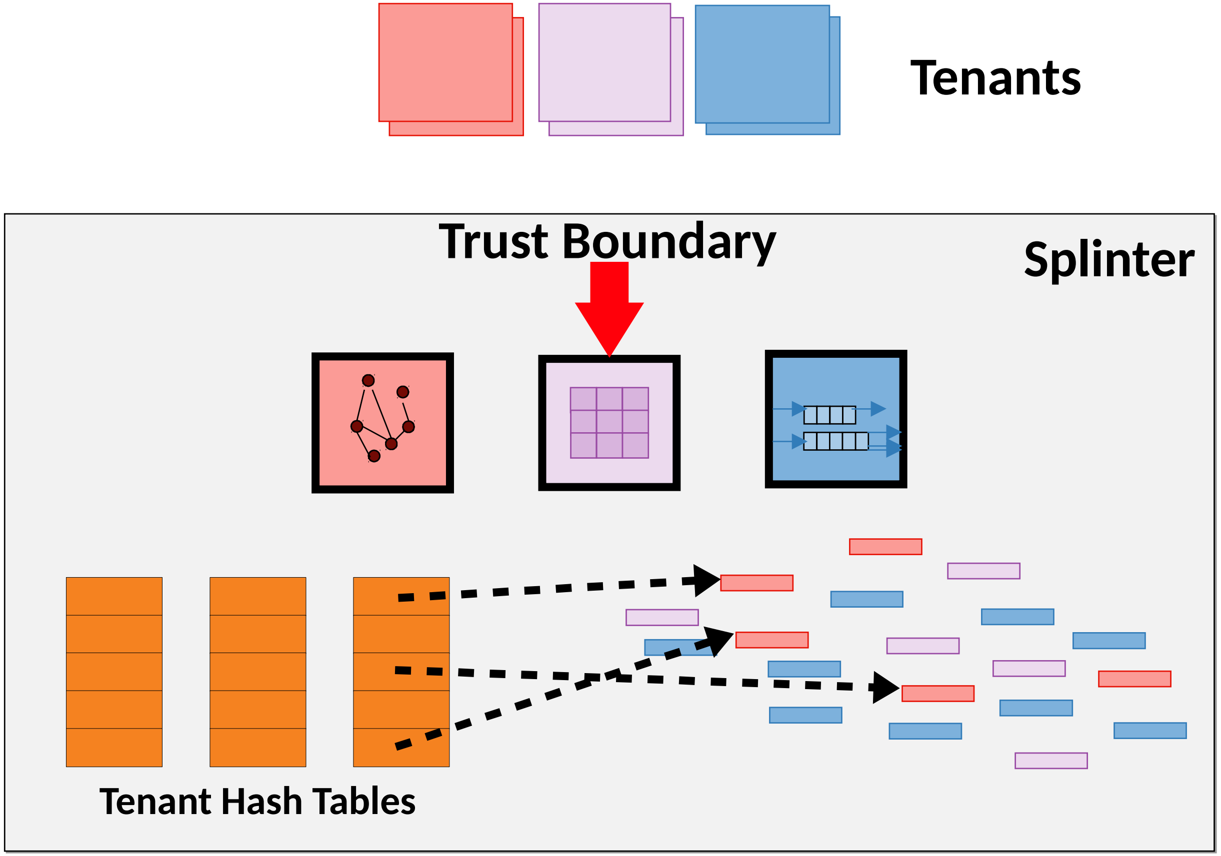


Tenants push extensions written in Rust

Splinter compiles, loads extensions Into address-space

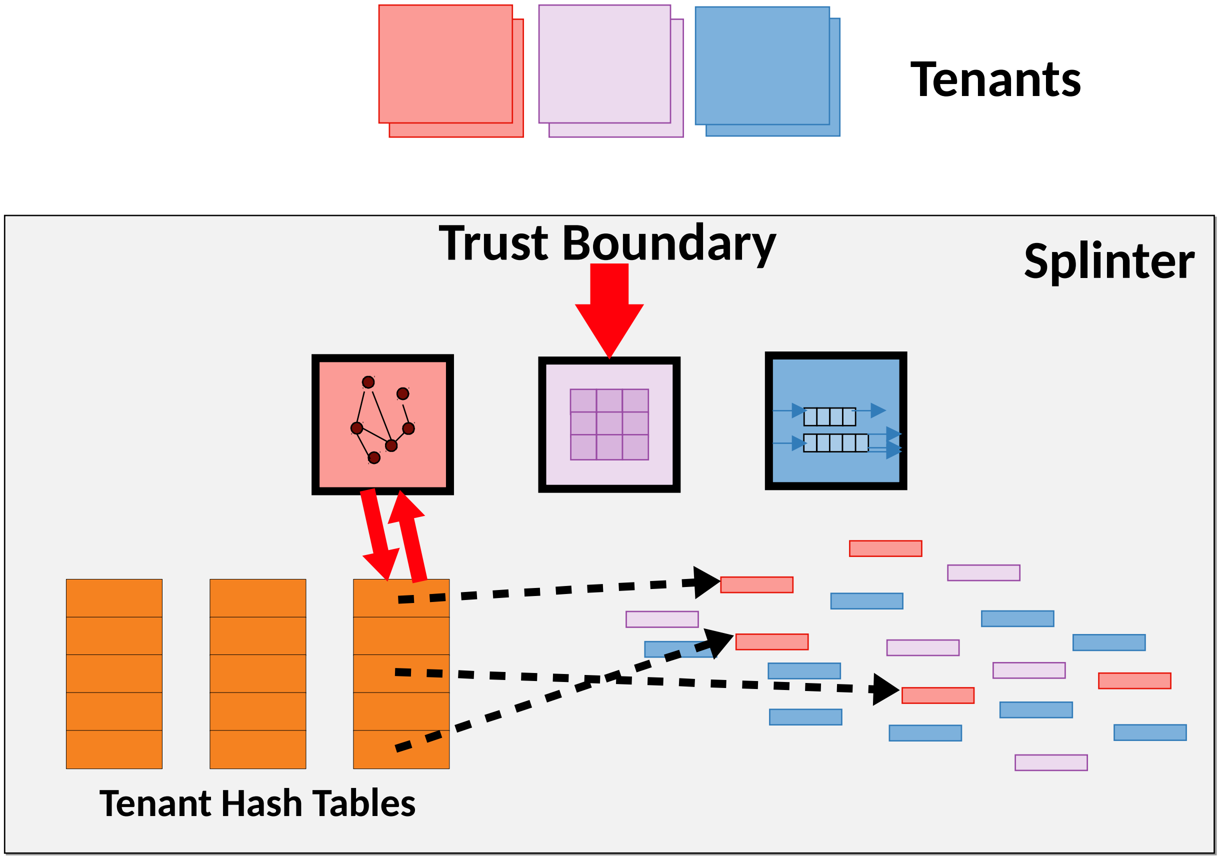
1000 Foot View Of Splinter



Rust provides memory-safety

Extensions do not share state

1000 Foot View Of Splinter



Extensions receive references to records

Each tenant sees a custom key-value store

Simple Aggregation With Splinter

Native mode

Client

1024 Tenants
100 GB Data

Splinter Server

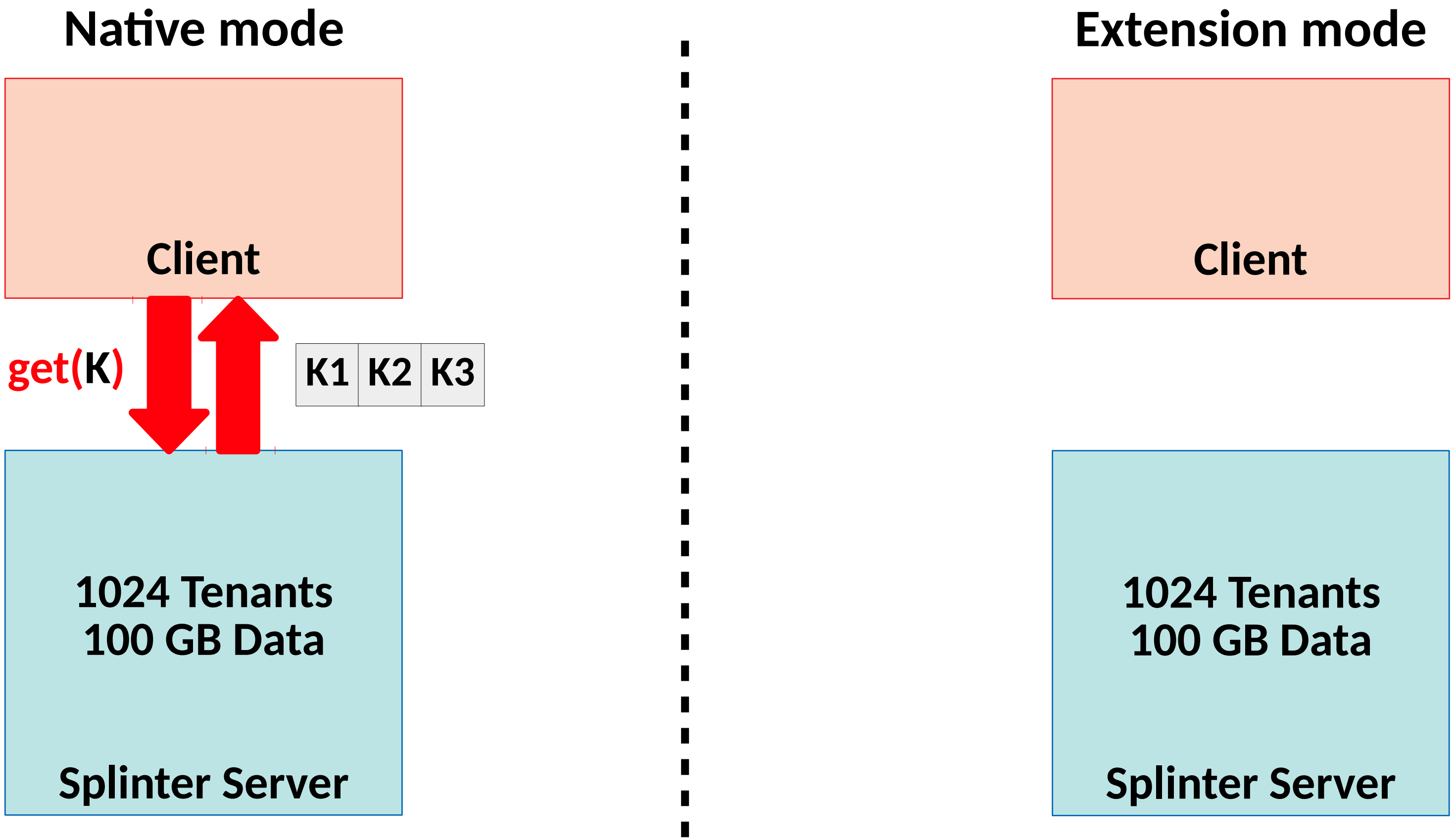
Extension mode

Client

1024 Tenants
100 GB Data

Splinter Server

Simple Aggregation With Splinter



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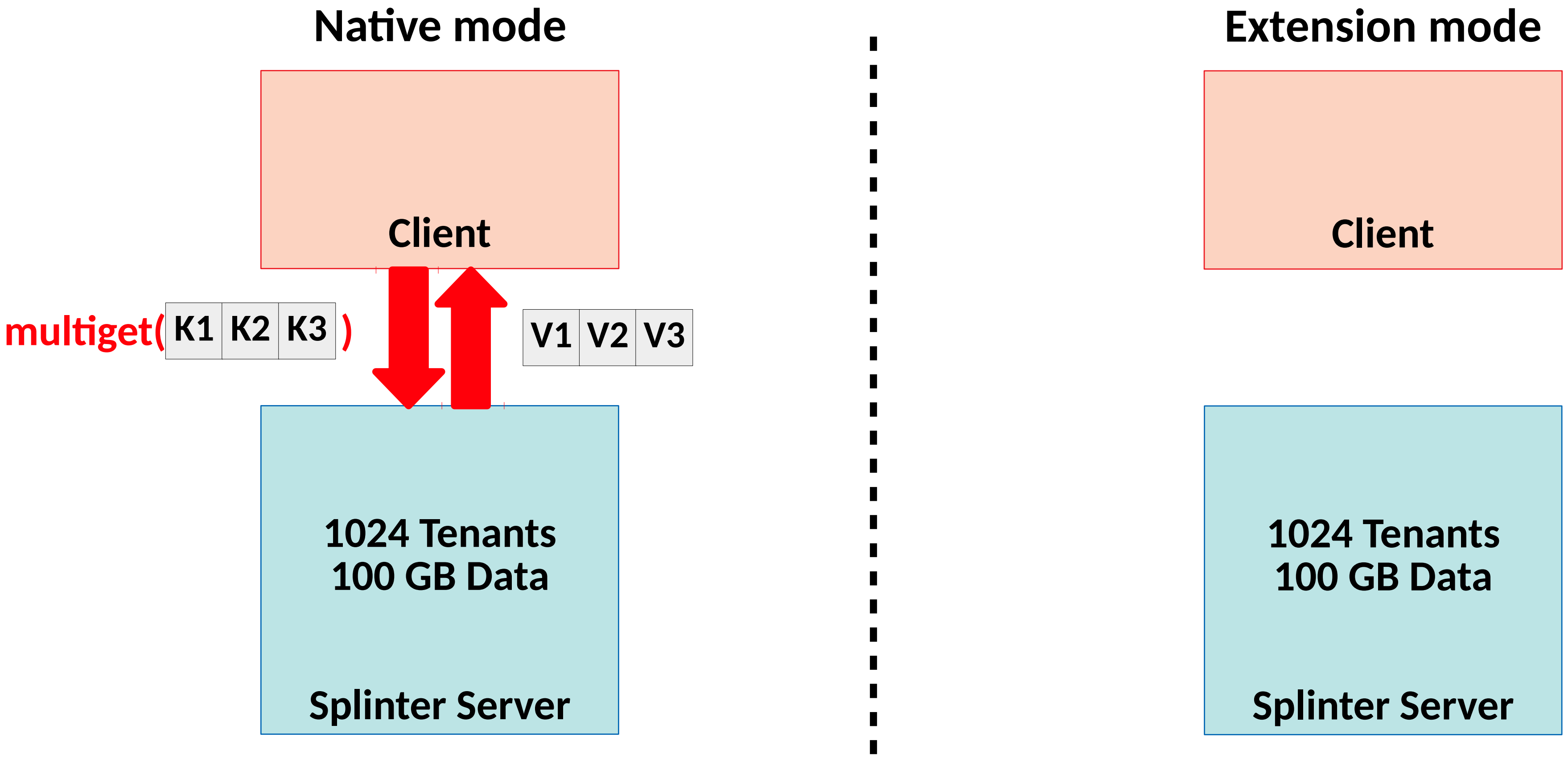

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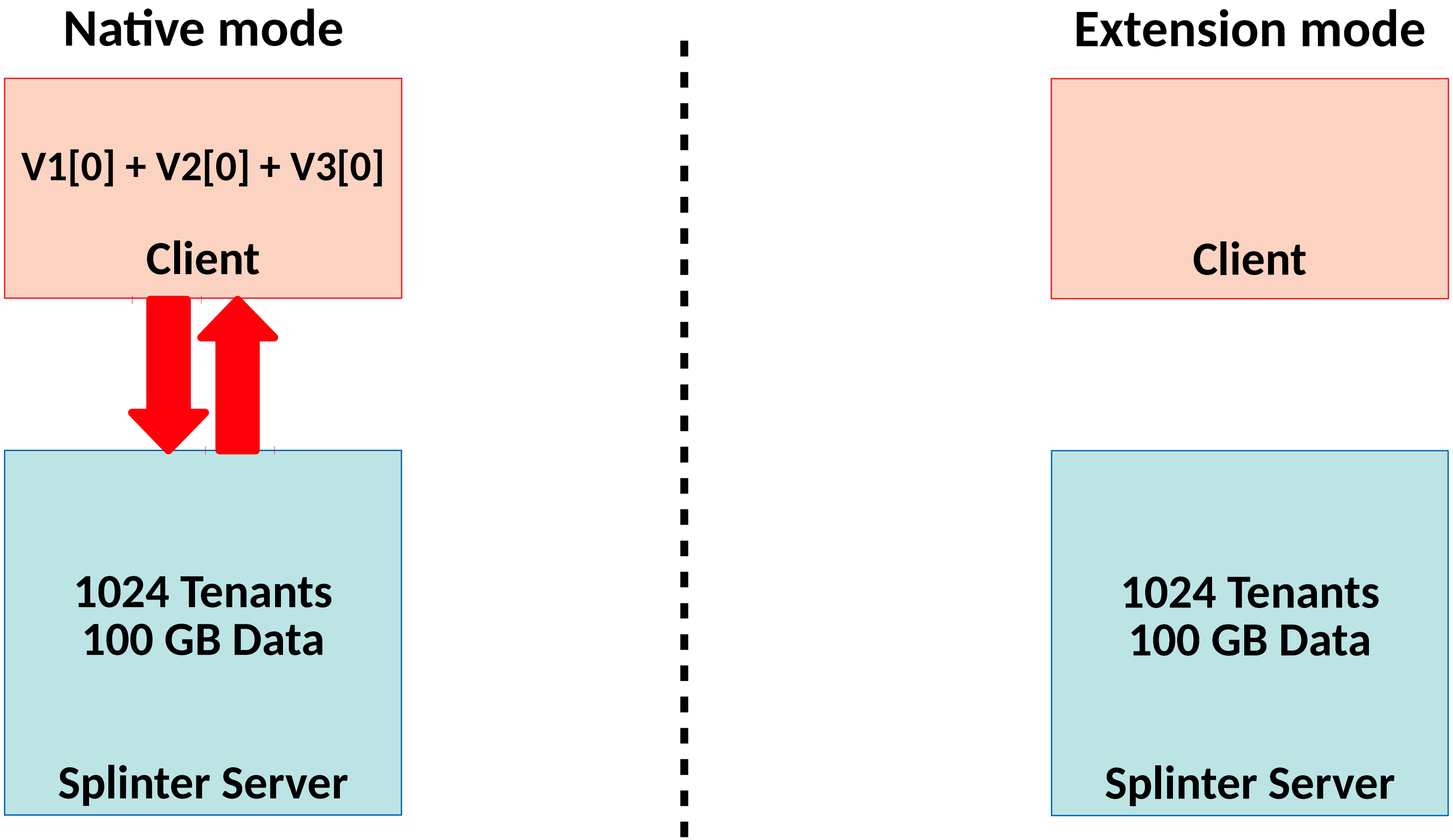

Native mode

V1[0] + V2[0] + V3[0]

Client

1024 Tenants
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Splinter Server

Extension mode

Client

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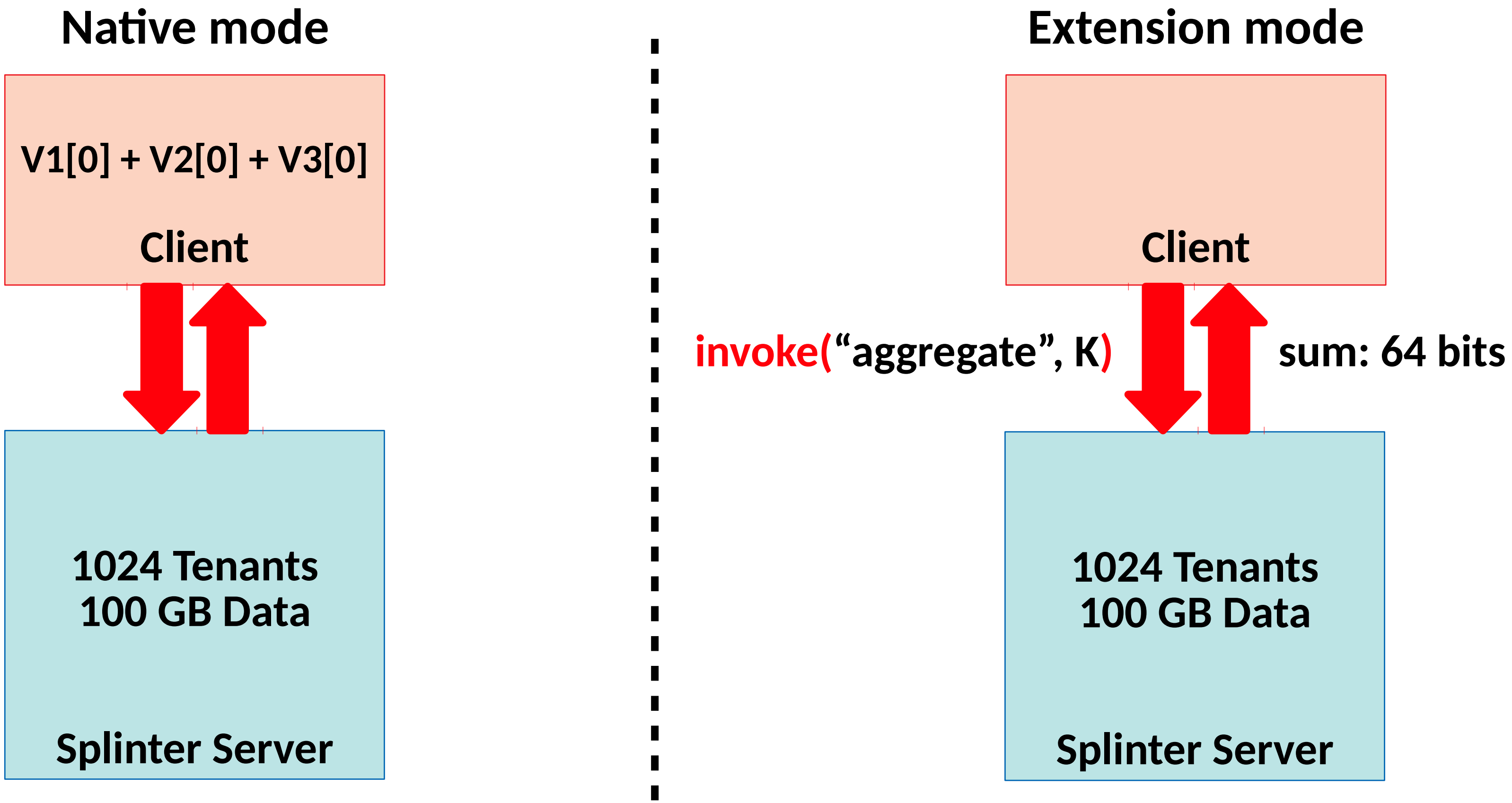
Simple Aggregation With Splinter



Native mode

V1[0] + V2[0] + V3[0]

Client

1024 Tenants
100 GB Data

Splinter Server

Extension mode

Client

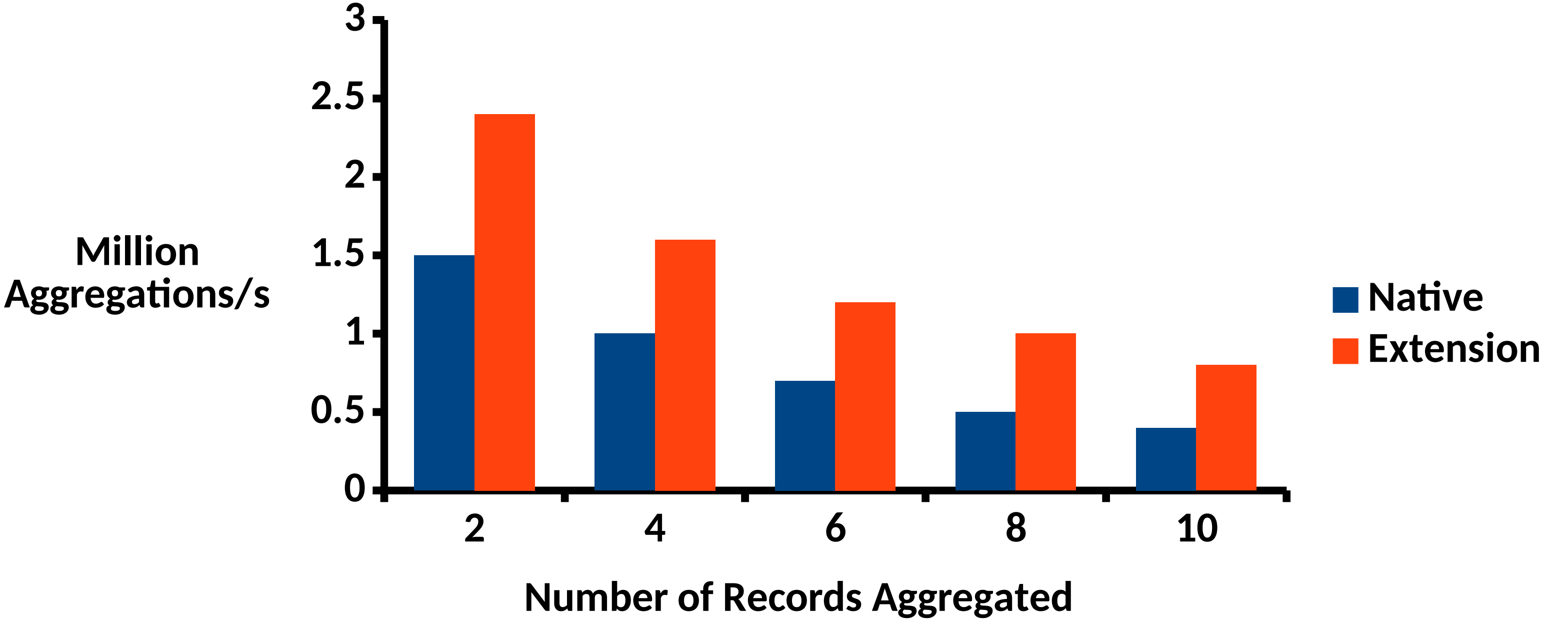
invoke(“aggregate”, K)

sum: 64 bits

1024 Tenants
100 GB Data

Splinter Server

Simple Aggregation With Splinter



Extension Mode → Few RPCs, Less Data movement → Better Throughput

Splinter: Design

- **Tenant Locality And Work Stealing**
  - Avoid cross-core coordination while avoiding hotspots

- **Lightweight Cooperative Scheduling**
  - Prevent long running extensions from starving short running ones

- **Low cost isolation**
  - No forced data copies across trust boundary

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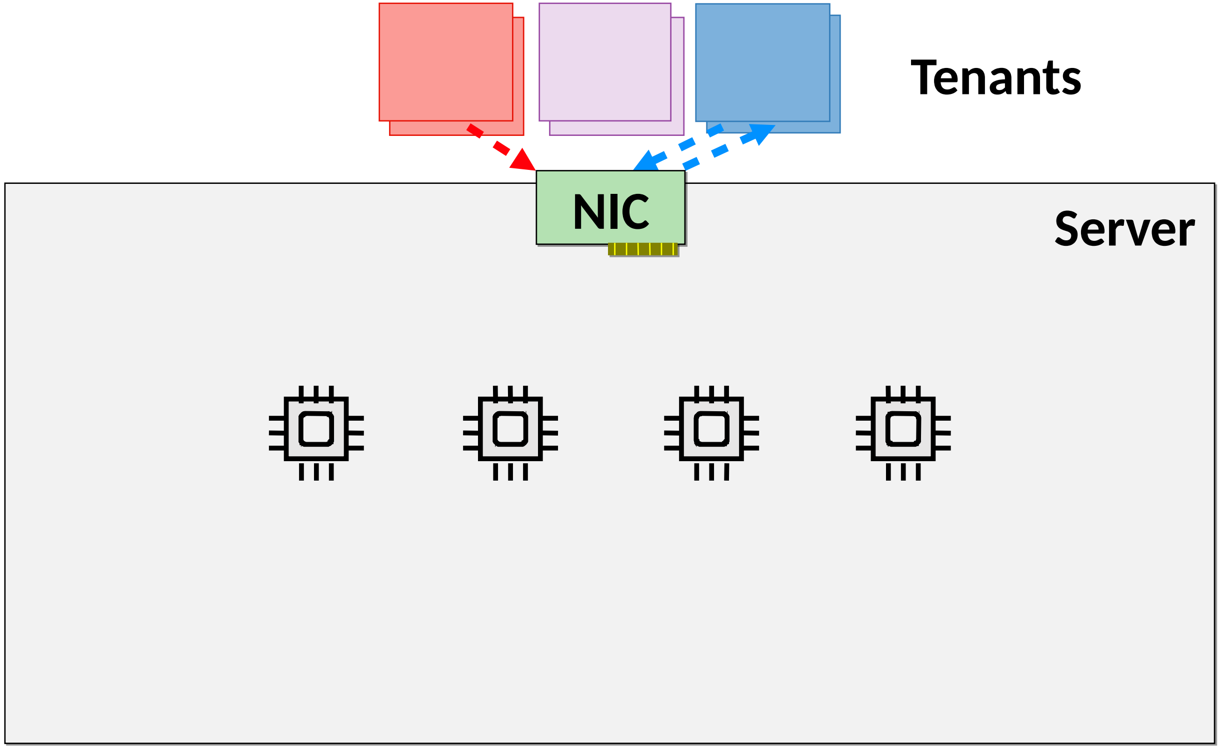
Splinter: Tenant Locality And Work Stealing

Problem: **Quickly dispatch requests to cores, avoid hotspots**

Solution: **NIC routes tenants to cores, cores steal work**



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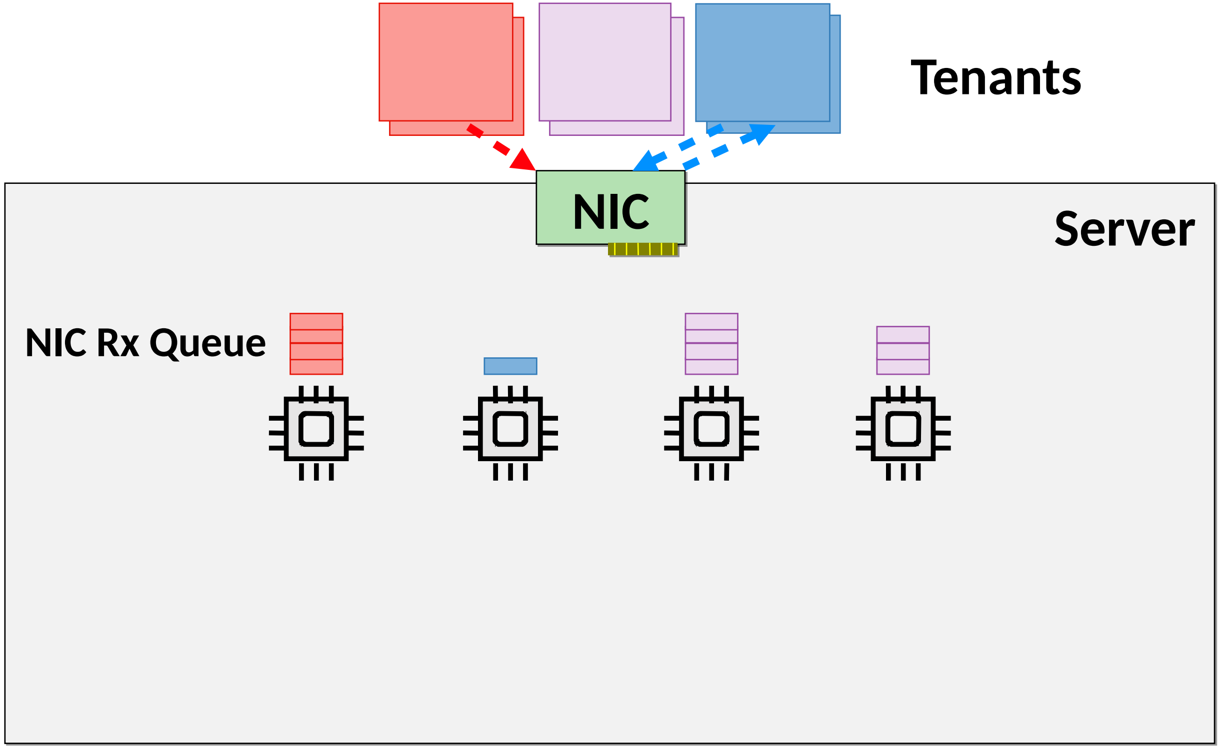

One Rx queue per core

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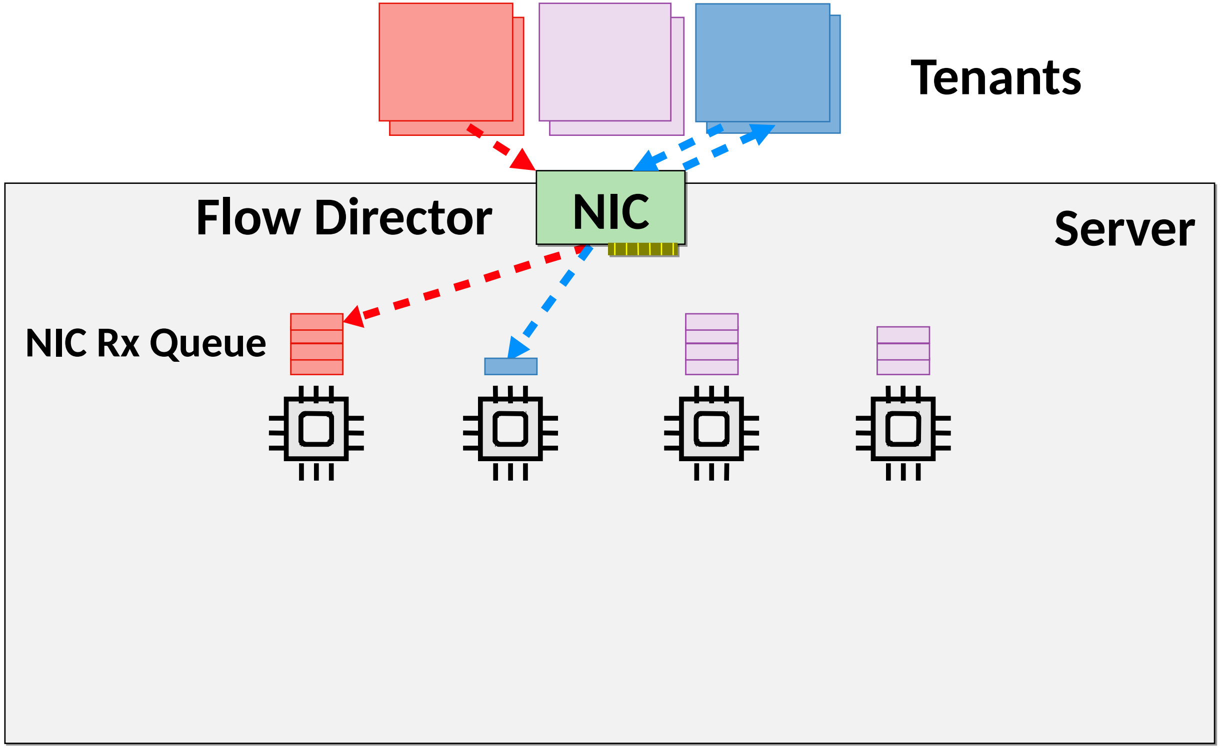

Maintain "Locality" route tenant to queue

Splinter: Tenant Locality And Work Stealing

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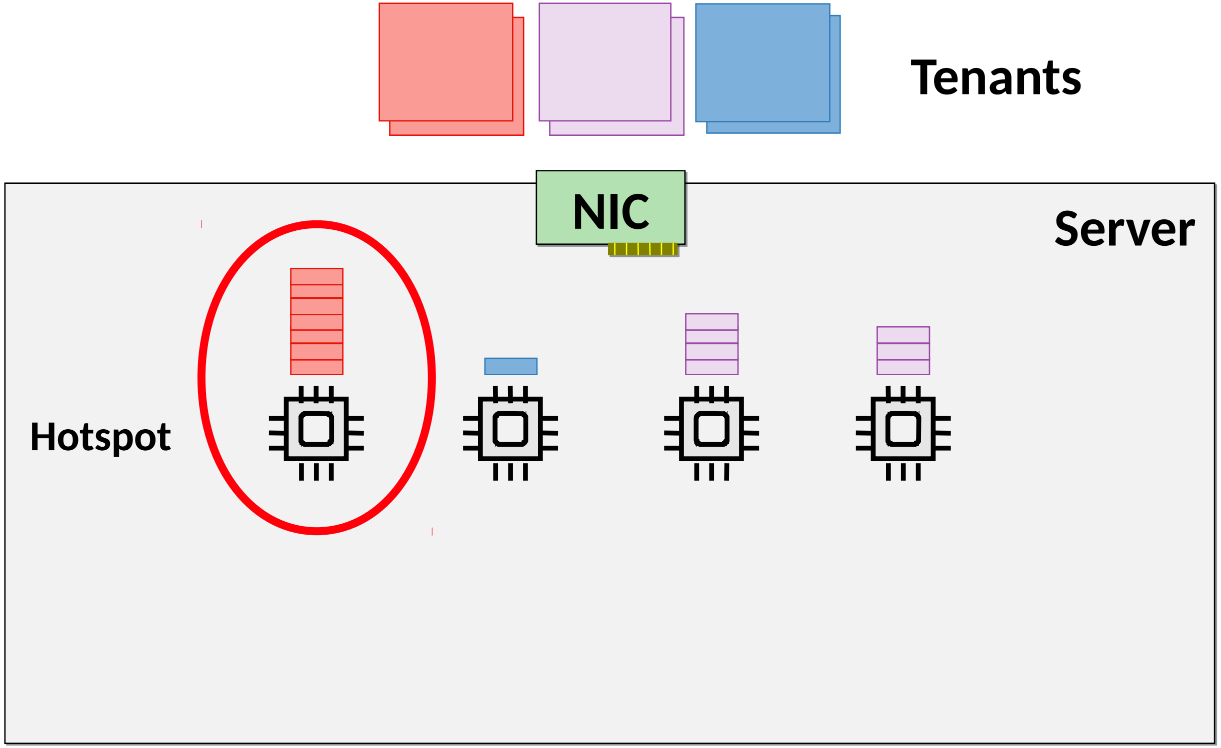

Few active tenants
Many idle tenants

Splinter: Tenant Locality And Work Stealing

Problem: **Quickly dispatch requests to cores, avoid hotspots**

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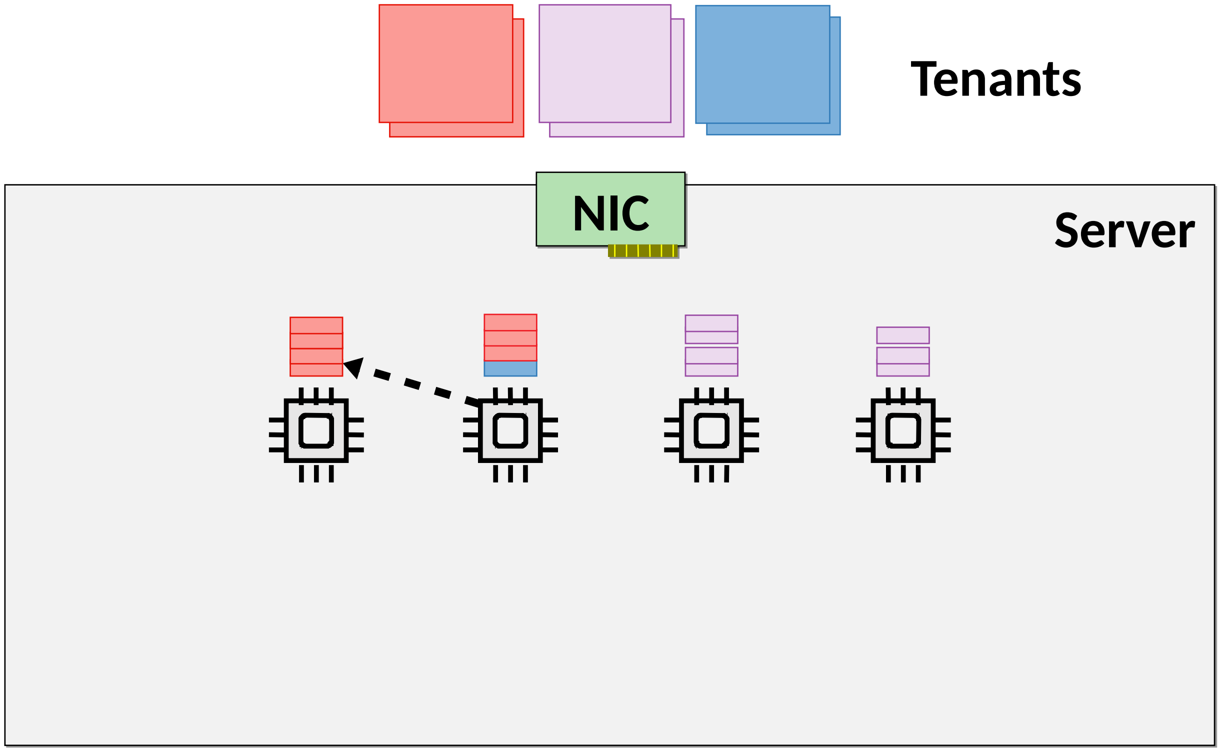


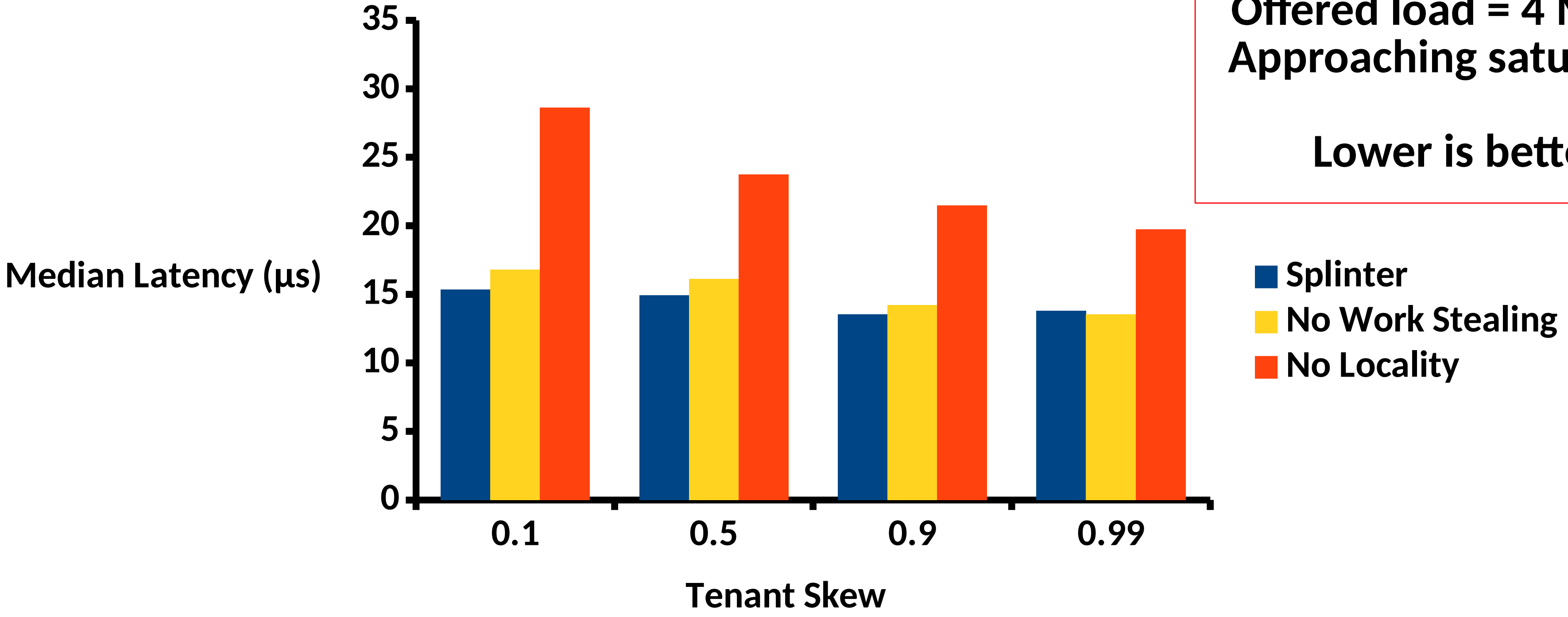
Cores steal from neighboring queue

What are the benefits of tenant locality & work stealing?

Setup:

- 1024 tenants
- Invoke small extension that reads one object

Performance With Tenant Locality & Work Stealing



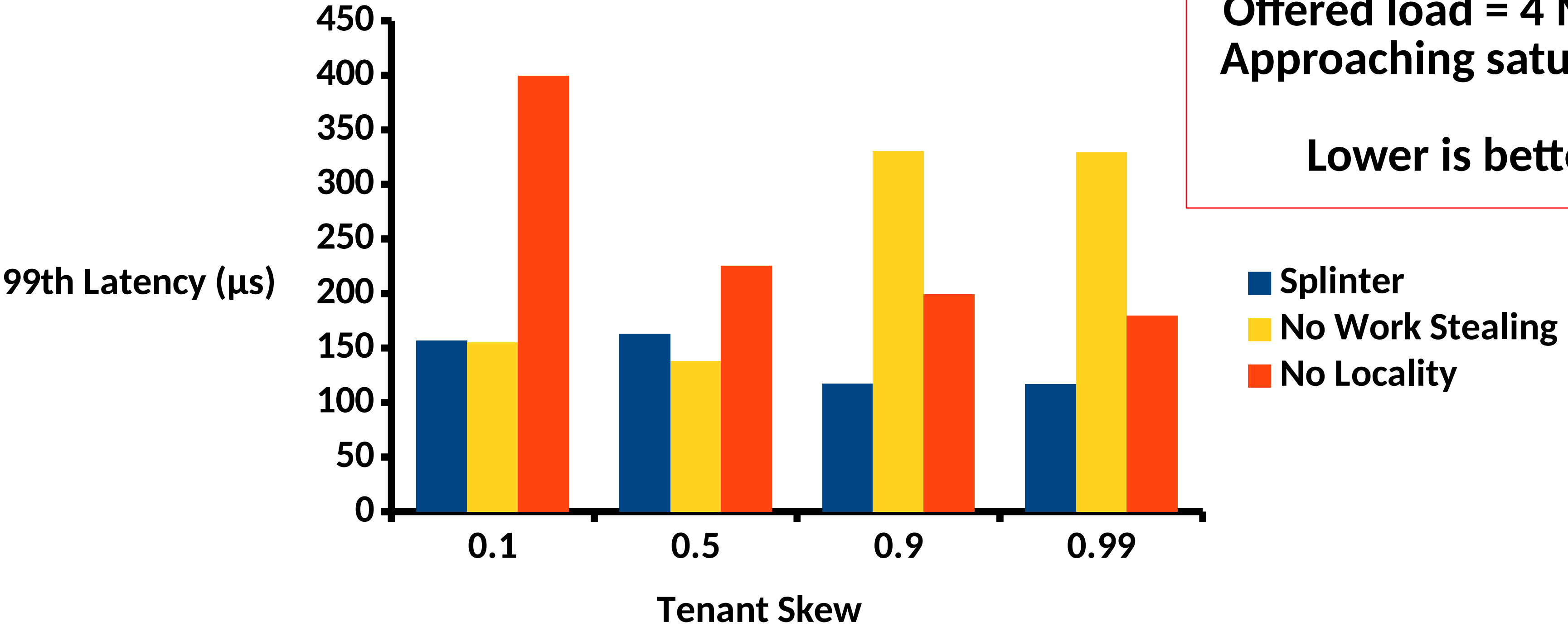
Offered load = 4 Mop/s
Approaching saturation

Lower is better

Higher tenant skew → Fewer active tenants

No Tenant Locality → Poor median Latency

Performance With Tenant Locality & Work Stealing



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Higher tenant skew → Fewer active tenants

No work stealing → Poor tail Latency under high skew

Splinter: Design

- Tenant Locality And Work Stealing
  - Avoid cross-core coordination while avoiding hotspots

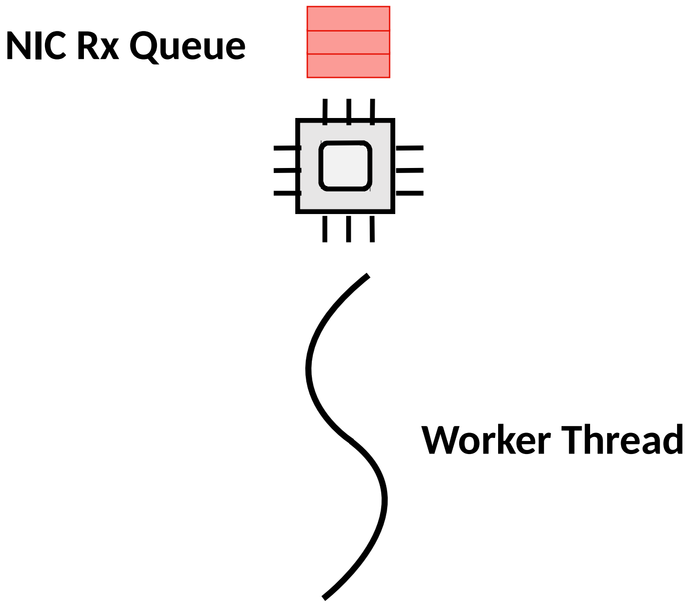
- **Lightweight Cooperative Scheduling**
  - Prevent long running extensions from starving short running ones

- Low cost isolation
  - No forced data copies across trust boundary

Splinter: Lightweight Cooperative Scheduling

Problem: Minimize trust boundary crossing cost

Solution: Run extensions in stackless coroutines



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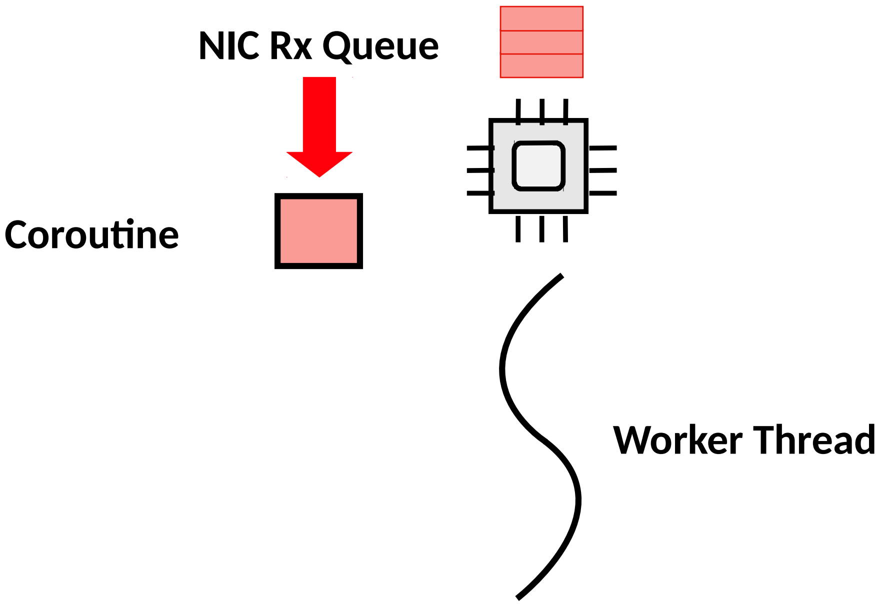

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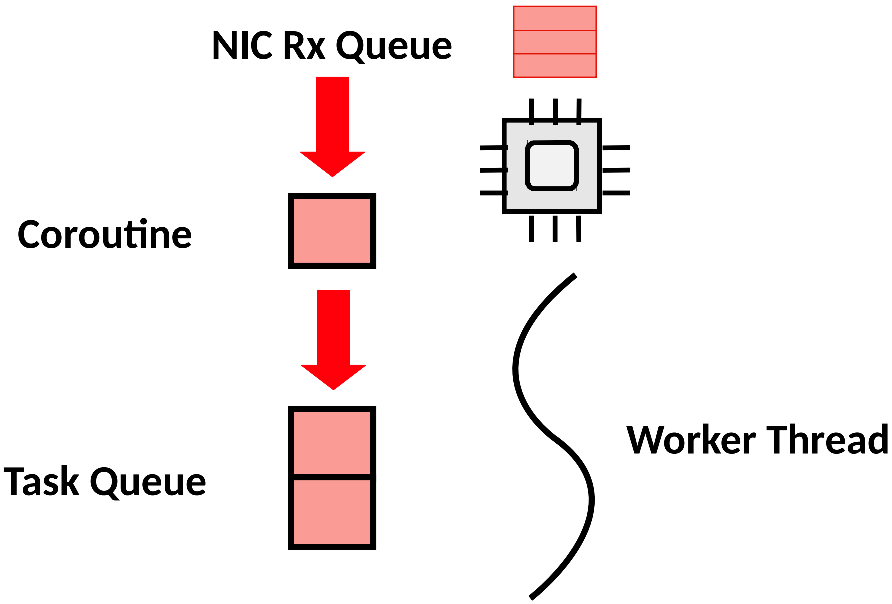

NIC Rx Queue

Coroutine

Task Queue

Worker Thread

Dedicated Dispatch task to construct coroutines

Splinter: Lightweight Cooperative Scheduling

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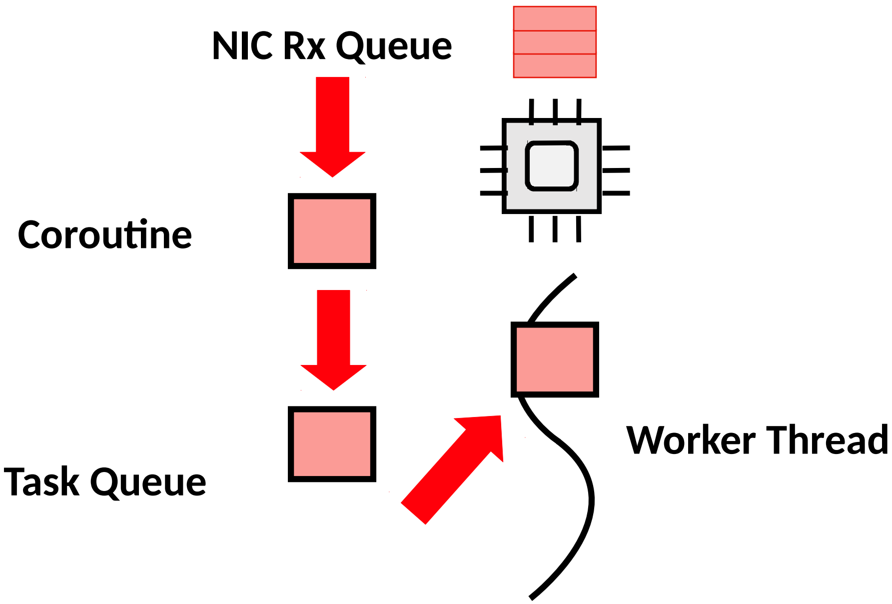

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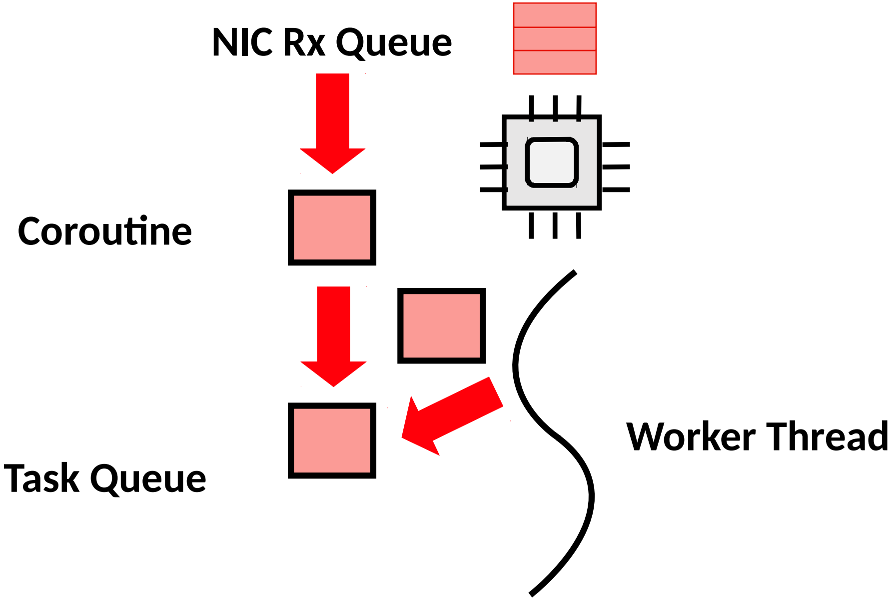


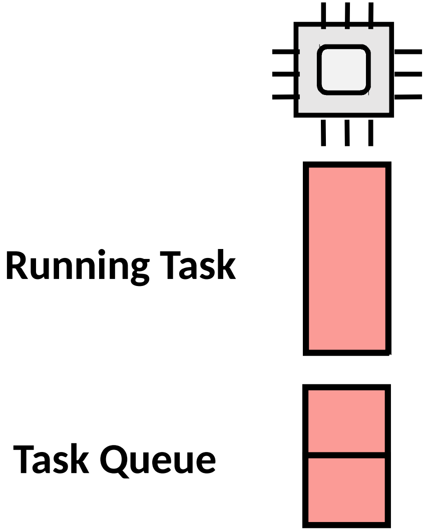
Task switch cost ~10ns

Run extension until it returns

Splinter: Lightweight Cooperative Scheduling

Problem: Long running tasks starve shorter tasks, hurt latency

Solution: Extensions are cooperative, must yield frequently



Preemption is too expensive!

Splinter: Lightweight Cooperative Scheduling

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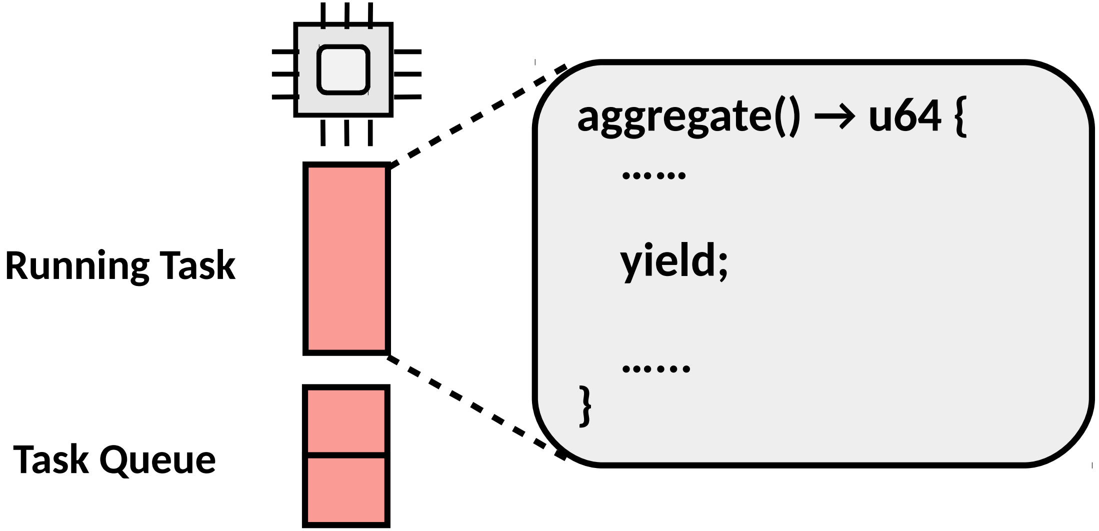


```
aggregate() → u64 {
    ……

    yield;

    ……
}
```

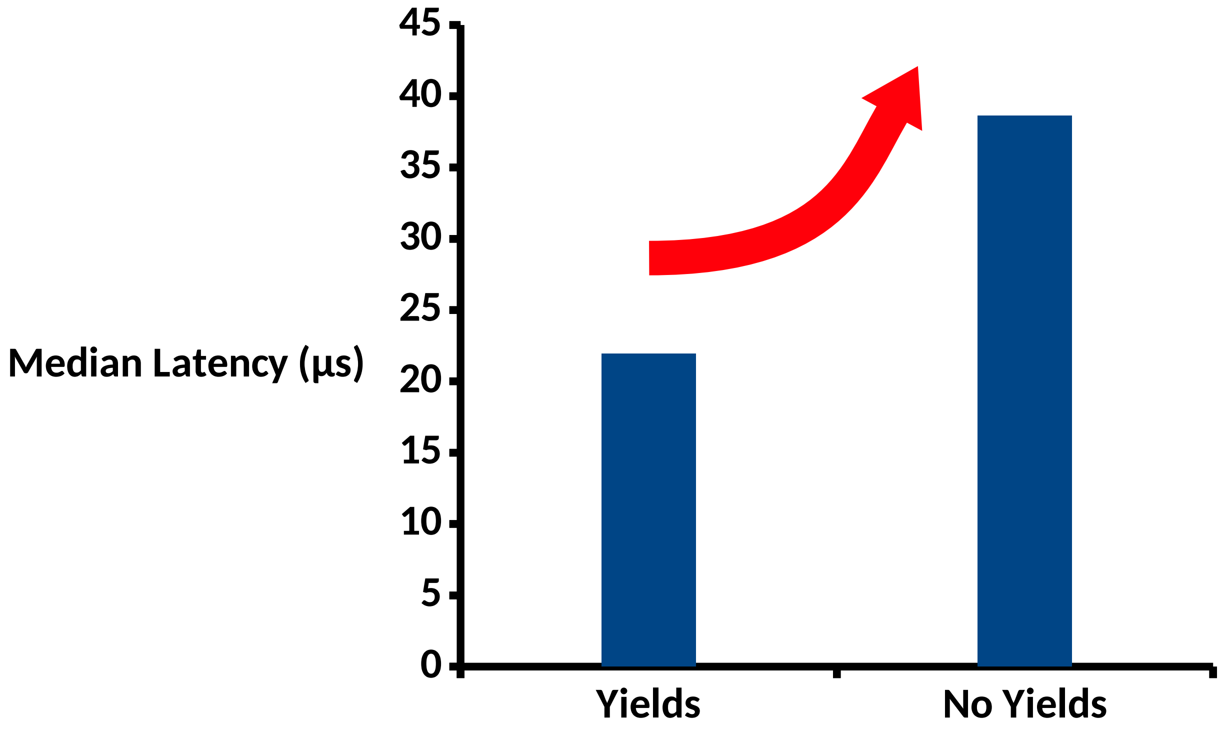
Compiler generates code to save & restore state

What are the benefits of cooperative scheduling?

Setup:

- 1024 tenants
- 85% requests invoke small extension that reads one object
- 15% requests invoke extension that reads 128 objects

Performance With And Without Yields



Offered load = 1 Mop/s

15% long running
Approaching saturation

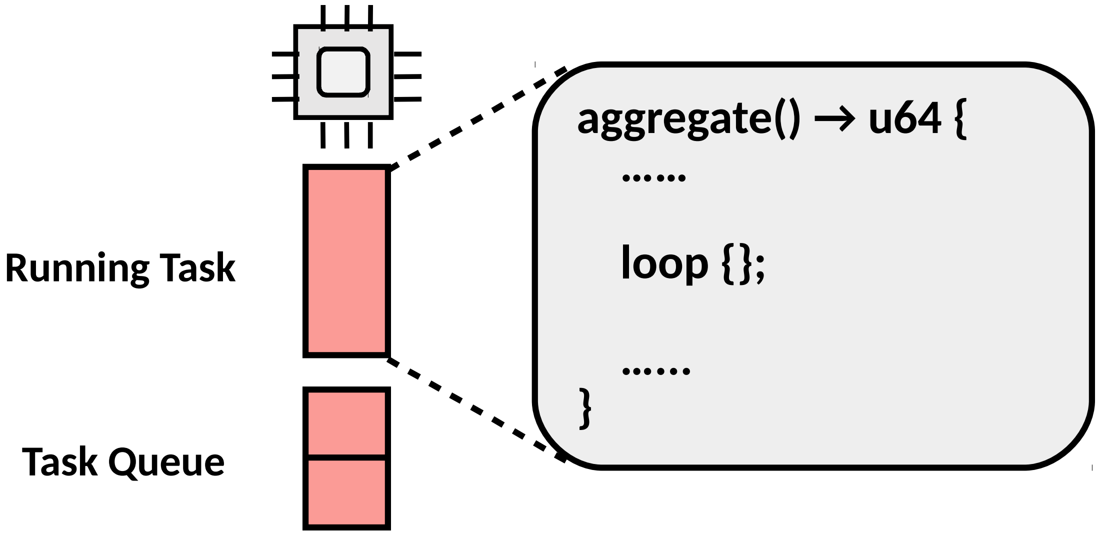
Lower is better

Yield frequently → Better Qos, Less interference

Splinter: Lightweight Cooperative Scheduling

Problem: **Uncooperative extensions**

Solution: **Trusted watchdog core**



```
aggregate() → u64 {
    ......

    loop {};

    ......
}
```

Splinter: Lightweight Cooperative Scheduling

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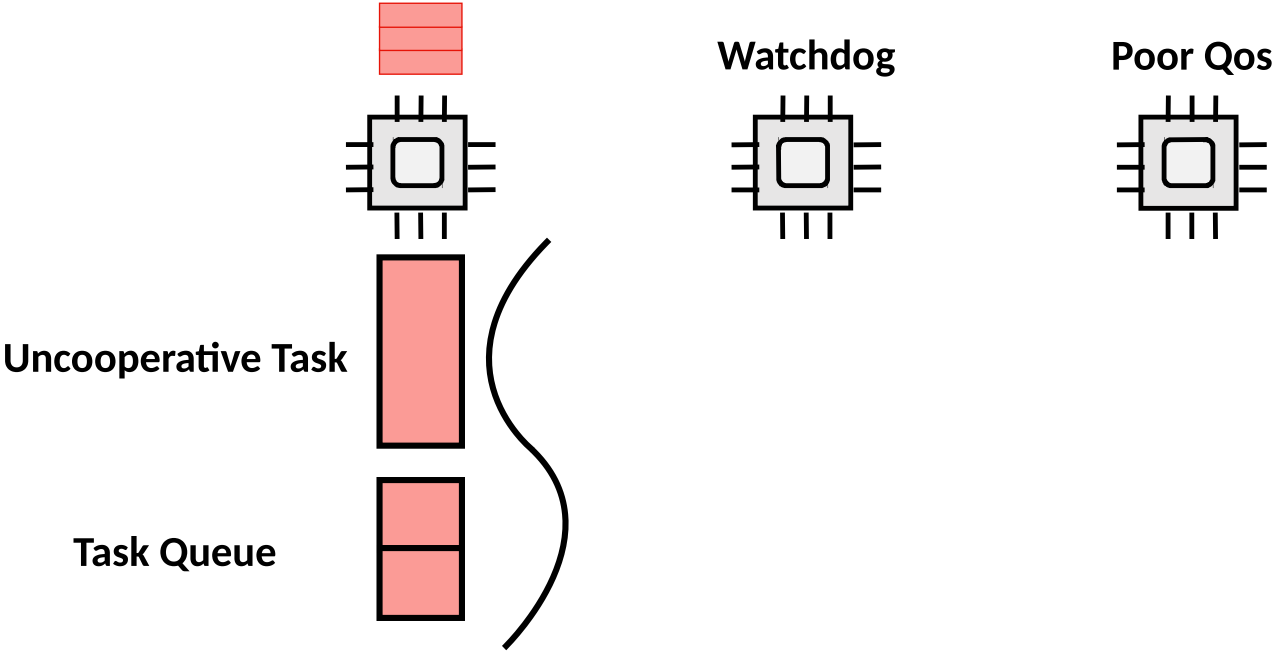
Solution: **Trusted watchdog core**



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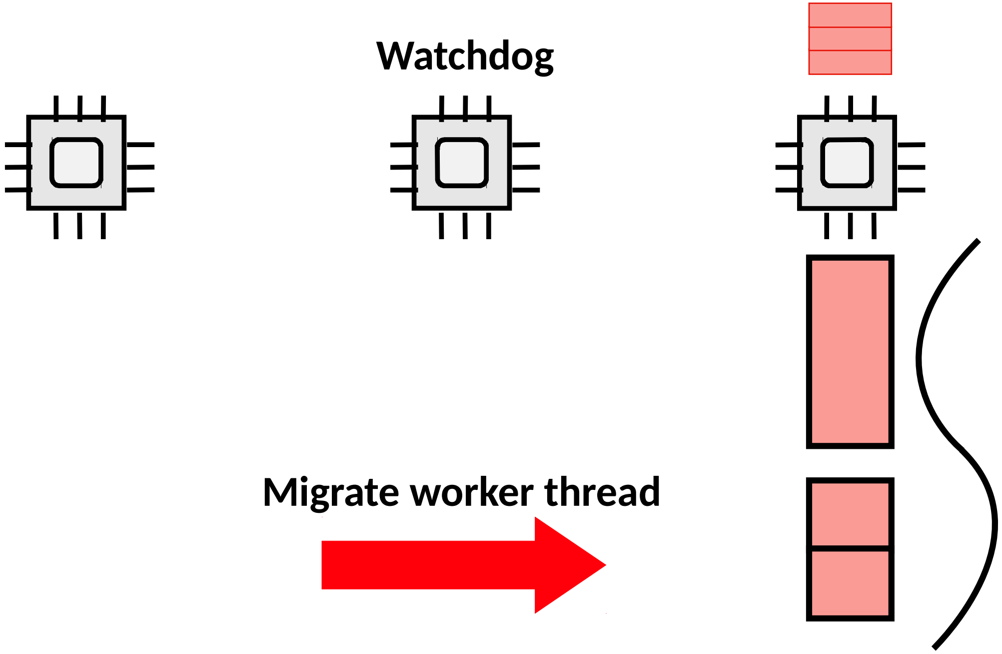
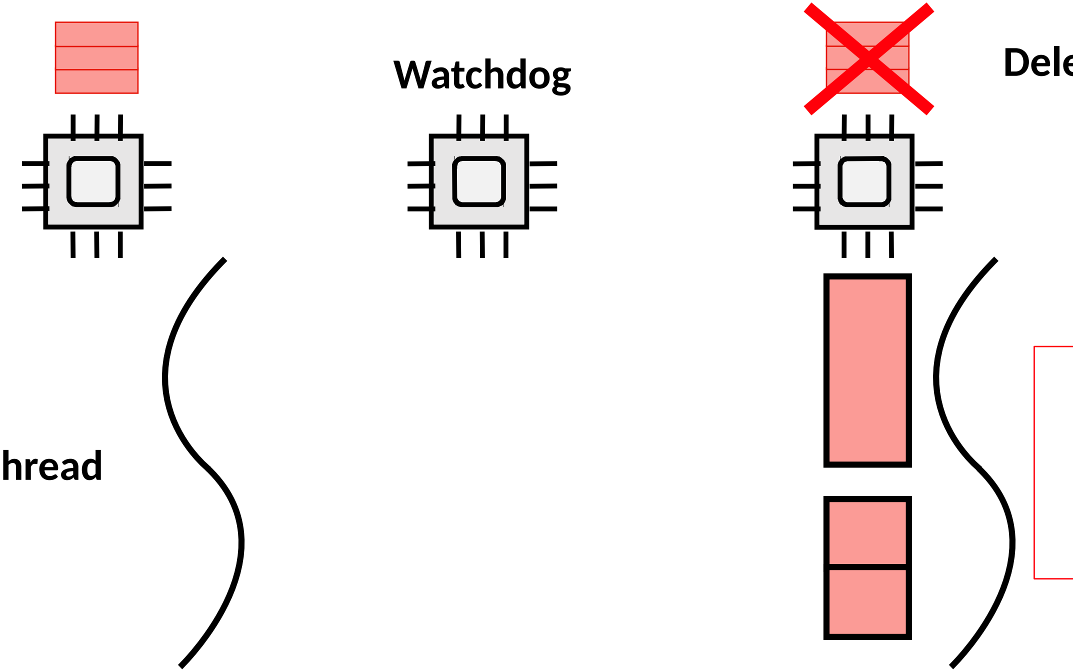


Splinter: Lightweight Cooperative Scheduling

Problem: Uncooperative extensions

Solution: Trusted watchdog core



Watchdog

Delete Rx queue

Spawn new worker thread

Extension cannot send/recv packets

Splinter: Lightweight Cooperative Scheduling

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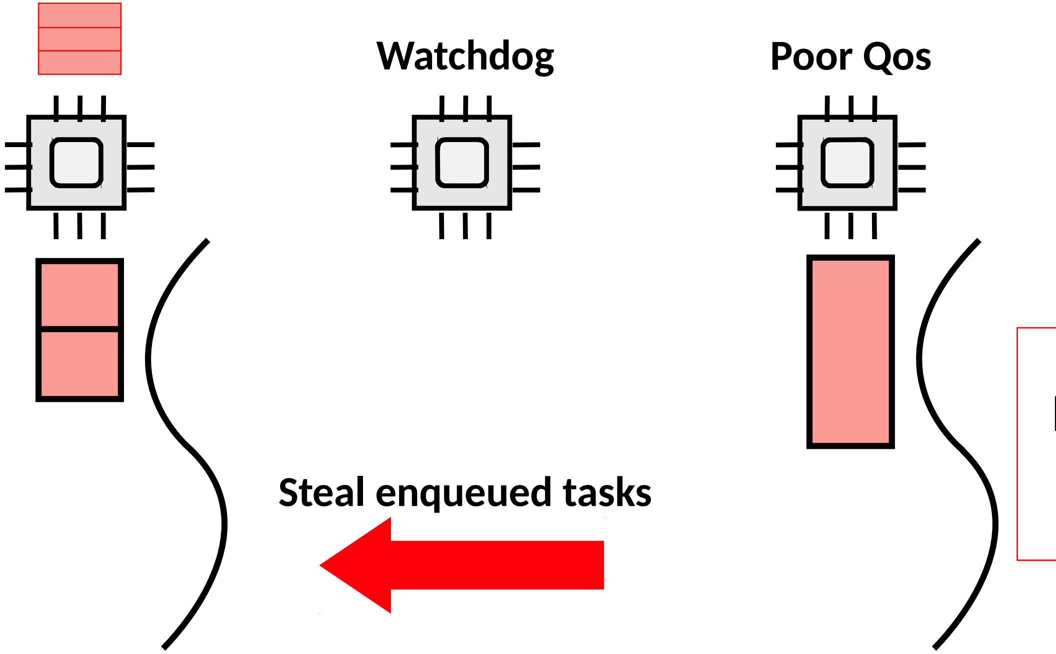


Kill worker thread when task yields

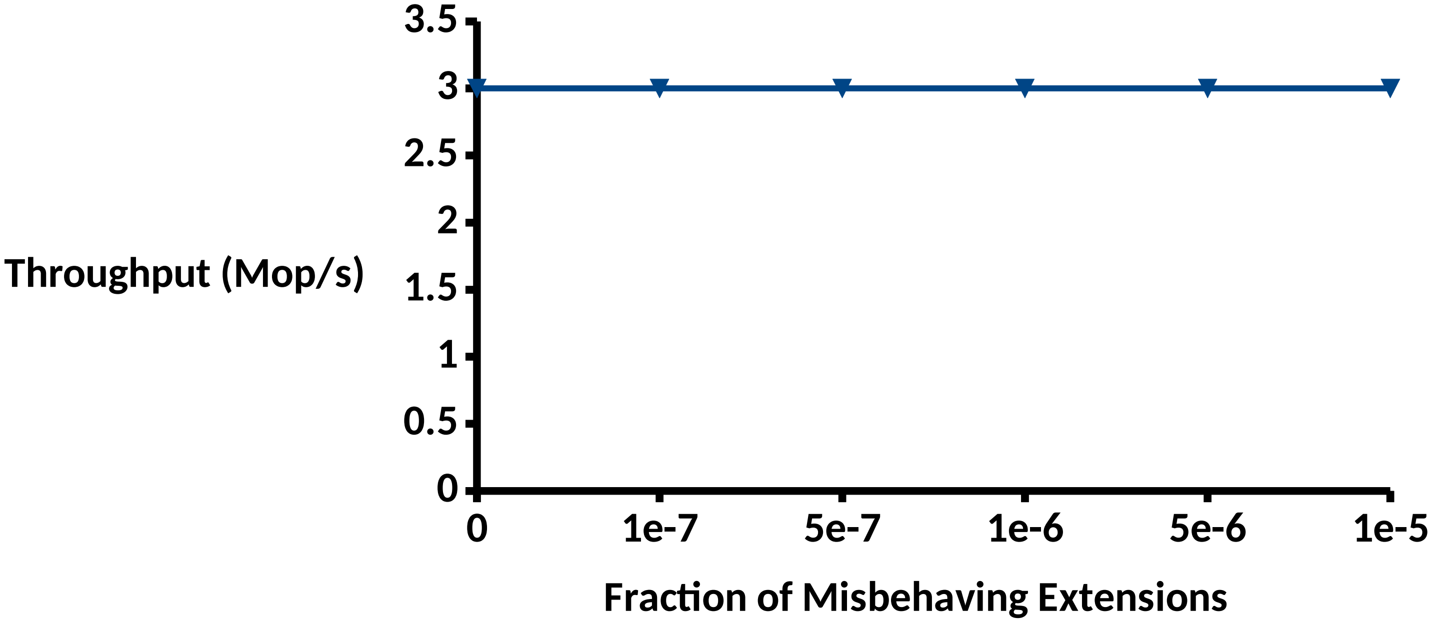
What are the benefits of the watchdog?

Setup:

- 1024 tenants
- Invoke small extension that reads one object

Performance With Misbehavior

Offered load = 3 Mop/s



Watchdog → Maintain performance during misbehavior

Performance With Misbehavior

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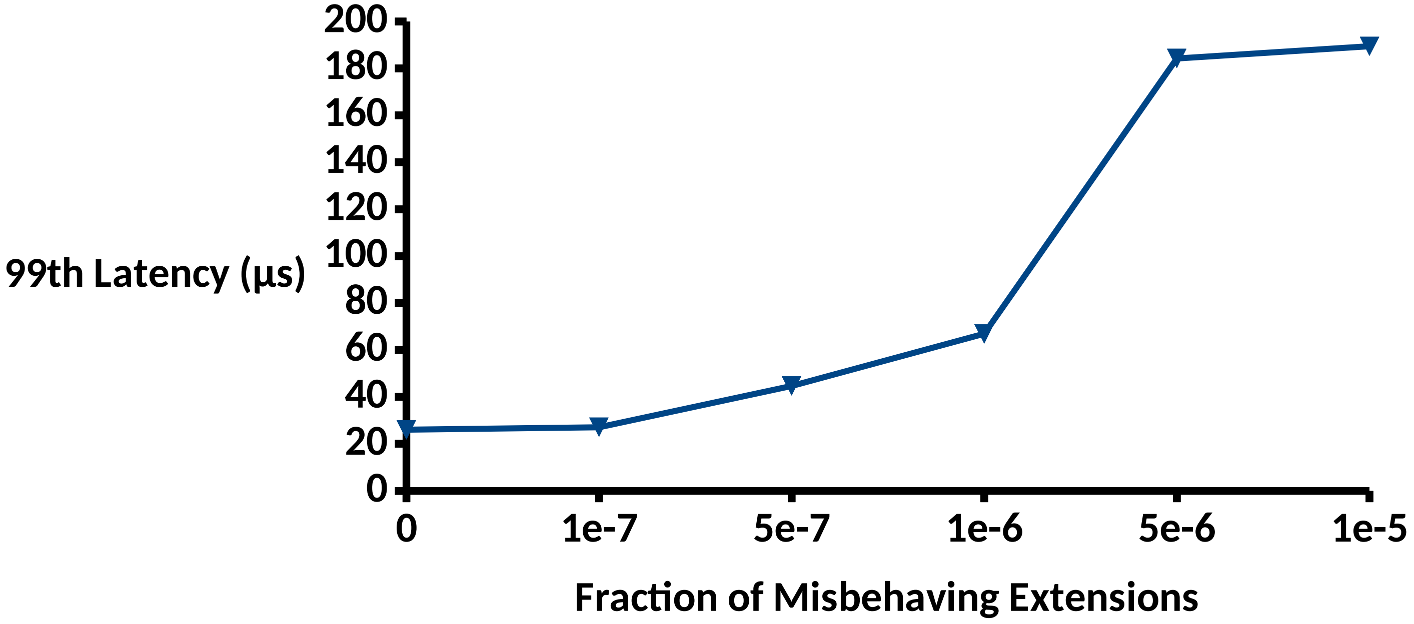
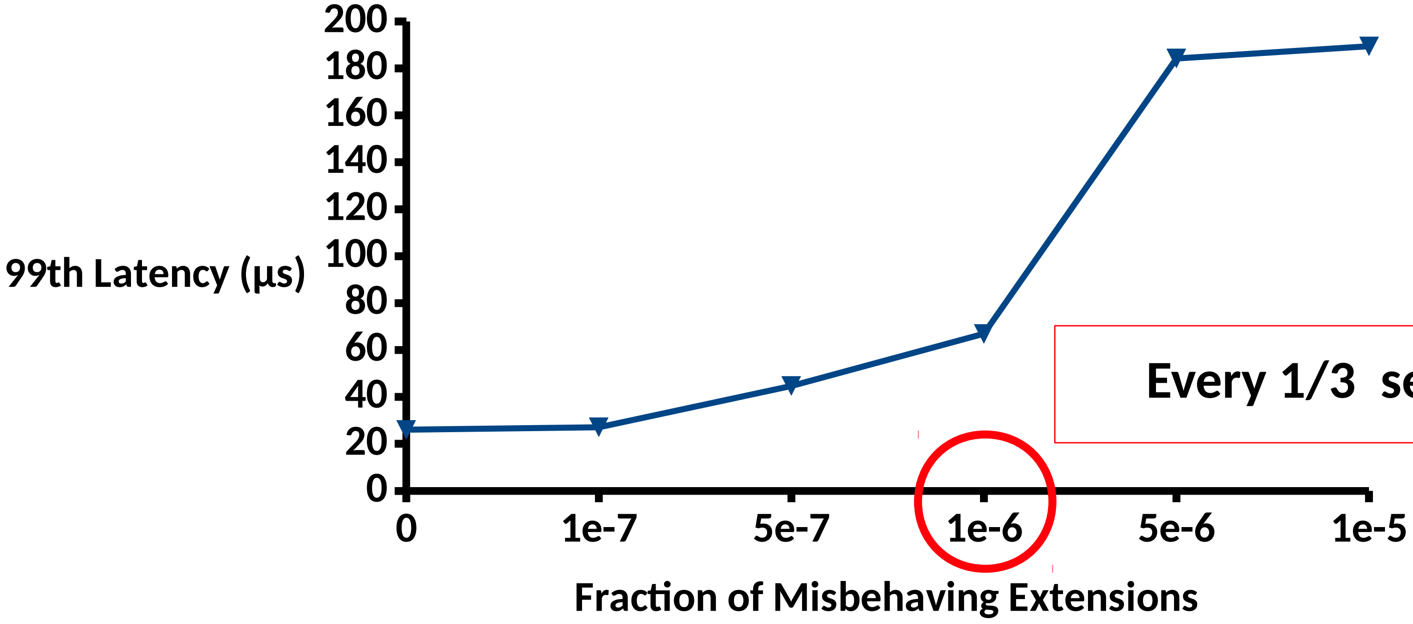


Performance With Misbehavior



Offered load = 3 Mop/s

Every 1/3 seconds

Will need tight admission control

Splinter: Design

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  - Avoid cross-core coordination while avoiding hotspots

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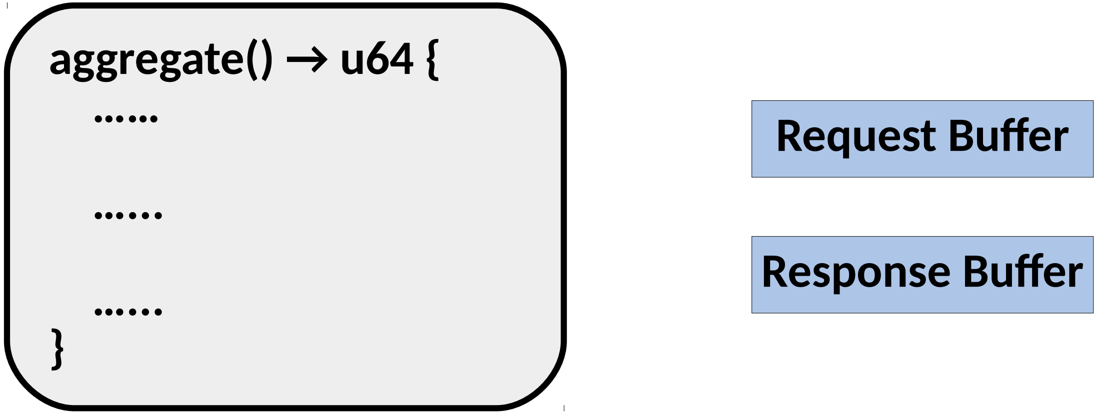
- **Low cost isolation**
  - No forced data copies across trust boundary

Splinter: Low Cost Isolation

Problem: **No forced data copies across trust boundary**

Solution: **Ensure buffers outlast reference lifetime**



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    ……
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Request Buffer

Response Buffer

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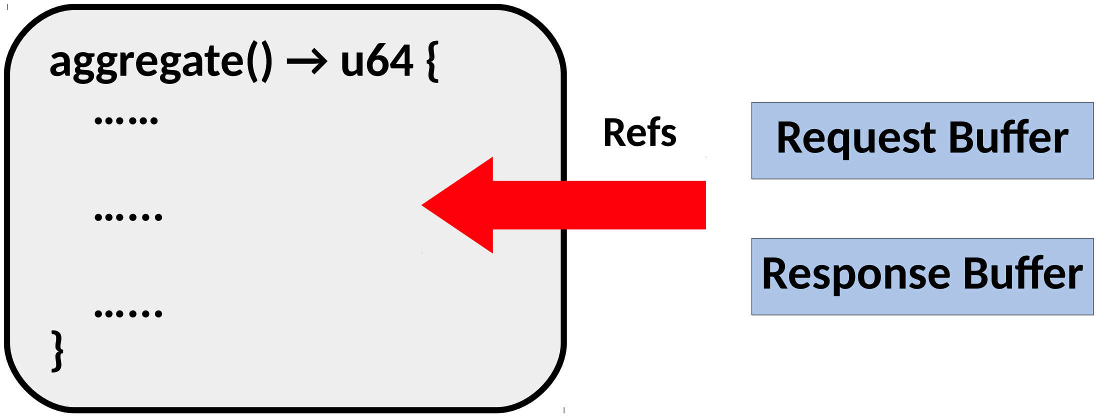

```
aggregate() → u64 {
    ……
    ……
    ……
}
```

Refs

Request Buffer

Response Buffer

Send references to extension

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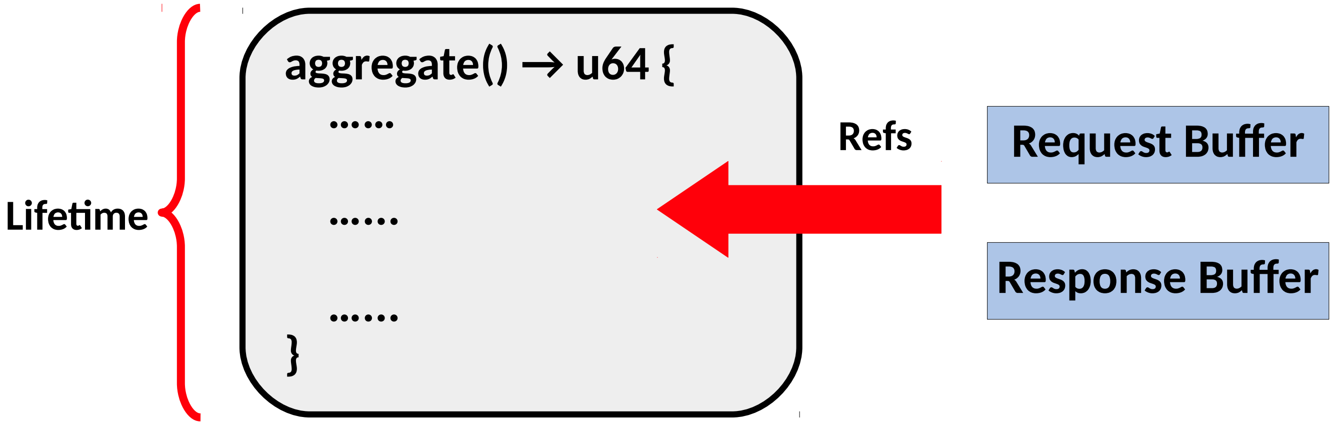

Statically ensure RPC buffers outlast lifetime

Splinter: Low Cost Isolation

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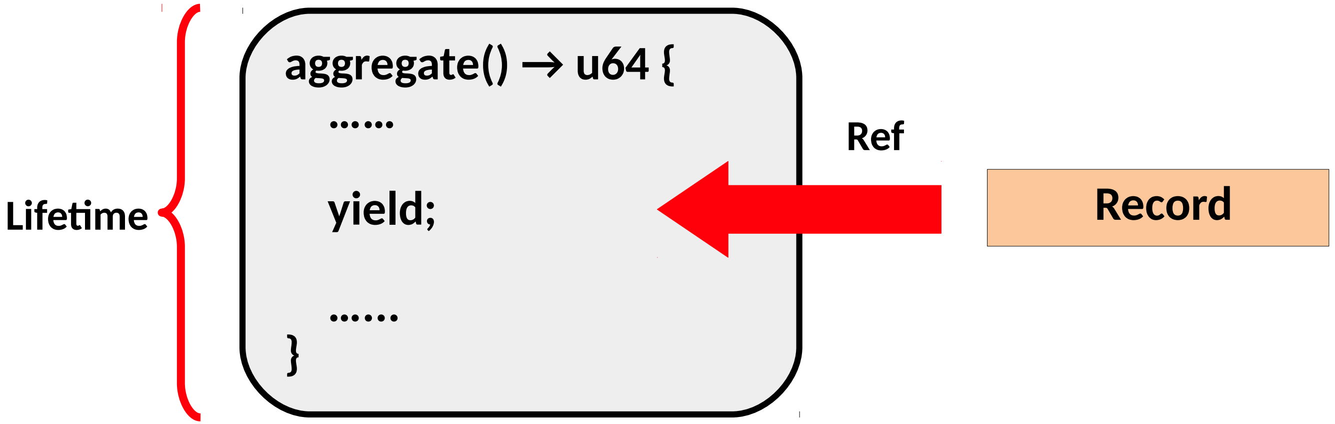
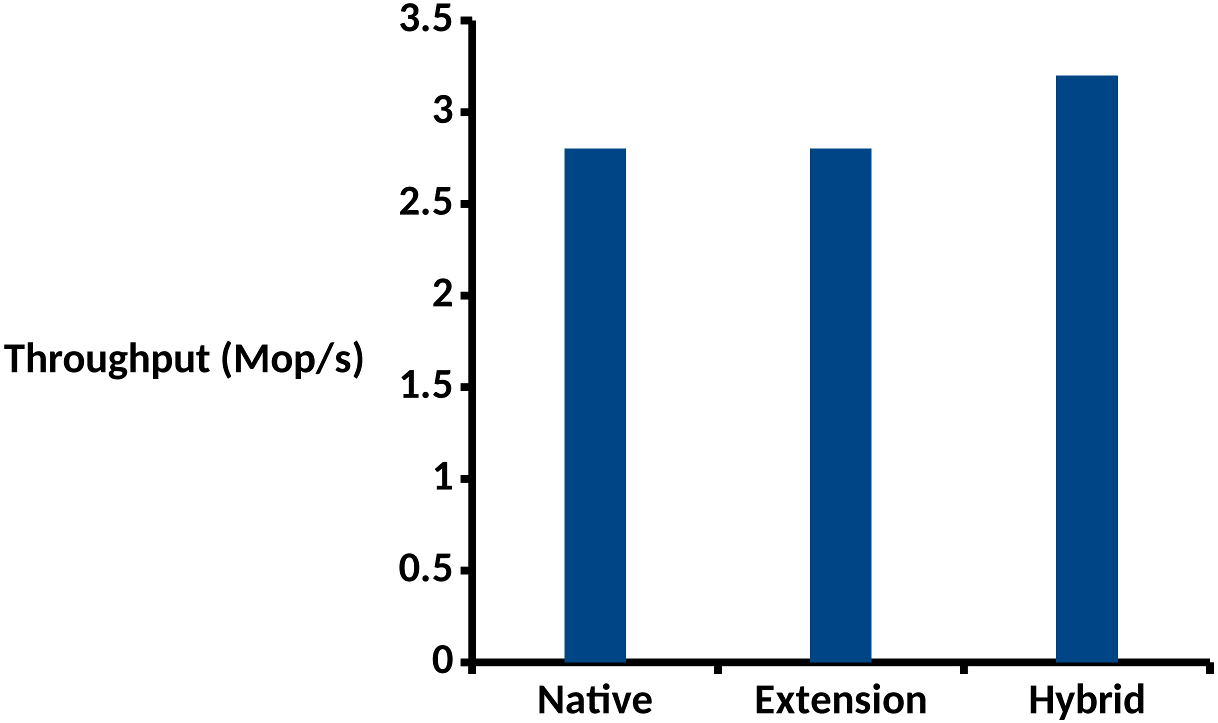


Statically ensure record stays stable across yields

Refer to paper

Pushing Facebook’s TAO To Splinter



Hybrid → get() for point ops, extension for dependencies

Best of both worlds!

Related Work

- **Language isolation for kernels – SPIN, Singularity**
  - Low runtime overheads, zero-copy interface

- **Using Rust for memory safety – NetBricks, Tock**
  - Small set of static functions; does not target massive tenant densities

- **Software fault isolation**
  - Requires data copies, page table manipulation

- **Pushing extensions/compute to storage – Malacology, Redis etc**
  - Extensions are usually trusted, SQL not very good for ADTs

Conclusion

- **Kernel-bypass** key-value stores offer **< 10µs** latency, **> Mops/s** throughput
  - Fast because they're just dumb?

- **Problem:** Leverage performance → **share** between tenants
- **Problem:** Apps require rich data models. Ex: Facebook's TAO
  - Implement using gets & puts? → **Data movement, client stalls**
  - Push code to key-value store? → **Isolation costs limit density**

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