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SnapBPF: Exploiting eBPF for Serverless Snapshot Prefetching

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In a nutshell

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***FaaS Cold Start Overhead**:*
→ Sandbox creation dominates function latency
→ Exacerbated with microVM sandboxing

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State-of-the-art (REAP, FaaSnap, Faast):
Capture and ***prefetch*** the function ***working set***
→ Minimize snapshot loading overhead
→ Implemented in userspace
→ *Storage and memory duplication*

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***FaaS Cold Start Overhead**:*
→ Sandbox creation dominates function latency
→ Exacerbated with microVM sandboxing

microVM ***snapshotting:***
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Our Proposal: ***SnapBPF***
→ ***eBPF*** capture and prefetch
→ Implemented in *kernelspace*
→ No working set serialization
→ *Working set deduplication*
→ PV free page filtering

Outline

→ FaaS Snapshotting

→ Working Set Prefetching

→ SnapBPF

i. eBPF capture and prefetch

ii. PV free page filtering

→ Evaluation

→ Conclusion

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Sandboxing serverless functions

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Physical Server

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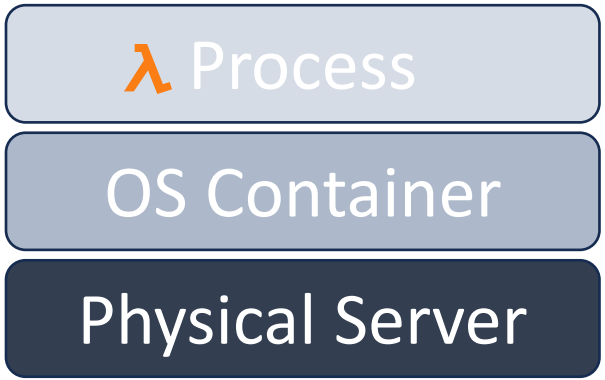

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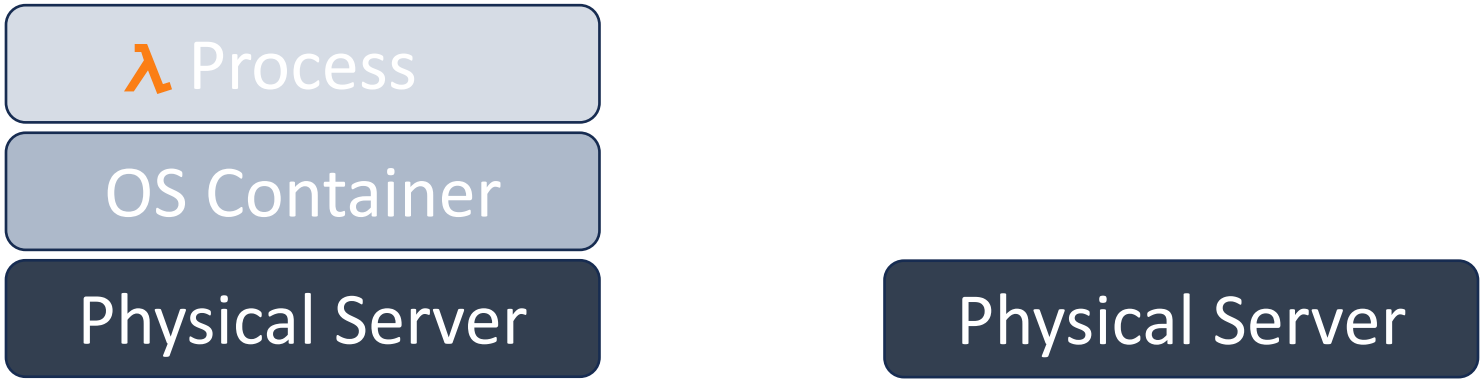

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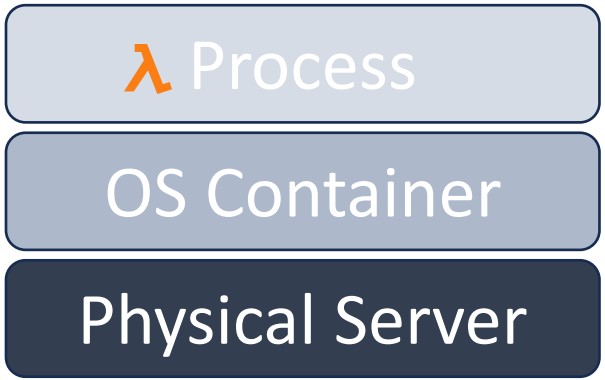

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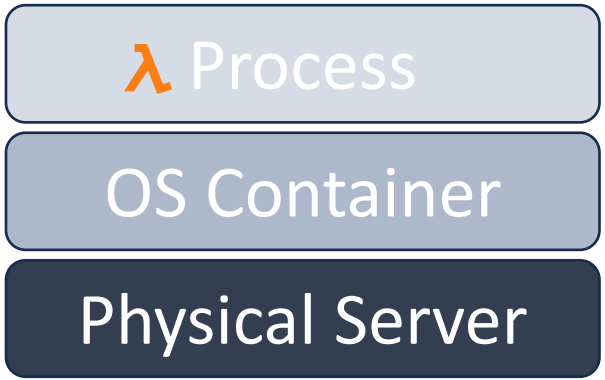

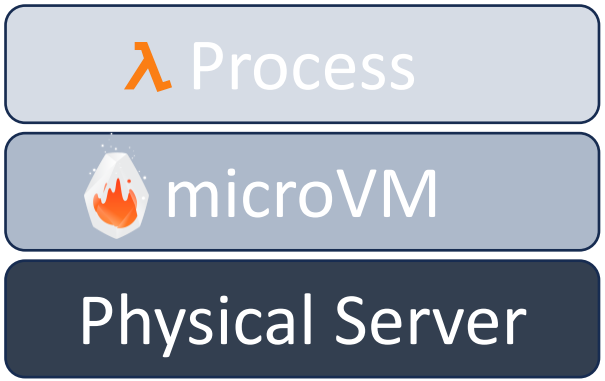

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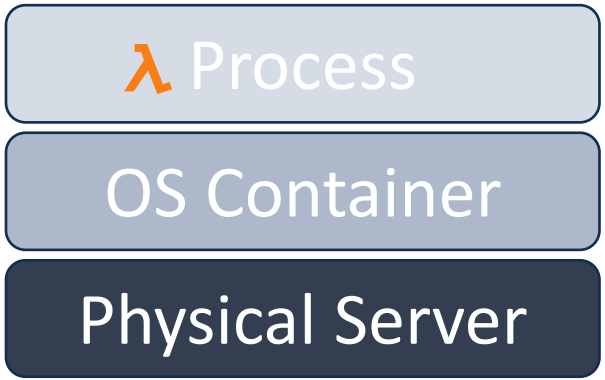

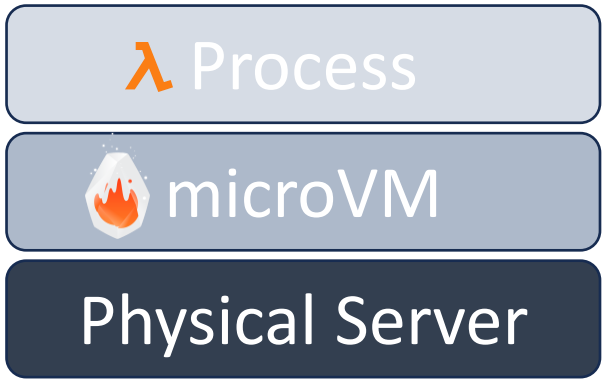

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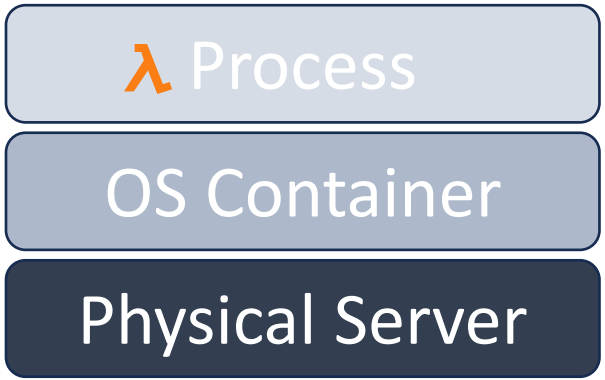

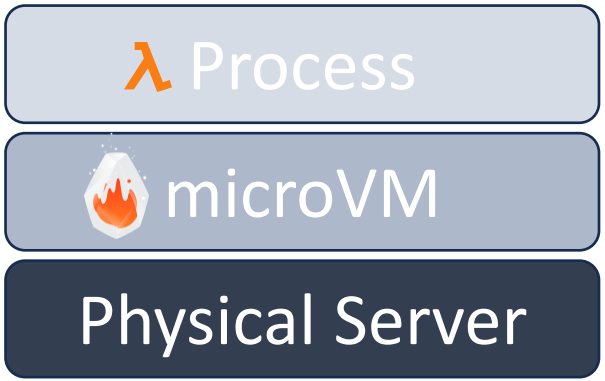

Isolation Performance

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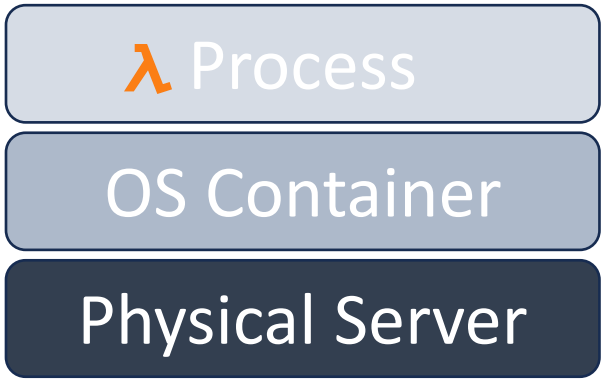

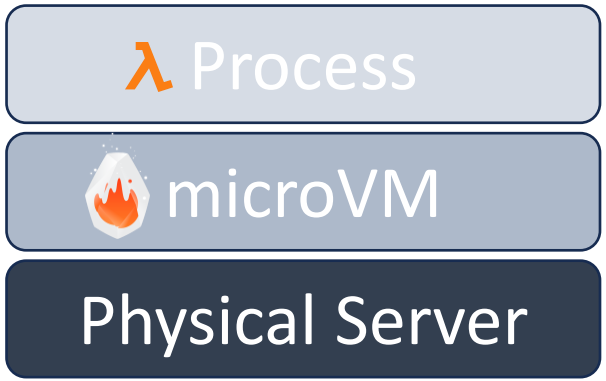

Isolation Performance

Isolation Guarantees

The cold-start pain

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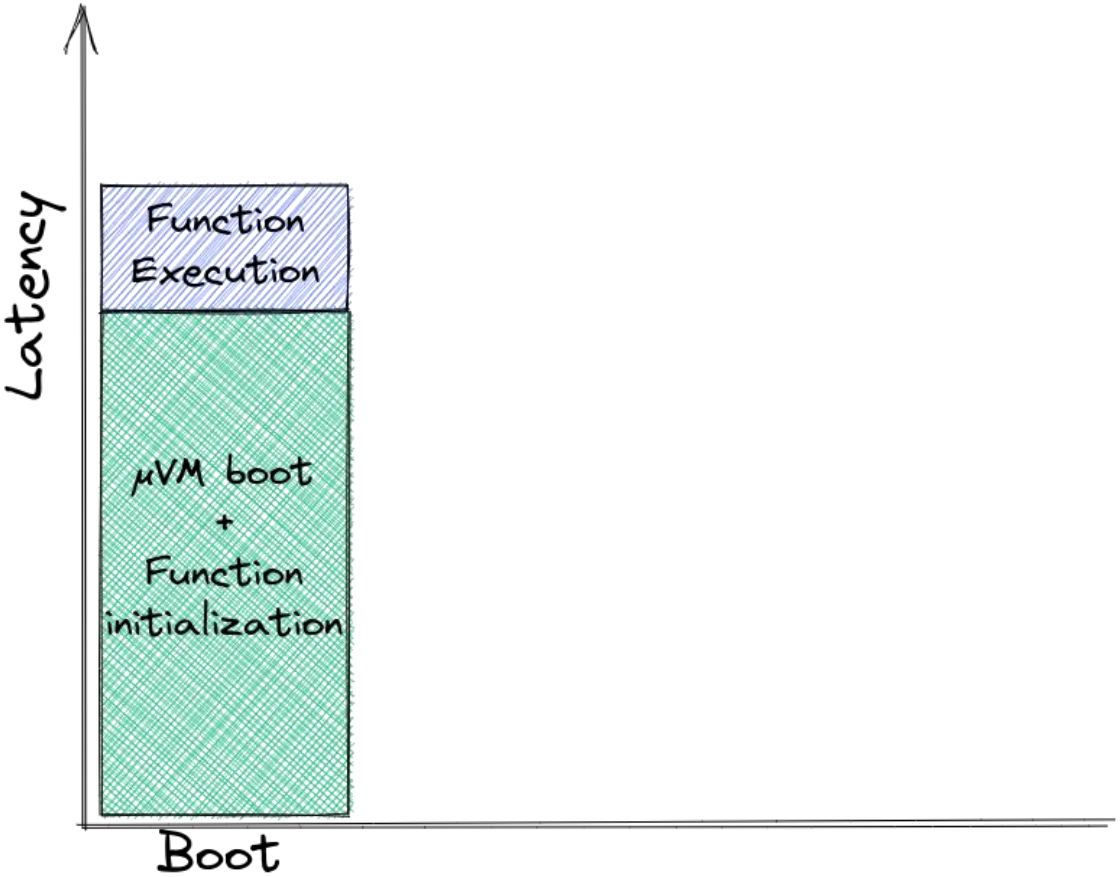

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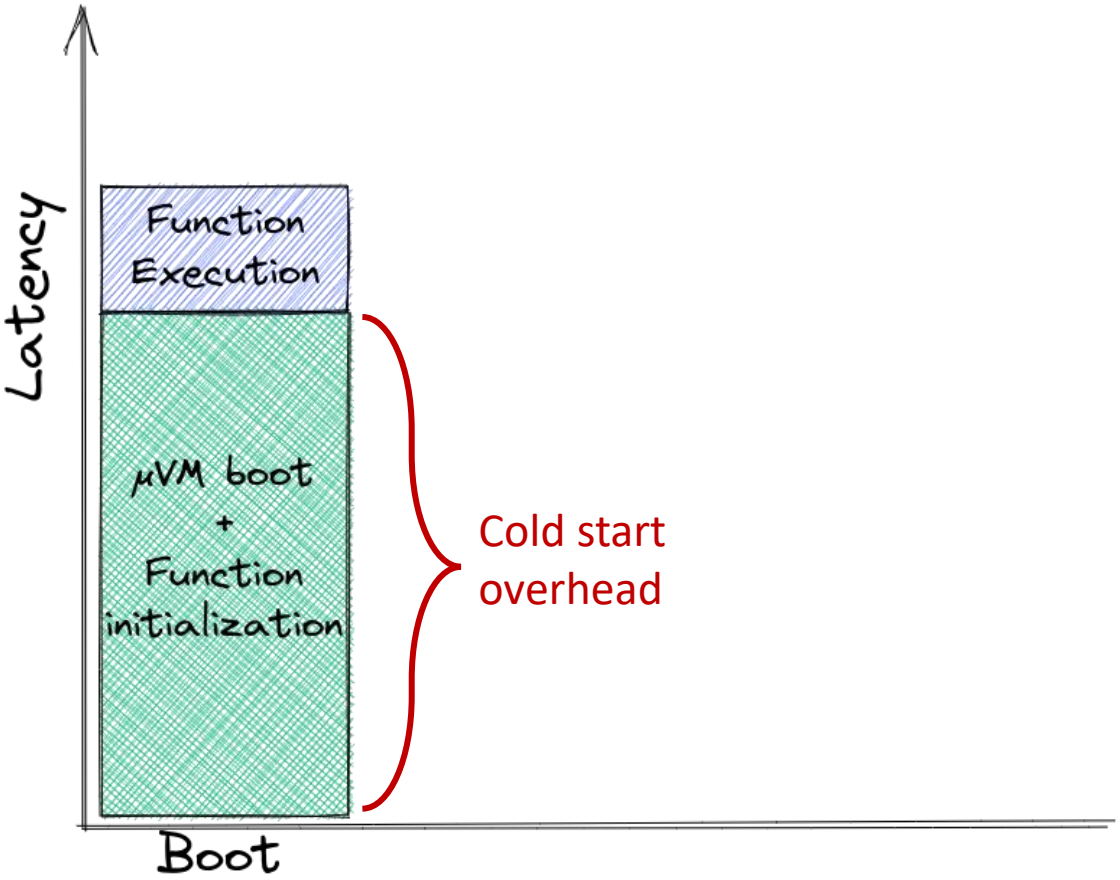

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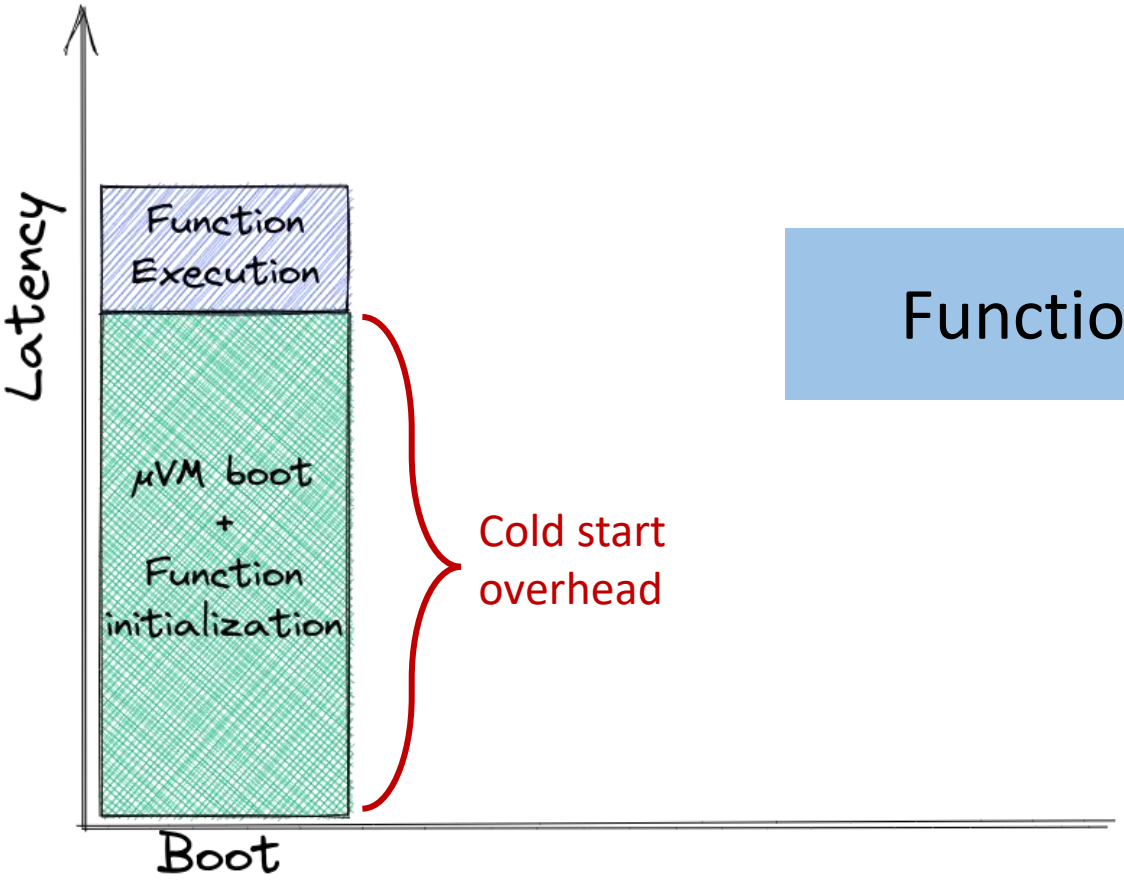

Functions are short-lived

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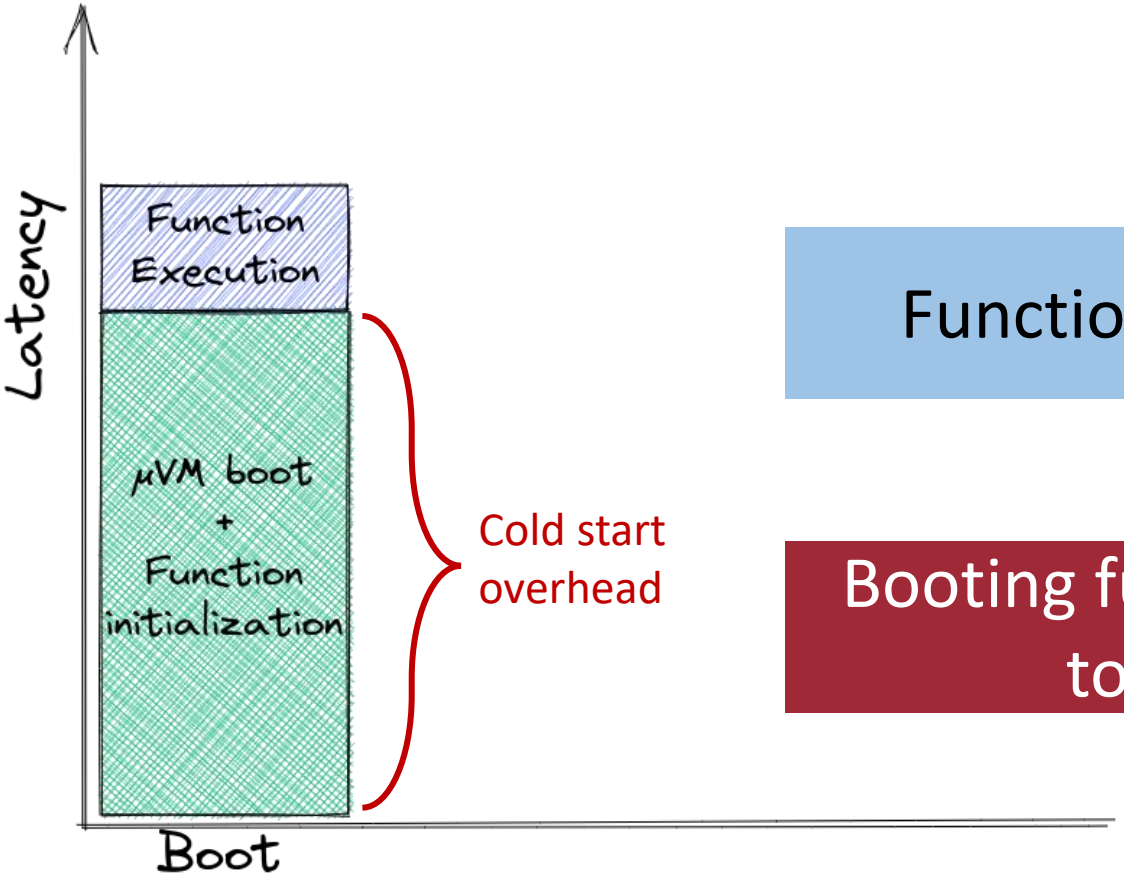
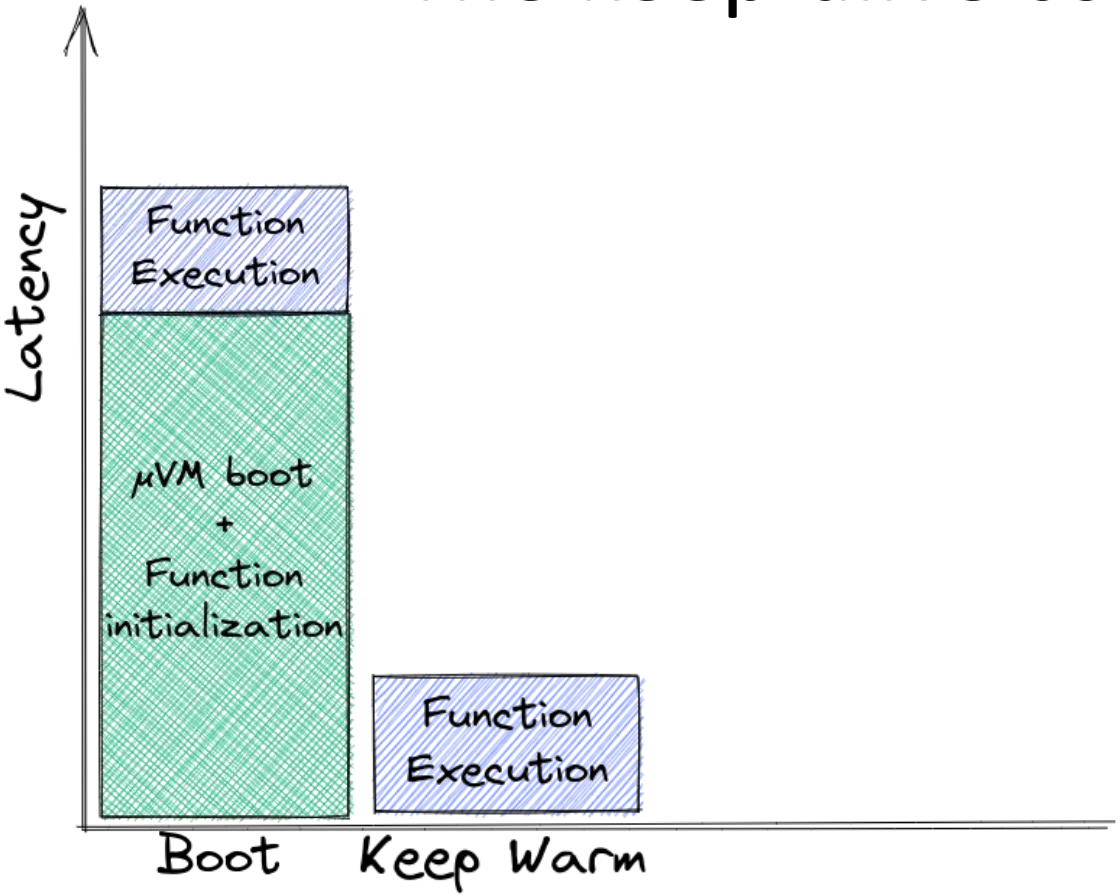


Functions are short-lived

Booting function instances is too expensive

The keep-alive conundrum



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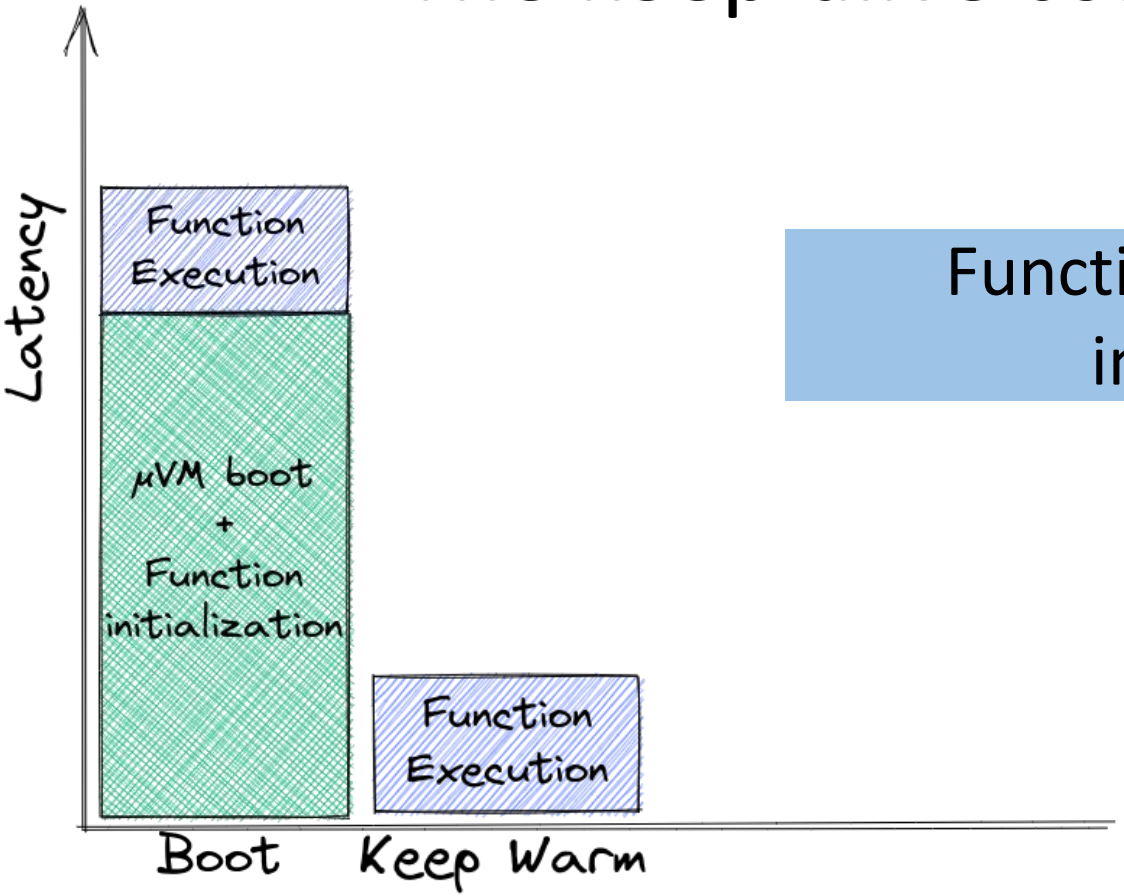

Functions are invoked infrequently

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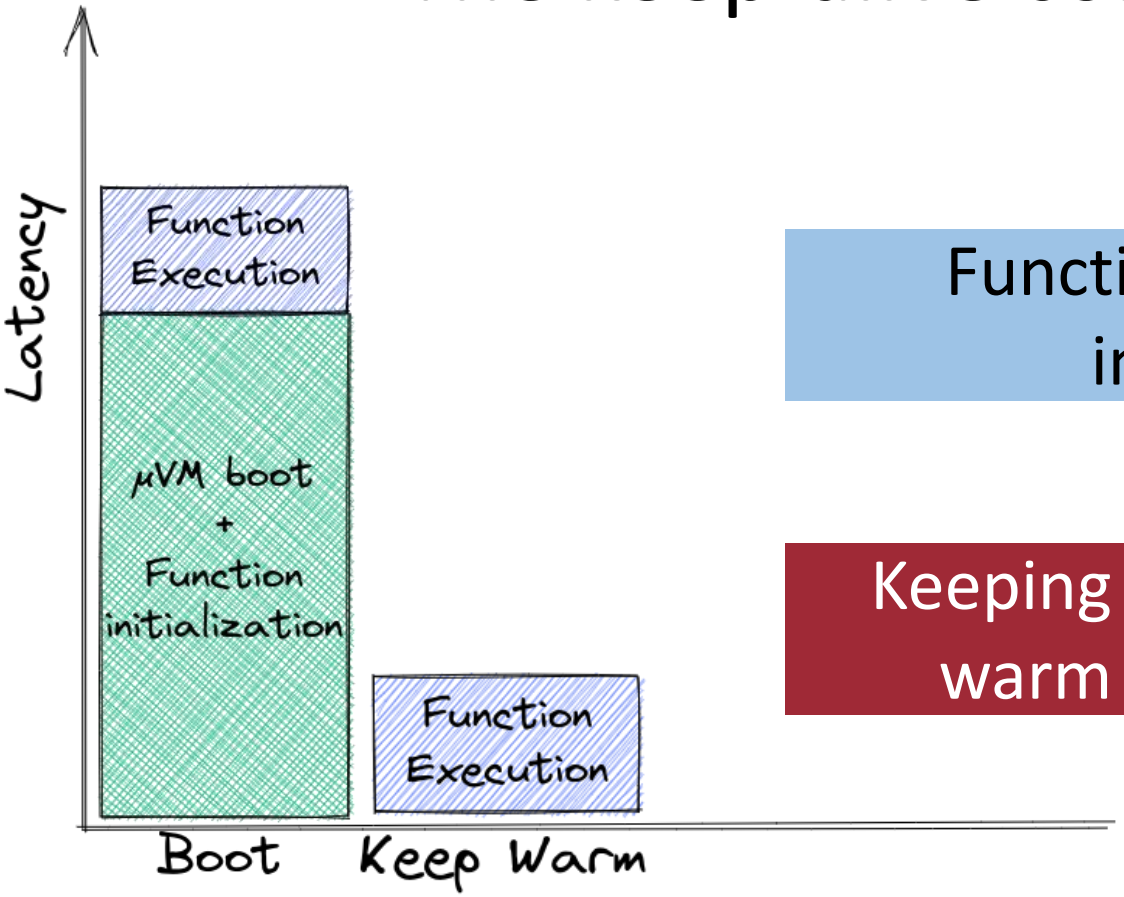

Functions are invoked infrequently

Keeping function instances warm is too expensive

Snapshots to the rescue!

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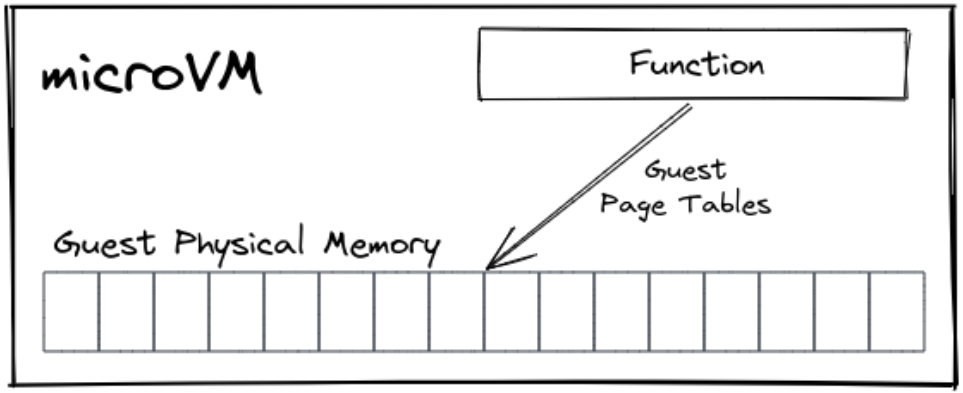

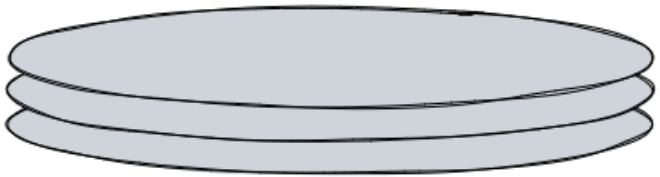

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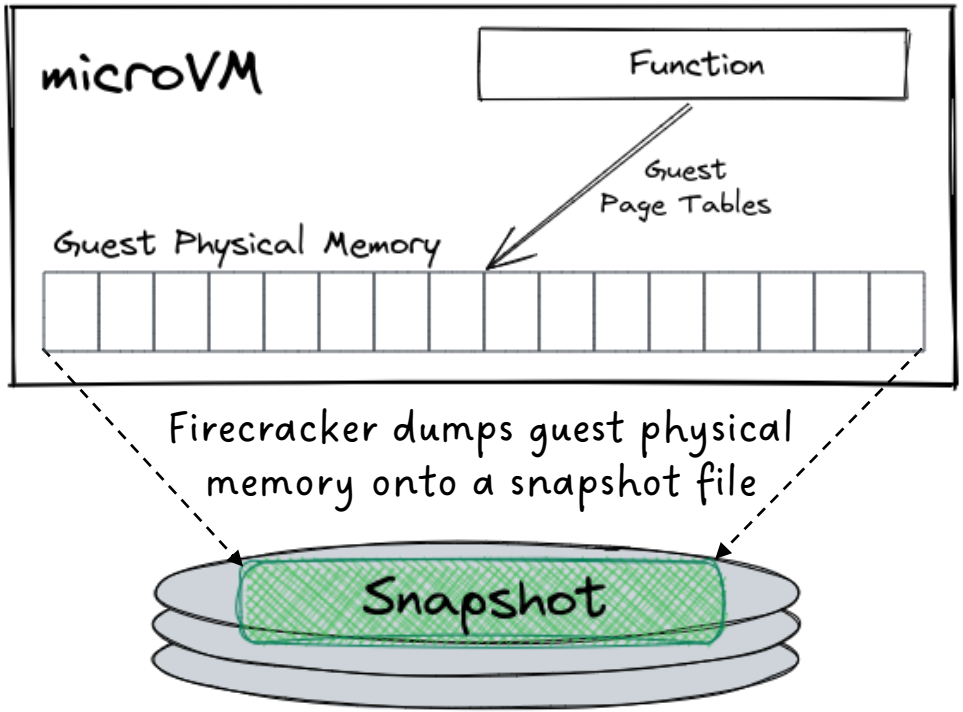

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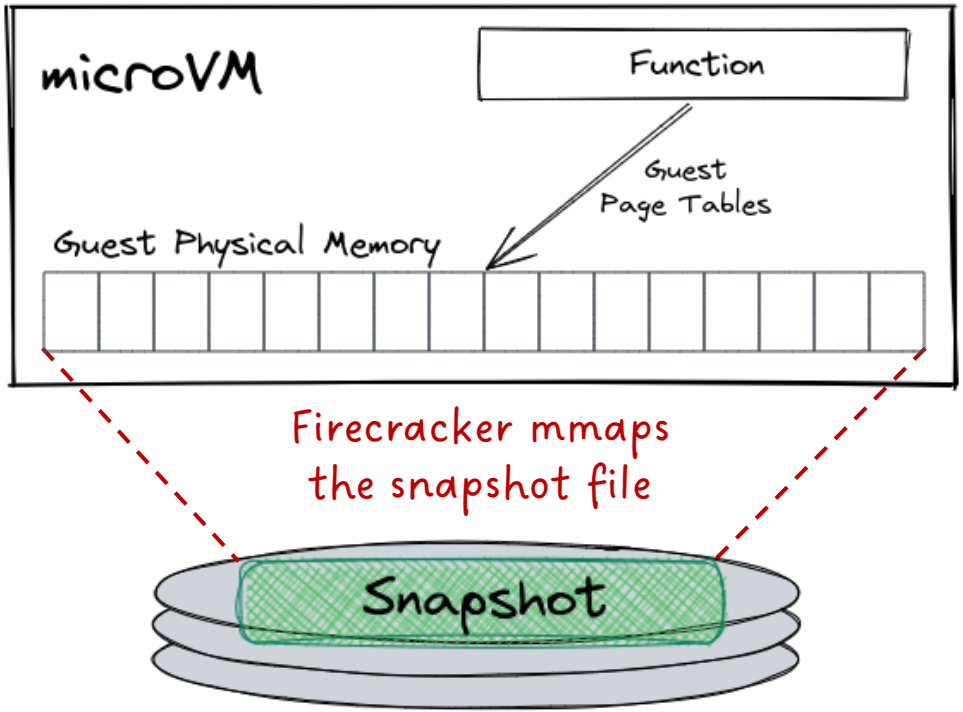

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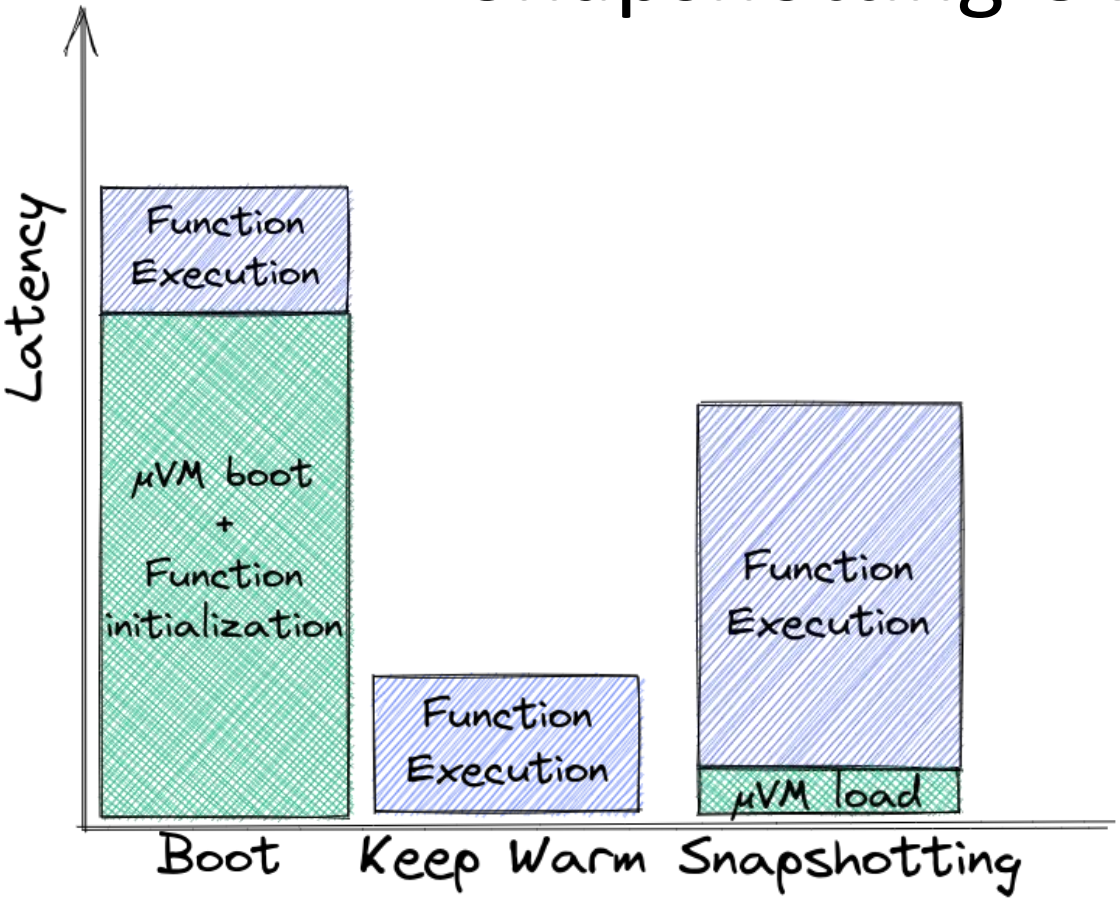

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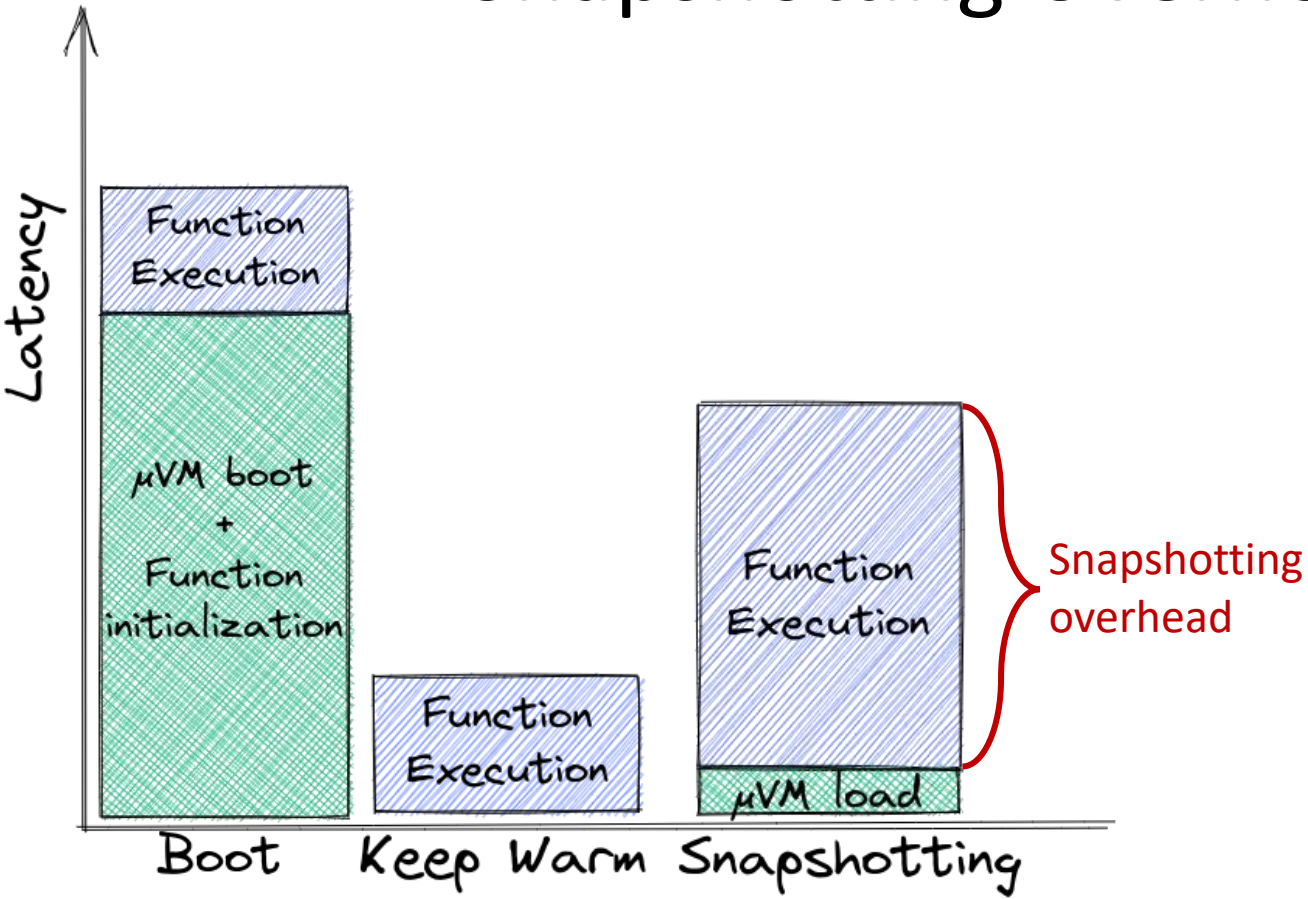

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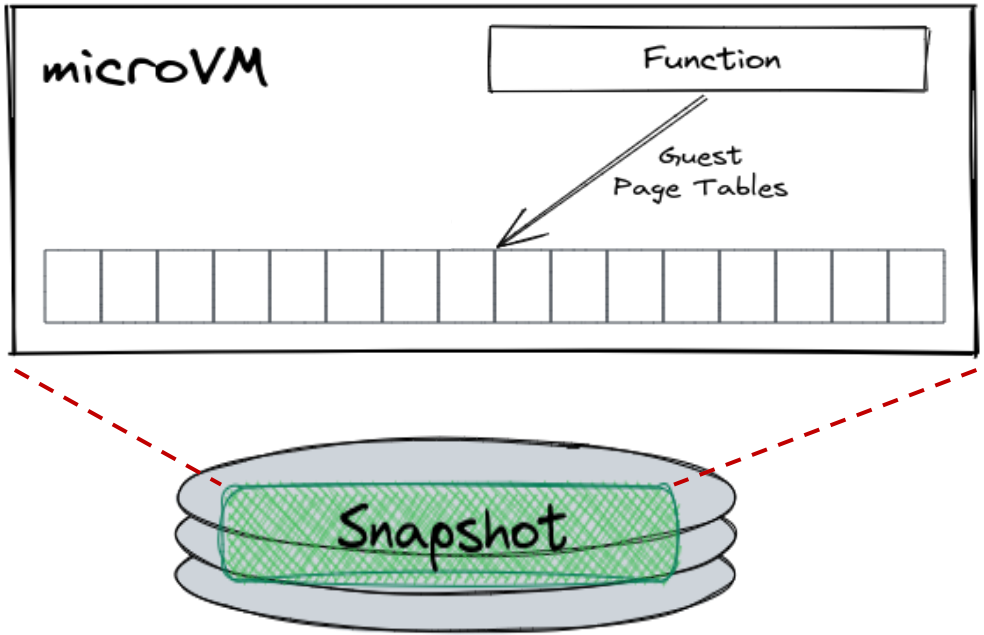

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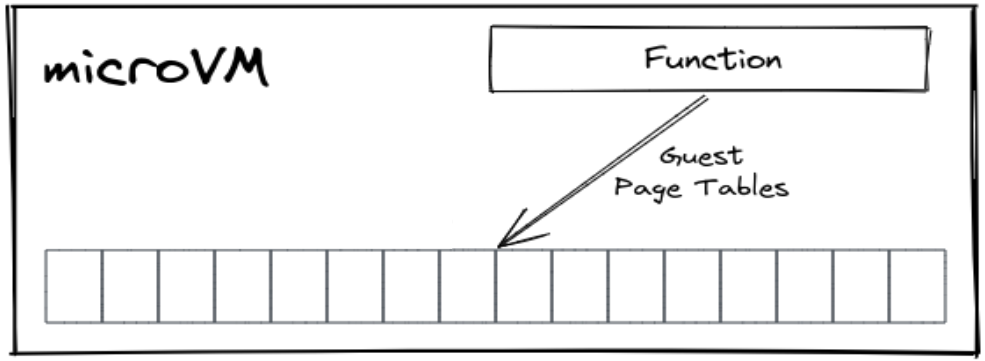

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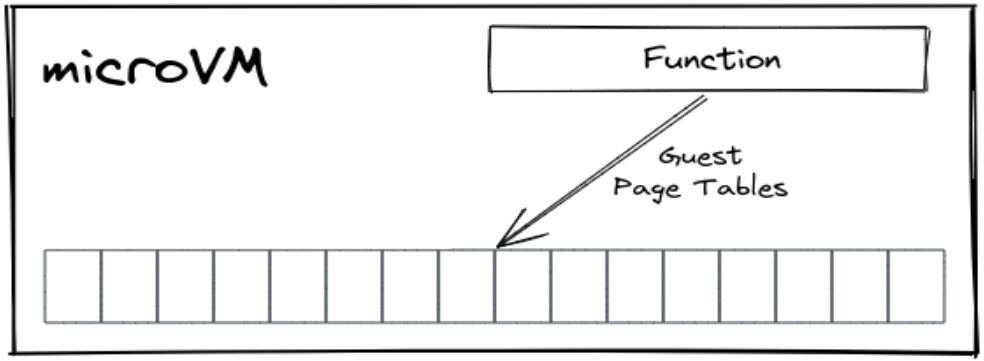

OS Page Cache

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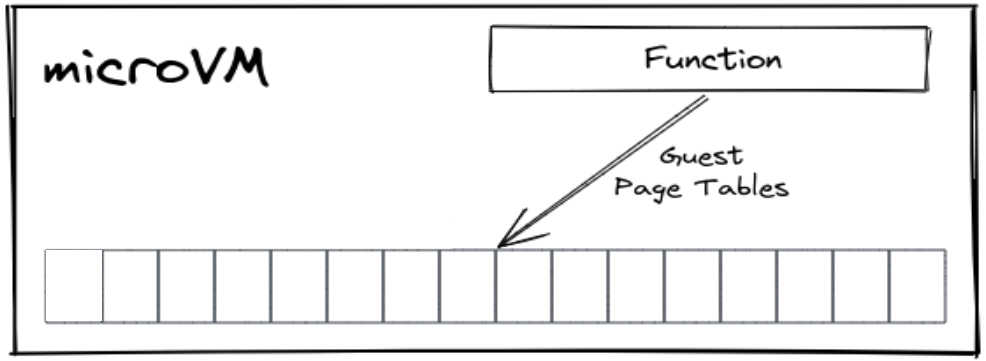

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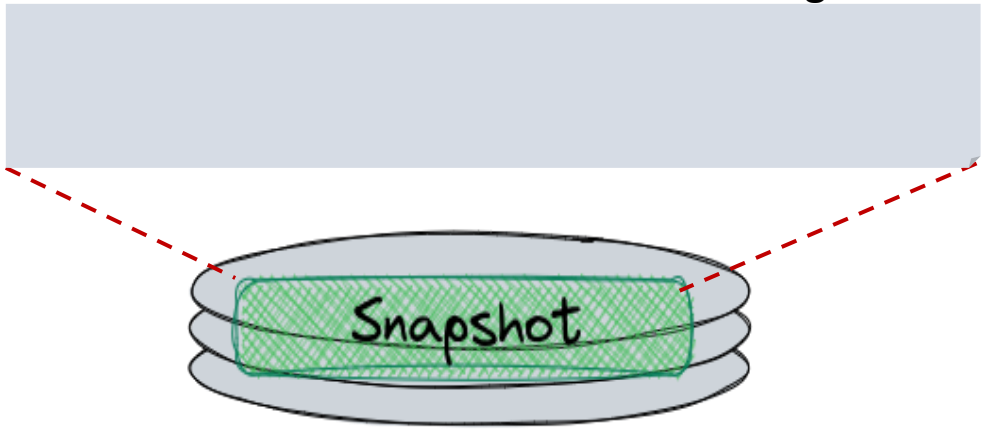

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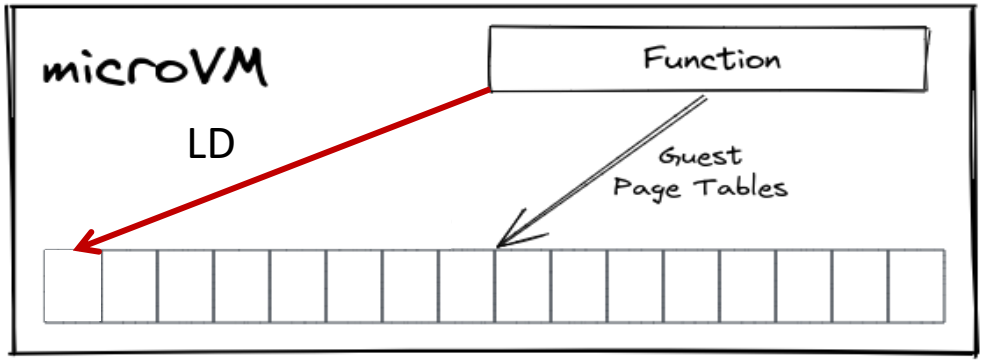

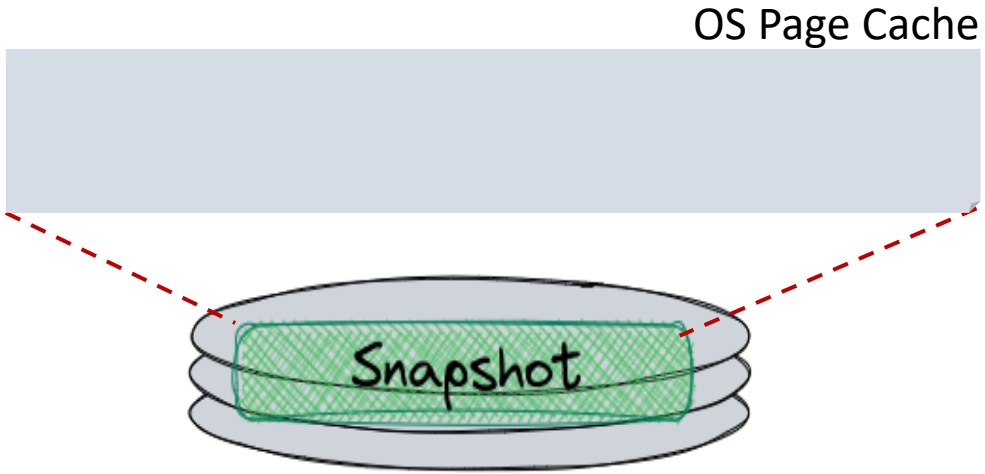

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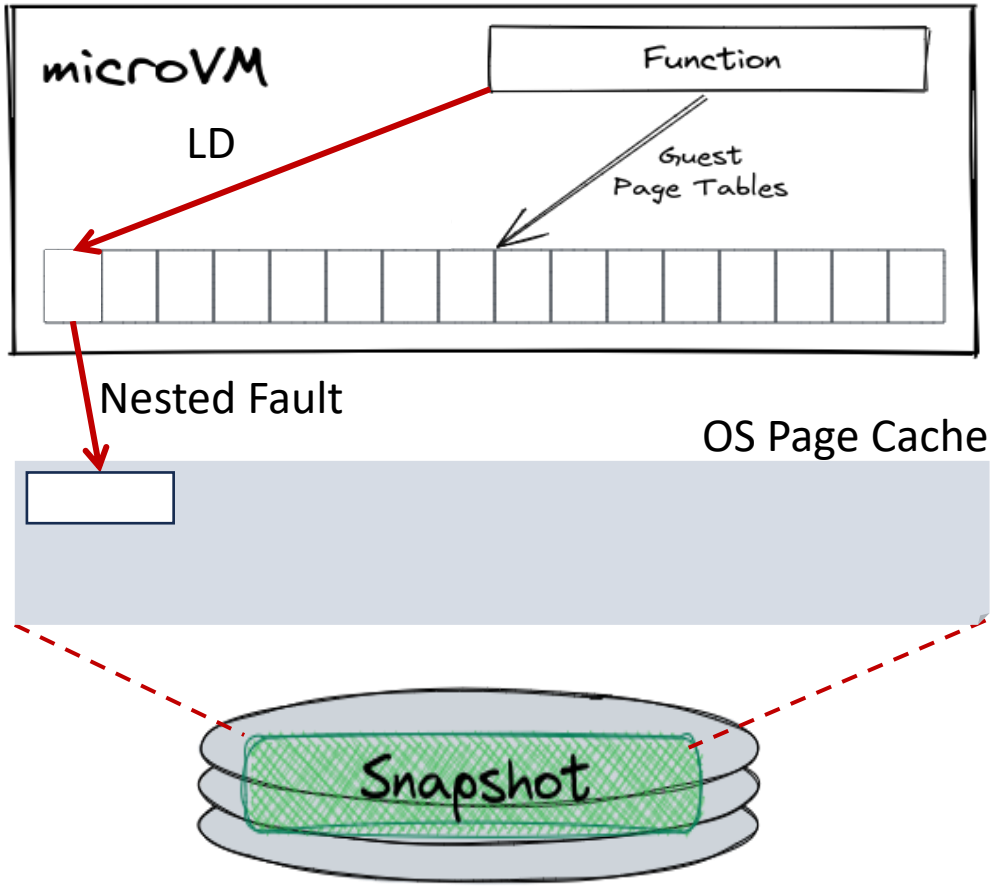

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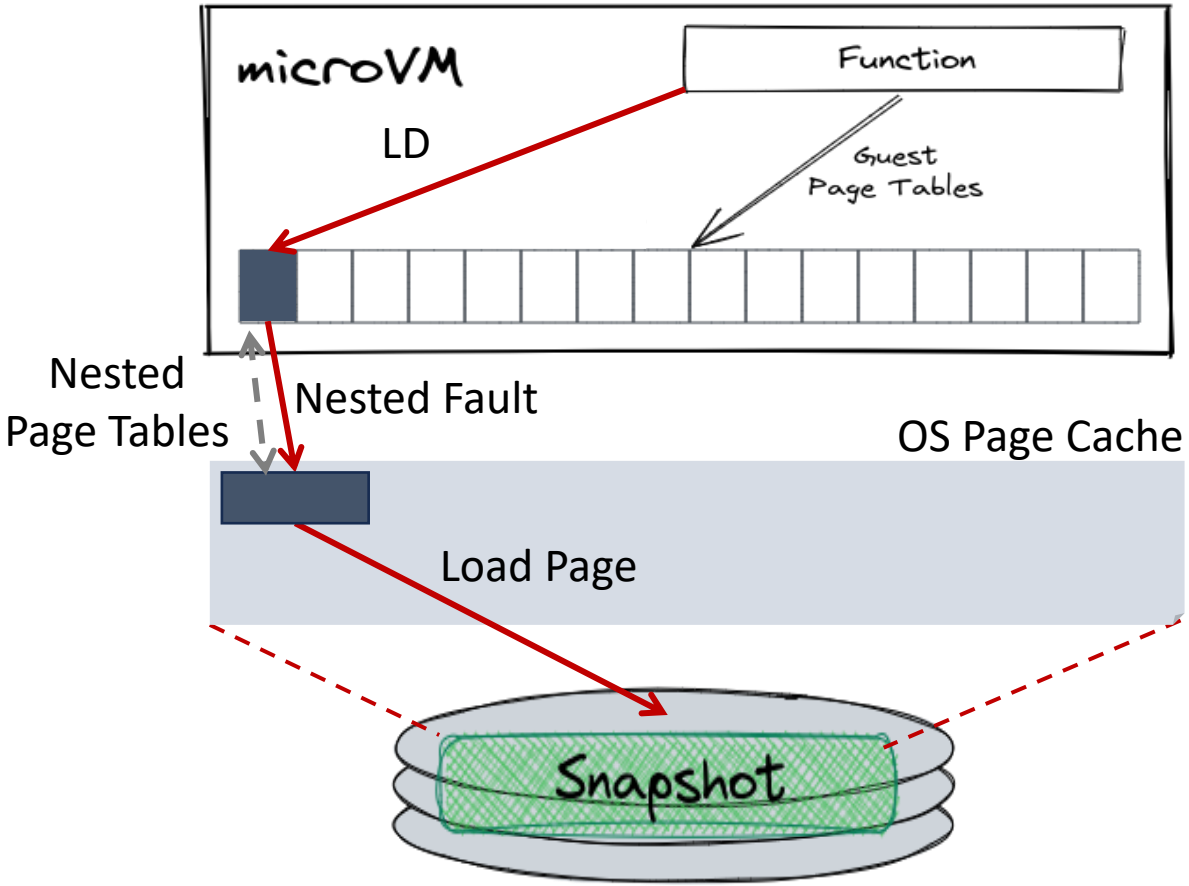

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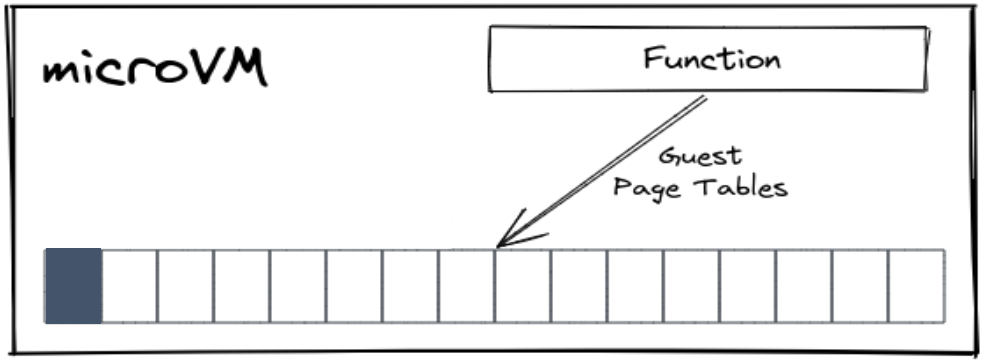

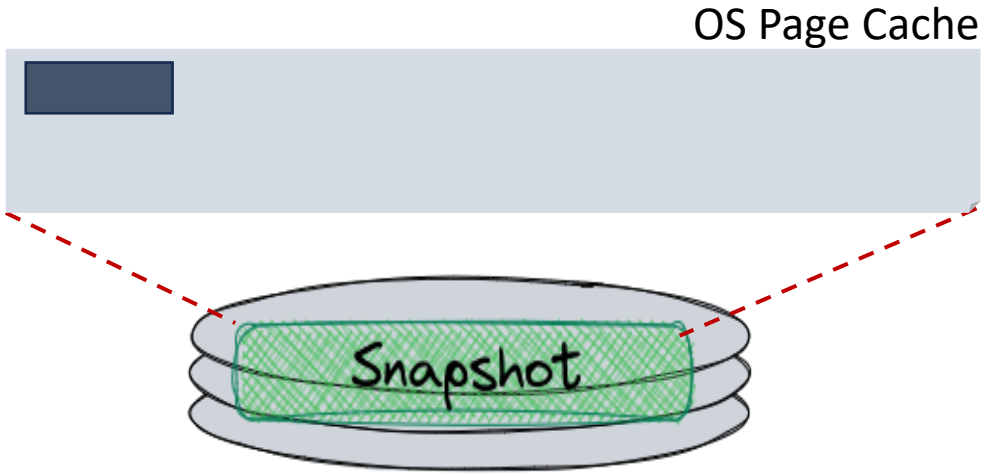

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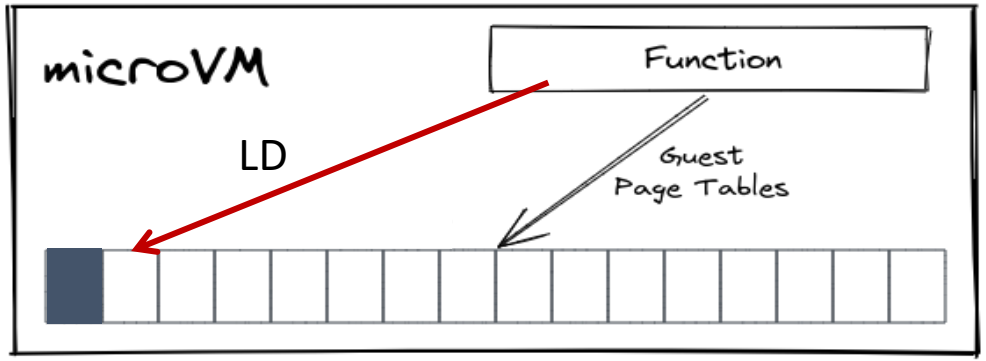

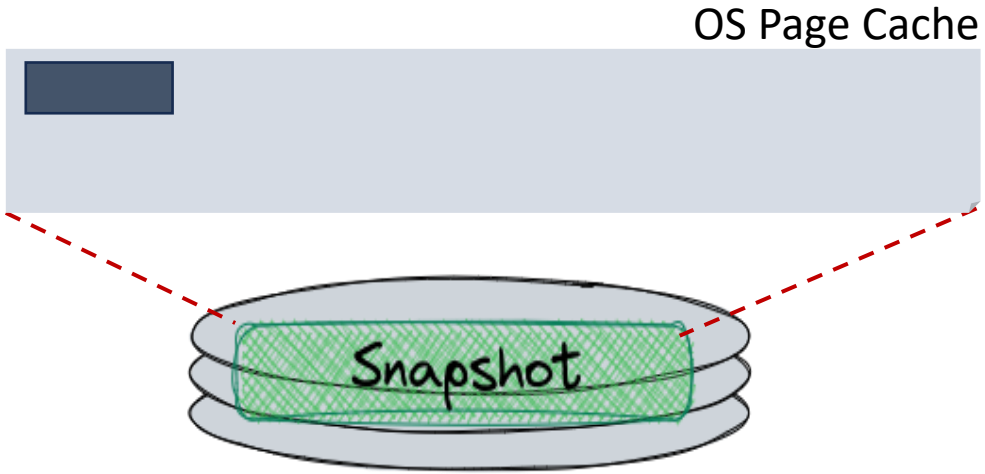

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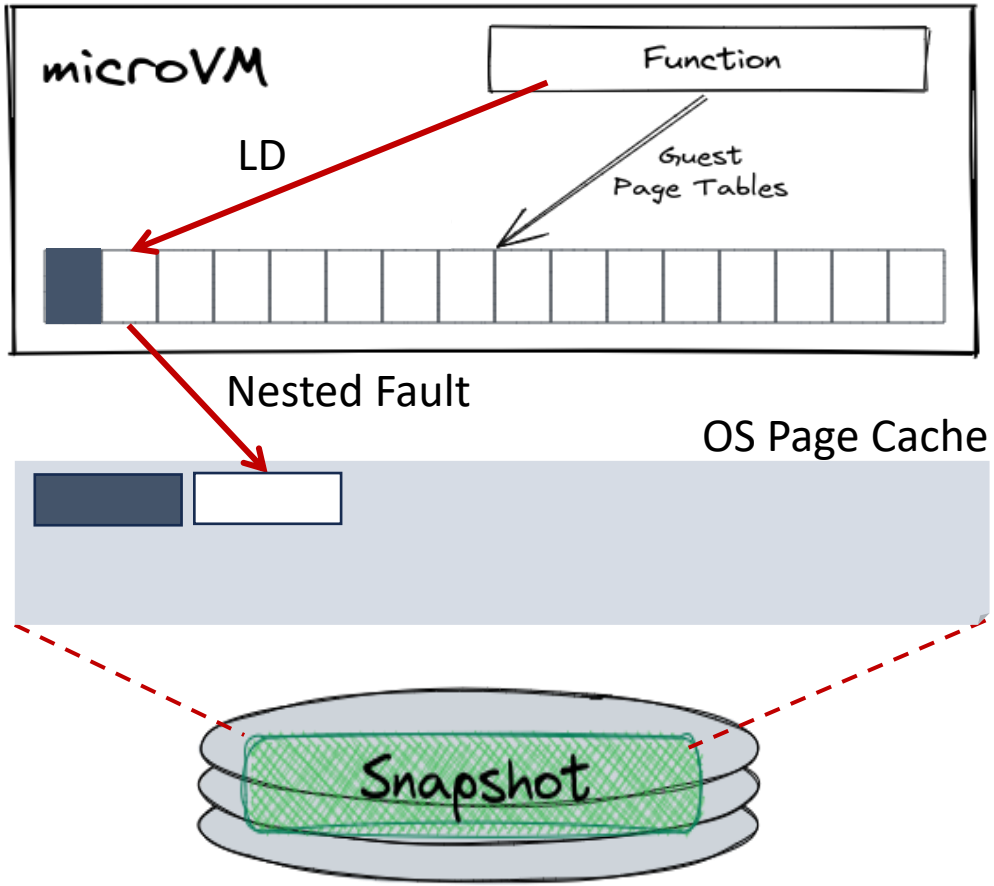

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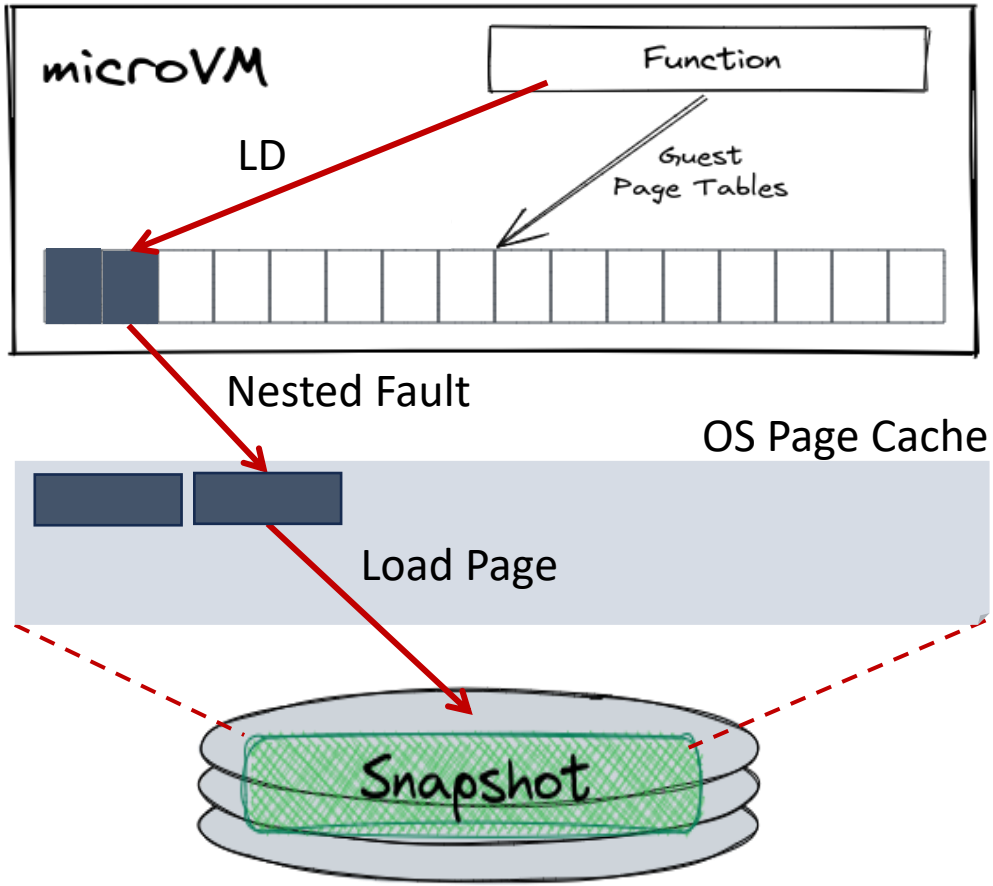

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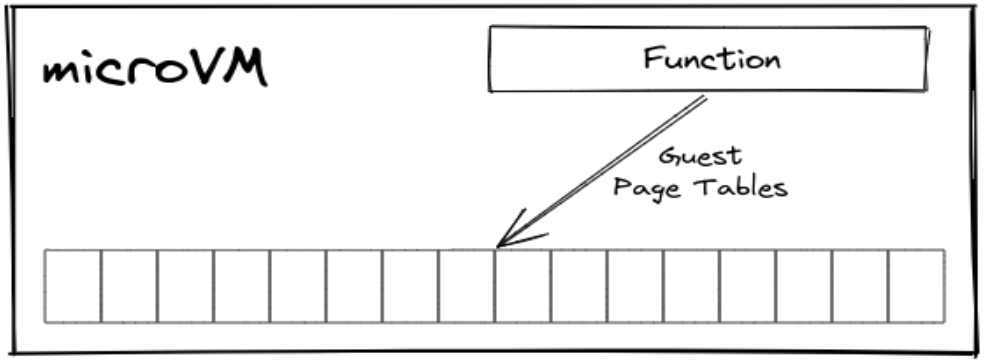

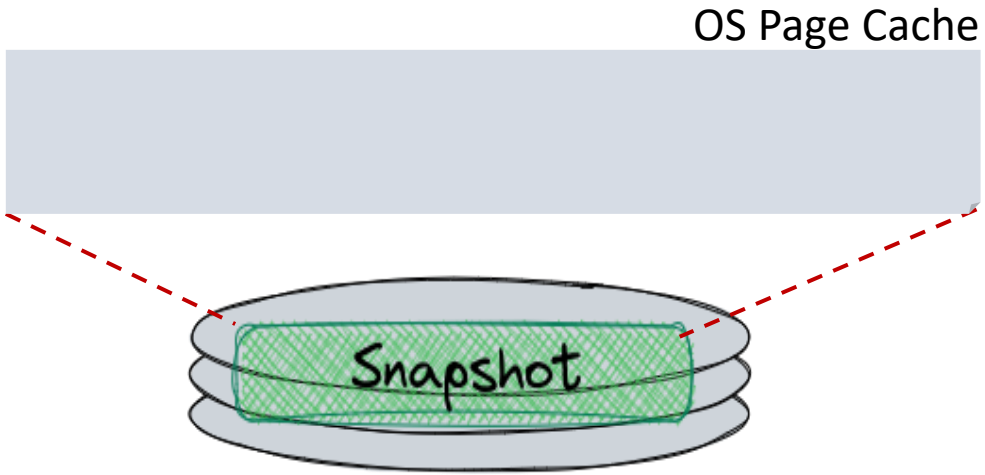

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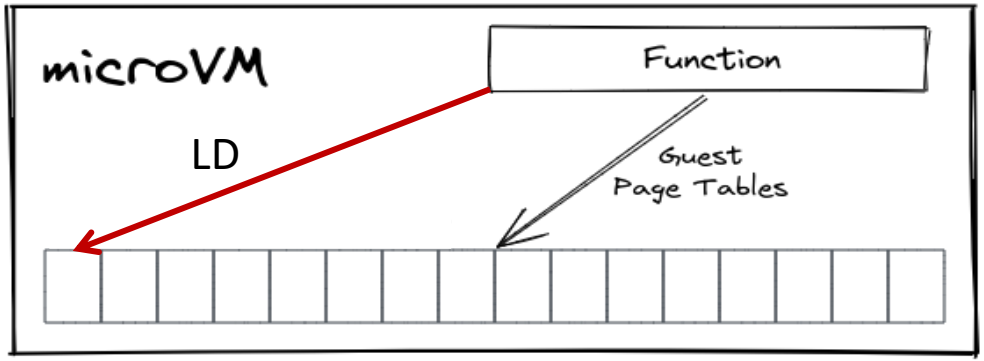

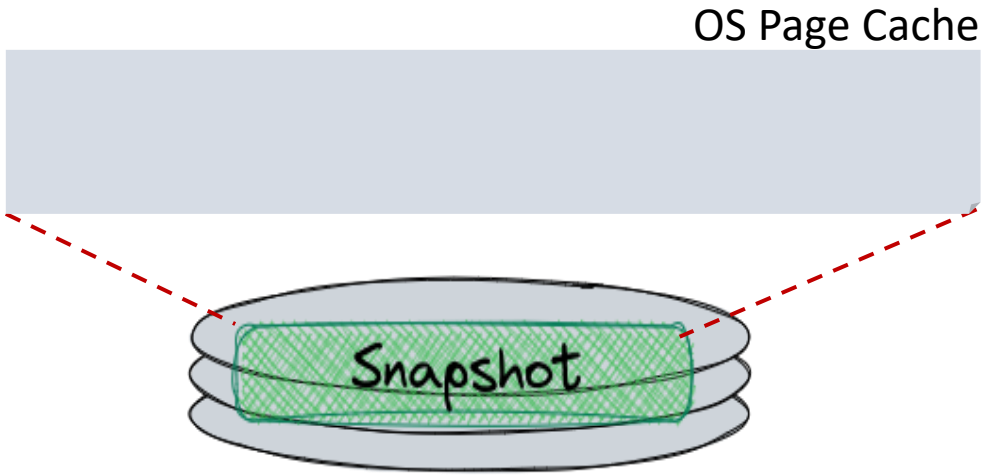

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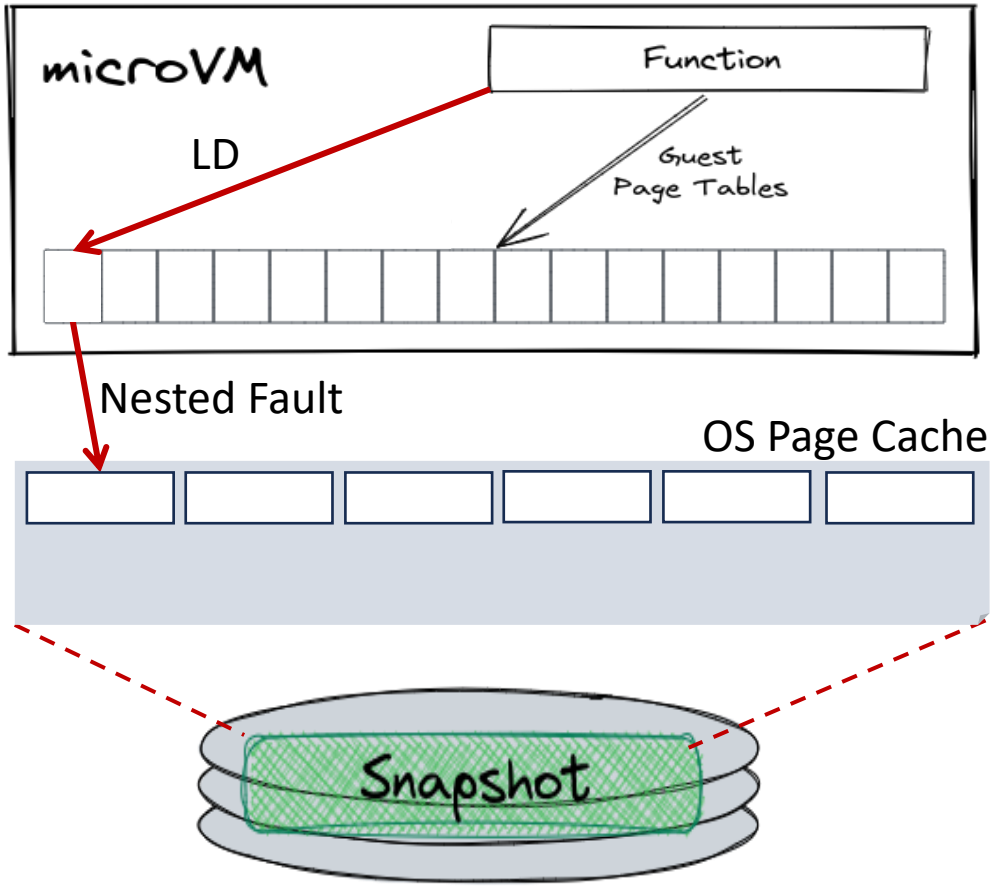

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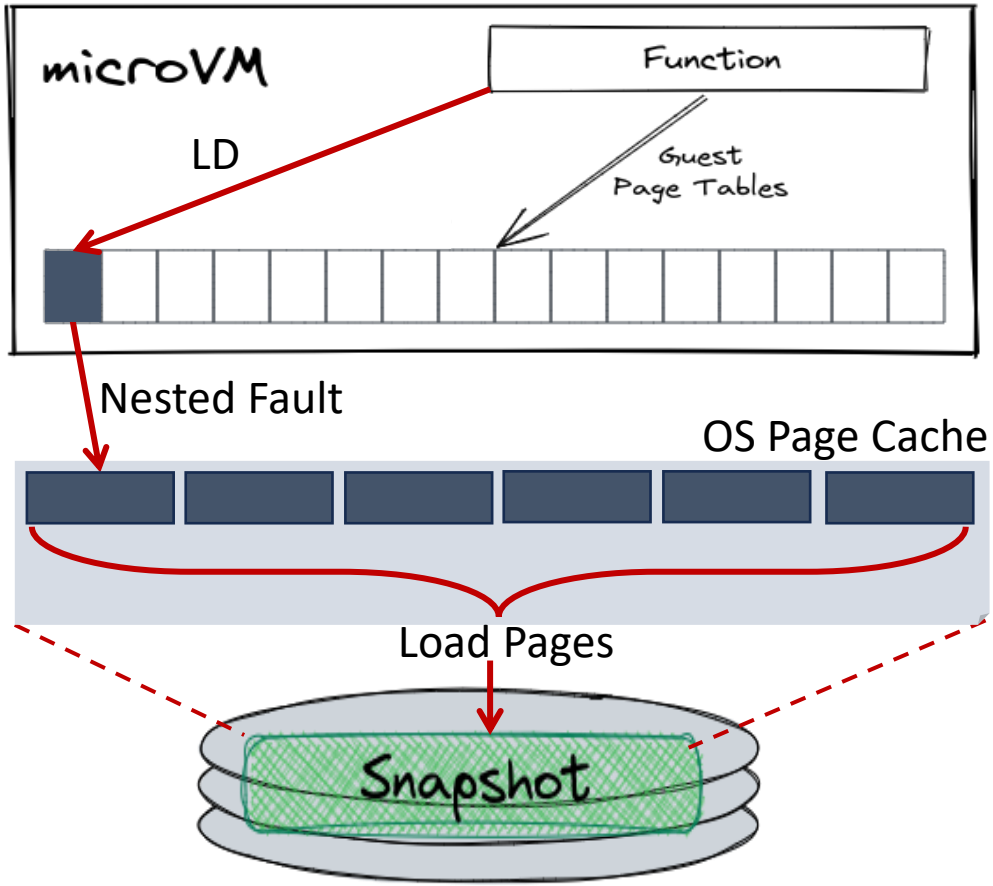

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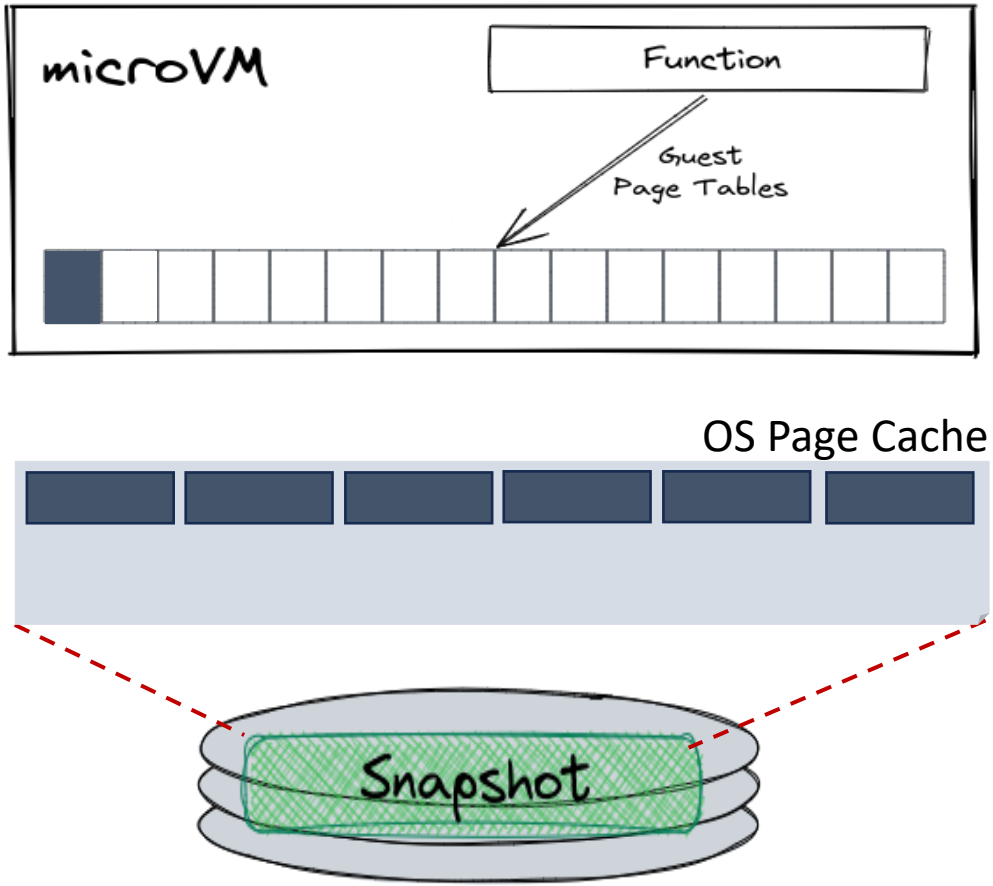

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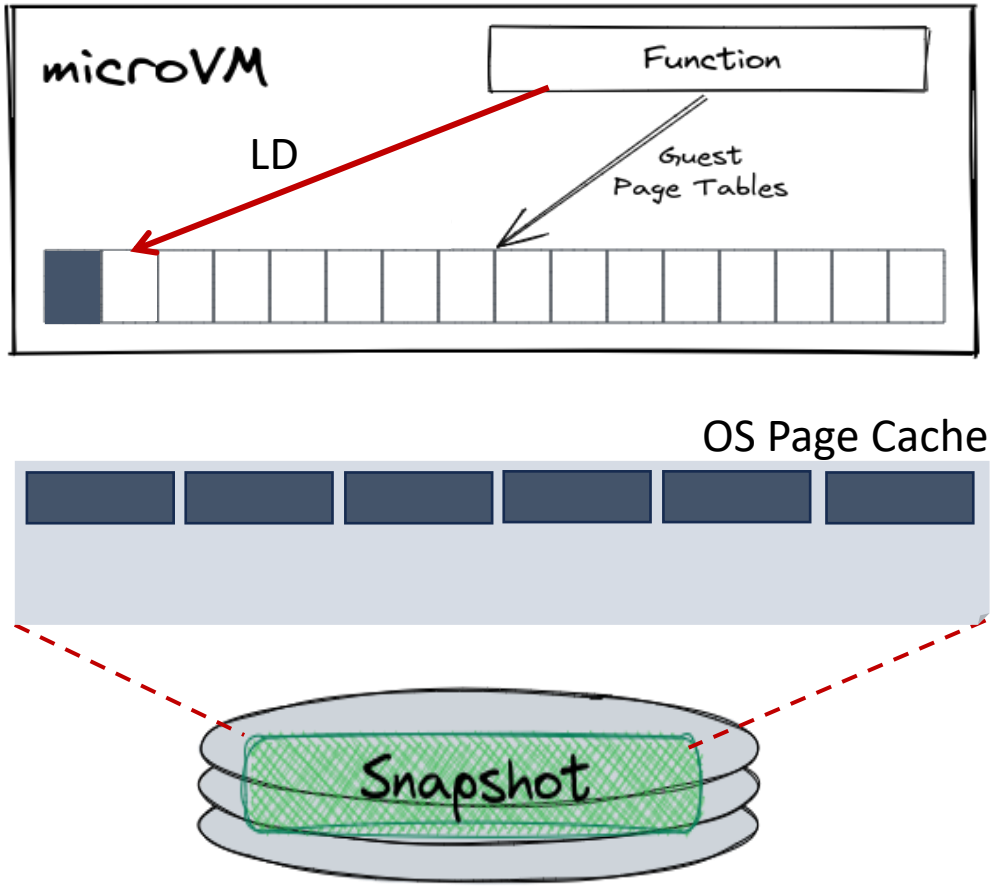

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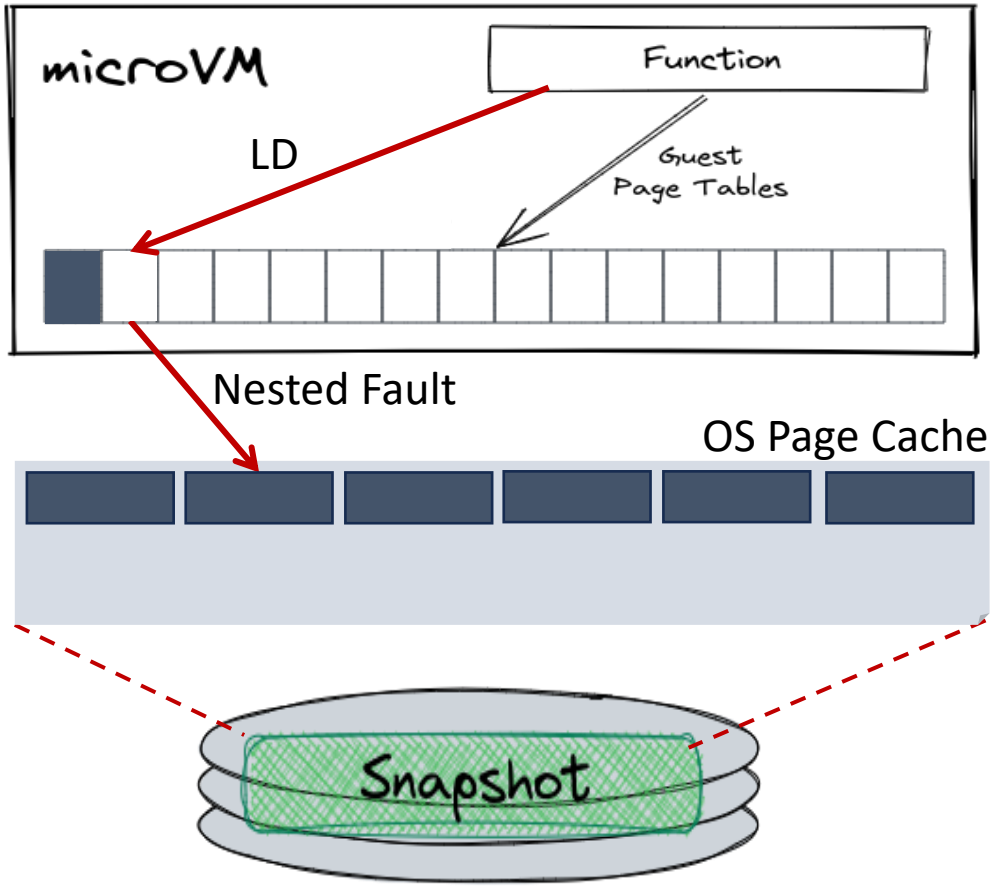

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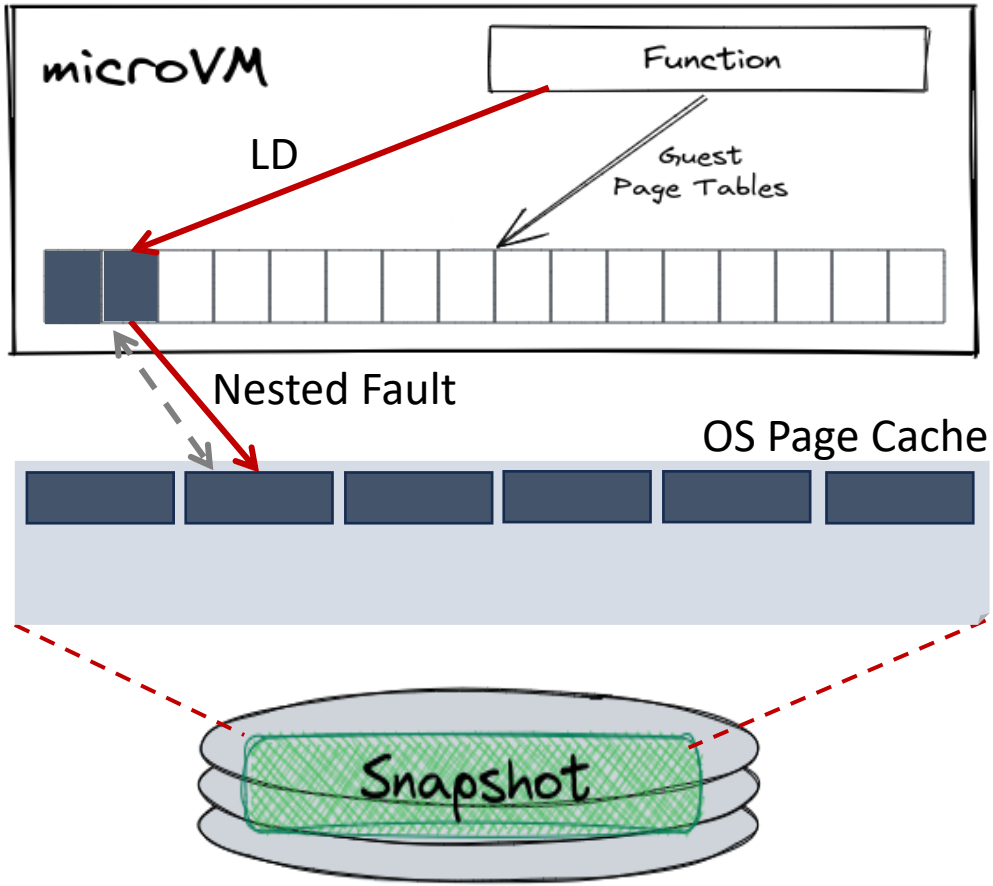

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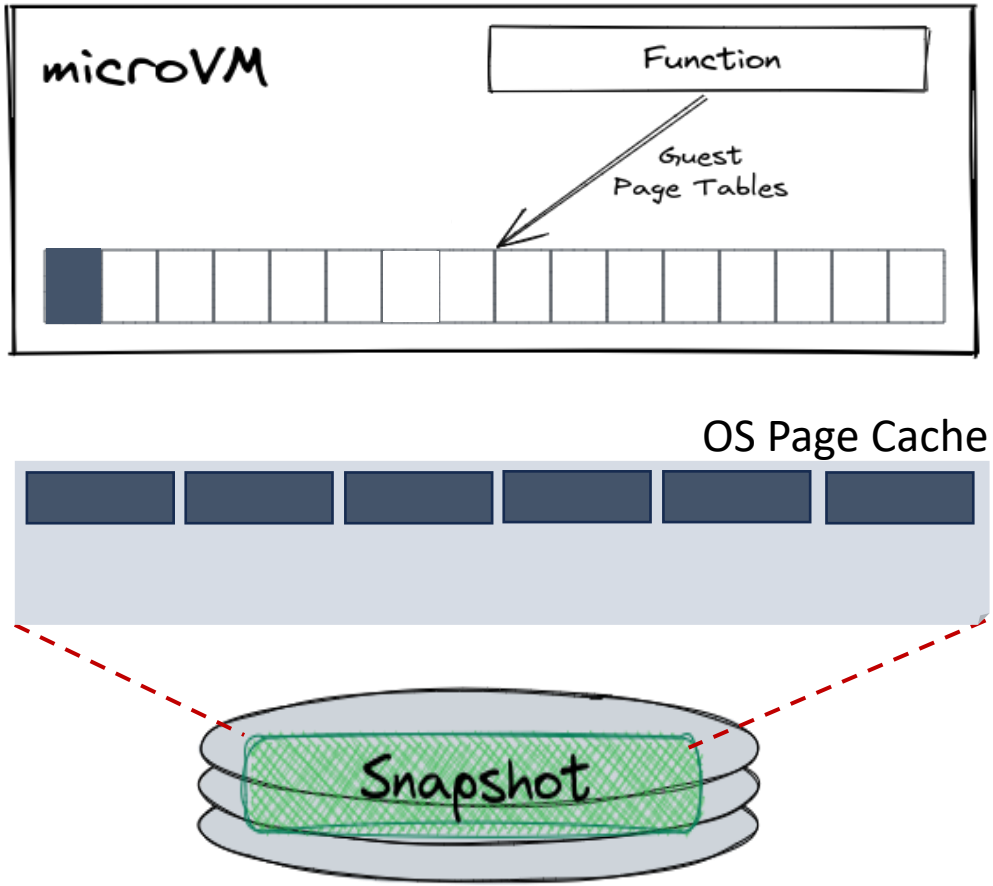

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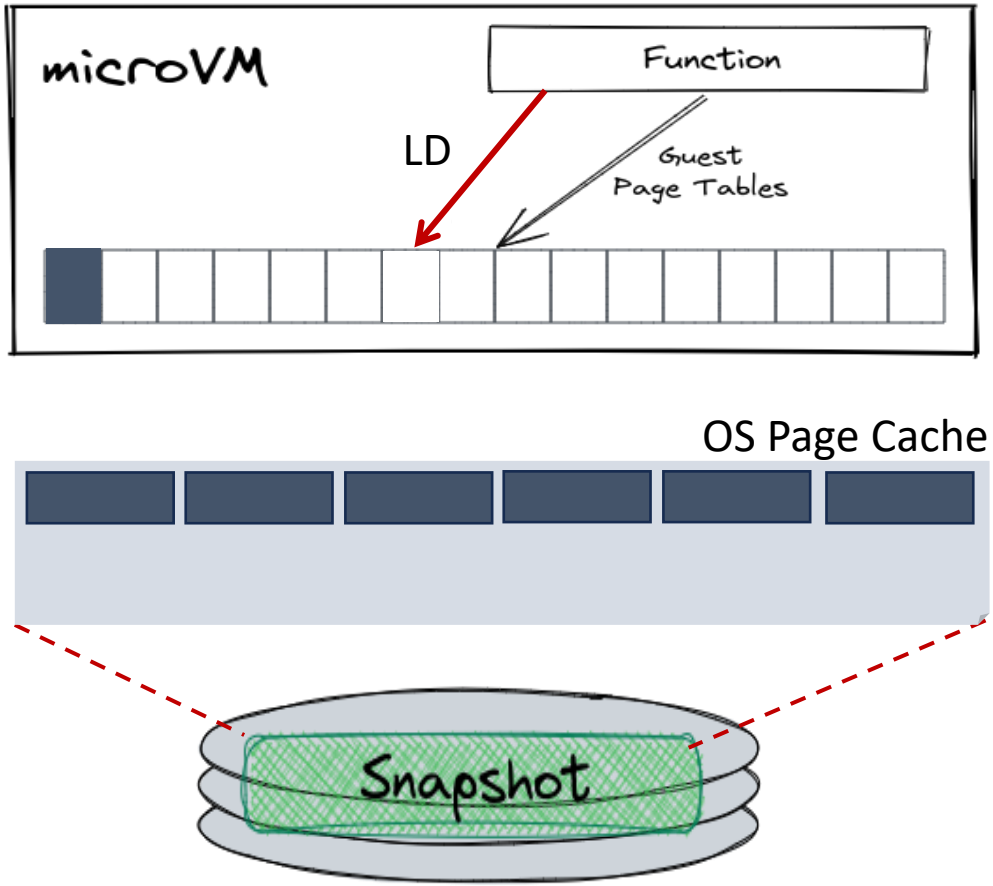

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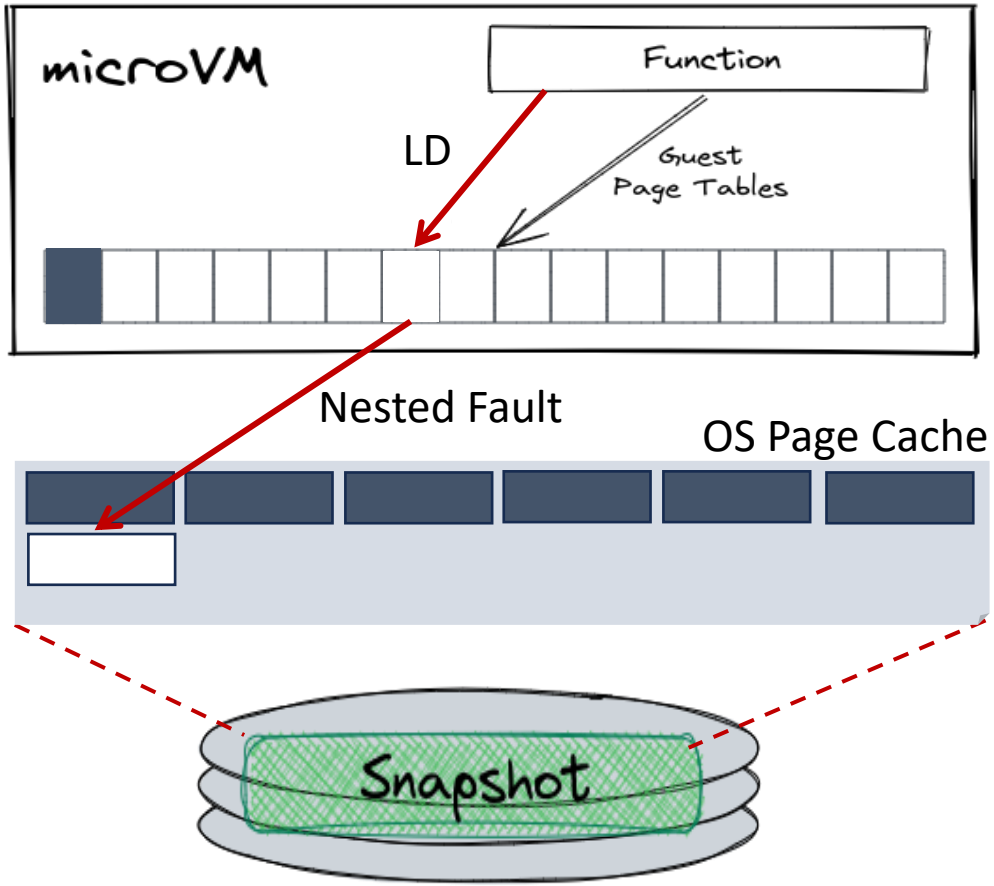

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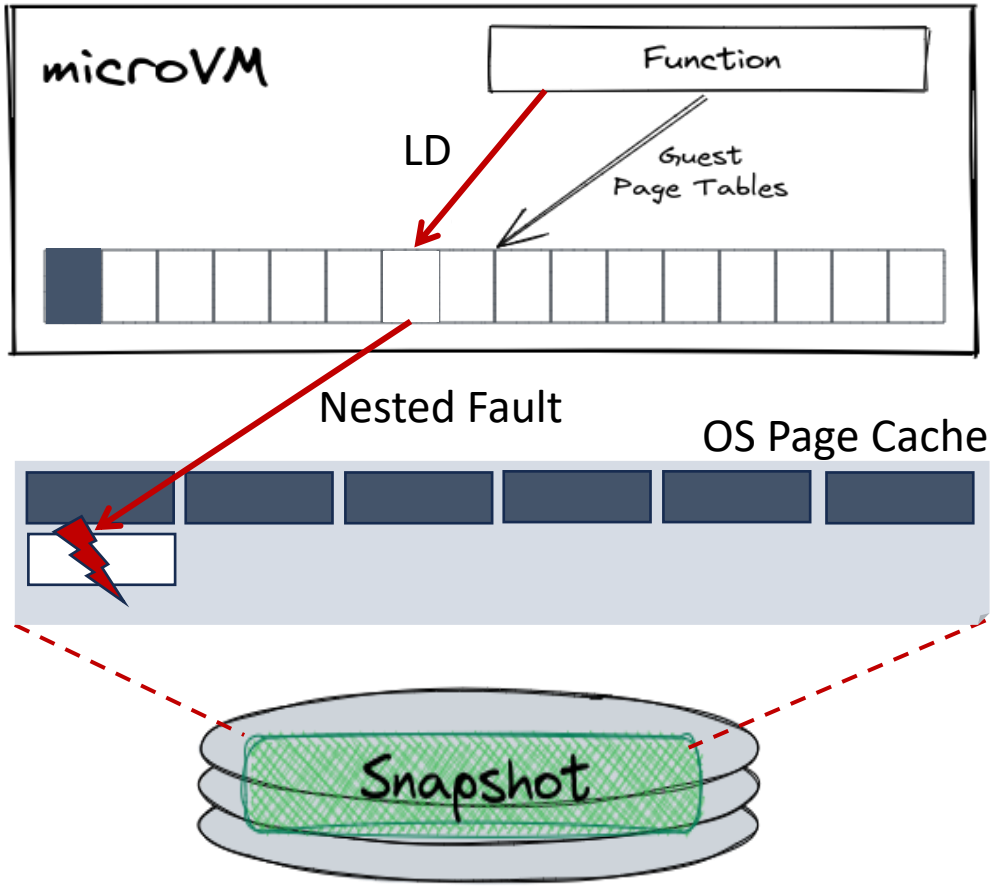

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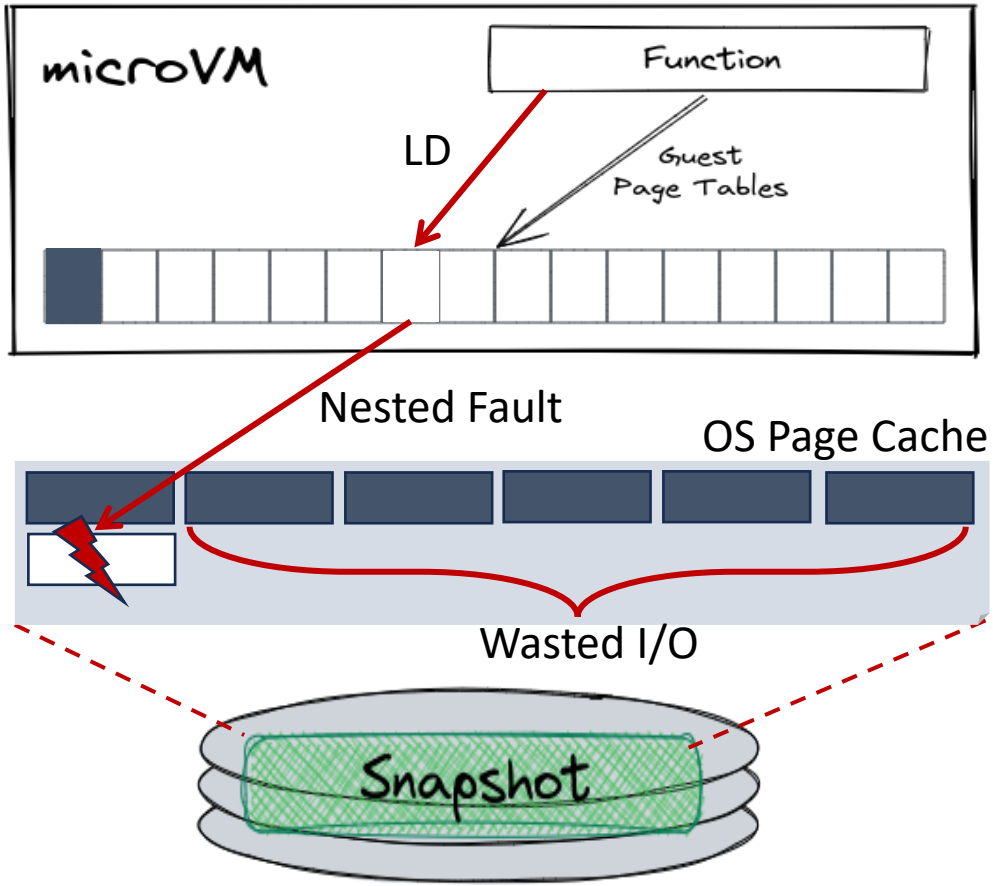

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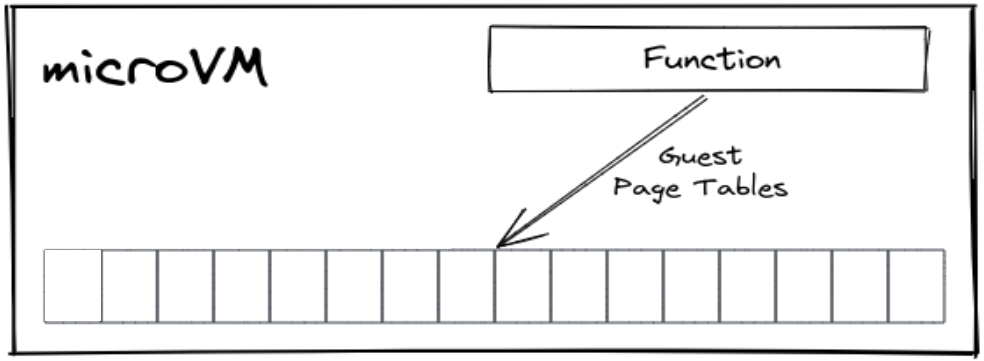
→ Conclusion

Working Set Prefetching: REAP / Faast



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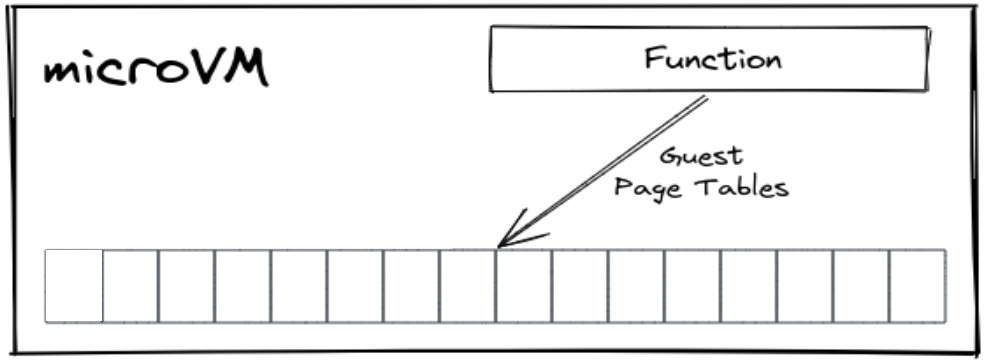
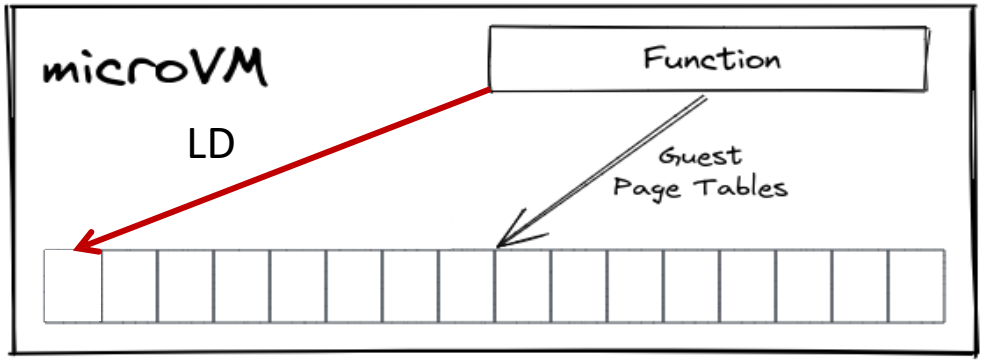


Userfaultfd
Agent

Anonymous Memory

Working Set Prefetching: REAP / Faast



Userfaultfd
Agent

Anonymous Memory

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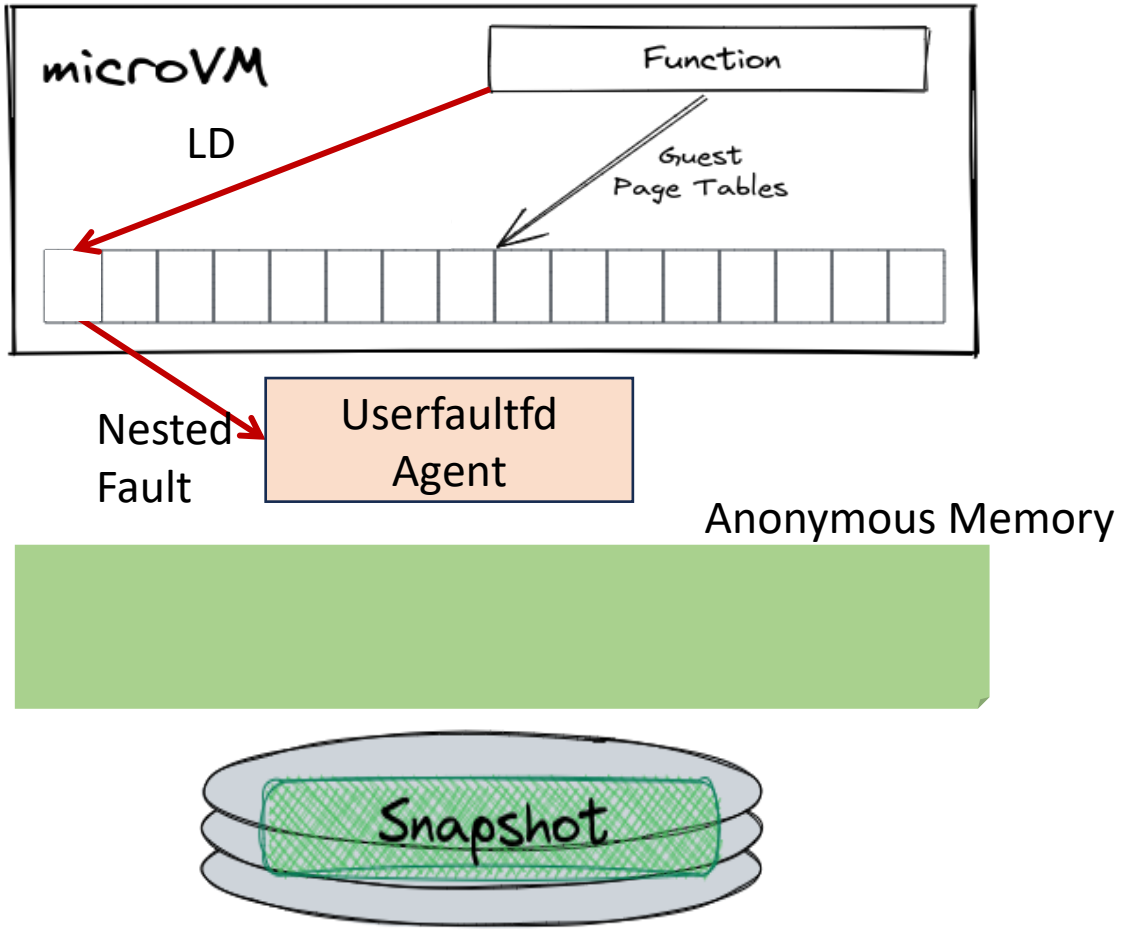

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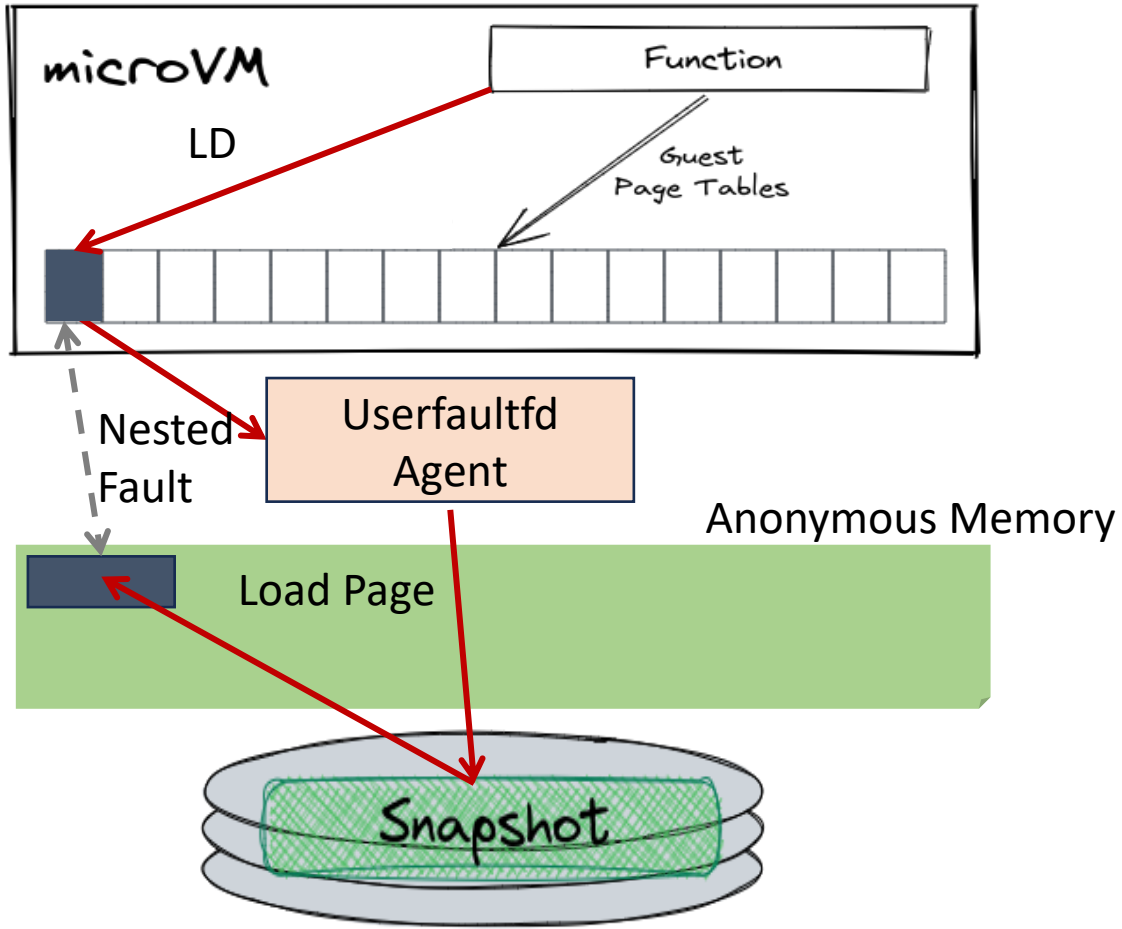

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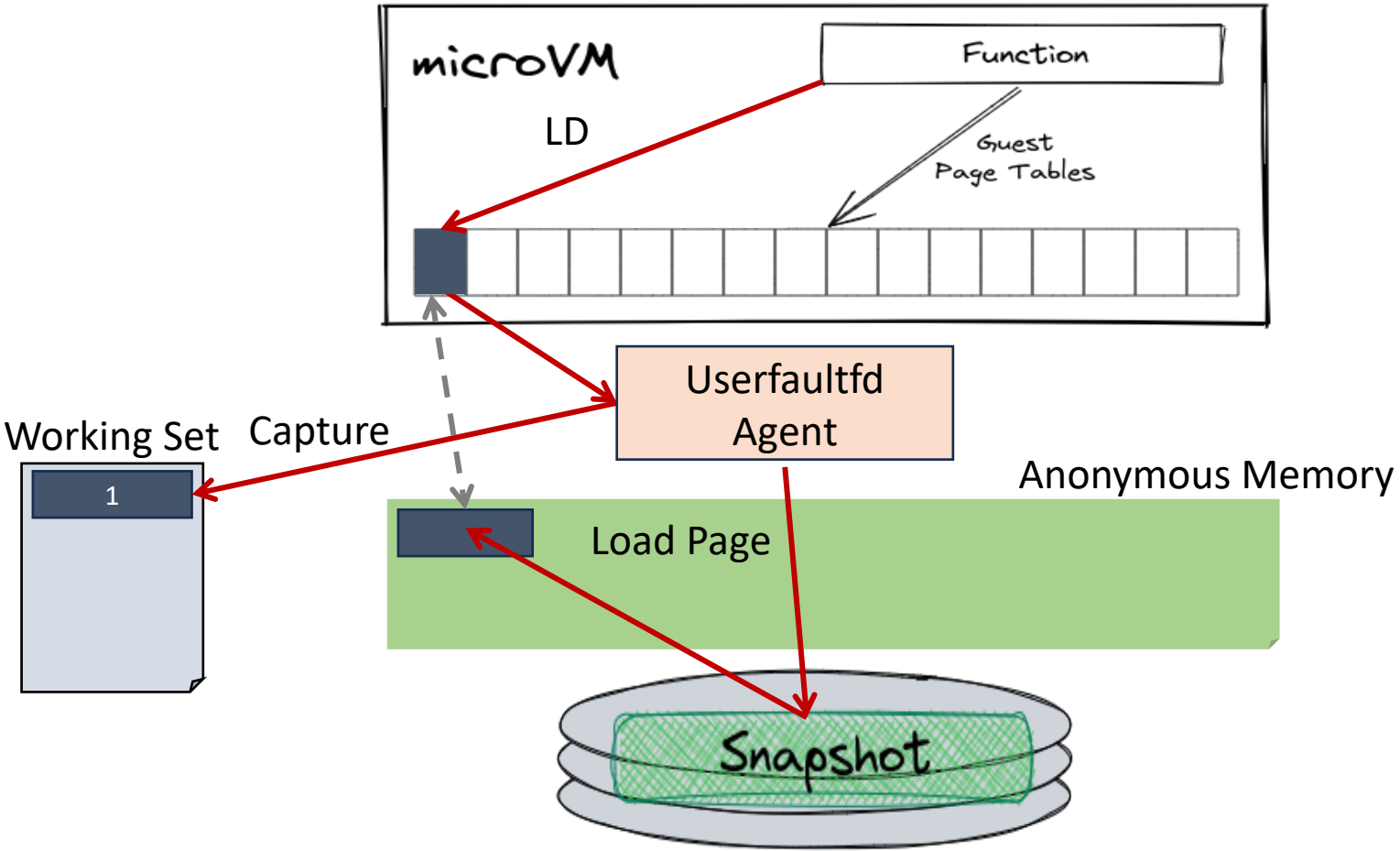

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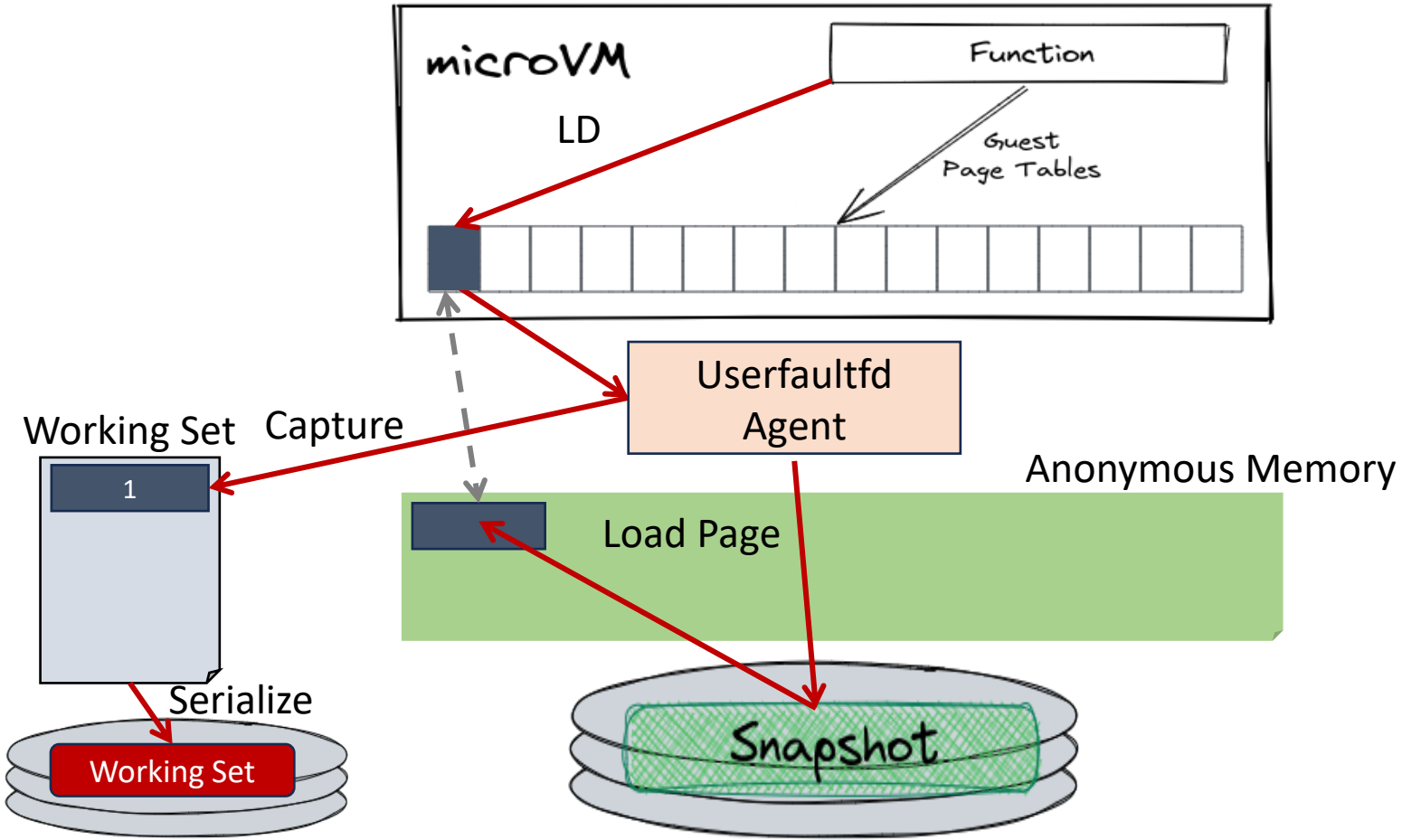

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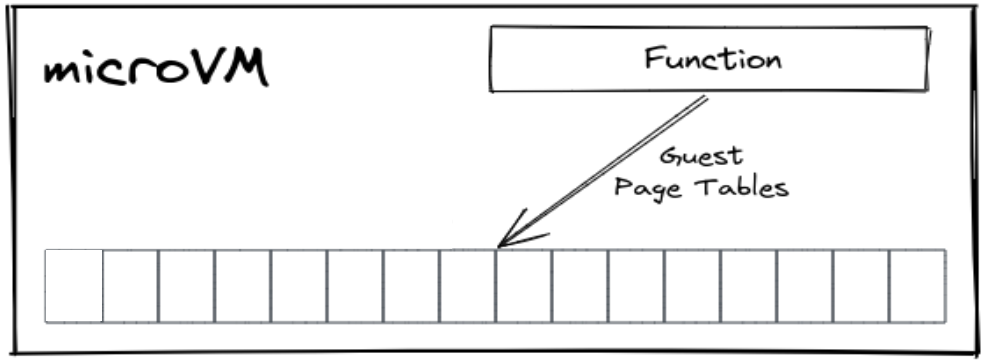
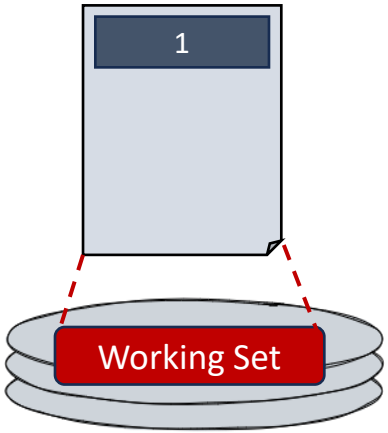


Userfaultfd
Agent

Working Set



Anonymous Memory

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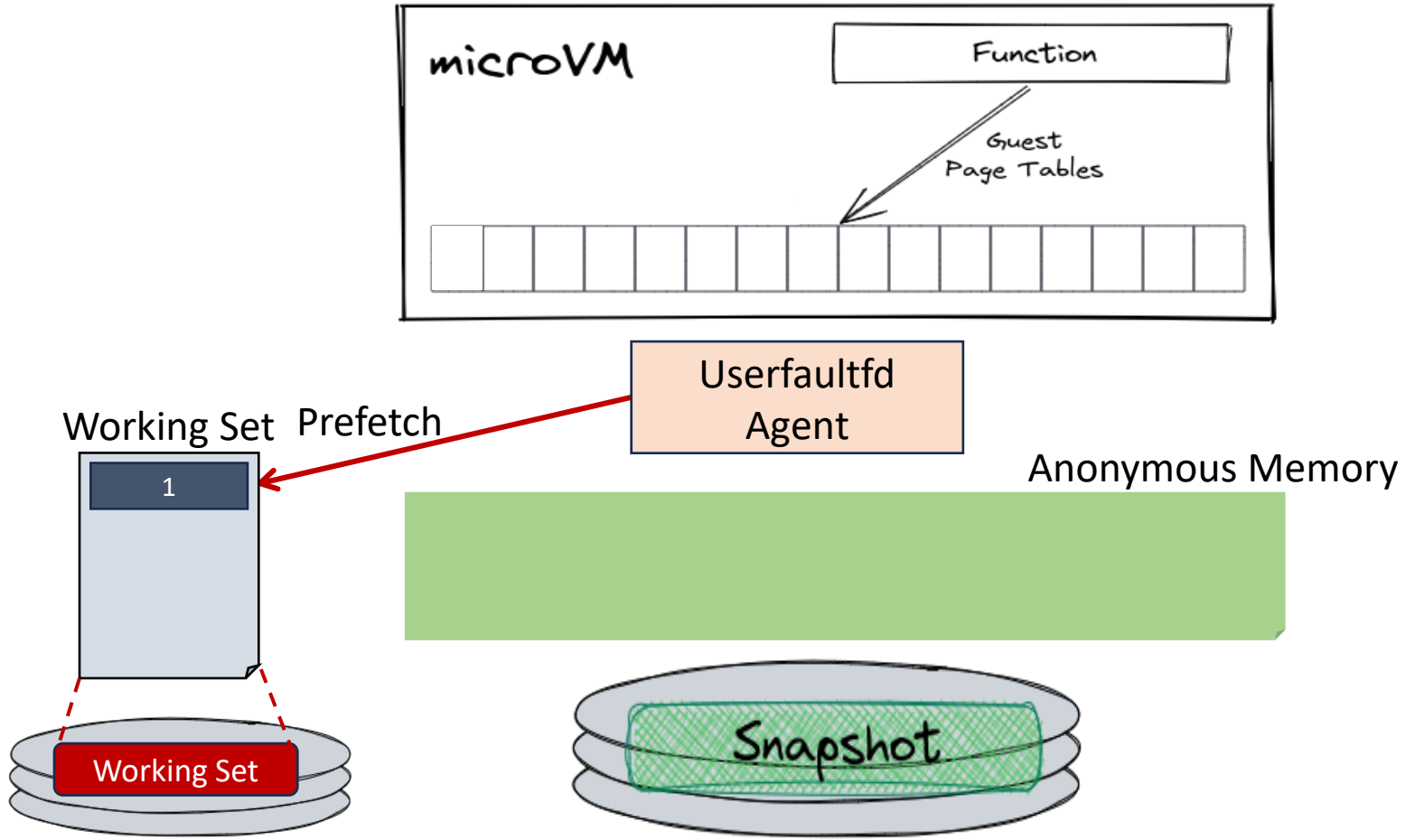

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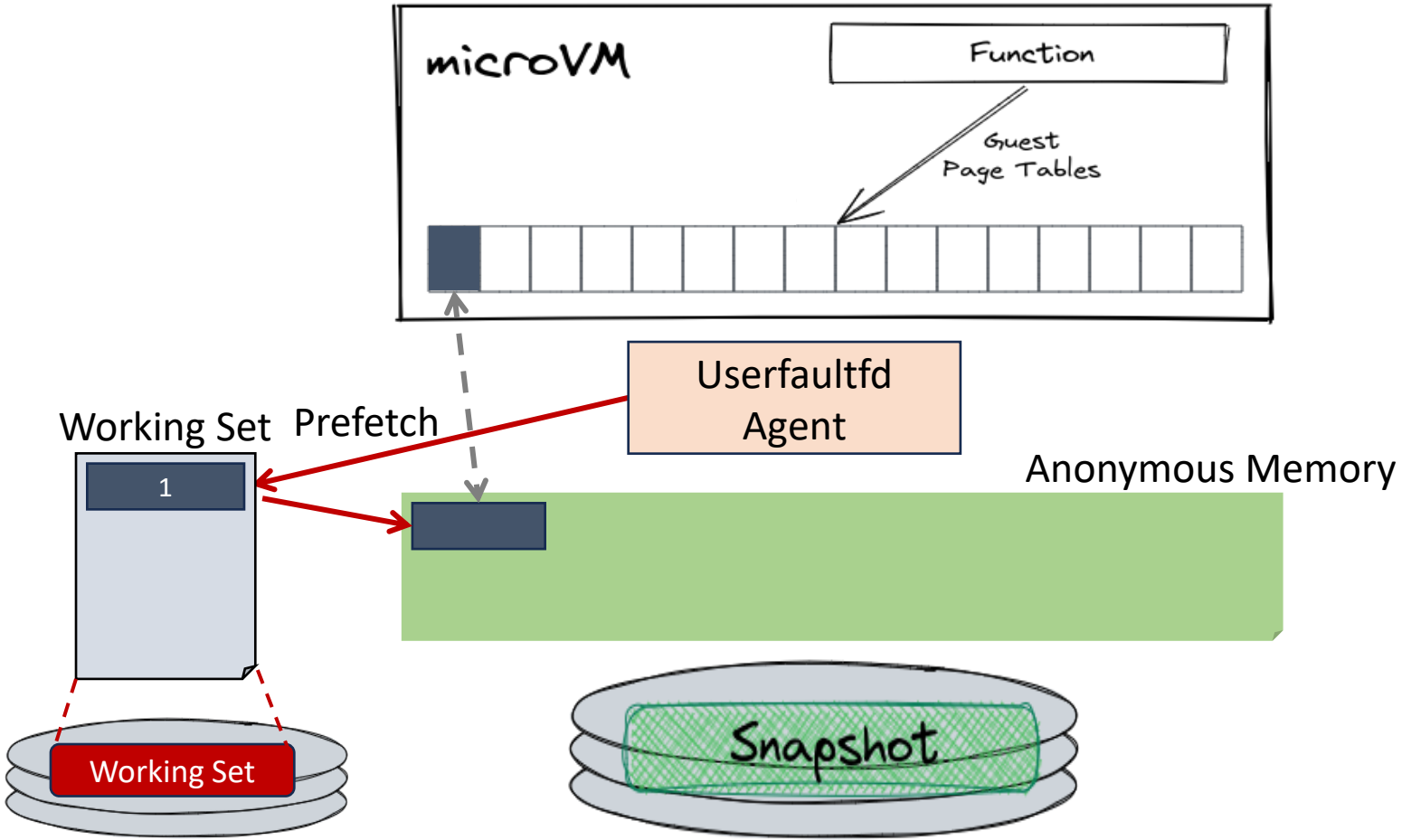

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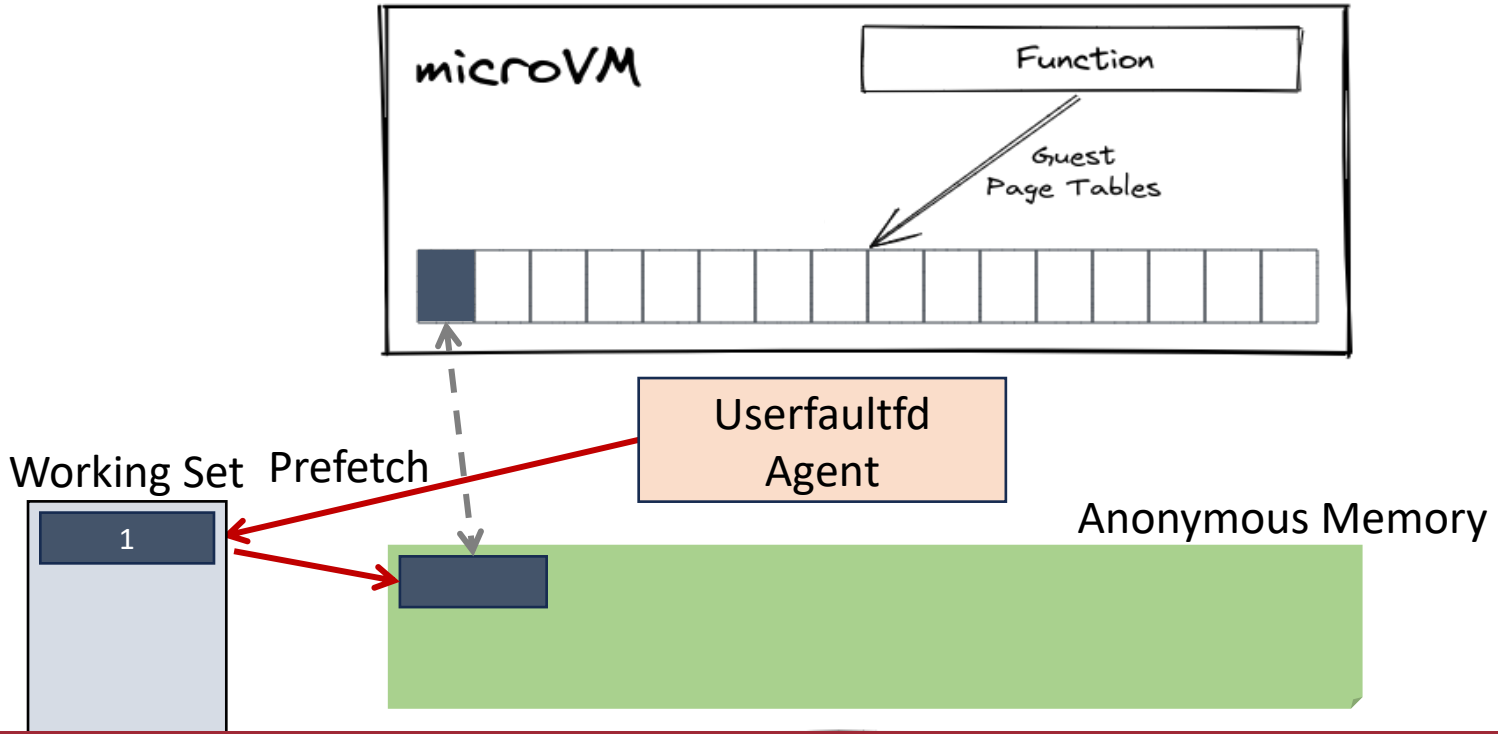

User <-> Kernel transition overhead

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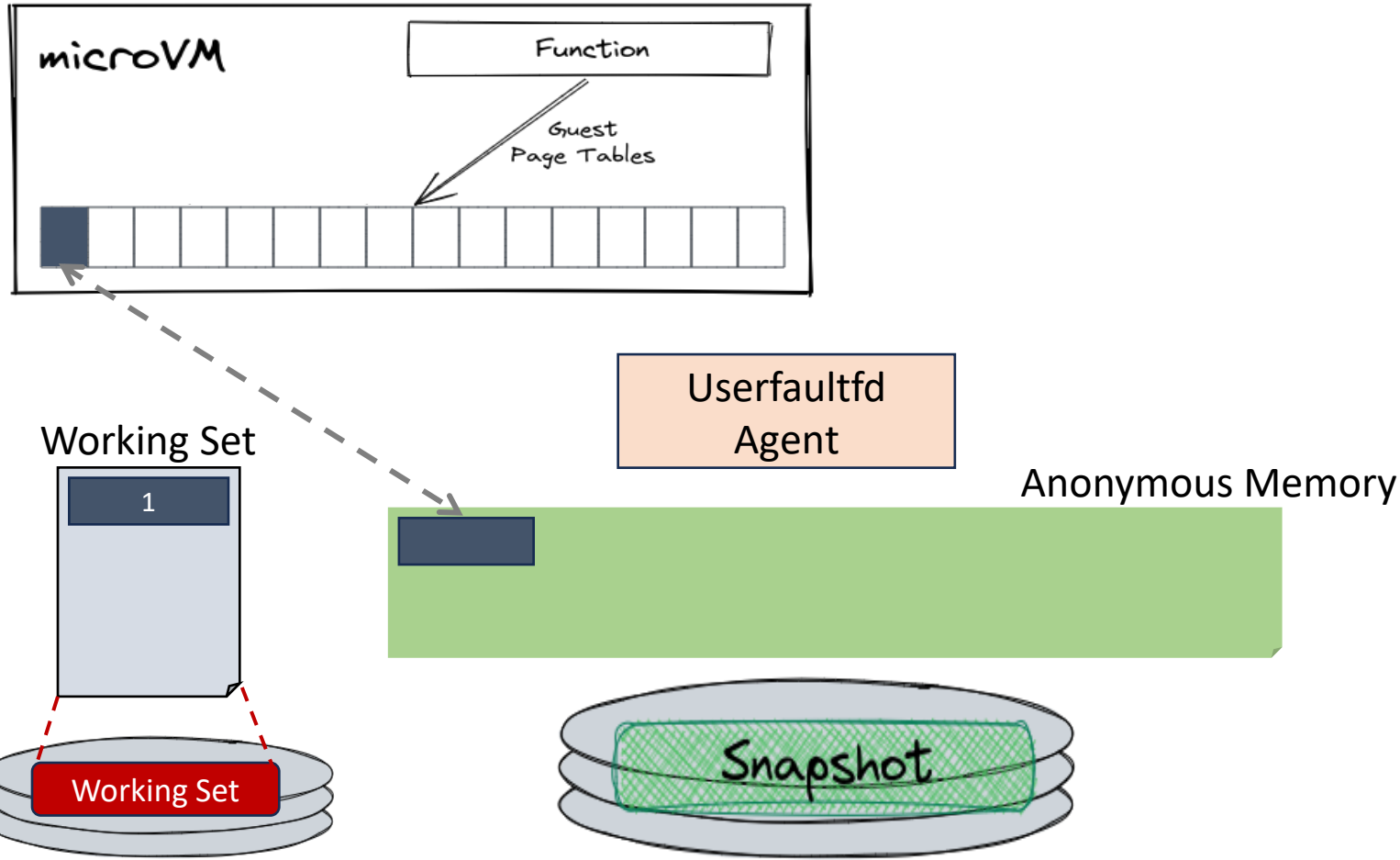

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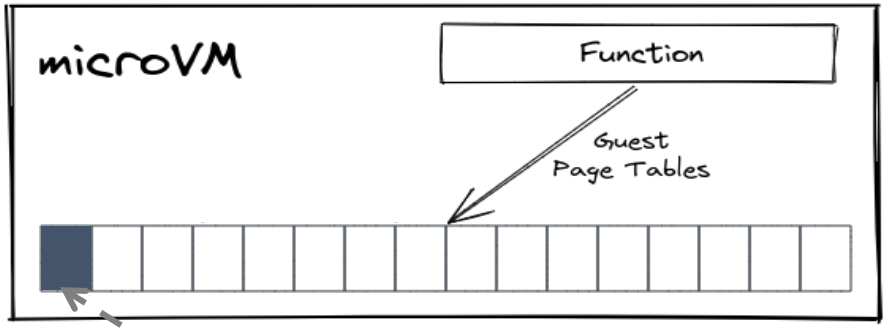
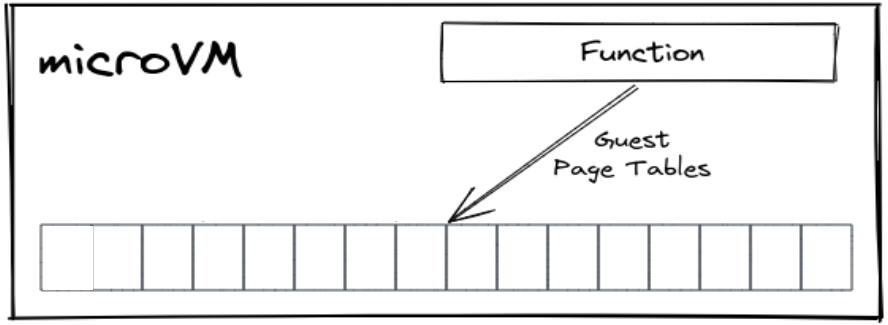
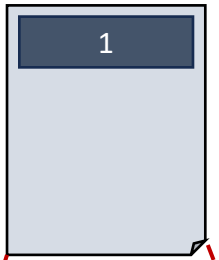




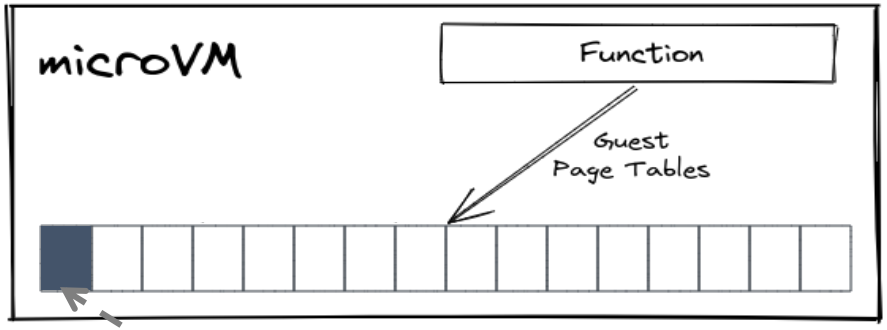
Userfaultfd
Agent

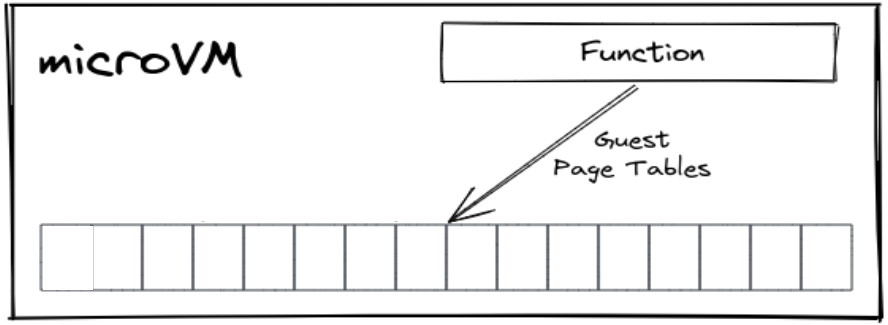
Working Set

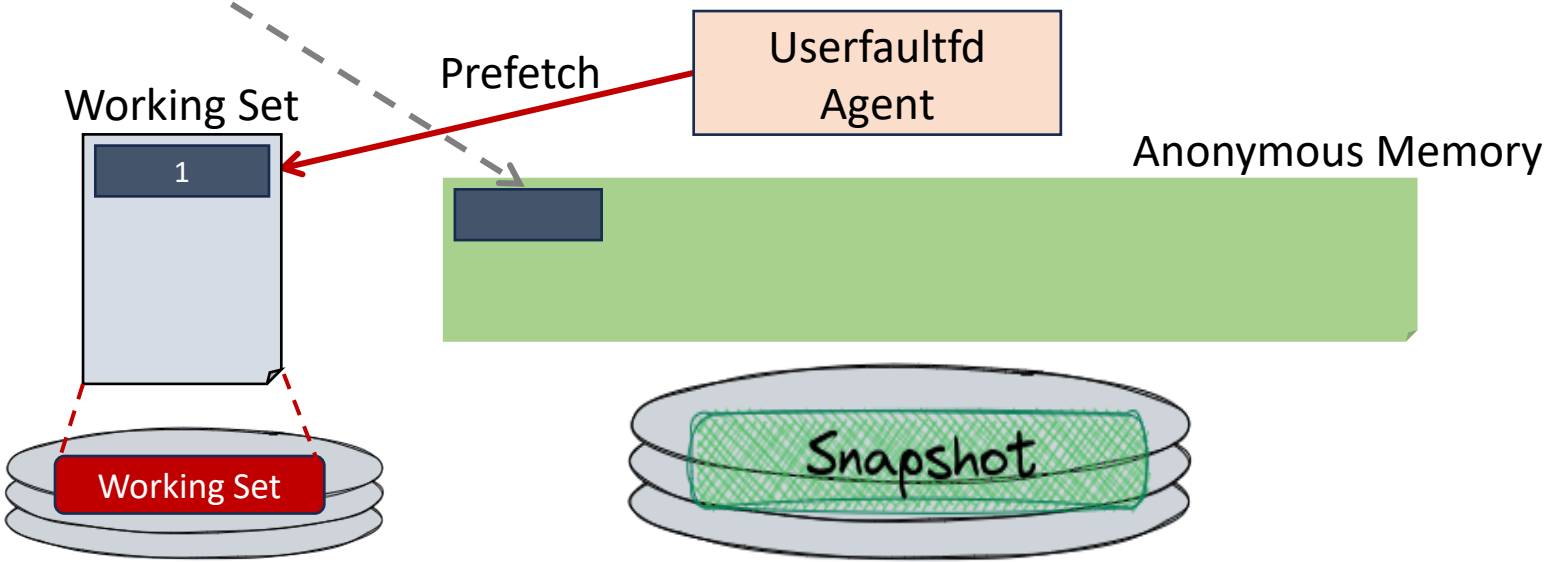


Anonymous Memory

Working Set Prefetching: REAP / Faast







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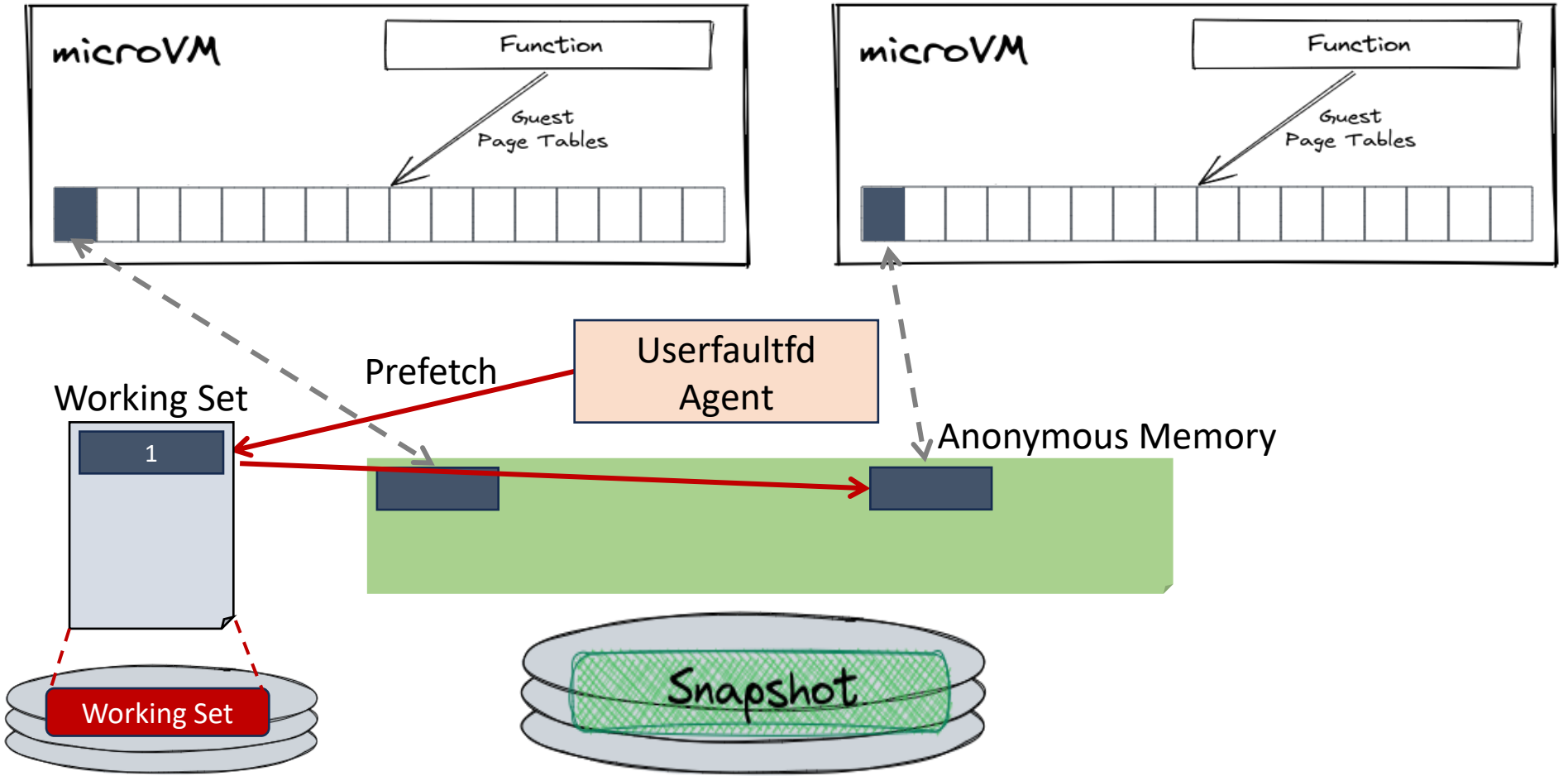

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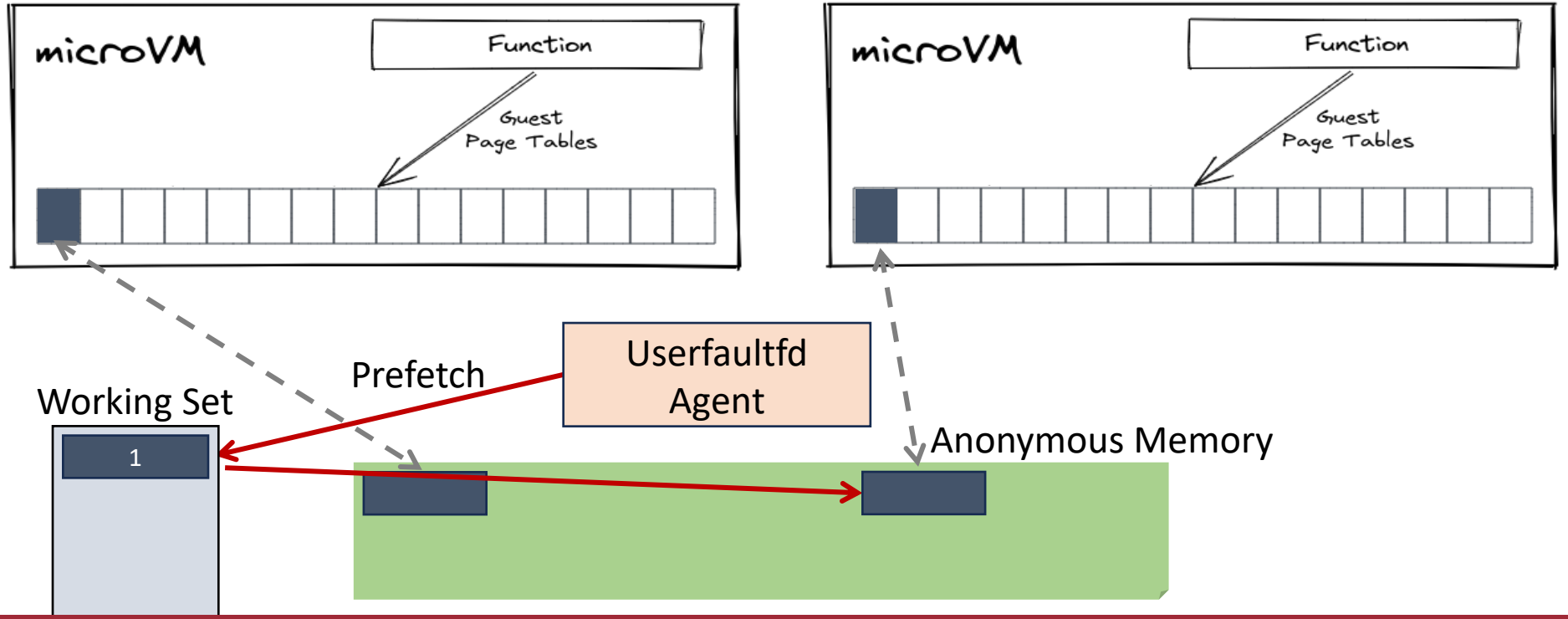

Bypasses page cache == No sharing

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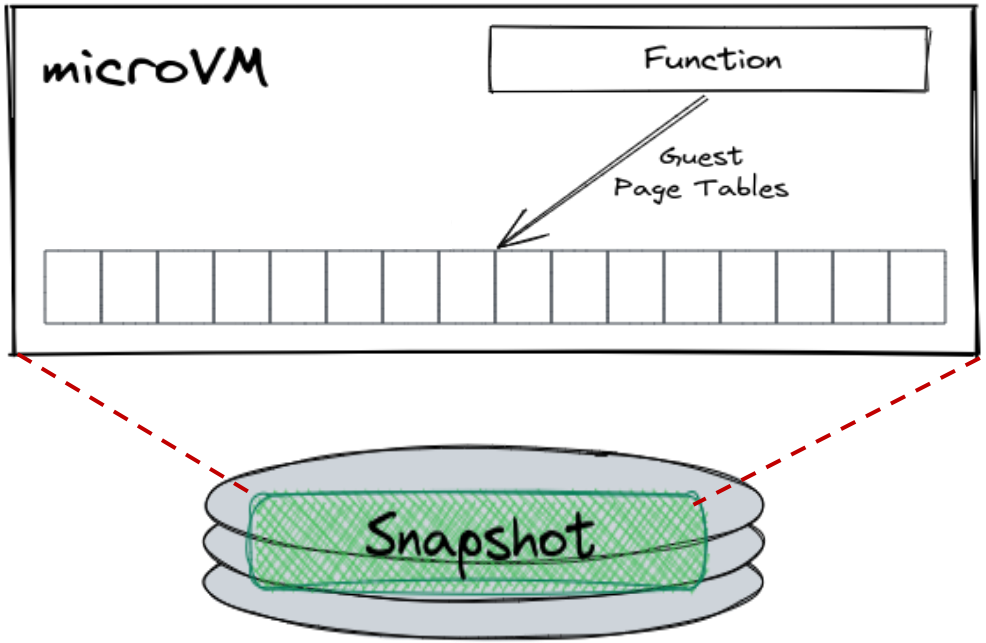

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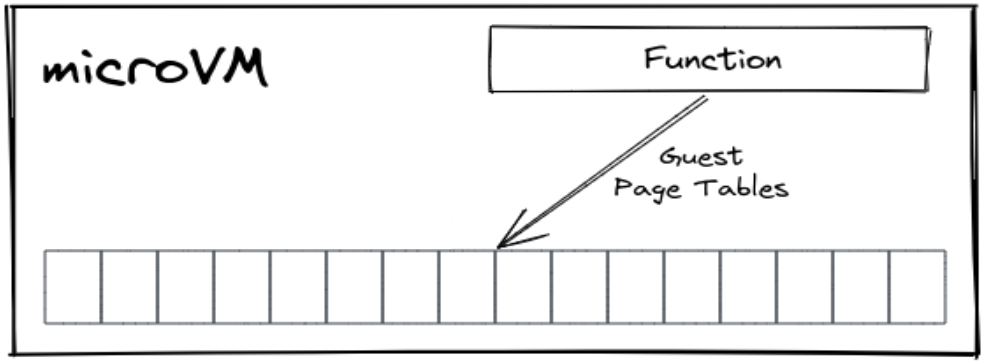

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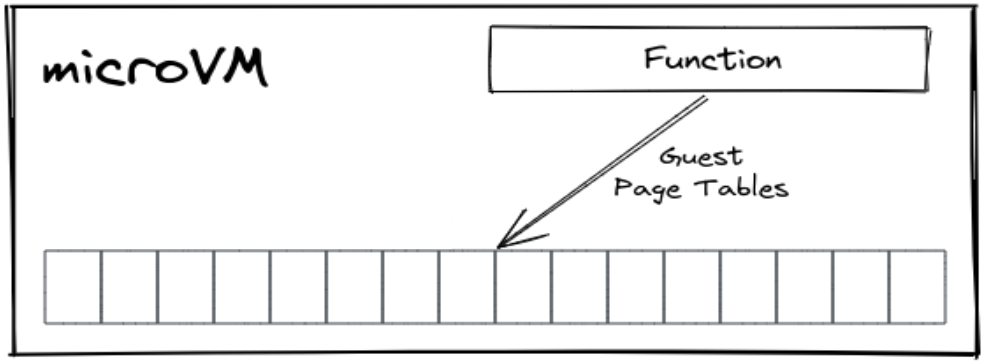

OS Page Cache

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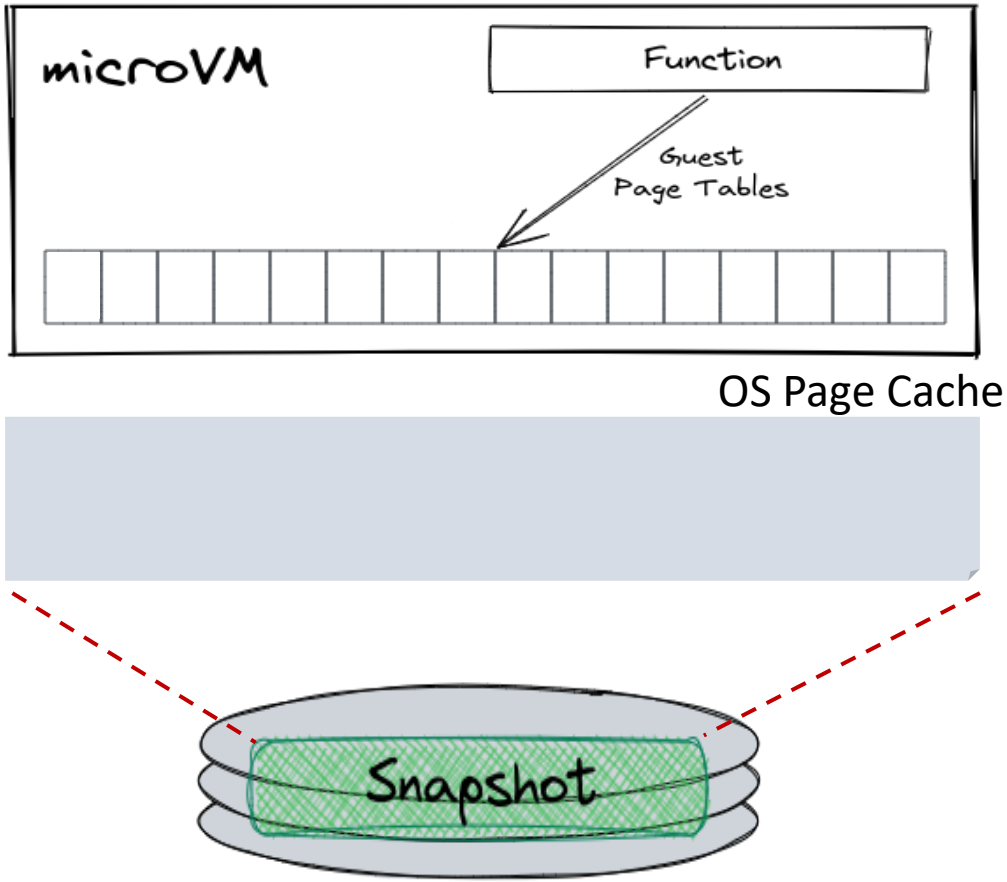

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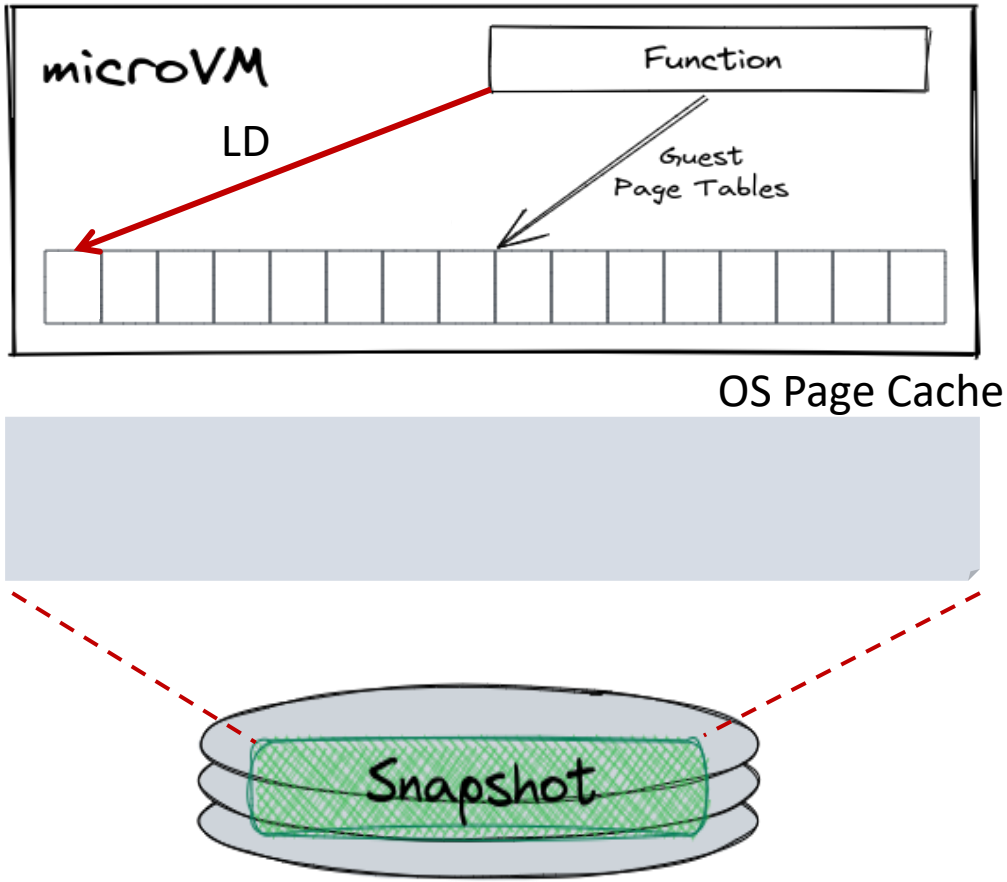

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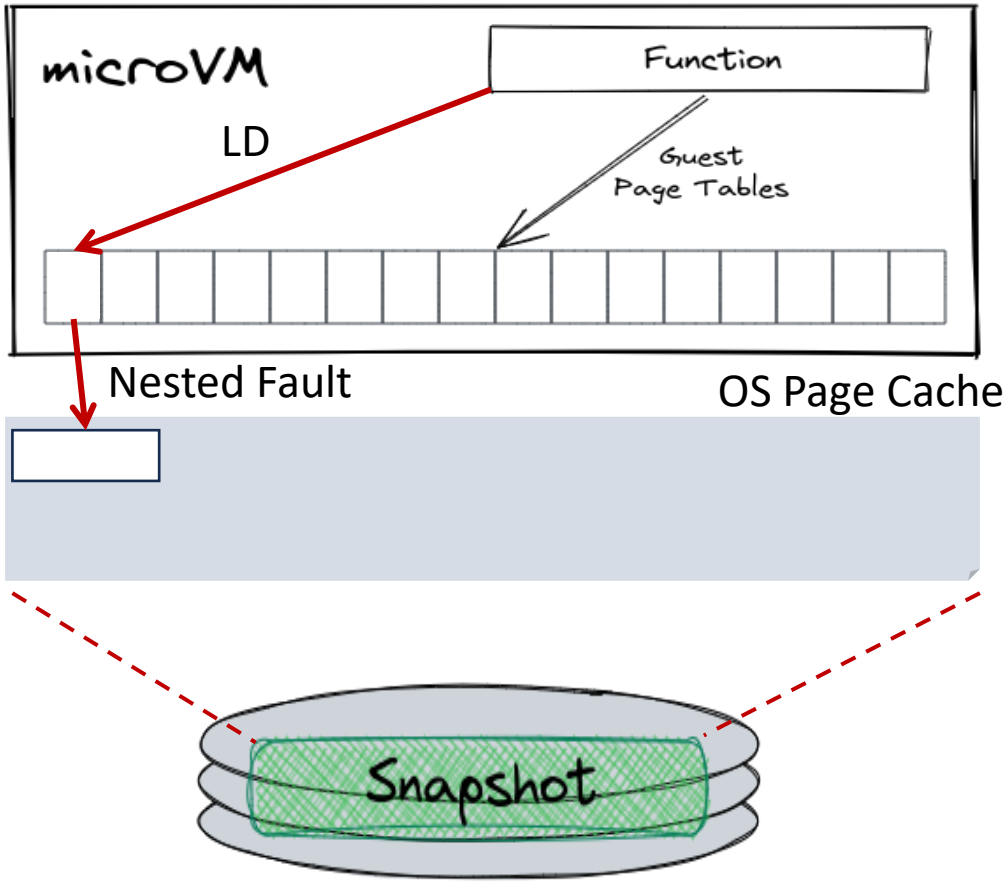

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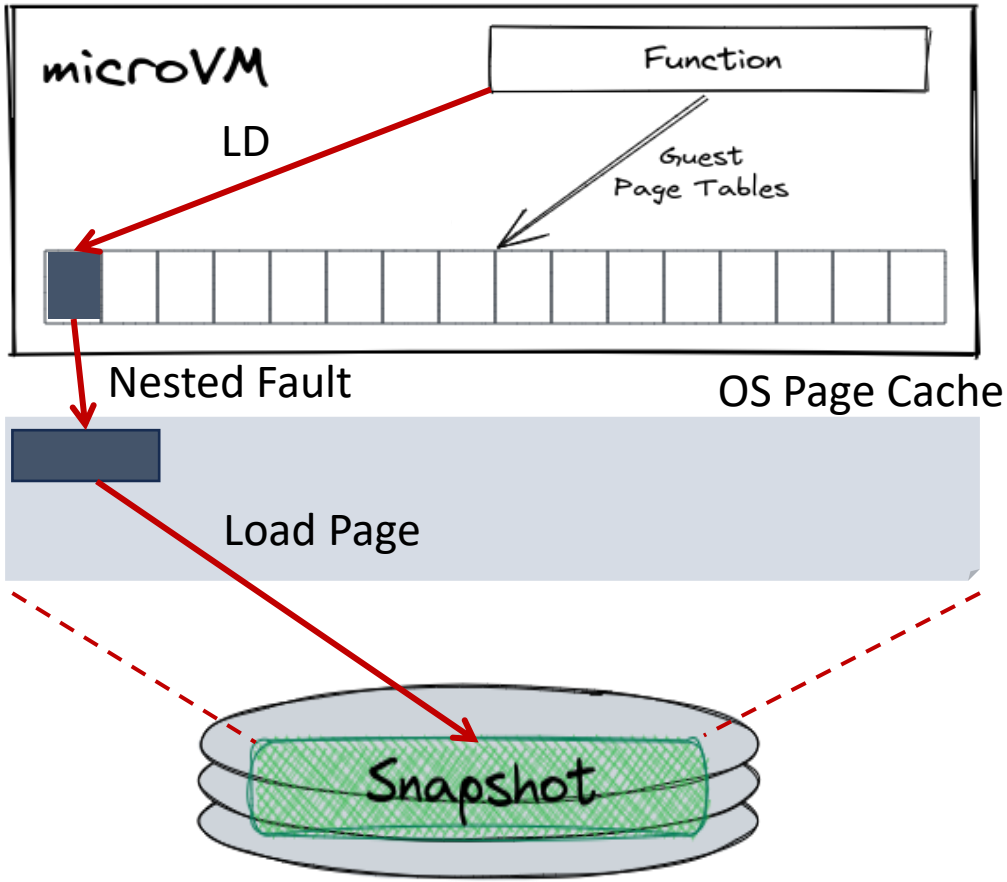

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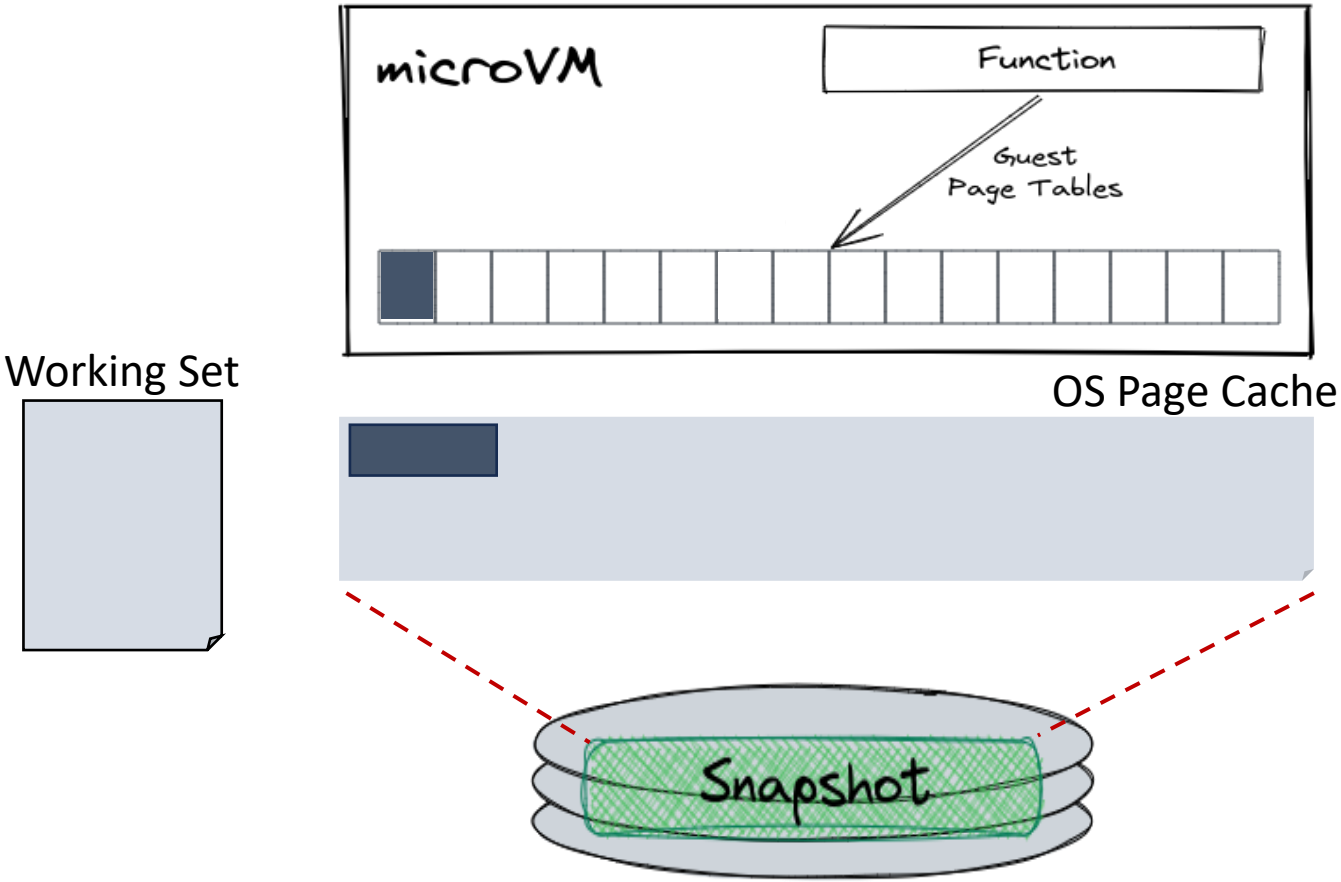

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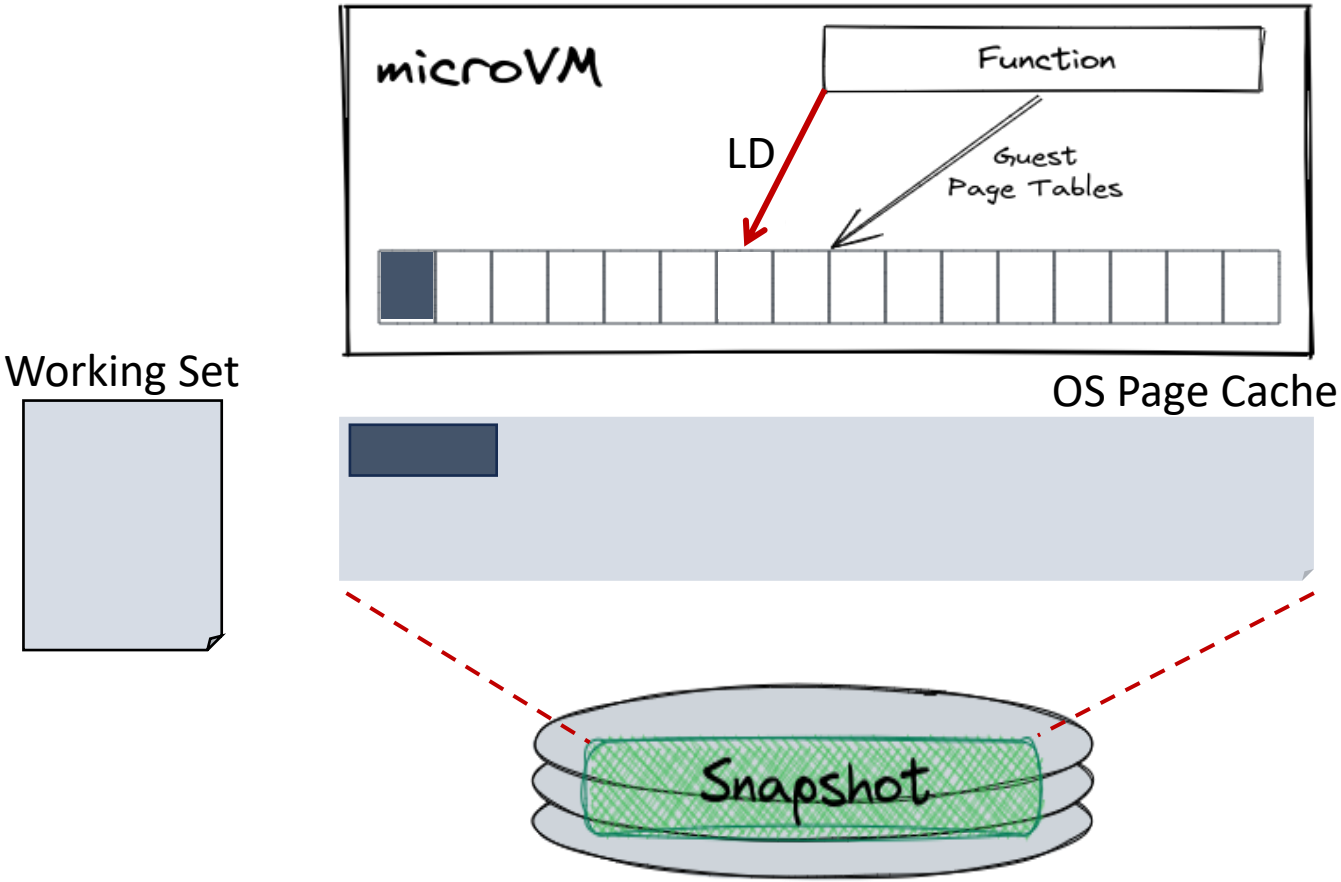

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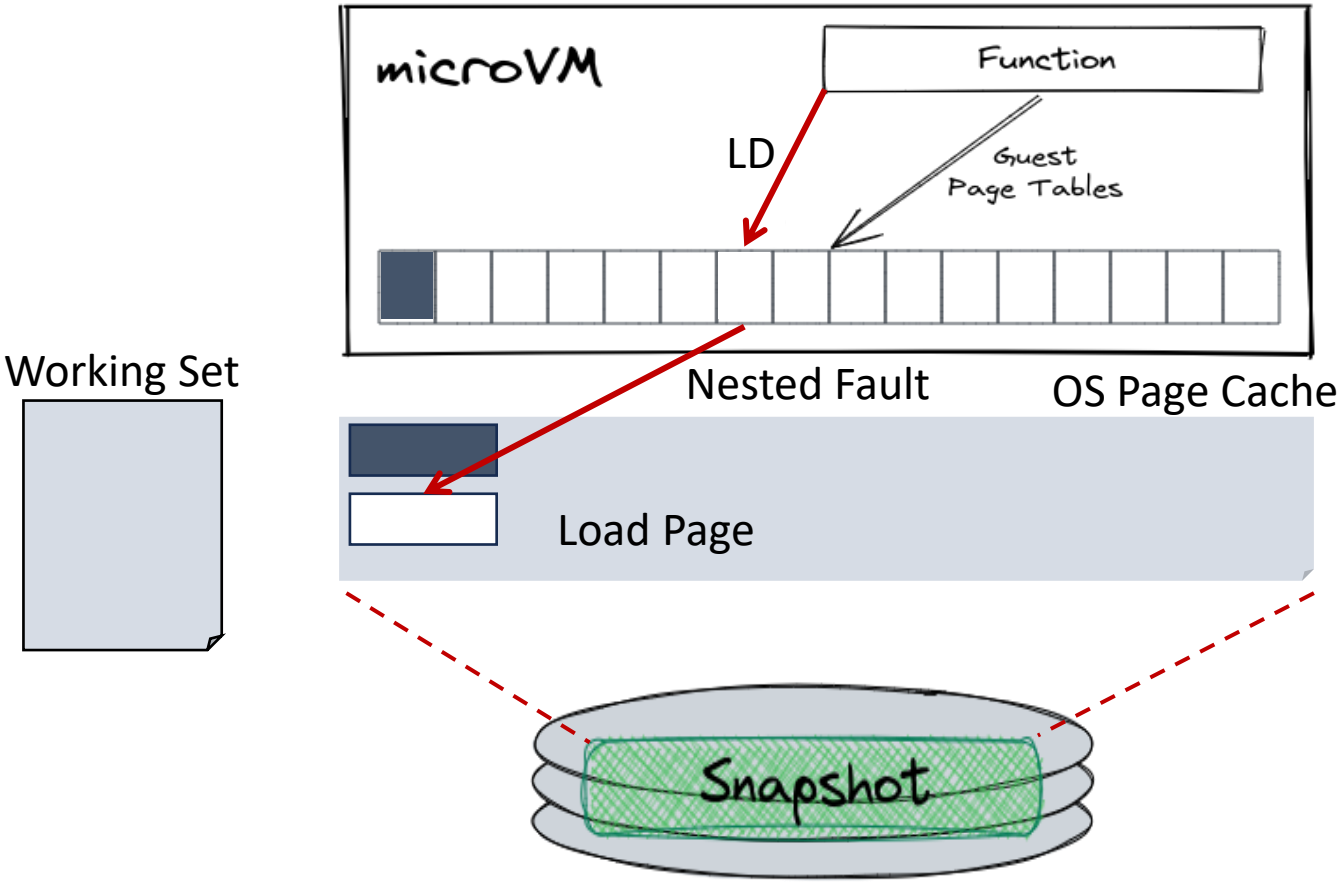

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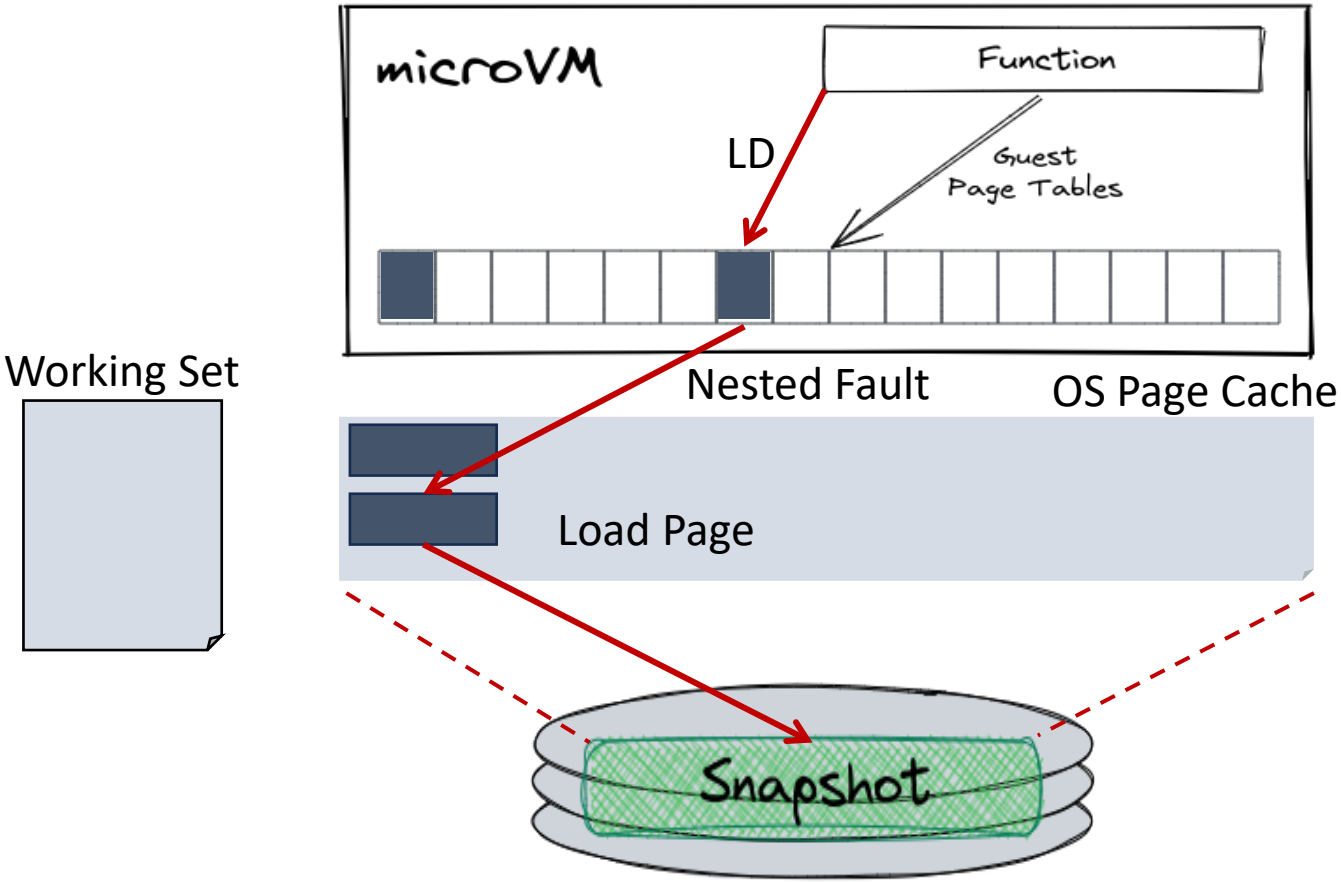

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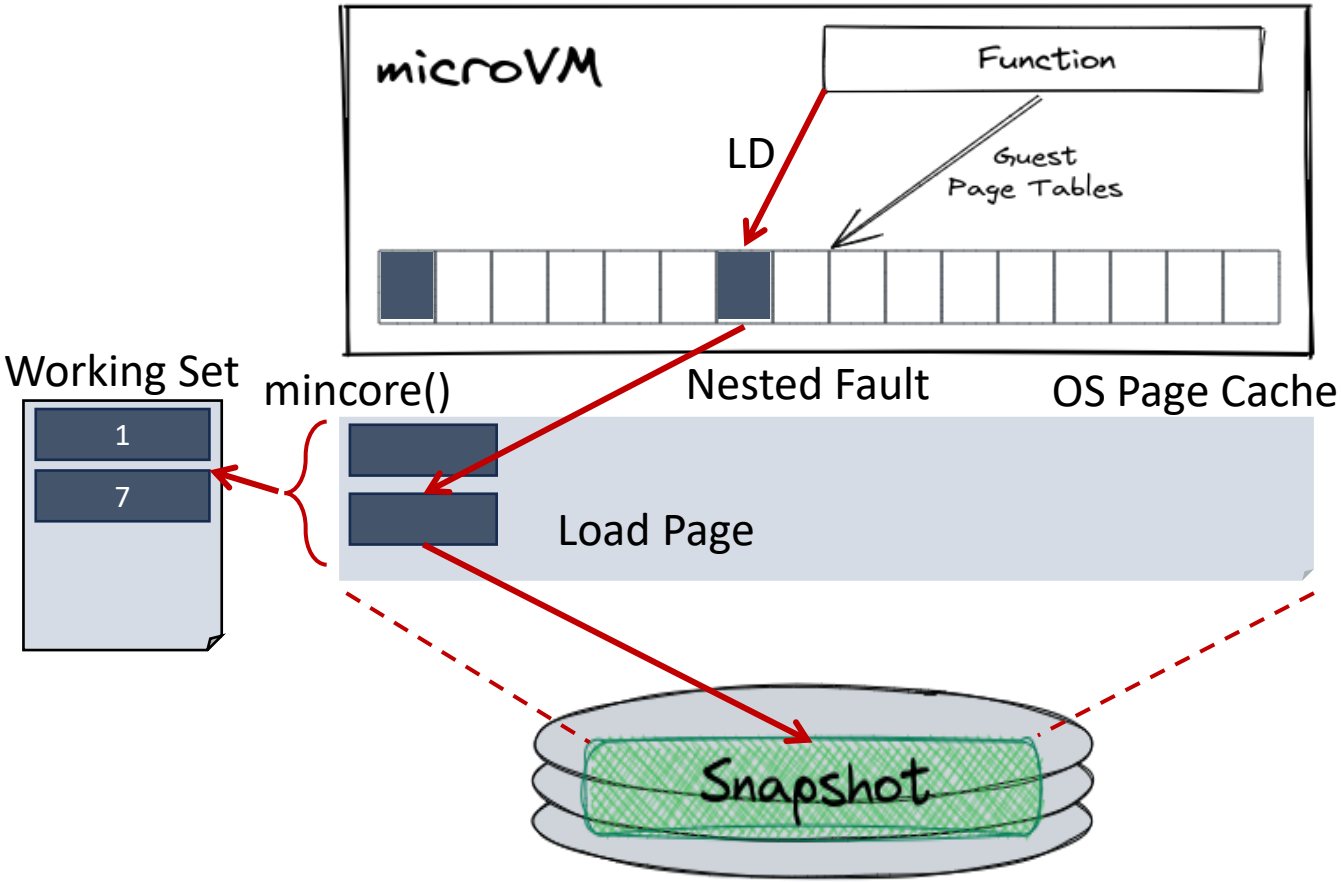

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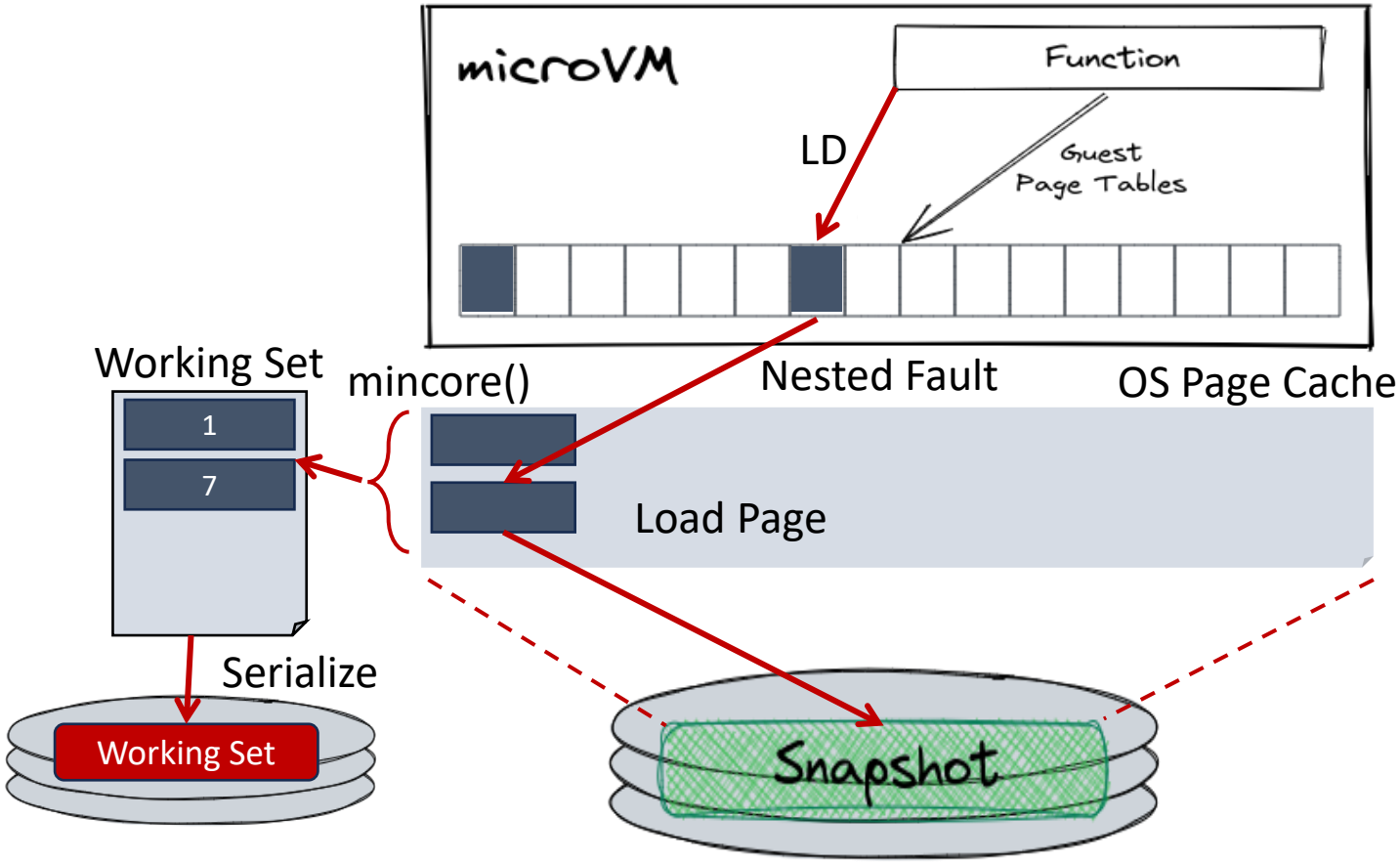

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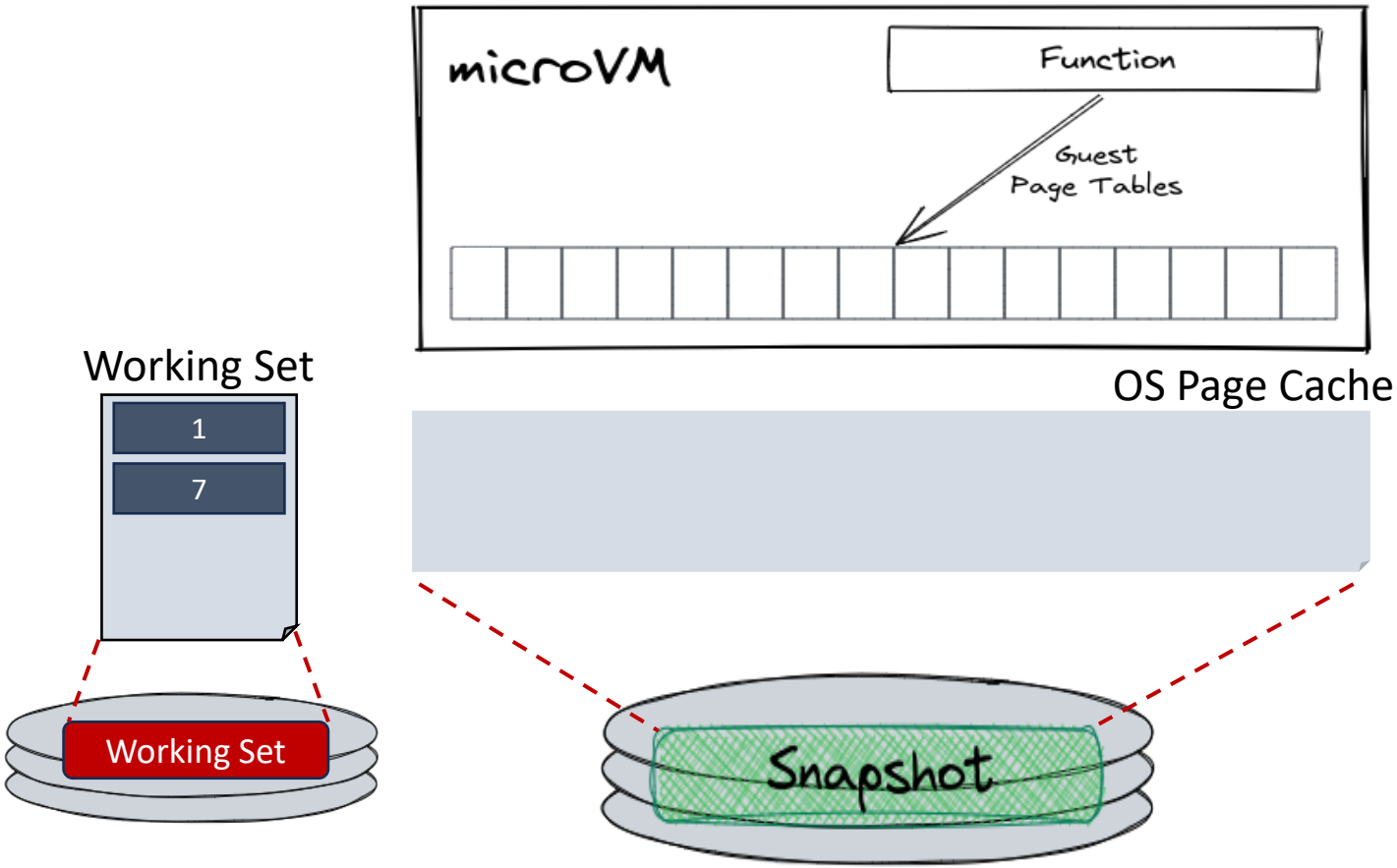

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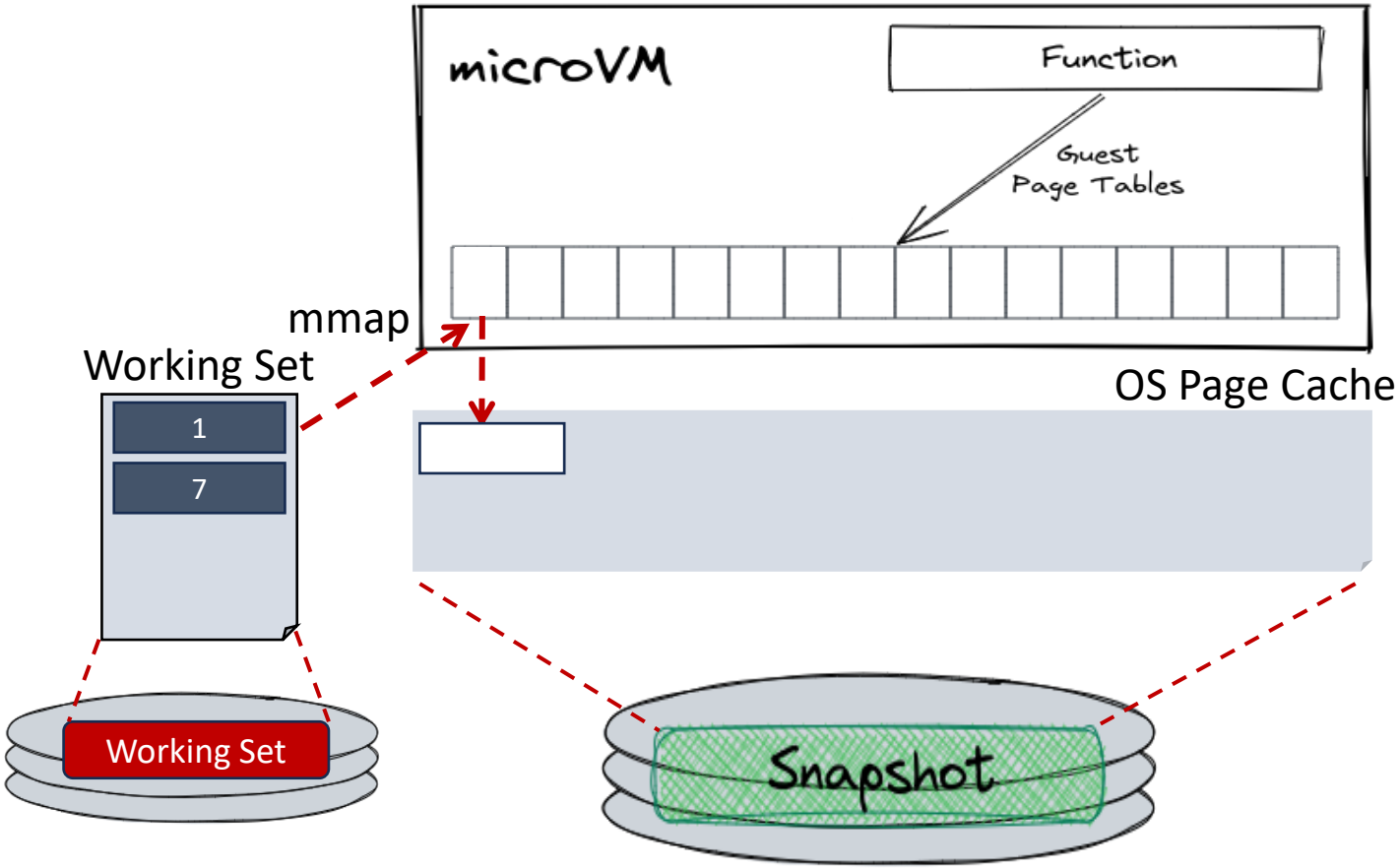

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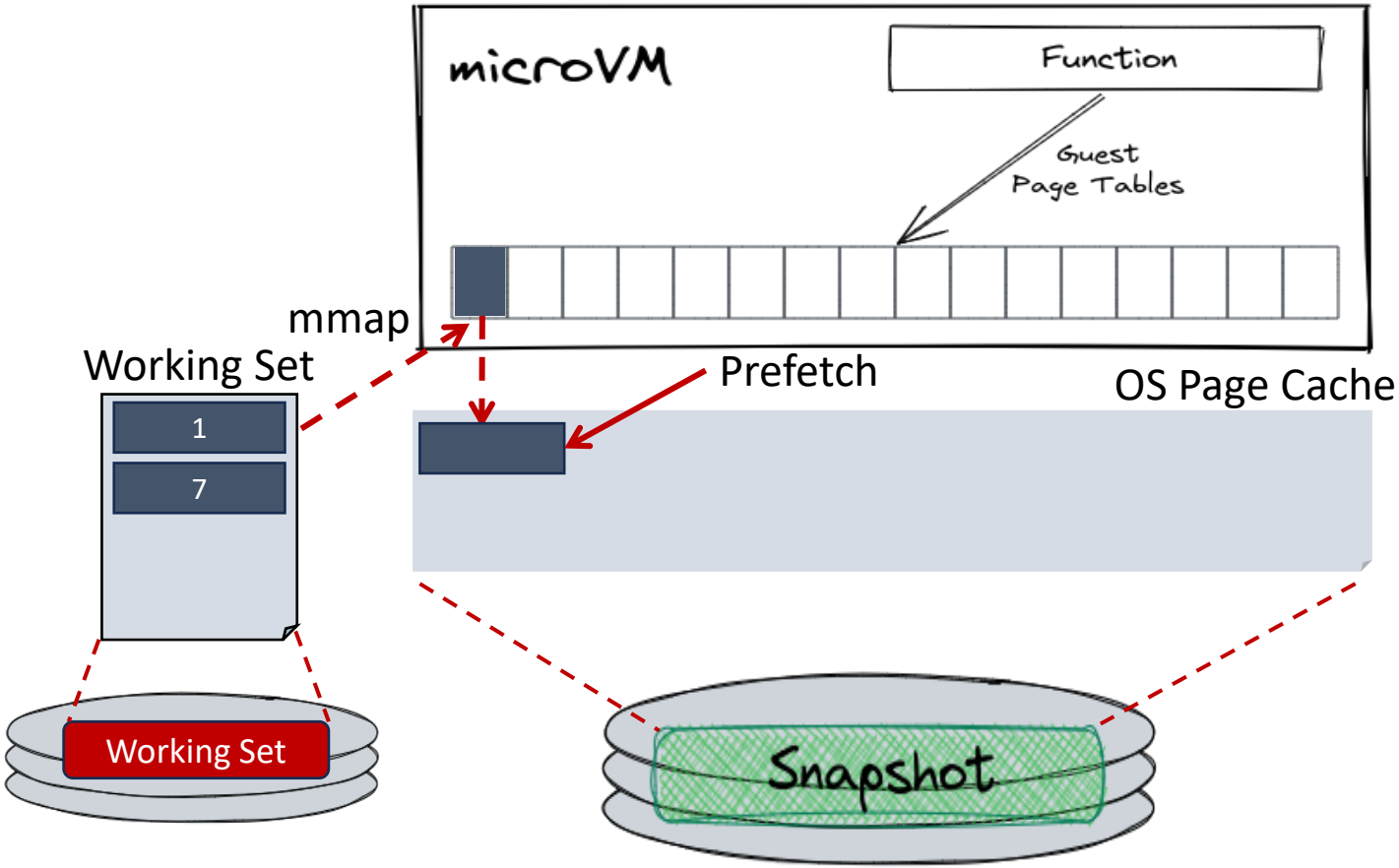

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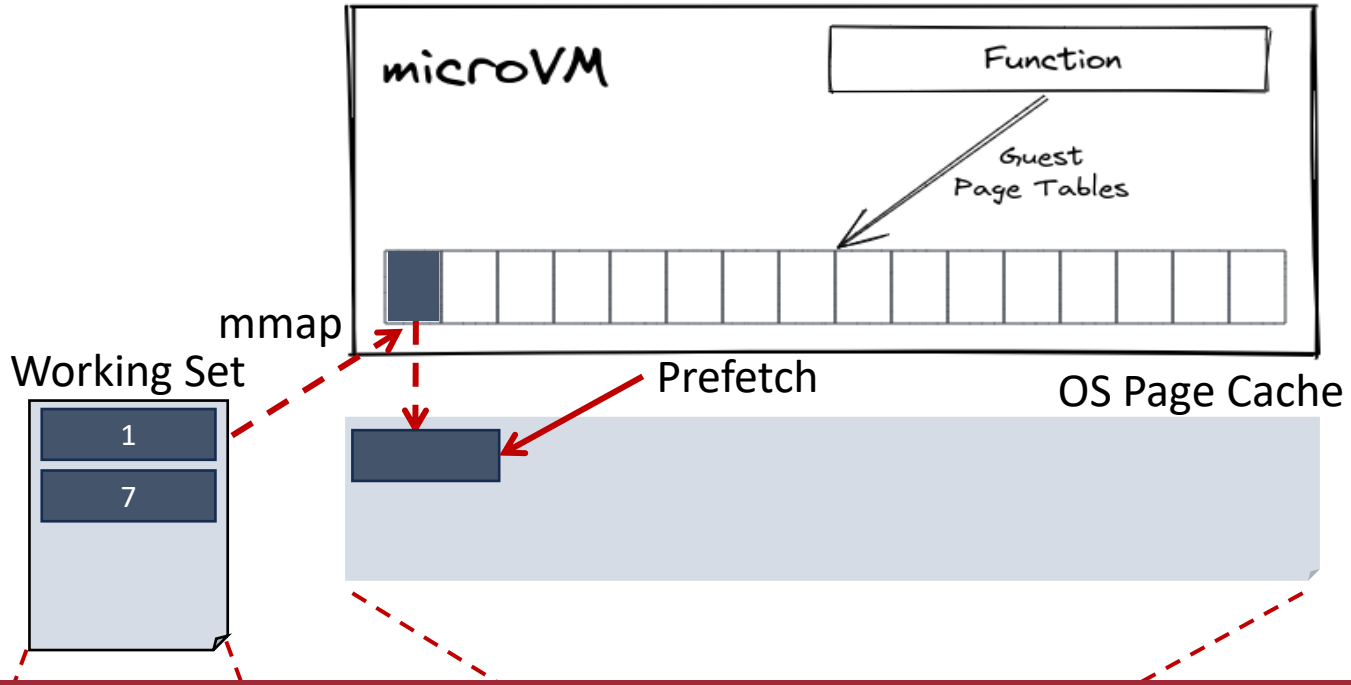

Fragmented working sets incur mmap() syscall overhead

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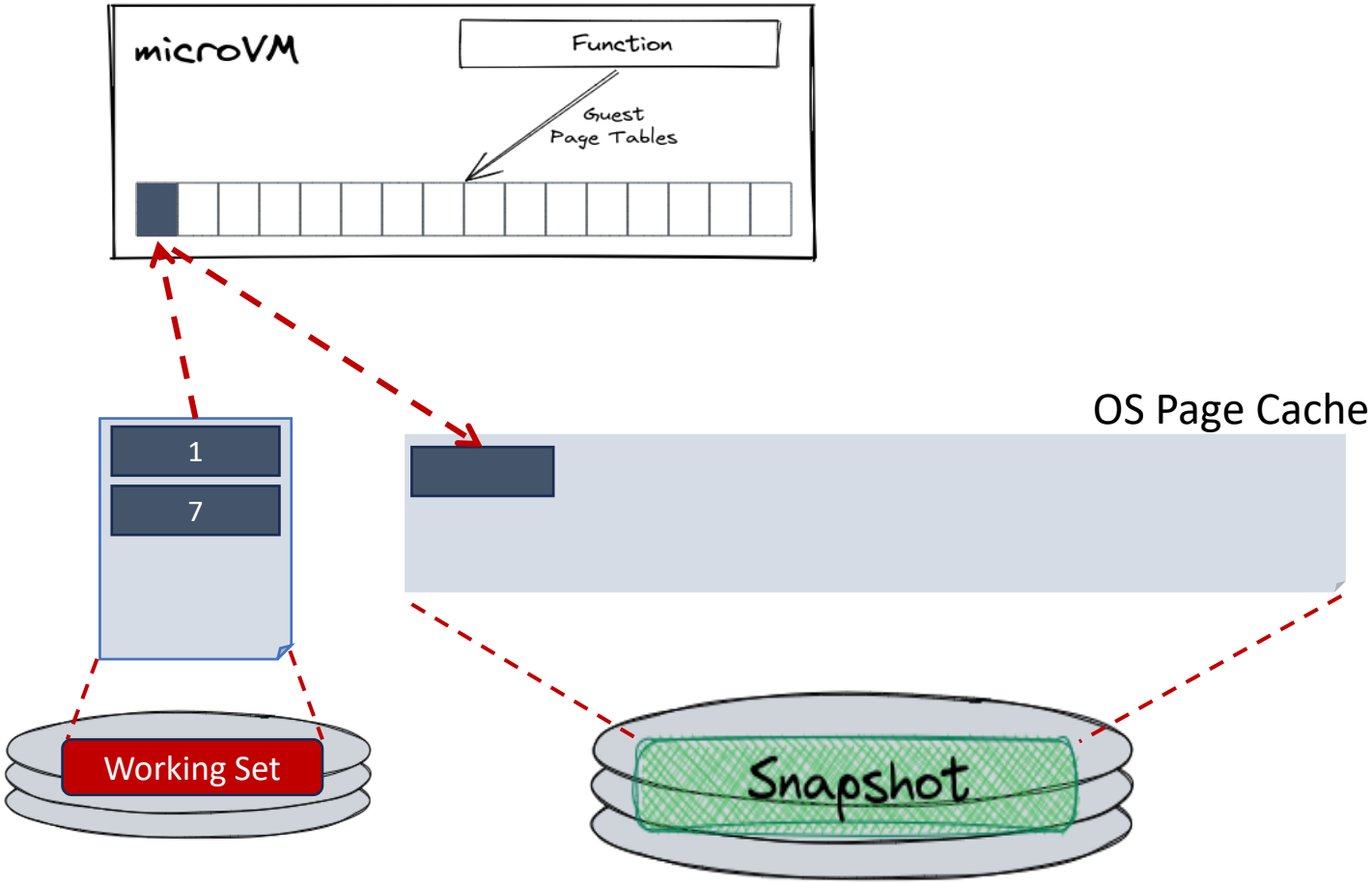

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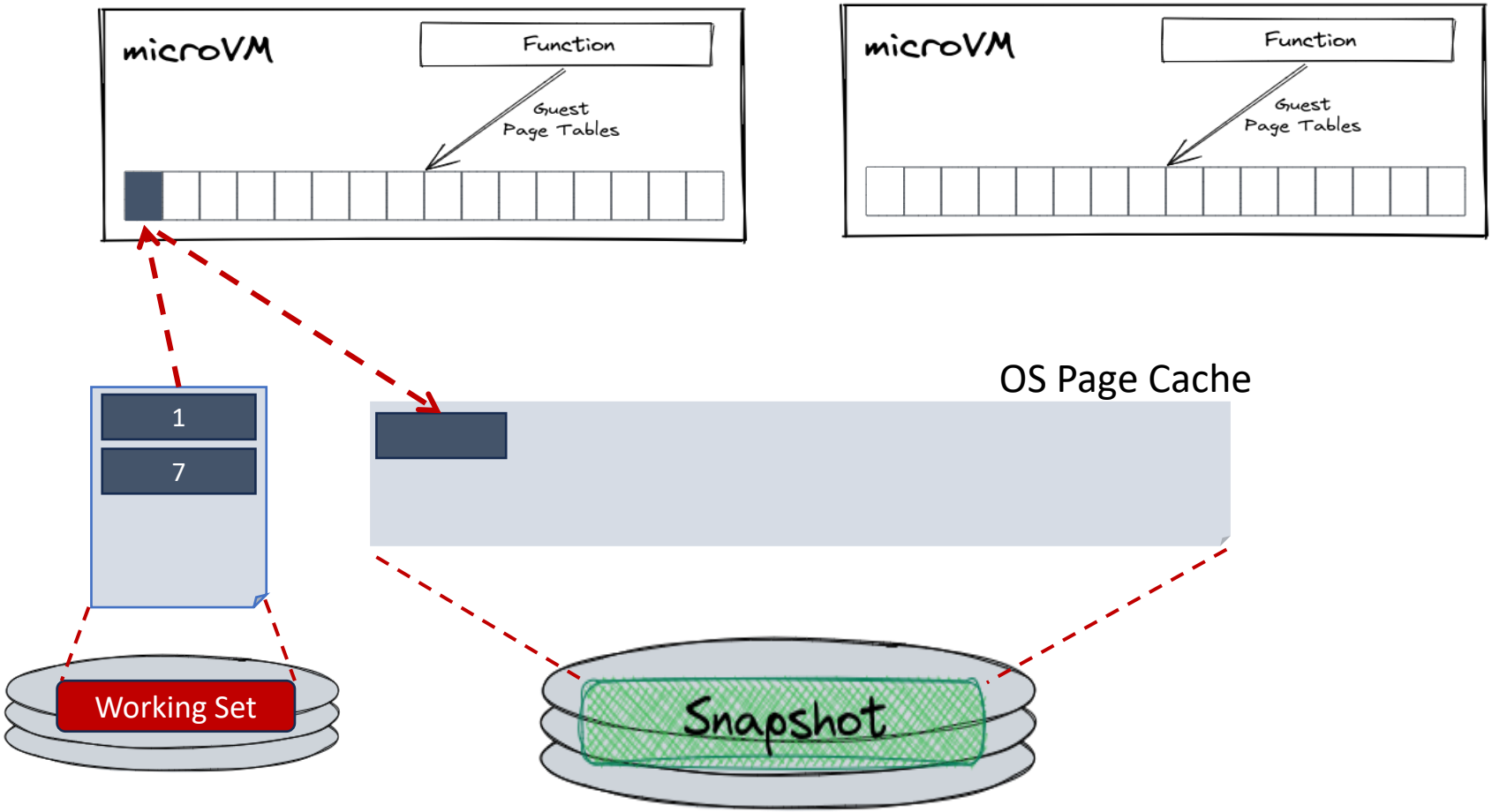

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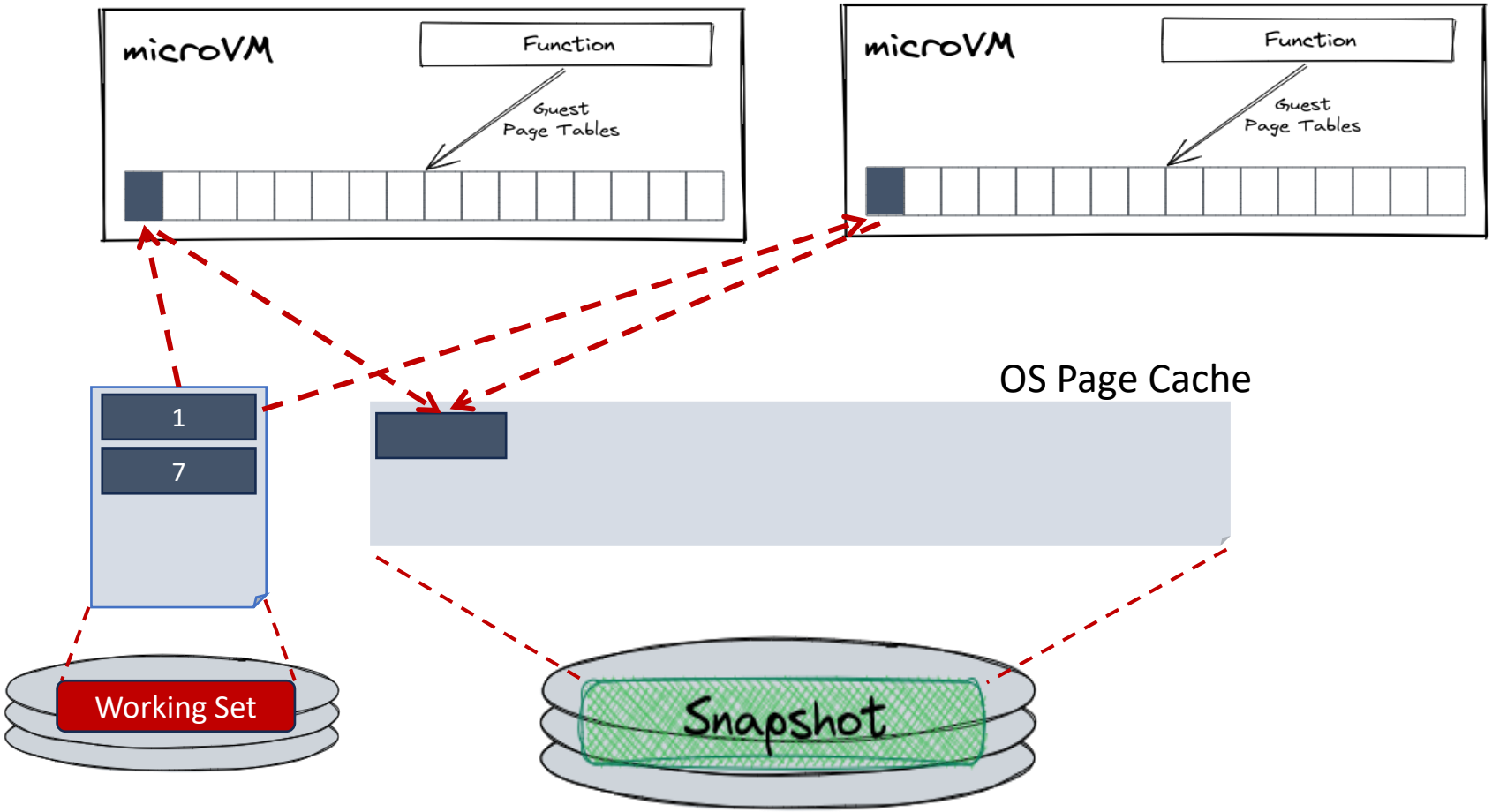

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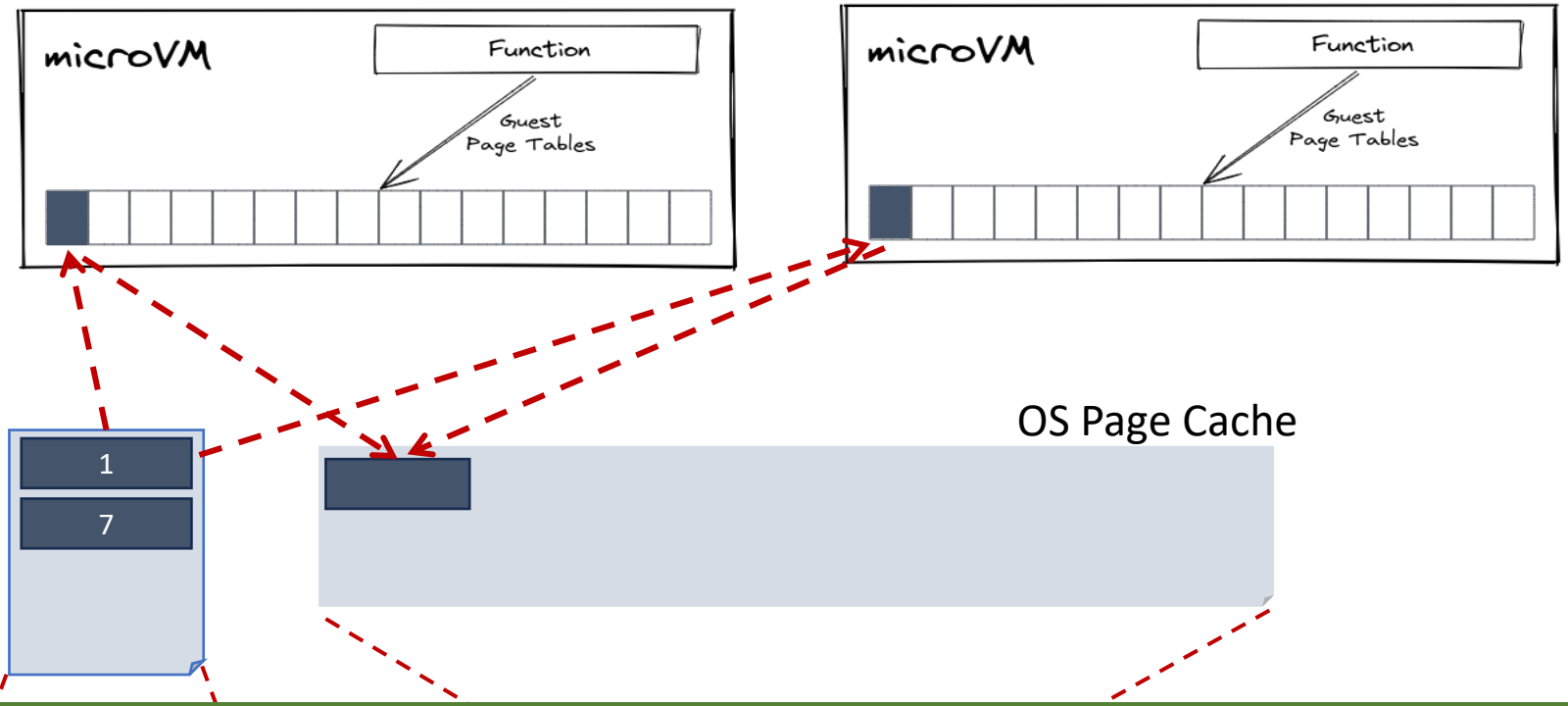
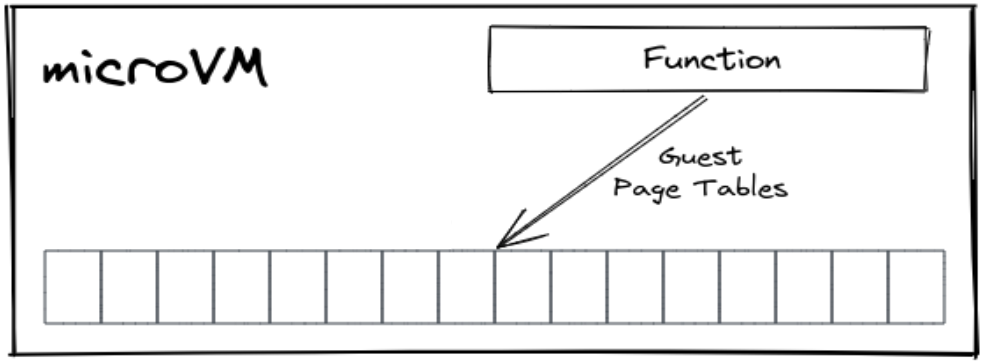
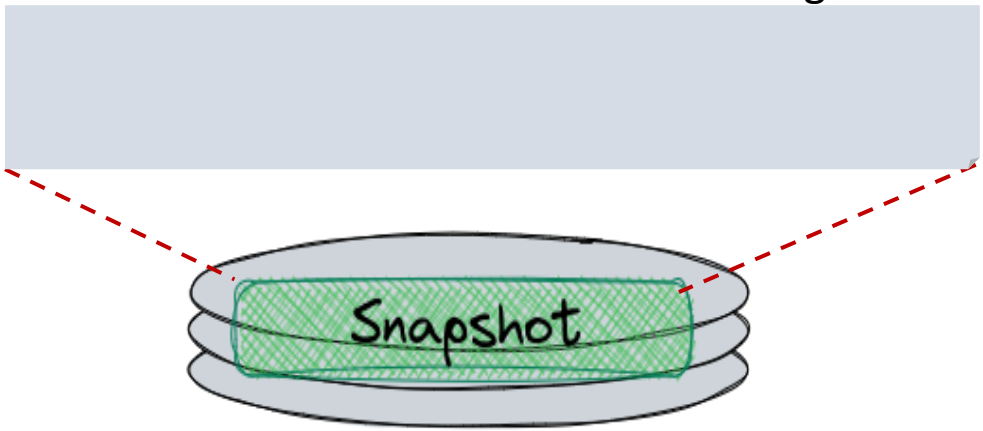


Deduplication via the page cache

The overhead of free pages



OS Page Cache



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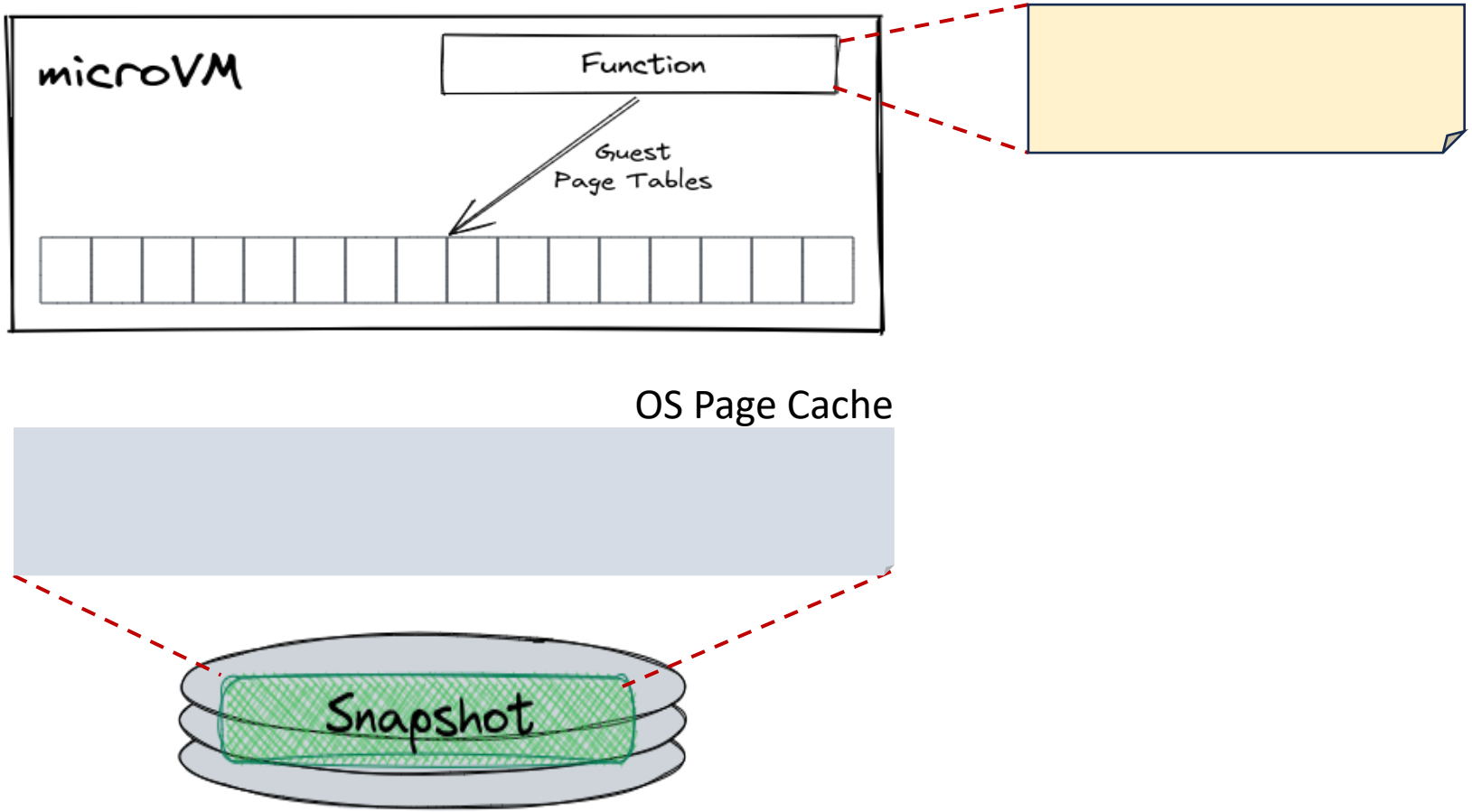

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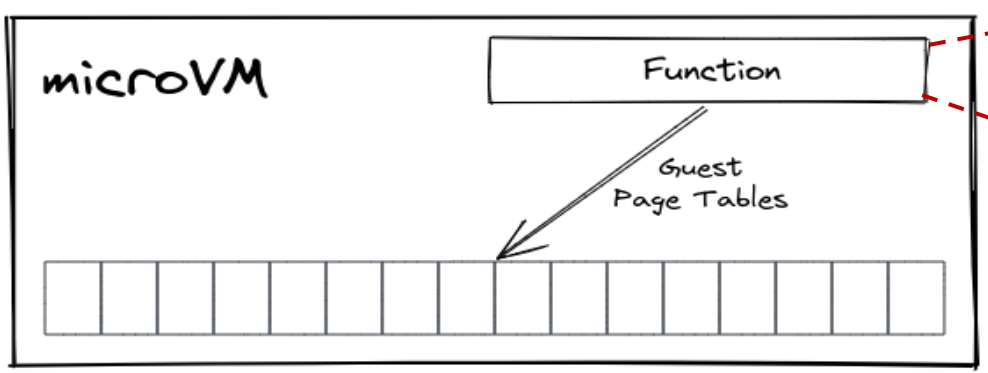
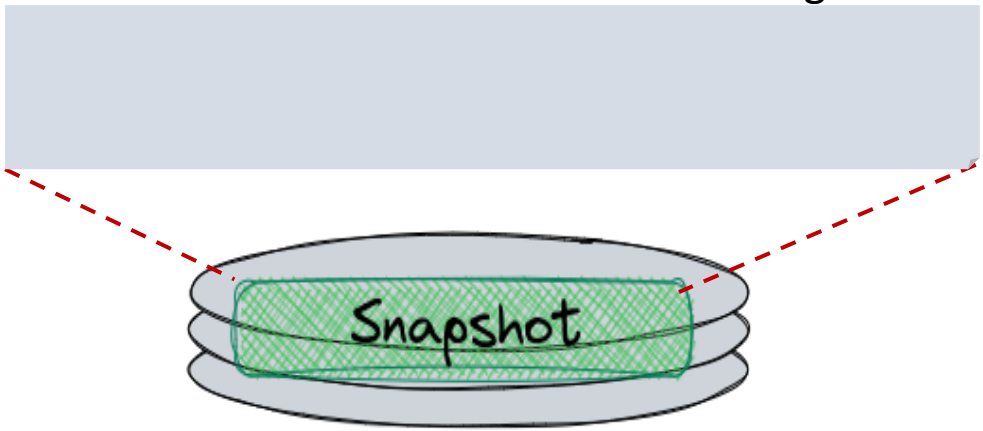



```
fn(input):
    output = malloc()
    return compute(input, &output)
```

OS Page Cache



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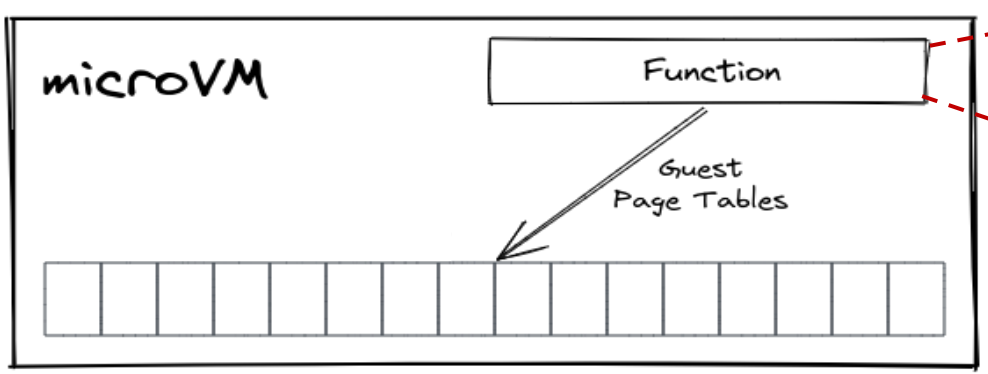


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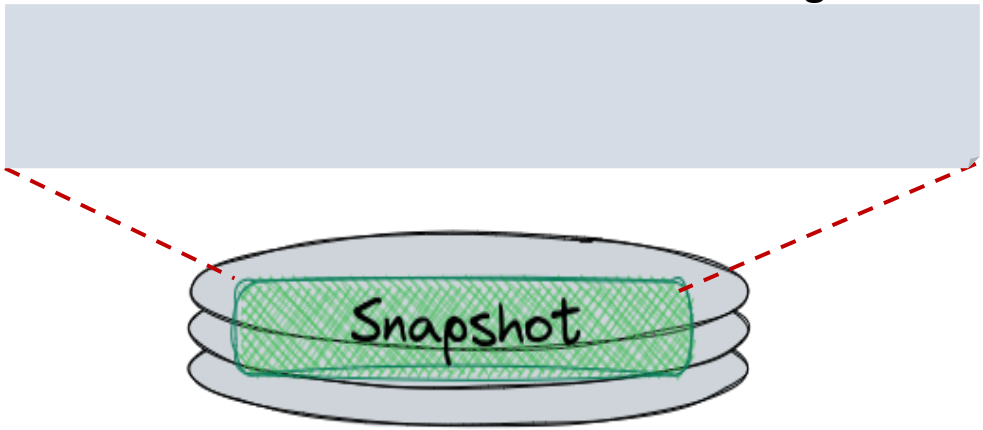
OS Page Cache



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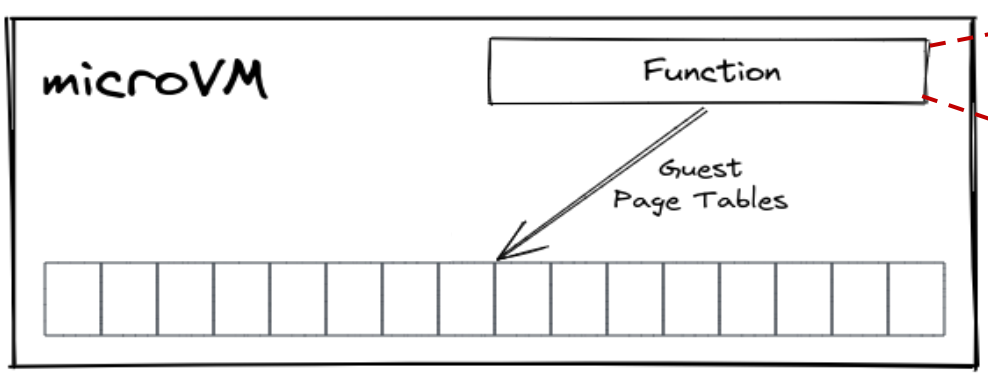


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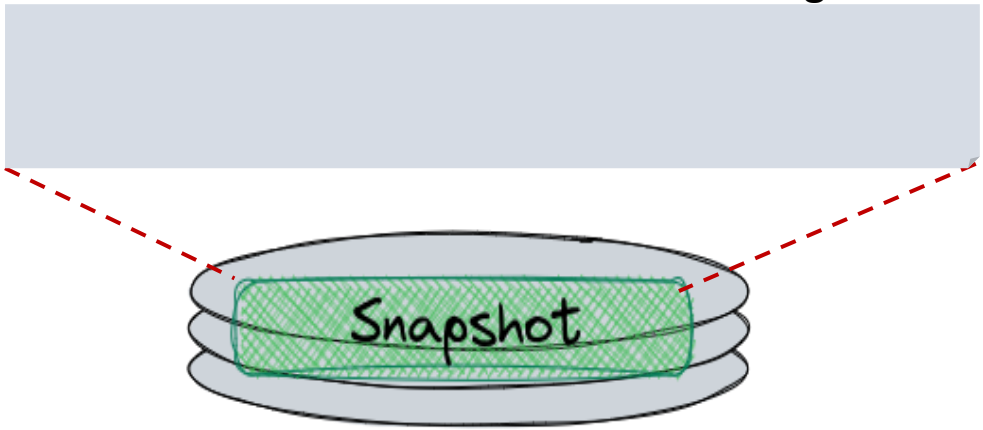
OS Page Cache



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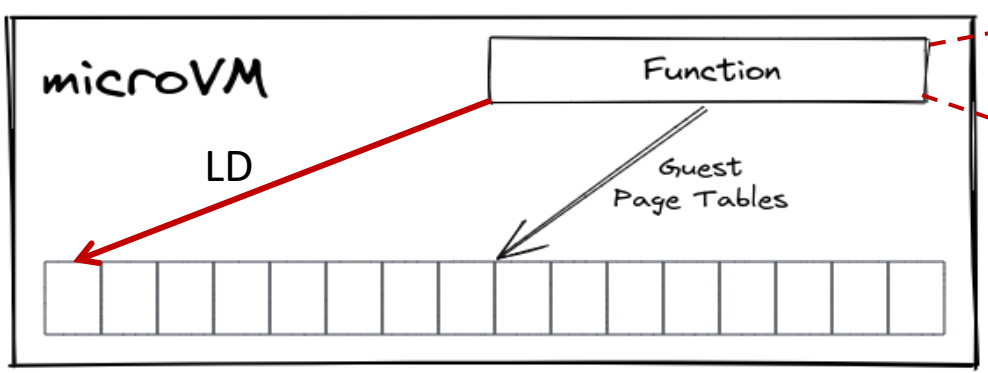


```
fn(input):
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```
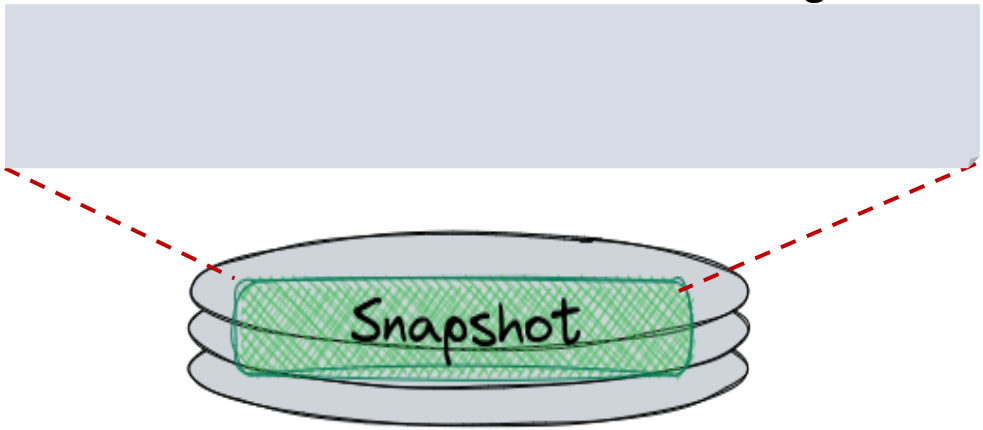

OS Page Cache



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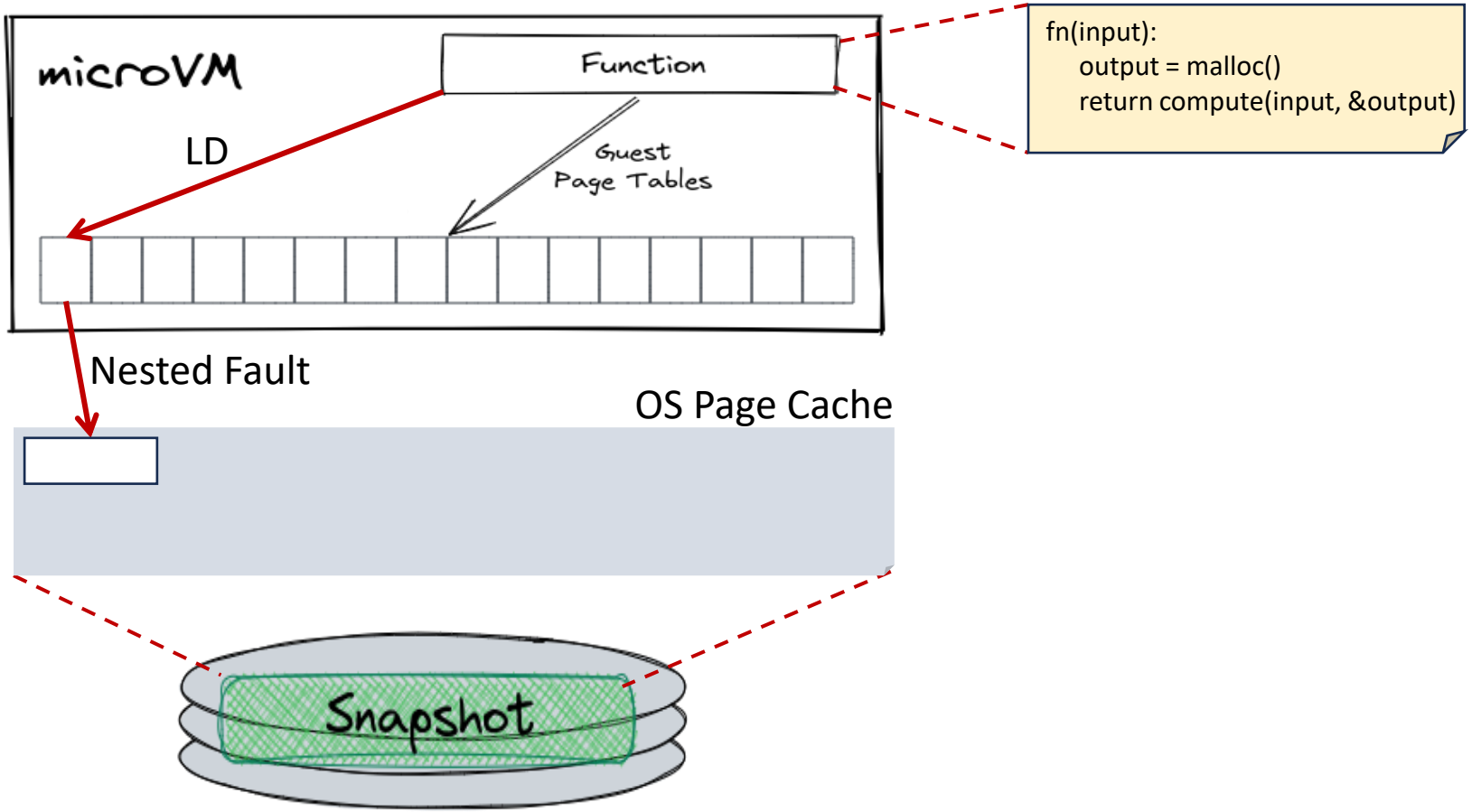

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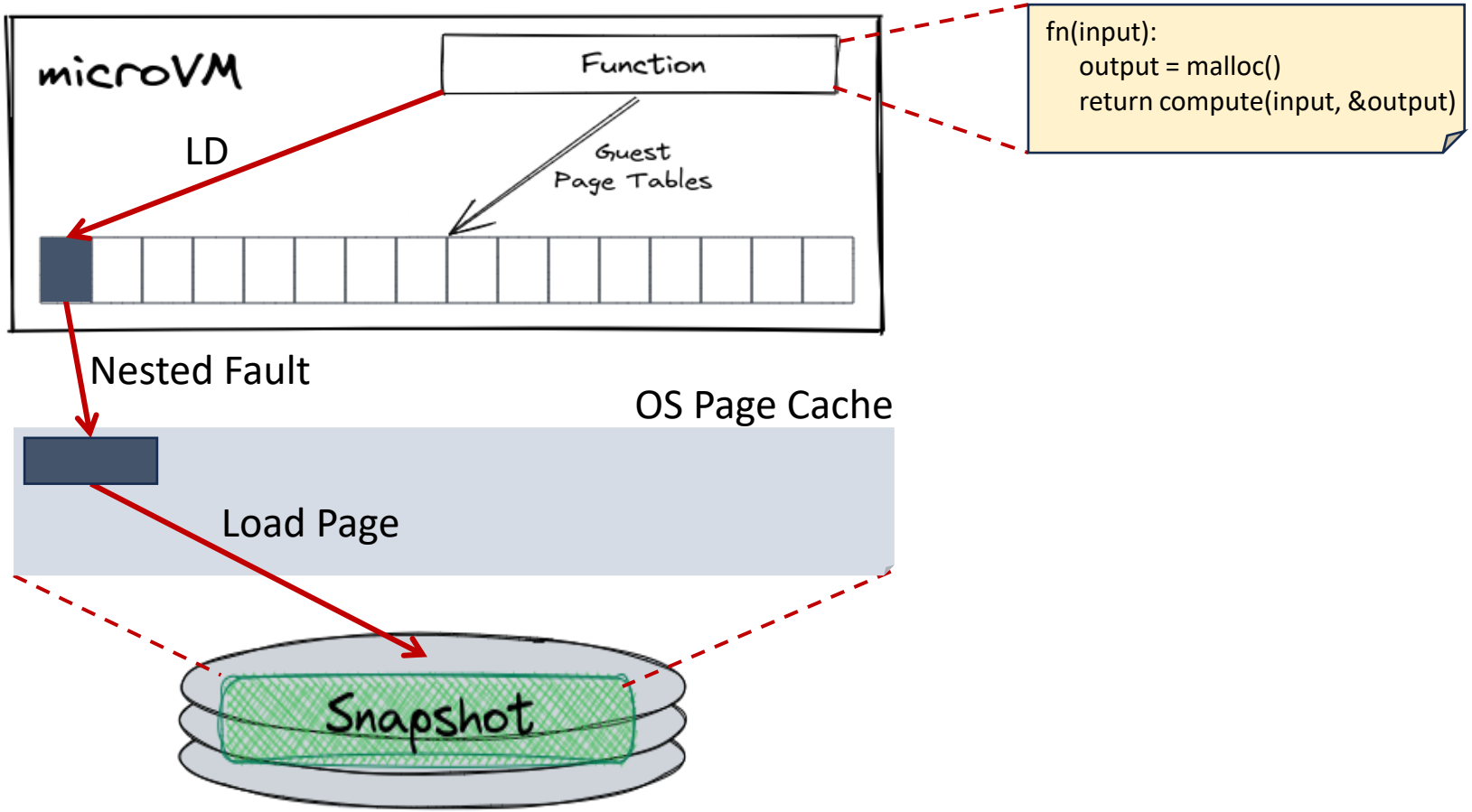

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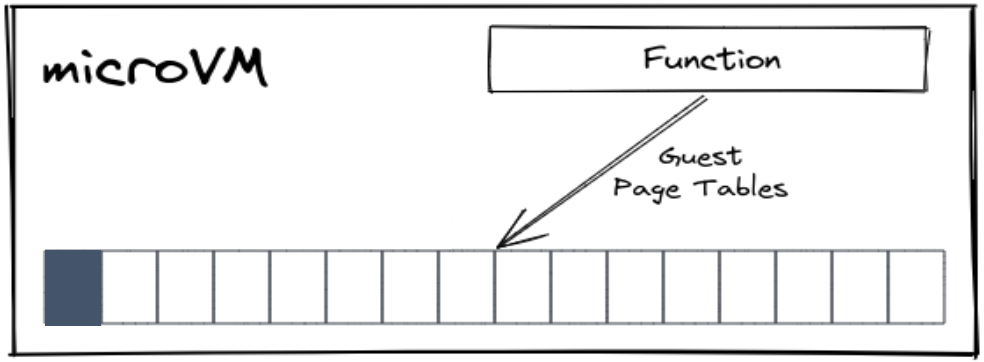
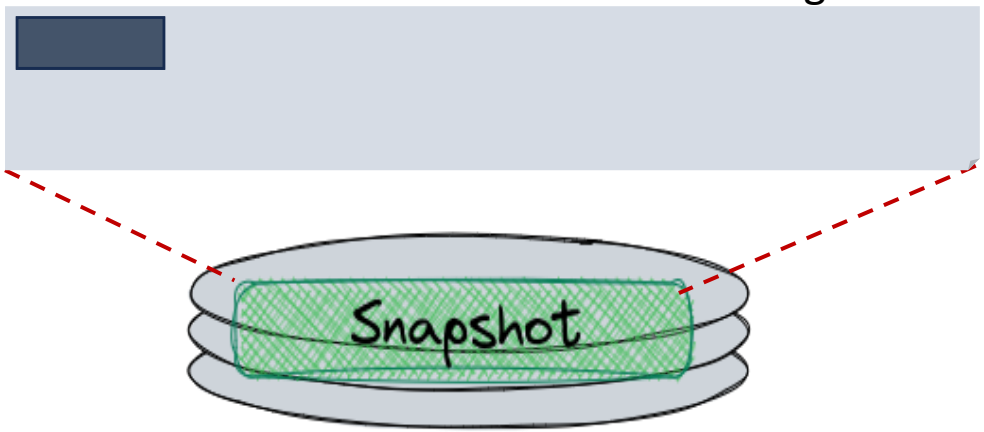
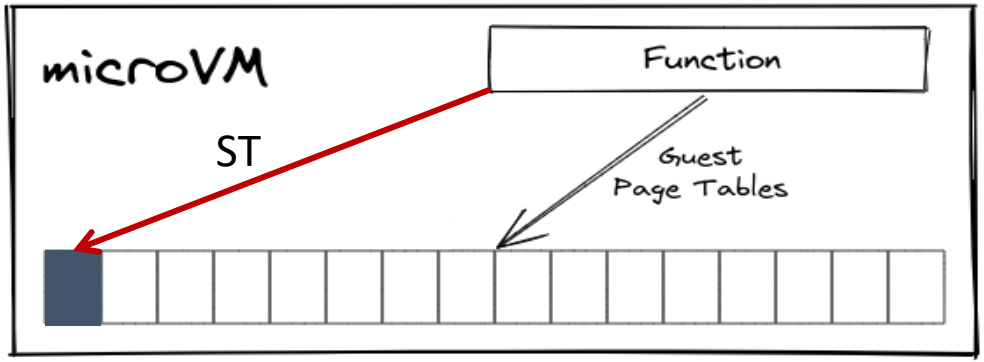


OS Page Cache

Anonymous Memory

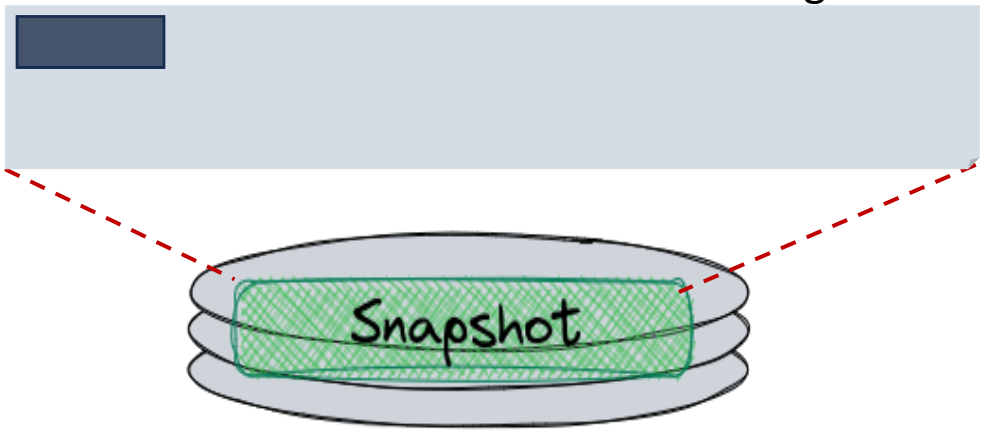


The overhead of free pages

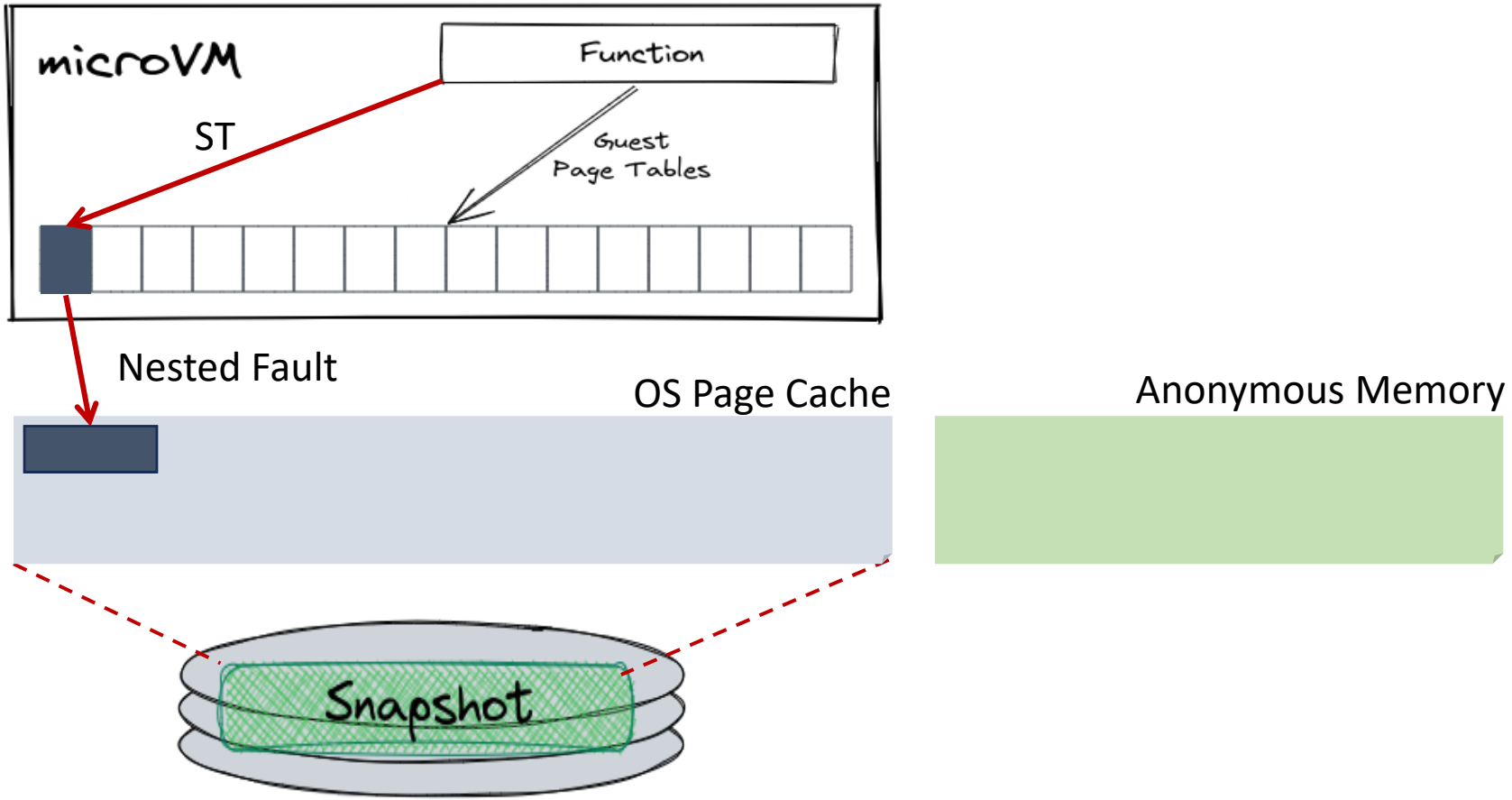


OS Page Cache

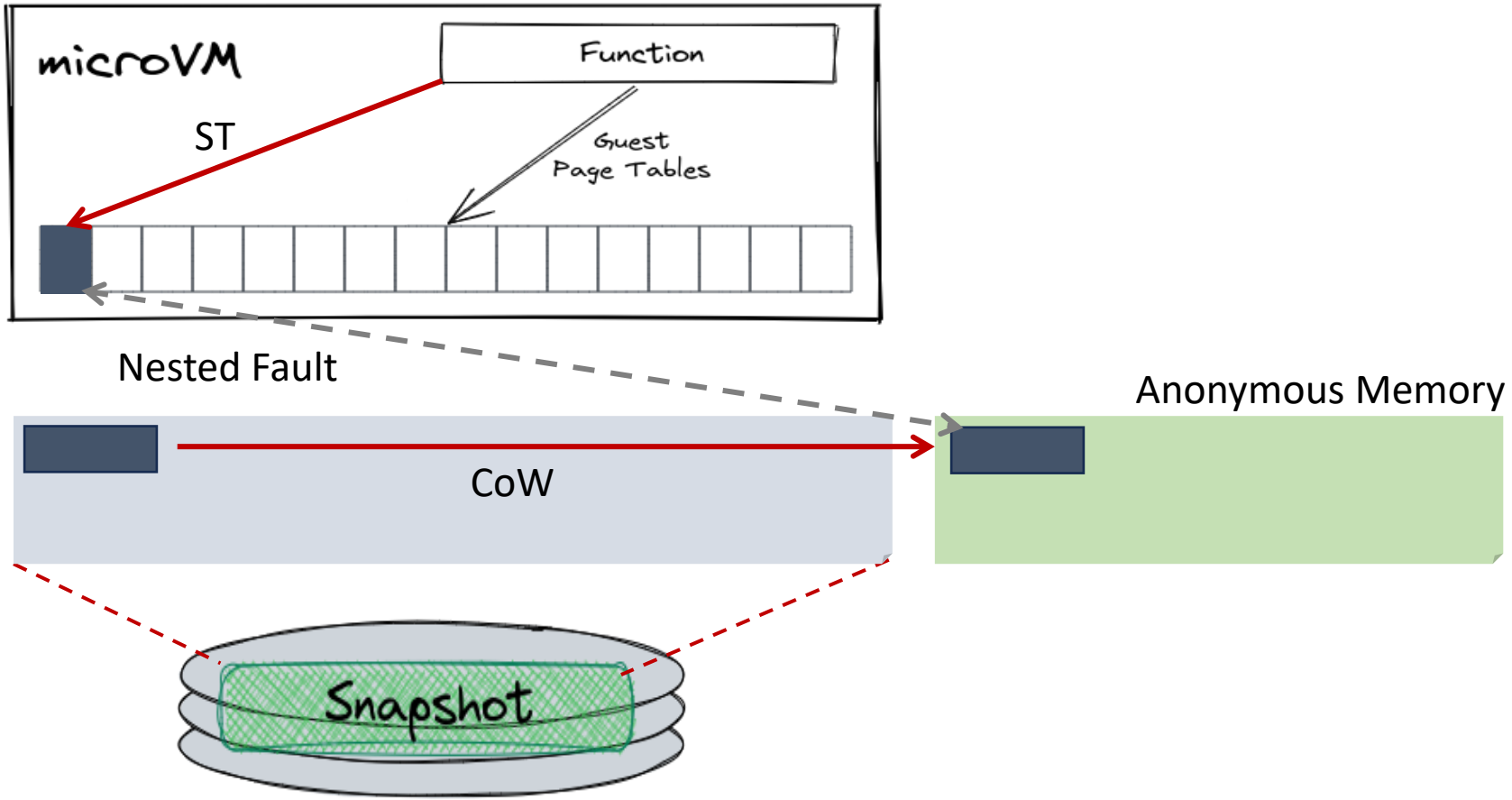
Anonymous Memory



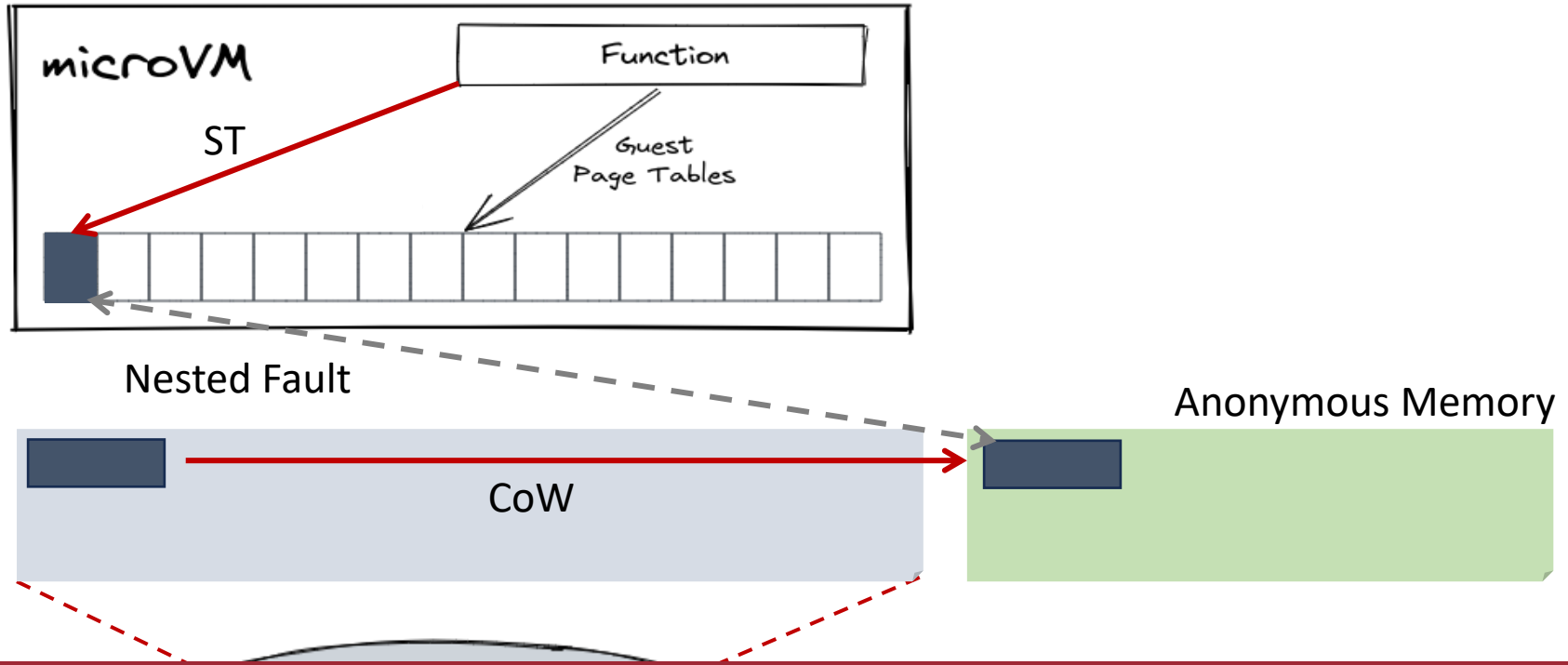
The overhead of free pages



The overhead of free pages

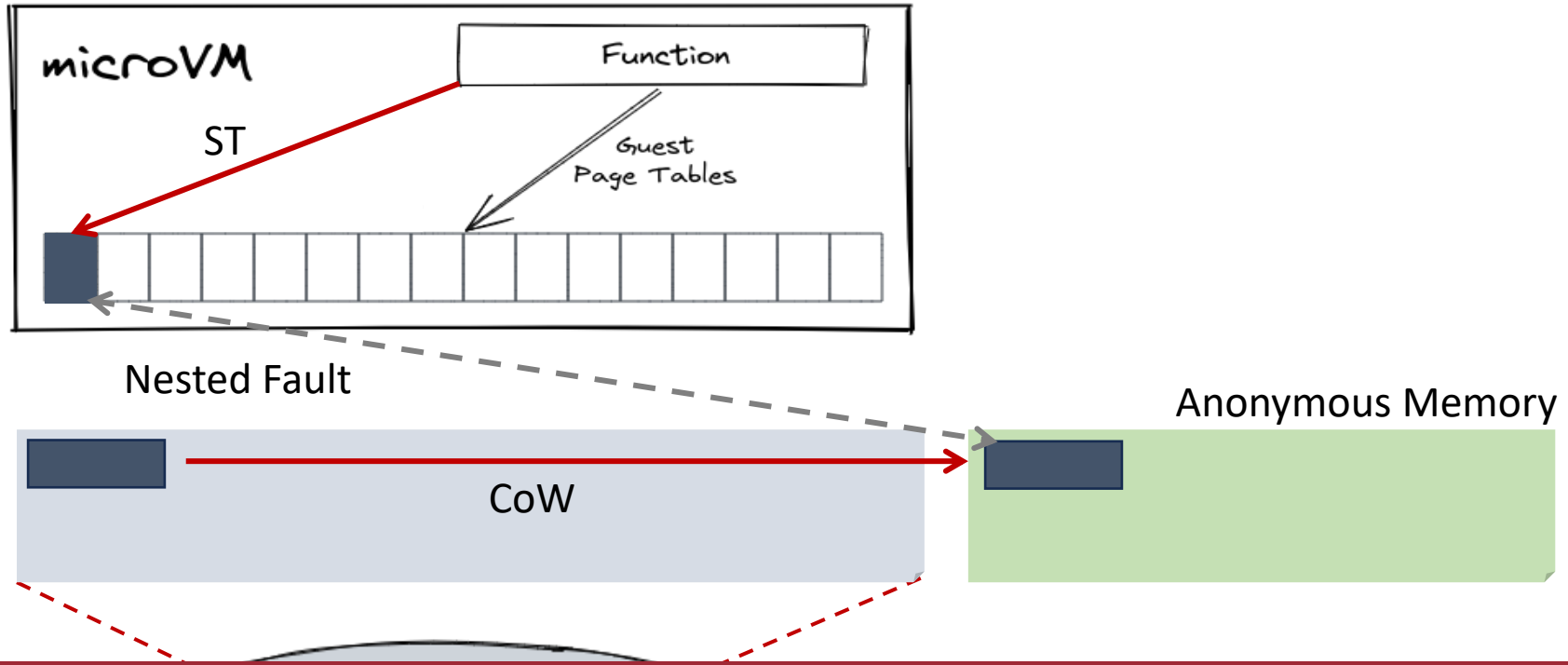


The overhead of free pages



Free pages contain no valid contents == Wasted I/O

The overhead of free pages



Prior art filters free pages from loading via snapshot scanning

Outline

→ FaaS Snapshotting

→ Working Set Prefetching

→ SnapBPF

i. eBPF capture and prefetch

ii. PV free page filtering

→ Evaluation

→ Conclusion

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→ FaaS Snapshotting

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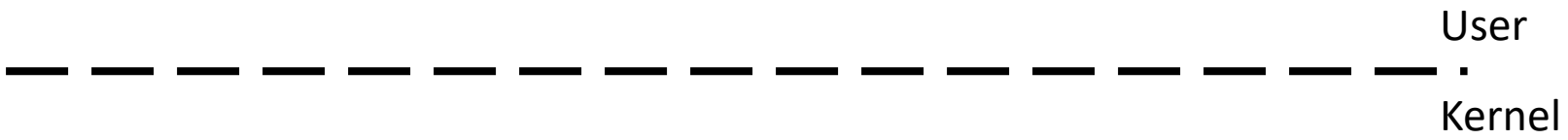
eBPF primer



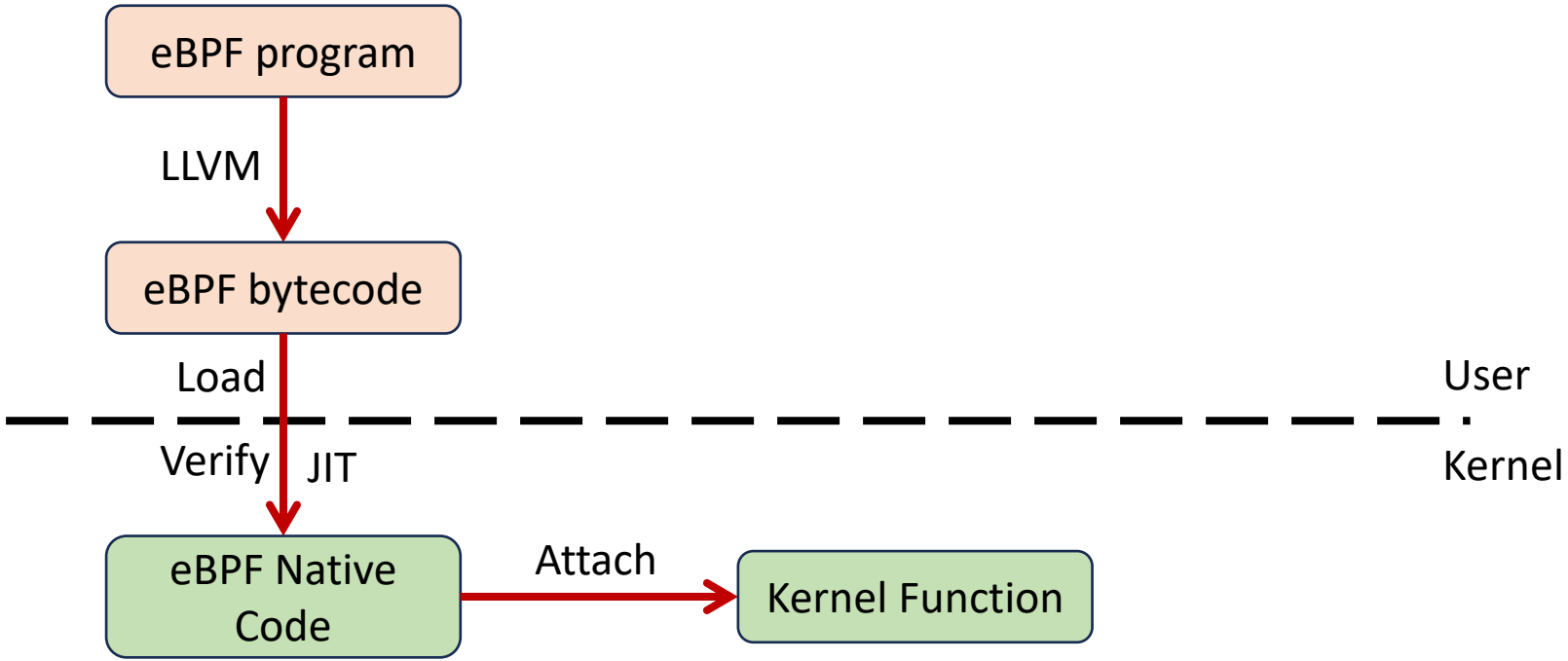
eBPF primer

eBPF primer

eBPF primer


eBPF program
LLVM
eBPF bytecode
Load
User
Verify
JIT
Kernel
eBPF Native Code

eBPF primer


eBPF program
LLVM
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Load
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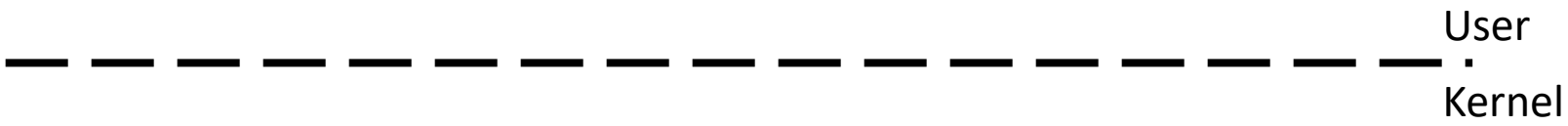
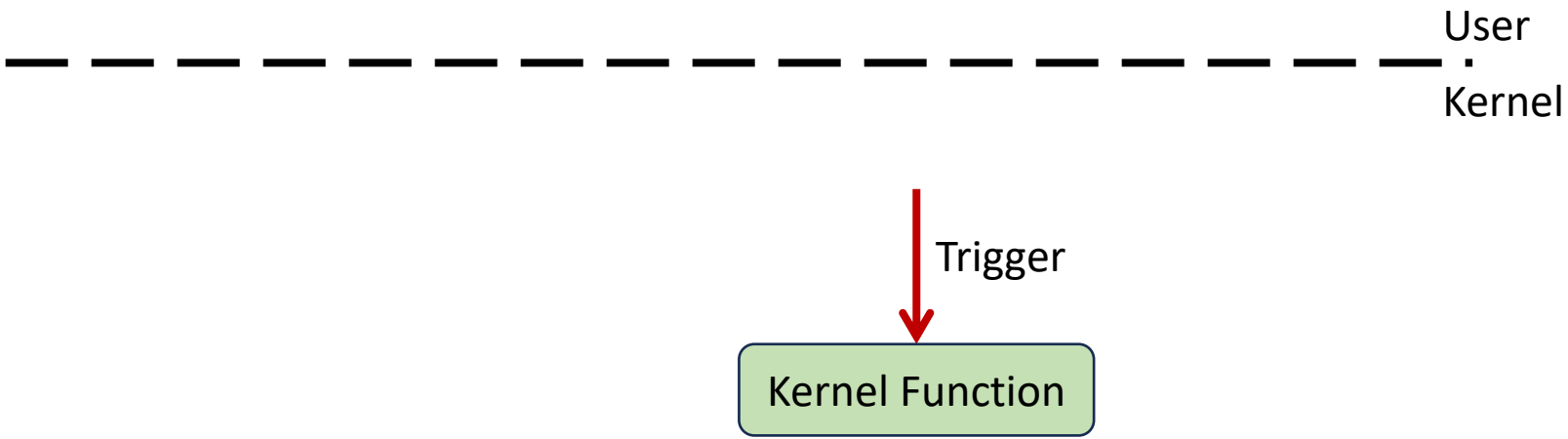
Kernel
eBPF Native Code
Attach
Kernel Function

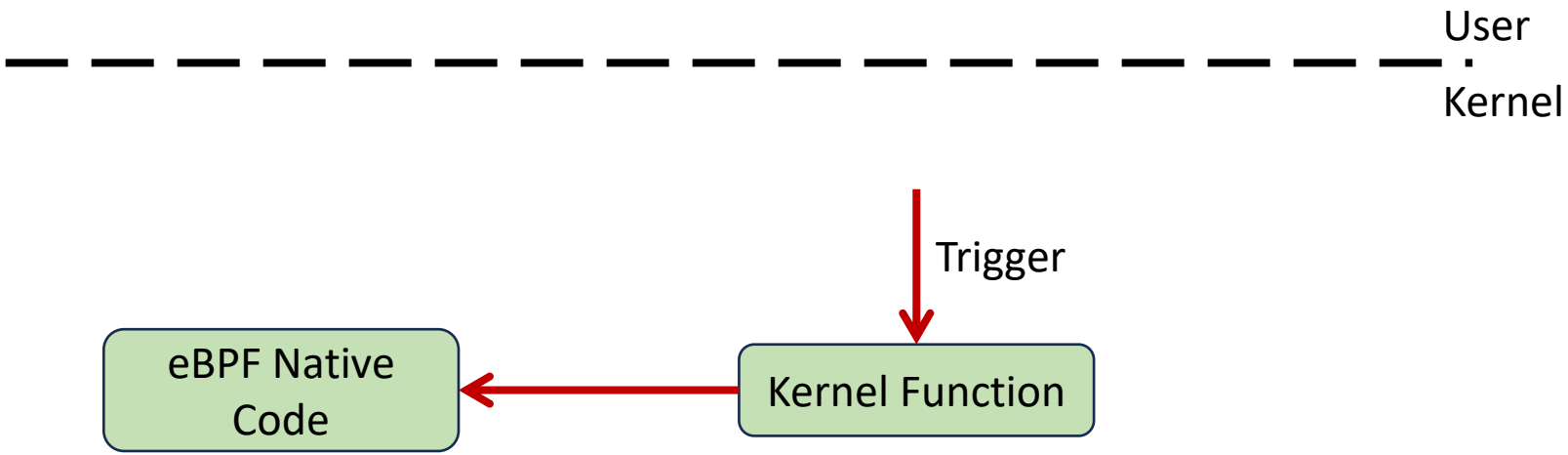
eBPF primer



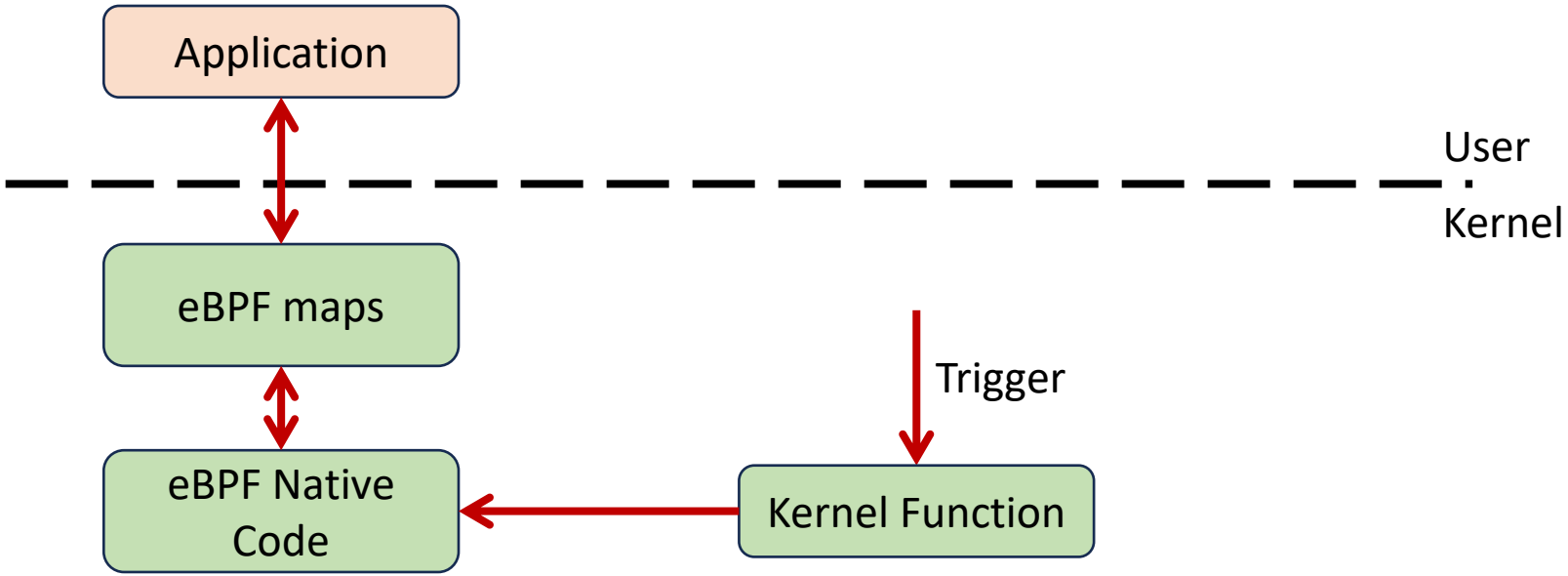
eBPF primer



eBPF primer



eBPF primer

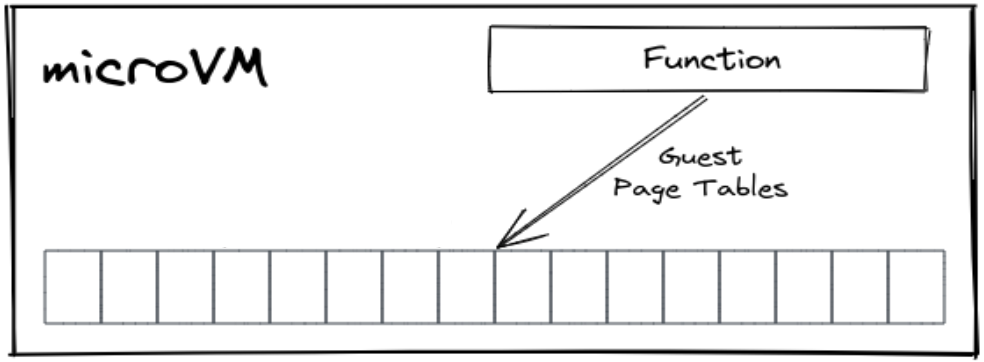

Application
User
Kernel
eBPF maps
Trigger
eBPF Native Code
Kernel Function

Insight:

Insight:

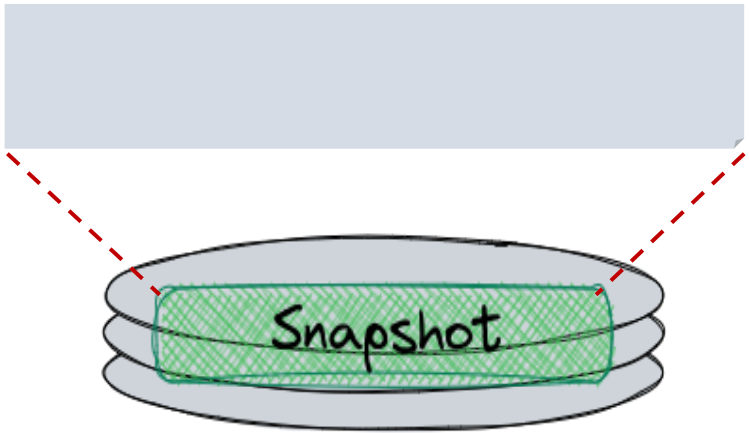
Use eBPF for kernelspace working set prefetching

eBPF Capture

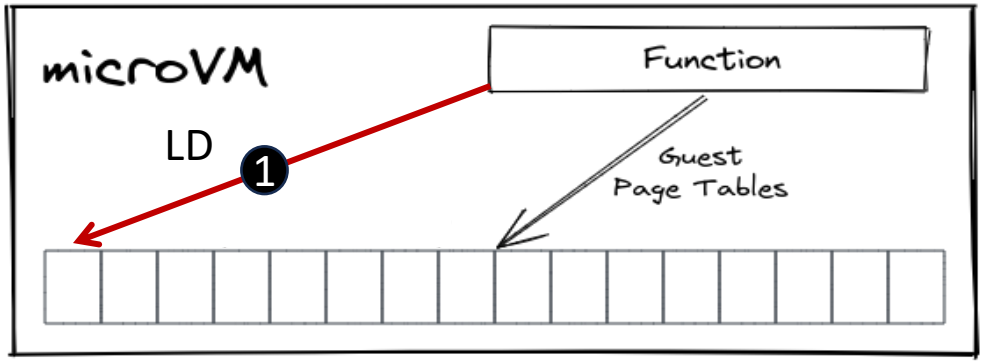


Host Kernel

OS Page Cache

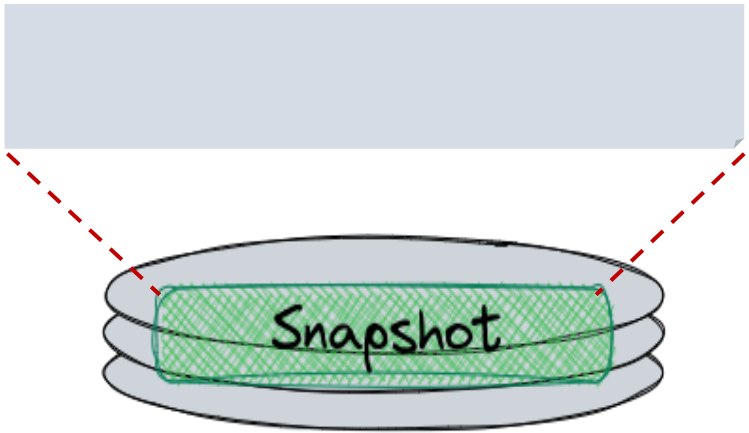


eBPF Capture

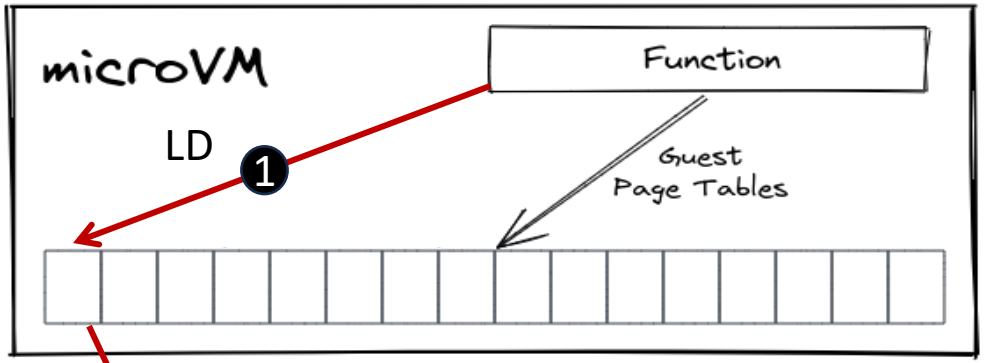


Host Kernel

OS Page Cache



eBPF Capture

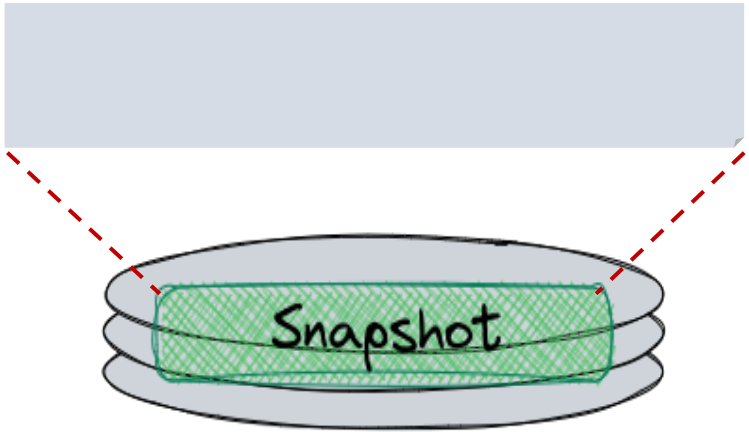


Nested Fault 2

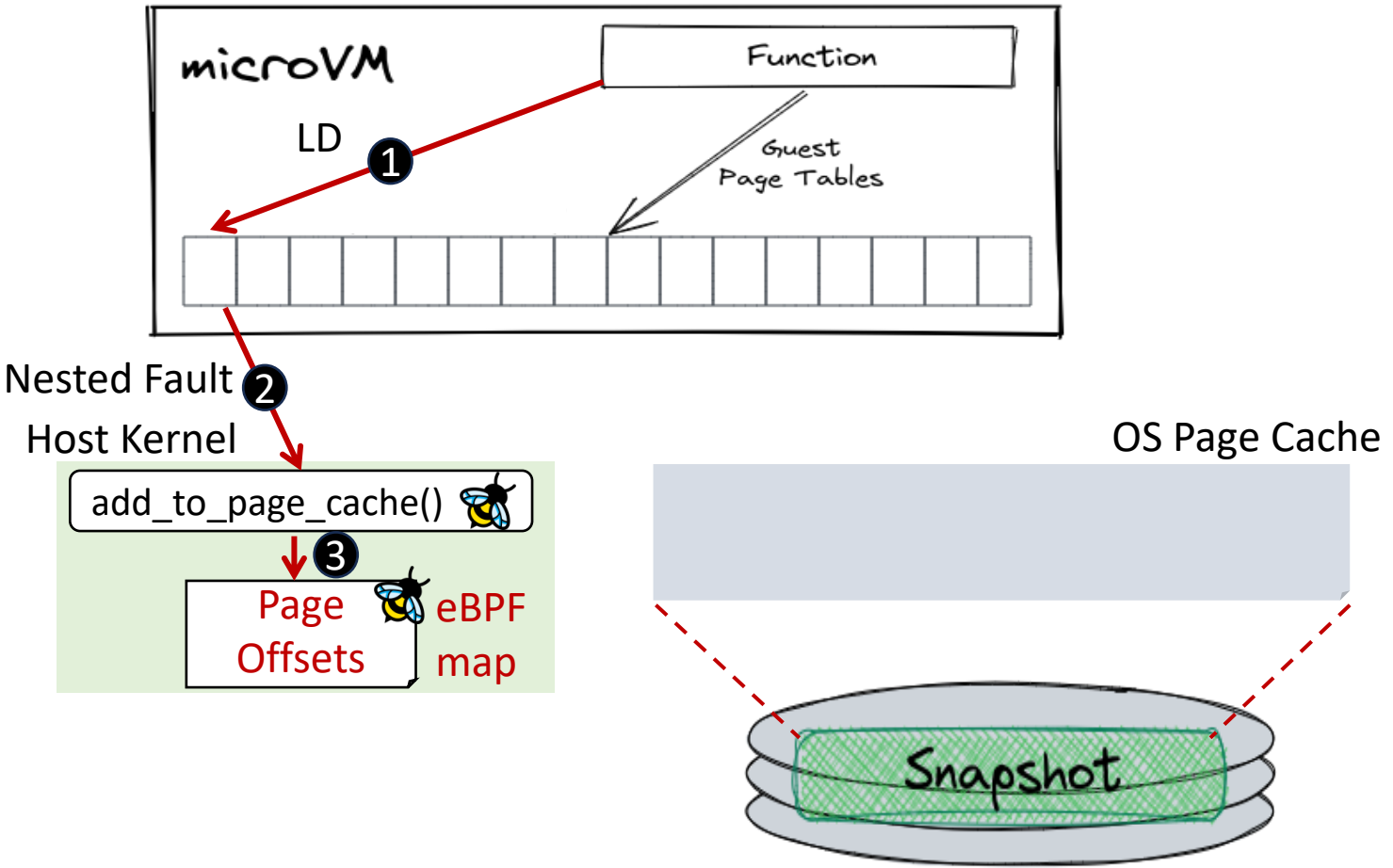
Host Kernel

add_to_page_cache()

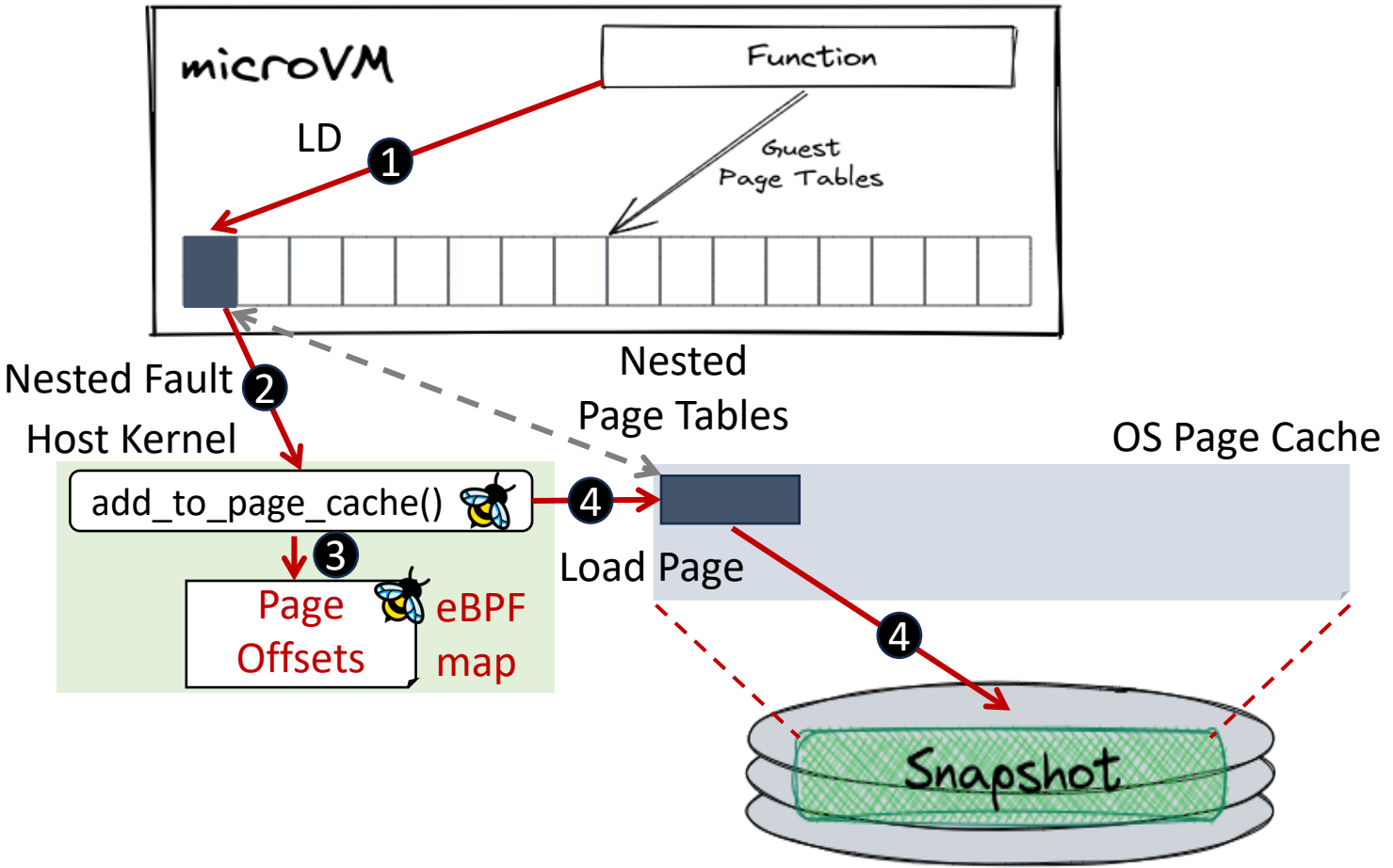
OS Page Cache



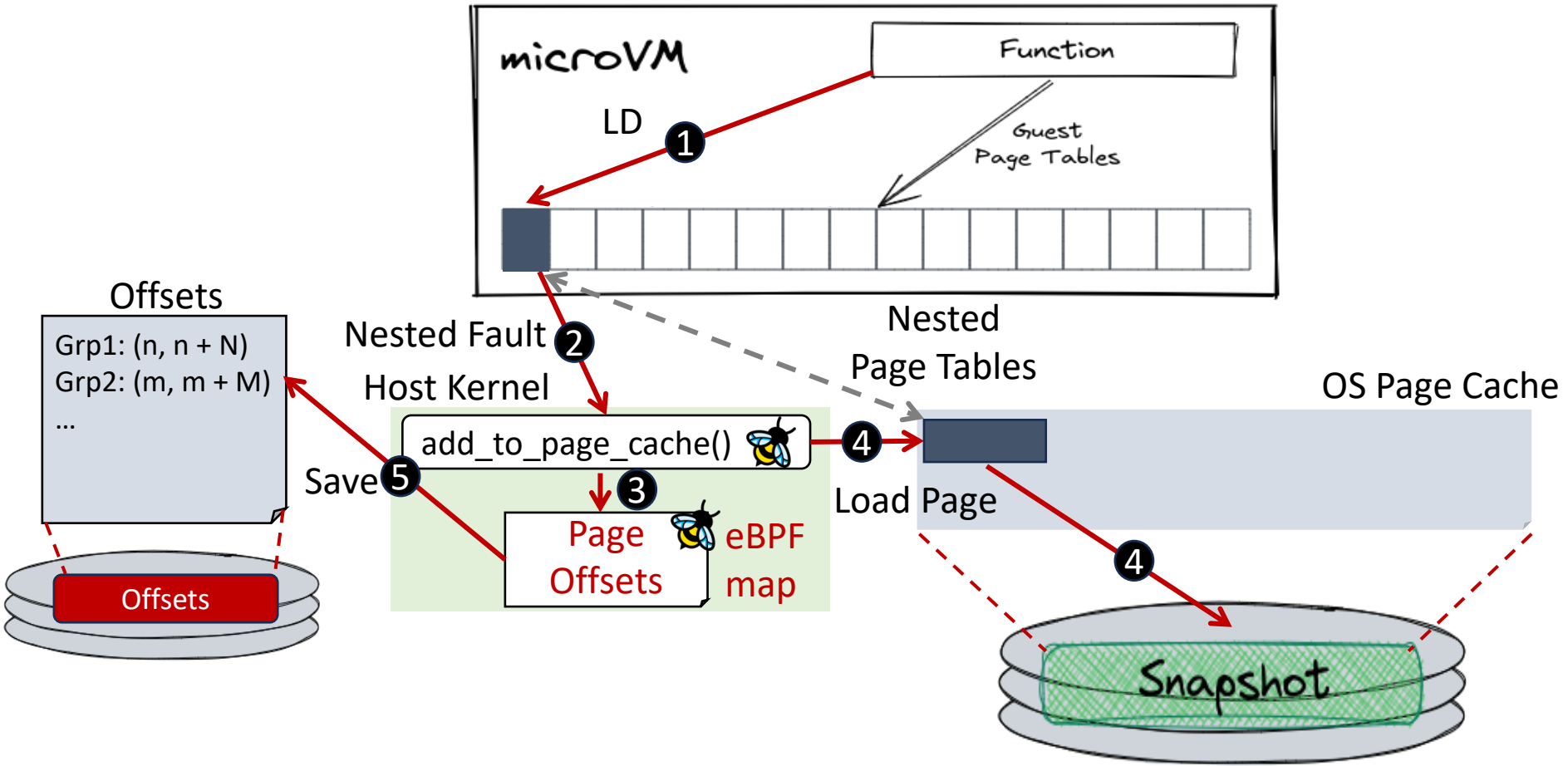
eBPF Capture



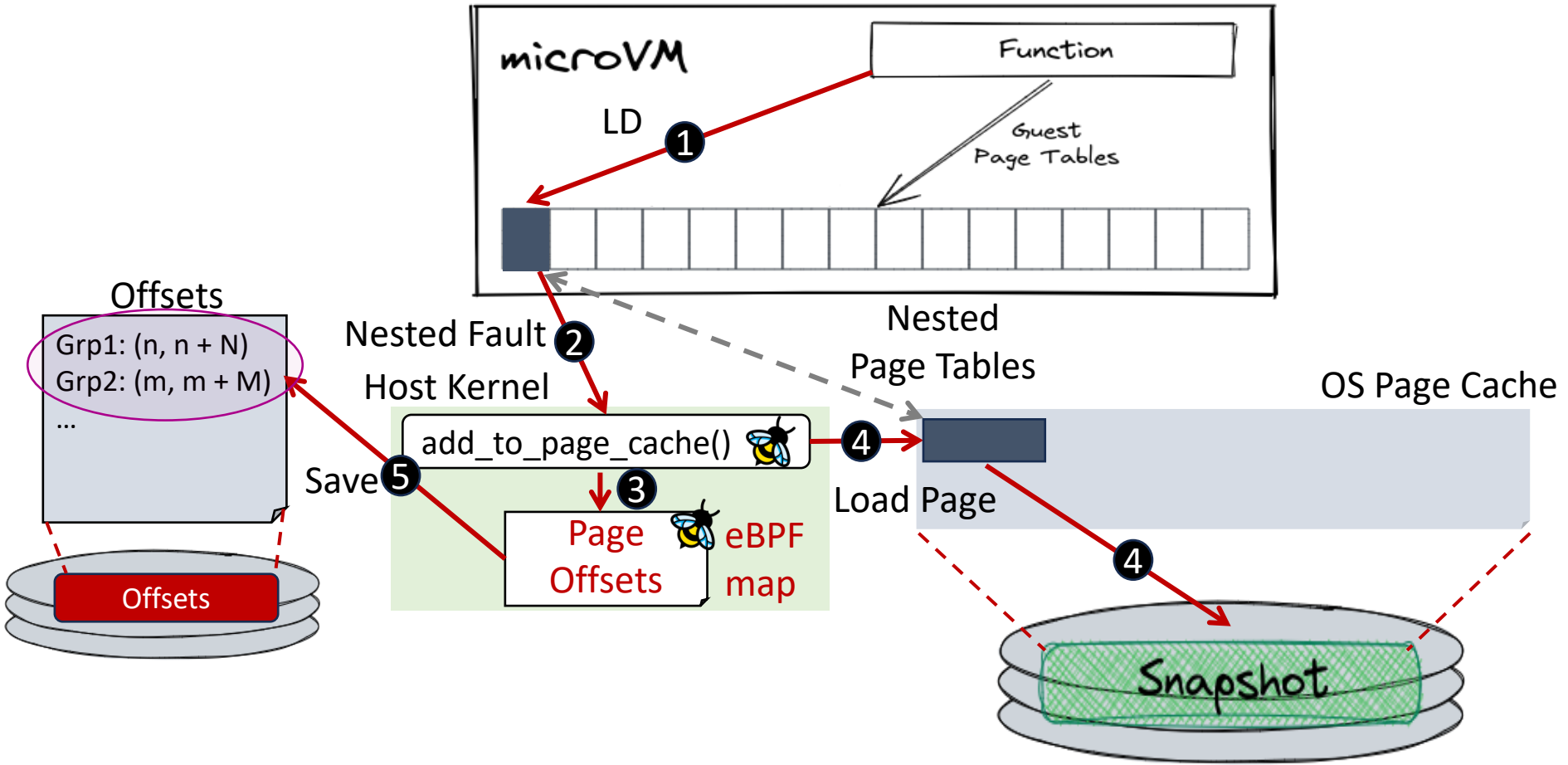
eBPF Capture



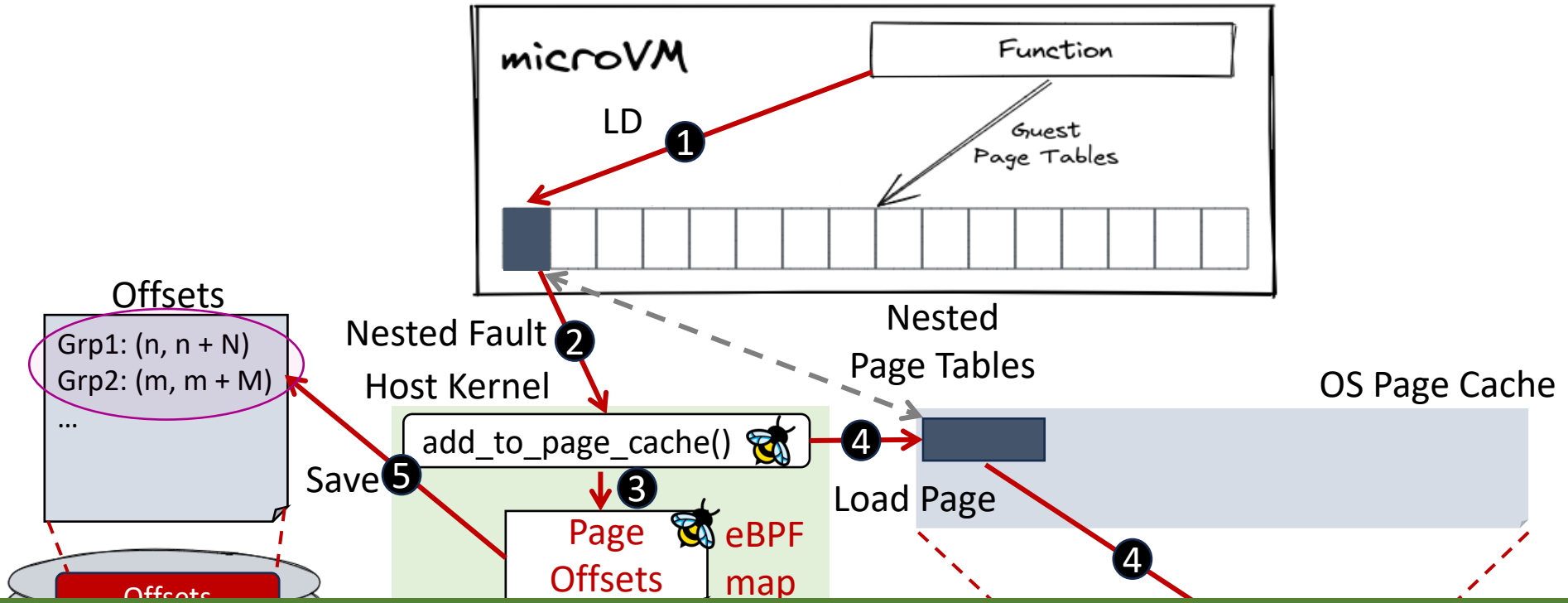
eBPF Capture



eBPF Capture

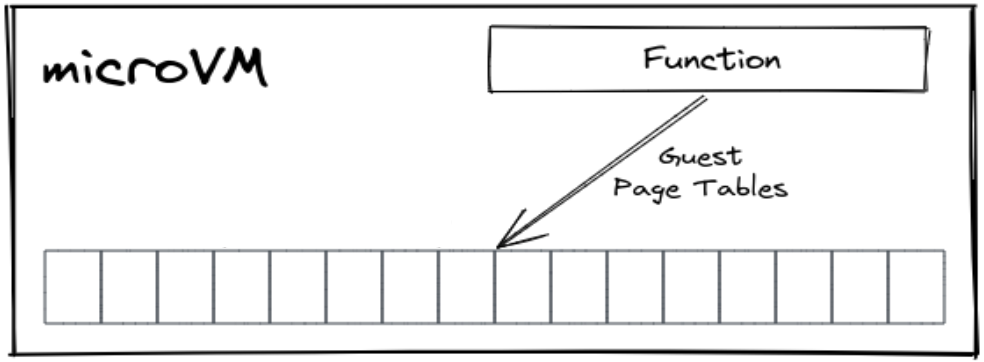


eBPF Capture



Precise and efficient working set capture in kernelspace

eBPF Prefetch

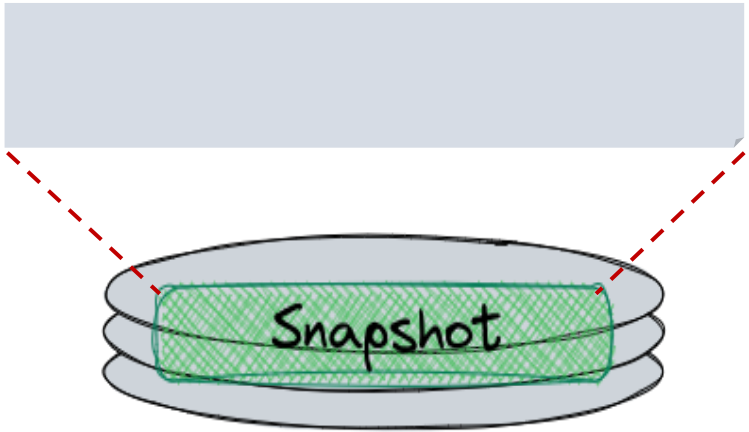


Offsets

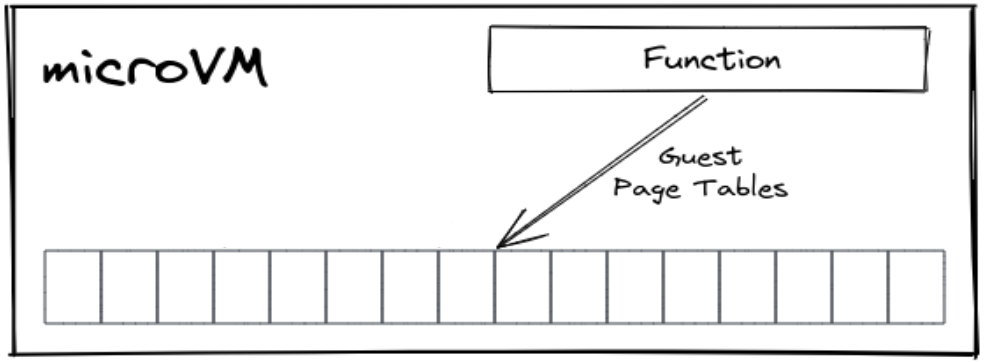
Grp1: (n, n + N)
Grp2: (m, m + M)
…

Host Kernel

OS Page Cache



eBPF Prefetch



snapbpf_load()

1

Offsets

Grp1: (n, n + N)
Grp2: (m, m + M)
…

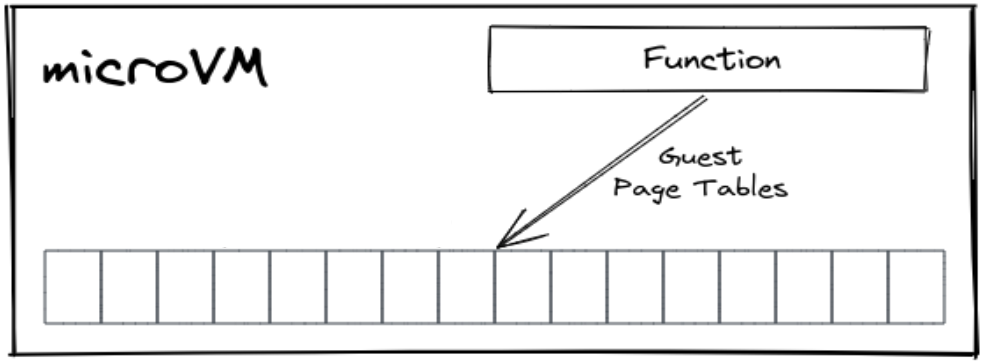
Offsets

Host Kernel

OS Page Cache

Snapshot

eBPF Prefetch



snapbpf_load()

1

Offsets

Grp1: (n, n + N)
Grp2: (m, m + M)
…

Host Kernel

OS Page Cache

Offsets

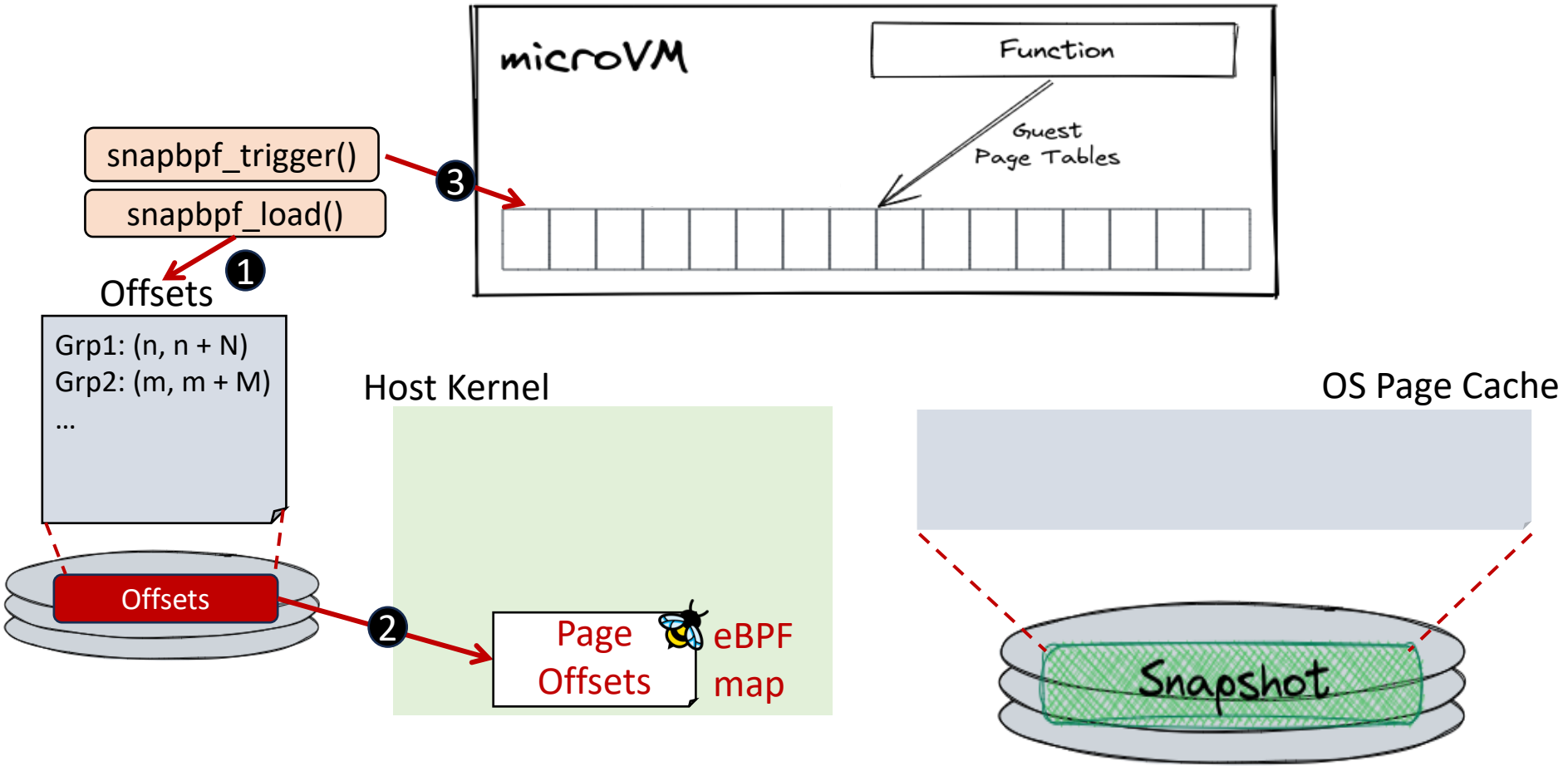
2

Page Offsets

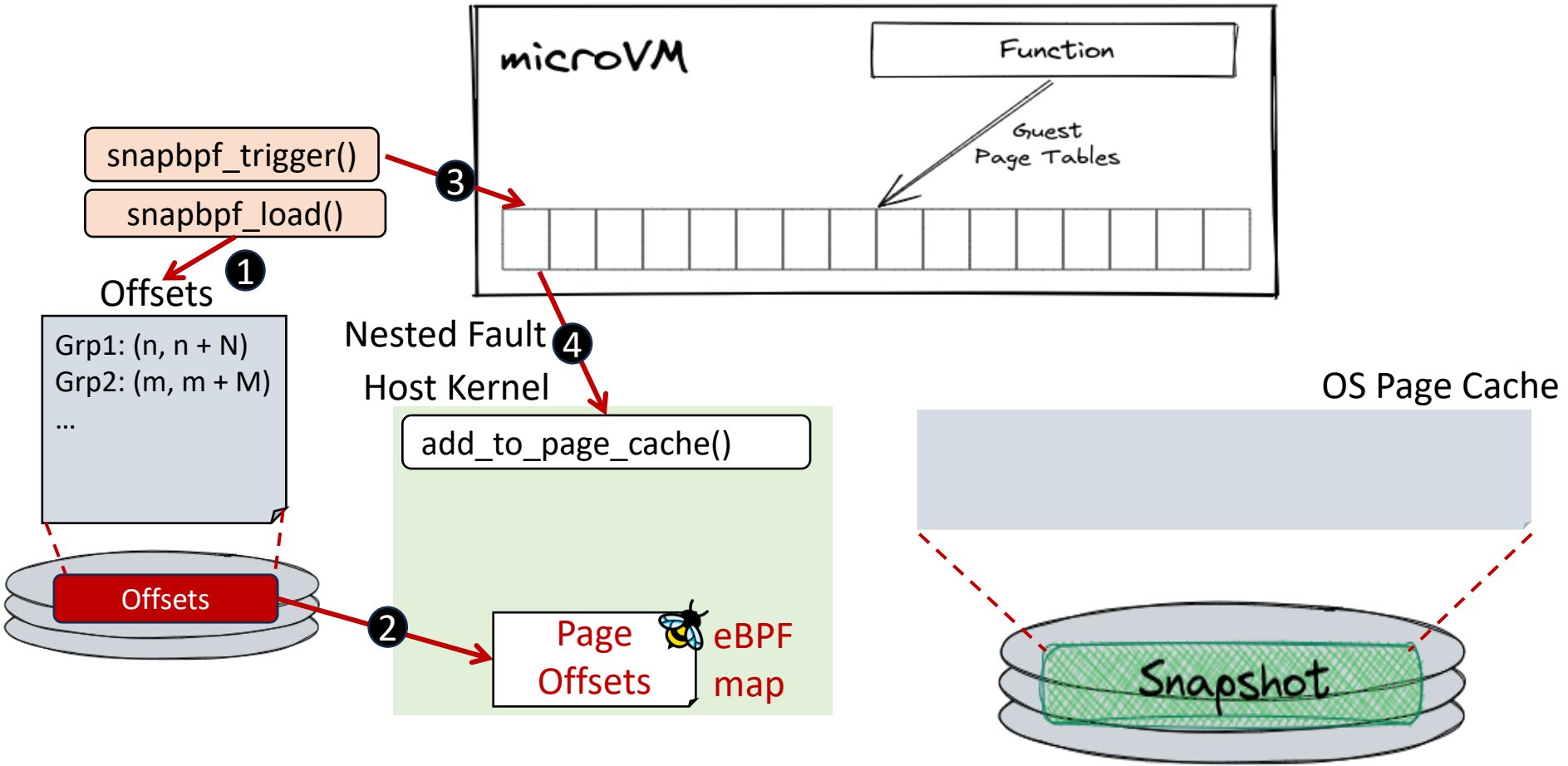
eBPF map

Snapshot

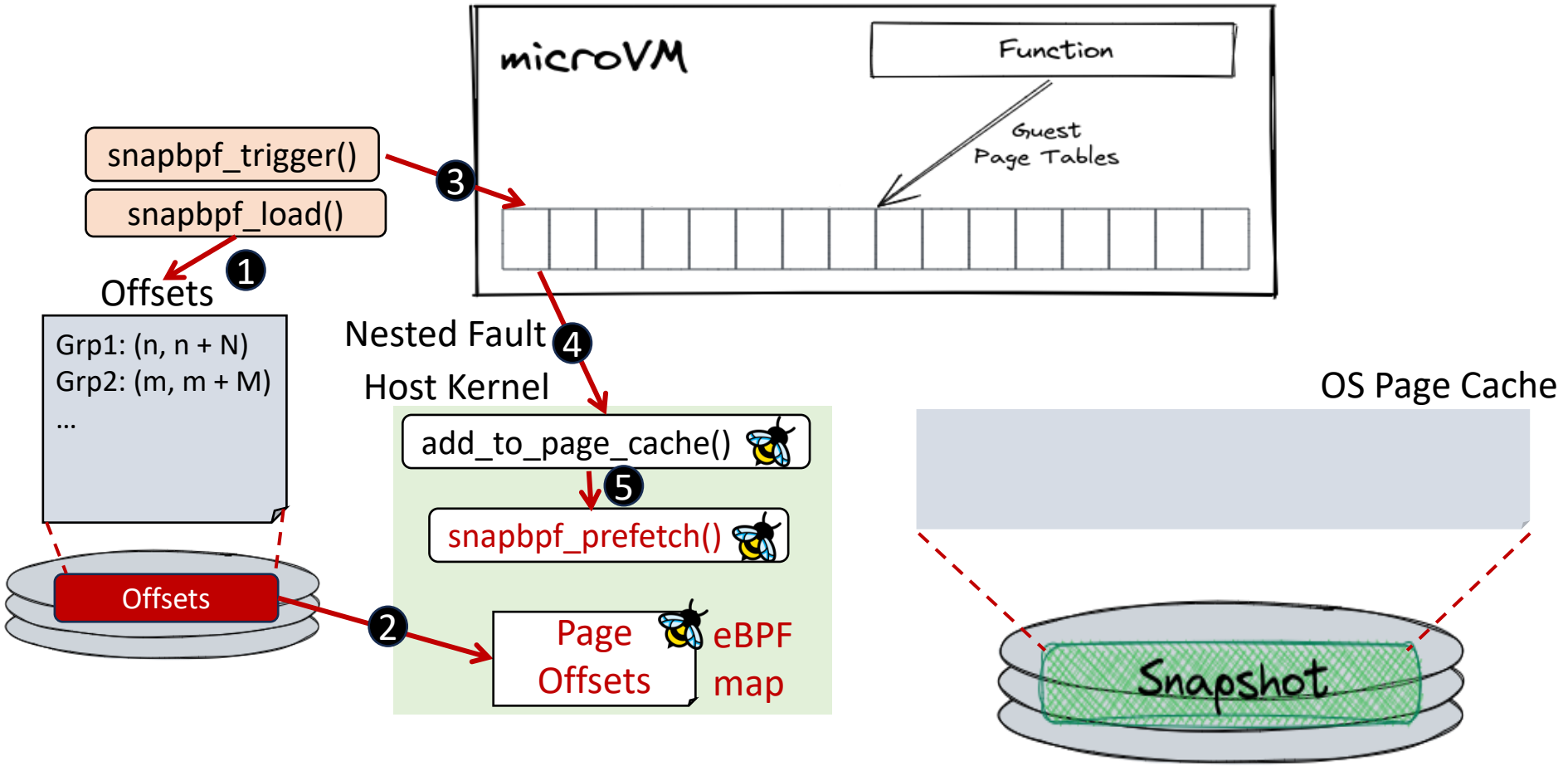
eBPF Prefetch



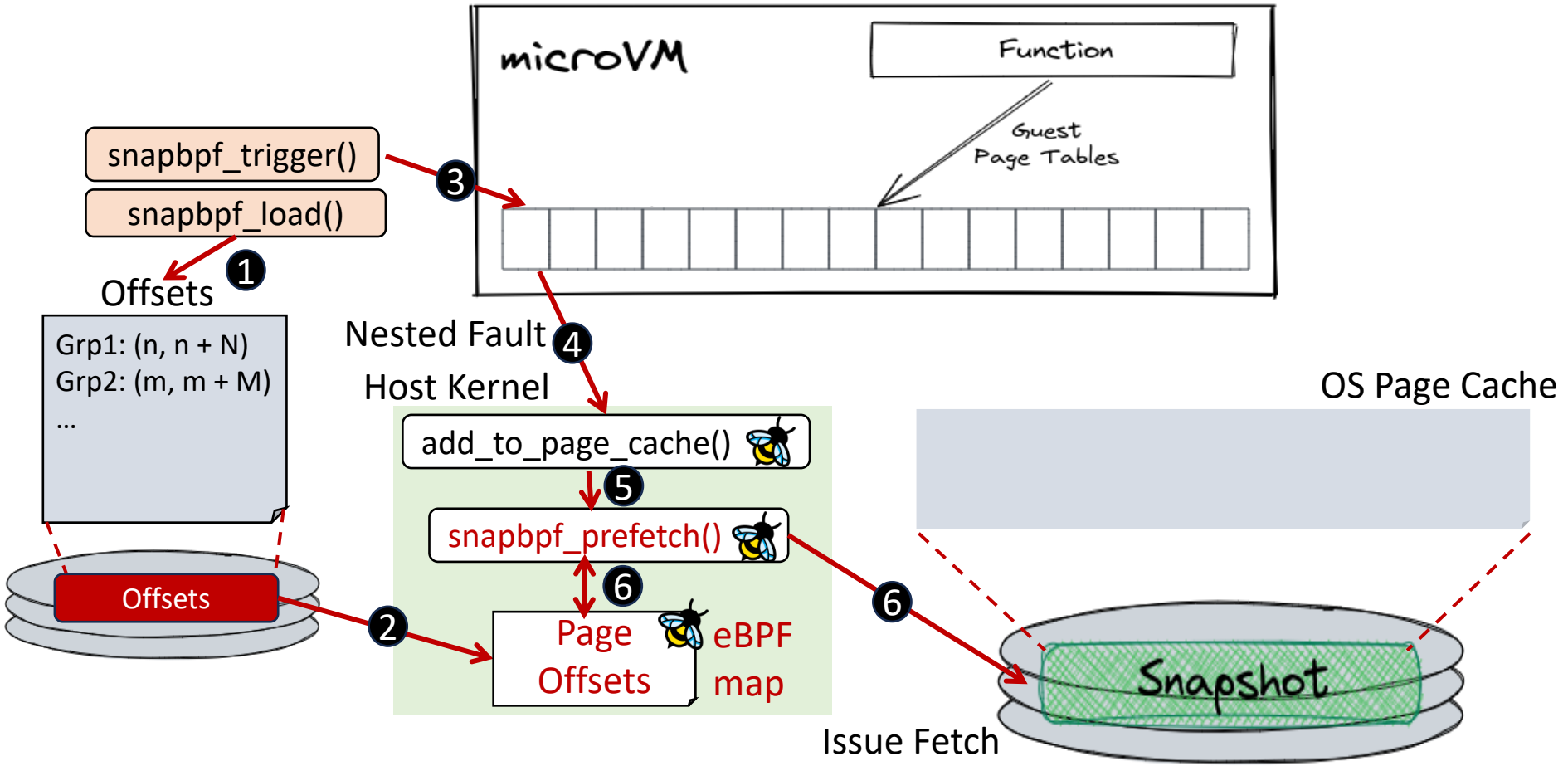
eBPF Prefetch



eBPF Prefetch



eBPF Prefetch



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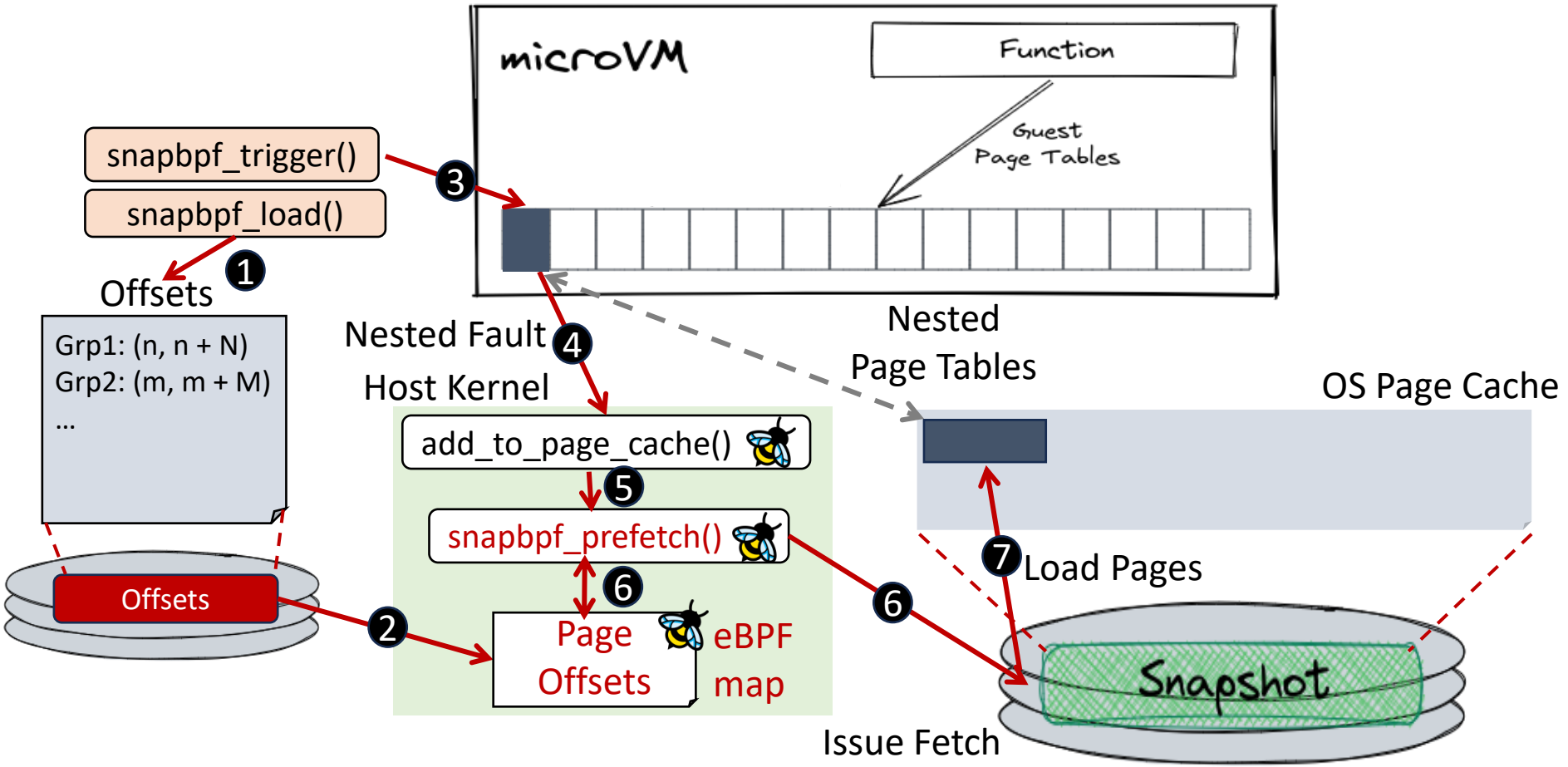
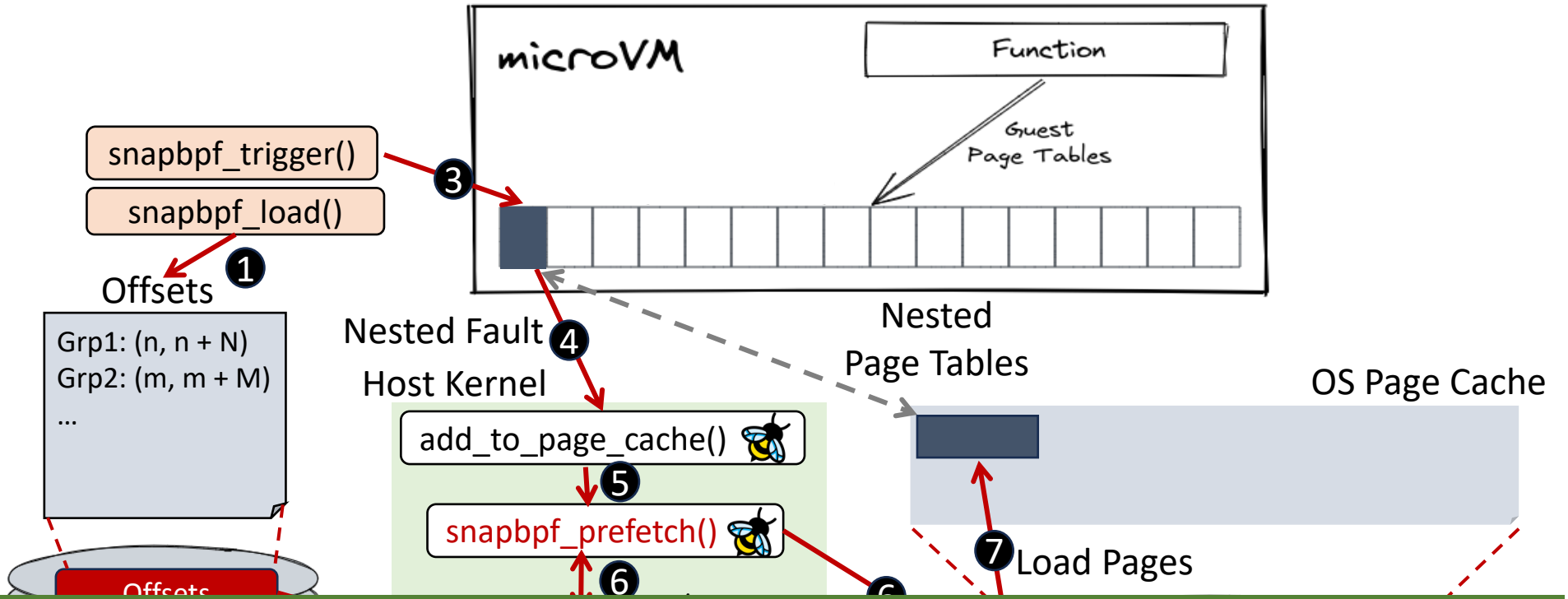


eBPF Prefetch



Fetch requests are asynchronous and overlap with microVM setup

Outline

→ FaaS Snapshotting

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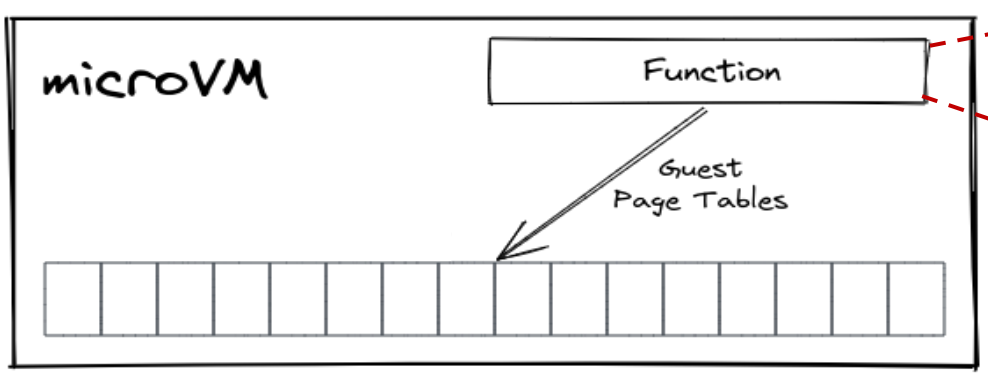
→ Evaluation

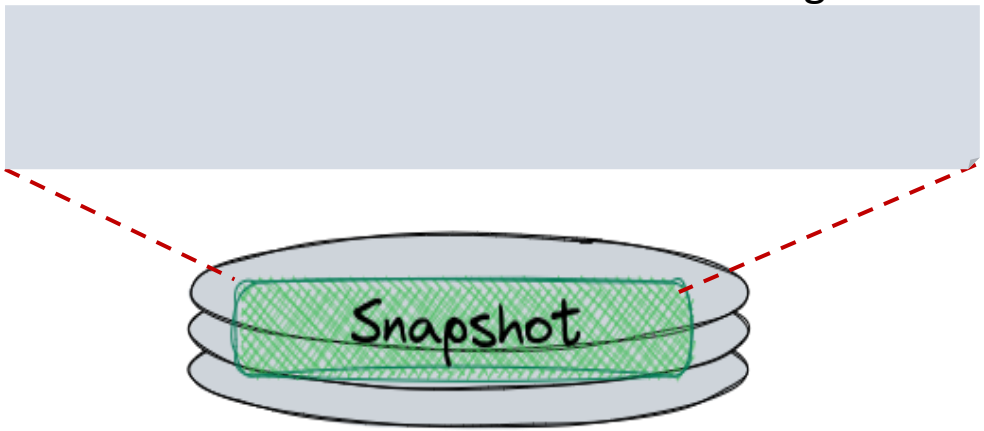
→ Conclusion

Free page filtering

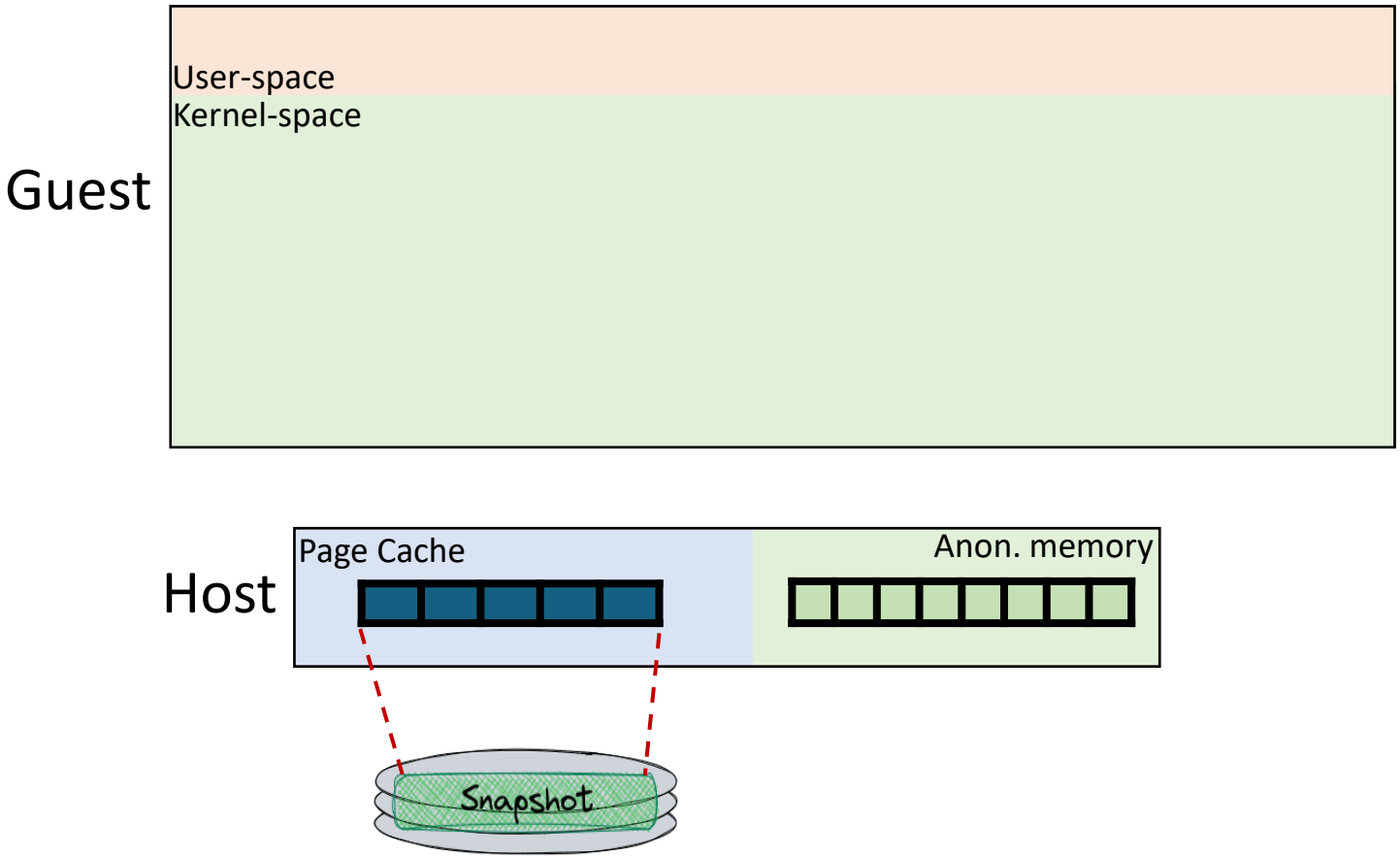



```
fn(input):
  output = malloc()
  return compute(input, &output)
```

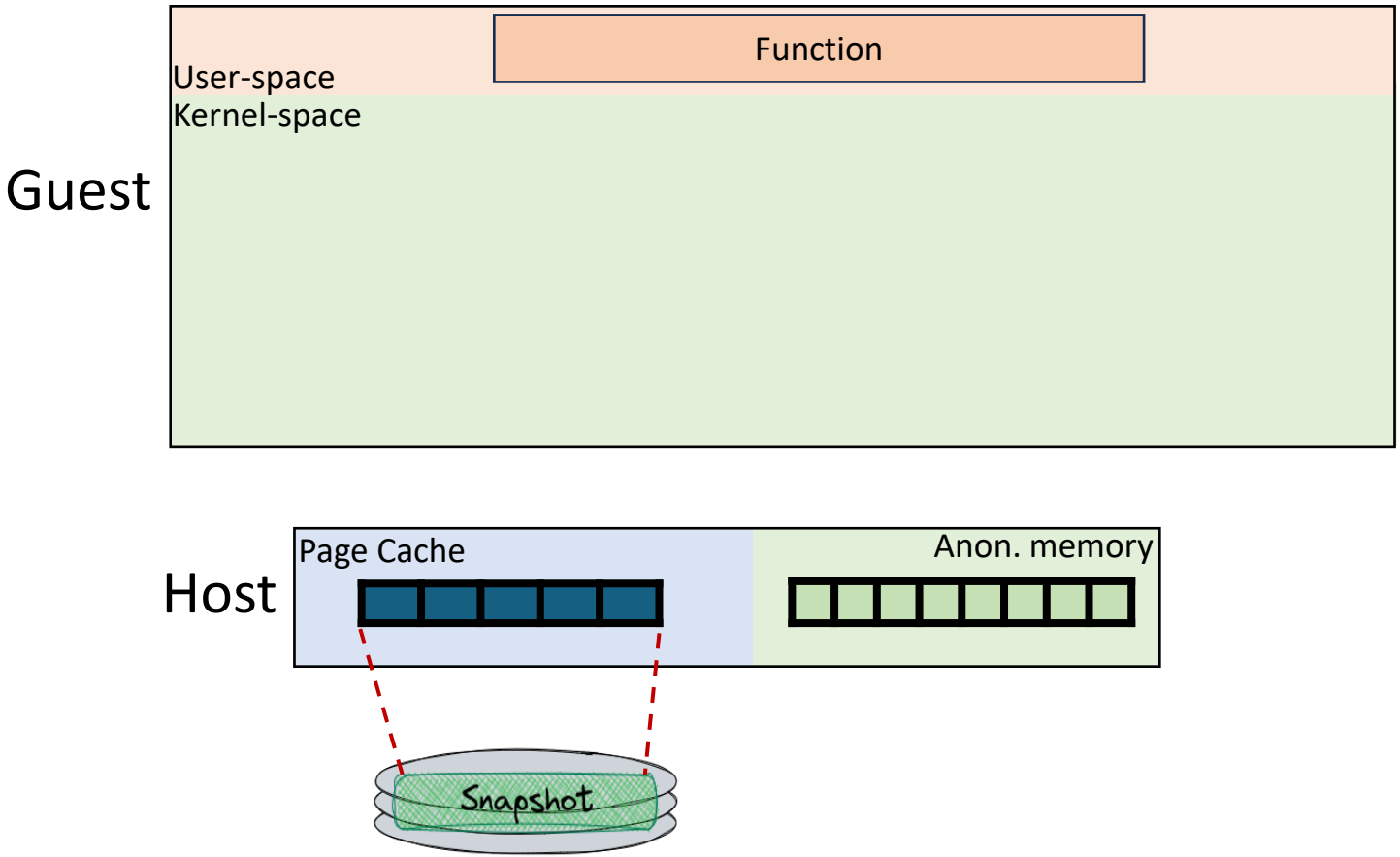
OS Page Cache



PV PTE marking



PV PTE marking



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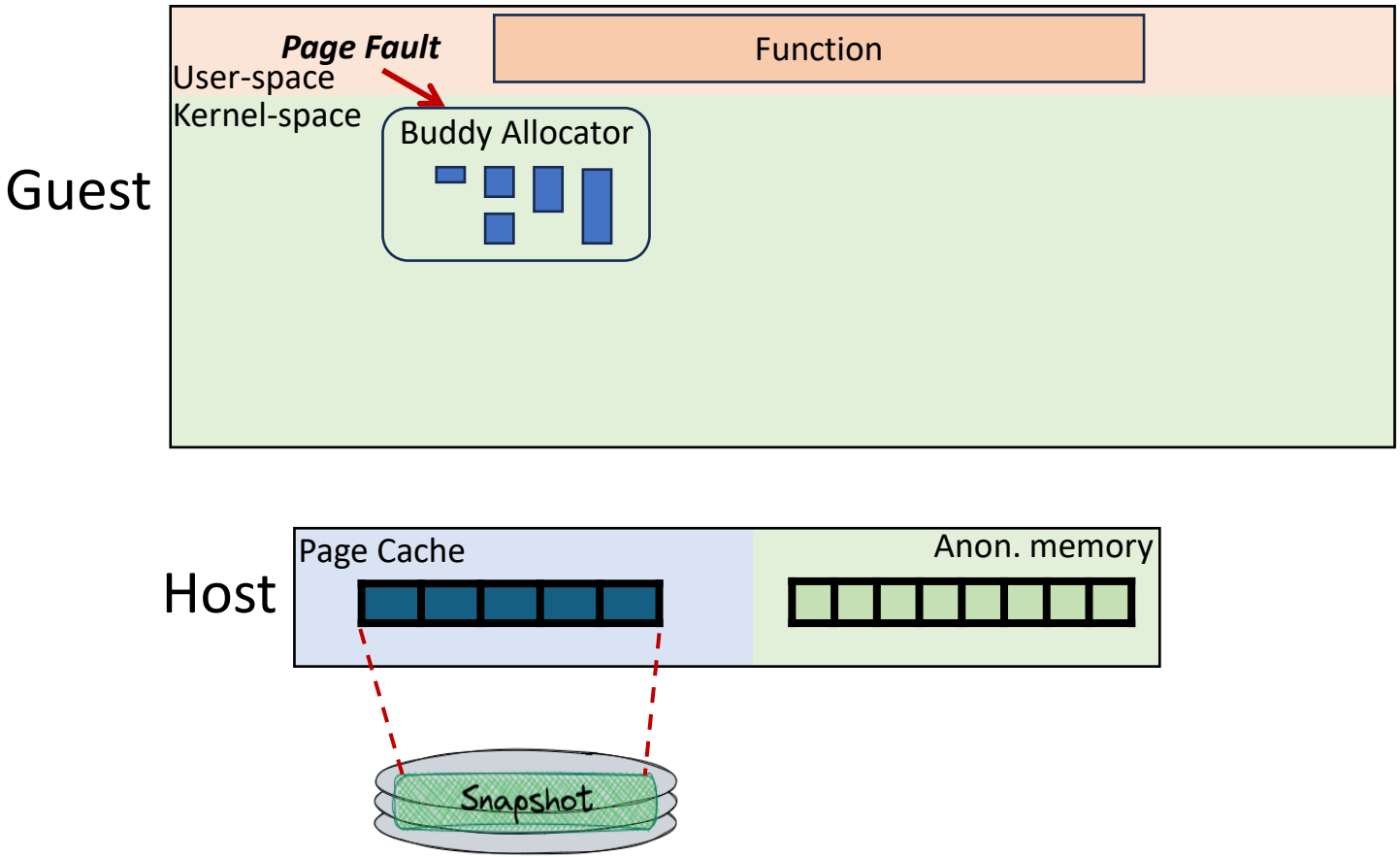
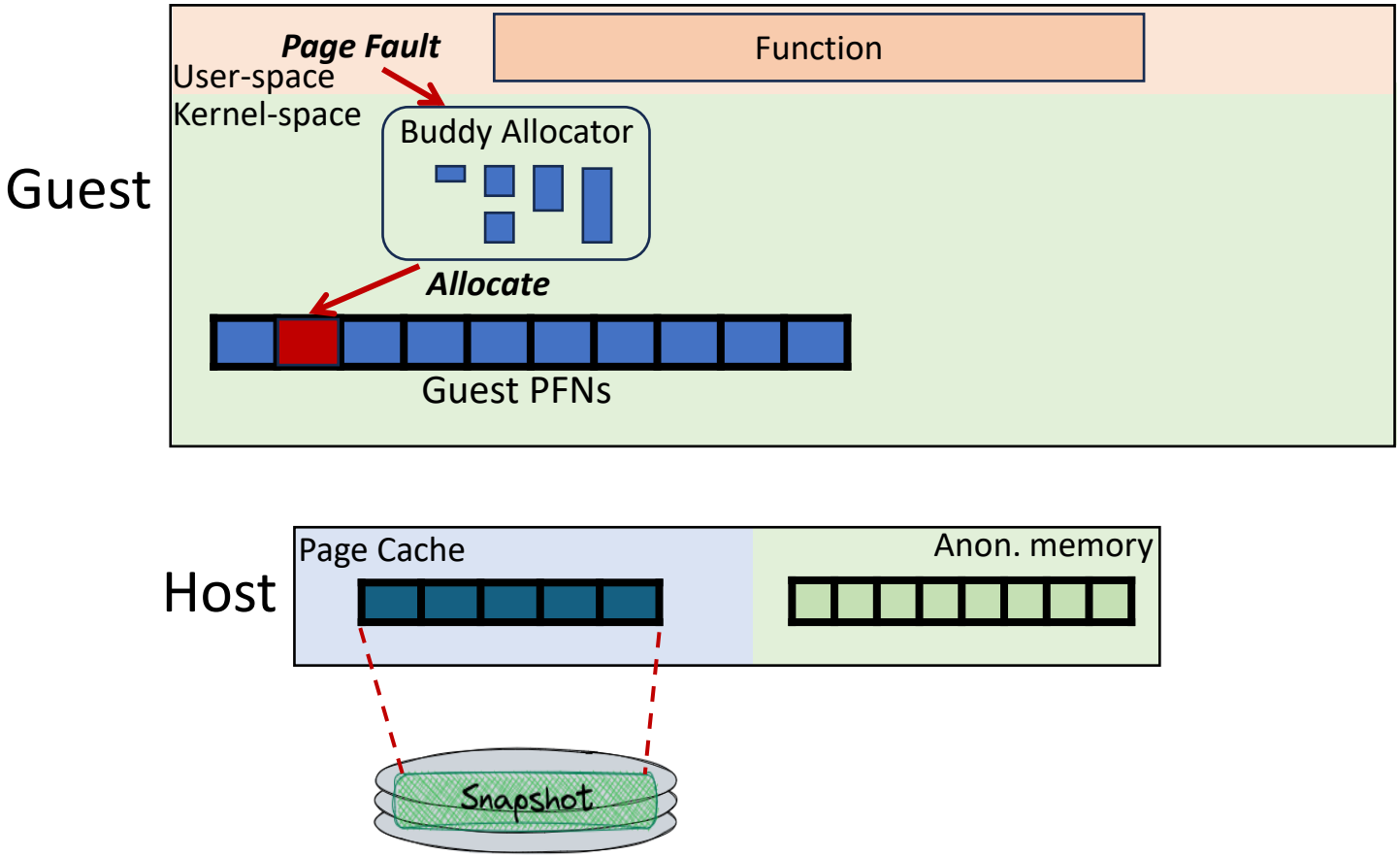
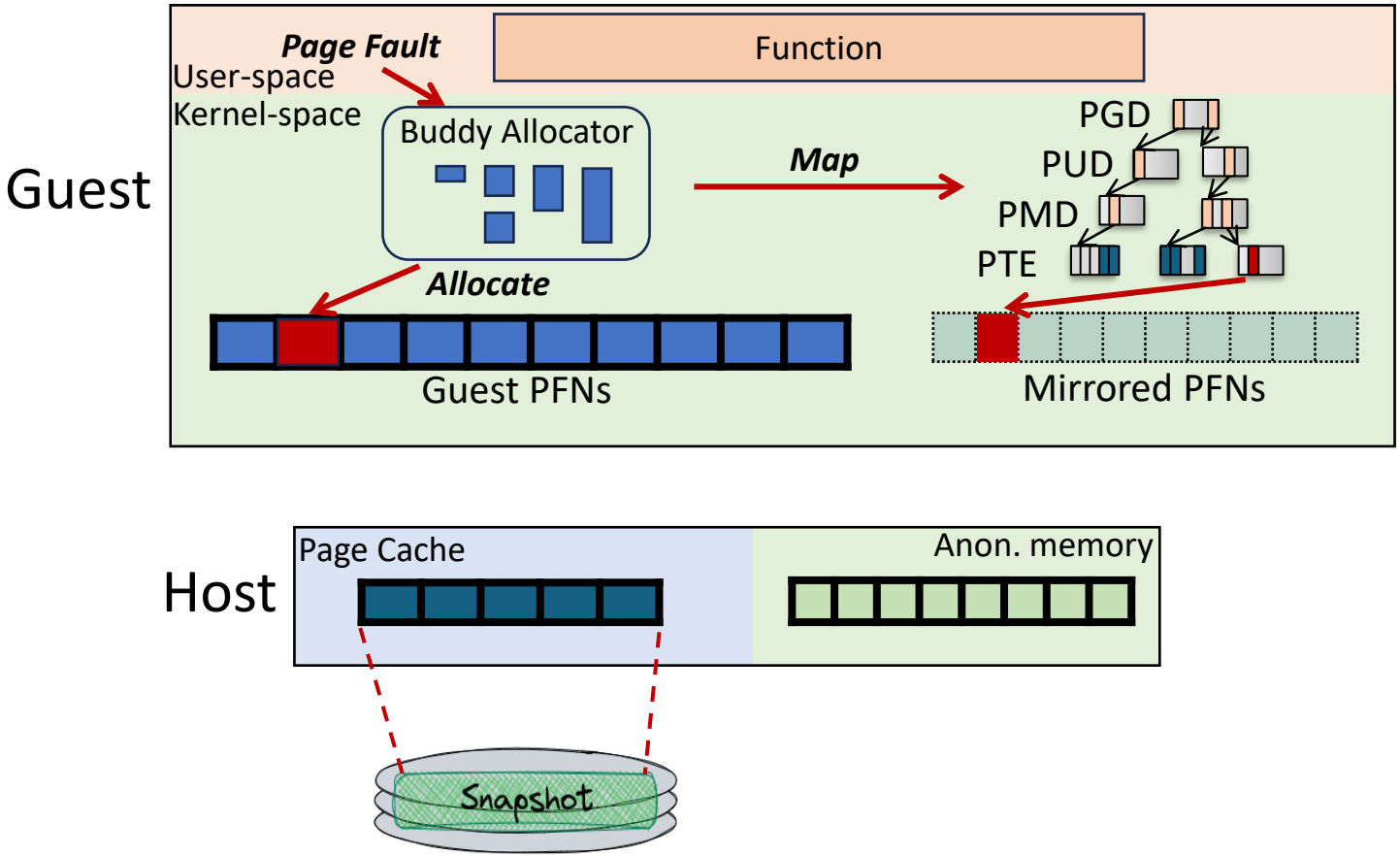


PV PTE marking



PV PTE marking



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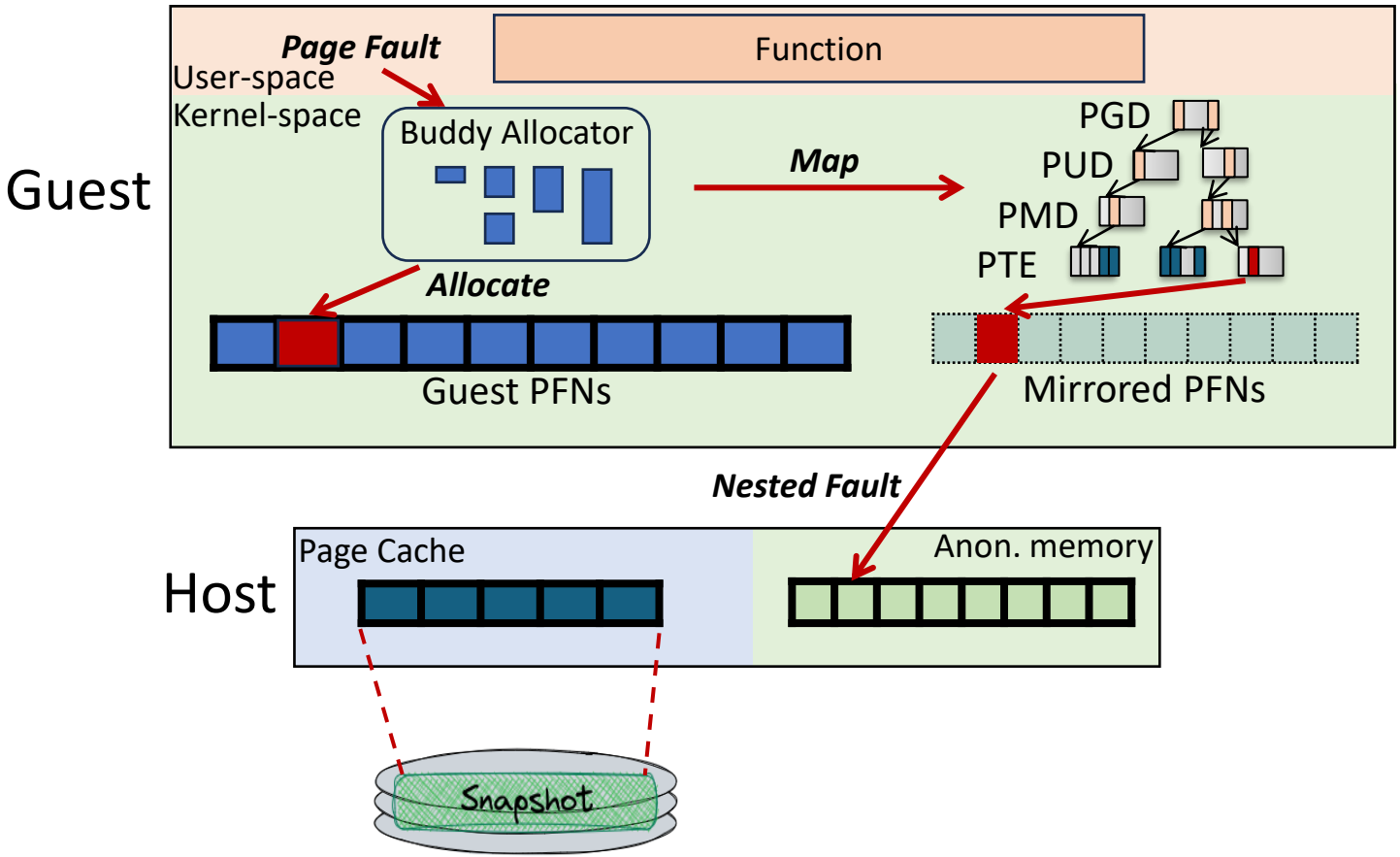
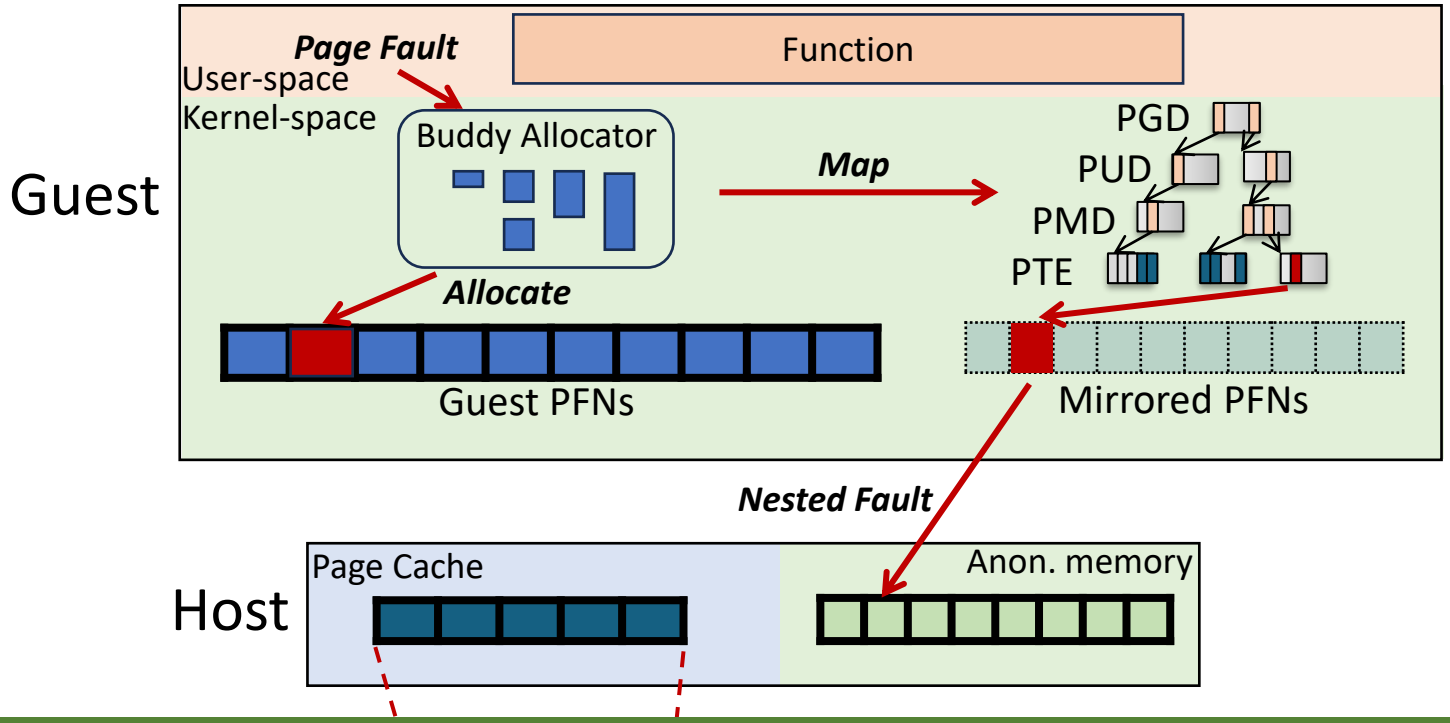


PV PTE marking



Online free page filtering with minimal overhead

Our proposal: SnapBPF

	Mechanism	Mode	WS serialization	WS deduplication	Free Page Filtering
REAP **Faast**	userfaultfd	userspace	Required	No	None Metadada Scanning
FaaSnap	mincore mmap	userspace	Required	Yes	Memory Scanning
		Our proposal			
SnapBPF	eBPF	kernelspace	None	Yes	PV / Online

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Experimental Setup

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→ Implemented in Linux v6.3 and Firecracker v1.11

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→ FunctionBench and real-world FaaS workloads

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→ AMD Zen2 evaluation testbed (AMD EPYC 7402)

Experimental Setup

- → Implemented in Linux v6.3 and Firecracker v1.11
- → FunctionBench and real-world FaaS workloads
- → AMD Zen2 evaluation testbed (AMD EPYC 7402)
- → Micron 5300 TLC NAND flash SATA SSD
  - → 95K random 4K read IOPS
  - → 540MB / sec 128K sequential read throughput

Evaluation Questions

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→ Can SnapBPF match SOTA performance without sequentially serialized working sets?

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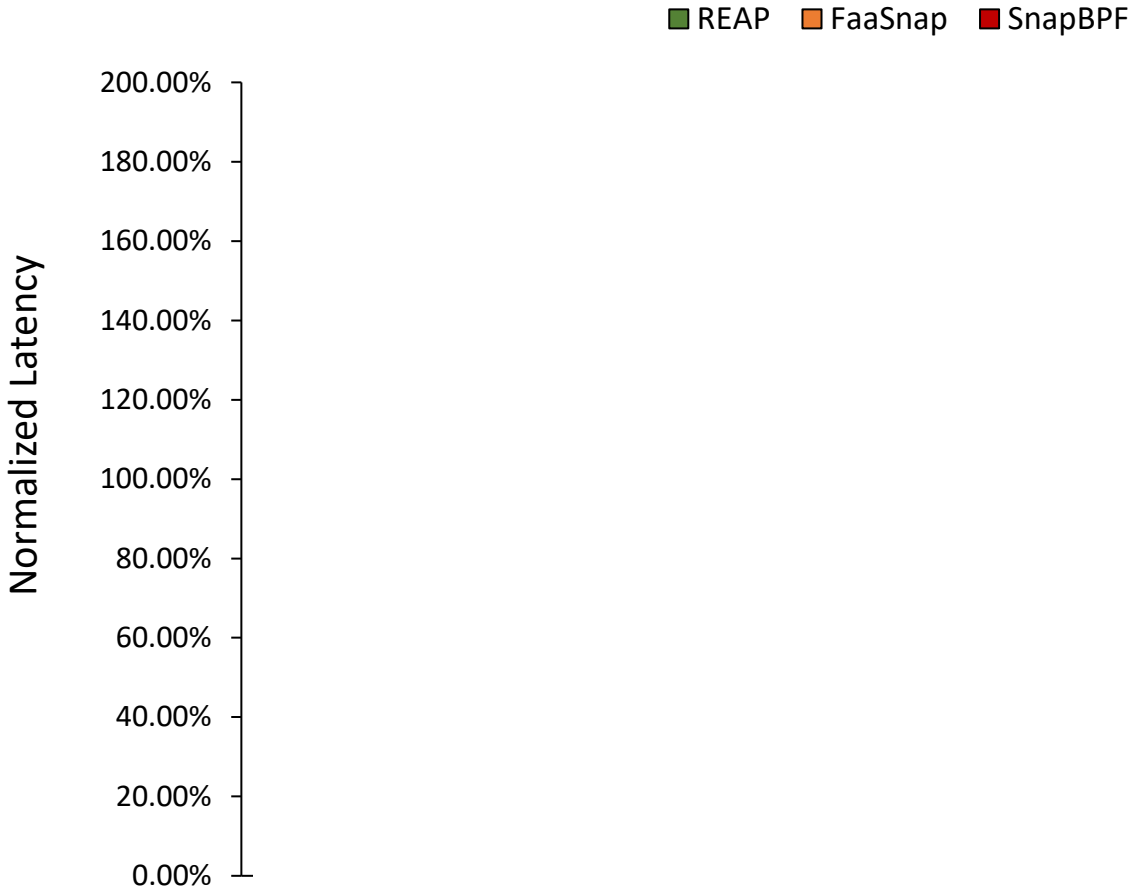
→ Can SnapBPF effectively deduplicate working sets in memory while sustaining performance?

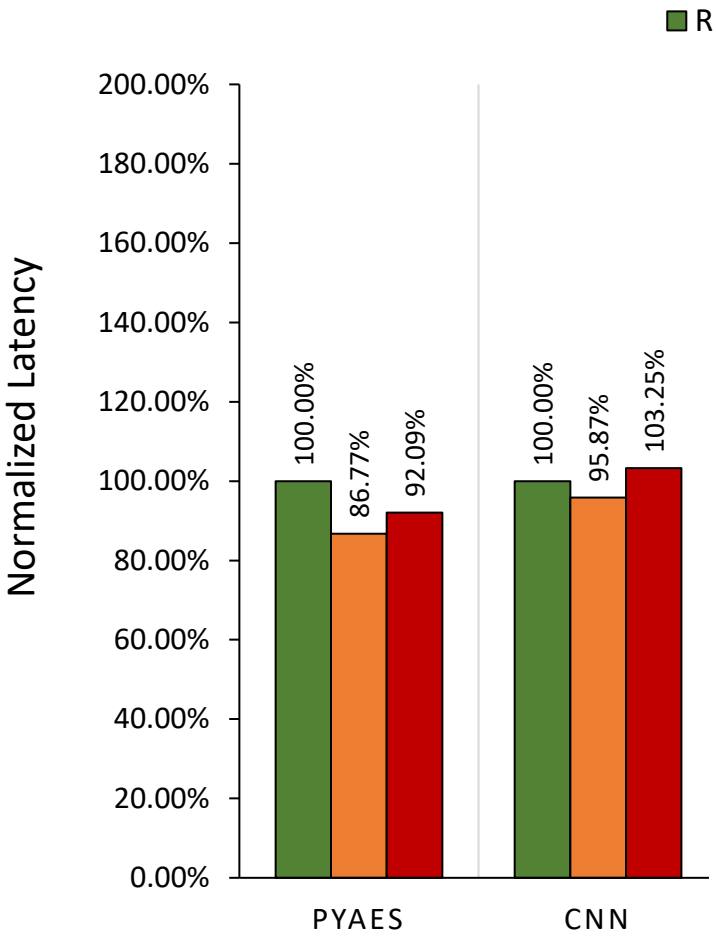
Single function E2E latency

Normalized Latency

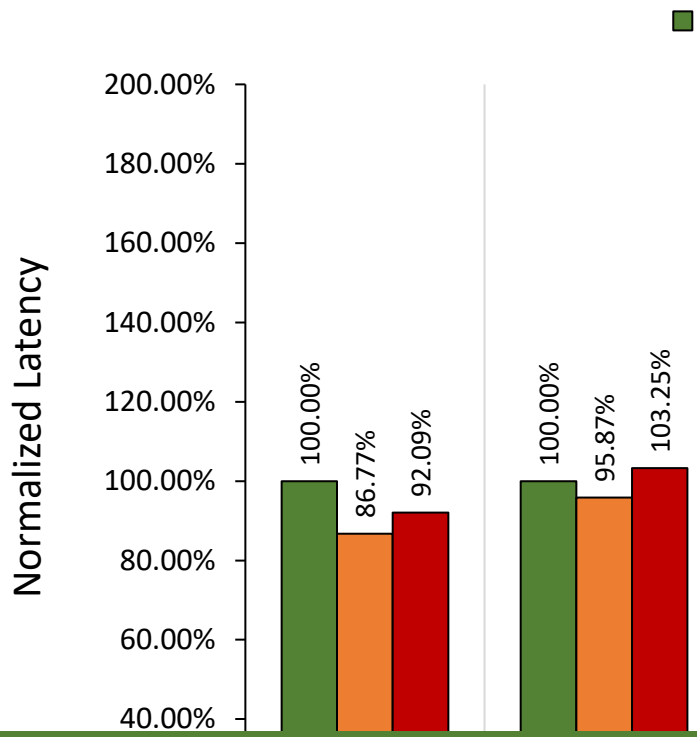
Single function E2E latency



Single function E2E latency

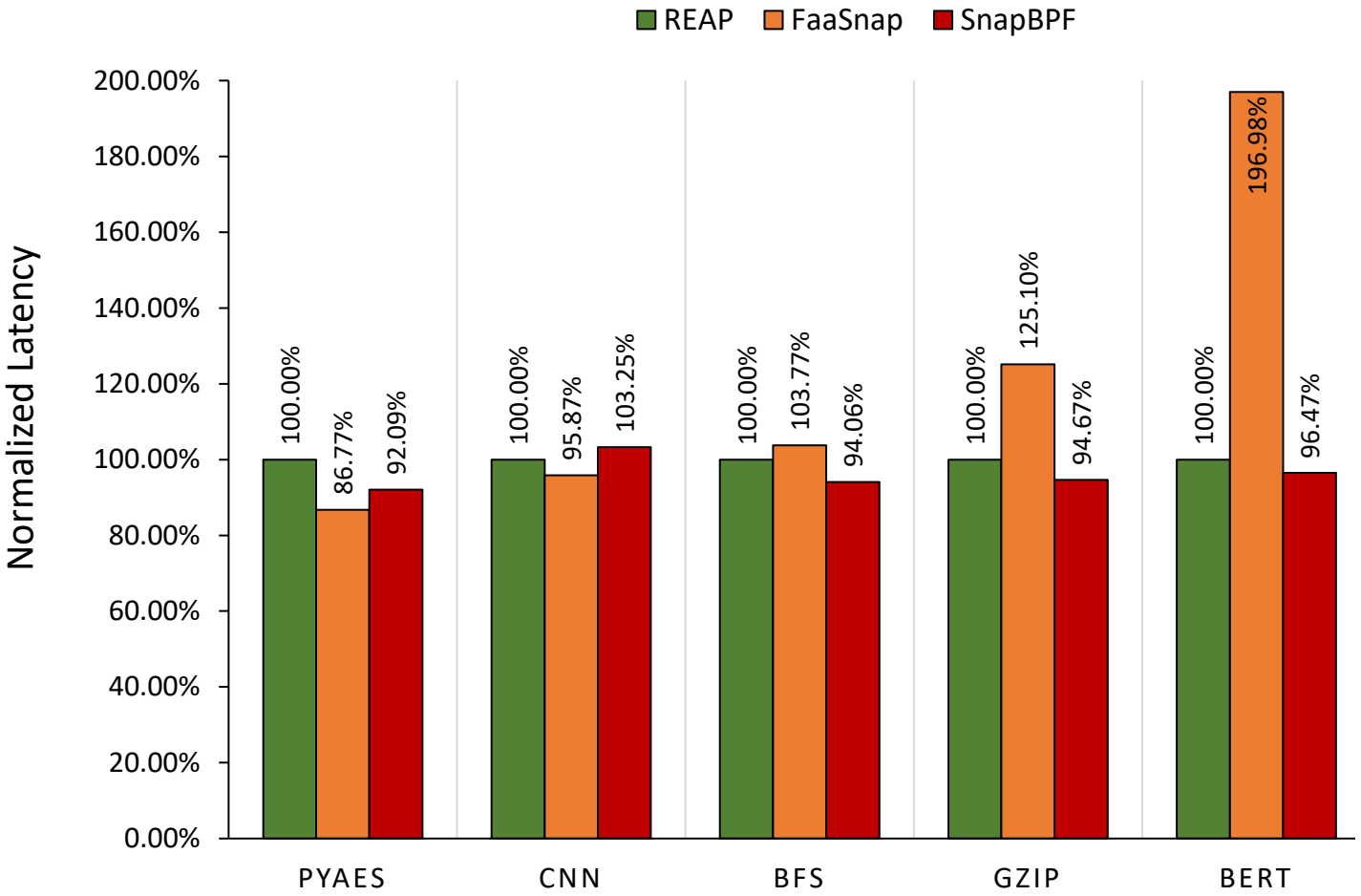


Single function E2E latency

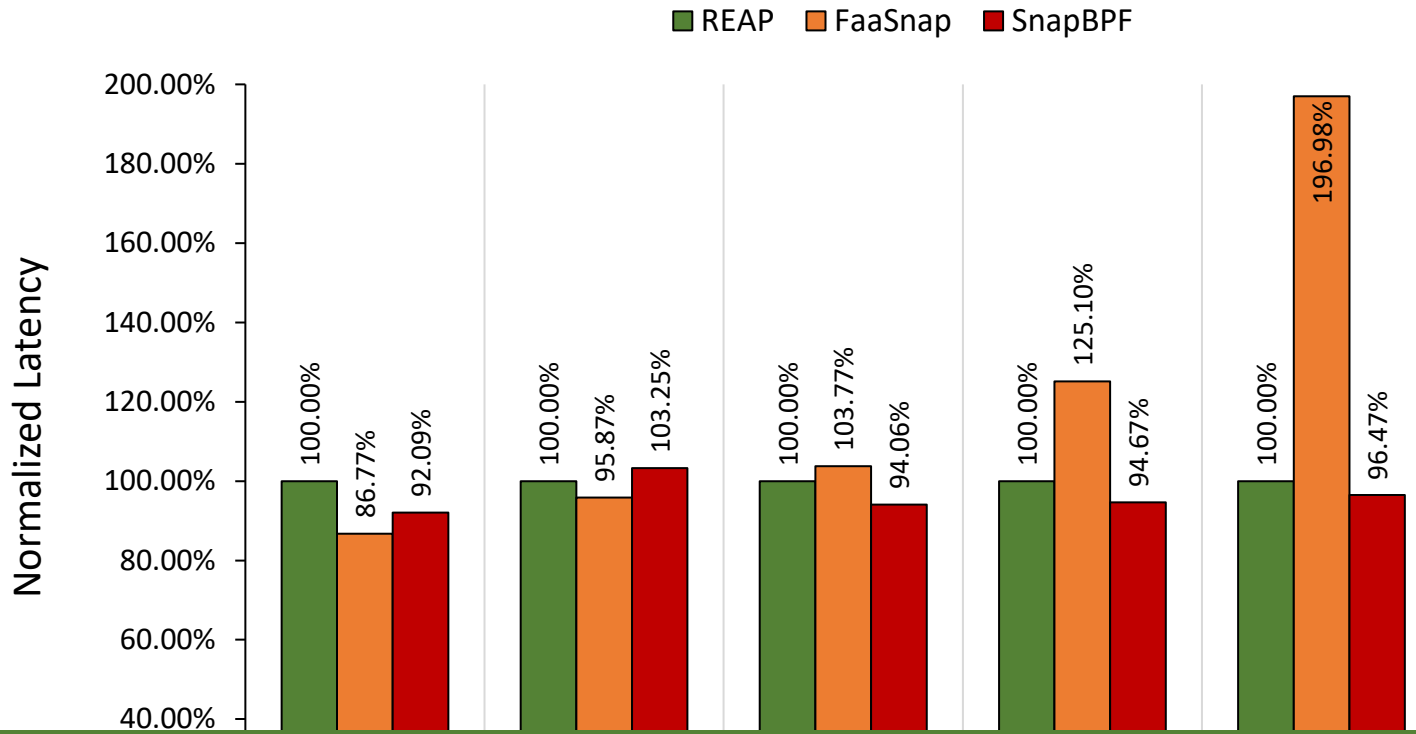


SnapBPF matches SOTA performance for small functions

Single function E2E latency

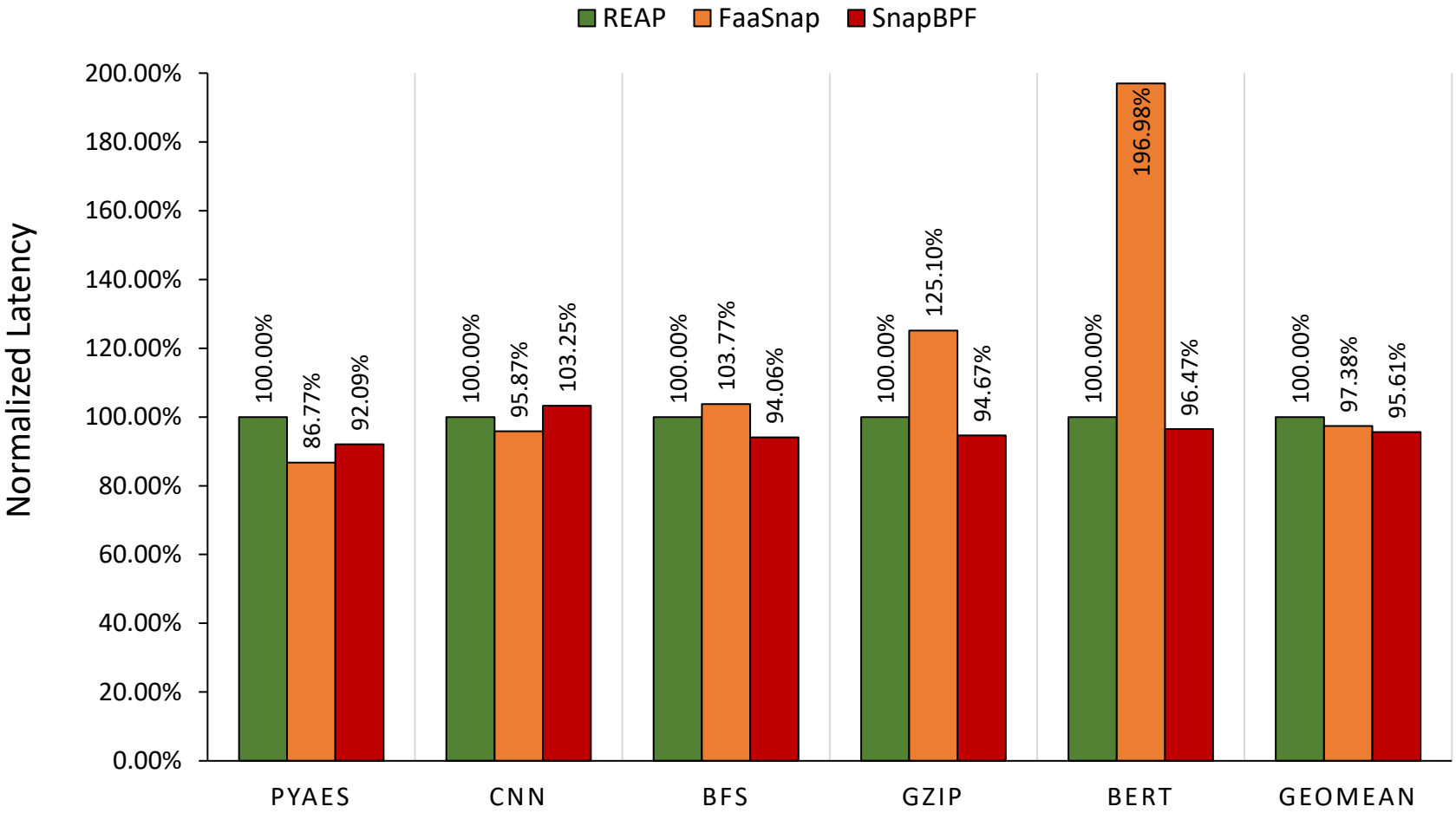


Single function E2E latency

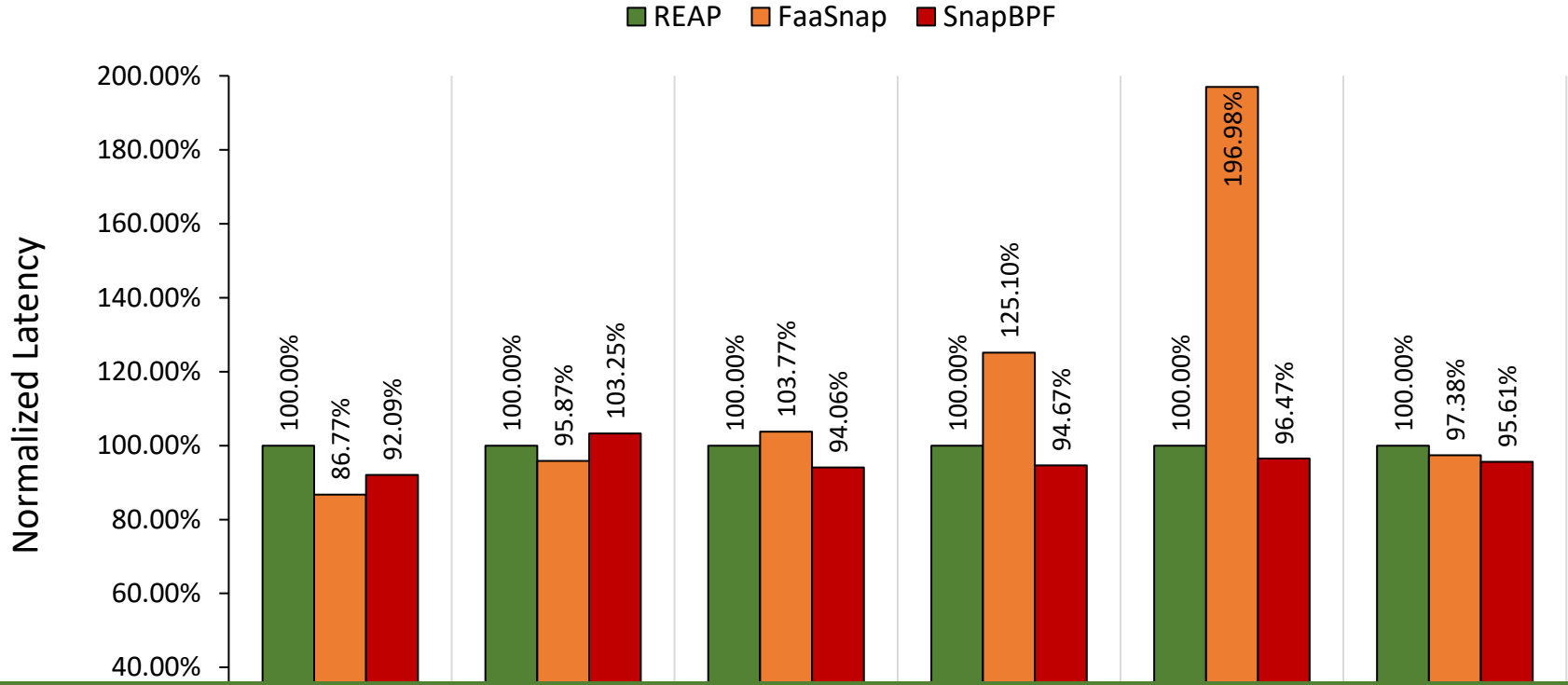


SnapBPF is resilient to working set fragmentation

Single function E2E latency



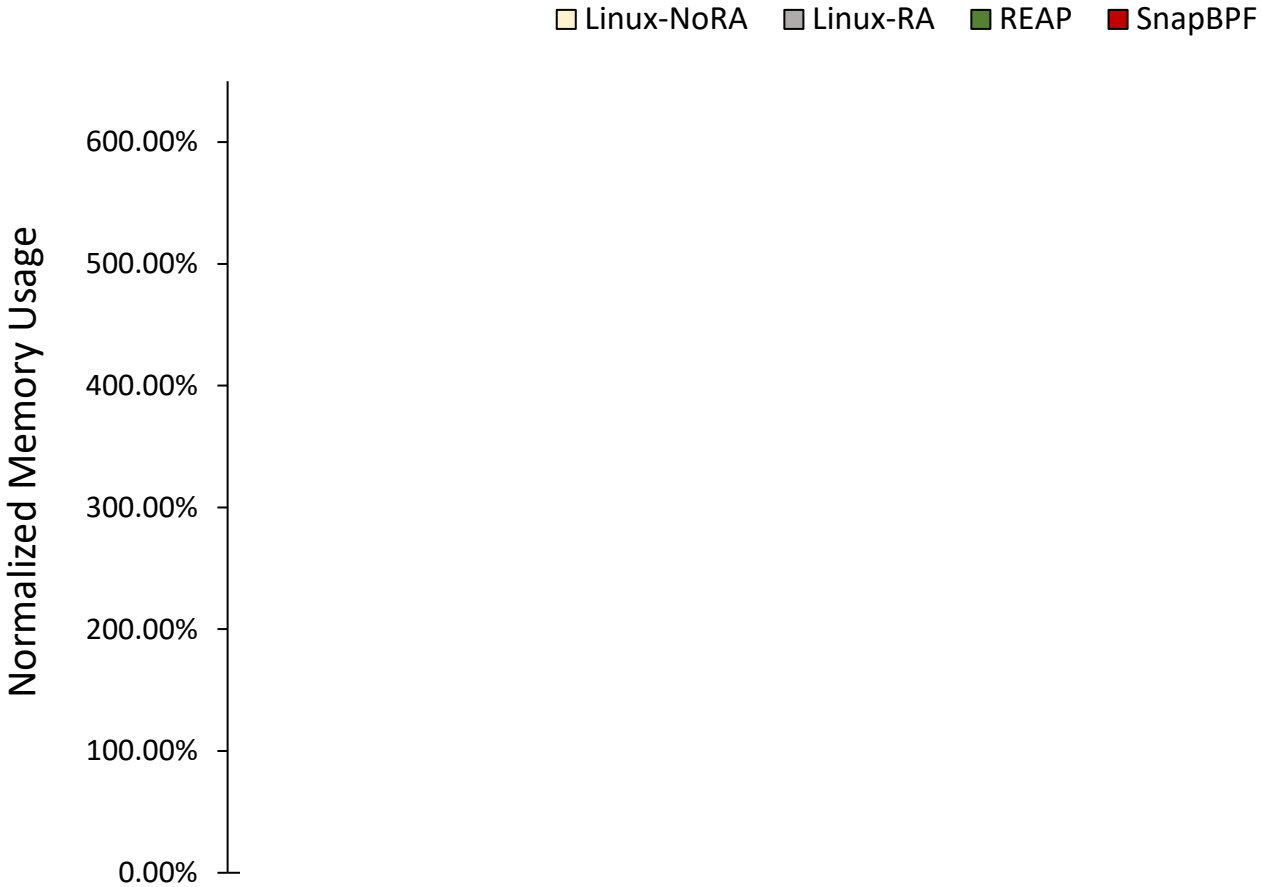
Single function E2E latency



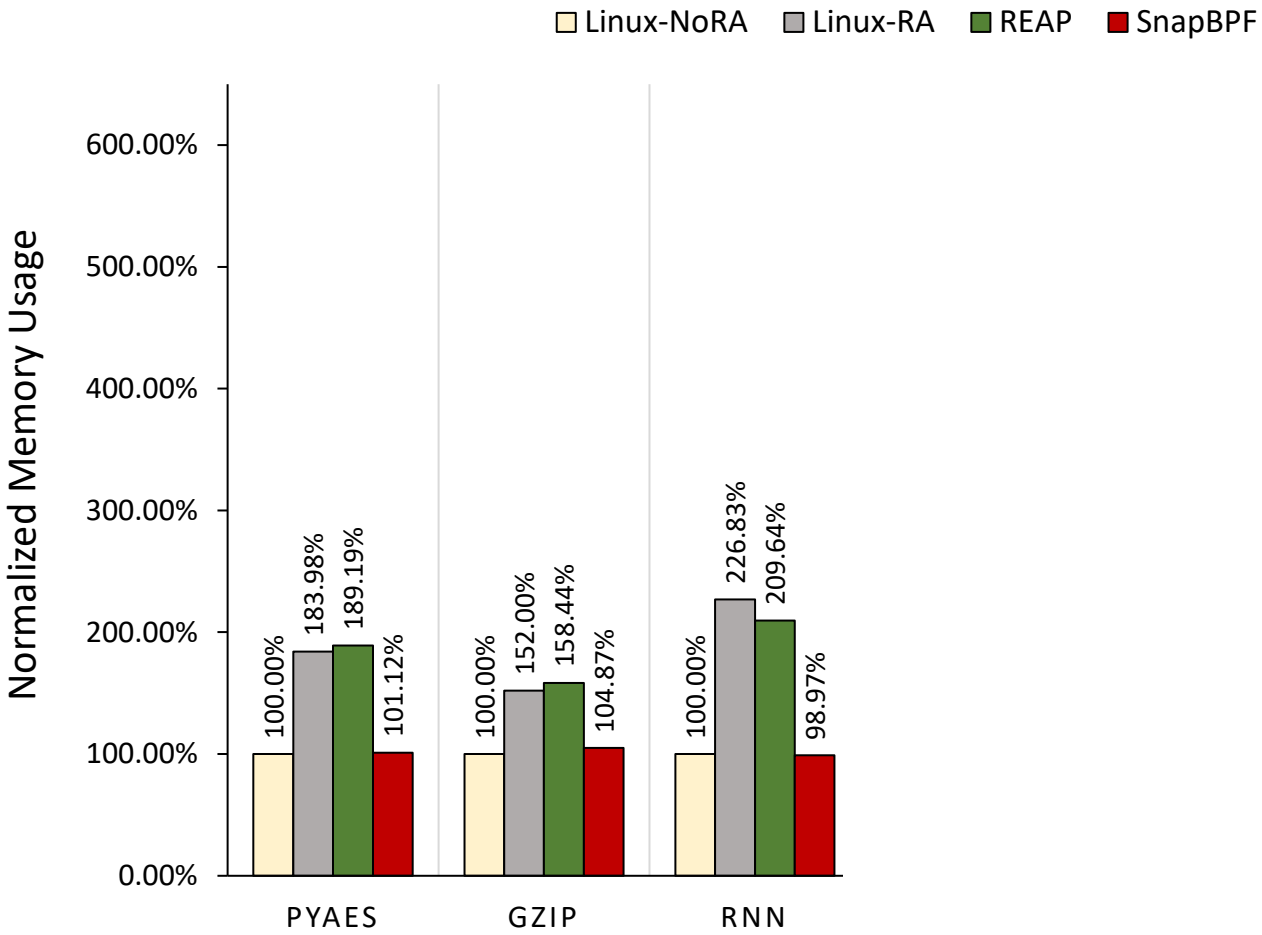
SnapBPF matches and outperforms SOTA on average without separately serialized working sets

Concurrent Execution: Memory

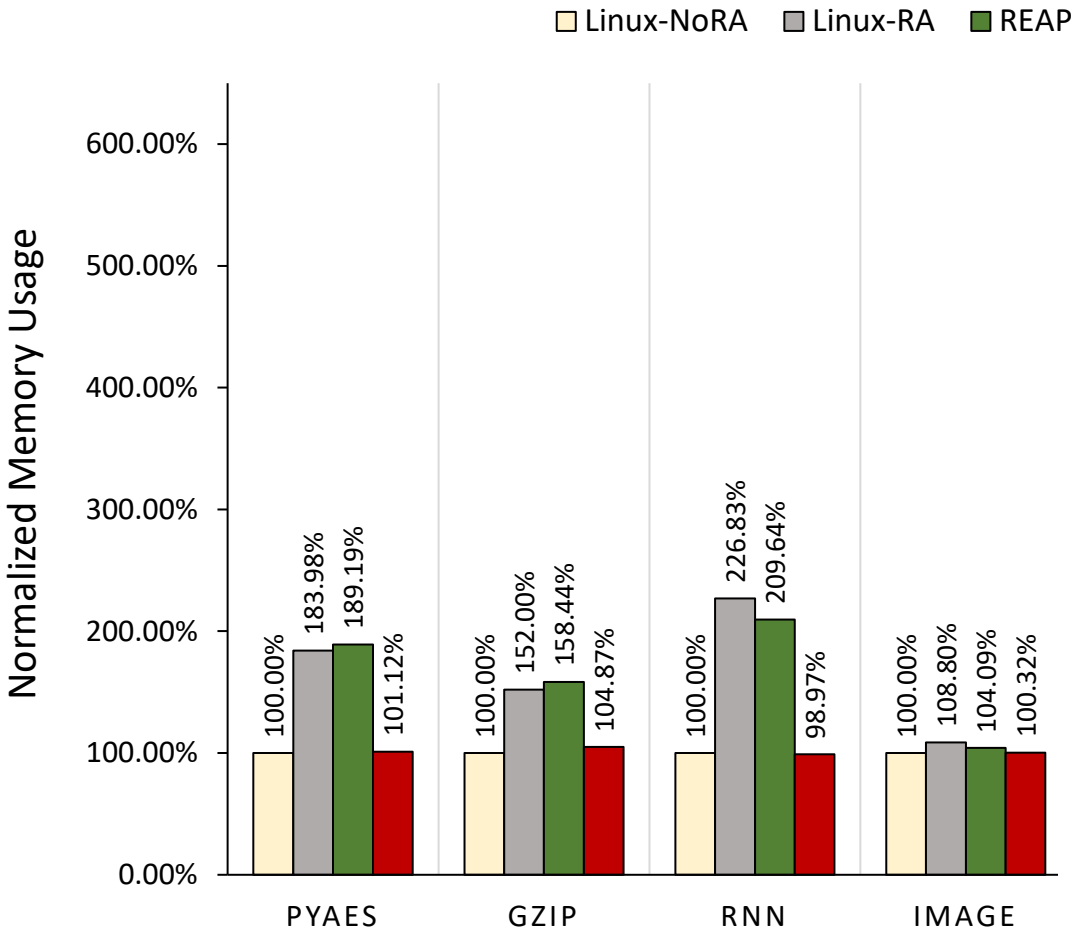
Concurrent Execution: Memory



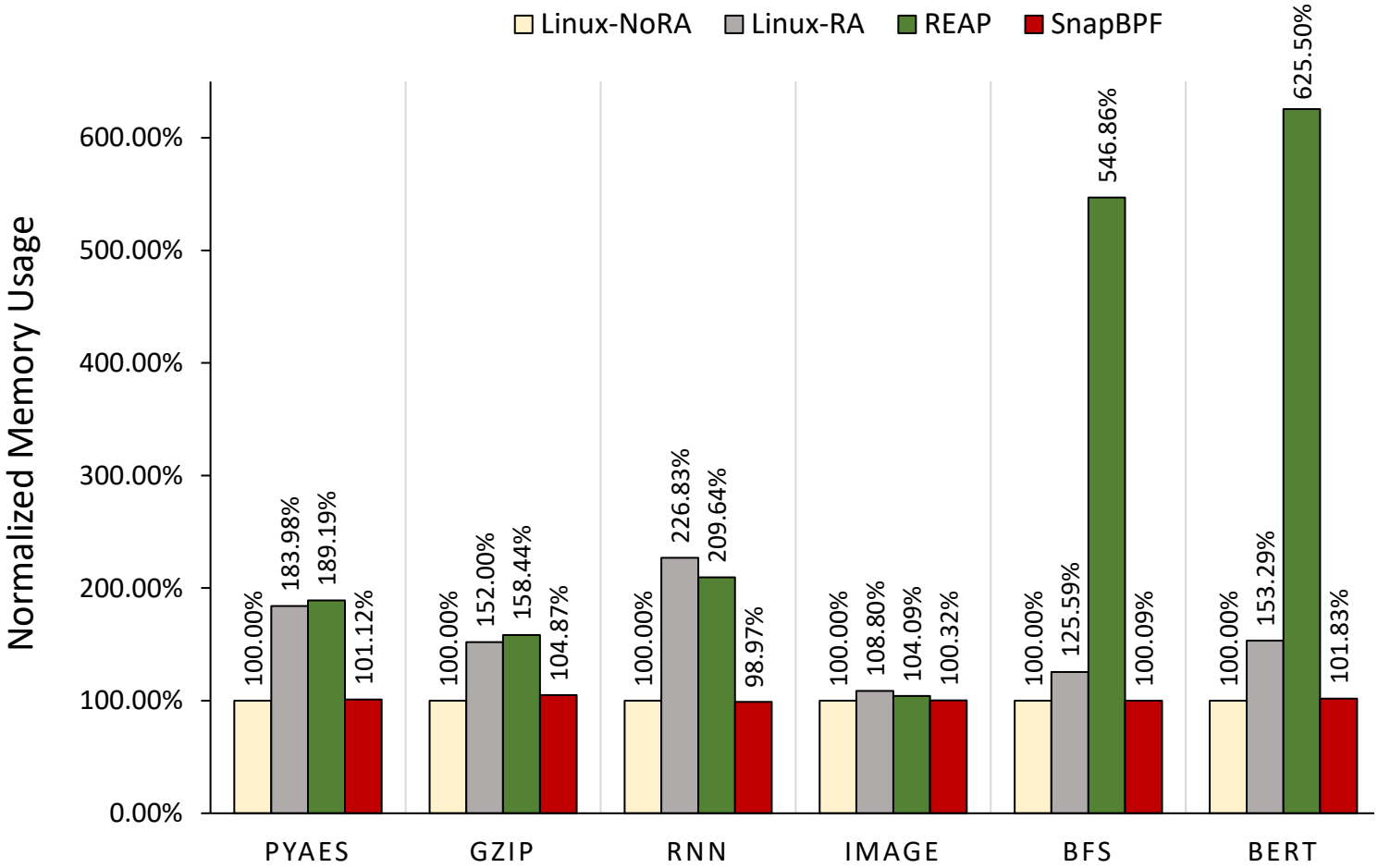
Concurrent Execution: Memory



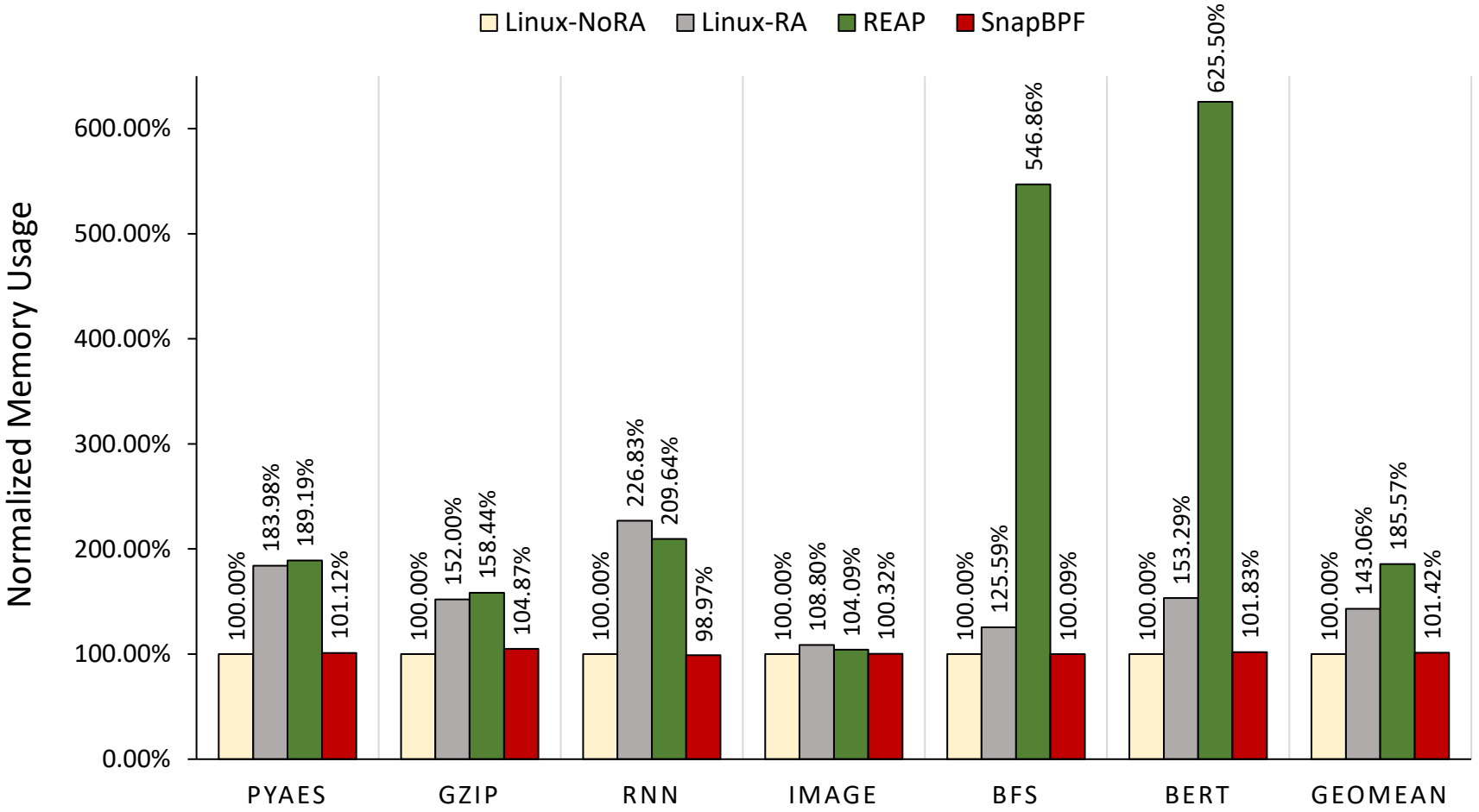
Concurrent Execution: Memory



Concurrent Execution: Memory



Concurrent Execution: Memory



Concurrent Execution: Latency

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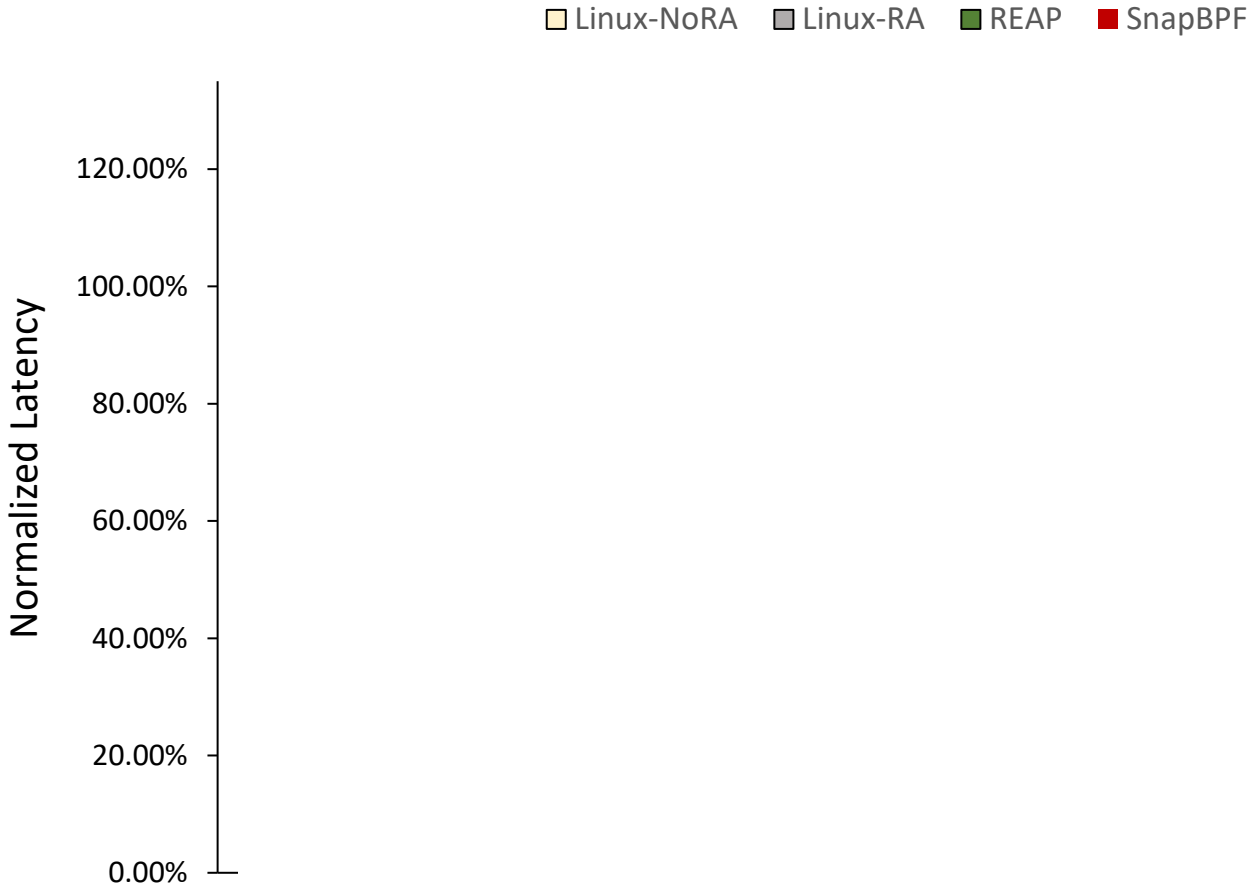
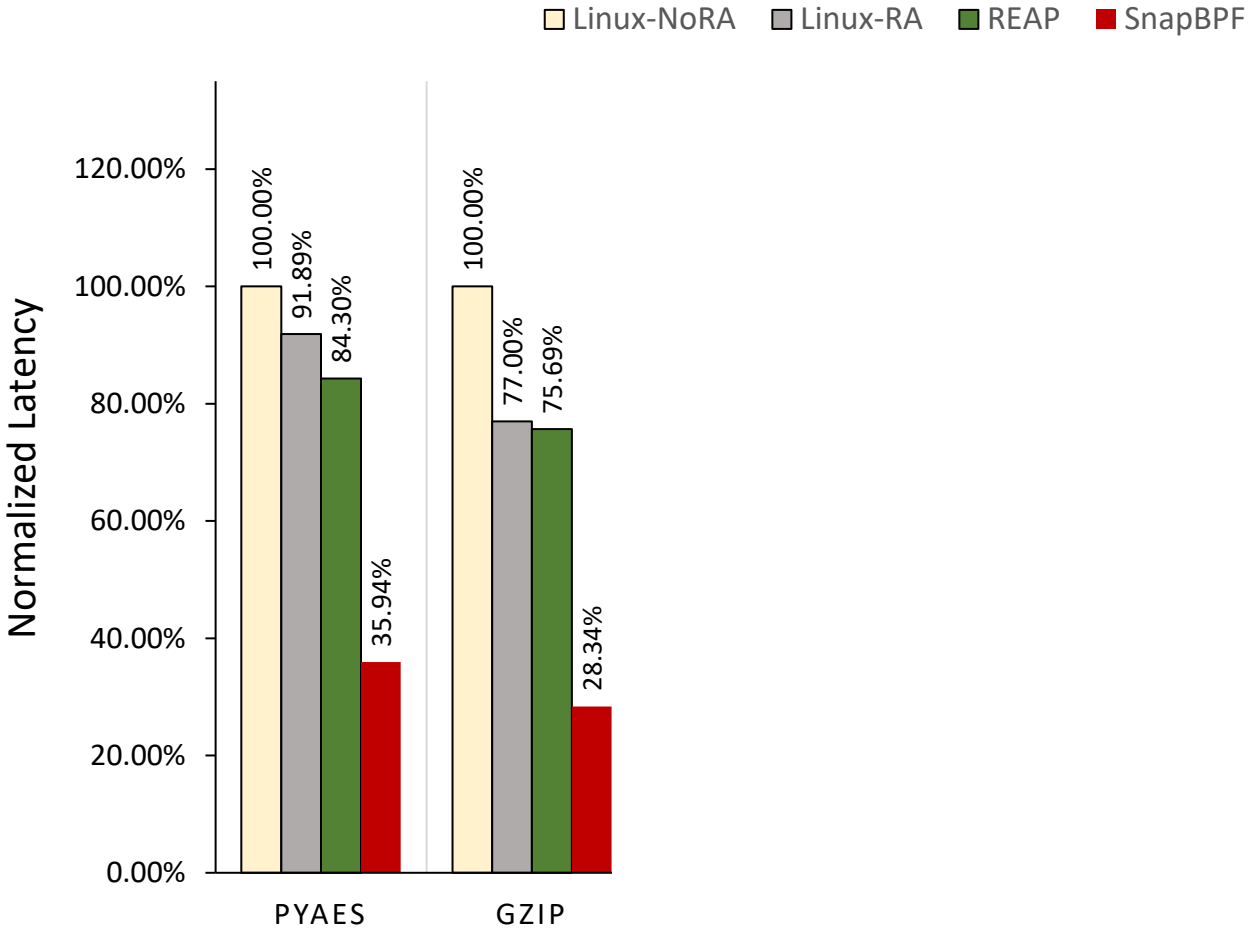
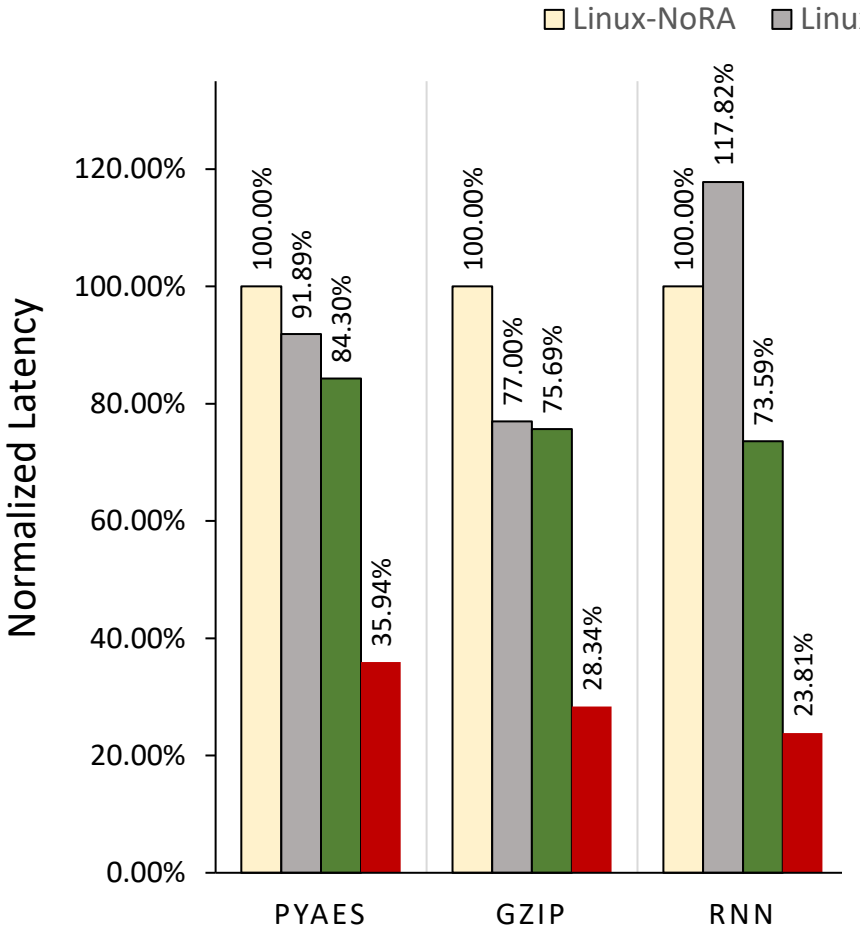


Concurrent Execution: Latency



Concurrent Execution: Latency



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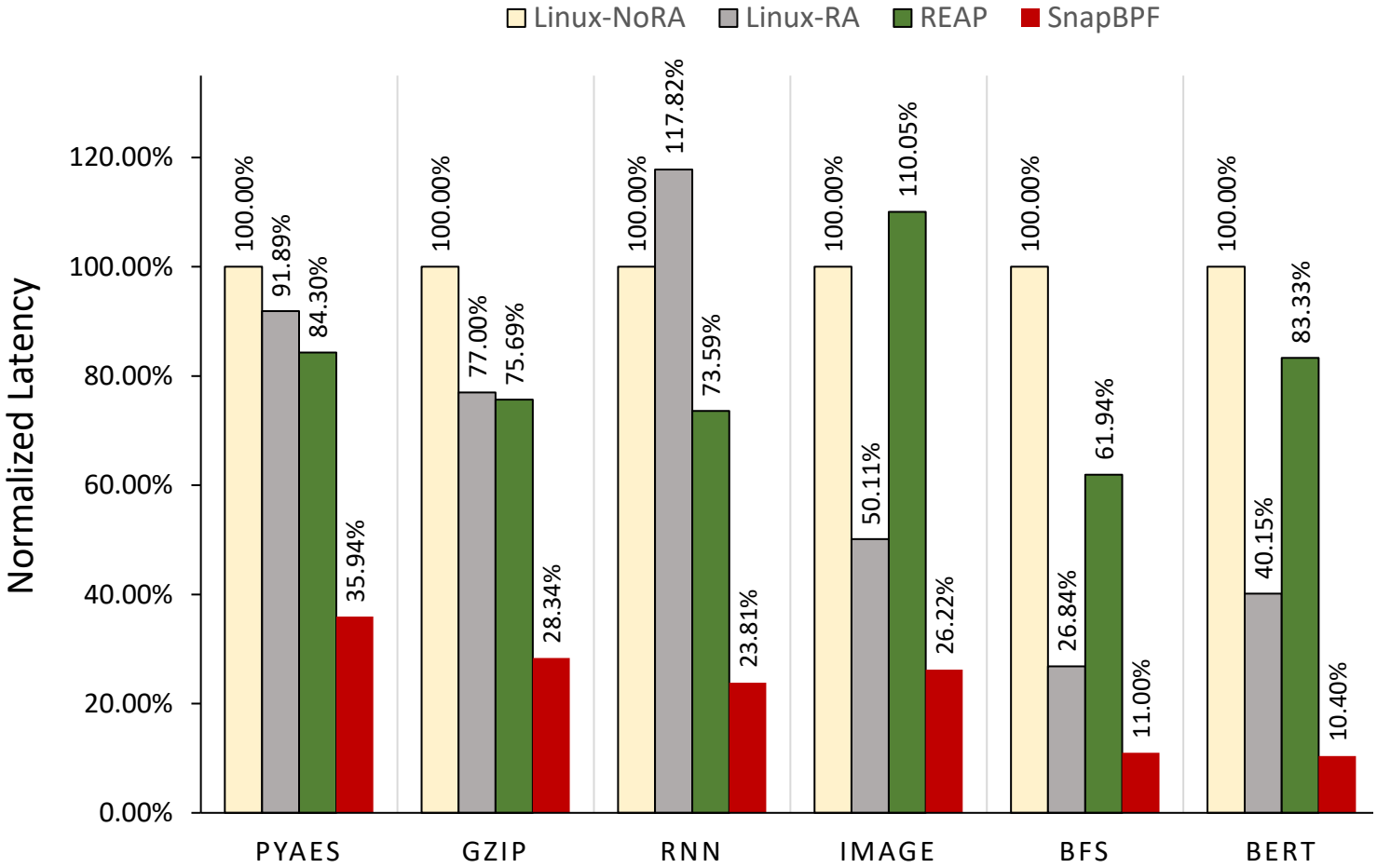
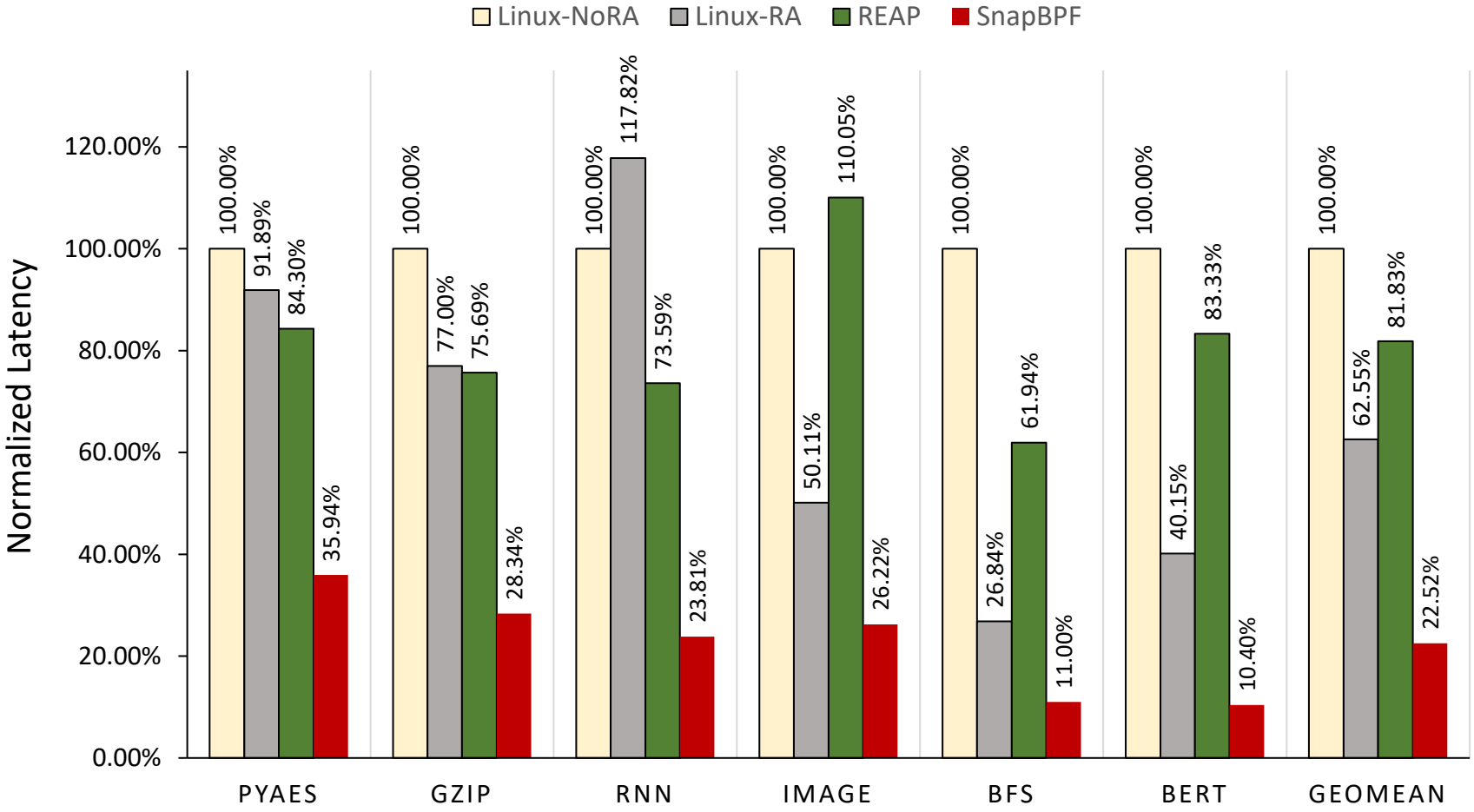
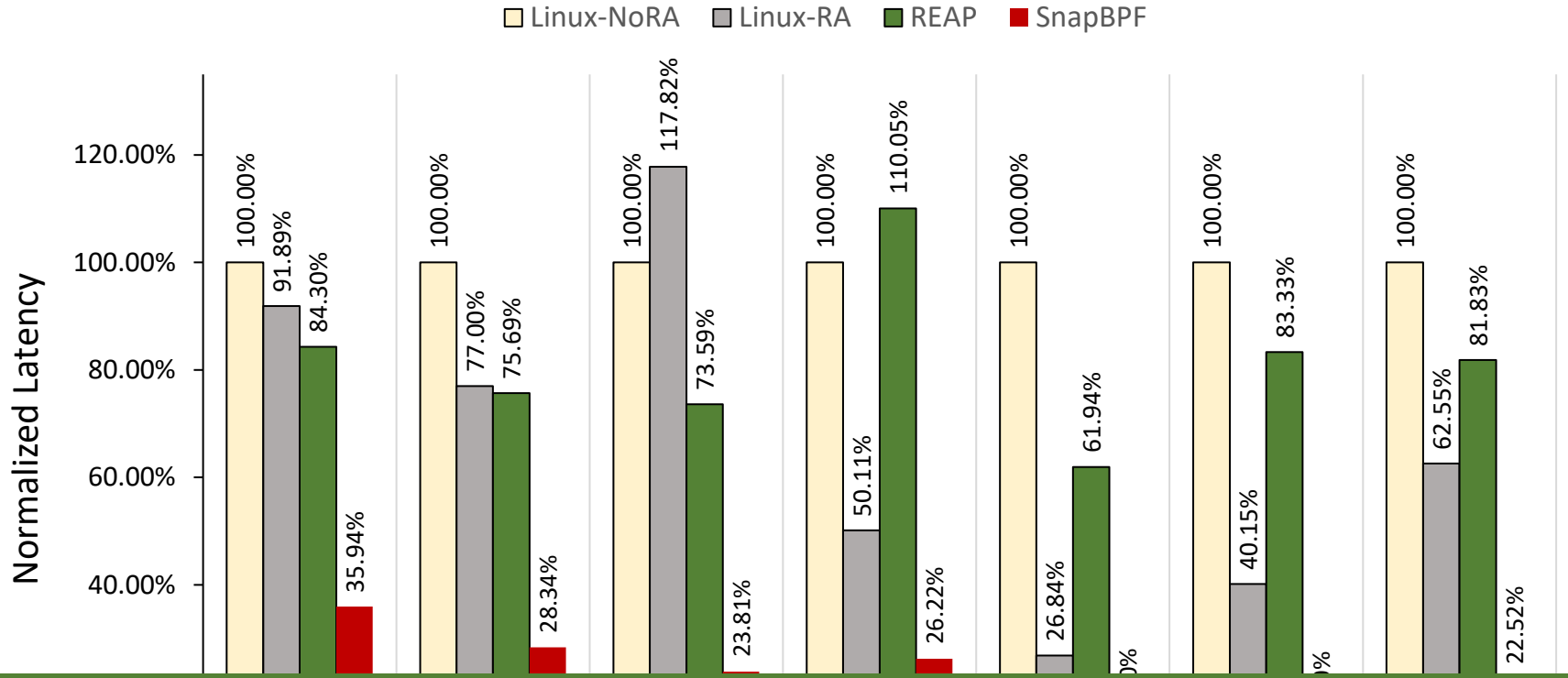


Concurrent Execution: Latency



Concurrent Execution: Latency



SnapBPF deduplicates memory without sacrificing performance

Outline

→ FaaS Snapshotting

→ Working Set Prefetching

→ SnapBPF

i. eBPF capture and prefetch

ii. PV free page filtering

→ Evaluation

→ Conclusion

Conclusion and next steps

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→ SnapBPF:

→ Minimizes complexity without sacrificing performance

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→ Device Performance: Sequential vs Random I/O

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Conclusion and next steps

→Device Performance: Sequential vs Random I/O

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→Userfaultfd features (remote fetch)

Thank you!

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Questions?

SnapBPF performance breakdown

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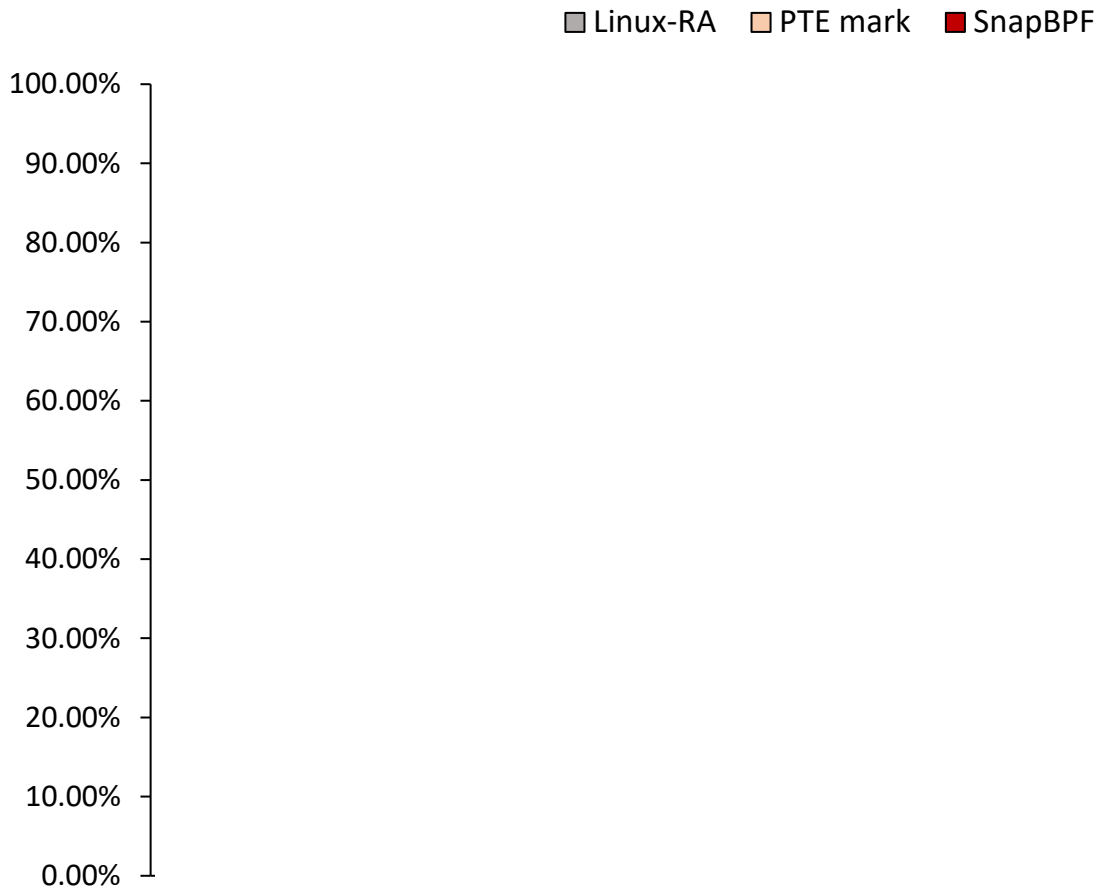
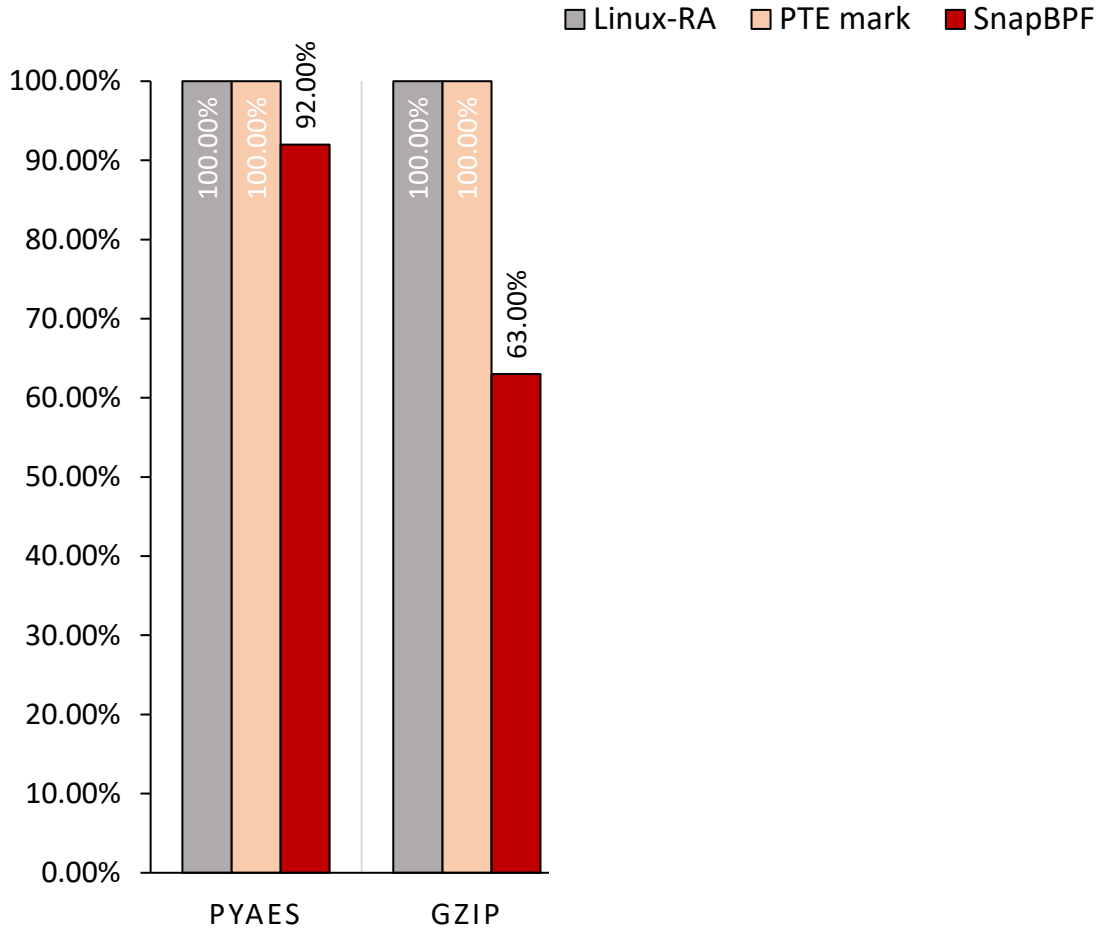
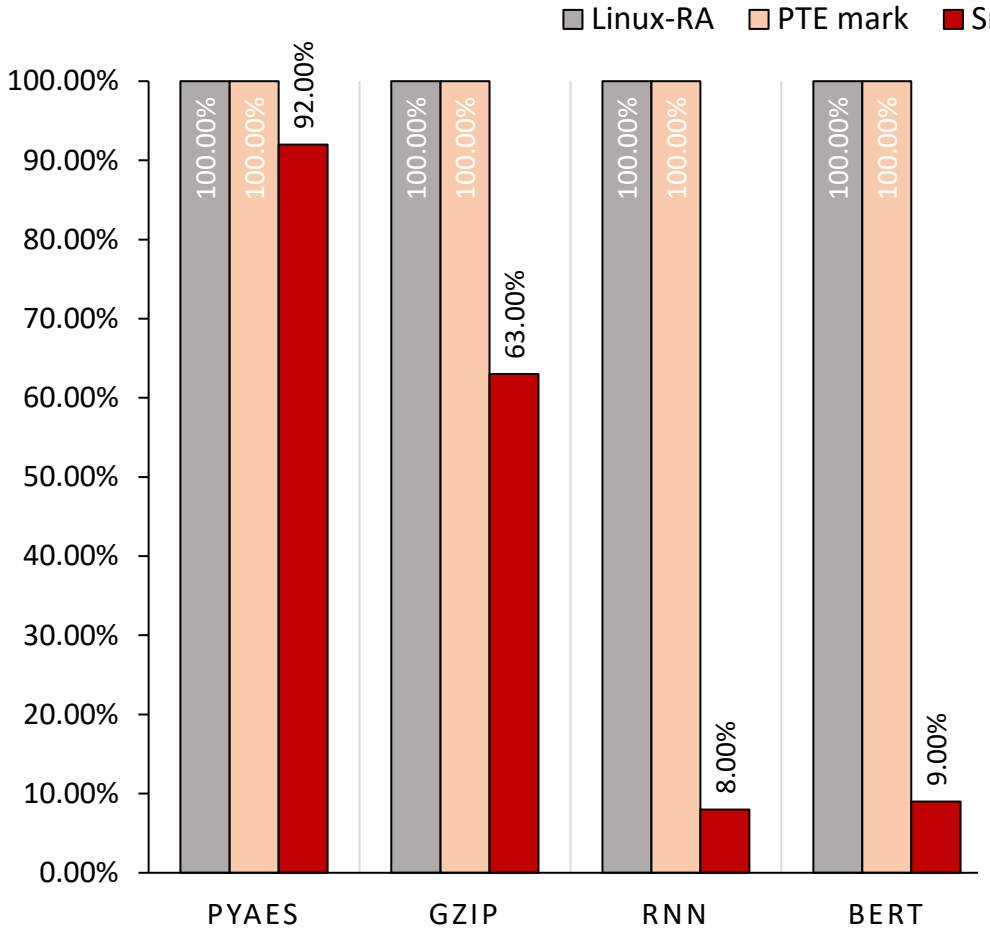


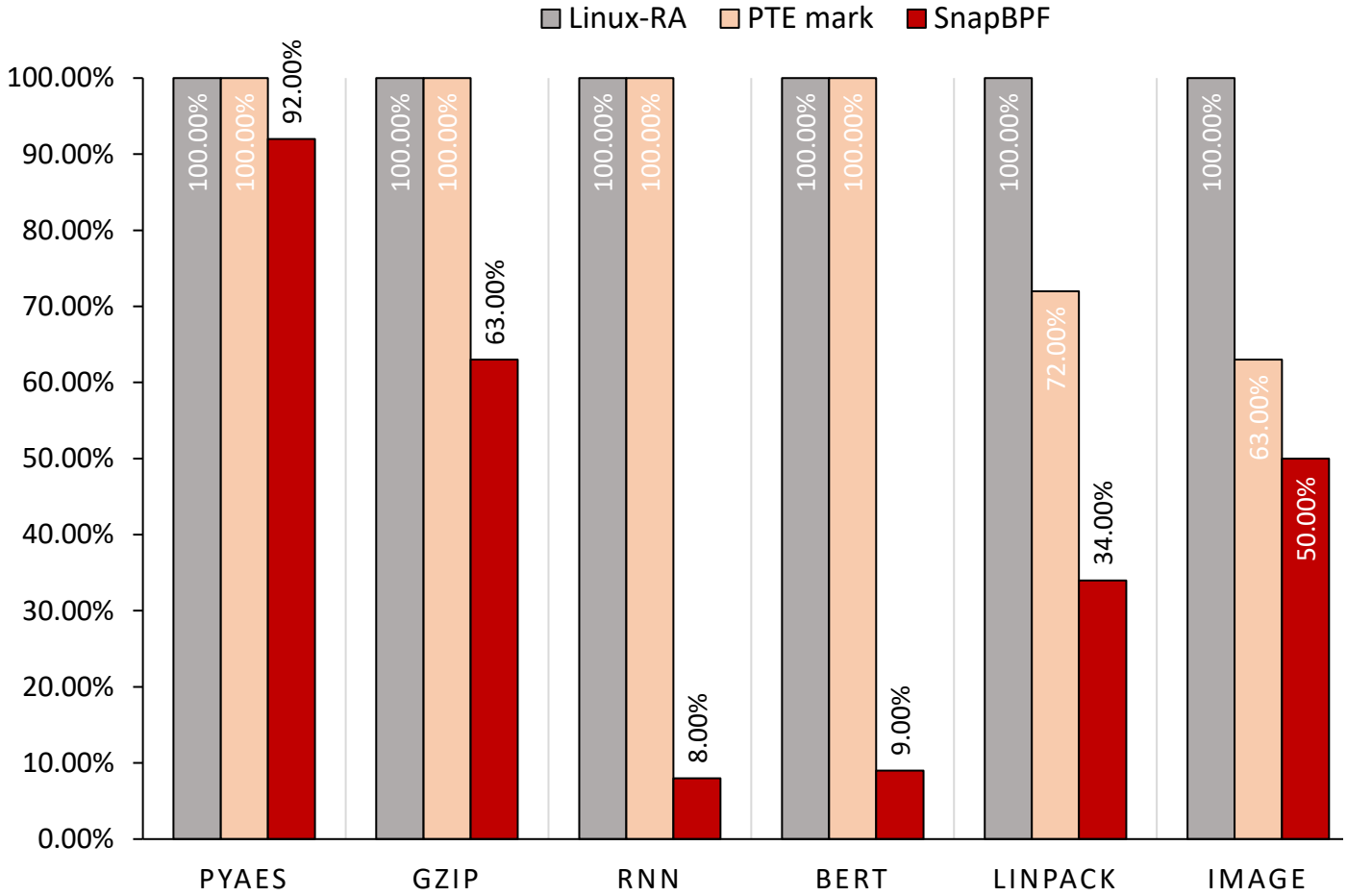
SnapBPF performance breakdown



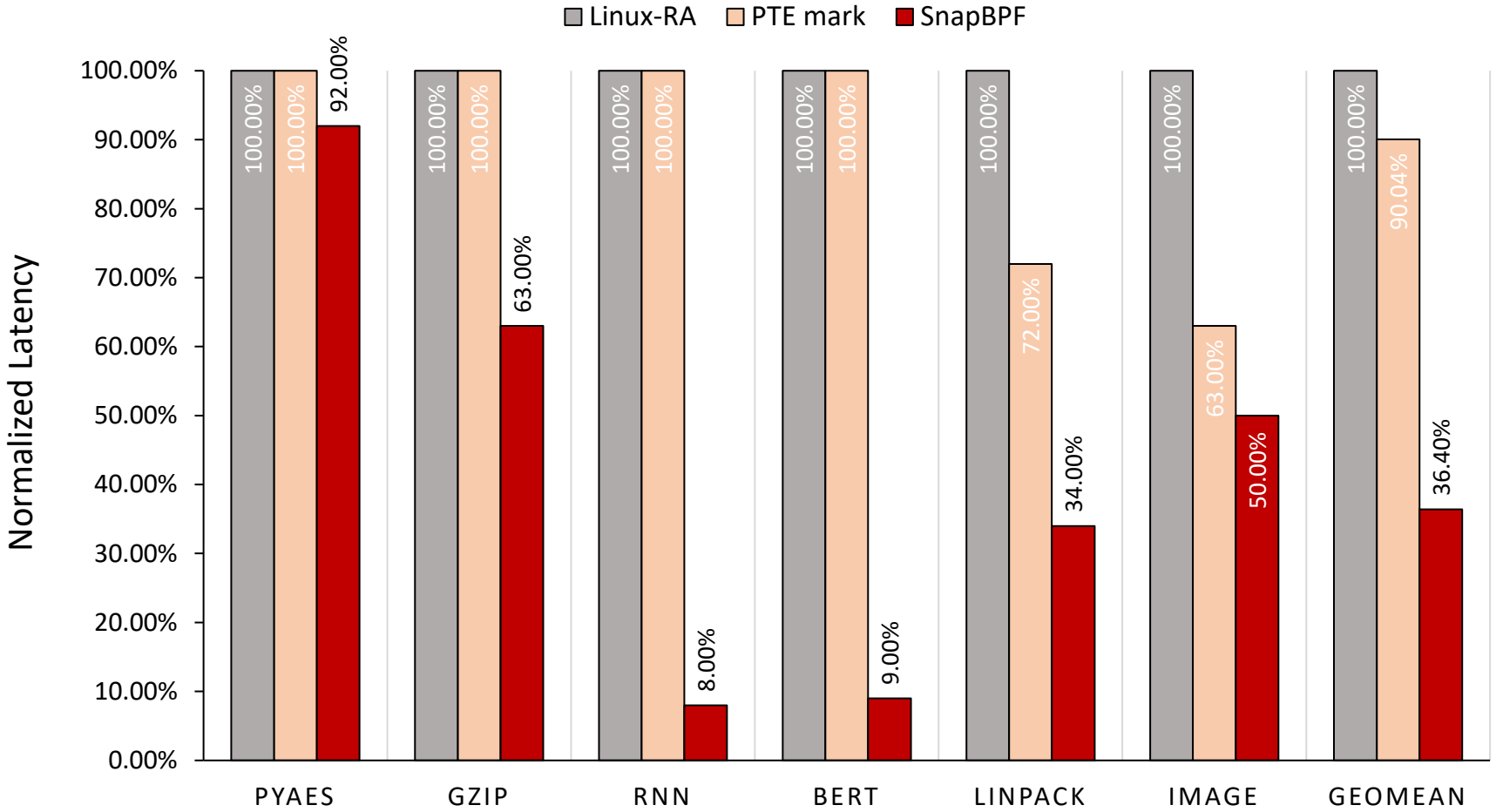
SnapBPF performance breakdown



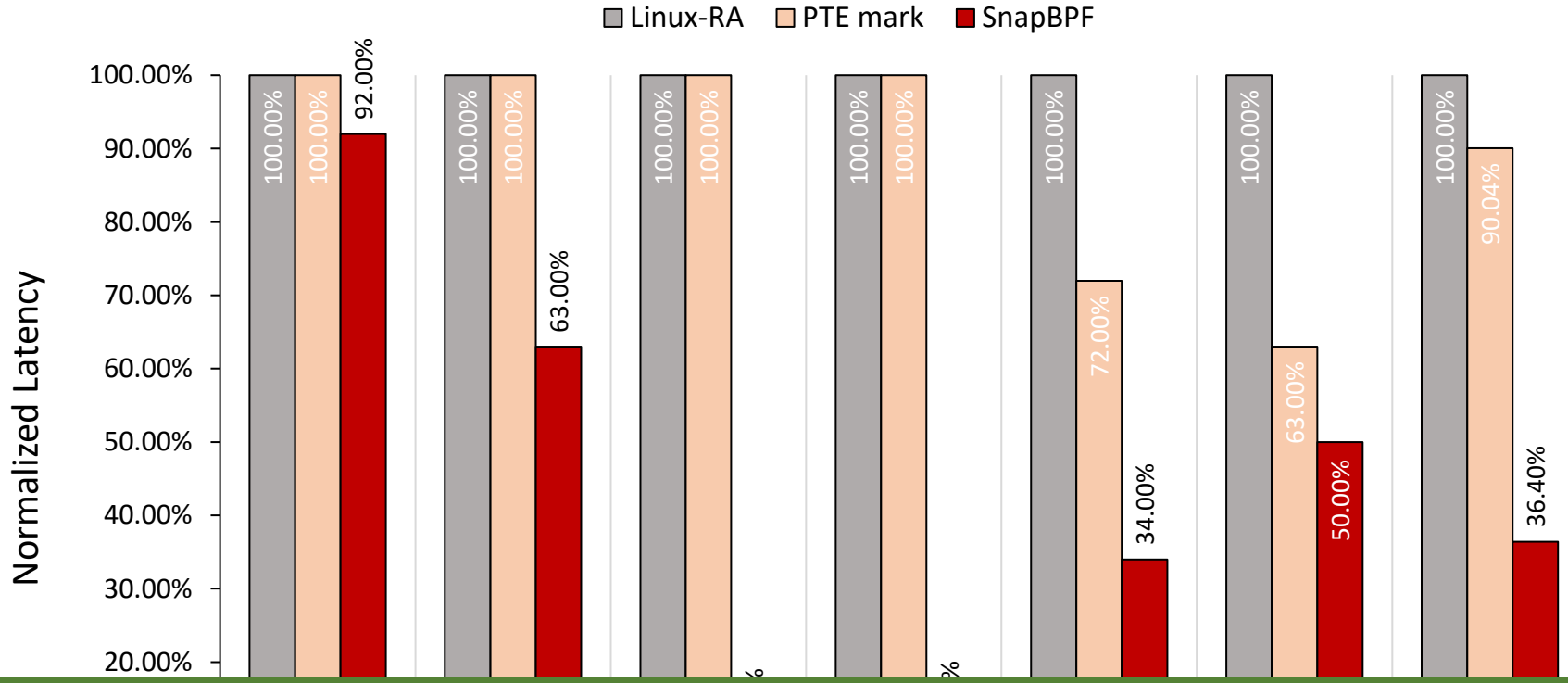
SnapBPF performance breakdown



SnapBPF performance breakdown



SnapBPF performance breakdown



Online free page filtering boosts performance for allocation-heavy functions