16TH SYMPOSIUM ON CLOUD COMPUTING (SOCC'25)

MEMORY MATTERS: LOAD-TIME DEDUPLICATION FOR UNIKERNELS

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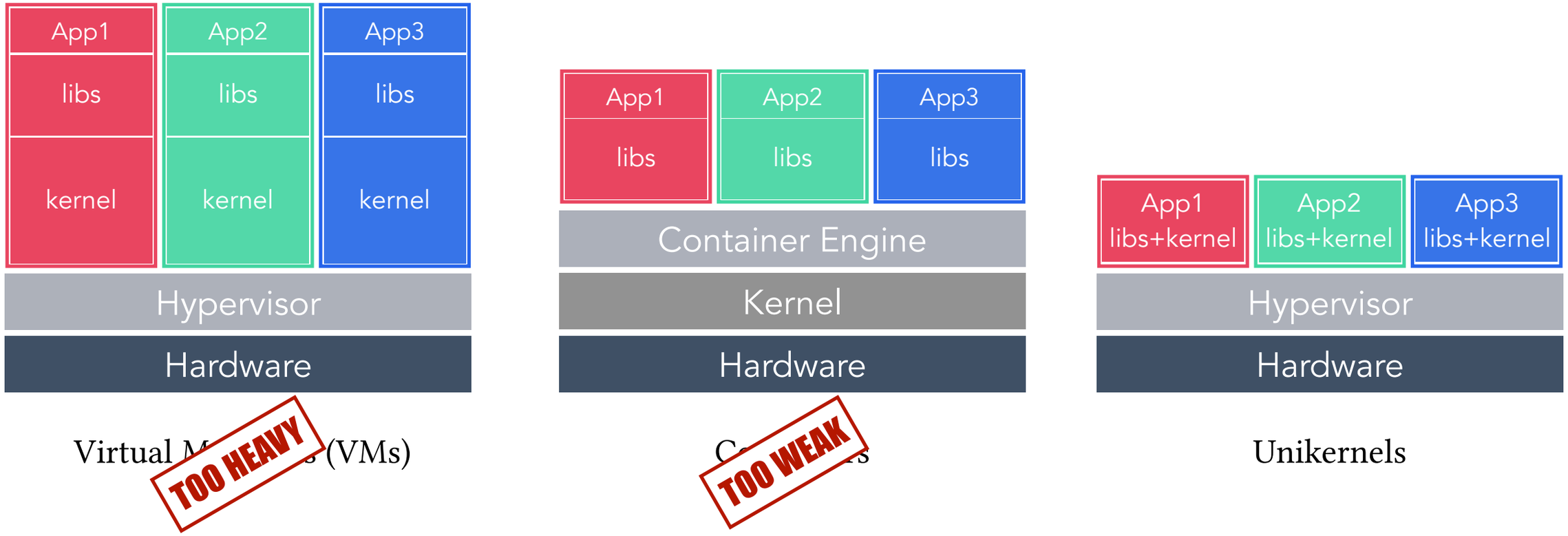
UNIKERNELS FOR CLOUD COMPUTING

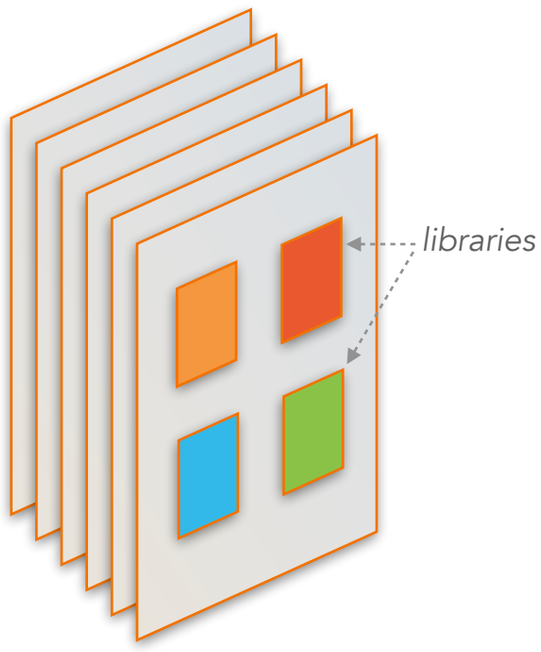
- Cloud workloads increasingly rely on massively parallel, short-lived functions
- Function as a Service (FaaS) platforms demand millisecond-scale startup, high density, and strong isolation



Unikernels are the **ideal** match for **serverless**: fast autoscaling, low overhead, reduced attack surface

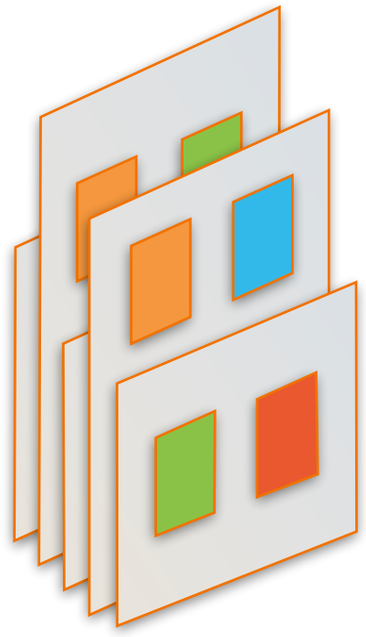
Running a large number of unikernels

Modern cloud platforms may launch **hundreds** or **thousands** of unikernels per machine



Same instance (identical unikernels)

same set of libraries



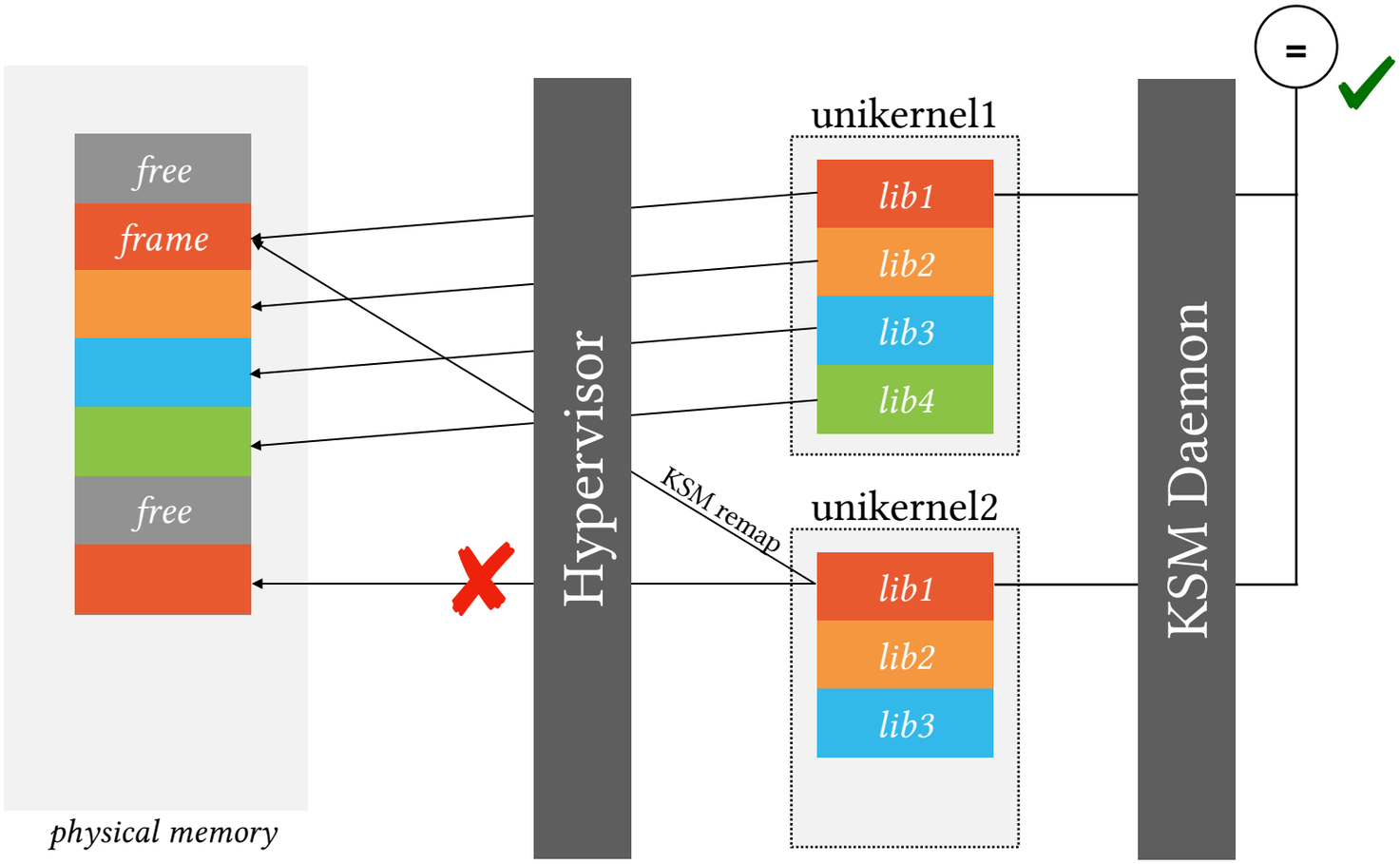
Different instances (≠ unikernels)

≠ sets of libraries

How can we reduce physical memory when dealing with many unikernels?

⇒ *Memory Deduplication*

Memory Deduplication & KSM

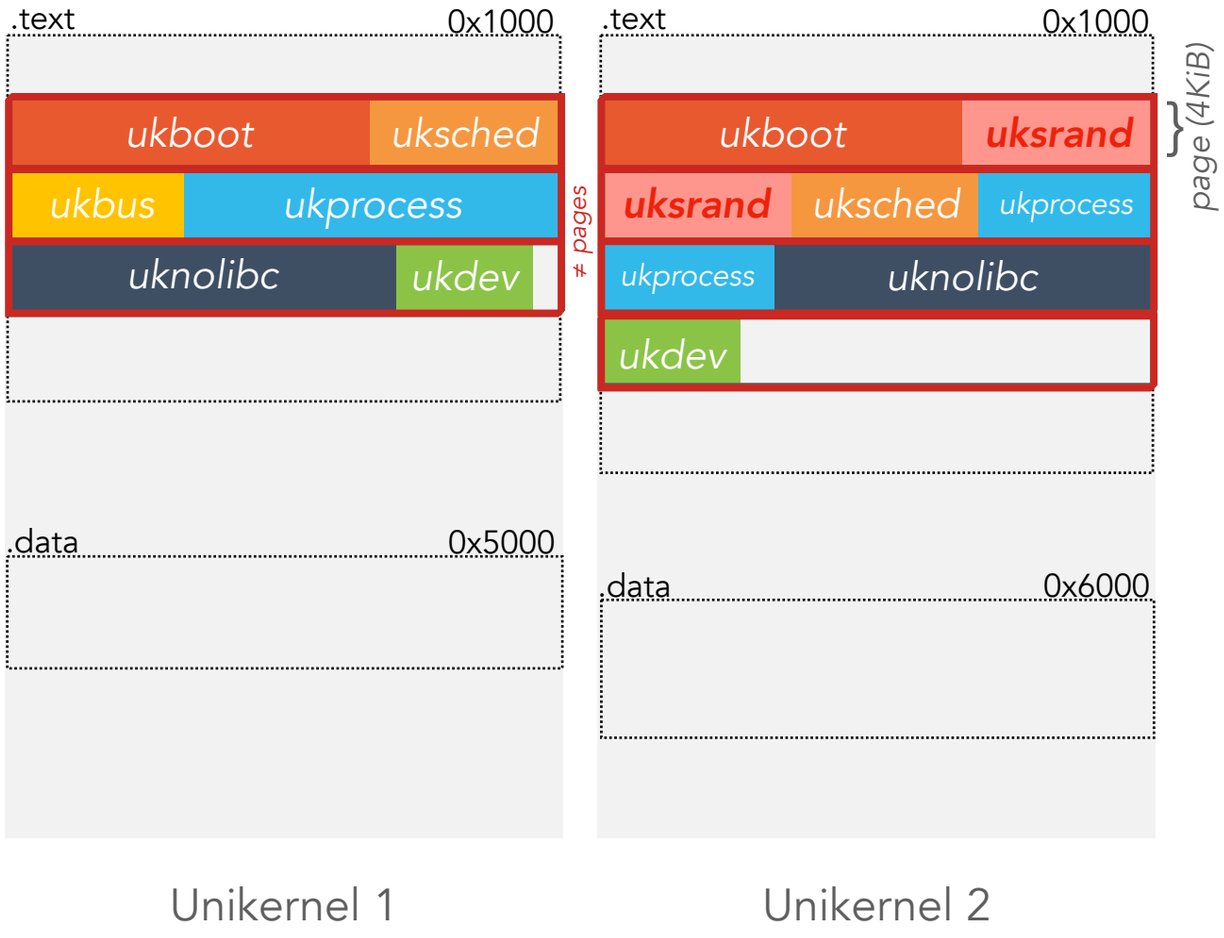


- Identical pages are merged via a memory deduplication runtime scanner
- Linux uses **KSM** (Kernel Samepage Merging) to detect duplicate pages
- KSM periodically scans memory, compares pages (checksum) and merges identical pages into the same single frame

DEALING WITH DIFFERENT UNIKERNELS

Unikernels are highly specialized and compact:

- Having **different** unikernels will result in **different** library configurations
- The library's code is compacted and spread across different pages between unikernels

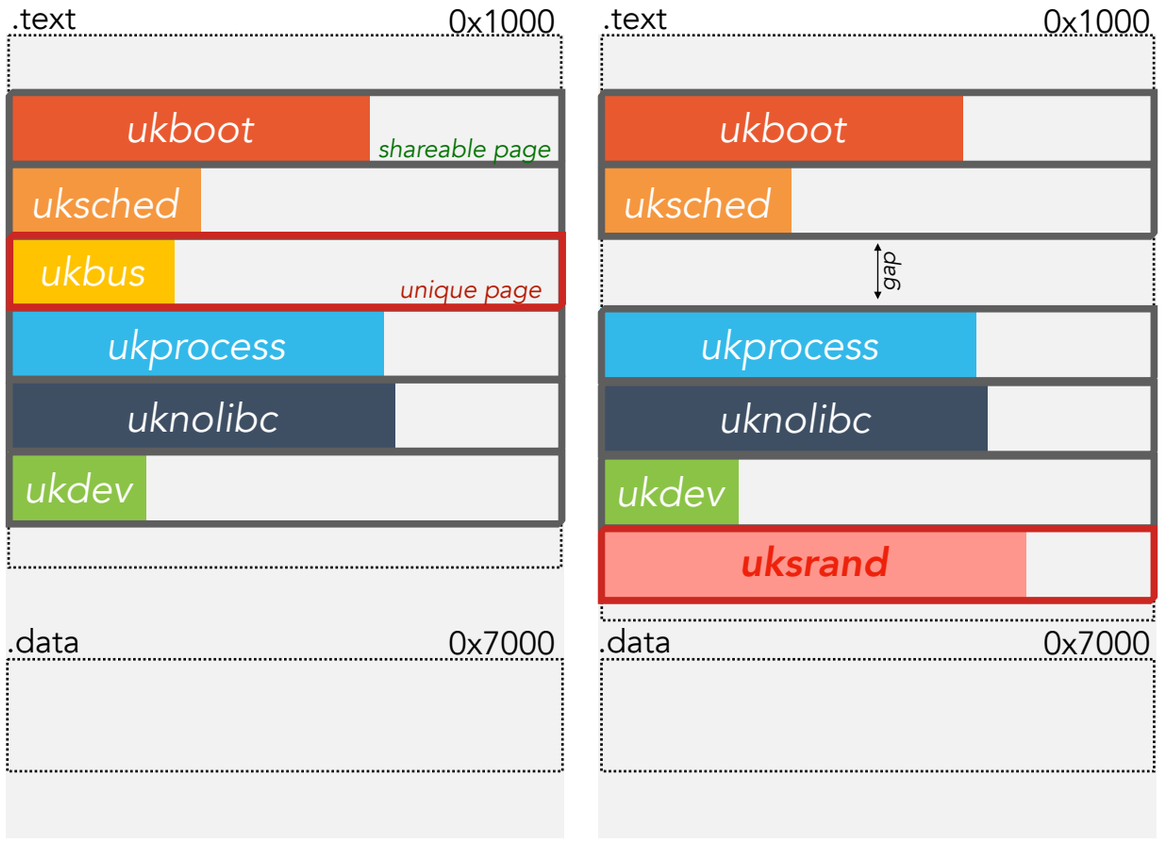


⟹ Different pages: **cannot** be shared between different unikernels, and thus, **higher** memory consumption

RELYING ON EXISTING WORK: SPACER

Increase sharing opportunities by using *Spacer*[1]:

- Unikernels are inflated by aligning libraries at fixed, page-aligned addresses



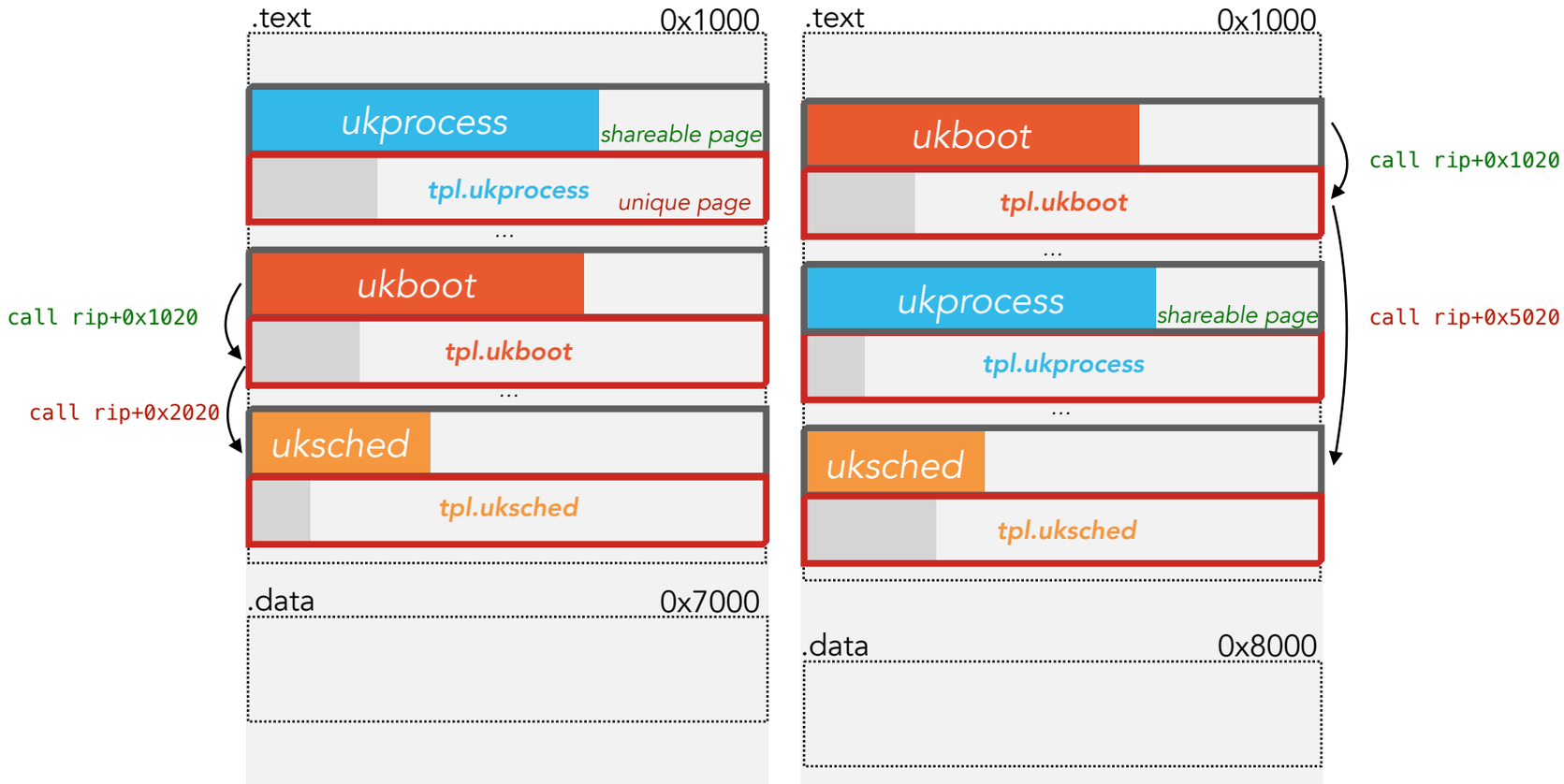
Unikernel 1 Unikernel 2

[1] "*Want More Unikernels? Inflate Them!*", In SoCC'22

Relying on existing work: Spacer

Increase sharing opportunities by using *Spacer*[1]:

- Unikernels are inflated by aligning libraries at fixed, page-aligned addresses



- Supports ASLR through the use of trampoline tables (*tpl*): problematic instructions
- Relies on **KSM** to actually merge identical pages at runtime

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KSM Drawbacks

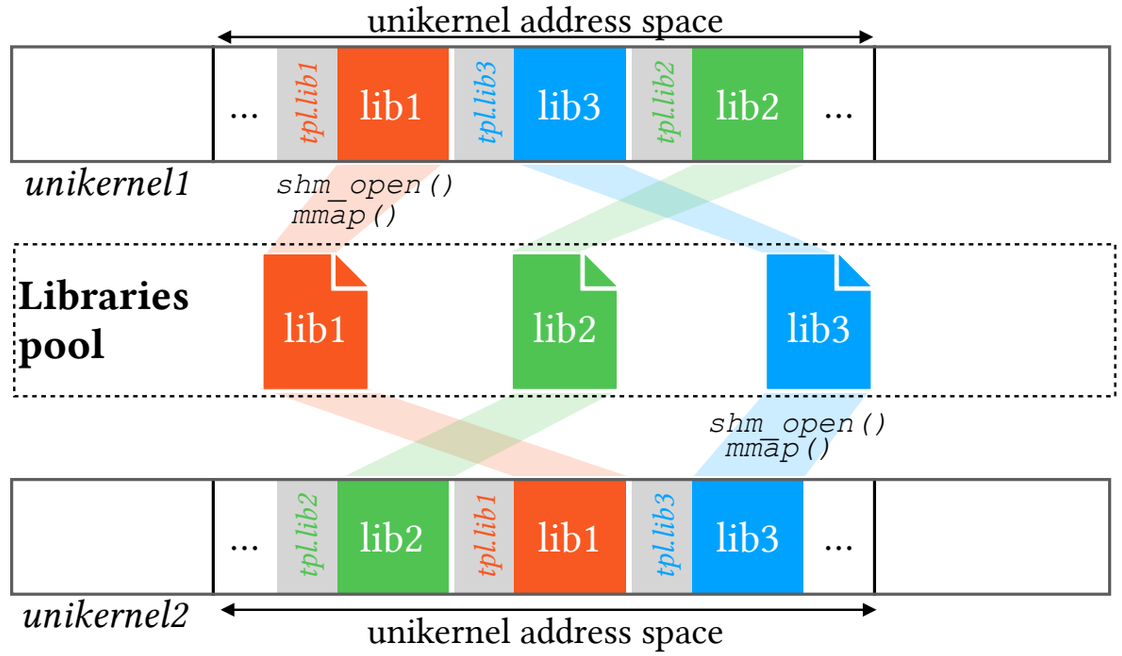
- **Slow convergence**: scanning memory takes time; short-lived functions may finish before pages are merged
- **High CPU overhead**: aggressive scanning consumes significant CPU cycles
- **Non-deterministic savings**: deduplication varies depending on timing and system pressure
- **Security risks**: merging writable pages introduces CoW-based timing side channels
- **I/O and TLB overhead**: merging pages forces extra page faults, copies, and TLB shootdowns

$\Rightarrow$ *Need a better approach*

SPACER-SLT: KEY IDEA

Spacer-SLT: "*Share at Load Time (SLT)*"

- Extends *Spacer* by performing deduplication at load time
- Uses a pool of libraries containing library code & read-only data
- Relies on a custom Firecracker-based loader to map identical pages directly
- Eliminates the need for a memory deduplication runtime scanner (KSM)



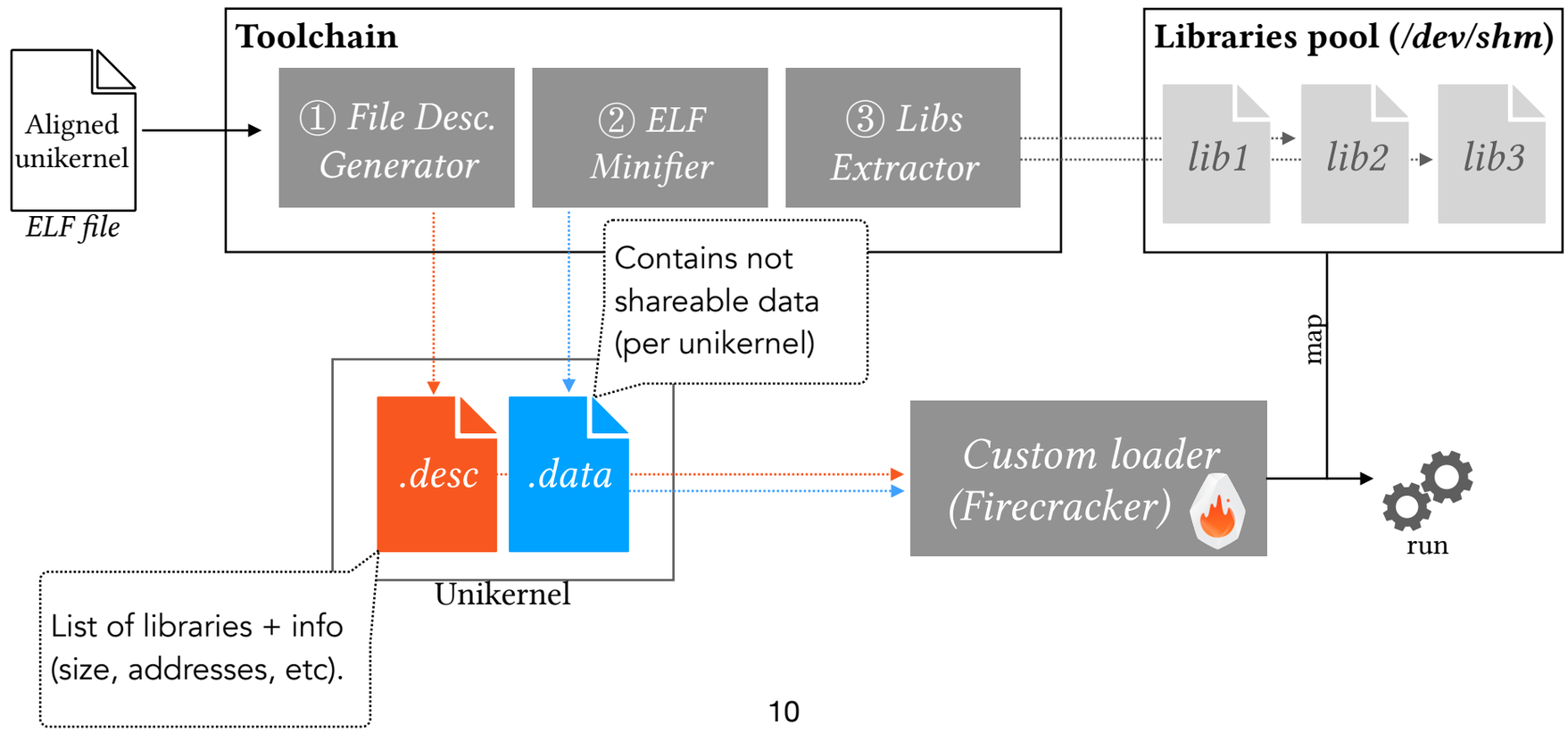
SPACER-SLT: TOOLCHAIN

- Performs all operations offline, eliminating overhead during unikernel runtime
- Use a toolchain that consists of several components:

① **File Description Generator**: Produces a description file (*.desc*) for each unikernel by analyzing its ELF layout

② **ELF Minifier**: Strips the ELF down to a minimal form, retaining only the aggregated writable data section (and trampoline tables for ASLR) into a *.data* file

③ **Libraries Extractor**: Extracts compiled libraries as standalone binary files and places them into a shared library pool

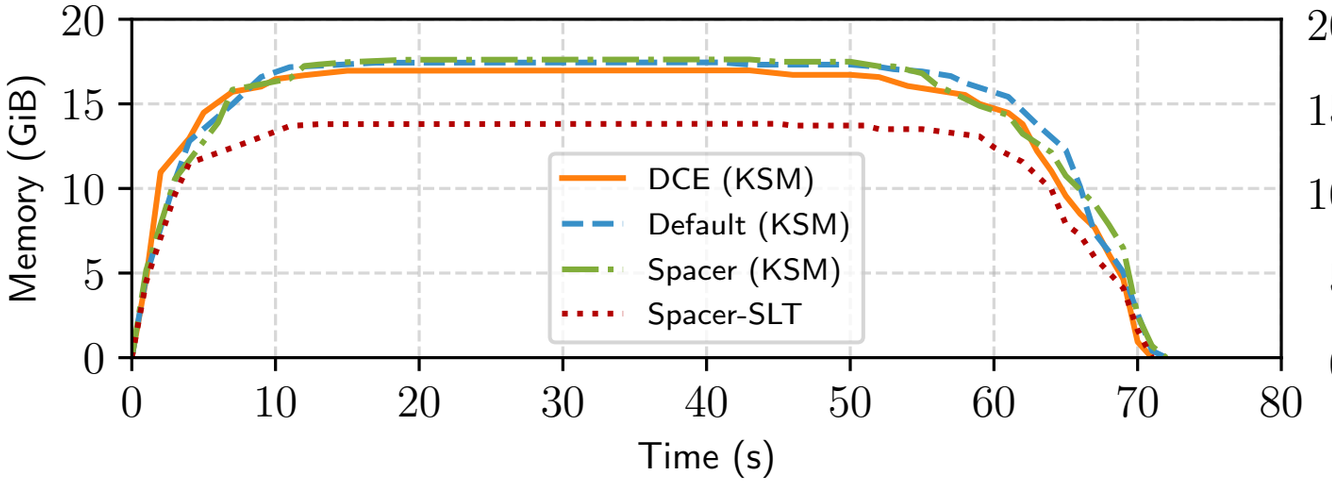


Evaluation: Methodology

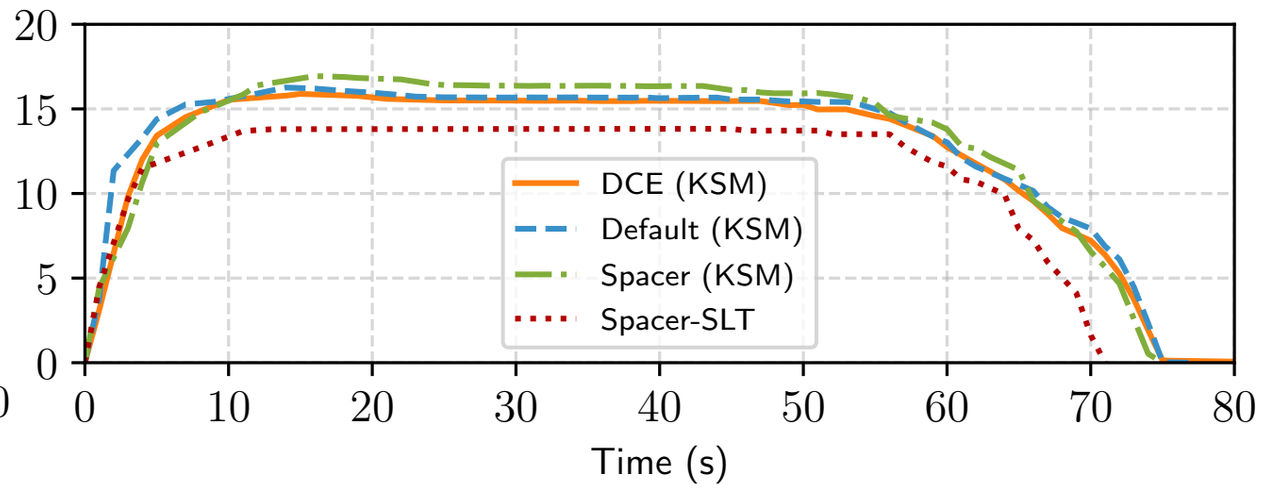
- Rely on the Unikraft Framework and Firecracker as a custom loader
- Compare Spacer-SLT against **DCE (Dead Code Elimination)**, **Default Unikraft**, and **Spacer**
- Evaluate both **homogeneous** and **heterogeneous** workloads:
  - 128 Go-based FaaS unikernels (identical instance)
  - 20 different applications ported as unikernels NGINX SQLite …
- Also, measure the **KSM behavior** under 2 modes:
  - *KSM-quiet (default): scan 100 pages every 20 ms*
  - *KSM-full (aggressive): scan 20000 pages every 1 ms*
- On several dimensions: memory consumption, file size and performance

Please refer to the paper for the full evaluation.

Evaluation: Memory



(a) ***KSM-quiet***: KSM takes time to identify and merge duplicate pages, resulting in minimal memory savings.



(b) ***KSM-full***: KSM achieves better memory reduction by using more CPU cycles, but it is overwhelmed by the rapid arrival of many unikernels.

Running many identical instances:

- Run 128 identical FaaS unikernels (Go) and benchmarked according to 2 KSM modes: ***KSM-quiet*** & ***KSM-full***
- Spacer-SLT achieves the **lowest** memory consumption in both cases **without** any performance penalties
- Up to 30% additional memory **savings** with Spacer-SLT compared to KSM-based configurations

Evaluation: Memory

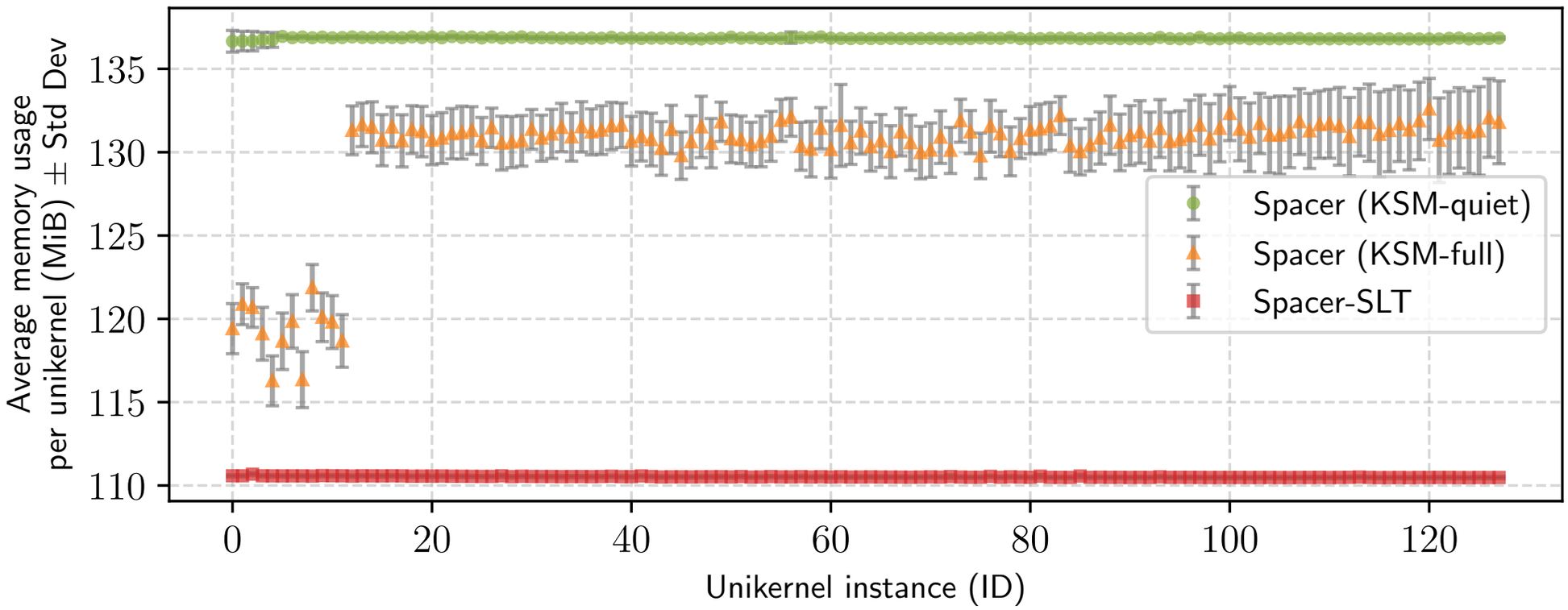


Figure: Average physical memory usage per instance for 128 benchmarked FaaS unikernels (including hypervisor).

- KSM-based configurations show **unstable** behaviour
  - Under ***KSM-full***, the first few unikernels benefit from memory deduplication
  - As the number of instances grows, KSM becomes **overloaded** and cannot merge effectively
- Spacer-SLT maintains **consistent** and **predictable** memory usage across all instances

Evaluation: Memory

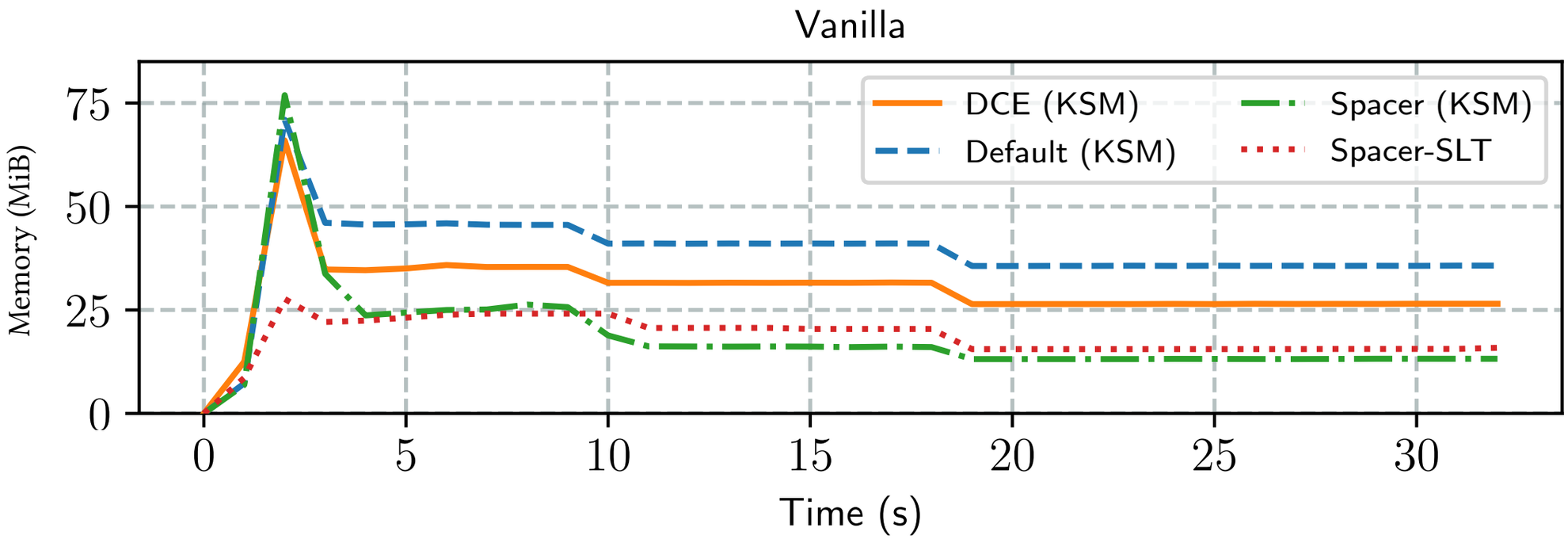


Figure: Evolution of the physical memory used by 20 different unikernels (all started at t=0s)

Running different instances:

- With KSM, memory peaks appear during startup
- KSM also merges identical writable pages, such as those related to the heap and video memory
  - KSM might achieve higher memory reduction than Spacer-SLT, but it comes with inherent issues

Evaluation: Performance & Filesize

Spacer-SLT Performance:

Library pool acting as a cache:

- Fewer page faults: up to 7× less
- Faster load times: up to 1.4× faster

No KSM daemon:

- No runtime CPU cost and no CoW faults
- 10–13× fewer TLB flushes, avoiding costly TLB shootdowns

$\Longrightarrow$ Better execution time: $\approx$ 10 % gain compared with *KSM-quiet*

$\Longrightarrow$ even **better** with *KSM-full*

Spacer-SLT Elf Size:

- Thanks to the library pool, the unikernels filesize is reduced by up to 5.8×

Why Not Dynamic Linking?

Ported Spacer-SLT and the Unikraft codebase to **userspace** *(reduced effort)*

- Extended Unikraft: support dynamically linked unikernels (extensive modifications)
- Implemented a lightweight userspace loader to run them

Apps	Spacer-SLT	SLT [ASLR]	Dynamic
helloworld	0,0000211	0,0000227	0,00003
nginx	0,174	0,177	0,211
mandelbrot	0,358	0,359	0,37
lambda	0,539	0,55	0,56
python	2,114	2,137	2,271
zlib	3,814	3,853	4,095
sqlite-speed	47,503	47,857	48,529

Table: Total execution time (in seconds)

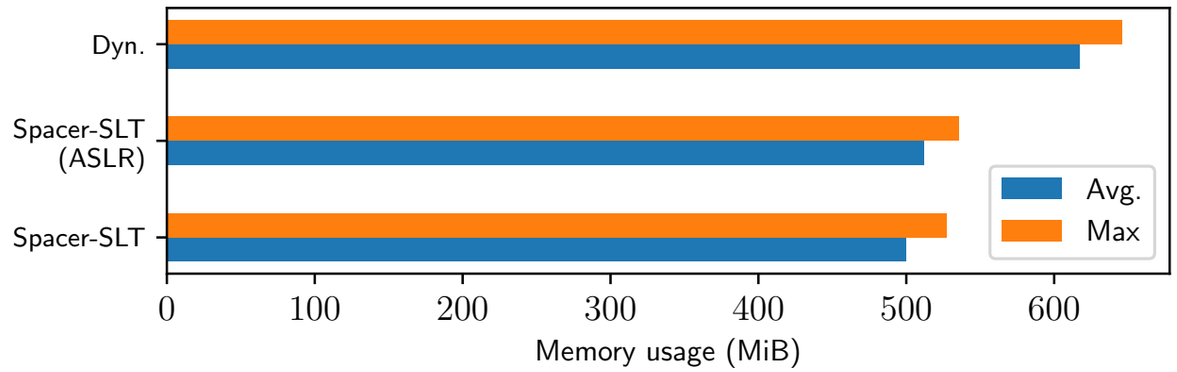


Figure: Memory usage of different unikernels (and the loader)

Dynamically linked unikernels consume **more memory** and have **higher** execution time:

- Memory penalty: overhead of the dynamic linker and additional structures such as PLT/GOT
- Time penalty: library relocations and symbol resolutions

\+ ***Security issues*** *(e.g., GOT overwritten, larger attack surface, etc.)*

Conclusion

- **Spacer-SLT:** deterministic **load-time** deduplication for statically linked unikernels
- Delivers **big wins** across the board: instant memory deduplication, fewer page faults, faster startup & execution time
- Enhances the efficiency of cloud infrastructures, especially for Microservices, FaaS, and short-lived workloads
- Easily **adaptable** to other unikernel frameworks and hypervisors
- Open source and available on GitHub

THANK YOU!

QUESTIONS?

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