Efficient Use-after-Free Prevention with Opportunistic Page-Level Sweeping

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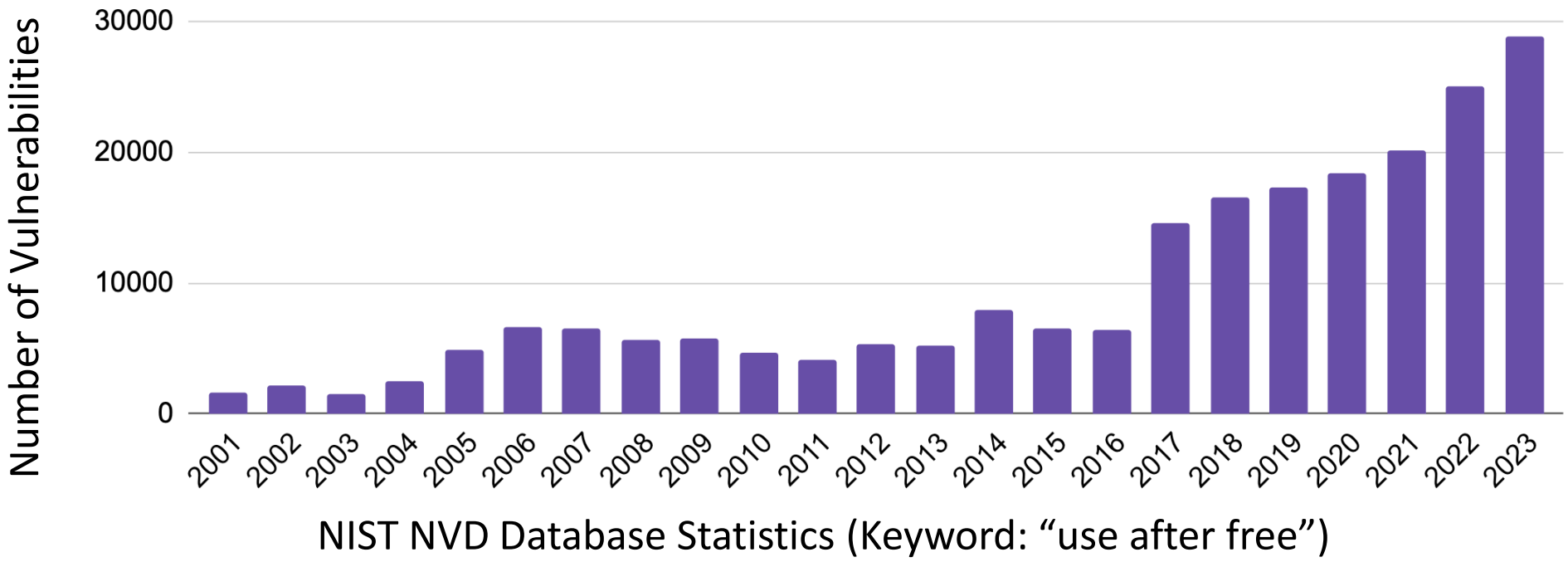
Use-after-Free is still Prevalent

- An increasing number of use-after-free vulnerabilities are reported every year.

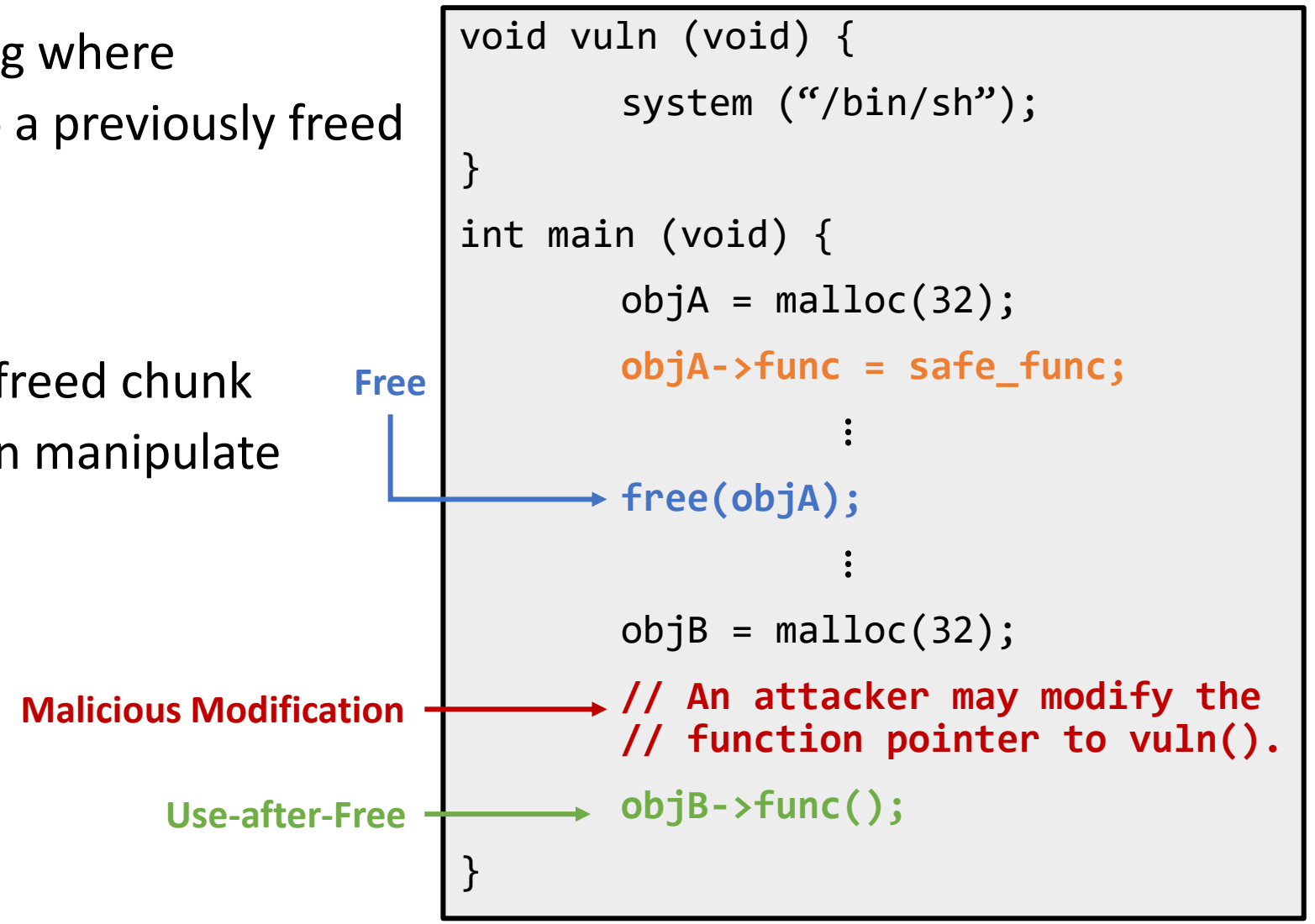


NIST NVD Database Statistics (Keyword: “use after free”)

Use-after Free: Example

- Use-after-Free (UaF) is a bug where a program uses a pointer to a previously freed heap chunk.

- An attacker controlling the freed chunk (i.e., reuse of the chunk) can manipulate the program's behavior.



Existing Approaches

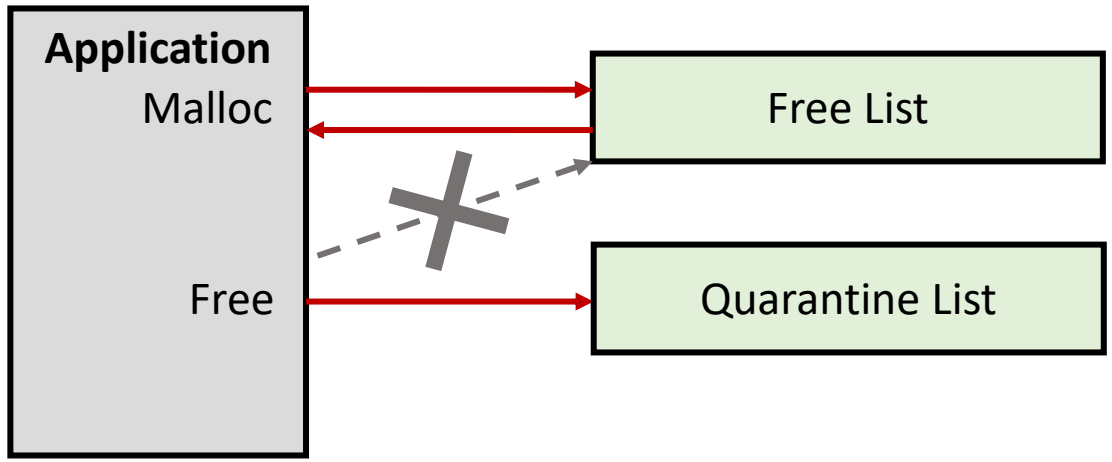
- Garbage collector-like (MarkUs, MineSweeper)
  - ➢ Reuse delayed freed chunks after Mark-Sweep to know the dangling pointer's existence.
- One-time Allocation (FFmalloc)
  - ➢ Only use the allocated region at once.

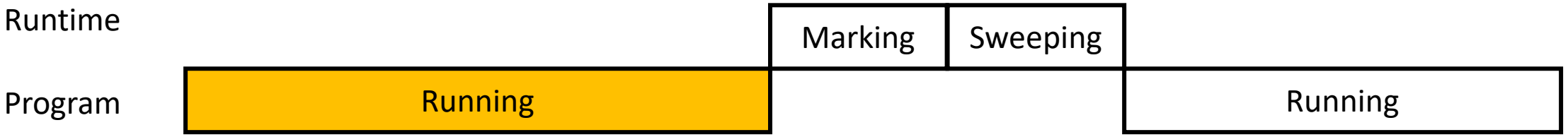
Binary-only
No Recompilation
No Custom Hardware

- Reference counting (CRCount) **Recompilation**
- Pointer nullification (DangNULL) **Recompilation**
- Access validation (ViK, PACMem) **Recompilation or Custom Hardware**

Garbage Collector-like: Allocation/Free

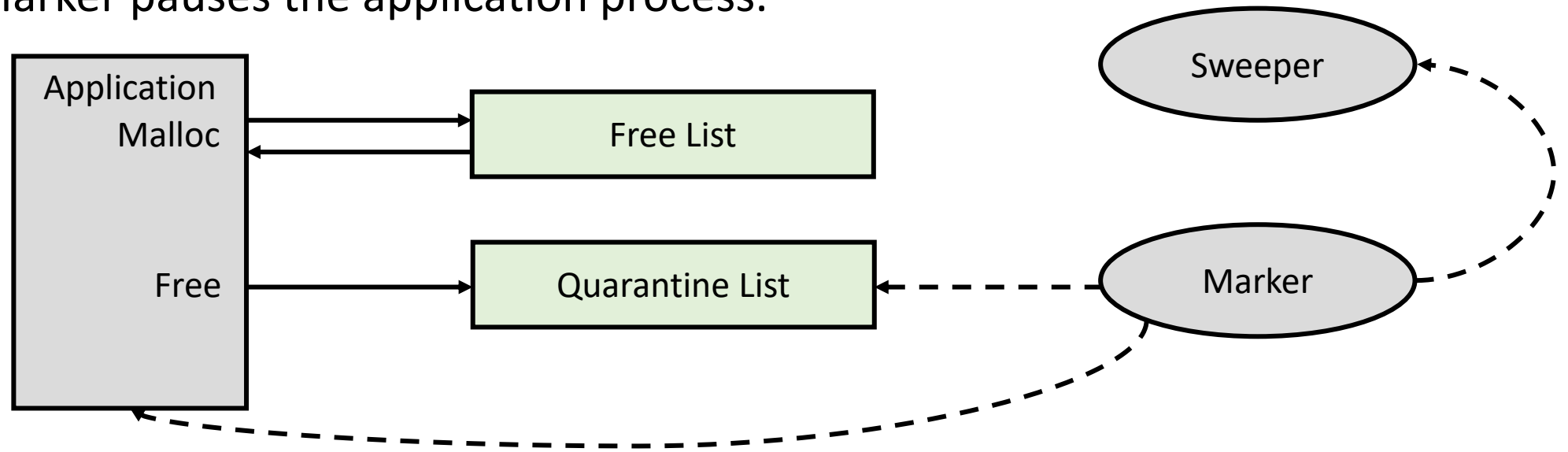
- Garbage Collector-like approaches delay deallocations.

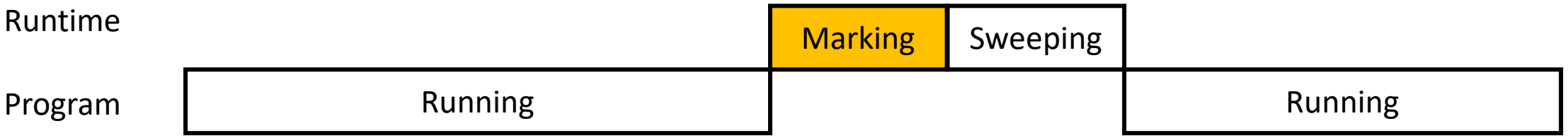




Garbage Collector-like: Marking

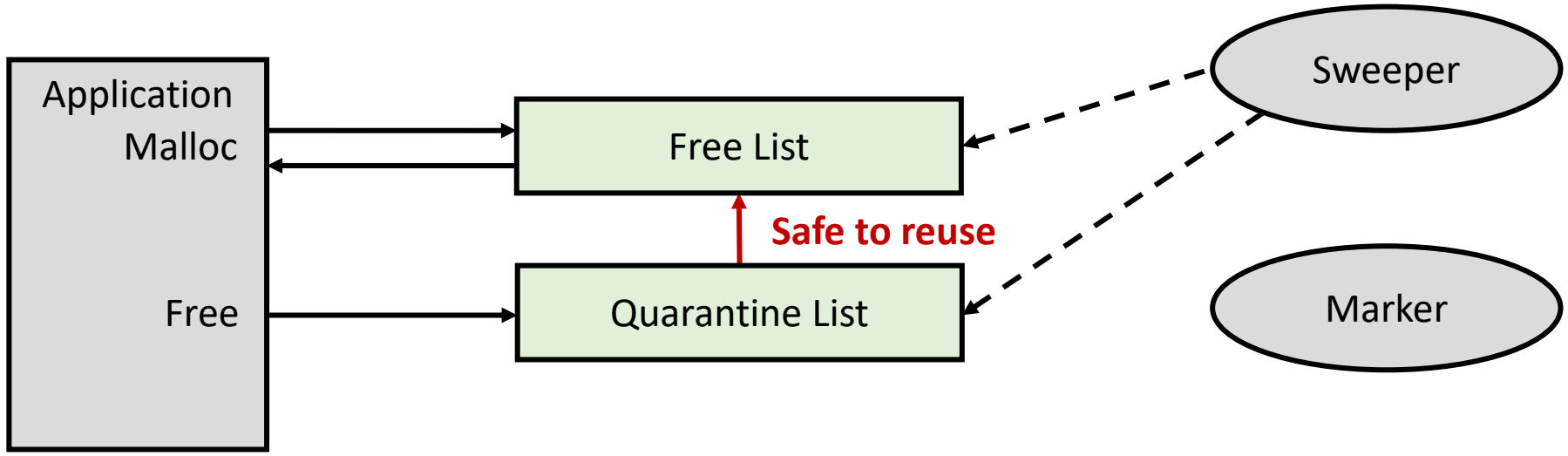
- Marker determines if each chunk can be safely reused or not by memory scanning.
- Marker pauses the application process.

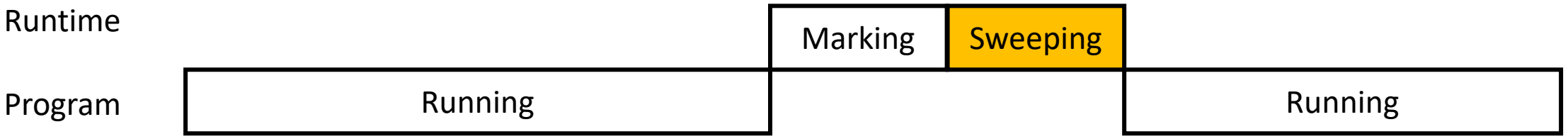




Garbage Collector-like: Sweeping

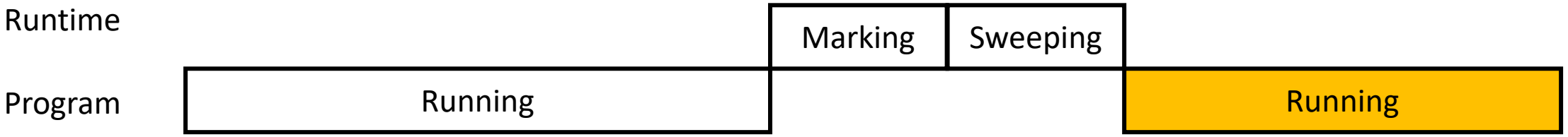
- Sweeper traverses quarantine list and inserts safe objects to the free list.





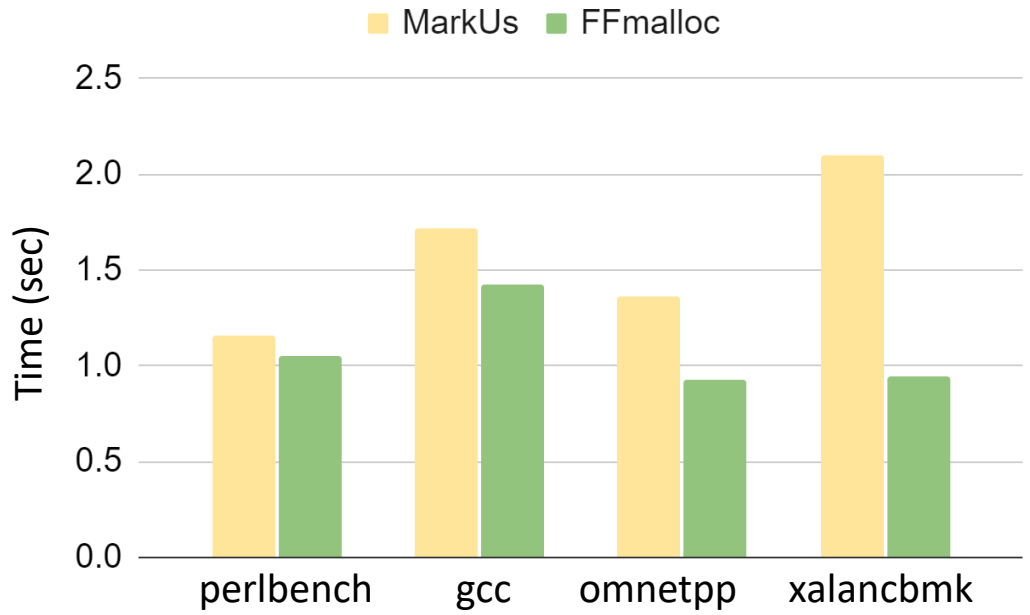
Garbage Collector-like: Reuse

- All chunks in the free list are guaranteed to be safe to reuse.



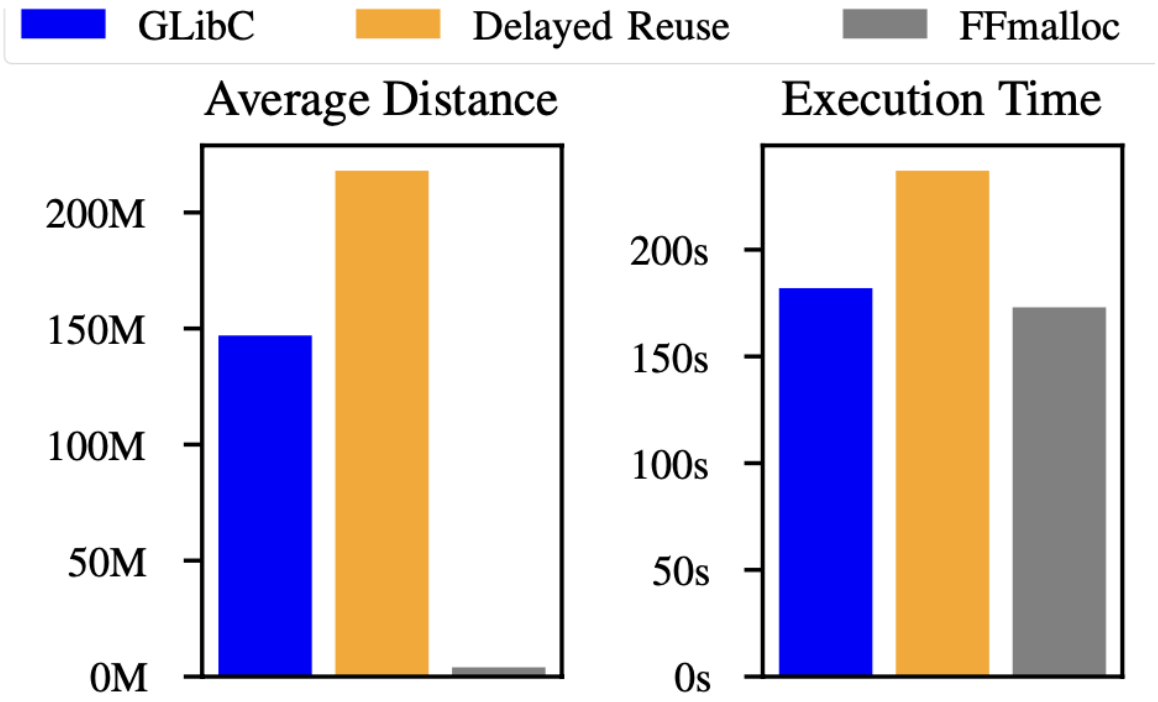
Observations

- Garbage collector-like approaches suffer from significant overhead on the execution time for allocation-intensive benchmarks.
- One-time allocator (OTA) does not … why?



Delayed Reuse Lowers Spatial Locality and Performance

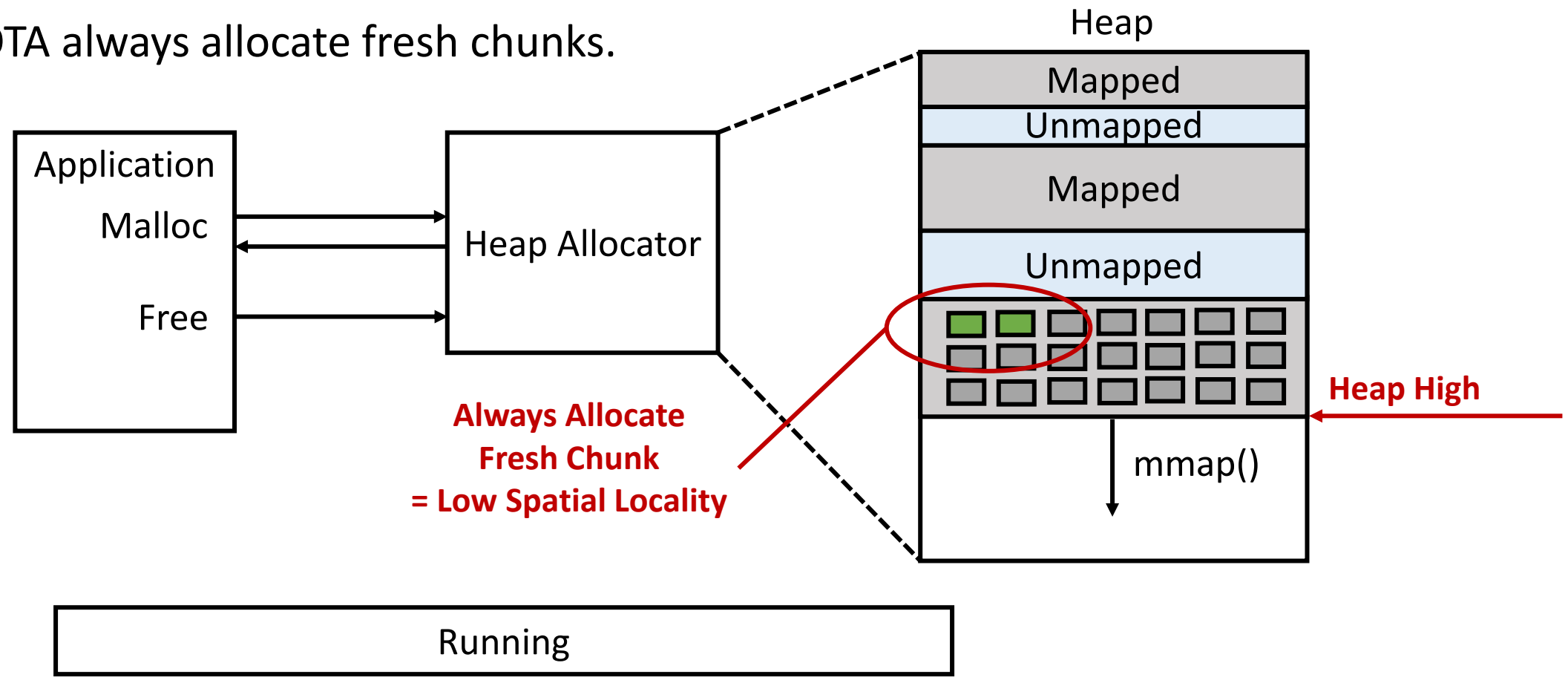
- **Delayed Reuse**: simply delays deallocations and reallocate them (no safety check).
- Just delaying the reuse lowers spatial locality of temporally local allocations.
- OTA does not harm the spatial locality.



Measurements while running SPEC CPU 2006 **xalancbmk**

One-time Allocation Details

- FFmalloc does not reuse virtual address space.
- OTA always allocate fresh chunks.

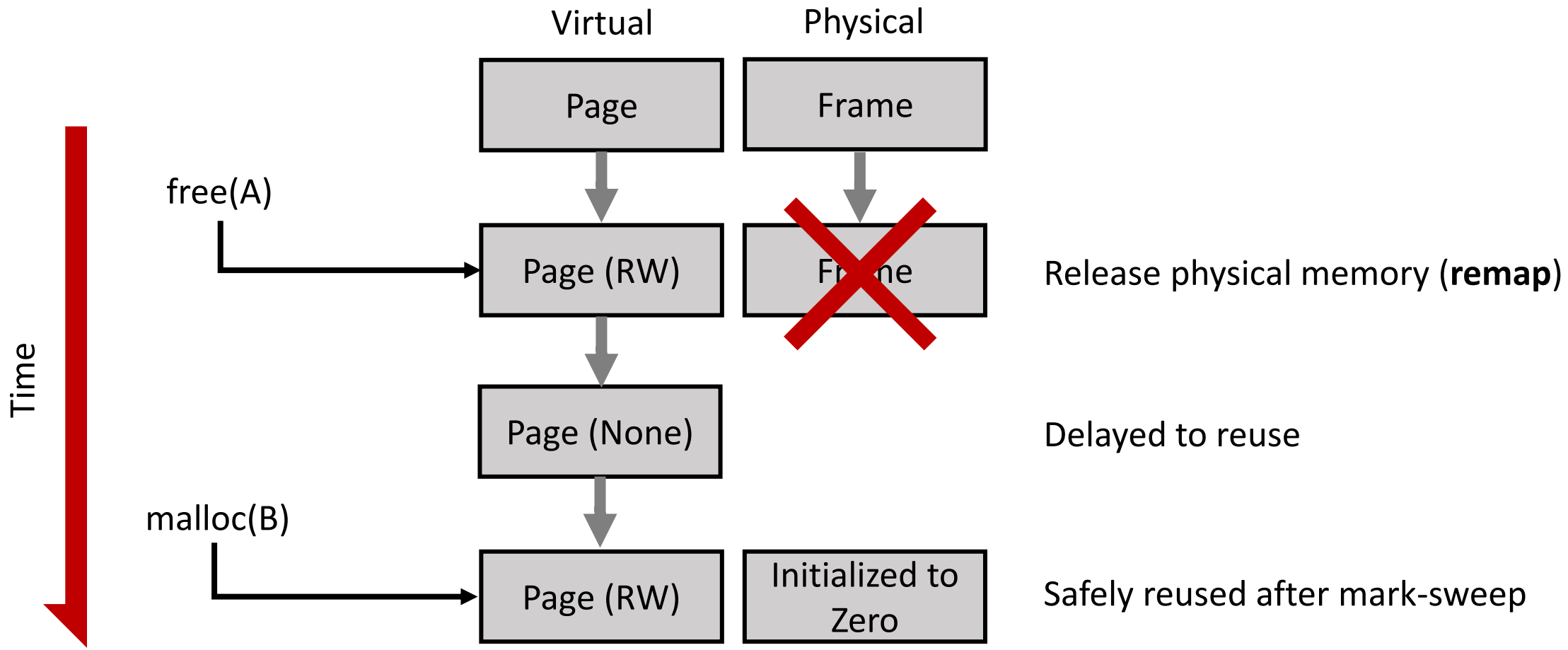


Our Approach

- Garbage Collector-like
  - ➢ **Significant overhead for allocation-intensive benchmarks**
- One-time Allocation
  - ➢ **Do not support indefinite applications**

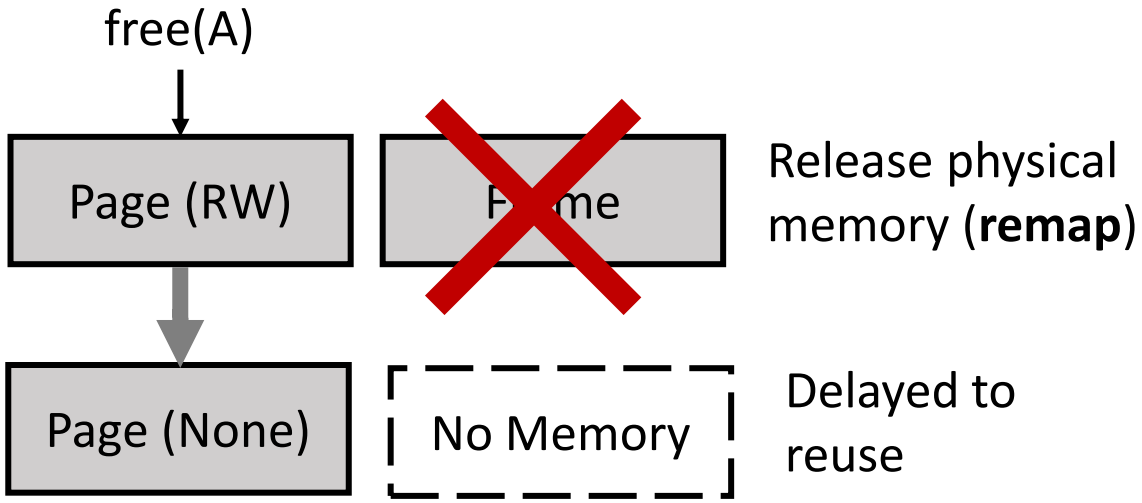
- HushVac
  - ➢ **Mark-Sweep allocator having allocation strategies of FFmalloc**

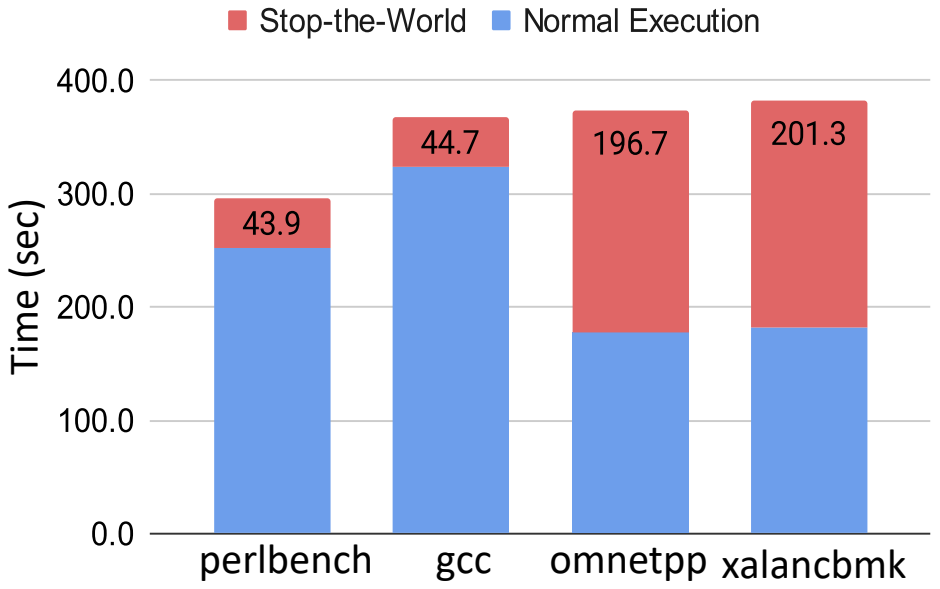
Virtual Address Space Reuse



Reuse Virtual Pages Opportunistically

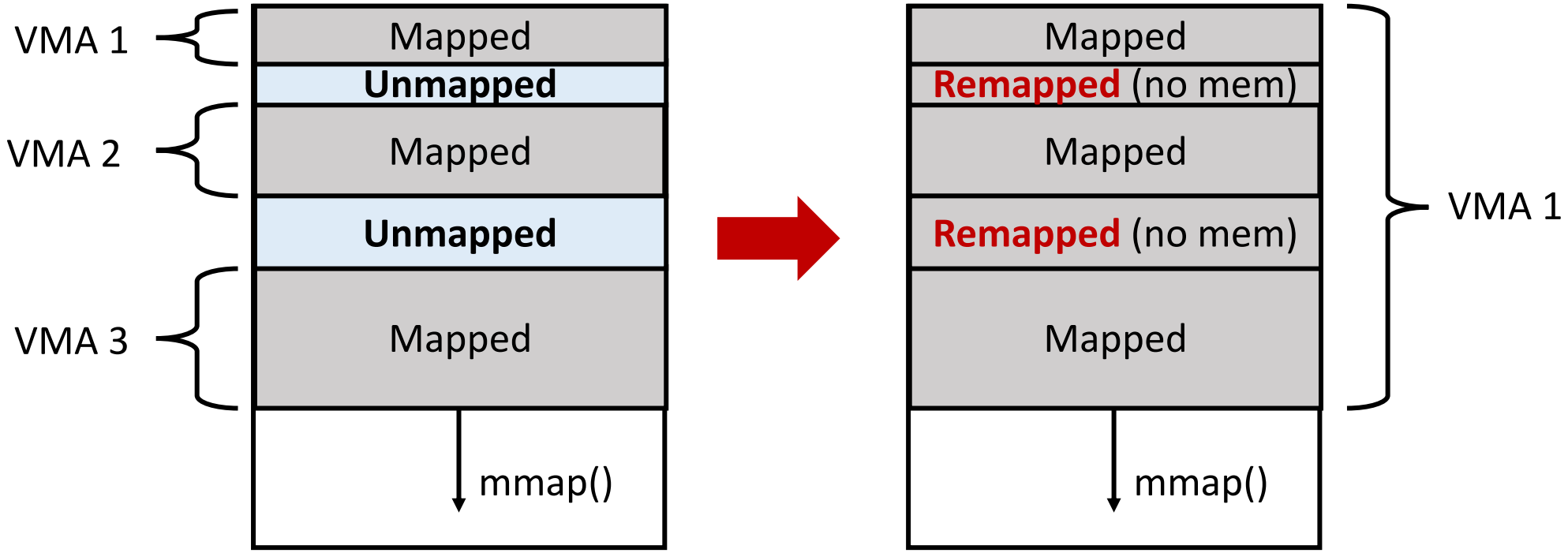
- Ok to do so because:
  - Long quarantine list does not imply the waste of physical memory.
  - Delaying the reuse of virtual pages does not lower spatial locality.
- Desired to do so because stop-the-world time becomes the increased exec time.





OK to Reuse at Page Level Rather than as a Batch

- HushVac detaches physical pages without splitting VMA unlike FFmalloc.
- Remapped virtual address space enables no concerns about VMA fragmentations.

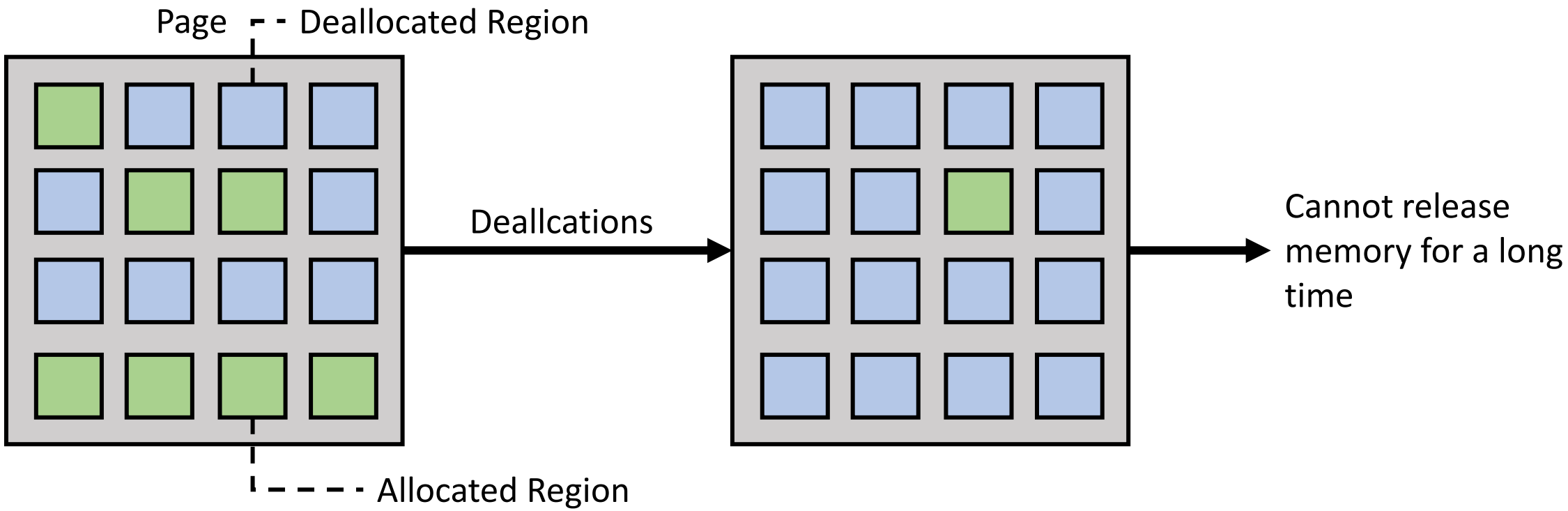


Additional Design Choices

- **Subpage reuse**
- Two staged marking
  - Concurrent marking to reduce stop-the-world cost.
- Comprehensive scanning
  - Scanning entire memory more.

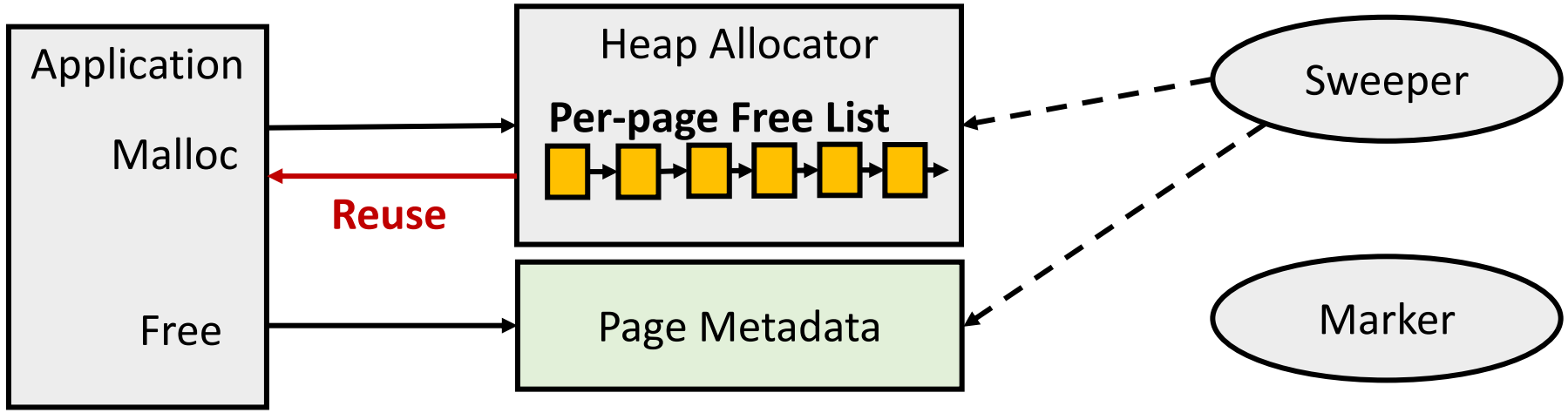
Internal Fragmentation of FFmalloc

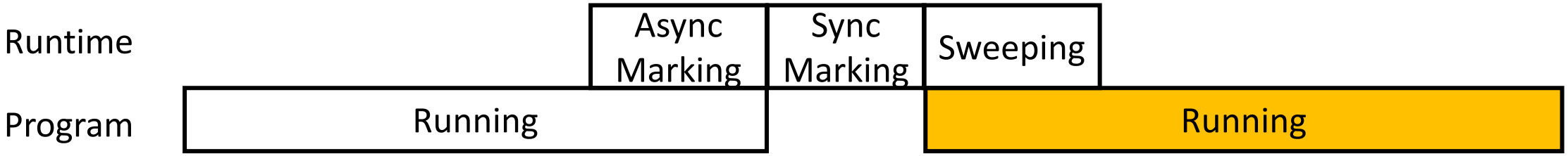
- Long-lived objects prevent a page from being released.



Subpage Reuse for Mitigating Internal Fragmentation

- HushVac maintains a per-page free list inspired by mimalloc.
- HushVac consumes the free list as much as possible.

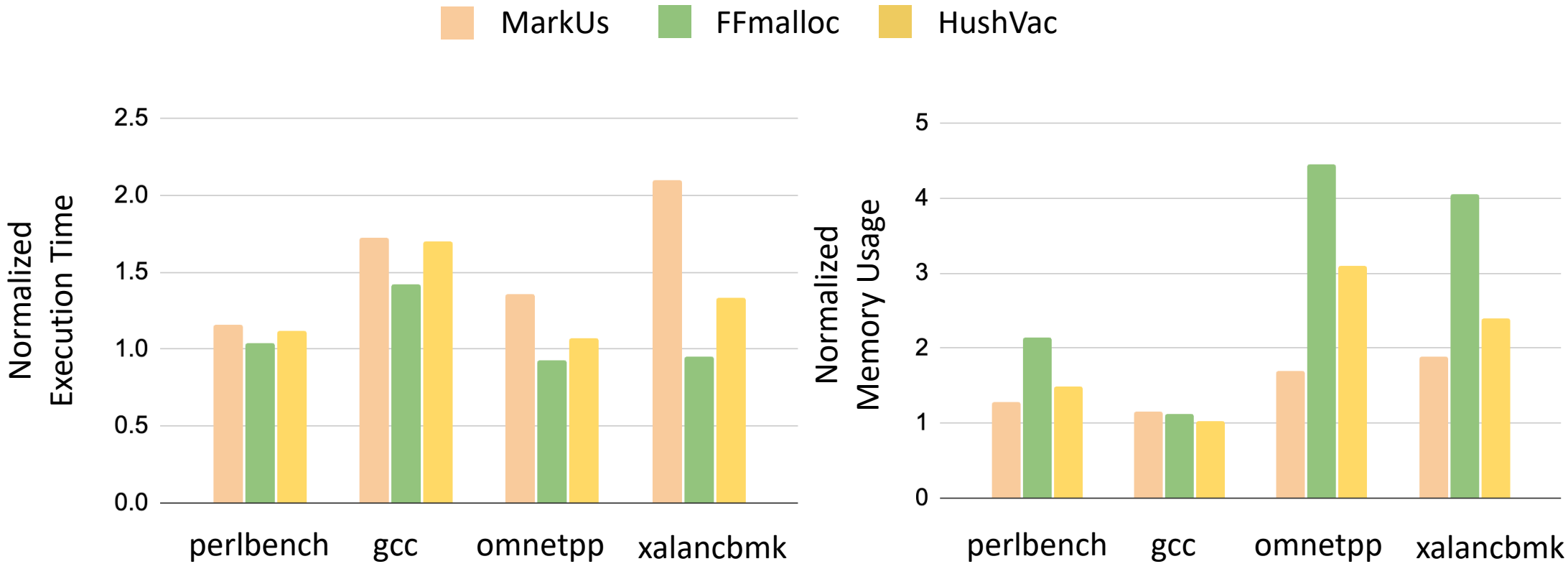




Experimental Setup

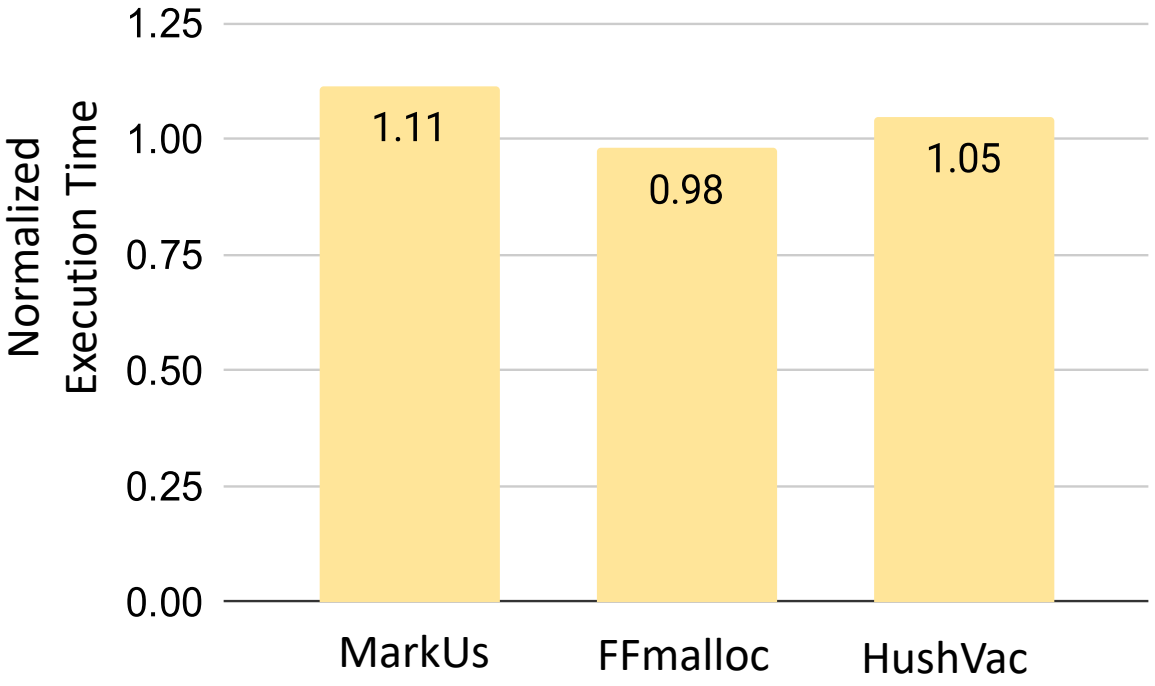
- Ubuntu 18.04 with Linux 5.4.0-150-generic
- AMD Ryzen 5 2600
- 32GB Main Memory
- HushVac runs one mark-sweep thread and 10 marker threads
- The baseline is glibc

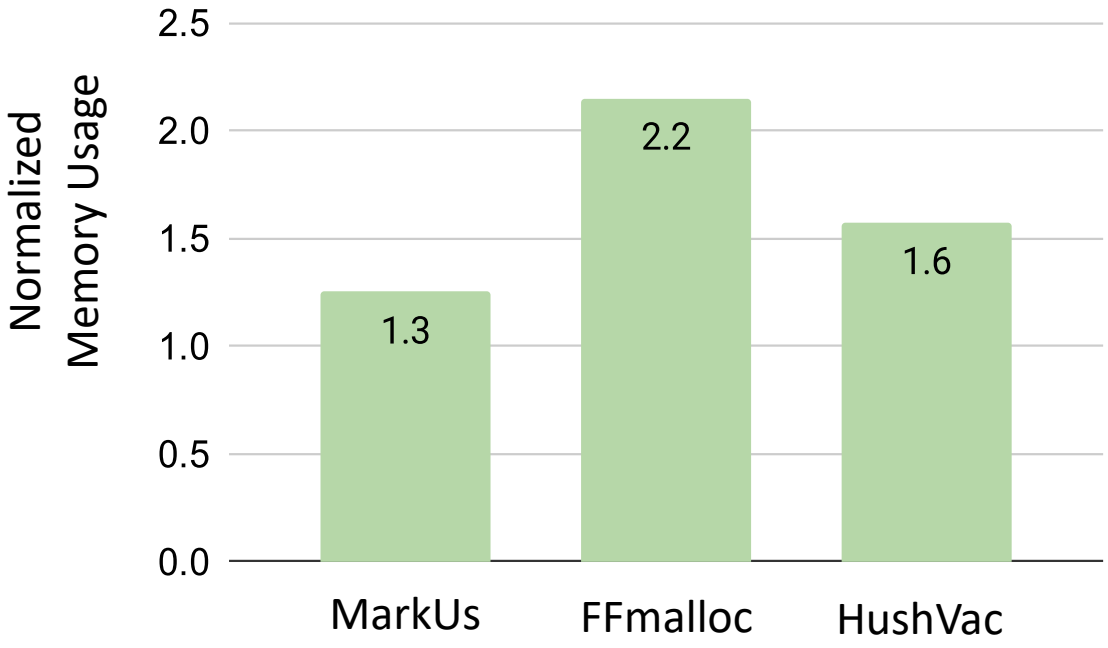
Performance in Allocation-intensive Benchmarks



HushVac is faster than Markus and has lower memory usage than FFmalloc.

Average Performance on SPEC 2006





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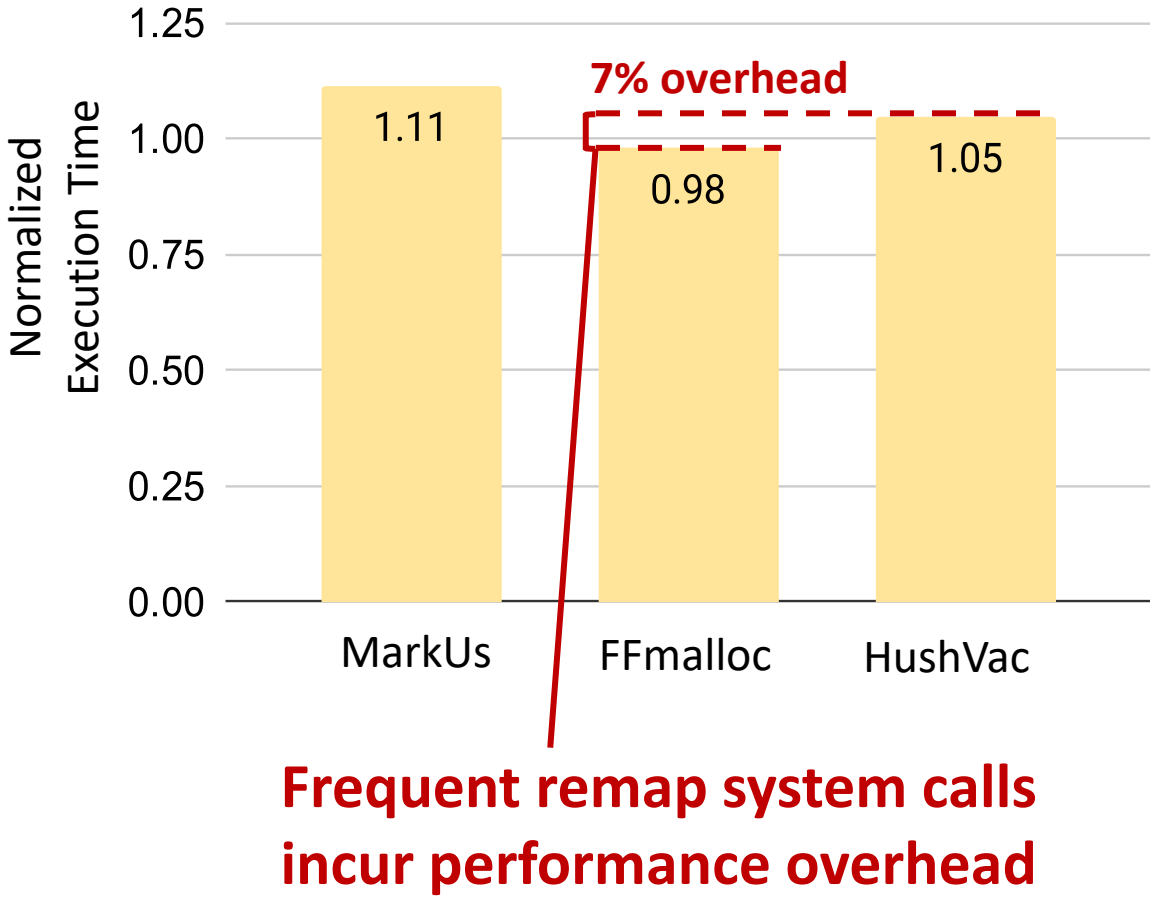
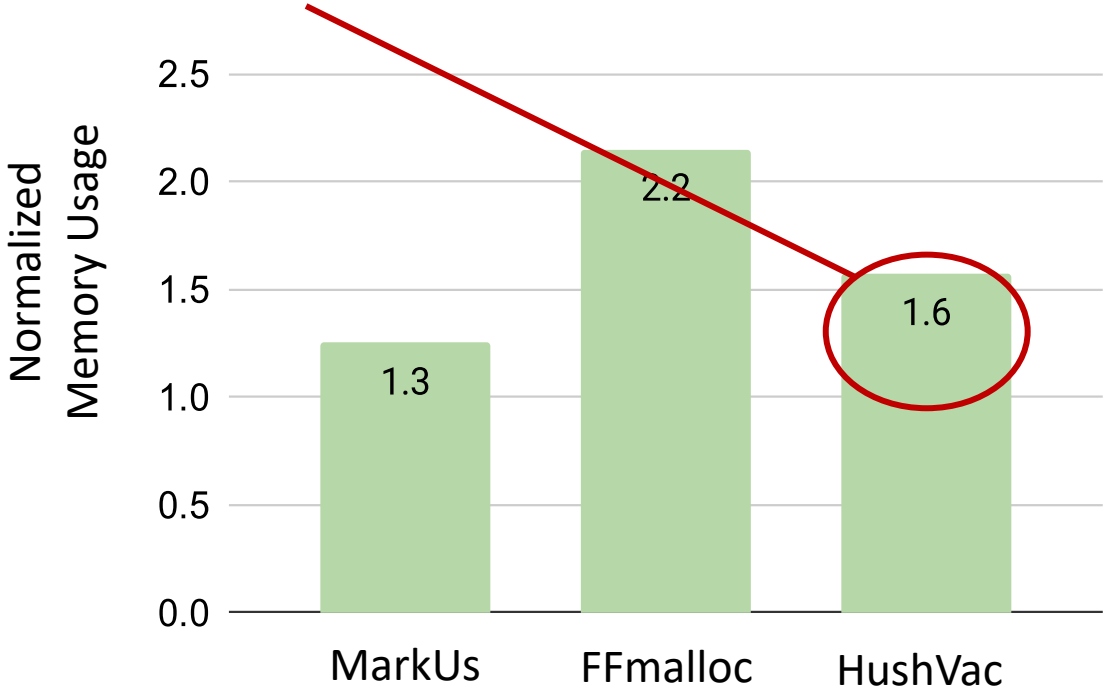
Limitations



Frequent remap system calls incur performance overhead

Internal fragmentation as FFmalloc
It is impossible to fully safely reuse every page



Conclusion

- The root cause of overhead in garbage collector-like approaches.
  - The spatial locality of temporally local allocations affects the performance.
  - Simply delaying the reuse of freed chunks reduces spatial locality.

- Giving preference to top chunks, as in the OTA, results in higher spatial locality.

- Combining the strengths of the two with several design choices leads to HushVac:
  - Allocation that is aware of spatial locality for both fresh and previously freed chunks.
  - Reduced performance overhead compared to the garbage collector-like approach.
  - Decreased memory overhead and additional ability to reuse chunks compared to OTA.