uCache

A Customizable Unikernel-based IO Cache

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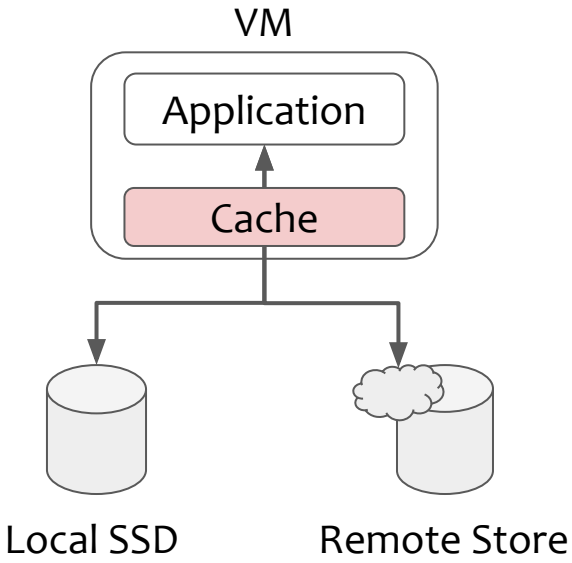
IO caching in the cloud

- Data-intensive cloud applications
  - Database systems
  - ML systems

- High-performance IO devices
  - NVMe SSDs, NICs
  - PCI 5.0: up to 10s of GiB/s



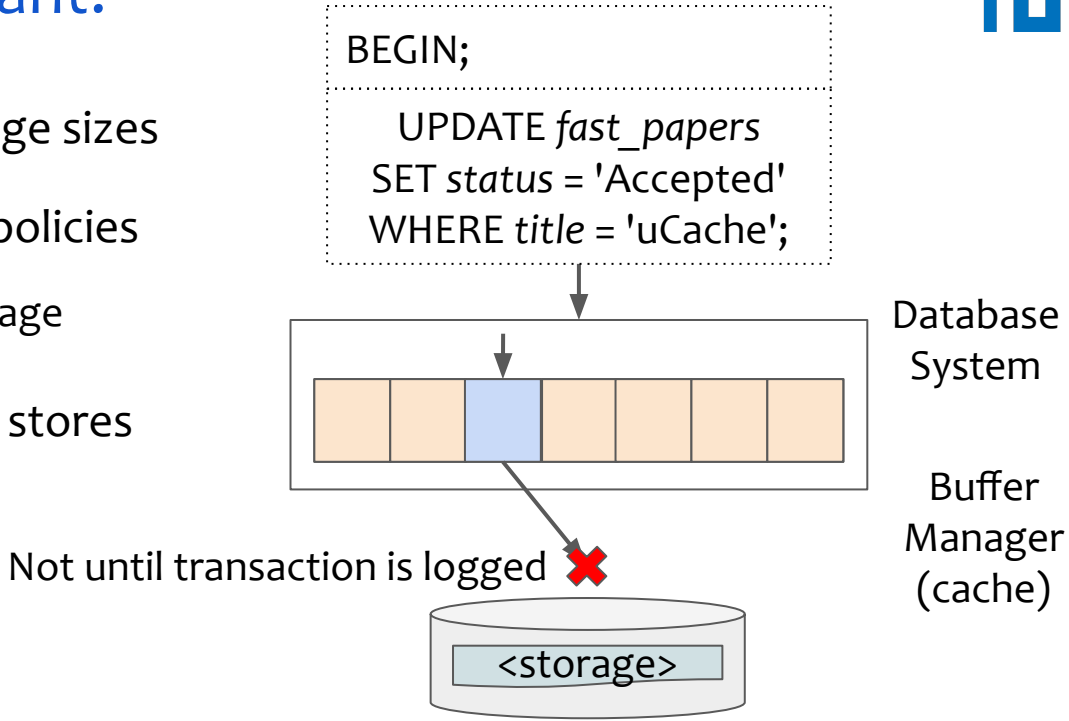
What are the applications requirements for the cache?

What do applications want?

1. Non-hardware supported page sizes
2. Custom cache replacement policies

-> Cheaply prevent the eviction of a page

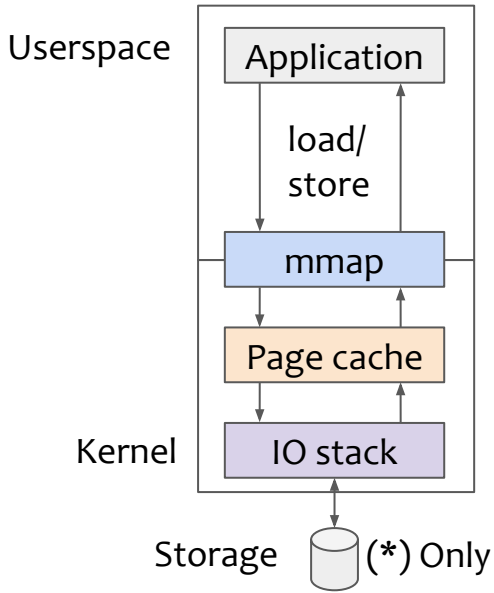
3. Access local drives and remote stores



What are the options for caching?

Cache design approaches

Traditional: OS-level caching



+ General(*)
+ Simple

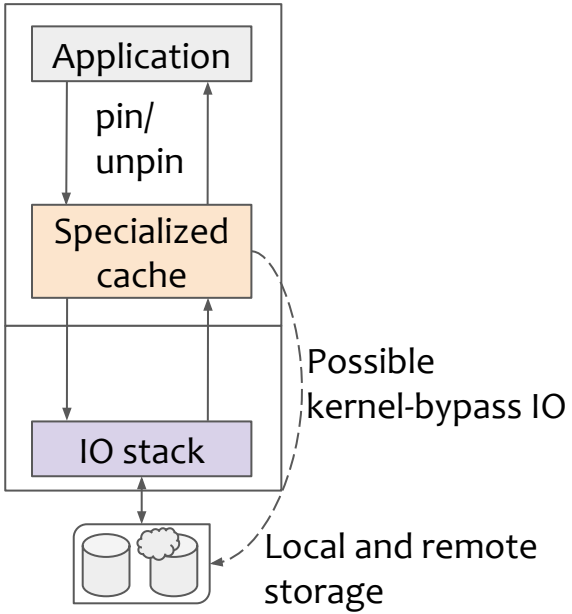
- Performance
- Control

(*) Only local SSD

State-of-the-art: Explicit userspace caching

+ Performant
+ Flexible

- Simplicity



Can we overcome the limitations of each approach?

Problem statement

Can the OS provide a simple, flexible and performant IO cache?

Our proposal: uCache

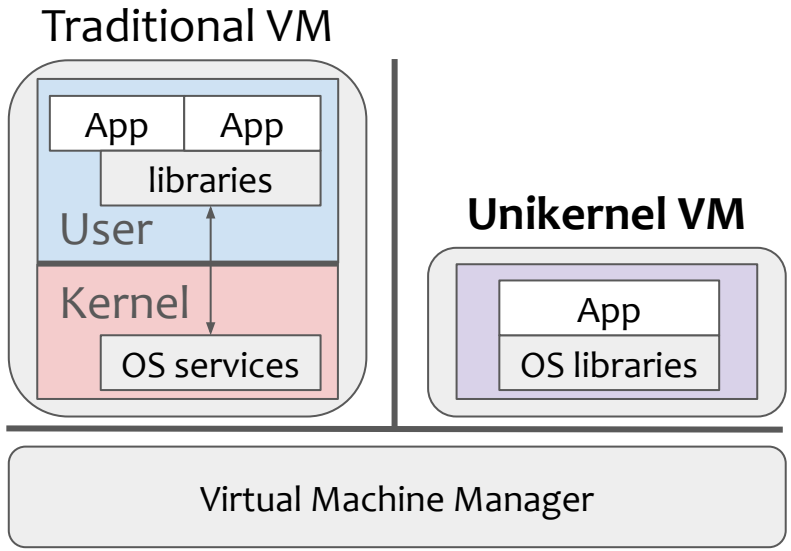
A customizable memory-mapped IO caching framework

Design Goals:

- Flexibility, adapt to the multiple workloads and storage solutions
- Simplicity, the application decide the level of control
- Performance, enable applications to leverage high-performance IO devices

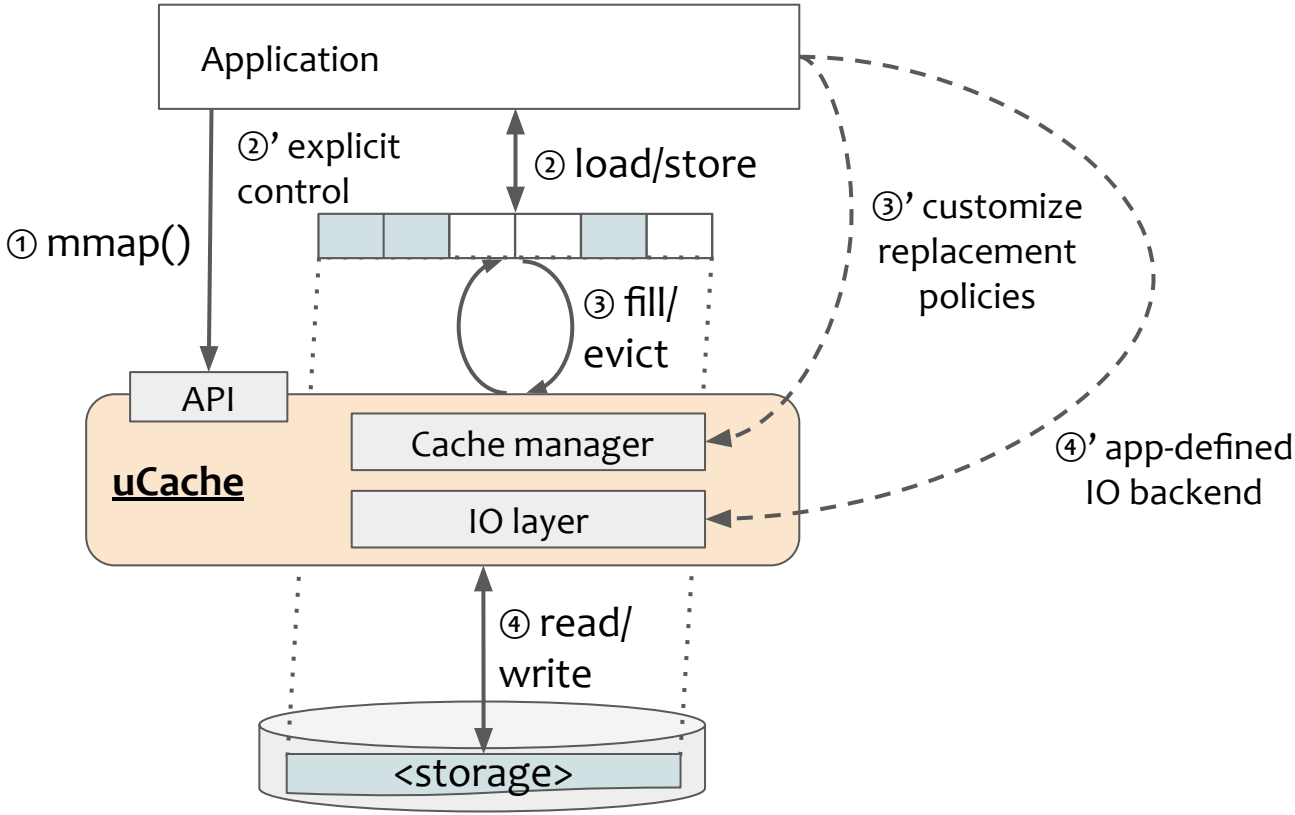
Key idea: A unikernel architecture

1. **Single** address-space
2. **Library** OS
3. Built into a **VM image**



The unikernel architecture enables OS/App co-design

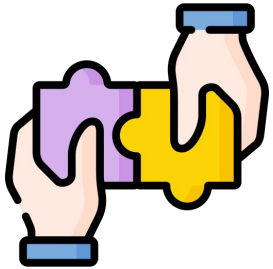
Overview


Application
② load/store
②' explicit control
① mmap()
③' customize replacement policies
③ fill/ evict
API
Cache manager
uCache
IO layer
④' app-defined IO backend
④ read/ write
<storage>

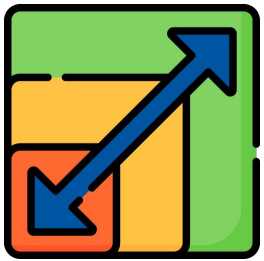
Outline

- ~~Overview~~
- Design
- Evaluation

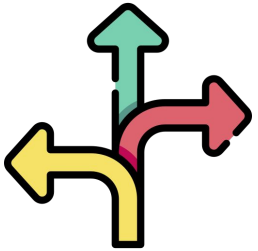
Challenges



Application/OS coordination



Scalable cache operations



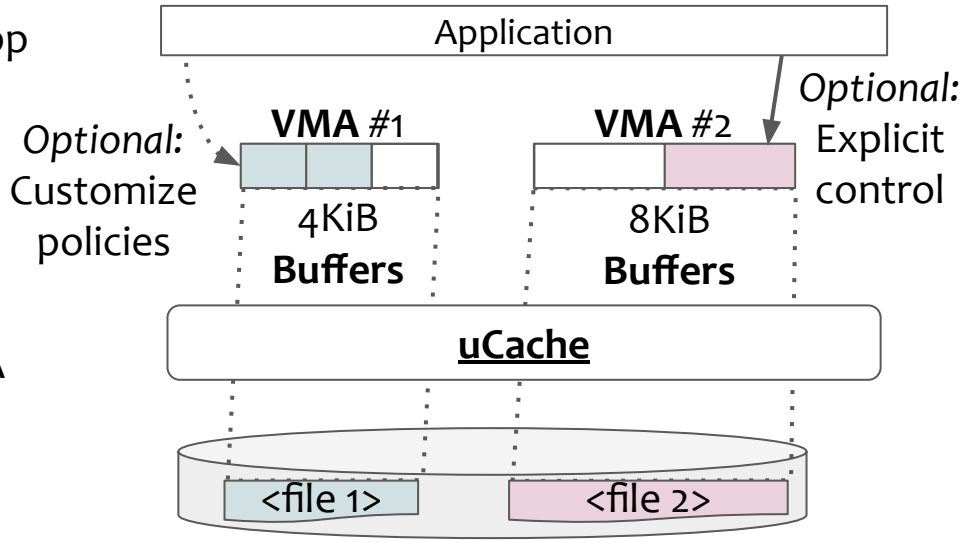
Flexible IO abstraction

Challenge #1: Application/OS coordination

How to enable a **spectrum** of interactions models?

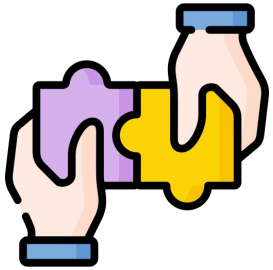
Solution #1: uCache memory abstractions

- Virtual memory area (**VMA**)
  - Shared between the OS and the app
- **Buffer**
  - Granularity for primitives
- **Customizable** policies:
  - Attach function callbacks to a VMA

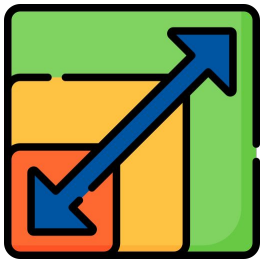


uCache enables OS/App coordination through shared VMA and Buffer abstractions

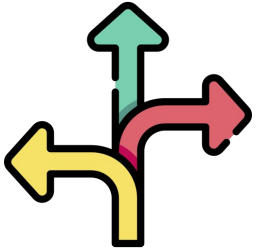
Challenges



Application/OS coordination

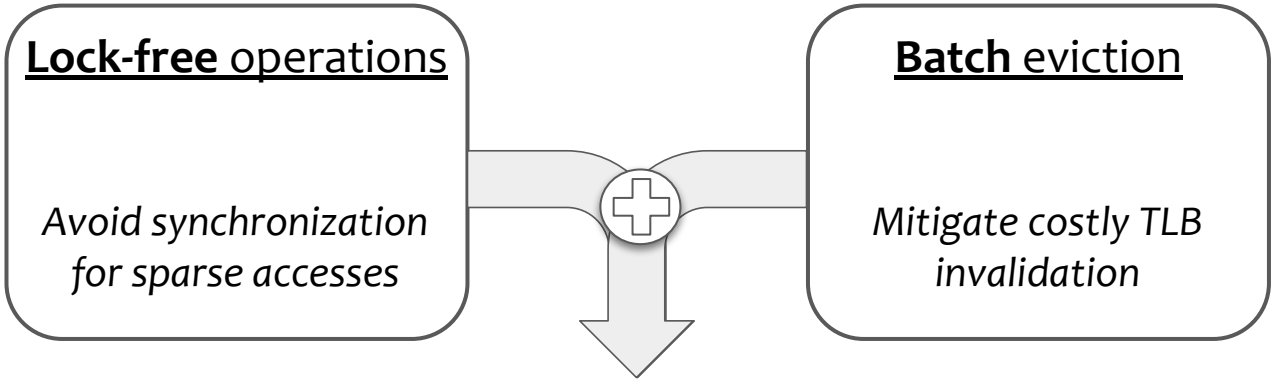


Scalable cache operations



Flexible IO abstraction

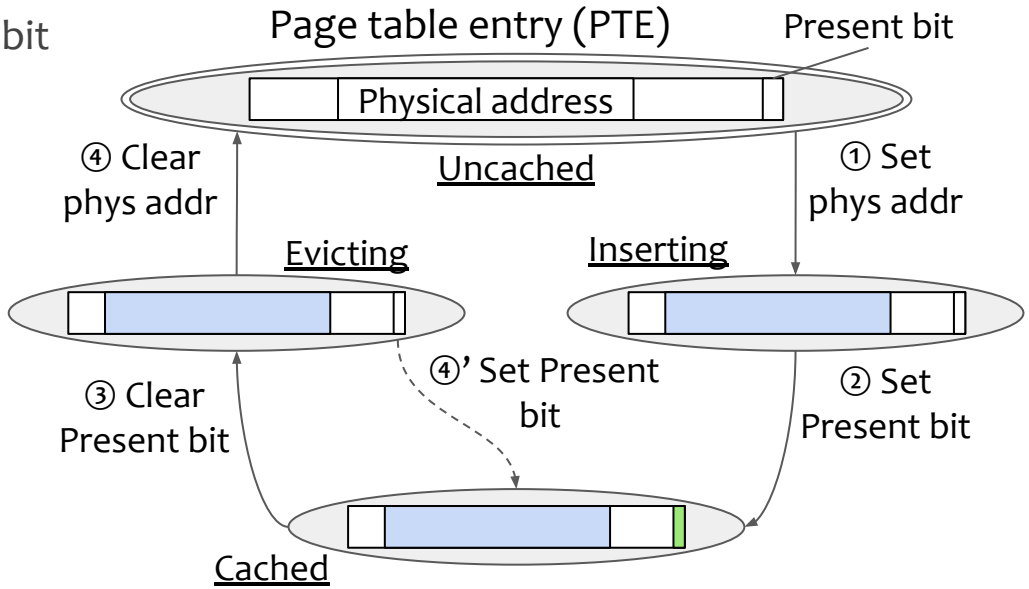
Challenge #2: Scalable cache operations



How to modify the page table in a **lock-free** manner with **batching**?

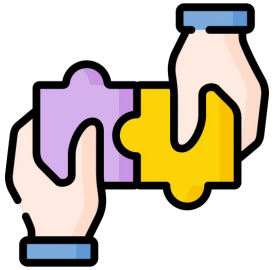
Solution #2: Optimistic cache operations

- **Two-step** CAS operations
  - Separate phys addr and present bit
- During eviction:
  - Accumulate candidates
  - Accesses **cancel** eviction
- Works also for "**big pages**"
  - More details in the paper

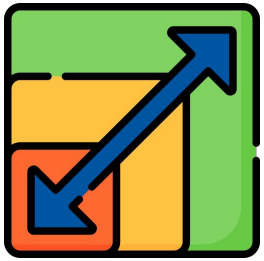


uCache uses **optimistic operations** to limit synchronization even when batching

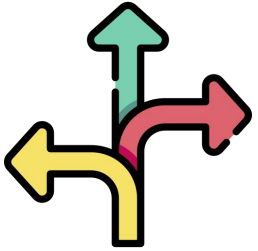
Challenges



Application/OS coordination

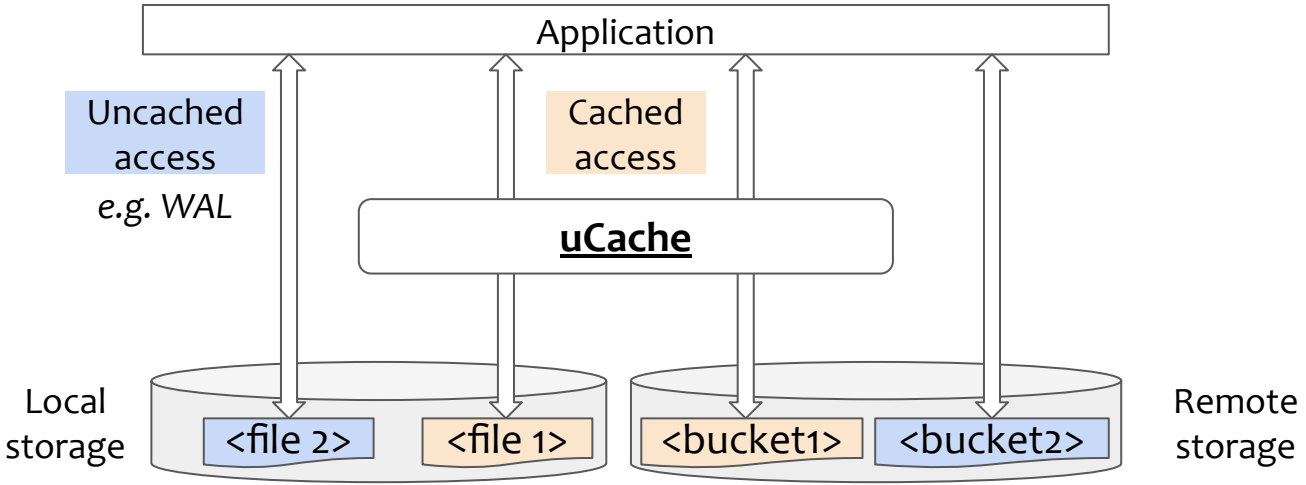


Scalable cache operations



Flexible IO abstraction

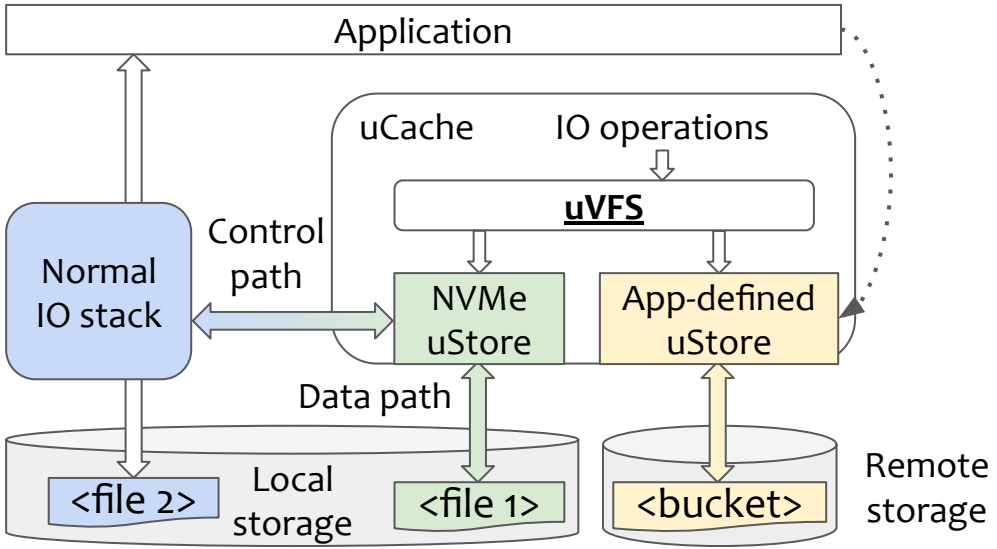
Challenge #3: Flexible IO abstraction



How to enable flexible storage access to applications?

Solution #3: uCache IO abstractions

- uVFS: Abstracts IO stack
  - dispatches to uStores
  - App-defined uStores
- NVMe uStore
  - performant data path
  - compatible control path



uCache enables performant and customizable IO without hindering compatibility

Implementation

- Built on the **OSv** unikernel

- Cache manager
  - Default: CLOCK replacement
  - Physical memory allocation: LLFree[ATC'23]

- IO layer
  - ext4-compatible NVMe uStore

Outline

- ~~Overview~~
- ~~Design~~
- Evaluation

Evaluation

1. How performant are cache management operations?
2. ~~How much footprint does uCache introduce?~~
3. ~~What is the performance of the IO layer?~~
4. Use cases
   a. Is uCache a compelling replacement to mmap?
   b. Can uCache be used for the buffer manager of database systems?
   c. ~~Can uCache be used to improve the performance of accessing data files?~~

More evaluation in the paper

Experimental setup

Setup:

- AMD EPYC 9654 (96C), 768GiB RAM
- Kioxia CM-7 NVMe SSD (PCI 5.0)

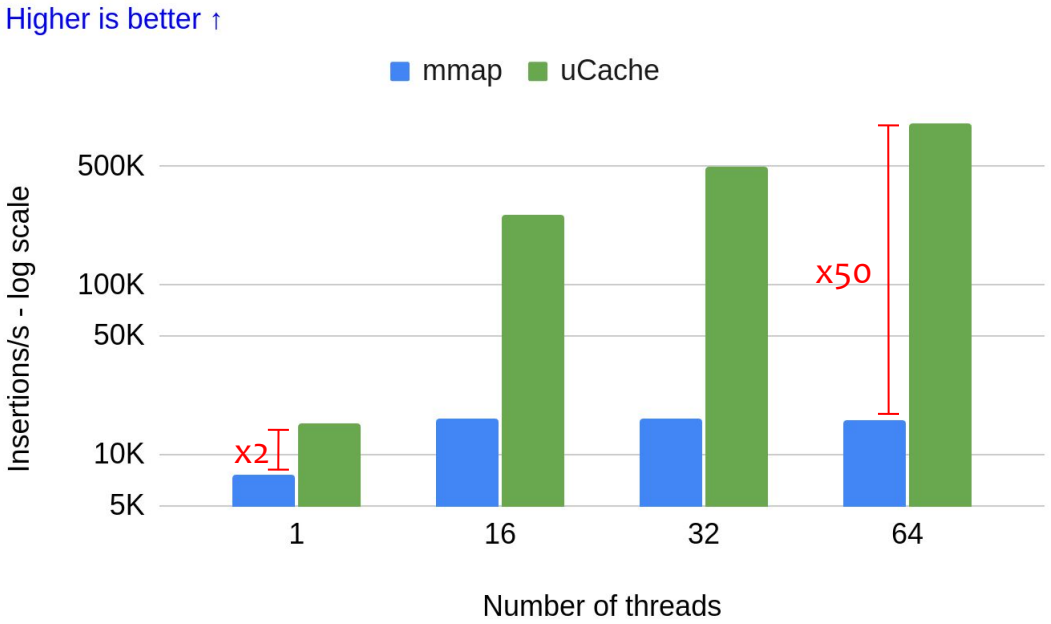
Variants:

- mmap in Linux VM
- Specialized userspace cache
- uCache

Microbenchmarks

Insertions per second

- focus on out-of-memory case
- includes evictions (no writes)

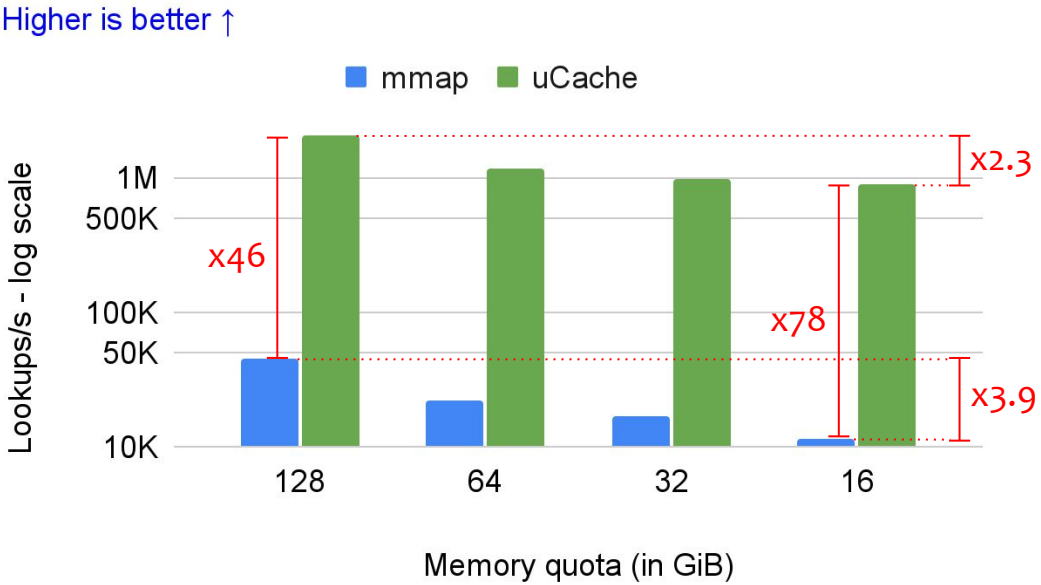


uCache scales linearly with the number of threads

End-to-end performance

Lookups per second:

- random access pattern
- 200GiB data size
- 64 threads



uCache is a compelling replacement to mmap performance-wise

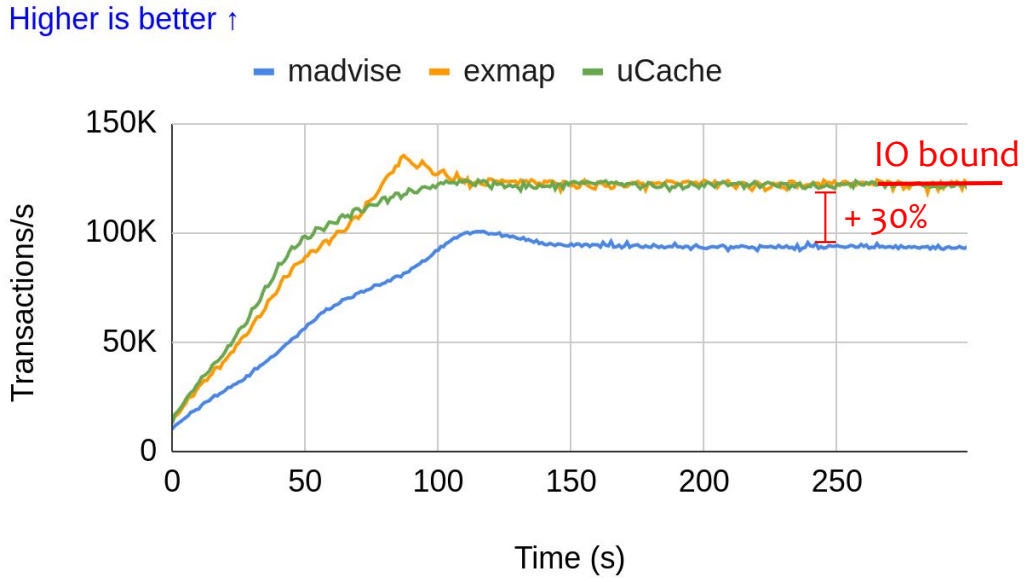
Use case: Database systems buffer management

Buffer cache: vmcache[SIGMOD'23]

- with POSIX (madvise)
- with kernel module (exmap)
- ported to uCache

TPC-C:

- size 5000 (~1TiB)
- cache 128GiB
- 64 threads



uCache can integrate complex application semantics without incurring overheads

Conclusion

Can the OS provide simple, flexible and performant memory-mapped IO caching?

uCache

- Aims to be convenient like OS-level caches while performant and flexible
- Customizable and scalable caching framework through the unikernel architecture
- Outperforms mmap and customizable like specialized caches

Try it out !

TUM-DSE/uCache