`cache_ext`: Customizing the Page Cache with eBPF

Tal Zussman Columbia
Ioannis Zarkadas Columbia
Jeremy Carin Columbia
Andrew Cheng Columbia
Hubertus Franke IBM
Jonas Pfefferle IBM
Asaf Cidon Columbia

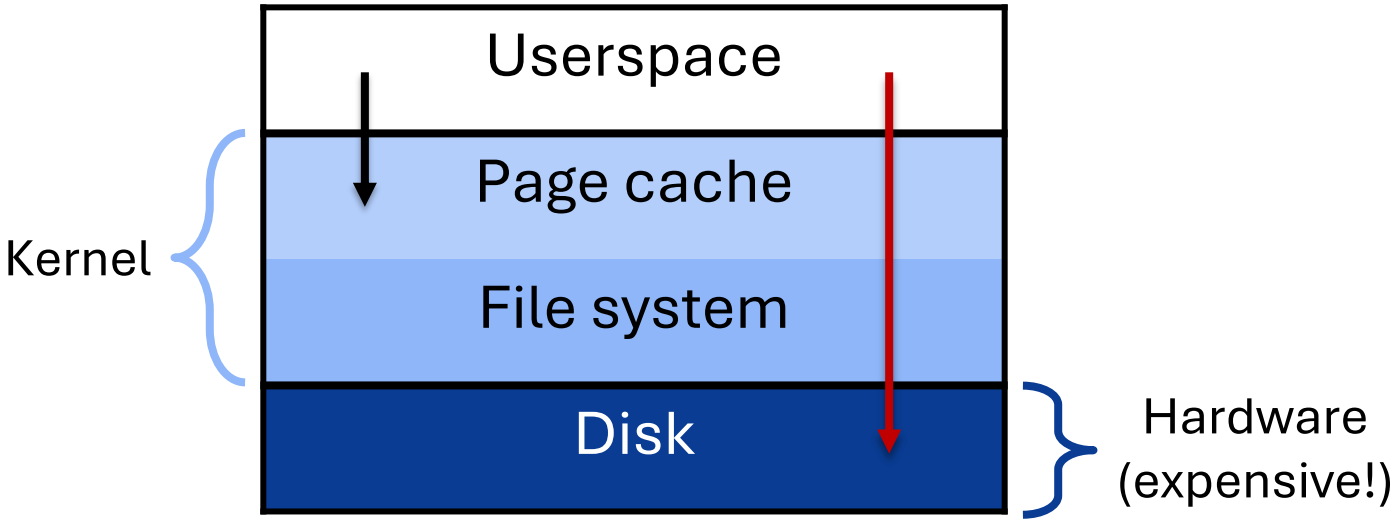
Columbia University
IBM Research

TLDR;

- The Linux page cache doesn’t work so well with many workloads…
- cache_ext allows applications to customize page cache policies to improve performance using eBPF
- Experimentation with policies and application hints are necessary to maximize performance

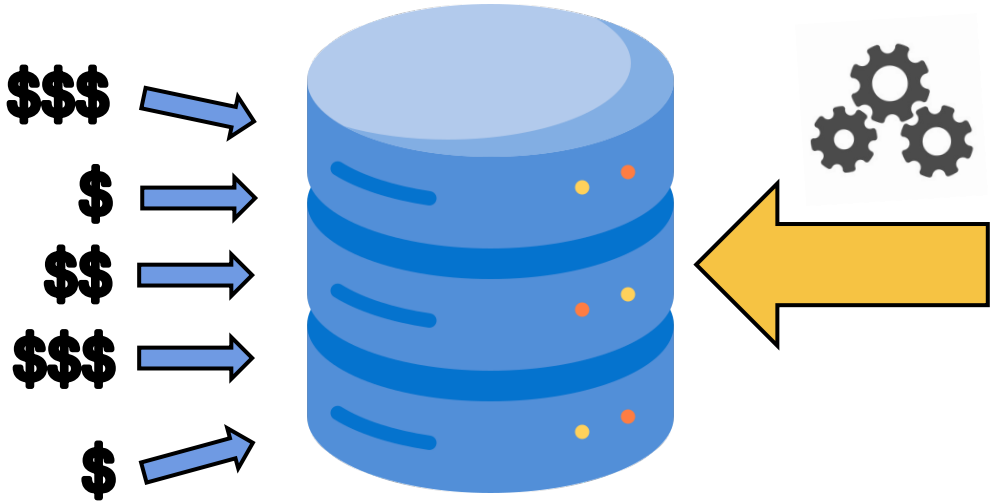
Linux page cache significantly affects performance

LRU-approximation algorithm – **doesn't work well for all workloads!**



Linux page cache struggles with many workloads

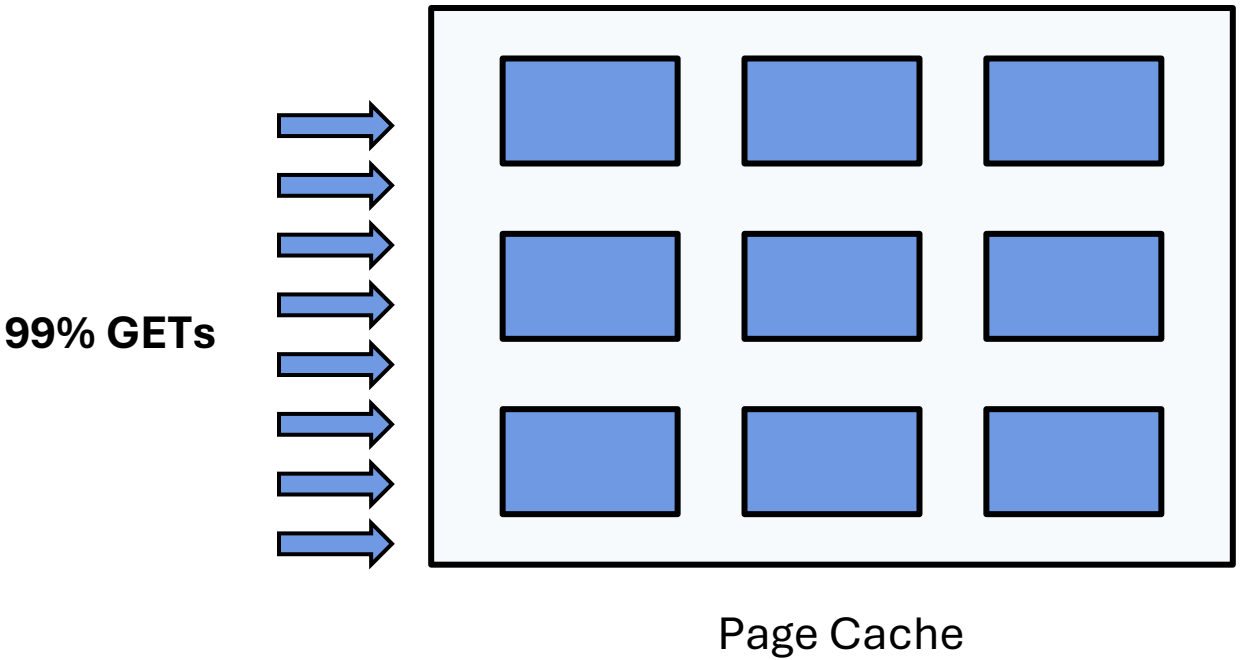
- Many tiny transactions
- A few massive background tasks



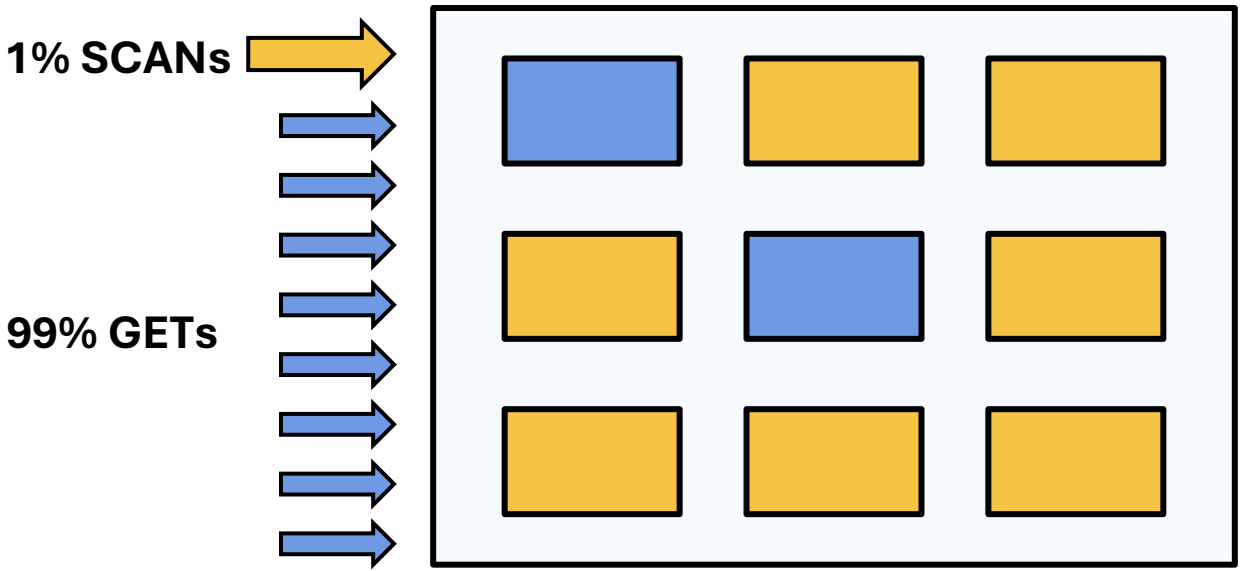
HTAP-like:
Mix of Transactional (GET) and Analytical (SCAN)

Shinjuku (NSDI ’19),
Syrup (SOSP ‘21)

Linux page cache struggles with many workloads



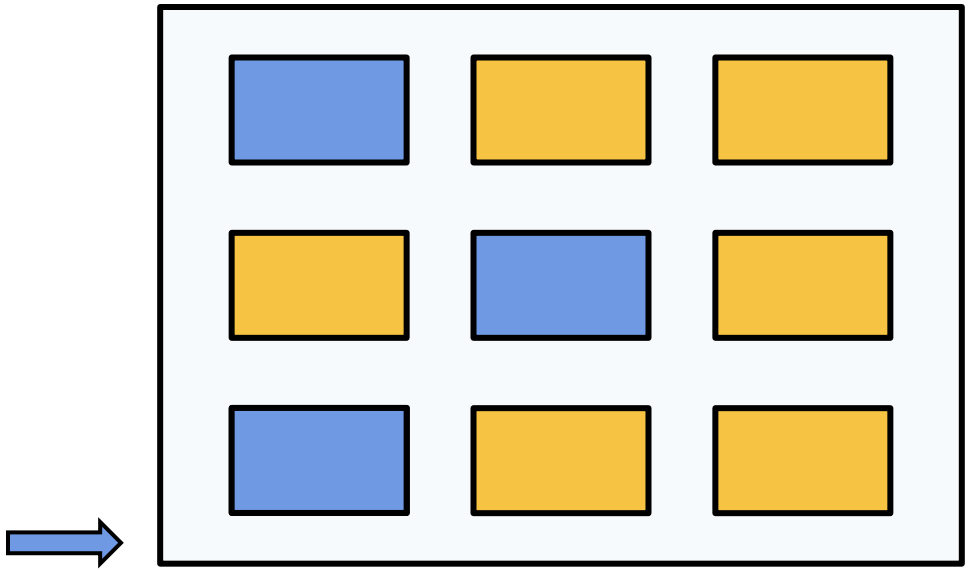
Linux page cache struggles with many workloads



Data is 99% SCAN and 1% GET

Linux page cache struggles with many workloads

We've been thrashed!



Page Cache

The page cache is not flexible enough

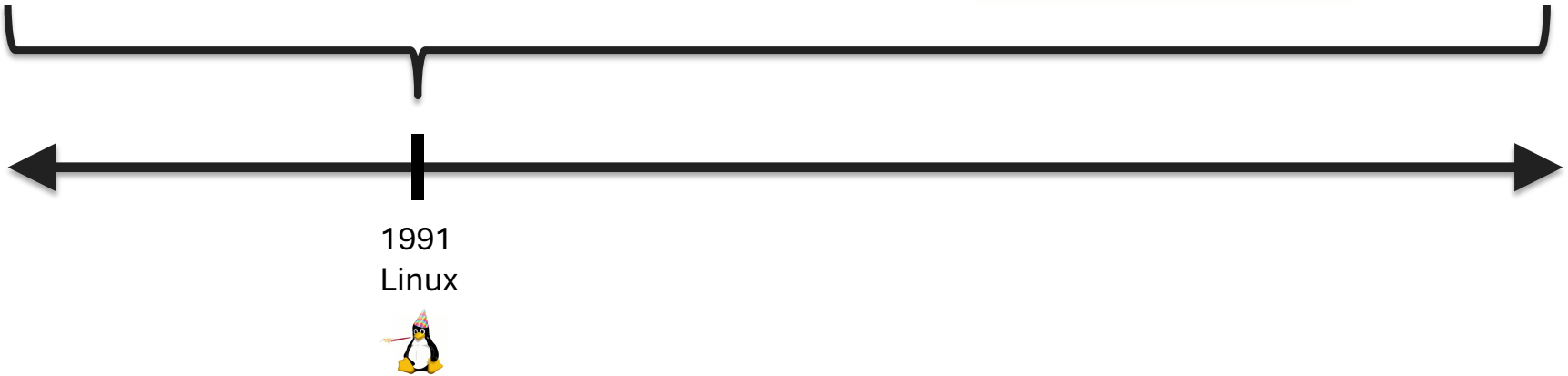
We are leaving performance on the table

A brief history lesson...

A brief history lesson...

September 17, 1991: Linux released!

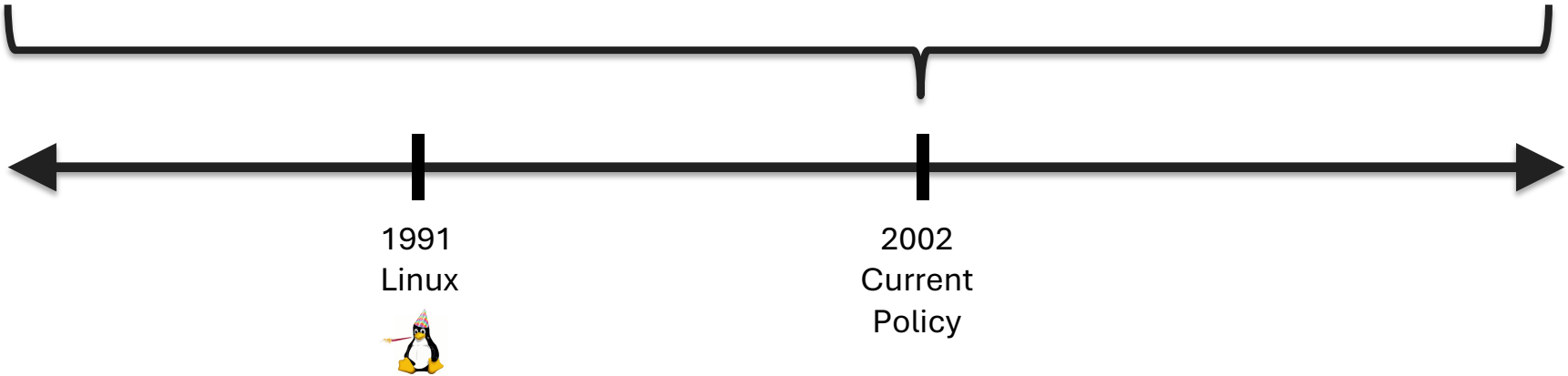
Later added a global LRU policy



The default policy is old

2002: LRU-approximation (current policy) added in Linux 2.5.46

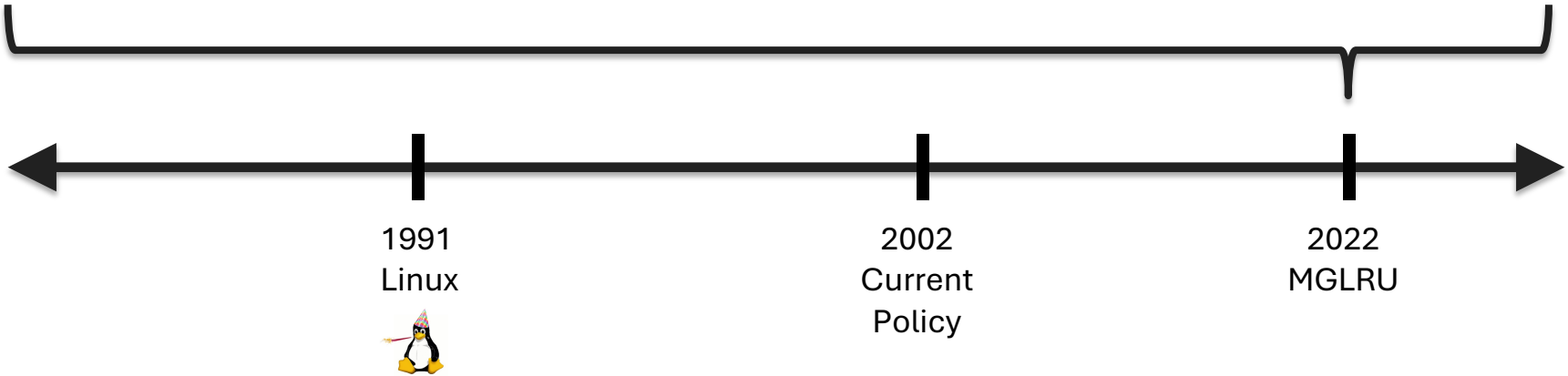
Also in 2002: My coauthors Jeremy and Andy were born!



Changing the policy is hard

2022: MGLRU merged in Linux 6.1 as new experimental policy!

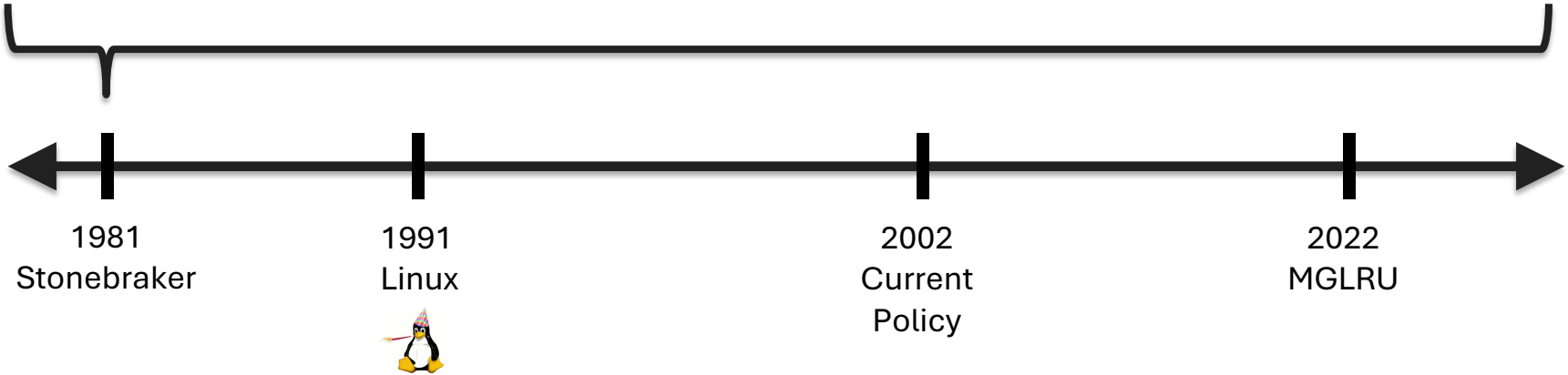
- Several years of effort
- Still not default upstream
- Global policy change



A brief history lesson… (Hints)

"For an OS to provide buffer management, **some means must be found to allow it to accept "advice" from an application program** (e.g., a DBMS) concerning the replacement strategy."

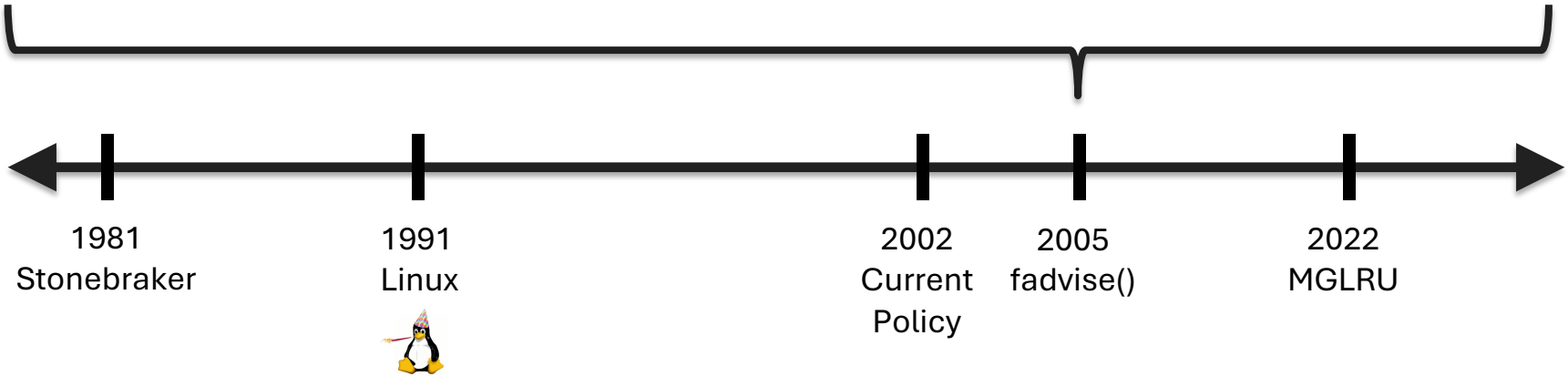
– Michael Stonebraker



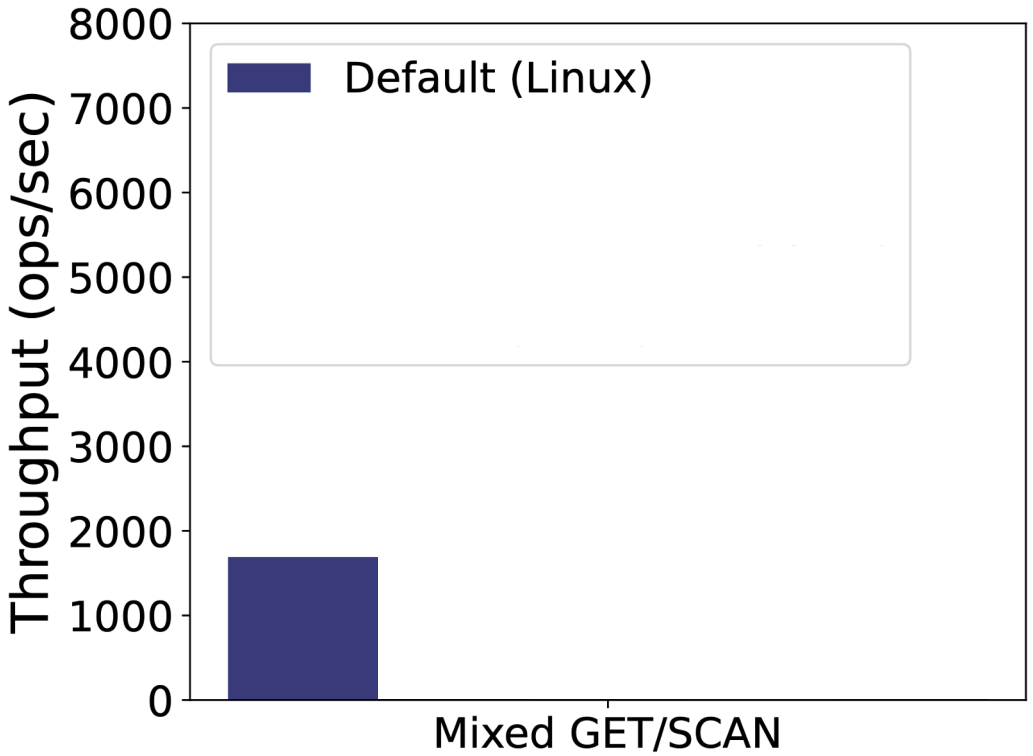
`fadvise()` isn't powerful enough

2005: `fadvise()` added in Linux 2.5.60

- 6 flags
- **`FADV_NOREUSE`** was a no-op until Linux 6.3 (2023)



Existing hint interfaces are insufficient



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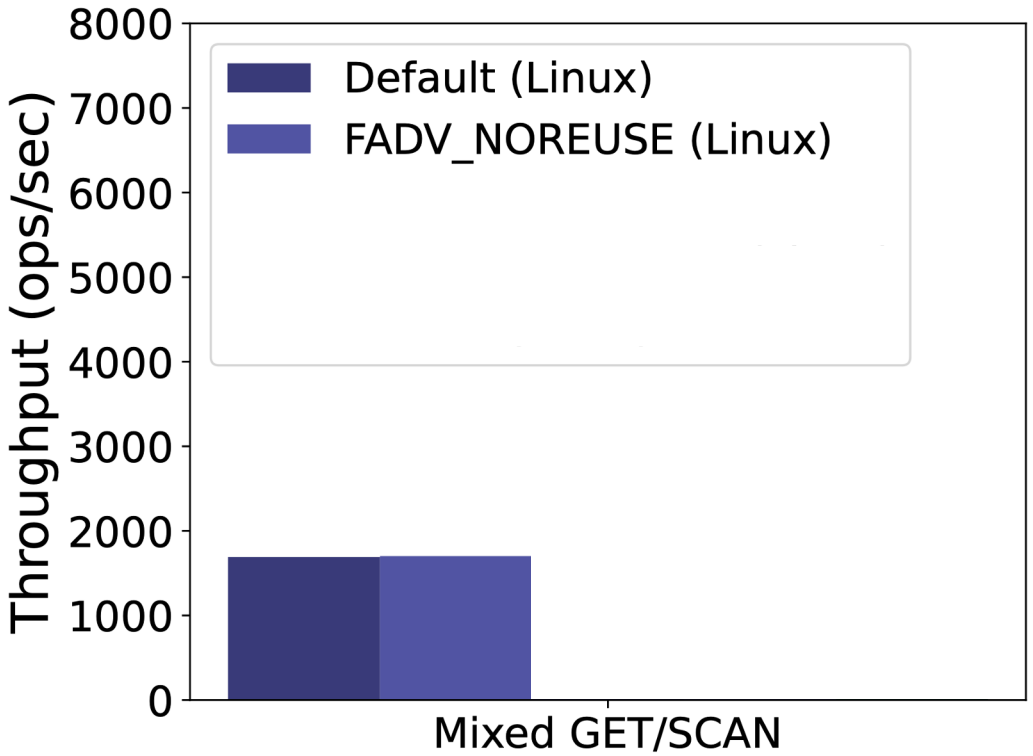

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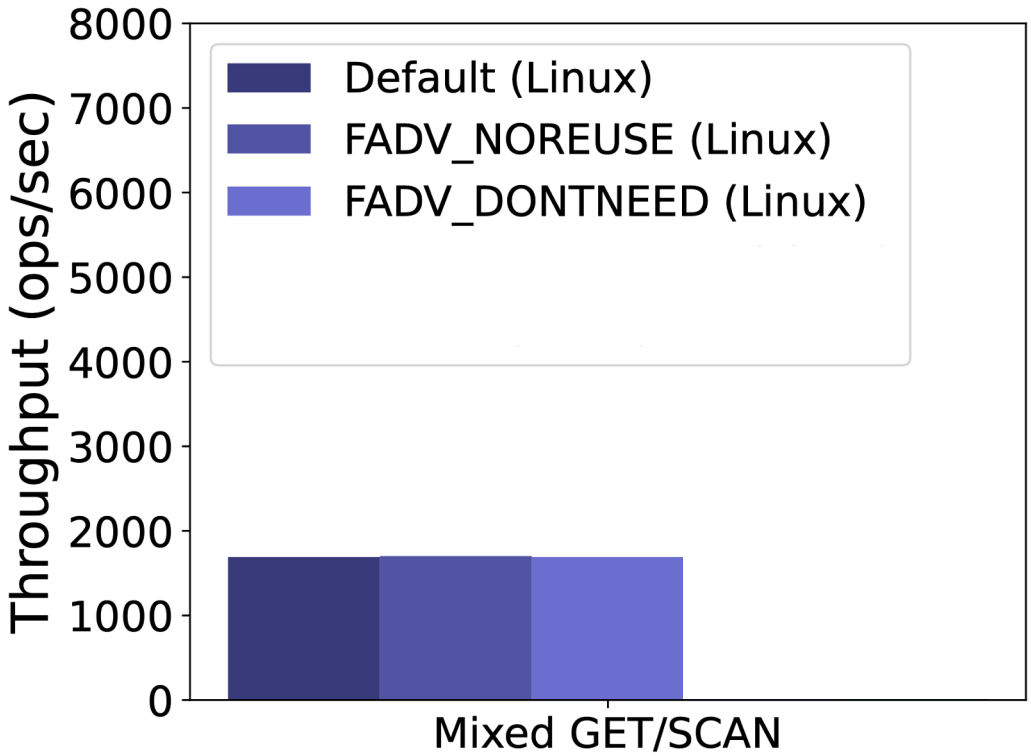

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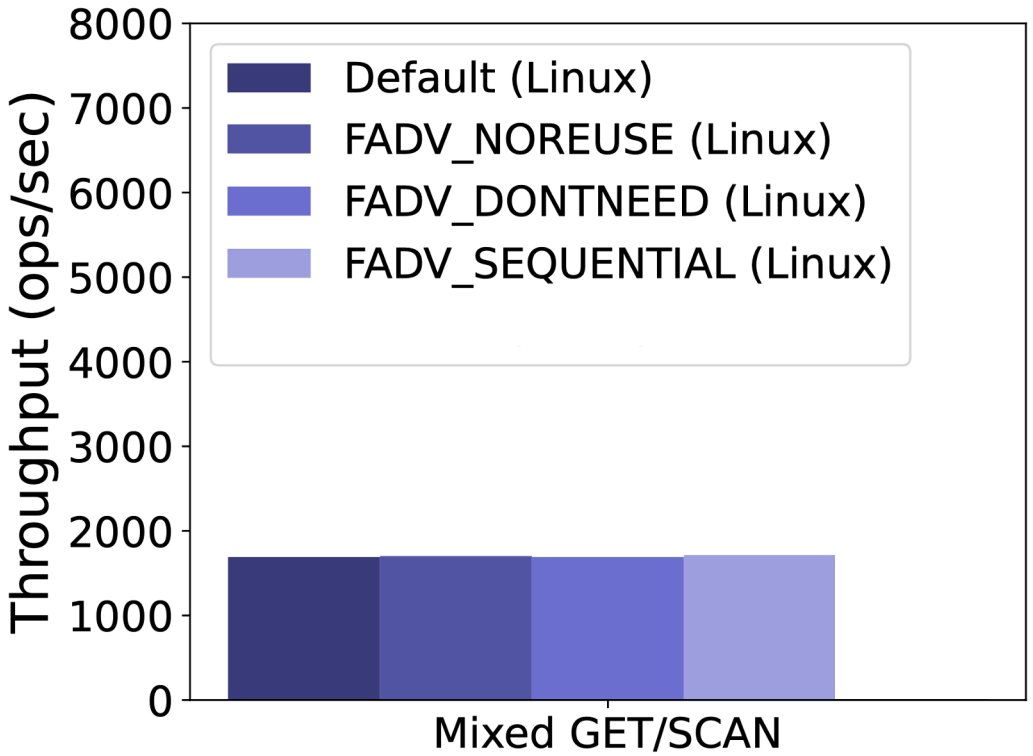

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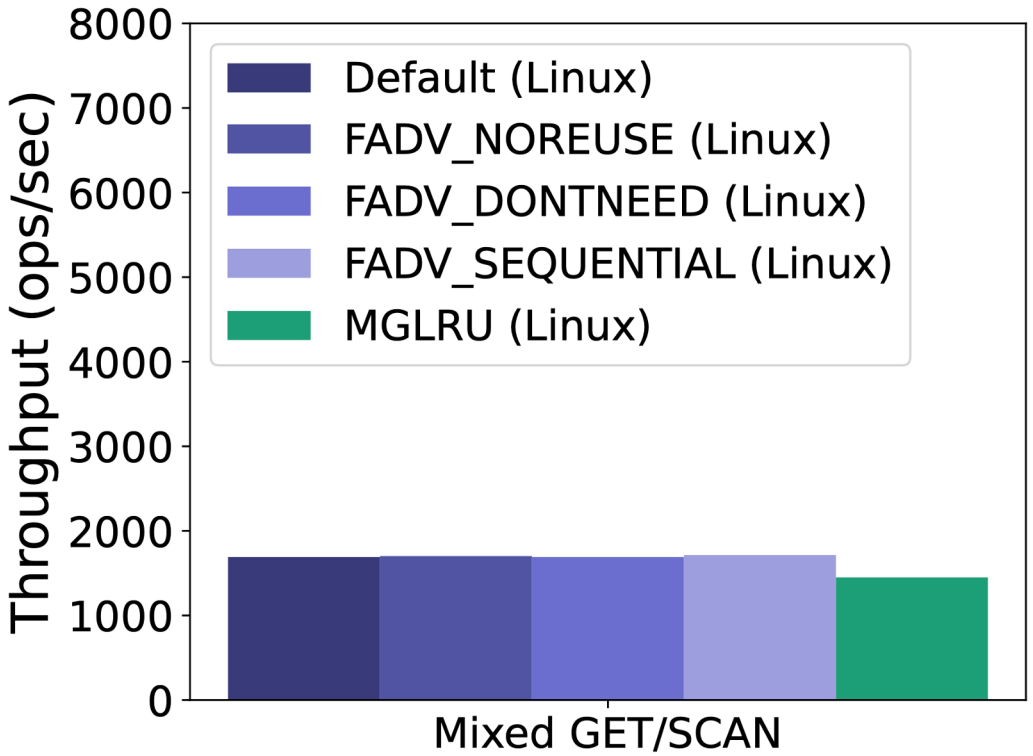


Hints don’t work!

How can we improve page cache behavior?

	Change the policy	Userspace hints	Application-level caching
Customizability	✅	❌	✅
Simplicity	❌	✅	❌
Isolation	❌	✅	✅ / ❌

We need to change the underlying policy

Like scheduling, networking, file systems, etc.

cache_ext: Custom page cache policies

- Simplicity: No kernel changes for developers ✅
- Isolation: Per-cgroup policies ✅
- Customizability: ✅

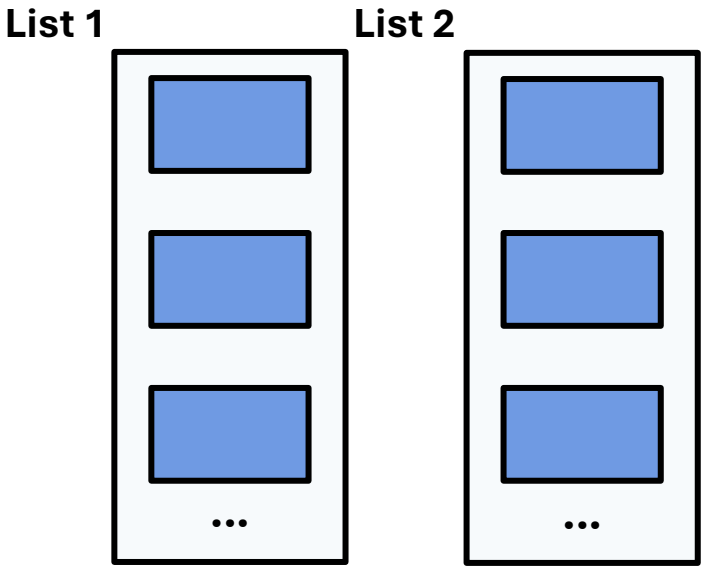
eBPF to the rescue!

- Safely run userspace code in the kernel
- Similar approaches taken for scheduling, networking, etc.

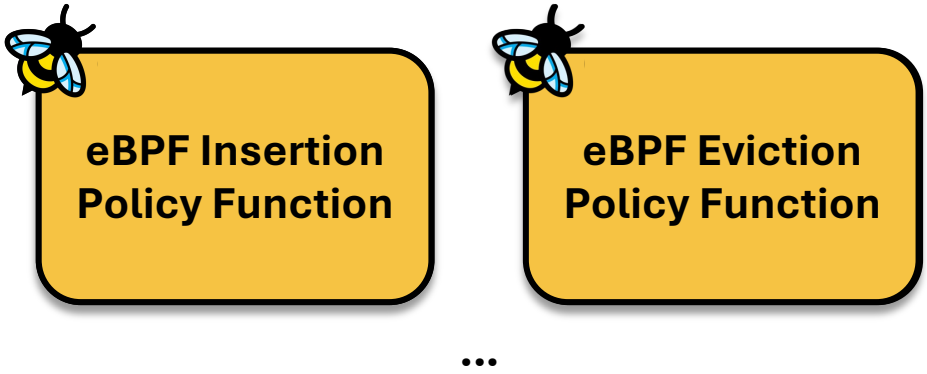
  sched_ext, Syrup (SOSP ‘21), ghOSt (SOSP ‘21), XDP, XRP (OSDI ‘22), …

cache_ext: Simple API yields powerful policies

eBPF Eviction Lists



Policy Functions



cache_ext: Simple API yields powerful policies

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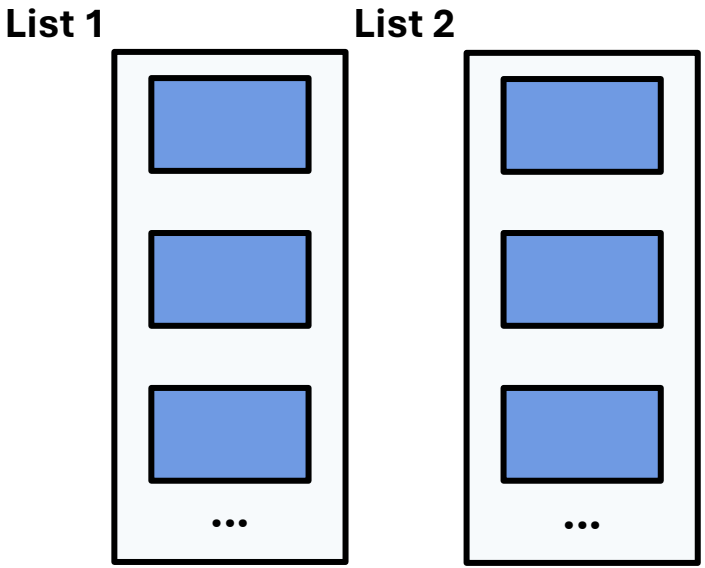

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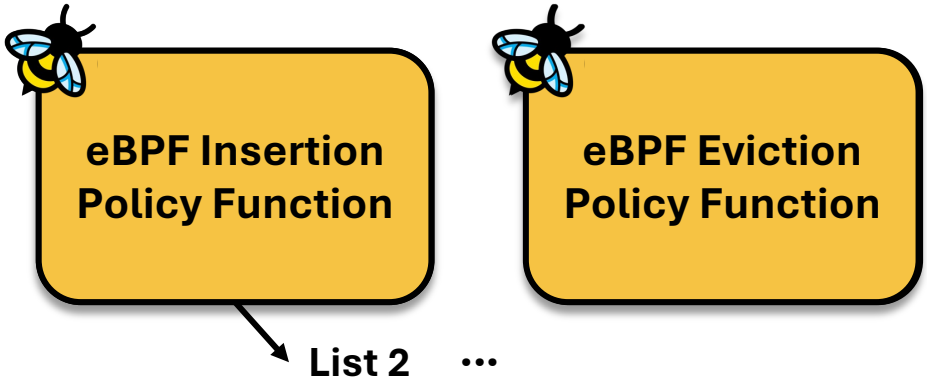
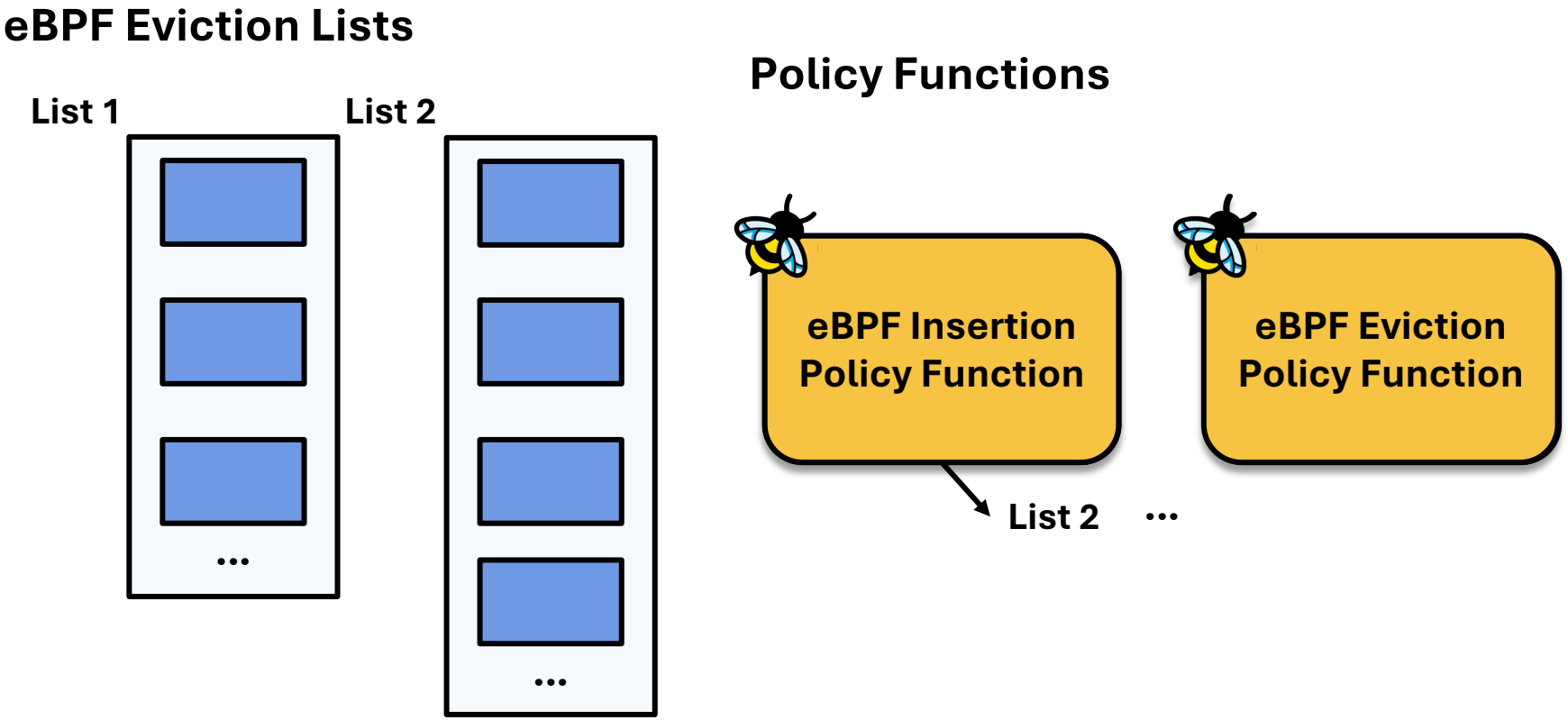
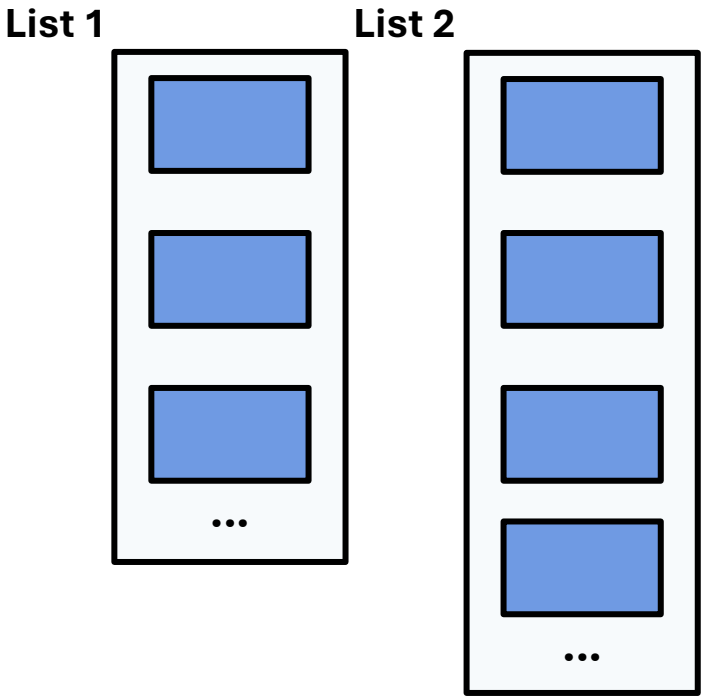


cache_ext: Simple API yields powerful policies



cache_ext: Simple API yields powerful policies

eBPF Eviction Lists



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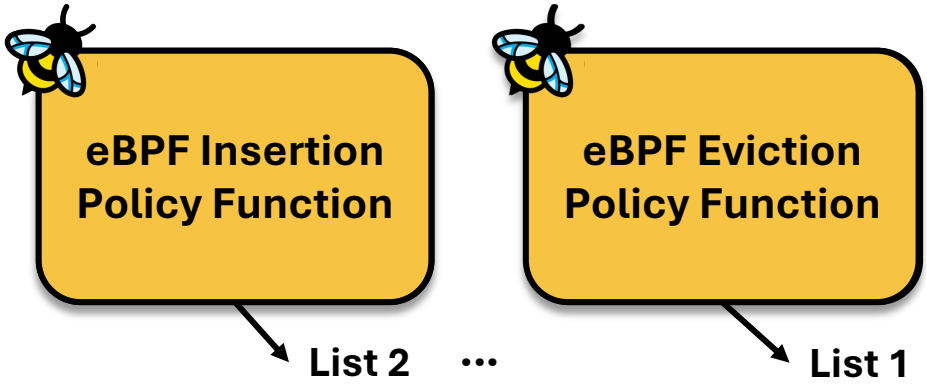
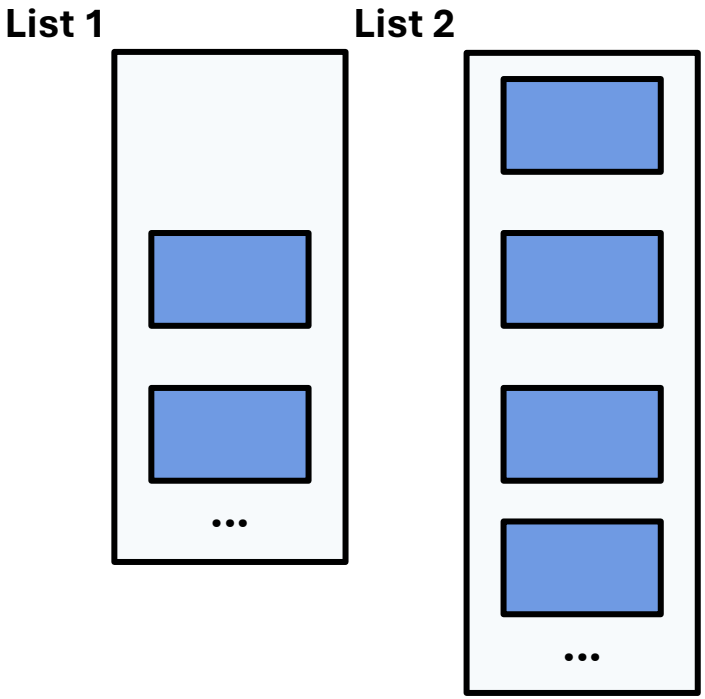


cache_ext: Simple API yields powerful policies

eBPF Eviction Lists



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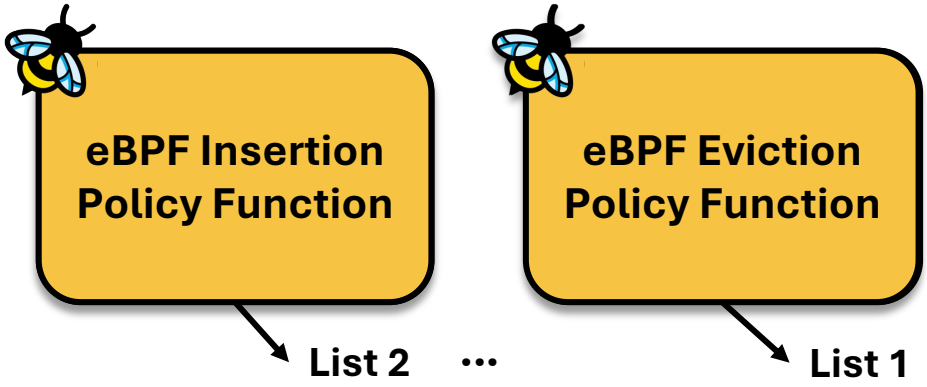
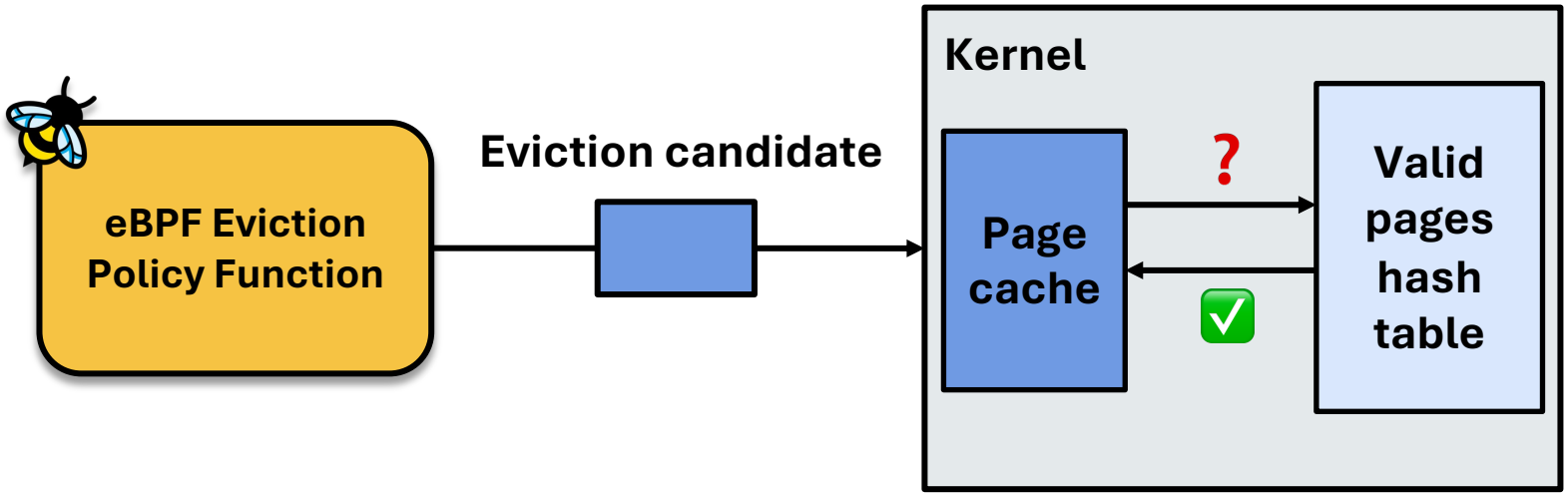


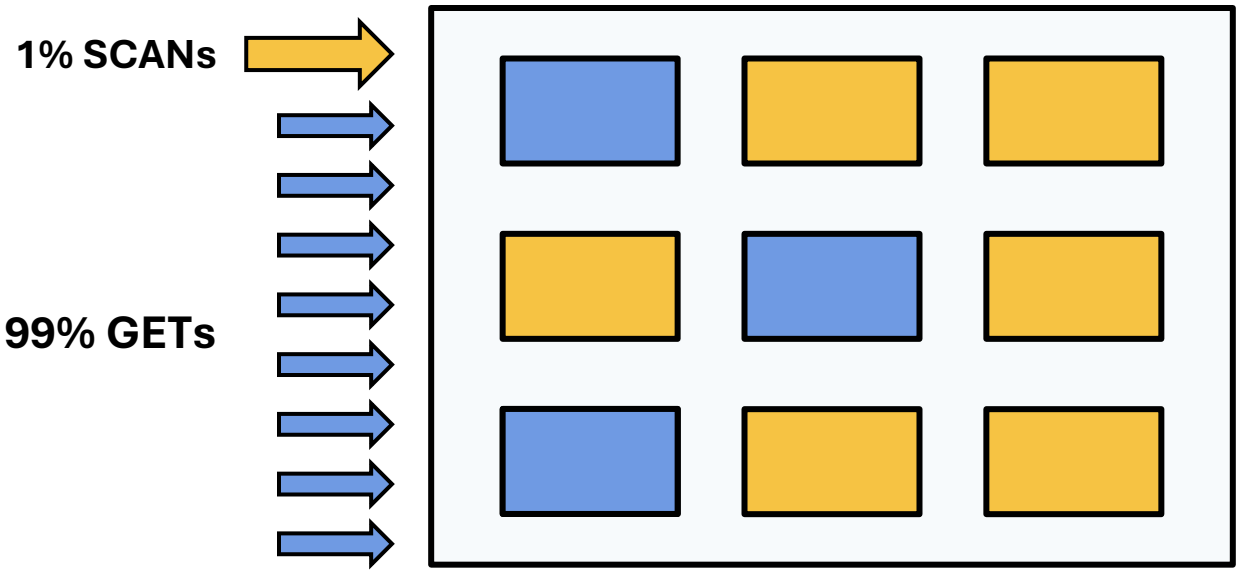
Most policies can be implemented with lists!

Challenge: Ensuring memory safety

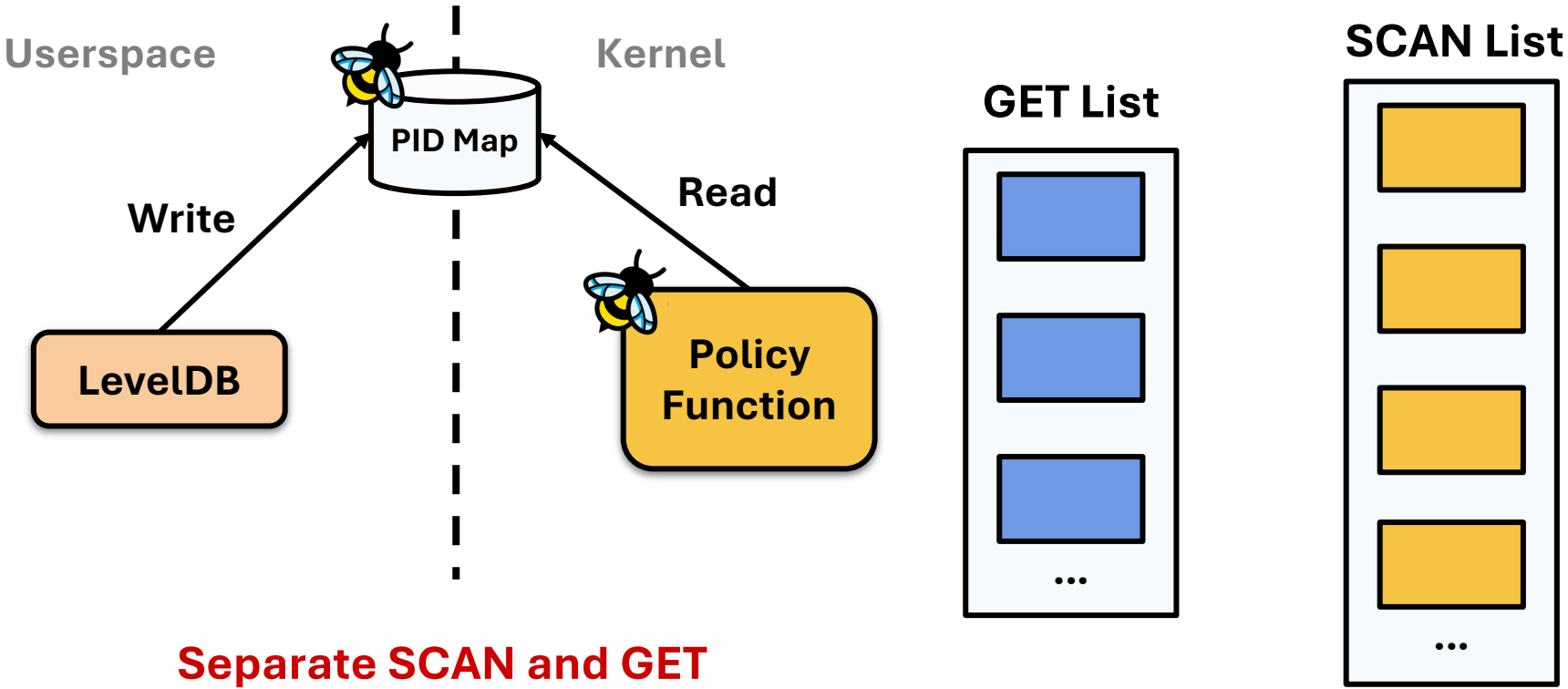
- eBPF eviction function can return any value… could be invalid
- Solution: Kernel maintains “valid pages” hash table
- Also stores the eviction list nodes



GET/SCAN doesn’t work well with default policy

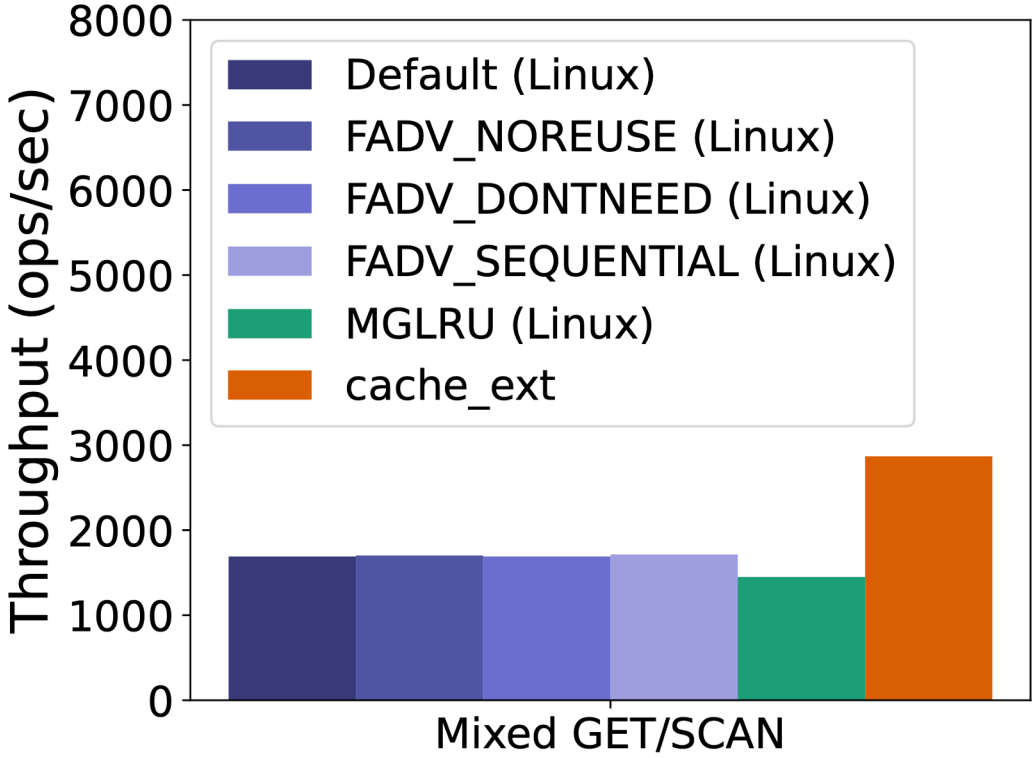


cache_ext enables application-informed policies



Separate SCAN and GET data by request PID

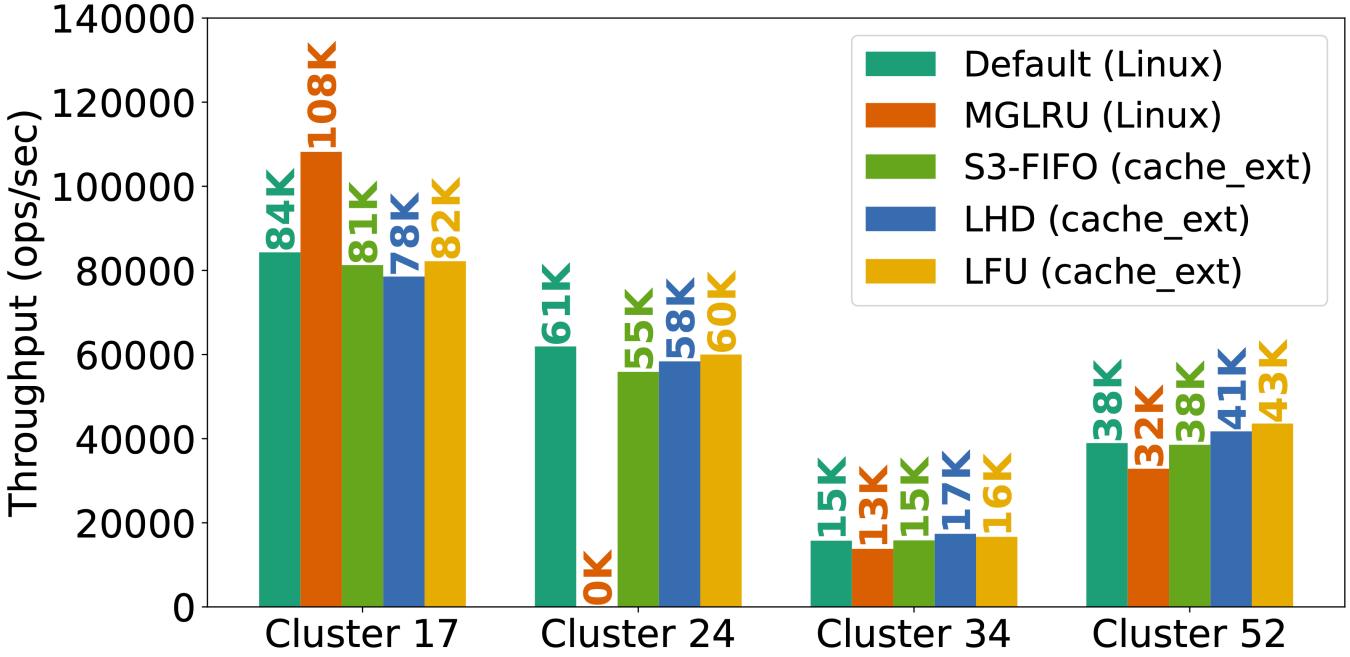
Application-informed policies improve performance



70% GET throughput increase

57% tail latency decrease

Customizability yields better performance



Twitter traces (OSDI ‘20),
S3-FIFO (SOSP ‘23),
LHD (NSDI ‘18)

Up to 37% throughput improvement for YCSB

No one policy performs best in all cases!

cache_ext enables modern page cache usage

- In order to maximize performance, must be able to experiment
- Policies can be reused across applications
- Applications can have their own per-cgroup policies (multi-tenancy)

Thank you!

- cache_ext enables custom page cache policies to better match applications
- Up to 70% higher throughput and 58% lower tail latency
- Open source!
- More in the paper: Policies, multi-tenancy, admission filter, security, overhead…

Paper and code:

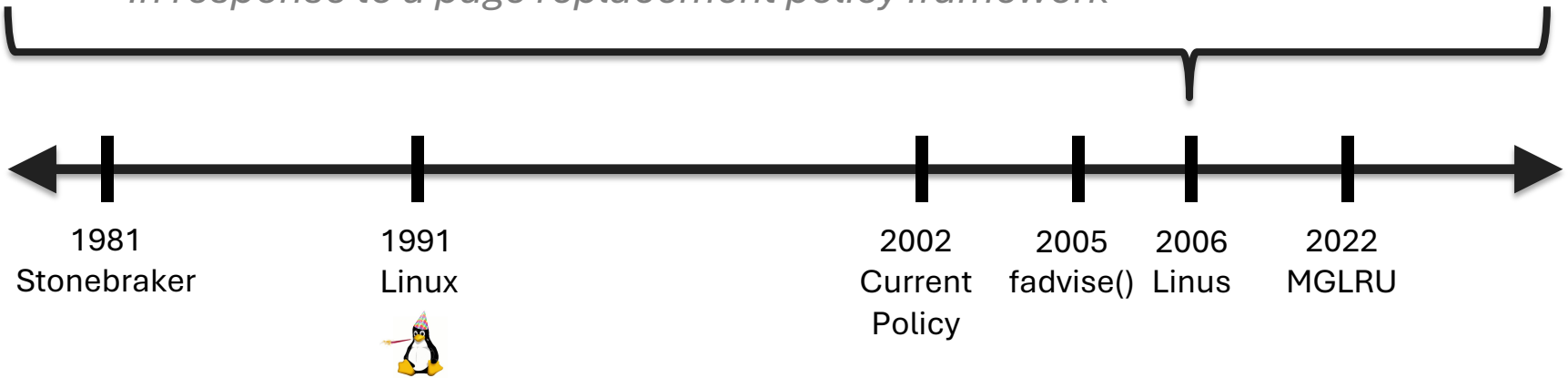
Tal Zussman
tz2294@columbia.edu

github.com/cache-ext/cache_ext

Linux page cache is widely used

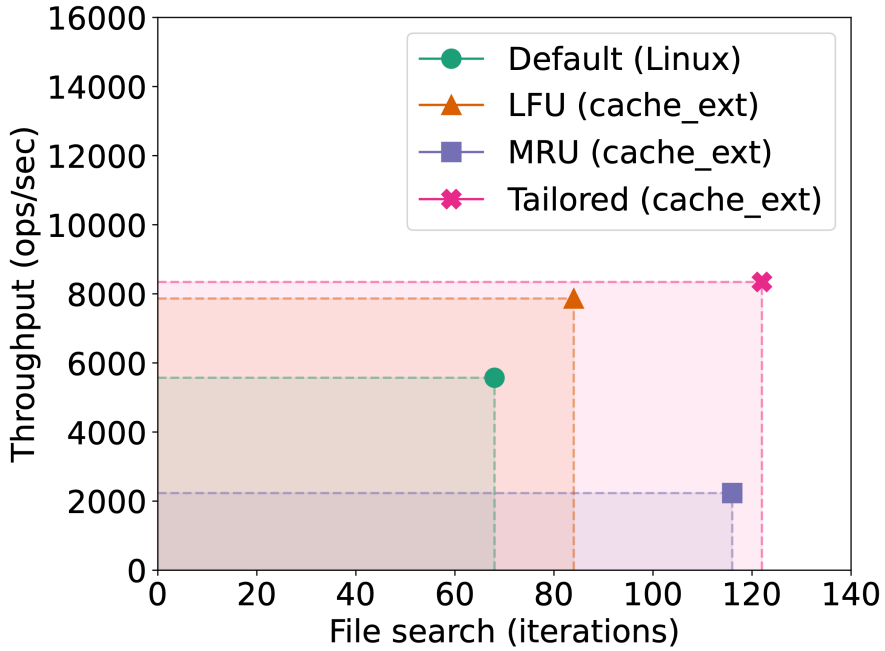
A brief history lesson…

> “Please name a load that really actually hits the page replacement today. **It smells like university research to me.**”
>
> – Linus Torvalds, 2006
>
> *In response to a page replacement policy framework*



Each application can run its own policy

cgroup 1

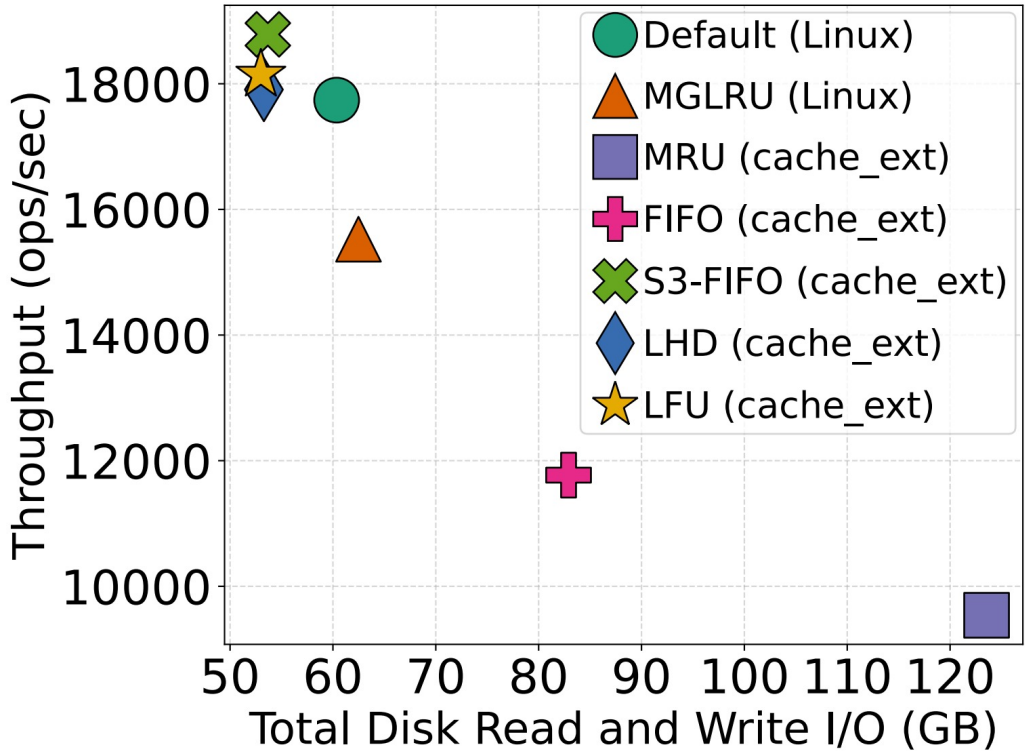


cgroup 2

Optimal performance when each cgroup runs a policy matching its workload:

50% and 80% improvements over baseline

Disk access reduction



LFU policy

```
u64 lfu_list;
int lfu_policy_init(struct mem_cgroup *cg) {
    lfu_list = list_create(cg);
    return 0;
}
void lfu_folio_added(struct folio *folio) {
    u64 freq = 1;
    list_add(lfu_list, folio, true); // Add to tail
    bpf_map_update_elem(&freq_map, &folio, &freq);
}
void lfu_folio_accessed(struct folio *folio) {
    u64 *freq = bpf_map_lookup_elem(&freq_map, &folio);
    __sync_fetch_and_add(freq, 1); // Increment freq
}
```

```
long score_lfu(int id, struct folio *folio) {
    return bpf_map_lookup_elem(&freq_map, &folio);
}
void lfu_evict_folios(struct eviction_ctx *ctx, struct
     mem_cgroup *cg) {
    struct iter_opts opts = { /* Set scoring mode */ };
    list_iterate(cg, lfu_list, score_lfu, &opts, ctx);
}
void lfu_folio_removed(struct folio *folio) {
    bpf_map_delete_elem(&freq_map, &folio);
}
```

cache_ext hooks

```
// Policy function hooks
struct cache_ext_ops {
    s32  (*policy_init)(struct mem_cgroup *memcg);
    // Propose folios to evict
    void (*evict_folios)(struct eviction_ctx *ctx,
         struct mem_cgroup *memcg);
    void (*folio_added)(struct folio *folio);
    void (*folio_accessed)(struct folio *folio);
    // Folio was removed: clean up metadata
    void (*folio_removed)(struct folio *folio);
    char name[CACHE_EXT_OPS_NAME_LEN];
};

struct eviction_ctx {
    u64 nr_candidates_requested; /* Input  */
    u64 nr_candidates_proposed;  /* Output */
    struct folio *candidates[32];
};
```