`cache_ext`: Customizing the Page Cache with eBPF

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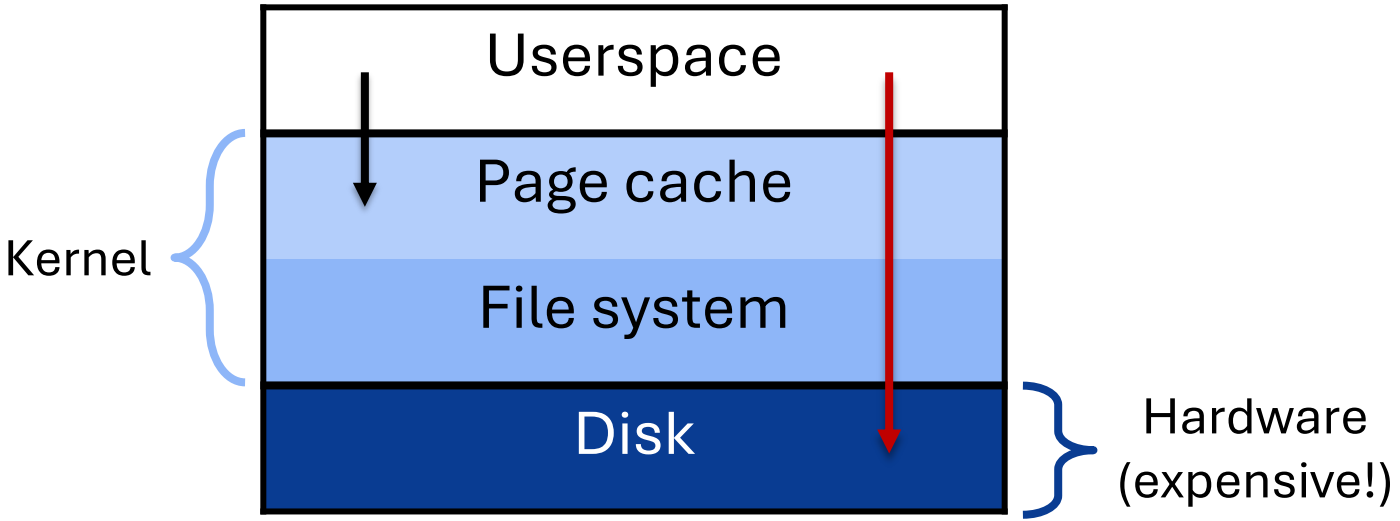
TLDR;

- The page cache doesn’t work so well with some 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

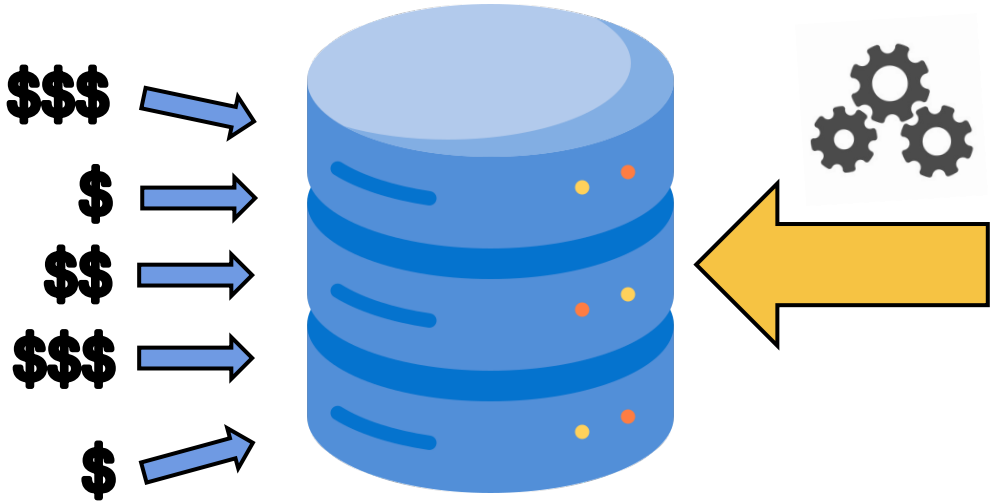
Linux page cache significantly affects performance

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



Linux page cache struggles with some workloads

- Many tiny transactions
- A few massive background tasks



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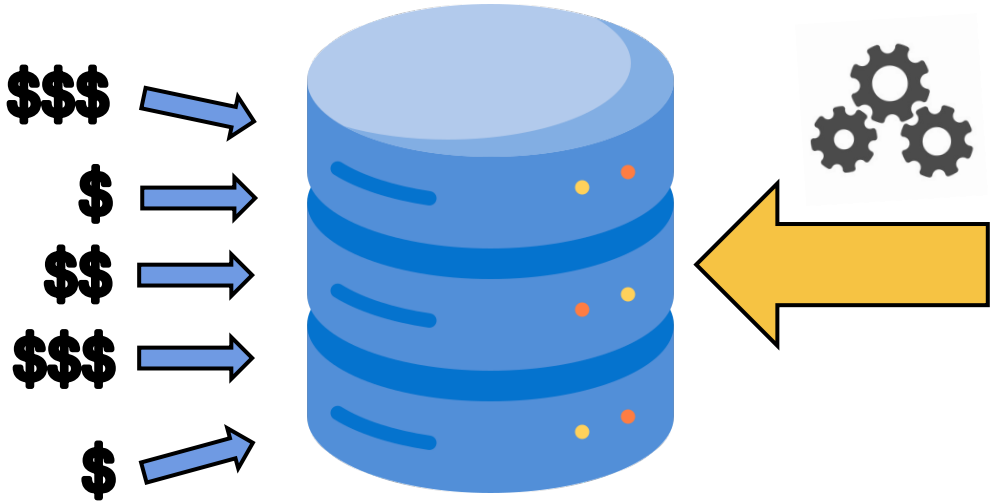
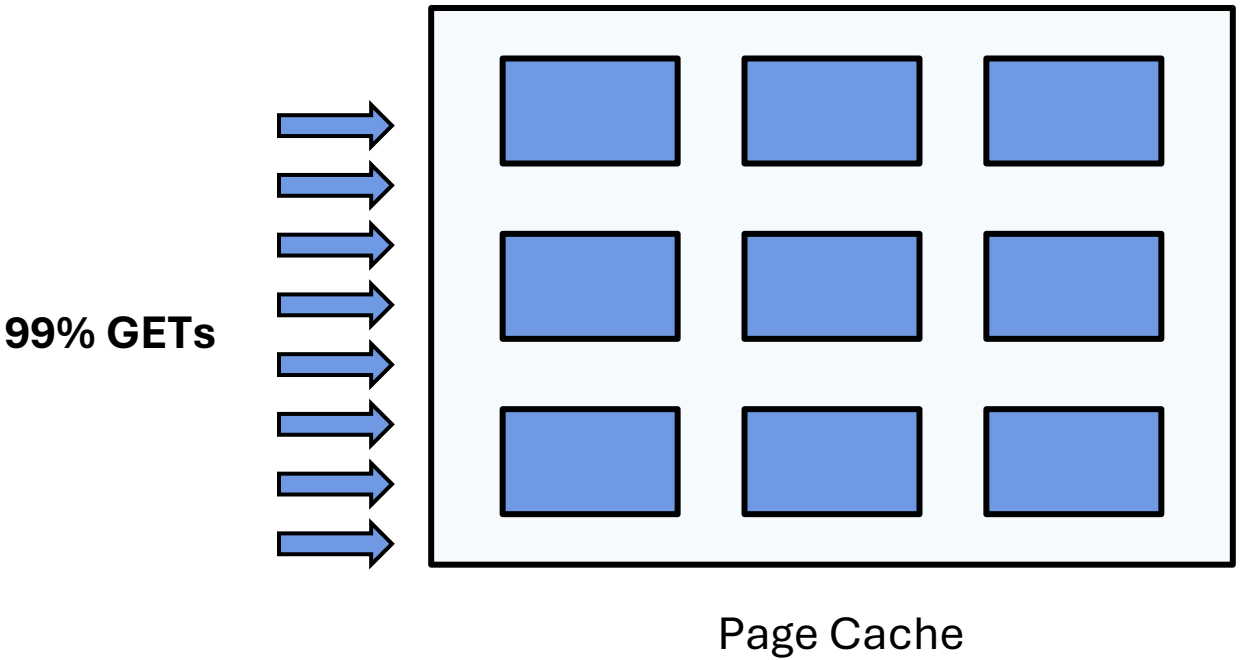


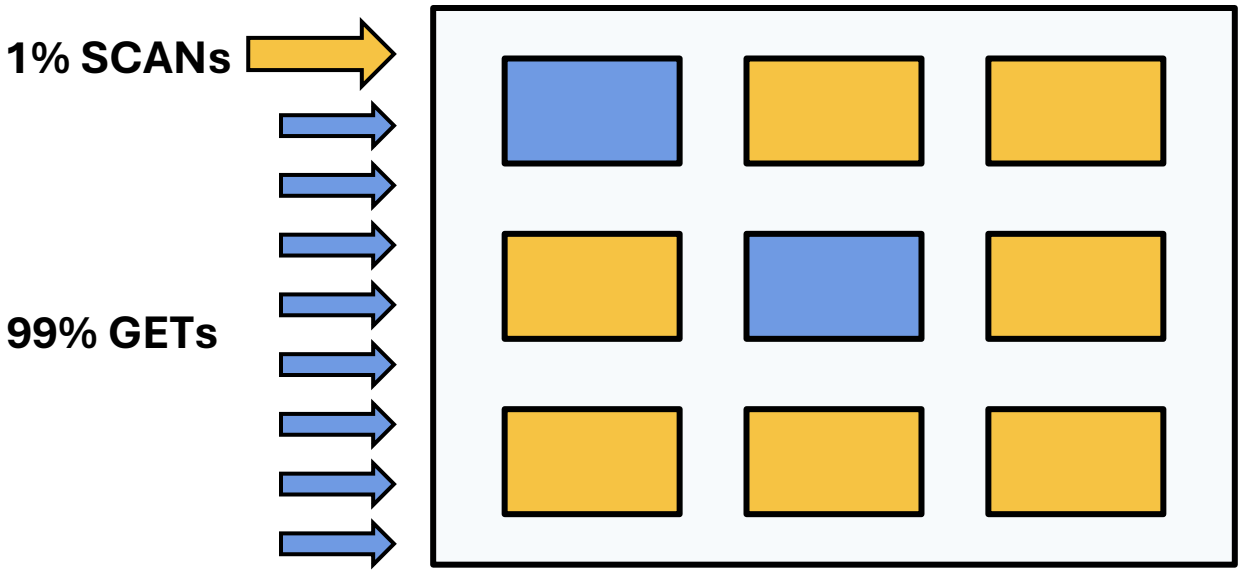
HTAP-like:
Mix of Transactional (GET) and Analytical (SCAN)

Shinjuku (NSDI ’19),
Syrup (SOSP ‘21)

Linux page cache struggles with some workloads



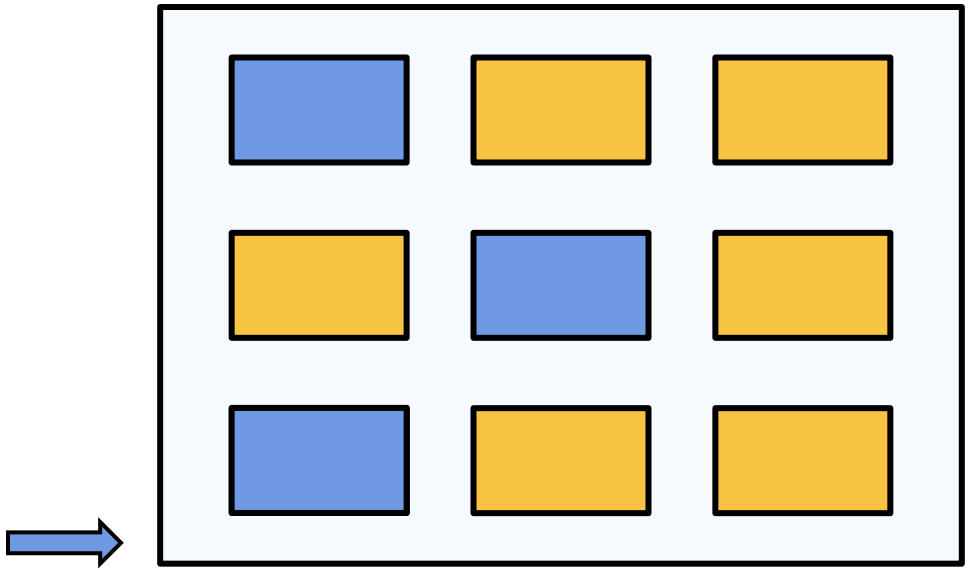
Linux page cache struggles with many workloads



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

Existing solutions

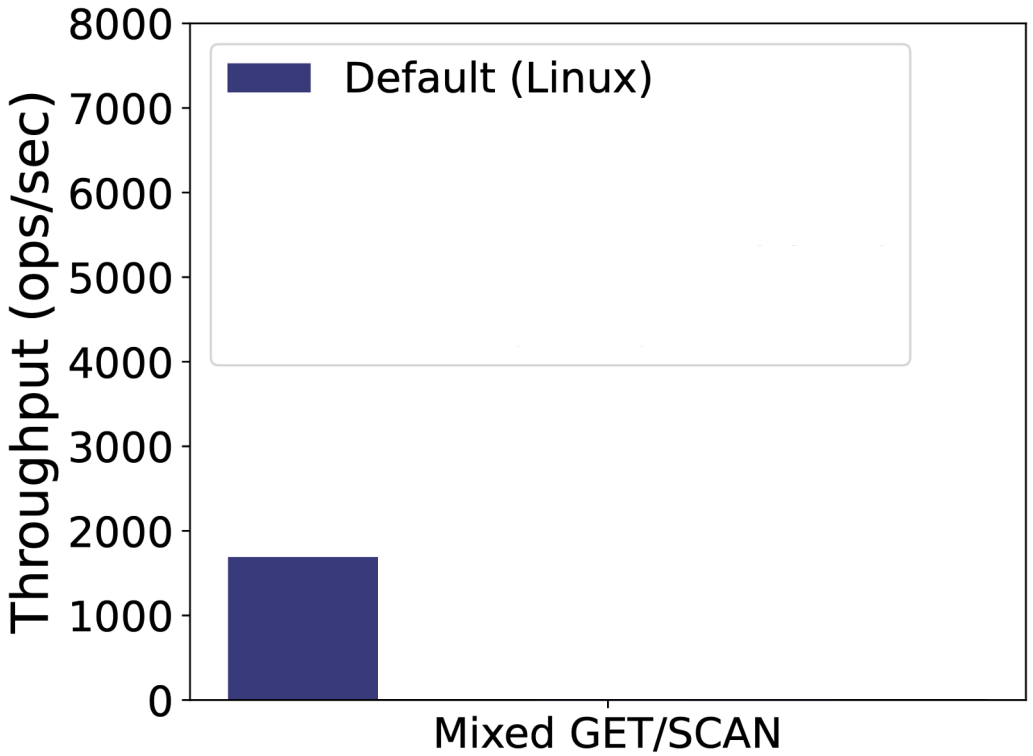
- Change the policy
- Userspace hints
- Application-level caching

Changing the policy is hard

MGLRU merged in Linux v6.1 as new experimental policy

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

Existing hint interfaces are insufficient



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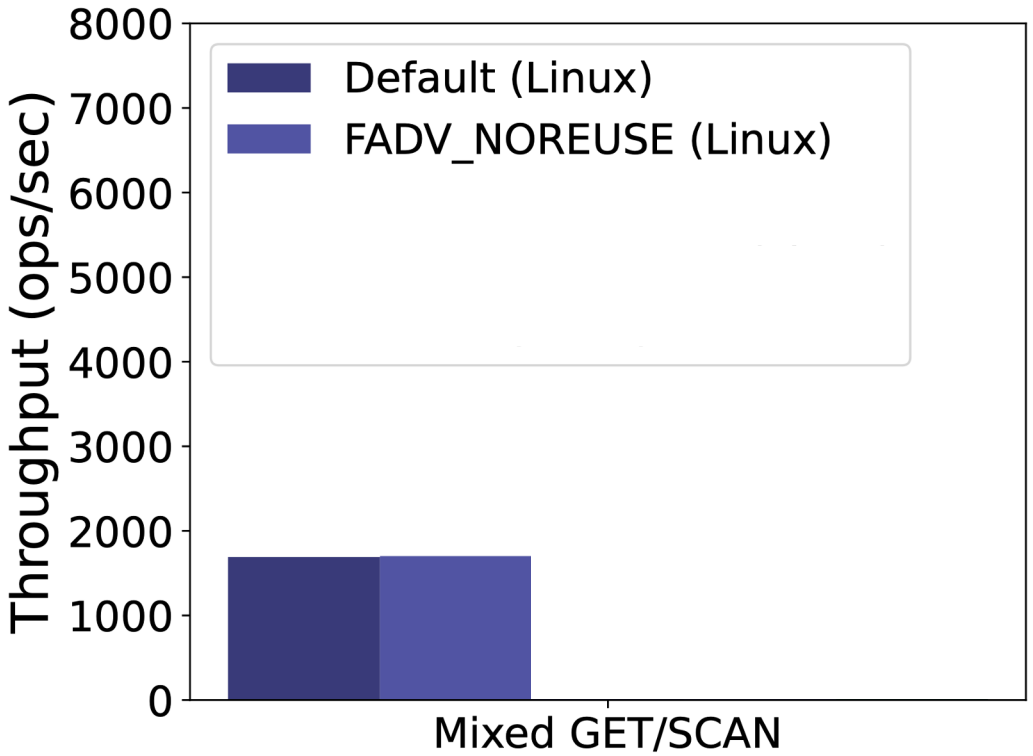

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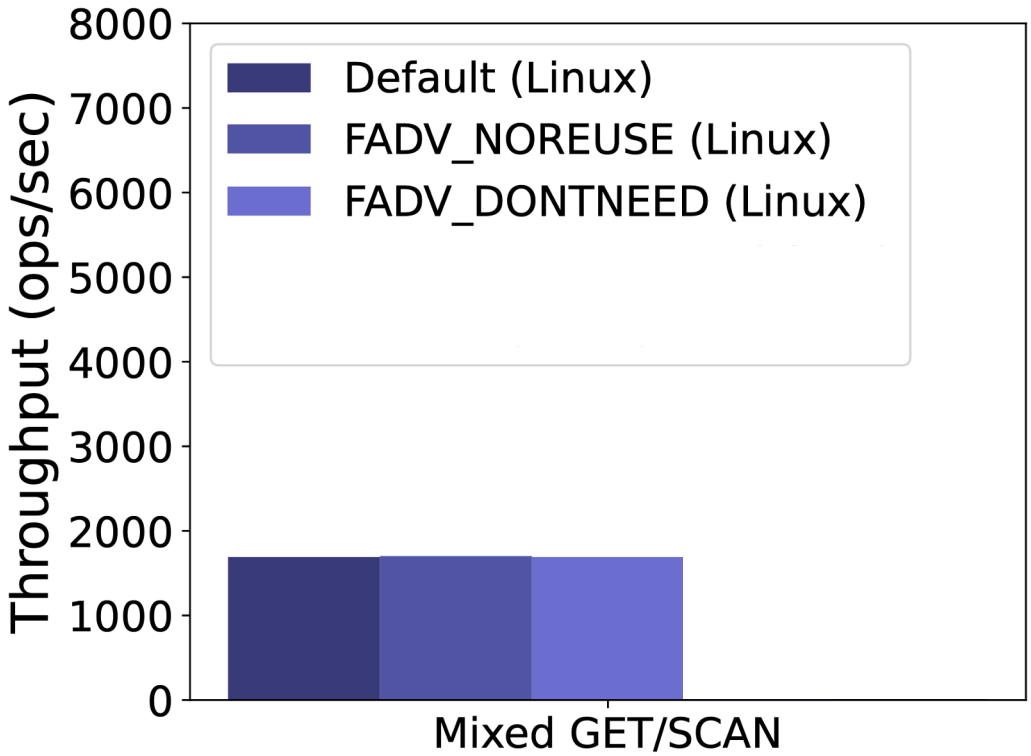

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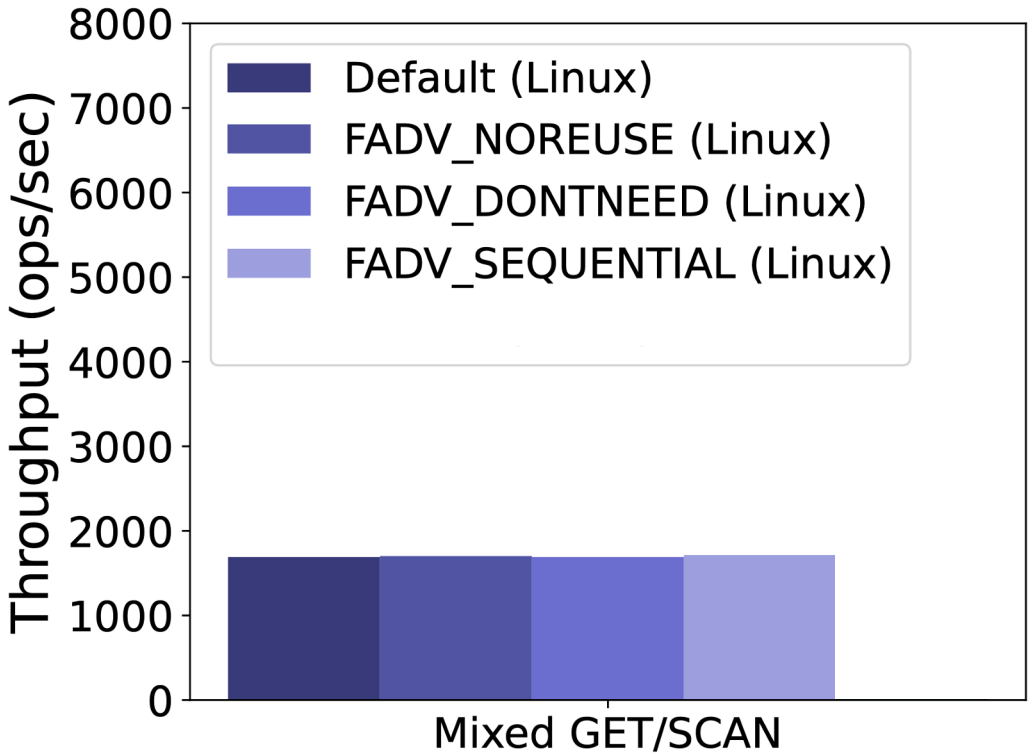

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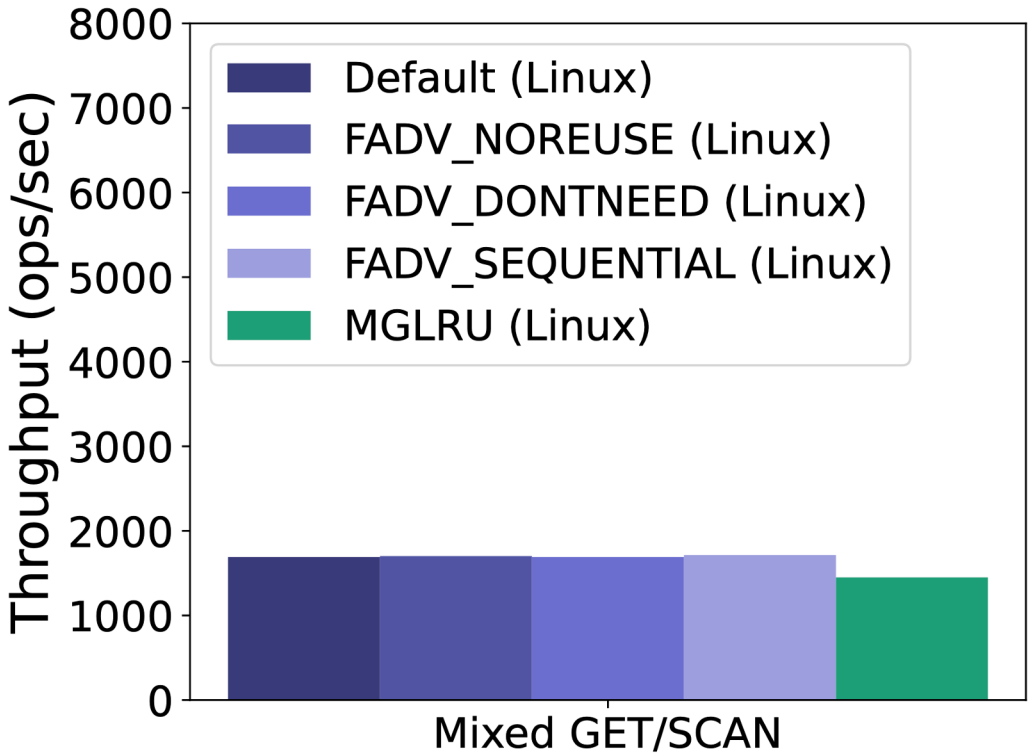


Hints don’t work!

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 ✅

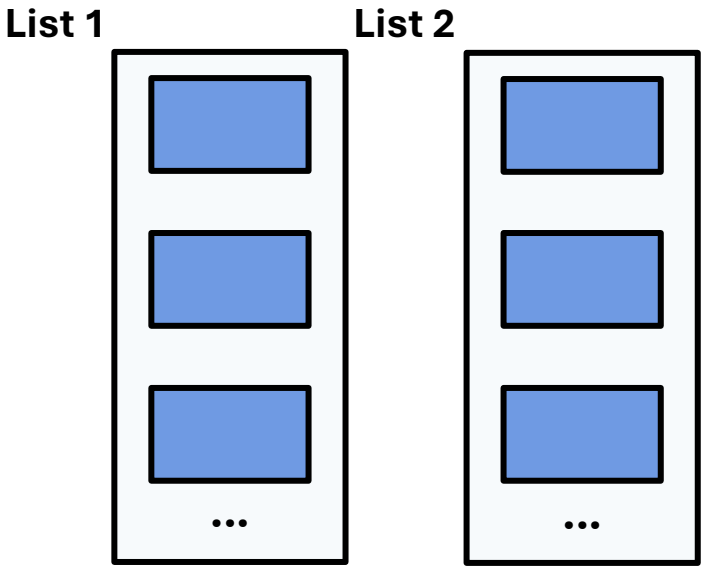
cache_ext interface

- struct_ops hooks added to page cache implementation
- ~200 LoC in page cache code (mostly batching eviction)

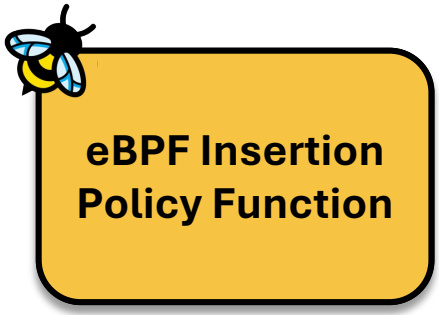
```
// Policy function hooks
struct cache_ext_ops {
    s32  (*policy_init)(struct mem_cgroup *memcg);
    // Propose folios to evict
    void (*evict_folios)(struct eviction_ctx *ctx,
         struct mem_cgroup *memcg);
    void (*folio_added)(struct folio *folio);
    void (*folio_accessed)(struct 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];
};
```

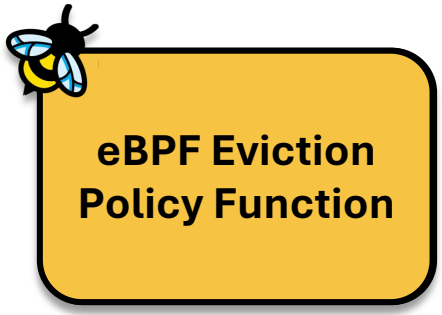
cache_ext: Simple API yields powerful policies

eBPF Eviction Lists



Policy Functions





...

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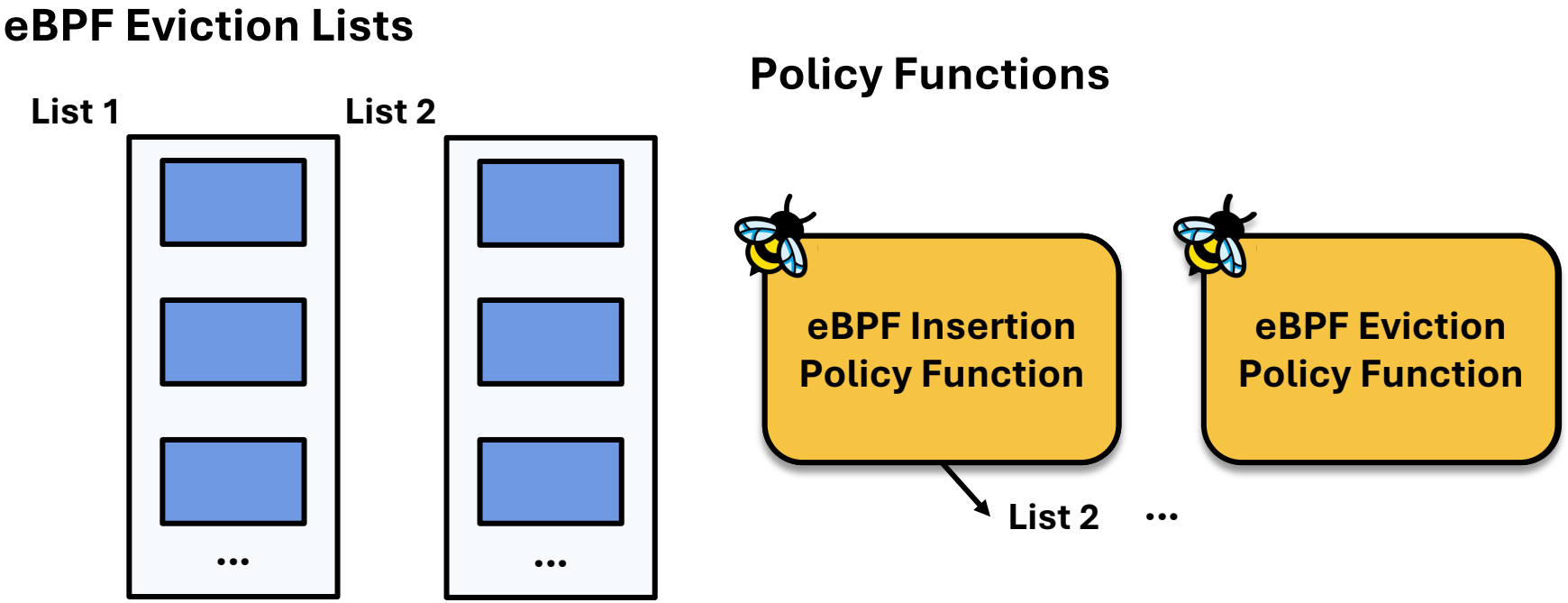

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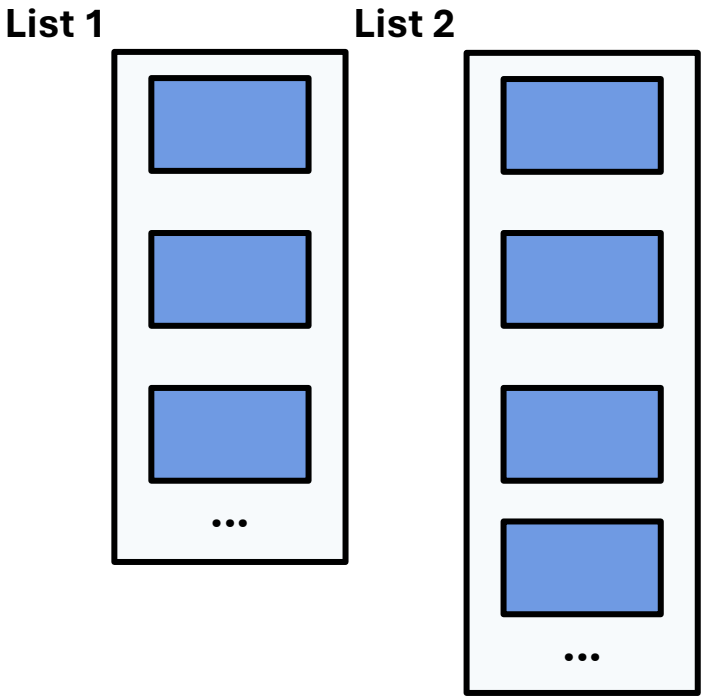

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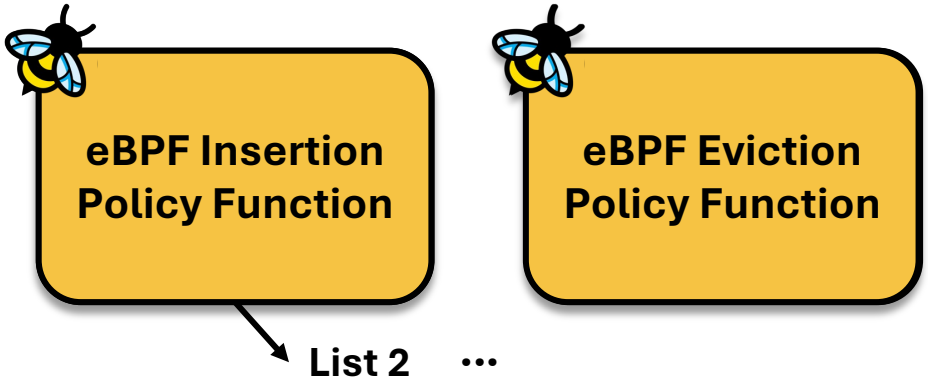

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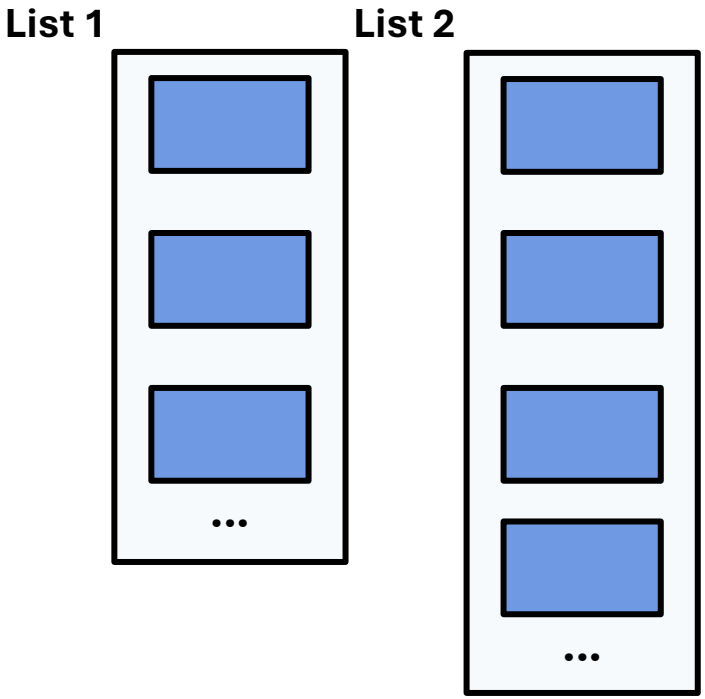

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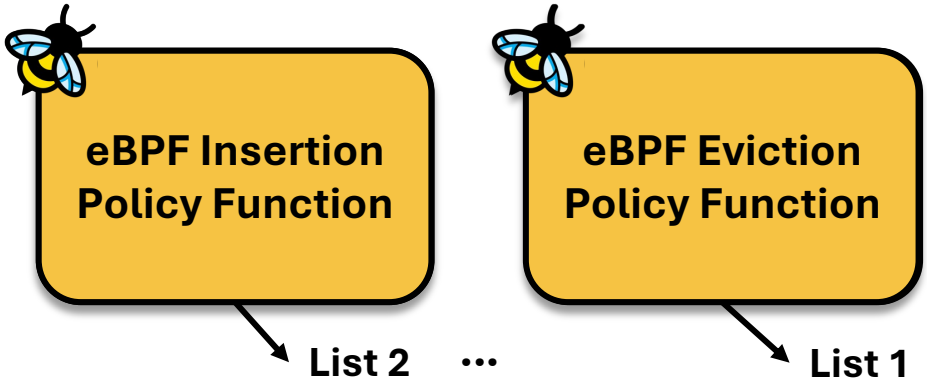

cache_ext: Simple API yields powerful policies

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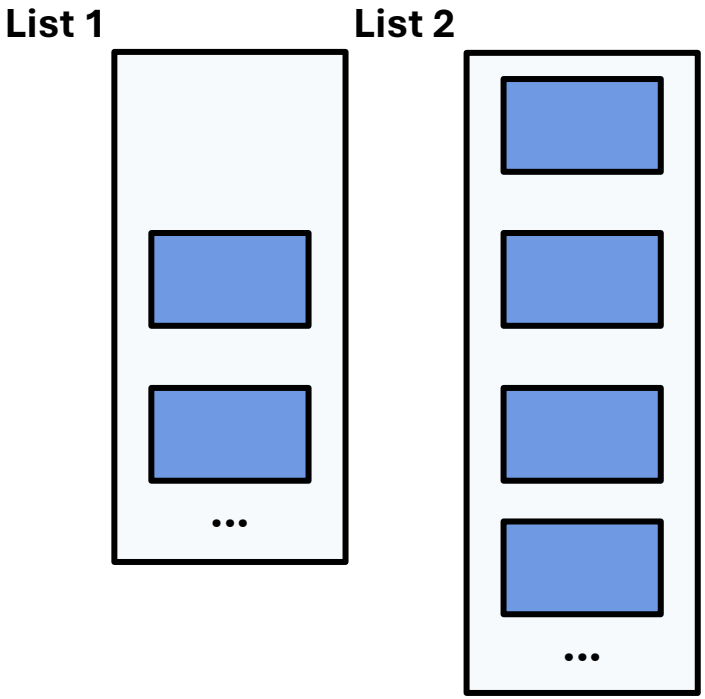

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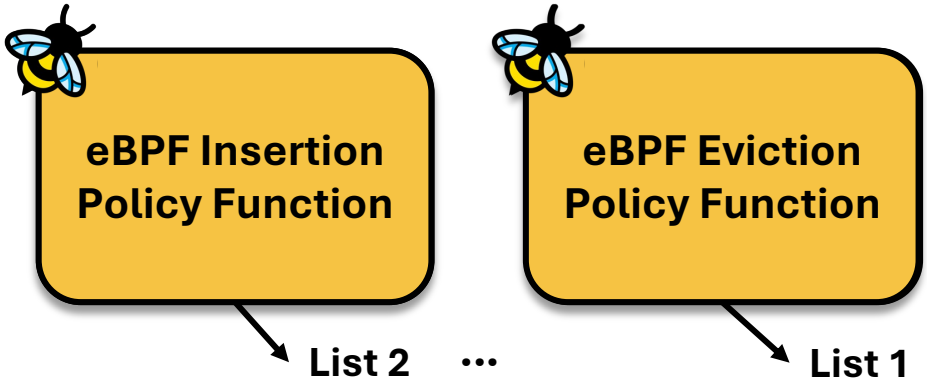

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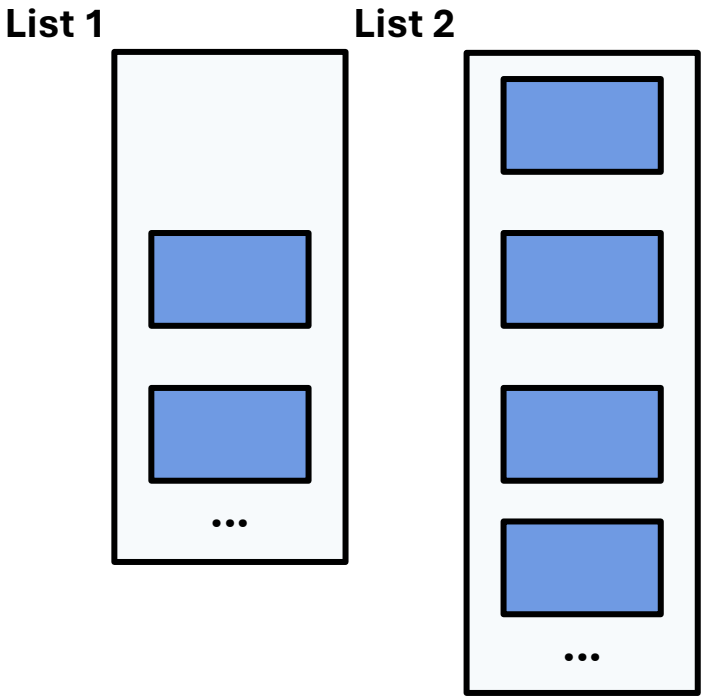

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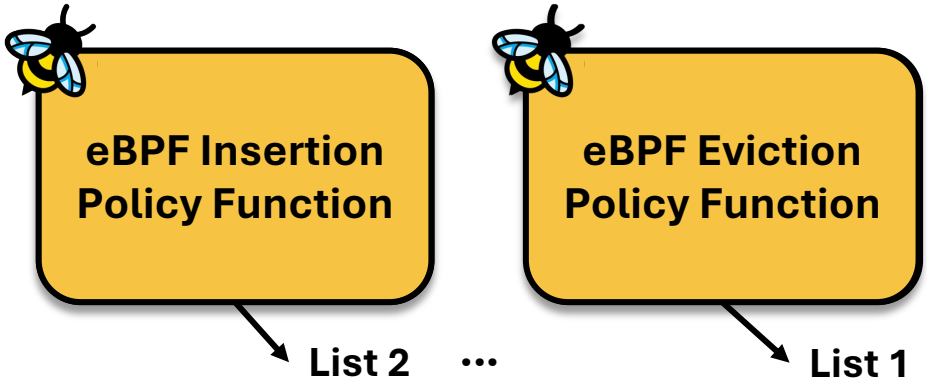


Most policies can be implemented with lists!

cache_ext list kfuncs

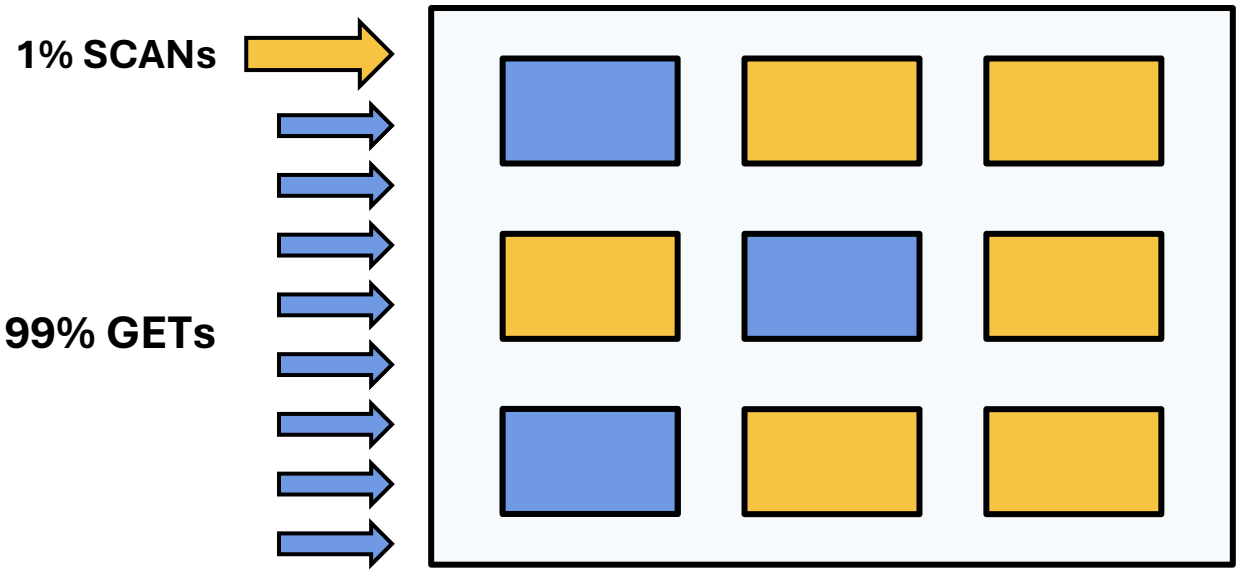
Eviction lists are similar to sched_ext DSQs

Eviction list API
`u64 list_create(struct mem_cgroup *memcg)`
`int list_add(u64 list, struct folio *f, bool tail)`
`int list_move(u64 list, struct folio *f, bool tail)`
`int list_del(struct folio *f)`

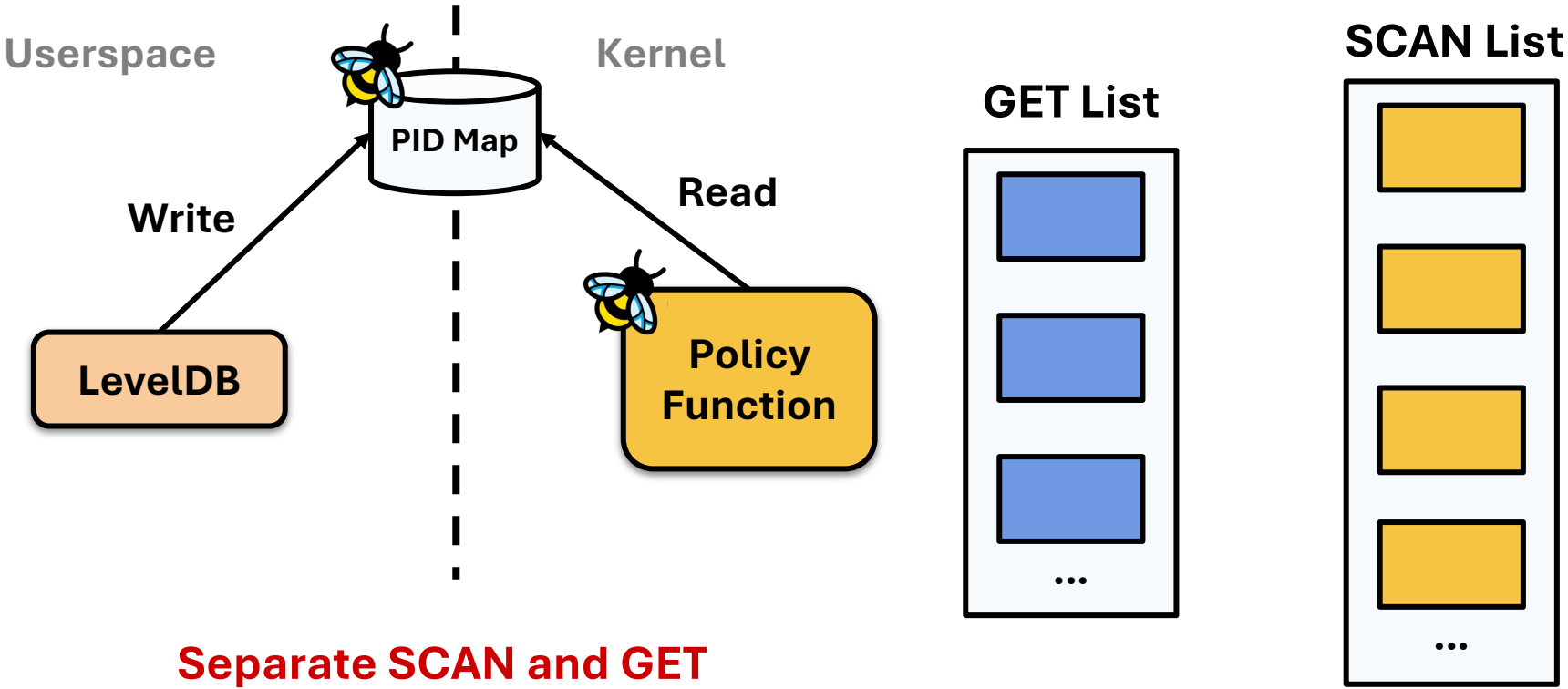
`int list_iterate(struct mem_cgroup *memcg, u64 list,`
`  s64(*iter_fn)(int id, struct folio *f),`
`  struct iter_opts *opts, struct eviction_ctx *ctx)`

Note: These kfuncs are namespaced with a cache_ext prefix

GET/SCAN doesn’t work well with default policy

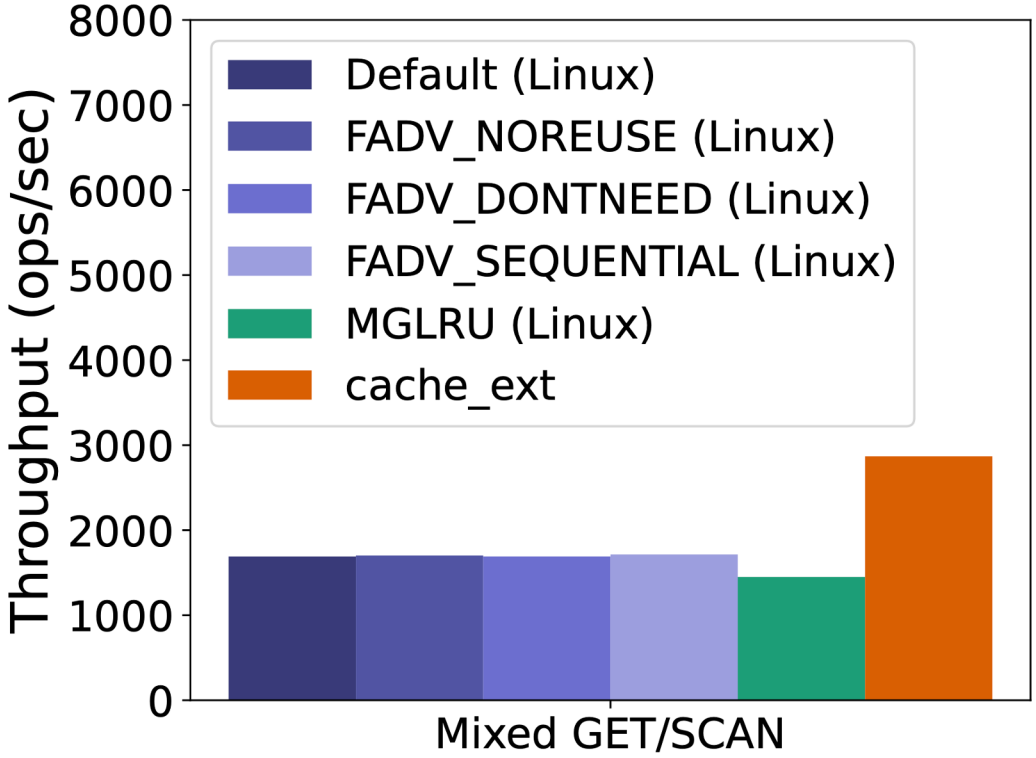


cache_ext enables application-informed policies



Separate SCAN and GET data by request PID

Application-informed policies improve performance



70% GET throughput increase

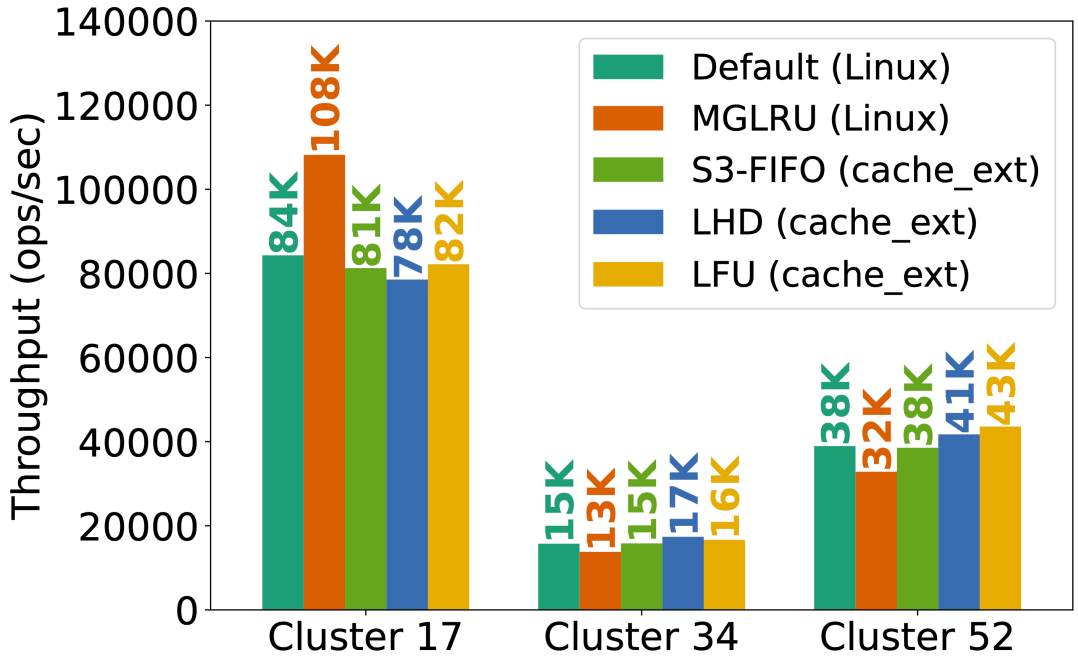
57% tail latency decrease

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);
}
```

Customizability yields better performance



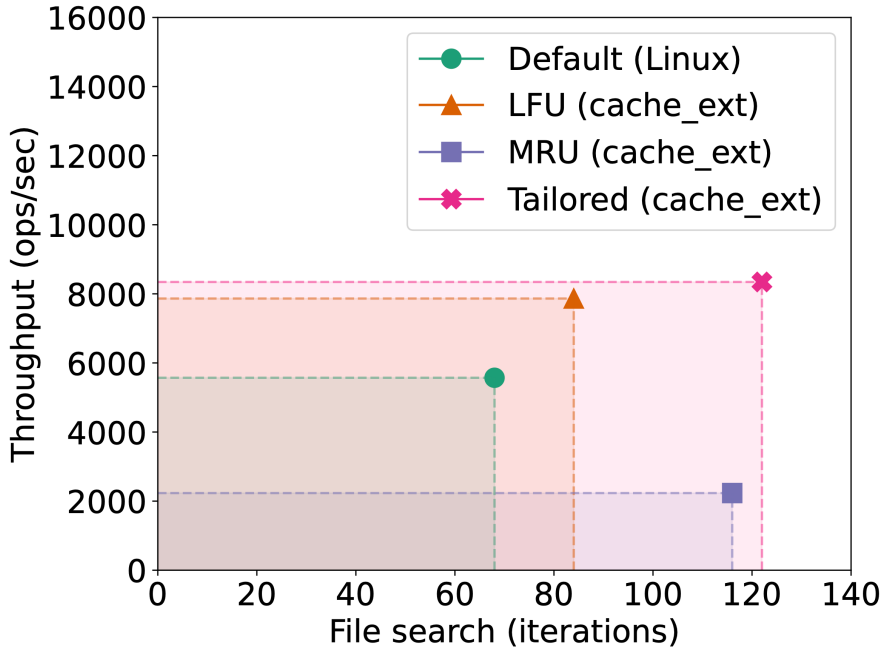
Twitter traces (OSDI '20),
S3-FIFO (SOSP '23),
LHD (NSDI '18)

Also ran with YCSB:
Up to 37% throughput improvement

No one policy performs best in all cases!

Per-cgroup policies

cgroup 1



cgroup 2

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

50% and 80% improvements over baseline

The case for BPF

- The perfect one-size-fits-all policy is a fantasy
- Tweak behavior for one workload without regressing other workloads
- Need to be able to experiment and specialize (app-informed policies)

Challenges / Open Questions

- Per-cgroup struct_ops
  - Discussed on-list for BPF OOM, sched_ext – solvable
- Use trusted pointers to simplify reference counting
- Live switching policies + cgroup lifetime management
- Is the eviction iteration interface powerful enough? Other data structures? Arenas?

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
- More in the paper: Policies, admission filter, security, overhead…

Paper and code:

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github.com/cache-ext/cache_ext