PageFlex: Flexible and Efficient User-space Delegation of Linux Paging Policies with eBPF

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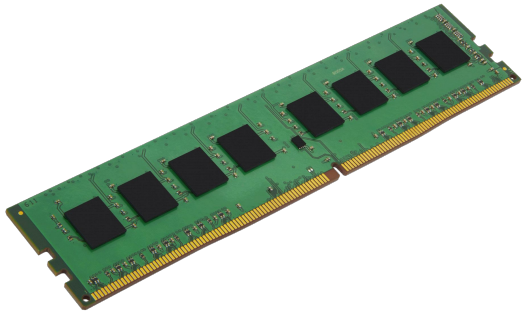
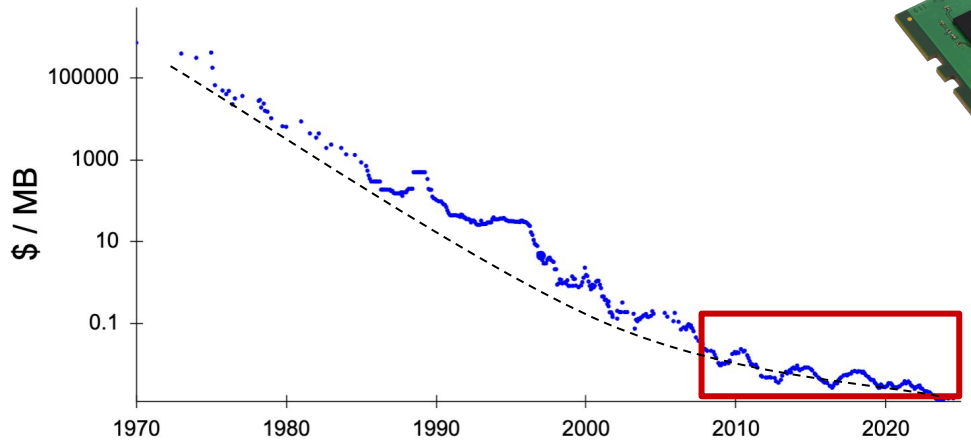
Rising DRAM cost in data centers

- DRAM cost scaling has nearly flattened
- **Majority of the server cost** in data centers

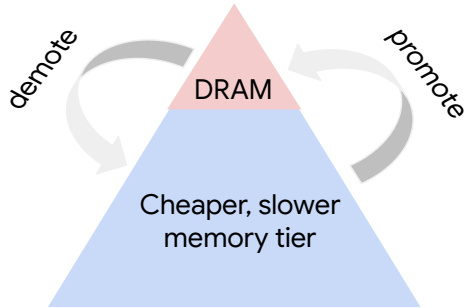




https://jcmit.net/memoryprice.htm

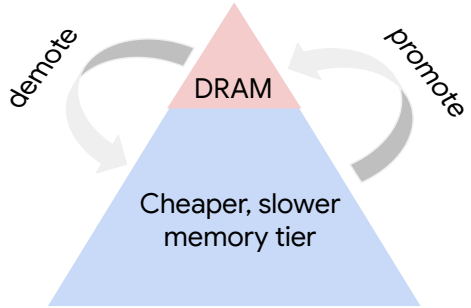
Cost saving: Offload cold data

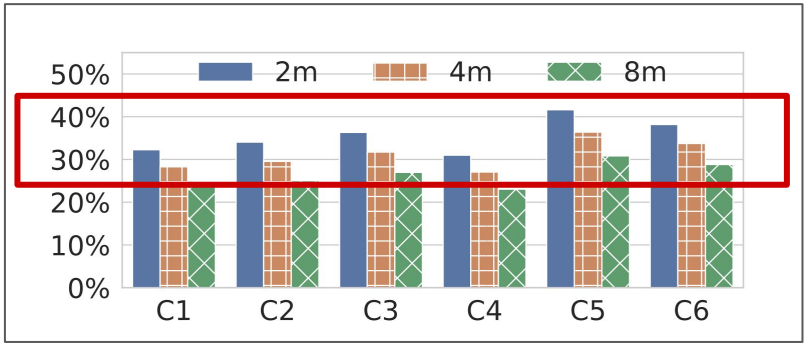
- Cheaper substrates such as a compressed DRAM tier (zswap) or SSD
- But much (5-50x) slower → Offload infrequently accessed or “cold” data



Cost saving: Offload cold data

- Cheaper substrates such as a compressed DRAM tier (zswap) or SSD
- But much (5-50x) slower ⟶ Offload infrequently accessed or “cold” data
- **20–40% of the data is very cold!**





Cold memory % across Google’s clusters [ASPLOS’ 19]

Production-scale DRAM offloading

Google Software-defined Far Memory (g-swap) [ASPLOS ’19]

Meta Transparent Memory Offloading [ASPLOS ‘22]

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- With **OS paging** and **LRU**, they show **20-30%** memory savings

Production-scale DRAM offloading

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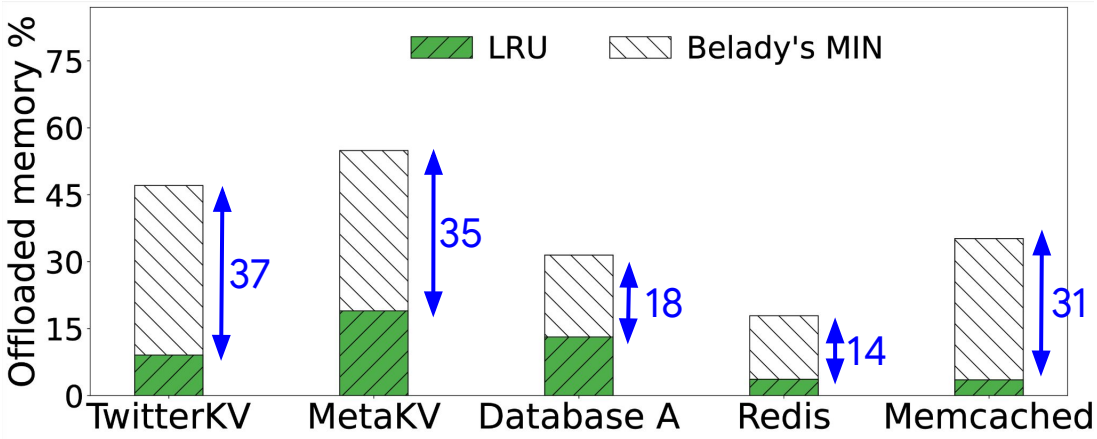
Meta Transparent Memory Offloading [ASPLOS '22]

- With **OS paging** and **LRU**, they show **20-30%** memory savings
- LRU is generally good but we can do better

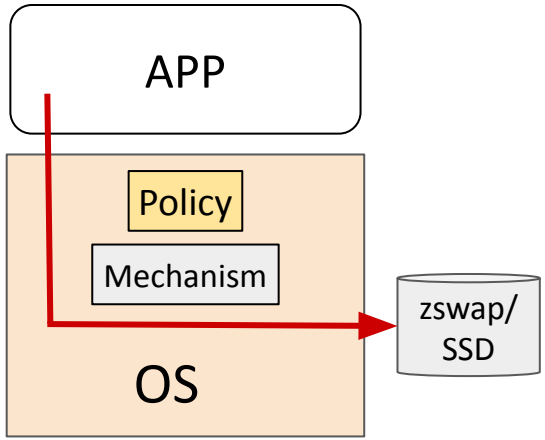
Examples
LRU-K
LIRS
ARC
Hyperbolic [ATC '17]
LHD [NSDI '18]
LRB [NSDI '20]

There is more room for policy improvement



Simulated Optimal-LRU gap for real workload traces at **<1%** miss rate.

Challenge: OS-based paging policy



	OS
No app changes	✅
Re-use swap stack	✅

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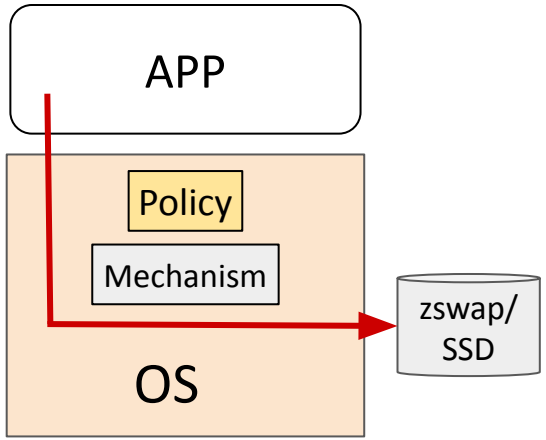

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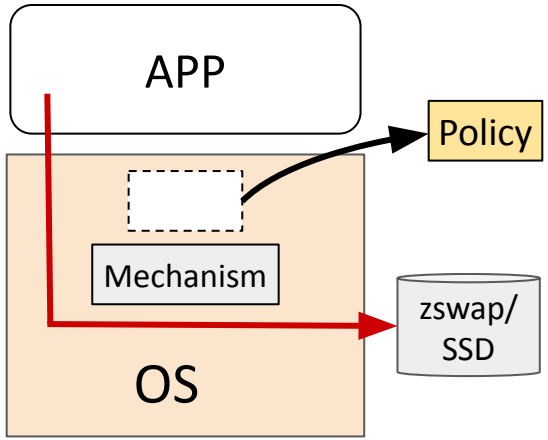

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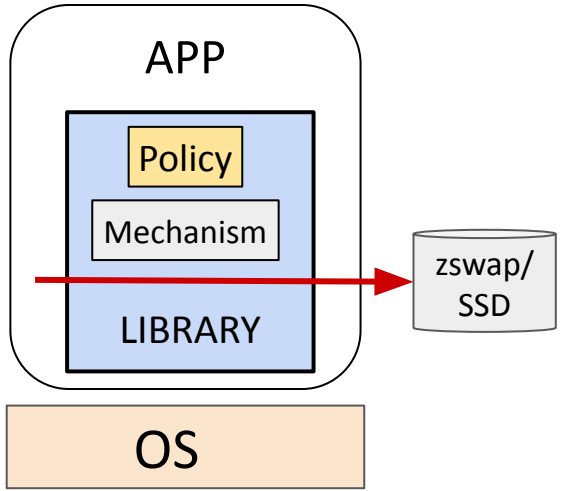
Solution: Bring policy of OS (code)

1. Custom libraries are not practical (yet)



	OS	LIB
Fungible policy	❌	✅
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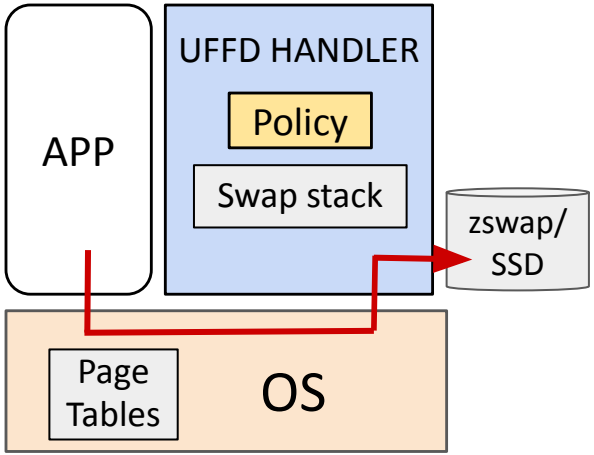
Re-use swap stack	✅	

AIFM [OSDI '20]
Mira [OSDI '20]
TrackFM [ASPLOS '24]

2. User-level paging (userfaultfd)



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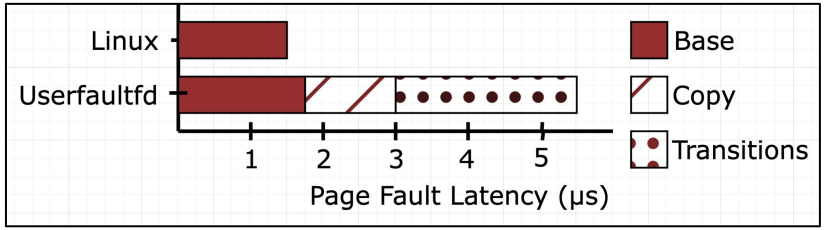

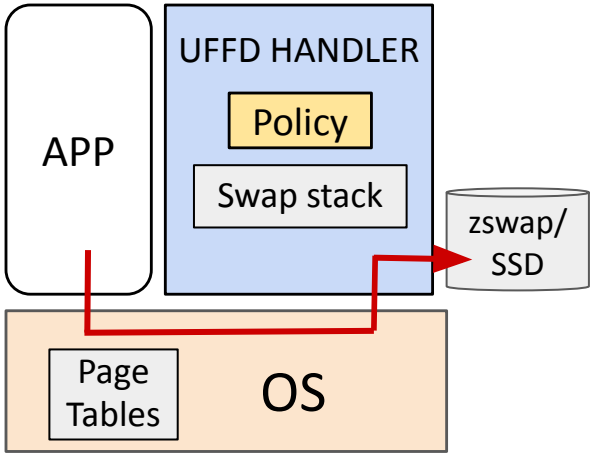

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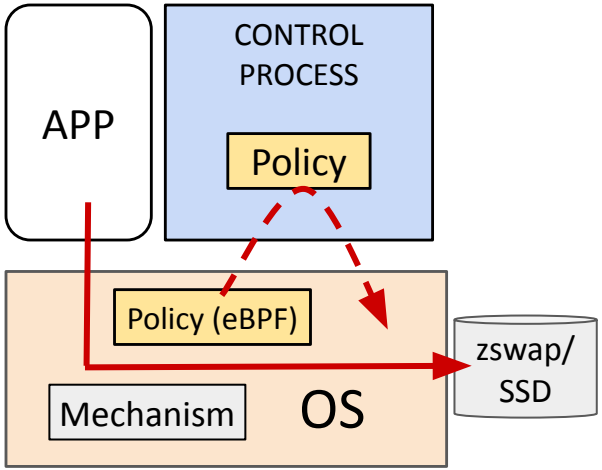
No overhead	✅		❌

Can we externalize policy while still keeping the mechanisms intact?

Our answer: PageFlex



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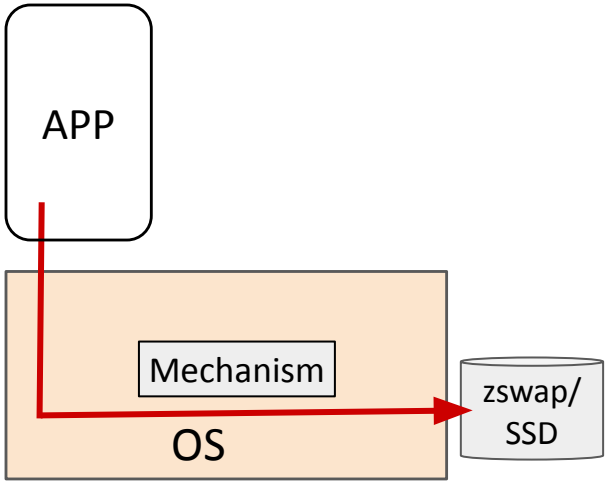

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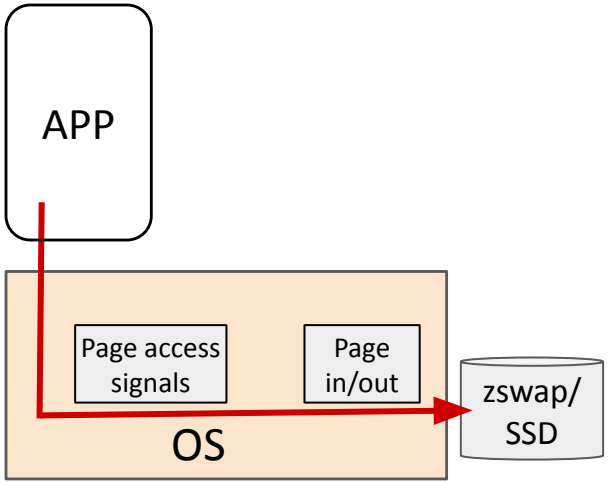

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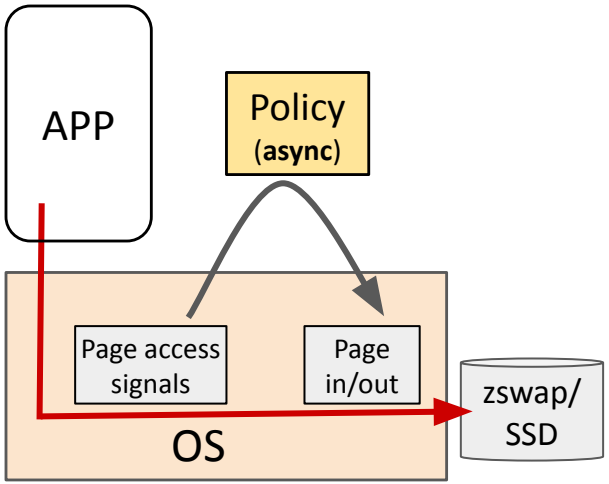

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   a. On-demand policy intact but rarely used
   b. Proactive offloading and Prefetching

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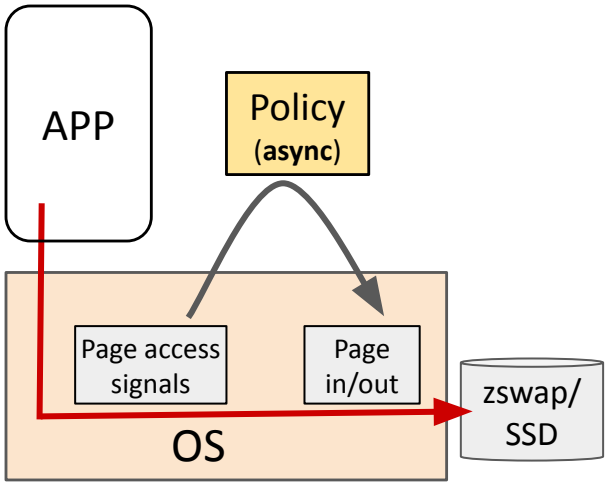

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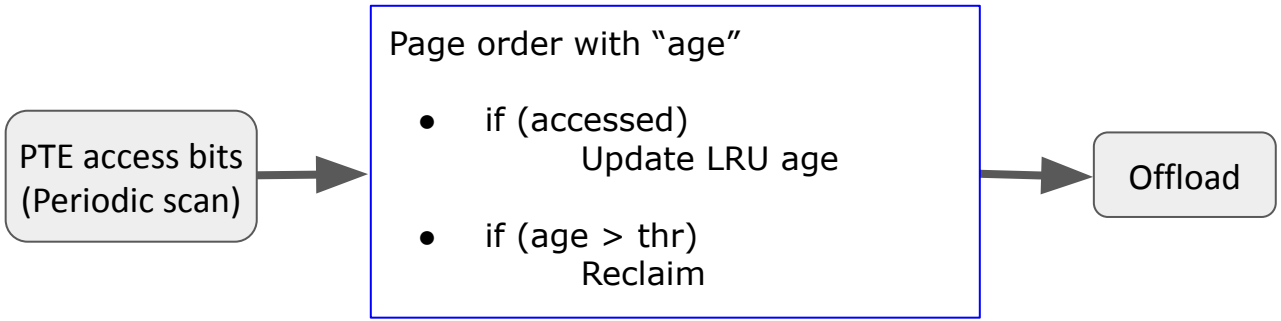
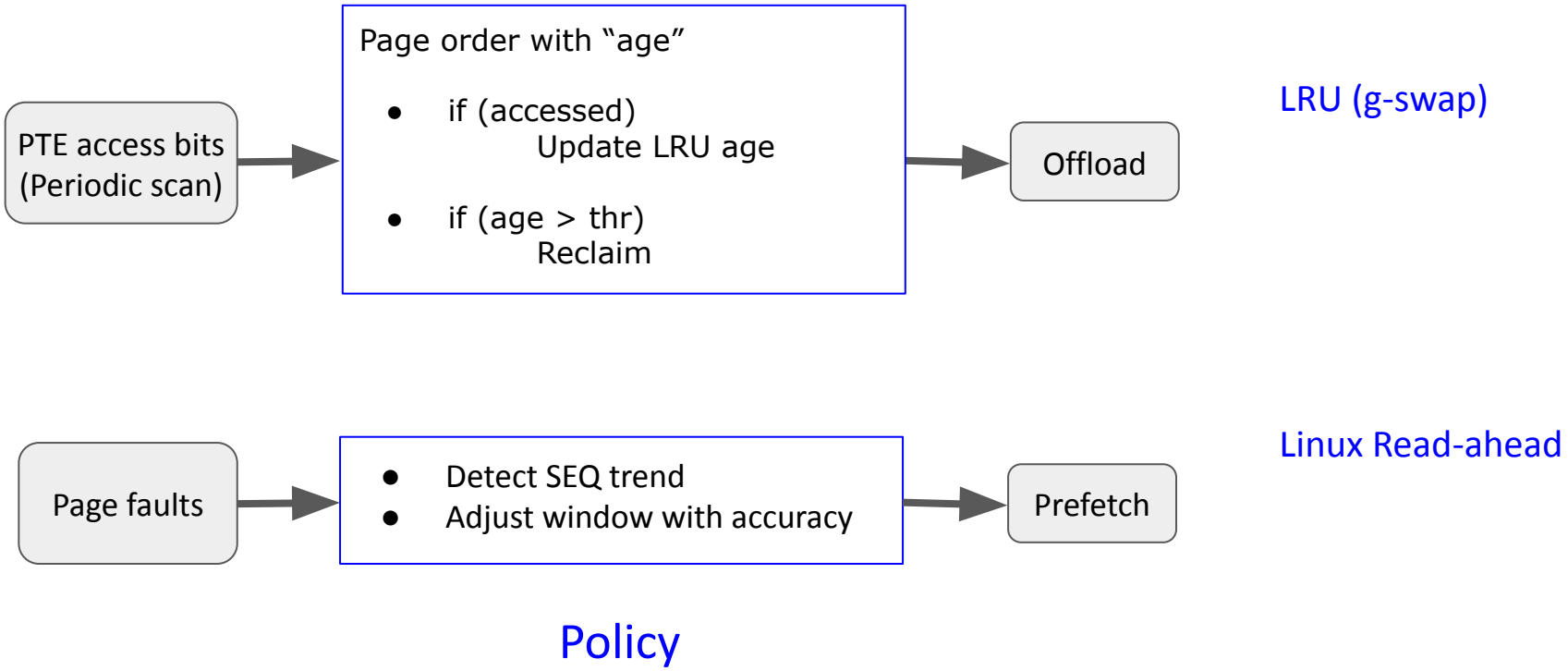
How current policies work



Policy

LRU (g-swap)

How current policies work



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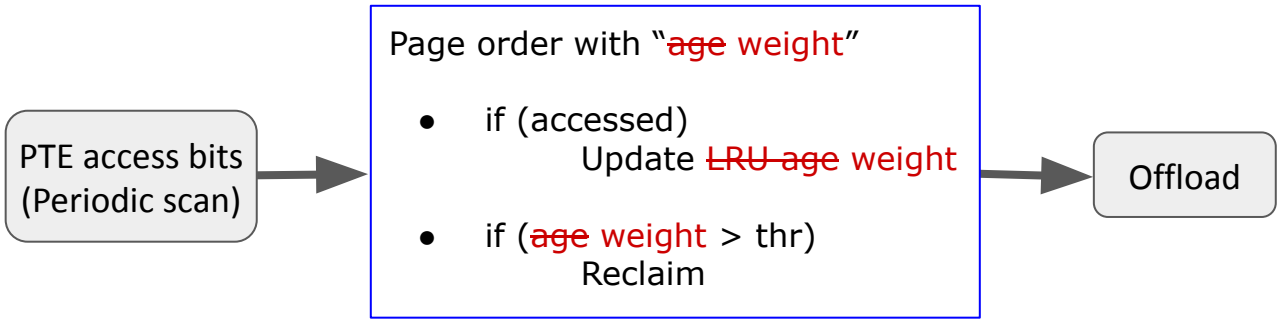
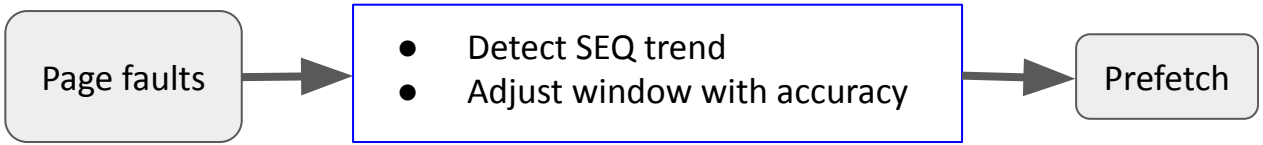


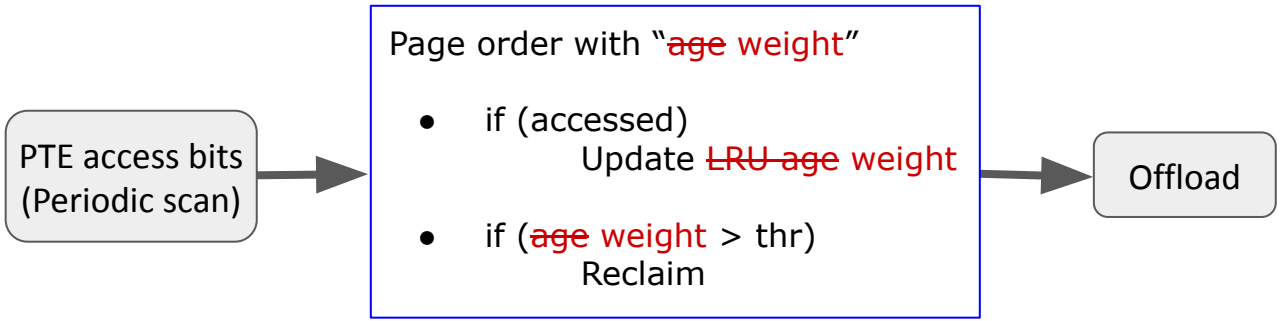
LRU (g-swap)
LFU
Hyperbolic [ATC '17]



Linux Read-ahead

Policy

How ~~current~~ most policies work



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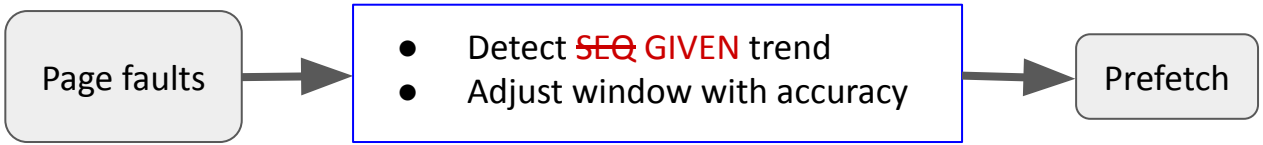
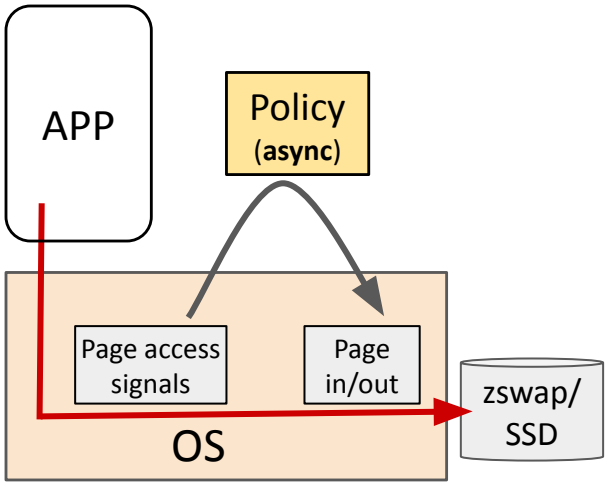


Linux Read-ahead
Leap [ATC '20]

Policy

Observation #2



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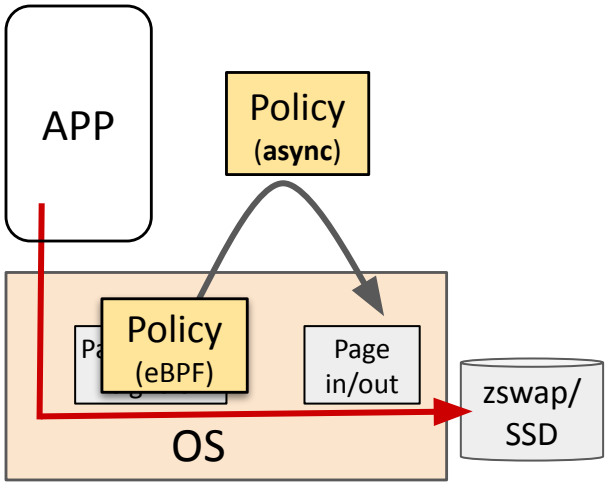

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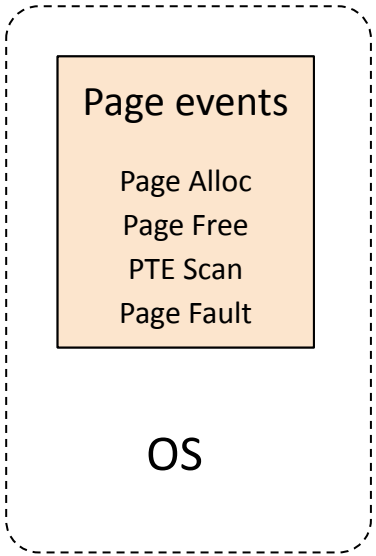
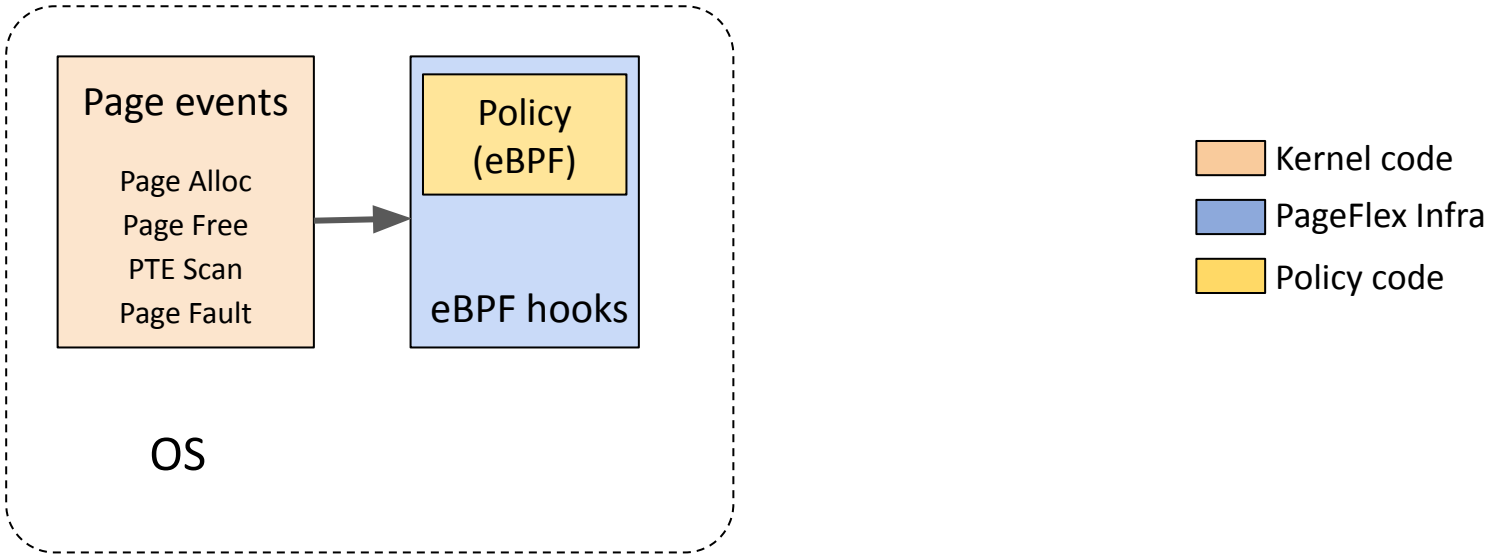
⟶ **Low-overhead customization with eBPF**

System overview



Kernel code

System overview



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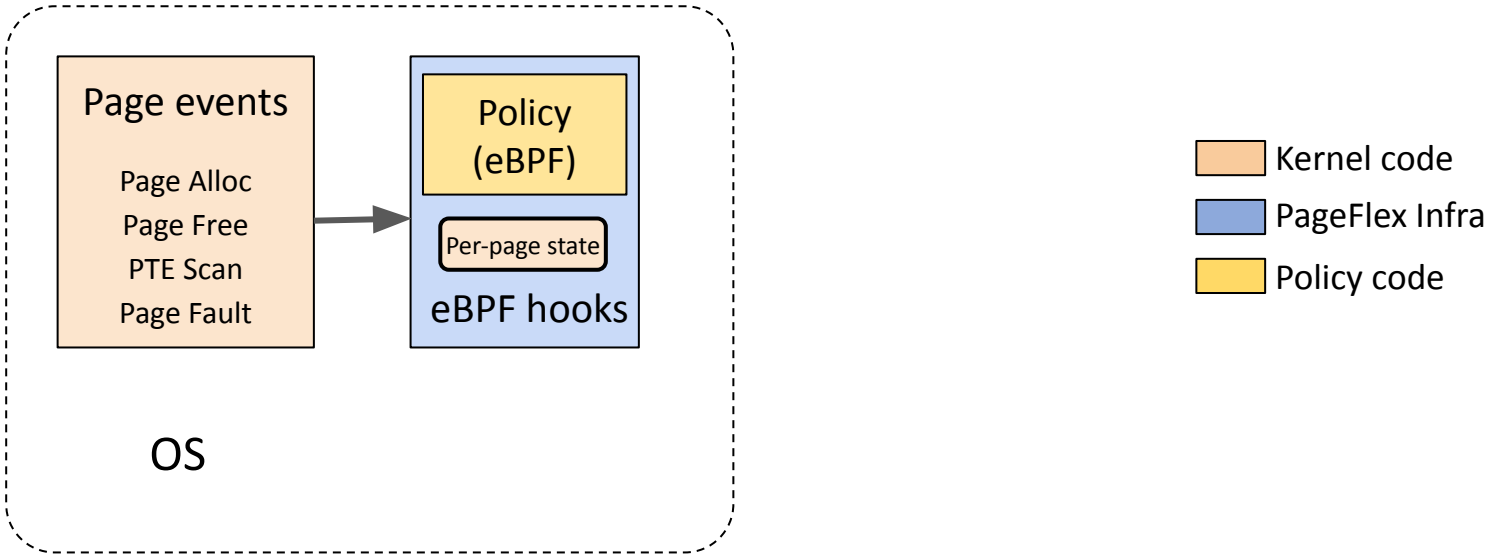

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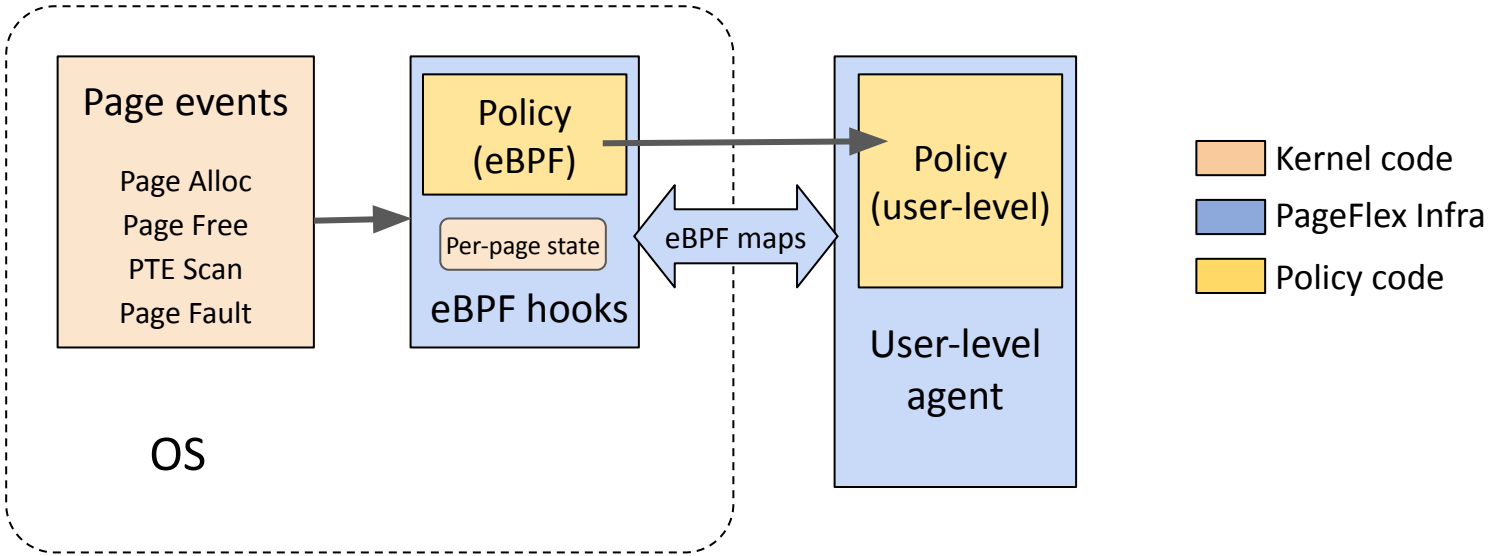

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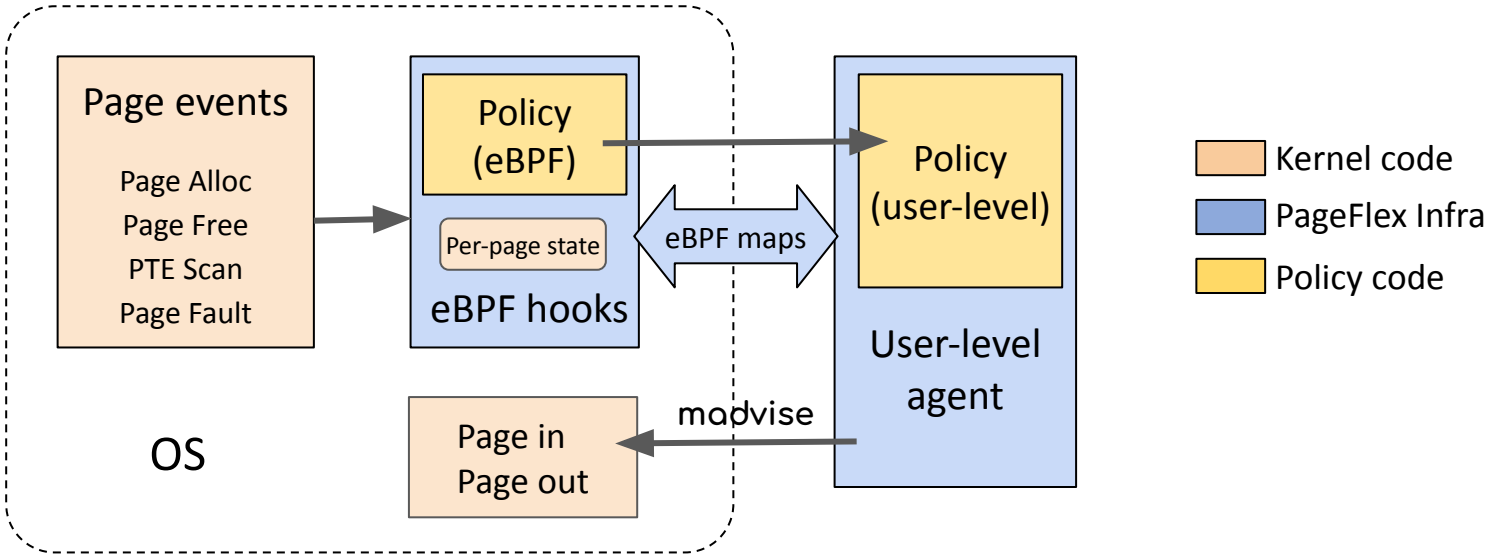
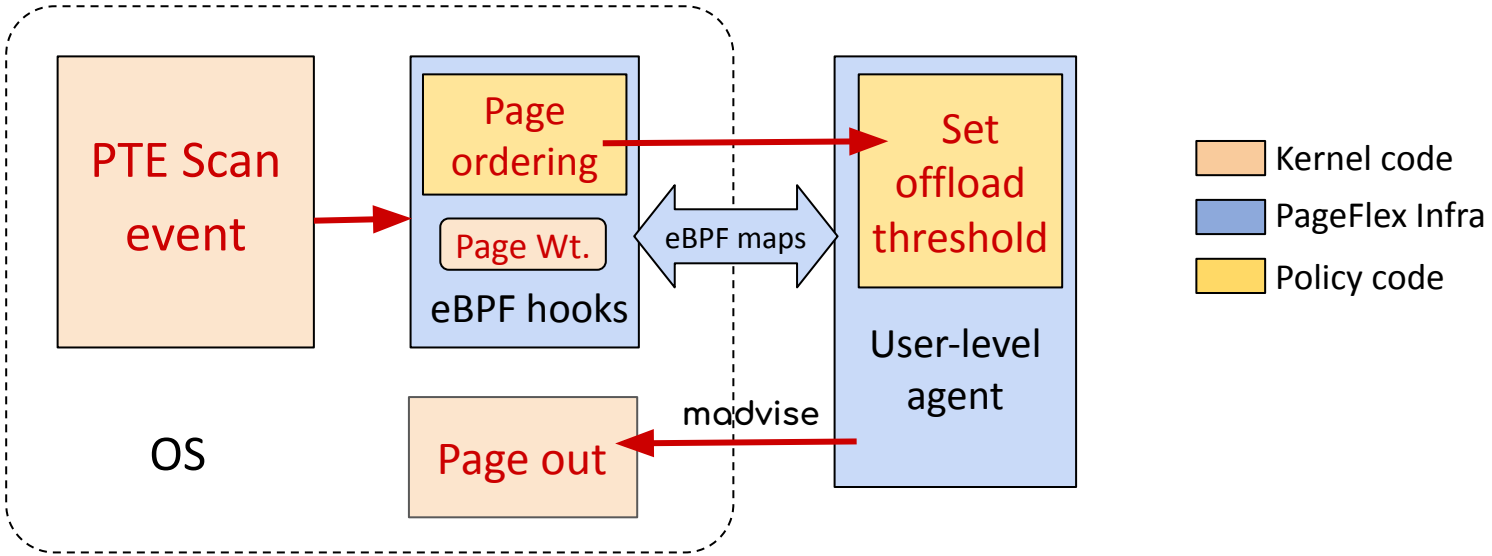


General data offload policy



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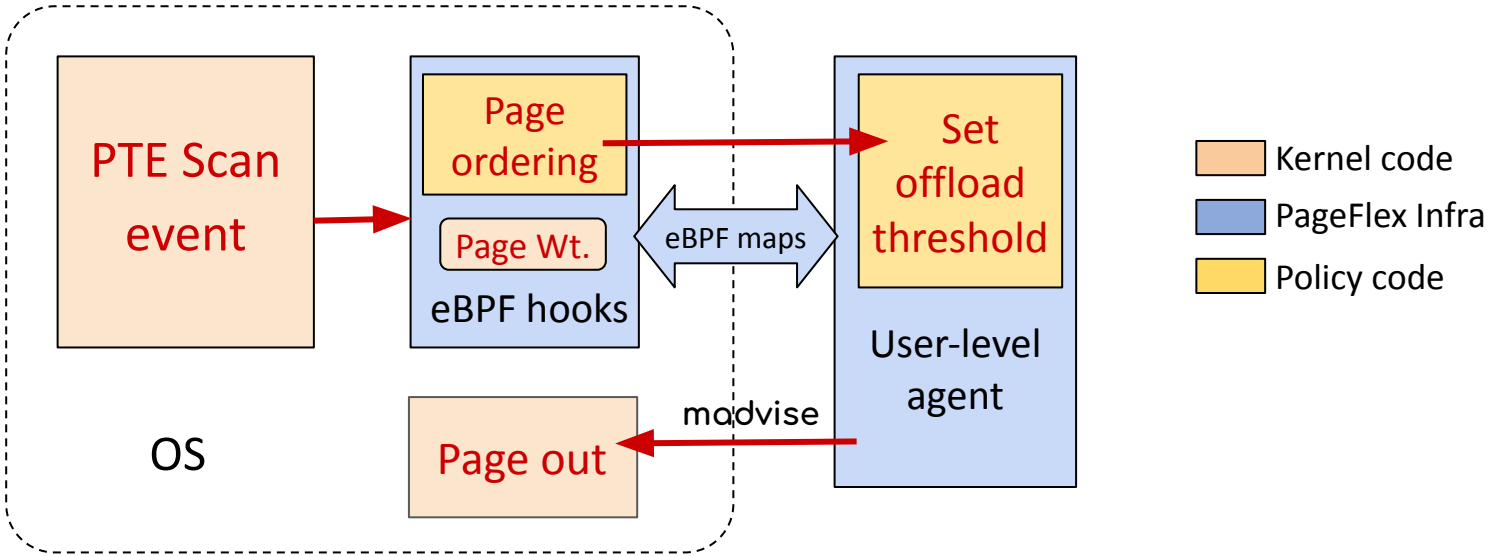
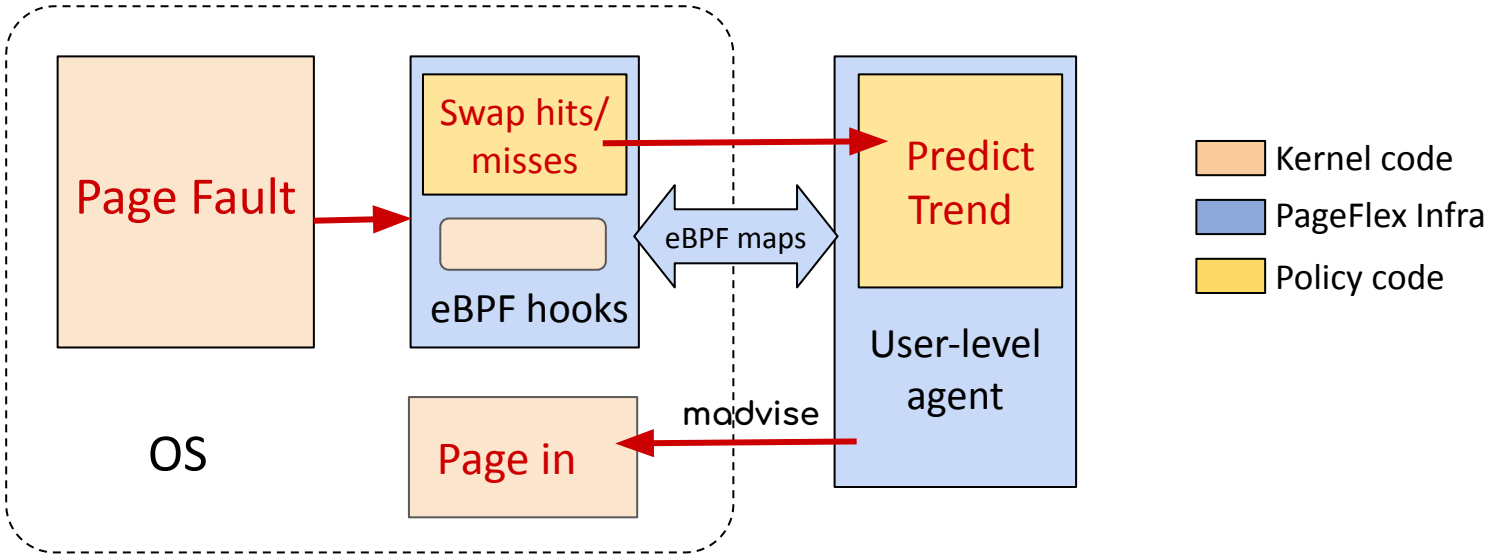


LRU, LFU, Hyperbolic [ATC'17] in ~10 lines

General prefetching policy



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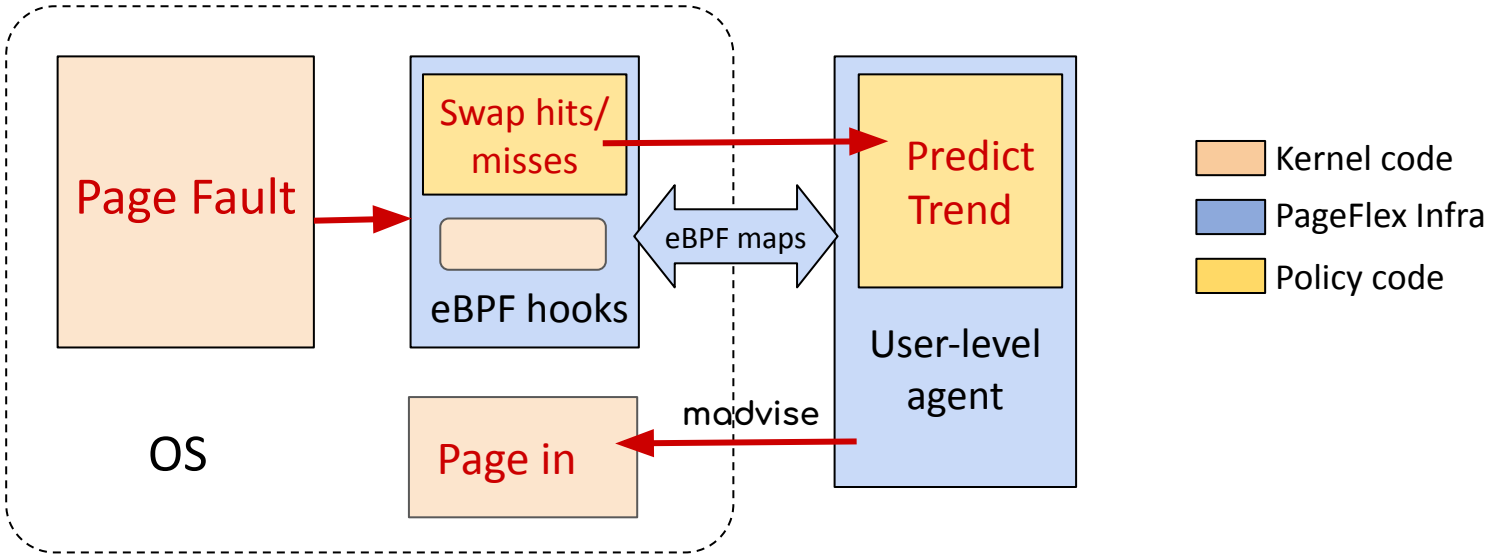
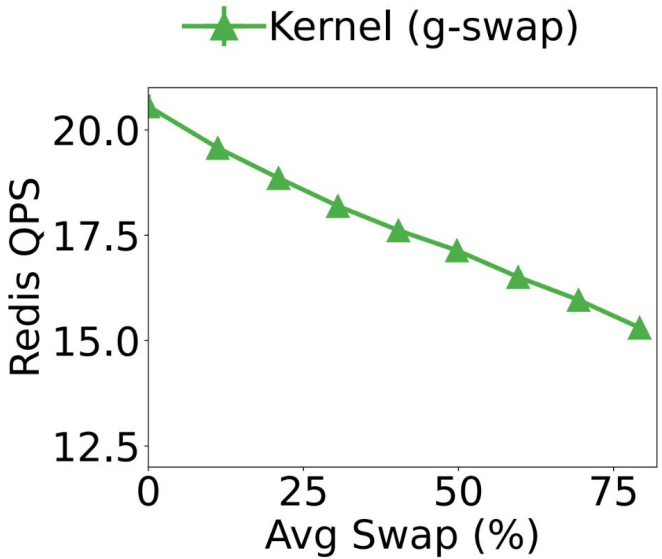
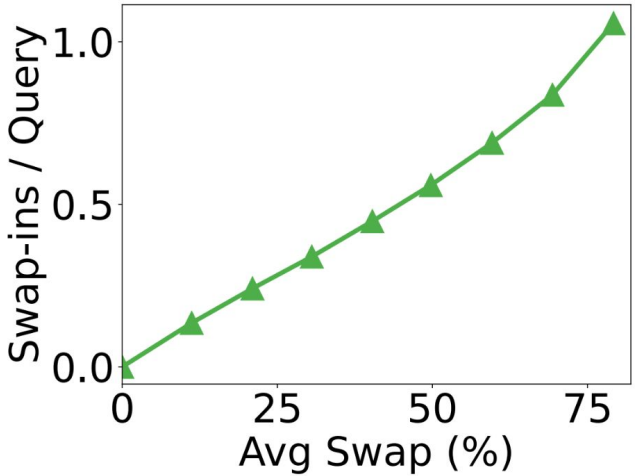


Leap [ATC '20] in ~180 lines (160 original)

Performance overhead (with LRU)





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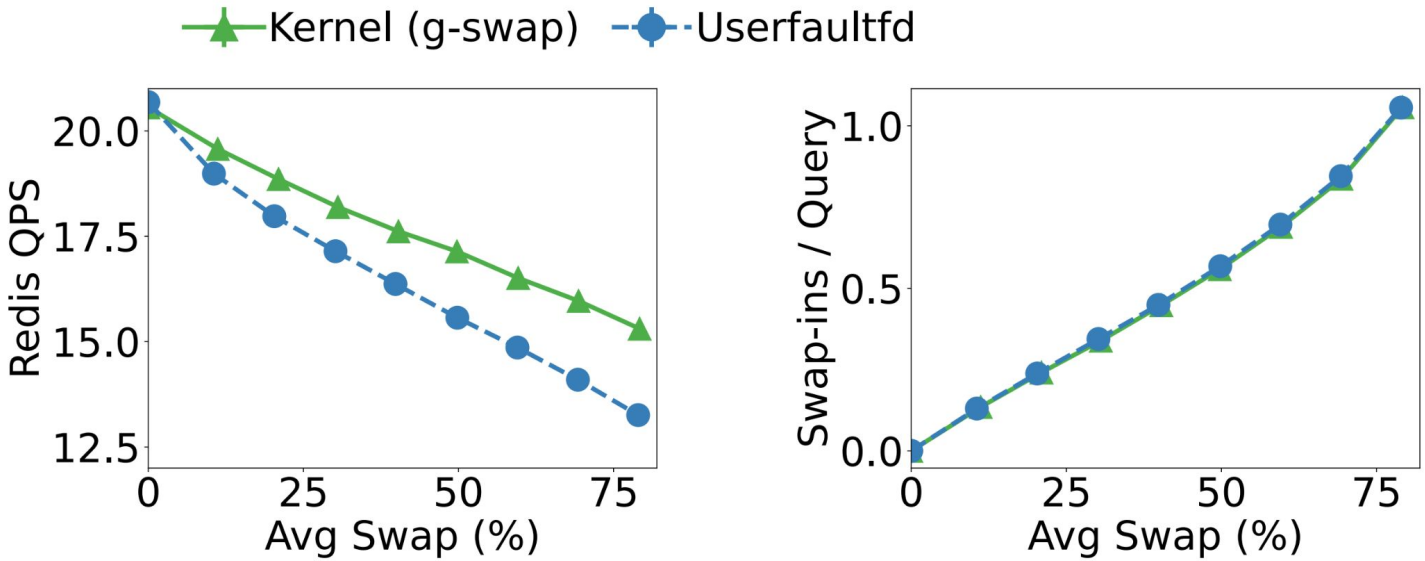

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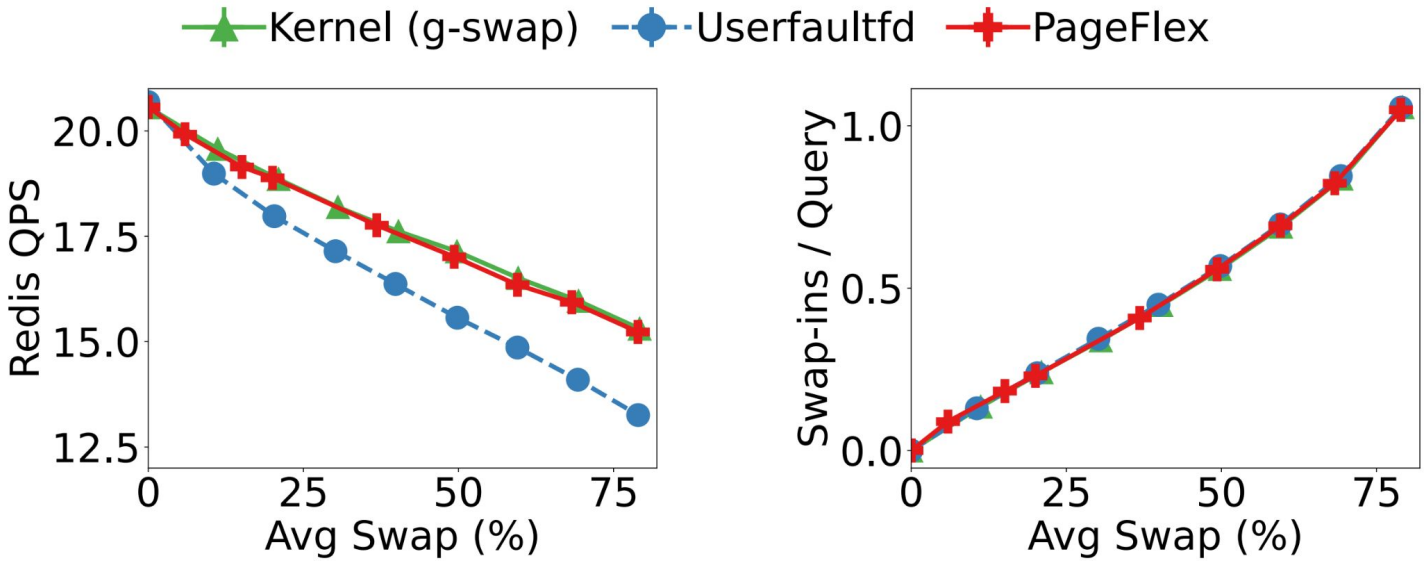

PageFlex adds very little (<1%) overhead!

Further policy specialization

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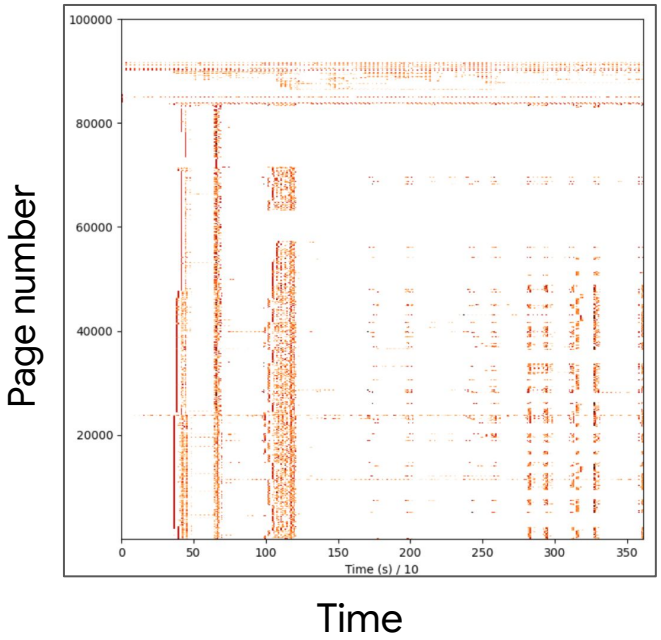
Key Idea:
Access patterns vary over space and time.



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Access patterns vary over space and time.
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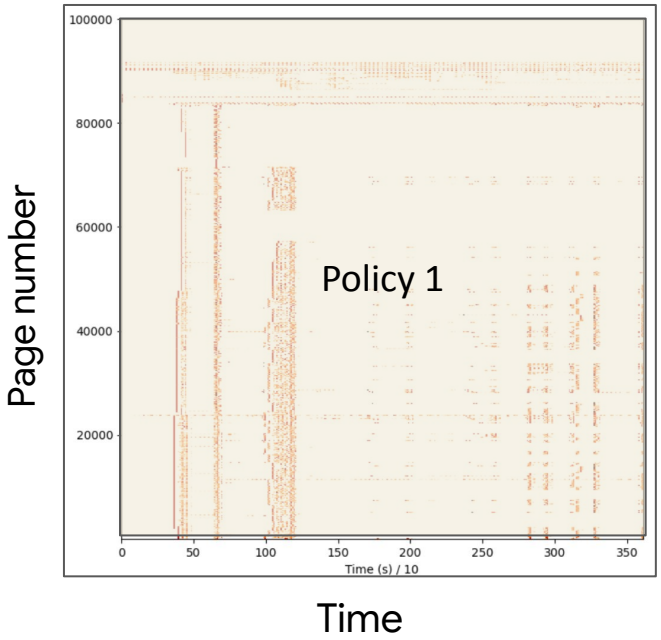

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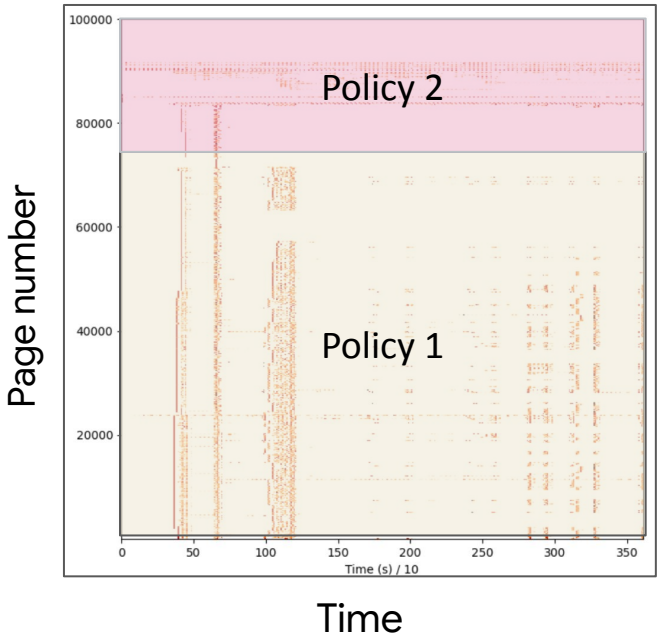
Examples:

- Region-aware:
  Single LRU threshold ⟶ Per-region threshold



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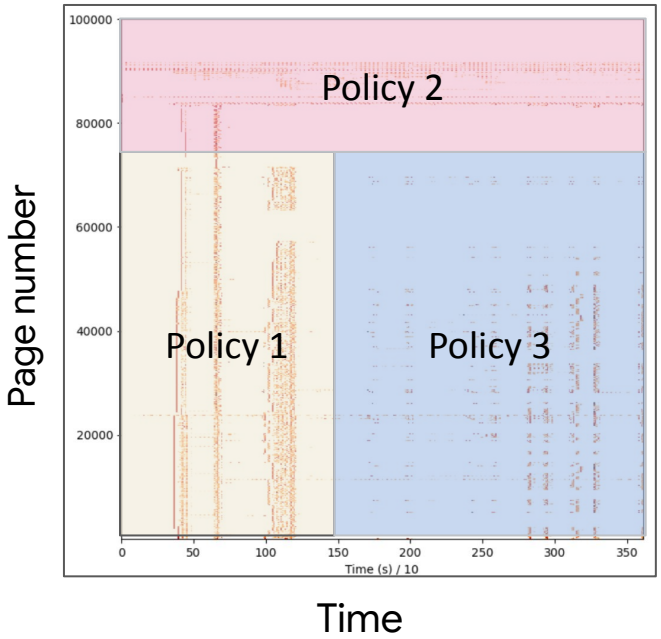
- Phase-aware:
  LRU always ⟶ Switch LRU/MRU



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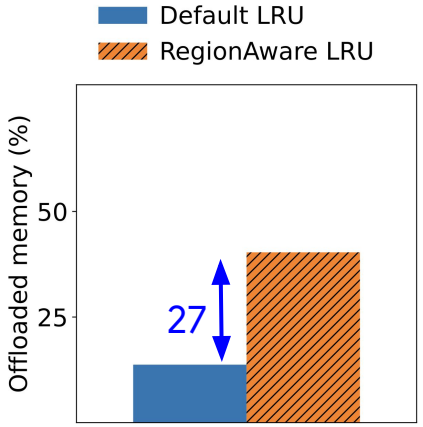
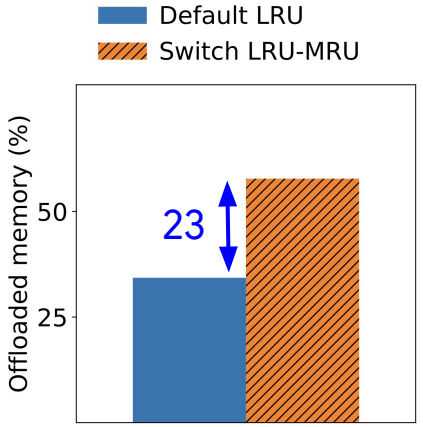
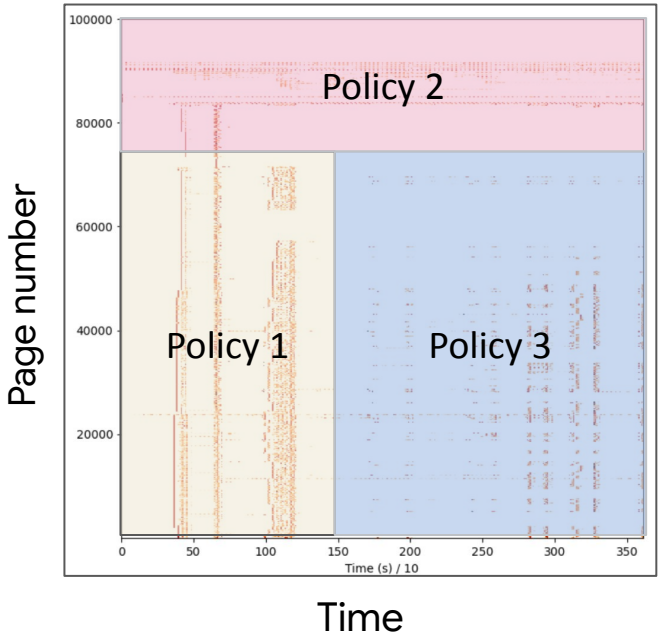




Conclusion

- Paging policies dictate memory savings
- OS-based policies are hard to evolve
- **PageFlex cleanly separates policy**
  - Fully-compatible (with existing deployments)
  - Low-overhead



Google

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