DAMON-based Pages Migration for {C,G,X}PU [un]attached NUMA nodes

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Device and Specific Purpose Memory MC

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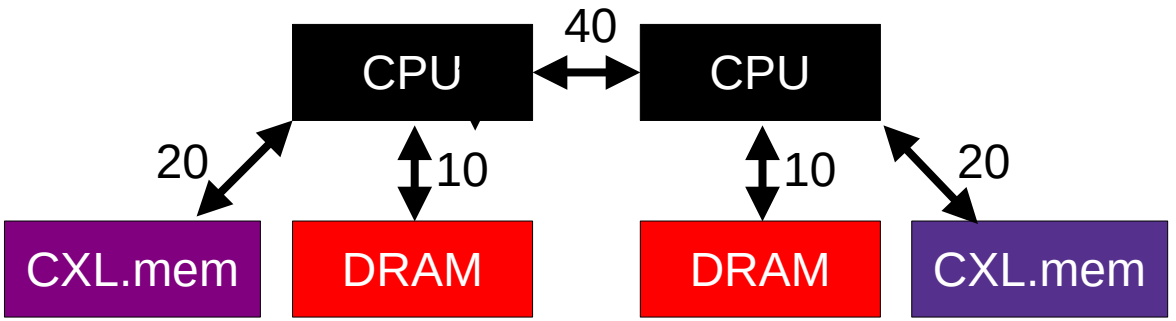
Background

NUMA for Dummies

- Access speed of memory depends on
  - Accessor (CPUs, GPUs, or ?PU),
  - Memory address, etc (e.g., compression rate)



Possible NUMA topology

	CPU1	CPU2
DRAM1	10	50
CXL.mem1	20	60
DRAM2	50	10
CXL.mem2	60	20

Relative access speed
from CPU to memory

DAMON in One Minute

- “Subsystem for efficient data access monitoring and access-aware operations”
- Inform monitored accesses
  - Location, Recency, frequency, stability
- DAMOS: Automate access-aware ops
  - e.g., reclaim cold memory

DAMON for Memory Tiering

SK Hynix: Capacity Expansion

- Migrate hot pages CXL → DRAM
- Migrate cold pages DRAM → CXL
- Hot/cold threshold: tuned for their case
- A part of SK Hynix HMSDK
- ~94% llama.cpp speedup

Meta: TPP-DAMON

- DAMON-based TPP idea implementation
- Auto-tune hot/cold thresholds for TPP goal
  - Put as many hot data as possible in upper tier
- ~4.42% Taobench score increase

Micron: Dynamic Interleaving

- Change interleaving weights in runtime
  - For dynamic access pattern changes
- ~25% benchmark speedup

And More

- Non-public success stories and WIP
- Academic researches

TPP-DAMON in More Details

- The idea is simple and scalable
  - Promote hot pages to the upper node, aiming high utilization of the upper node
  - Demote cold pages to lower node, aiming headroom free space of the node
- Applicable to N tiers

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_cold 1 --damos_access_rate 0% 0% \
        --damos_apply_interval 1s \
        --damos_quota_interval 1s --damos_quota_space 200MB \
        --damos_quota_goal node_mem_free_bp 0.5% 0 \
        --damos_filter reject young \
    --numa_node 1 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_hot 0 --damos_access_rate 5% max \
        --damos_apply_interval 1s \
        --damos_quota_interval 1s --damos_quota_space 200MB \
        --damos_quota_goal node_mem_used_bp 99.7% 0 \
        --damos_filter allow young \
        --damos_nr_quota_goals 1 1 --damos_nr_filters 1 1 \
    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --                    rvals_goal 4% 3 5ms 10s \
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        --damos_nr_quota_goals 1 1 --damos_nr_filters 1 1 \
    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

Start DAMON in kernel.

Dear DAMON user-space tool,

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_cold 1  -damos_access_rate 0% 0% \
        --                          1s \
        --                          1s                          200MB \
        --                          le_me
        --                                young
    --numa_node 1 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_hot 0 --damos_access_rate 5% max \
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        --damos_filter allow young \
        --damos_nr_quota_goals 1 1 --damos_nr_filters 1 1 \
    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

Create one DAMON worker thread, monitoring for node 0 (upper tier)

With auto-tuned monitoring intervals.

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_cold 1 --damos_access_rate 0% 0% \
        --damos_apply_interval 1s \
        --damos_q          interval 1s --damos_quota_space 200MB \
        -
        -
    --num                                                  5ms 10s \
        -                                                  s_rate 5% max \
        --damos_apply_interval 1s \
        --damos_quota_interval 1s --damos_quota_space 200MB \
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    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

And ask it to *migrate* un-accessed (access_rate *0%*) memory to node *1* (lower tier), *cold*est one first.
IOW, **demote** cold memory.

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --monitoring_intervals_goal 4% 3 5ms 10s \
       --damos_action migrate_cold 1 --damos_access_rate 0% 0% \
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    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

And do that once per second.

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_cold 1 --damos_access_rate 0% 0% \
        --damos_apply_interval 1s \
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        --damos_nr_quota_goals 1 1 --damos_nr_filters 1 1 \
    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

Within *one second*, do the migration only up to *200 MiB* of memory.

TPP-DAMON in More Details

```
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        --
        --
        --
        --damos_quota_goal node_mem_used_bp 99.7% 0 \
        --damos_filter allow young \
        --damos_nr_quota_goals 1 1 --damos_nr_filters 1 1 \
    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

Under the 200MiB/1s hard limitation, auto-tune the real soft limitation to make node 0's free memory ratio becomes 0.5% soon.

TPP-DAMON in More Details

```
damo start \
    --numa_node 0 --monitoring_intervals_goal 4% 3 5ms 10s \
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        --
        --
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        --damos_nr_quota_goals 1 1 --damos_nr_filters 1 1 \
    --nr_targets 1 1 --nr_schemes 1 1 --nr_ctxs 1 1
```

Btw, if the page is PG_Young, don't do the migration.
DAMON might identify young page as not accessed.

TP

Create another DAMON worker thread that monitors *node 1* (lower tier) with auto-tuned monitoring intervals.
Ask it to migrate memory shown *>=5%* access rate to *node 0* (upper tier), *hot*test first. IOW, **promote** hot pages.
Do the migration once per second, up to 200 MiB of memory.
Under the *200 MiB/s* hard limit, adjust the real soft limit aiming *node 0* memory utilization ratio *99.7%*.
Btw, to that only if the page is PG_*Young*.

```
damo
    -
                                                                  % \
        --damos_                    node_mem_free_bp 0.5% 0 \
        --damos_filter reject young \
    --numa_node 1 --monitoring_intervals_goal 4% 3 5ms 10s \
        --damos_action migrate_hot 0 --damos_access_rate 5% max \
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```

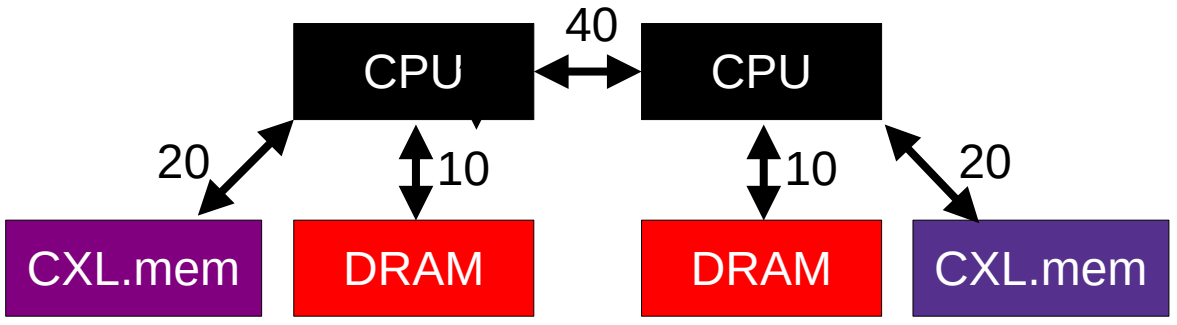
DAMON for Holistic NUMA Page Migration

Idea is Simple

- Tiering: special case NUMA management
  - All CPU [un]attached nodes
  - Single promotion/demotion path
- General NUMA: N Accessors
  - CPU, GPU, *PU
  - N promotion/demotion paths
  - Idea: run accessor-aware TPP for each path

Idea in Example

- TPP1 migrate CPU1-hot/cold memory
  - On DRAM1 → CXL.mem1 → DRAM2 → CXL.mem2 hierarchy
- TPP2 migrate CPU2-hot/cold memory
  - On DRAM2 → CXL.mem2 → DRAM1 → CXL.mem1 hierarchy



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Relative access speed
from CPU to memory

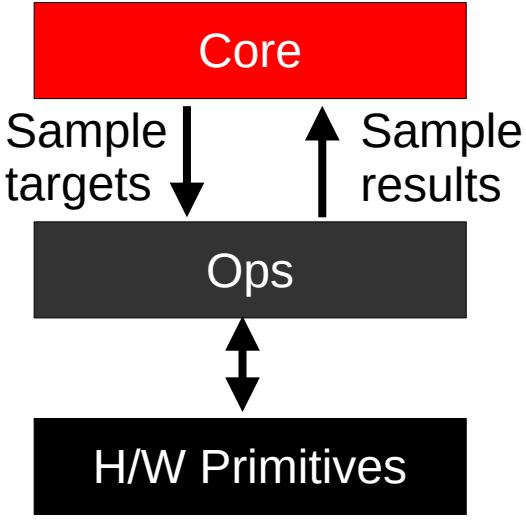
Can DAMON Do That for Me?

- No, since it cannot do per-CPU monitoring
- DAMON is willing to do that in future

Required DAMON Changes for Holistic NUMA Page Migration (Or, per-CPUs Monitoring)

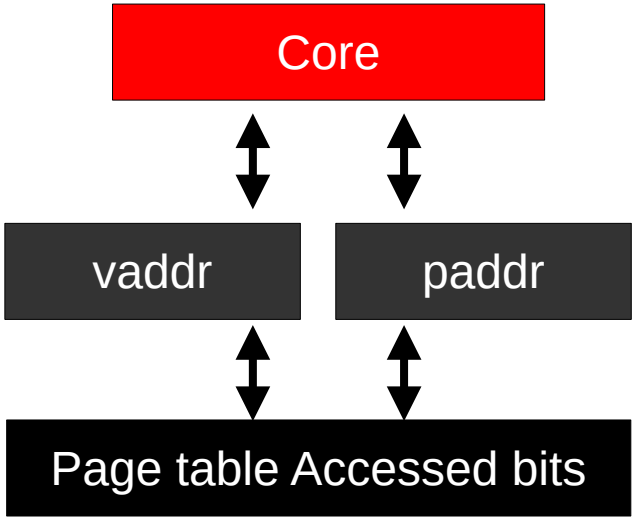
DAMON Core and Ops Layers

- Core: For pure software logic
  - Adaptively find pages to check access for
  - Assemble small samples to accurate pattern
- Ops: For h/w specific primitives
  - Check if core-specified samples got accessed
  - Using their favorite primitives
  - DAMON callers can implement their own ops



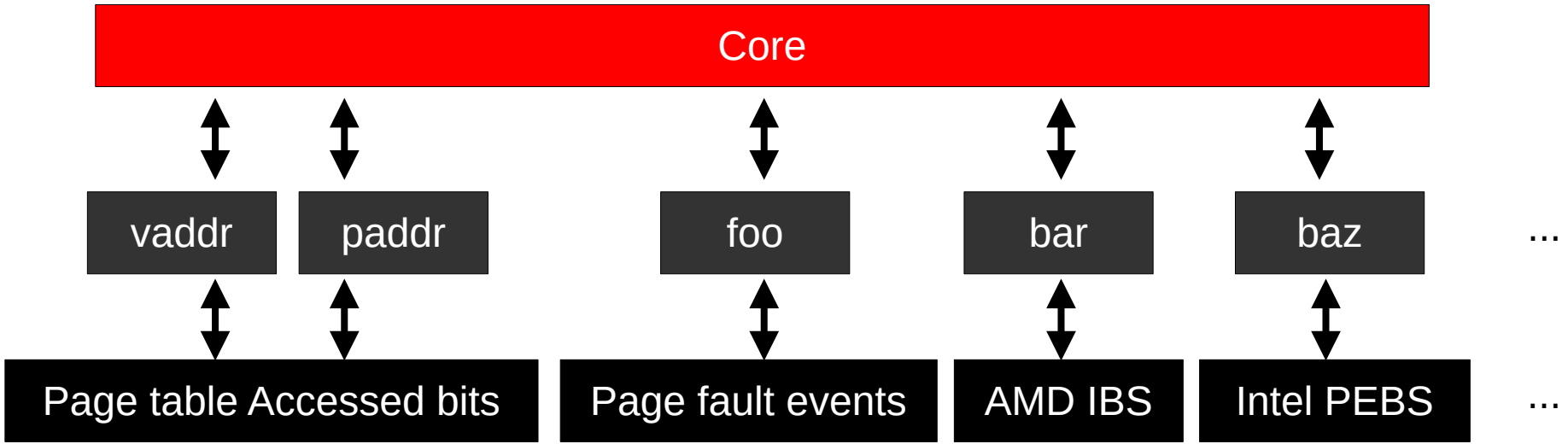
Existing DAMON Op Impls

- ‘vaddr’ and ‘paddr’
  - For virtual/physical address spaces monitoring
  - Both use page table Accessed bits
    - Lacks accessor CPU info



How Can We Make It?

- Add new ops for appropriate primitives
  - e.g., Page fault events or instruction sampling



Can It Be Upstreamed?

- New op: good for PoC but Maintenance
- Too many ops having duplications
- Upstream-aimed work in progress

damon_report_access()

- Let any kernel components
  (e.g., page fault handler, GPU driver, etc)
  report their observed access information
  to DAMON core
  with single function call

DAMON Sample Control

- API/ABI for setup of primitives to use
- API/ABI for filtering sampling results based on additional info

```
# damo start --sample_primitives page_fault \
             --sample_filter allow cpu 0-4 \
             --sample_filter allow threads 777,888,999 \
             --sample_filter reject write
```

Progress

- Per-CPUs/threads/read/write patchset
  - RFC v3 is posted

TODO

- Upstream per-CPUs monitoring
- Test damo-based holistic NUMA migration
- Add simple-interface kernel module (say, DAMON_NUMA_MIGRATE)

Challenges

- Page fault handling part change
  - Need alignment between stakeholders
    - NUMA balancing
    - Page fault handling
    - DAMON
  - Aim to make progress by LSFMMBPF’26

Wrapup

- DAMON was useful for specific NUMA case
  - Memory tiering
- TPP-DAMON can be extended
  - For holistic NUMA cases
- Works in progress, challenges exist

Discussion Time!

- Feel free to continue after this session on
  - Hallway
  - Mailing lists
  - DAMON Beer/Coffee/Tea chats
  - sj@kernel.org