LINUX STORAGE | FILESYSTEM | MM & BPF SUMMIT

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#LSFMMBPF

DAMON Updates and Future Plans:

Automation of DAMON tuning, tiering, and VM guest scaling

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https://damonitor.github.io

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  they do not reflect the views of his employers
- Slides are available at https://github.com/damonitor/talks or below QR code

QR code is generated by https://qr.io/

From: SeongJae Park <sj@kernel.org>

- Just call me “SJ” (easier to be consistently pronounced)
- Kernel Development Engineer at AWS
- Interested in the memory management and the parallel programming
- Maintaining DAMON (`mm/damon/`)

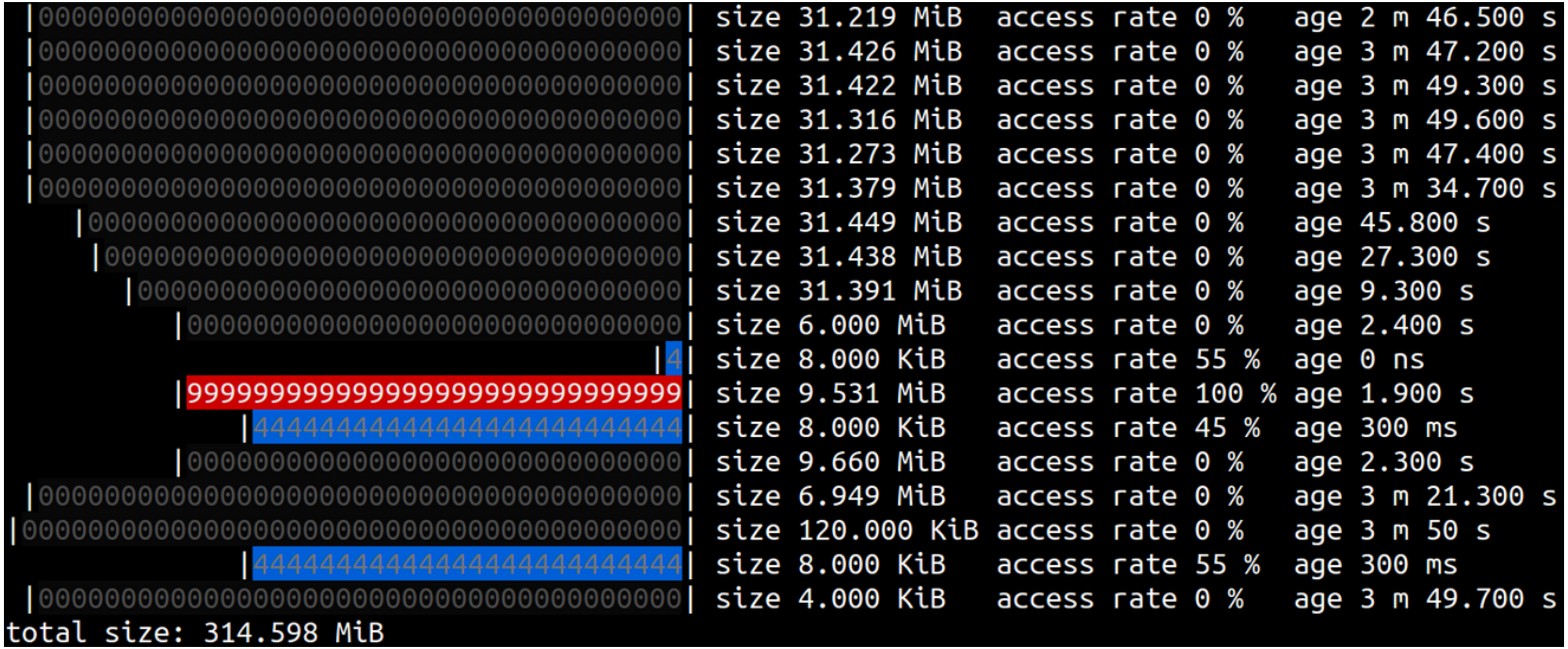
Overview

- DAMON in a Nutshell (2 min)
- Updates since LSFMM+BPF 2023 (5 mins)
  - Misc Things: Documentation, selftests, filters
  - DAMOS Auto-tuning
- Major Future Plans
  - Tiered Memory Management (5 mins)
  - Access/Contiguity-aware Memory Auto-scaling (5 mins)
  - Misc Things: LRU_SORT auto-tuning, THP, monitoring improvement (3 mins)
- Discussions (10 mins)

DAMON in a Nutshell

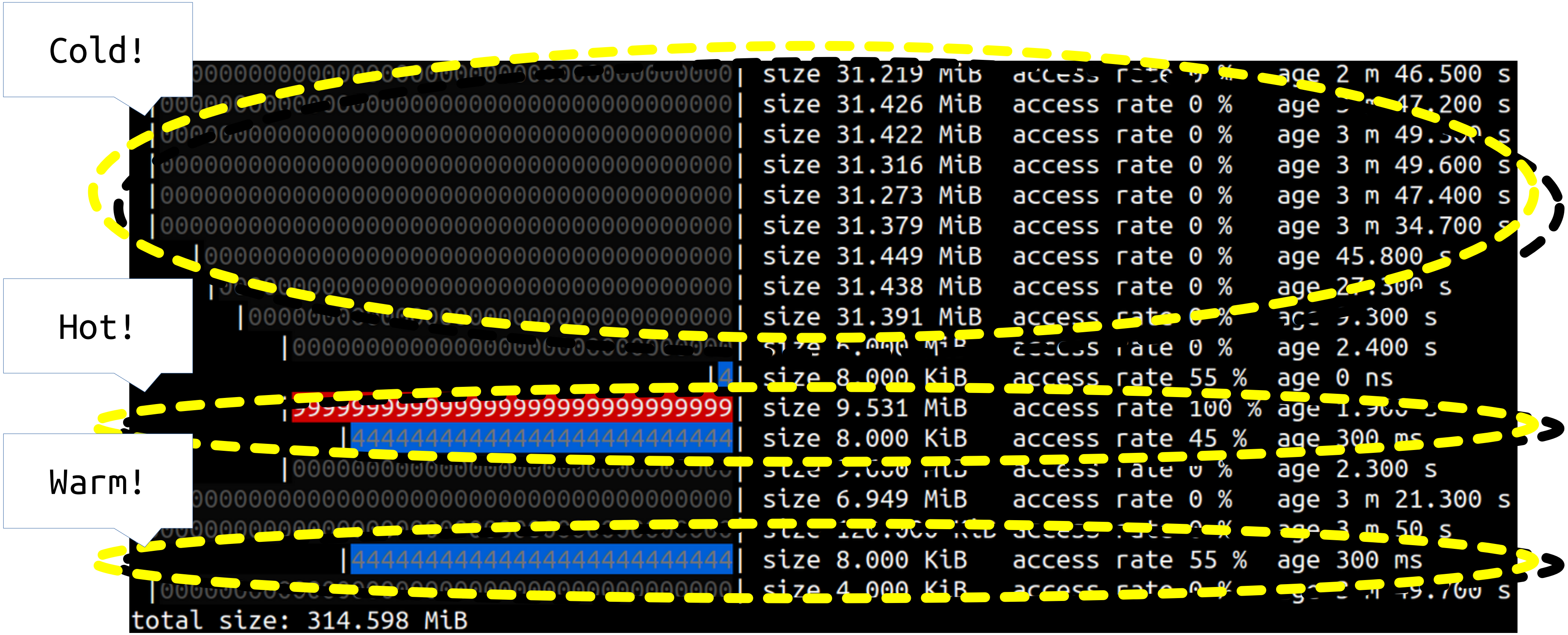
DAMON: Access Pattern Snapshot Generator

- Let user knows which *address range* is how *frequently* accessed for how *long* time



```
 |000000000000000000000000000000000000000| size 31.219 MiB  access rate 0 %   age 2 m 46.500 s
 |000000000000000000000000000000000000000| size 31.426 MiB  access rate 0 %   age 3 m 47.200 s
 |000000000000000000000000000000000000000| size 31.422 MiB  access rate 0 %   age 3 m 49.300 s
 |000000000000000000000000000000000000000| size 31.316 MiB  access rate 0 %   age 3 m 49.600 s
 |000000000000000000000000000000000000000| size 31.273 MiB  access rate 0 %   age 3 m 47.400 s
 |000000000000000000000000000000000000000| size 31.379 MiB  access rate 0 %   age 3 m 34.700 s
    |000000000000000000000000000000000000| size 31.449 MiB  access rate 0 %   age 45.800 s
     |00000000000000000000000000000000000| size 31.438 MiB  access rate 0 %   age 27.300 s
       |000000000000000000000000000000000| size 31.391 MiB  access rate 0 %   age 9.300 s
          |000000000000000000000000000000| size 6.000 MiB   access rate 0 %   age 2.400 s
                                       |4| size 8.000 KiB   access rate 55 %  age 0 ns
          |999999999999999999999999999999| size 9.531 MiB   access rate 100 % age 1.900 s
              |44444444444444444444444444| size 8.000 KiB   access rate 45 %  age 300 ms
          |000000000000000000000000000000| size 9.660 MiB   access rate 0 %   age 2.300 s
 |000000000000000000000000000000000000000| size 6.949 MiB   access rate 0 %   age 3 m 21.300 s
|0000000000000000000000000000000000000000| size 120.000 KiB access rate 0 %   age 3 m 50 s
              |44444444444444444444444444| size 8.000 KiB   access rate 55 %  age 300 ms
 |000000000000000000000000000000000000000| size 4.000 KiB   access rate 0 %   age 3 m 49.700 s
total size: 314.598 MiB
```

DAMON: Access Pattern Snapshot Generator



Cold!

Hot!

Warm!

```
     0000000000000000000000000000000000000| size 31.219 MiB   access rate 0 %   age 2 m 46.500 s
  |000000000000000000000000000000000000000| size 31.426 MiB   access rate 0 %   age 3 m 47.200 s
  |000000000000000000000000000000000000000| size 31.422 MiB   access rate 0 %   age 3 m 49.300 s
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  |000000000000000000000000000000000000000| size 4.000 KiB    access rate 0 %   age 3 m 49.700 s
total size: 314.598 MiB
```
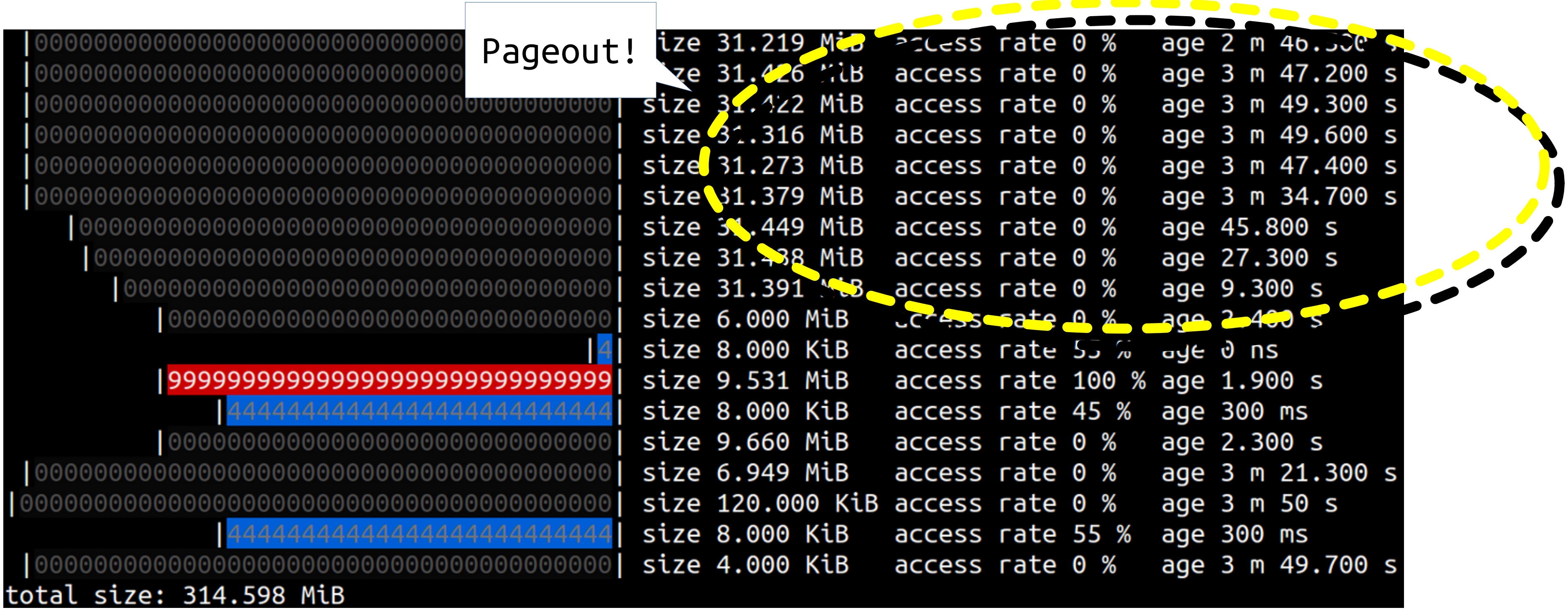

DAMOS: DAMON-based Operation Scheme

- Apply memory operation actions to regions of interesting access pattern

```
# # pageout memory regions that not accessed for >=5 seconds
# damo start --damos_action pageout --damos_access_rate 0% 0% --damos_age 5s max
```



Pageout!

```
 |000000000000000000000000000000000000000| size 31.219 MiB  access rate 0 %   age 2 m 46.500 s
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```

Features for Augmenting DAMOS Control

- Quotas: set aggressiveness of DAMOS
  - e.g., pageout cold pages up to 100 MiB per second (coldest 100 MiB pages)
- Filters: define target regions with non-access-pattern information
  - e.g., pageout cold pages of NUMA node 1 that associated with cgroup A and file-backed

DAMON Usages, To Maintainer’s Best Knowledge

- Products
  - Proactive memory reclaim on memory overcommit systems
  - CXL-based tiered memory management software development kit
- Researches
- Memory events reproducer
- DAMON is backported/enabled on multiple Distros
  - Amazon Linux (>=5.4), Android (>=5.10), CentOS (>=4.18), Fedora (>=6.2), UEK (>=5.15)
- User-space tool is packaged for multiple Distros
  - AUR, Debian, EPEL, Fedora, Kali, Raspian, Ubuntu

Communication Channels

- DAMON-dedicated open mailing list
- Bi-weekly community meetup series
- Presenting DAMON in conferences
  - LSFMM and Kernel Summit for discussion
  - OSSummit NA/EU for presentation
- Occasional/regular private meetings on demand
- Put your voice on the random evolution path of DAMON for your selfish purpose

DAMON Updates

DAMON Updates Since LSFMM 2023

- Documentation improvements
  - Motivated by last LSFMM comments
  - Design doc is nearly re-written to cover every DAMON features
- Selftest improvements
  - Motivated by last LSFMM comments on DAMON user-space tool inclusion in-tree merge plan
- New filter types
  - “address ranges” and “monitoring target” (e.g., for NUMA nodes and/or processes)
  - “young pages” (page-granular access double-check)
- Fast snapshot generation (once per sampling interval)
- DAMOS aggressiveness auto-tuning (user-input or self feedback-loop)
  - Memory PSI self feedback is supported

DAMON Future Plans

DAMOS Auto-tuning Based Tiered Memory Management

https://lore.kernel.org/damon/20231112195602.61525-1-sj@kernel.org/

Existing DAMOS-based Tiered Memory Management Approaches

- Tiered memory demotion (Alibaba)
  - Patchset is available (not yet merged; no updates for last 2 years)
- Two-tier memory promotion/demotion (HMSDK v2, SK hynix)
  - Patchset is available (actively working)
  - Motivated ‘young page’ type DAMOS filter
- MTM: Multi-Tiered Memory Management (Jie Ren et al., Eurosys’24)
  - Proposing monitoring improvement and fast migration node decision
- Patches leave policy to users
  - HMSDK v2 open-source the policy

DAMOS-based Tiered Memory Management Policy Proposal

- For each CPU-independent NUMA node,
  - If the node has a lower node,
    - Demote cold pages of the current node to the lower node,
      aiming little fraction (e.g. 5%) of free memory of the current node
  - If the node has a upper node,
    - Promote hot pages of the current node to the upper node,
      aiming big fraction (e.g., 96%) of used memory of the _upper_ node

```
node 0 (fast)  No lower node, do nothing
```

DAMOS-based Tiered Memory Management Policy Proposal

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  - If the node has a lower node,
    - Demote cold pages of the current node to the lower node,
      aiming little fraction (e.g. 5%) of free memory of the current node
  - If the node has a upper node,
    - Promote hot pages of the current node to the upper node,
      aiming big fraction (e.g., 96%) of used memory of the _upper_ node

```
node 0 (fast)  Demote cold pages in node 0 aiming 5% free memory of node 0
node 1 (slow)  Promote hot pages in node 1 aiming 96% used memory of node 0
```

DAMOS-based Tiered Memory Management Policy Proposal

- For each CPU-independent NUMA node,
  - If the node has a lower node,
    - Demote cold pages of the current node to the lower node,
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```
node 0 (fast)  Demote cold pages in node 0 aiming 5% free memory of node 0
node 1 (slow)  Promote hot pages in node 1 aiming 96% used memory of node 0
               Demote cold pages in node 1 aiming 5% free memory of node 1
node 2 (slowoo)Promote hot pages in node 2 aiming 96% used memory of node 1
```

Expectations, or Hopes

- High utilization of upper nodes, with more frequently accessed pages
- Low utilization of lower nodes, with less frequently accessed pages
- Keep slow but continuous promotion/demotion
  - Overlapping memory util/free goals
- Easy to be extended for multiple tiers

Progress

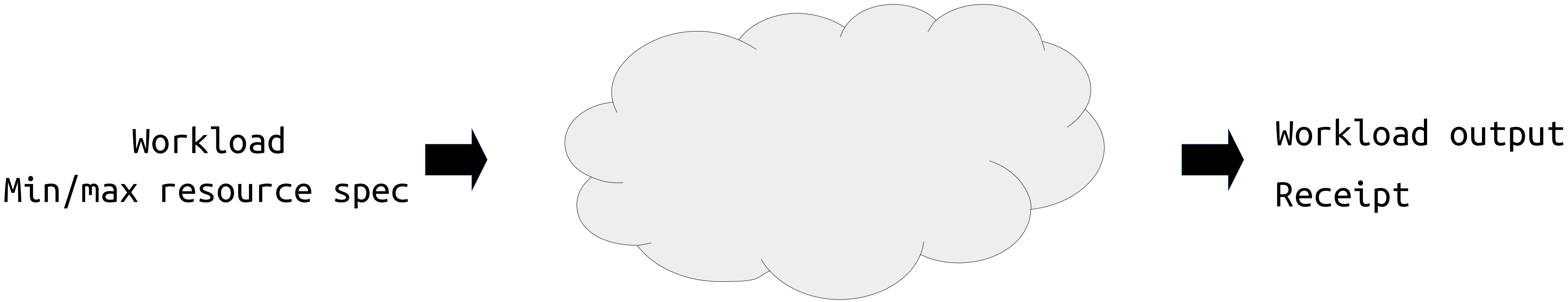
- No implementation at all
- Detailed RFC idea is sent to the mailing list

Access/Contiguity-aware Memory Auto-scaling (ACMA)

https://lore.kernel.org/damon/20231112195114.61474-1-sj@kernel.org/

Motive Business Model

- User request workload with min/max memory for the workload
- Service Provider runs it on their resource, and charges as the workload consumed
  - Estimate real memory demand and auto-scale the machine (over-commit memory)
  - For high performance and low price



Workload
Min/max resource spec

Workload output
Receipt

An Existing Approach: Orchestration of Four Kernel Features

- Collaborative overcommit (Free pages reporting)
- DAMON_RECLAIM for reporting more pages without performance degradation
- Periodic compaction for reporting level contiguity
- Memory hot-[un]plugging for hard limit and ‘struct page’ reduction
- Works well in real world

Limitations

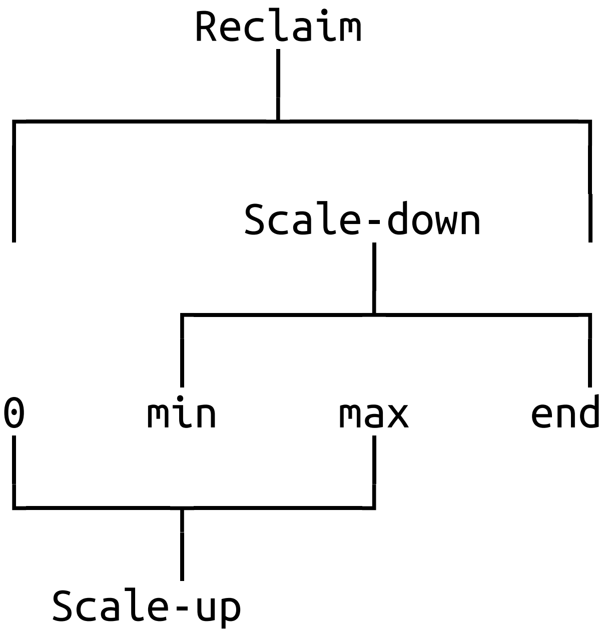
- Complexity of user-space driven multiple kernel features orchestration
- Memory hot-unplugging is slow and easy to fail
  - Due to coarse granularity and access obliviousness
- System-level compaction is wasteful and access oblivious
- Lack of after-report pages control
  - Any reported pages can be claimed again at any time
- Lack of non-collaborative guests control

DAMOS Actions for Access-aware Contiguous Memory Allocation

- `DAMOS_ALLOC`
  - Allocate given memory region with user-specified minimum contiguity
  - Notify (callback) the allocation to the user
  - “Repeatedly try to allocate cold memory regions, 2 MiB contig-regions at once”
- `DAMOS_FREE`
  - De-allocate the region with user-specified minimum contiguity

Access/Contiguity-aware Memory Auto-Scaling

- DAMON kernel module utilizing three DAMOS schemes
- Parameters: min-mem, max-mem, acceptable memory PSI
- Reclaim: Reclaim memory aiming “psi”
- Scale-down: ALLOC/report [min-mem, max) mem aiming “psi”
  - Auto-tune aggressiveness for higher PSI
  - Highest non-fully-DAMOS_ALLOC-ed memory block only
  - Apply ‘struct page’ reduction in some level (like HVO)
- Scale-up: FREE [0, max-mem) mem aiming “psi”
  - Auto-tune aggressiveness for lower PSI
  - Lowest partial-DAMOS_ALLOC-ed memory block only



ACMA-Ballooning

- Let virtio-balloon to adjust ACMA’s max-mem parameter
- Host-driven Access/contiguity-aware ballooning: Control non-collaborative guests

```
diff --git a/drivers/virtio/virtio_balloon.c b/drivers/virtio/virtio_balloon.c
[...]
@@ -472,6 +472,32 @@ static void virtballoon_changed(struct virtio_device *vdev)
        struct virtio_balloon *vb = vdev->priv;
        unsigned long flags;

+#ifdef CONFIG_ACMA_BALLOON
+       s64 target;
+       u32 num_pages;
+
+       virtio_cread_le(vb->vdev, struct virtio_balloon_config, num_pages,
+                       &num_pages);
+       target = ALIGN(num_pages, VIRTIO_BALLOON_PAGES_PER_PAGE);
+       acma_set_max_mem_aggressive(totalram_pages() - target);
+       return;
+#endif
+
        spin_lock_irqsave(&vb->stop_update_lock, flags);
        if (!vb->stop_update) {
                start_update_balloon_size(vb);
```

More Hopeful Usages of Access-aware Contiguous Memory Allocation

- Dynamic contiguous memory allocation pool allocation
- DRAM power saving
  - A variant of ACMA running on the bare metal
  - Do not report alloc-ed pages
  - Hot-unplug and power-off fully-alloc-ed memory blocks

Progress

- Detailed design and partial pseudo-code level patchset will be available by the talk

More Future Plans

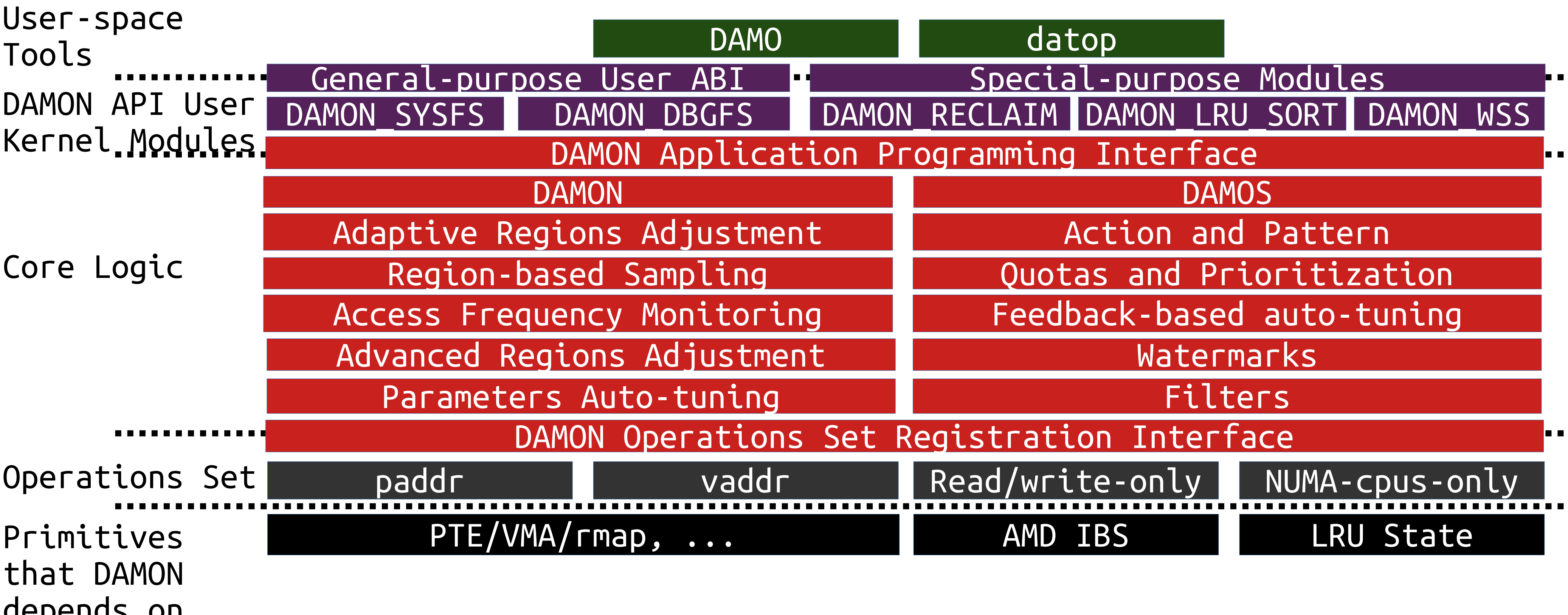
- Monitoring improvements
  - Auto-tuning
  - higher accuracy
- Write-only monitoring
- LRU-sort auto-tuning
- Access-aware THP assistant
- CPU-aware monitoring and NUMA-balancing

Discussion Time!

- The speaker has below questions at least
- ACMA
  - Is there existing alternatives for the motivation use case (memory over-commit VM systems)?
  - Ok to reuse pages reporting from ACMA?
  - Ok to reuse virtio-balloon’s interface for ACMA-Ballooning?
  - Will access-aware migration make real improvement? Recommending test workloads?
  - Do DAMOS_ALLOC-based dynamic CMA pool alloc and DRAM power saving make sense?
- Tiered-memory
  - Directly migrate to appropriate tier, instead of incremental bubbling up/down?
  - Any DAMON tuning failures from your tiering approach?
- Don’t forget sj@kernel.org, damon@lists.linux.dev, and DAMON Beer/Coffee/Tea Chat

Backup Slides

DAMON Stack, In a Future



User-space Tools

DAMO

datop

DAMON API User Kernel Modules

General-purpose User ABI

Special-purpose Modules

DAMON_SYSFS

DAMON_DBGFS

DAMON_RECLAIM

DAMON_LRU_SORT

DAMON_WSS

DAMON Application Programming Interface

Core Logic

DAMON

Adaptive Regions Adjustment

Region-based Sampling

Access Frequency Monitoring

Advanced Regions Adjustment

Parameters Auto-tuning

DAMOS

Action and Pattern

Quotas and Prioritization

Feedback-based auto-tuning

Watermarks

Filters

DAMON Operations Set Registration Interface

Operations Set

paddr

vaddr

Read/write-only

NUMA-cpus-only

Primitives that DAMON depends on

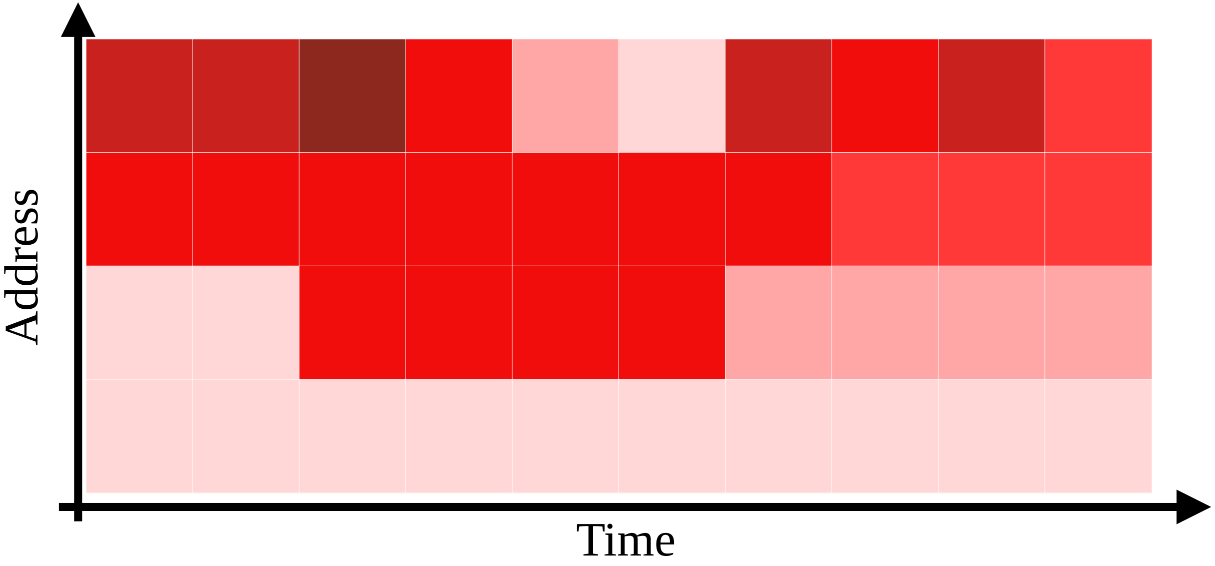
PTE/VMA/rmap, ...

AMD IBS

LRU State

DAMON: What It Provides?

- Conceptually, DAMON does periodic access check
  - Let users accumulated access checks results
- Allows users to know which memory area is how frequently accessed

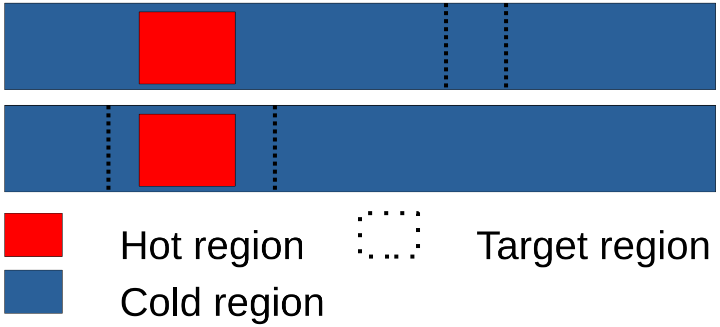


Conceptual Psudo-code of DAMON

```
while monitoring_on:
    for page in monitoring_target:
        if accessed(page):
            nr_accesses[page] += 1
    if time() % aggregation_interval == 0:
        for callback in user_registered_callbacks:
            callback(monitoring_target, nr_accesses)
        for page in monitoring_target:
            nr_accesses[page] = 0
    sleep(sampling interval)
```

Region-based Sampling

- Defines data objects in access pattern oriented way
  - “A data object is a contiguous memory region that all page frames in the region have similar access frequencies”
  - By the definition, if a page in a region is accessed, other pages of the region has probably accessed, and vice versa
  - Thus, checks for the other pages can be skipped
- By limiting the number of regions, we can control the monitoring overhead regardless of the target size
- However, the accuracy will degrade if the regions are not properly set

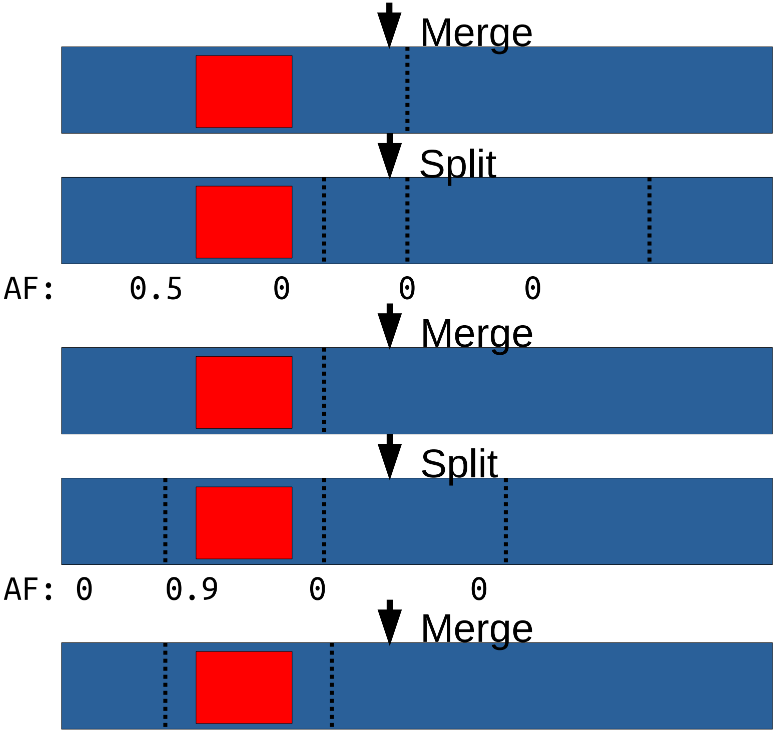


(Will result in poor accuracy)

(Will result in reasonable accuracy)

Adaptive Regions Adjustment

- Starts with minimum number of regions covering entire target memory areas
- For each aggregation interval,
  - merges adjacent regions having similar access frequencies to one region
  - Splits each region into two (or three, depend on state) randomly sized smaller regions
  - Avoid merge/split if the number of regions might be out of the user-defined range
- If a split was meaningless, next merge process will revert it (vice versa)
- In this way, we can let users control the upper bound overhead while preserving minimum and best-effort accuracy



AF: (Observed) Access Frequency

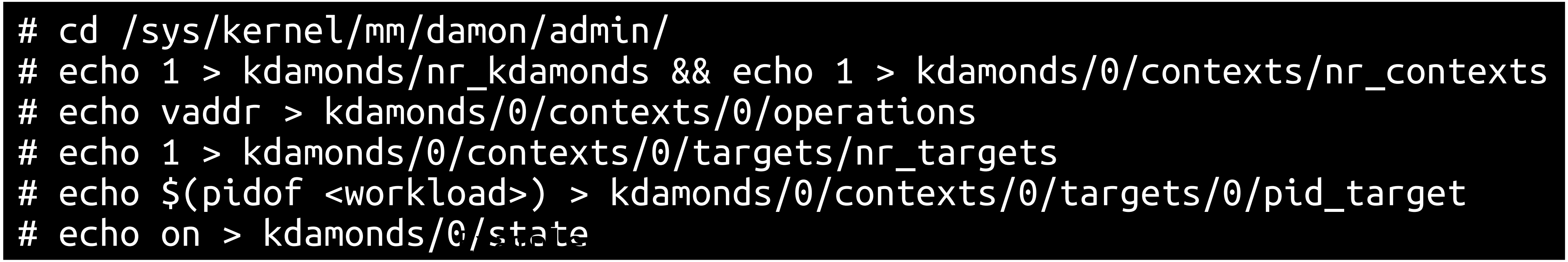
🟥 Hot region (AF 1.0)

🟦 Cold region (AF 0)

⬚ Target region

DAMON User Interfaces: How You Can Use DAMON

- DAMON provides only kernel API for other kernel components
- There is a Linux kernel module named DAMON sysfs interface
  - Implement pseudo-files on sysfs
  - Control DAMON using DAMON API, based on I/O to the sysfs file
  - User-space users can control DAMON via the sysfs files
  - Manual use of the files is tedious, though
  - User-space tools doing the file operations instead can be developed



```
# cd /sys/kernel/mm/damon/admin/
# echo 1 > kdamonds/nr_kdamonds && echo 1 > kdamonds/0/contexts/nr_contexts
# echo vaddr > kdamonds/0/contexts/0/operations
# echo 1 > kdamonds/0/contexts/0/targets/nr_targets
# echo $(pidof <workload>) > kdamonds/0/contexts/0/targets/0/pid_target
# echo on > kdamonds/0/state
```

DAMOS for Access-aware Optimizations with No Code

- DAMOS is a feature of DAMON for offloading the effort to DAMON
  - Users can simply
    - specify the access pattern of their interest, and
    - the action they want to apply to the regions of the pattern
  - Then, DAMON finds regions of the pattern and apply the action
  - No code, just request specification
  - Provides some more important features, but out of scope of this talk

```
{
        "access_pattern": {
                "sz_bytes": {"min": "4K", "max": "max"},
                "nr_accesses": {"min": "0 %", "max": "0 %"},
                "age": {"min": "2 m", "max": "max"}
        },
        "action": "pageout"
}
```

A json-format DAMOS scheme asking
“Page out memory regions of >=4K that not accessed at all for >=2 minutes”