DAMON Updates and Future Plans:

Automation of DAMON tuning, tiering, and VM guest scaling

SeongJae Park <sj@kernel.org>

https://damonitor.github.io

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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/`)

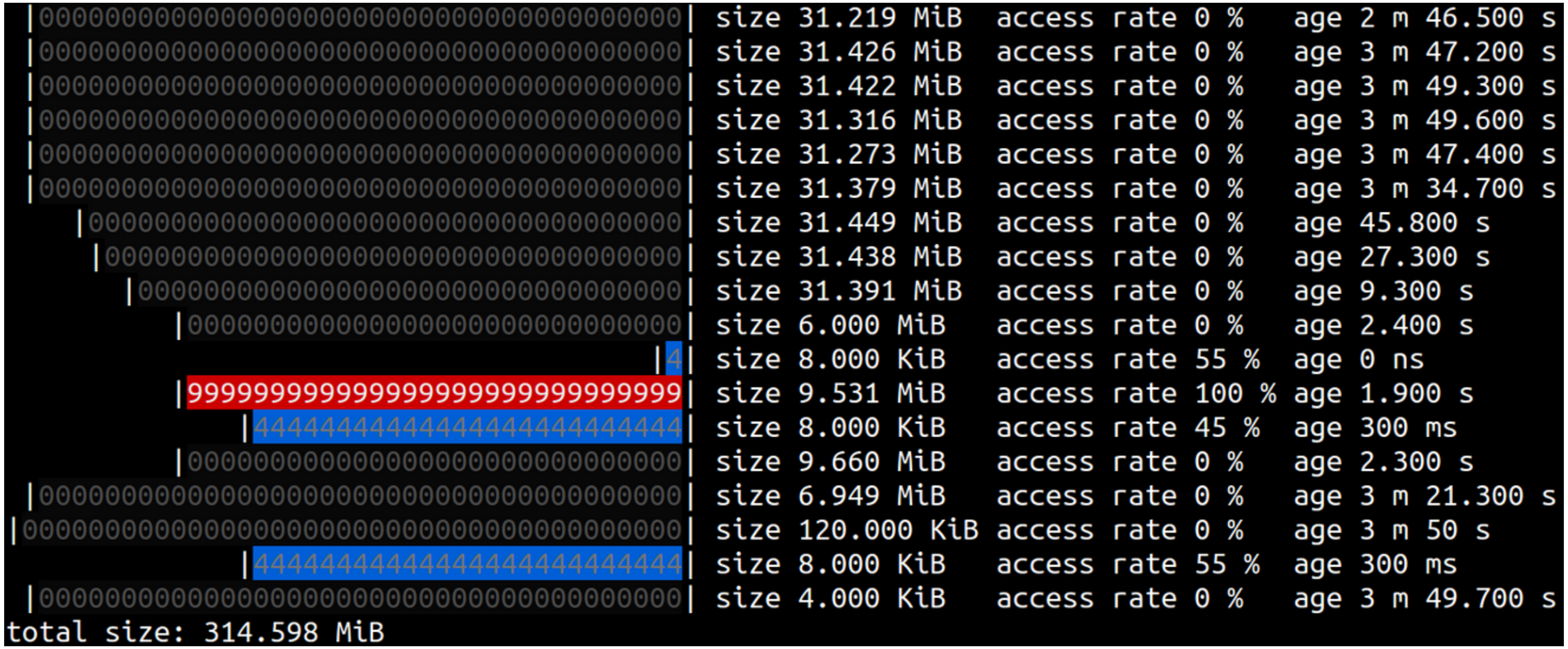
Overview

- 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

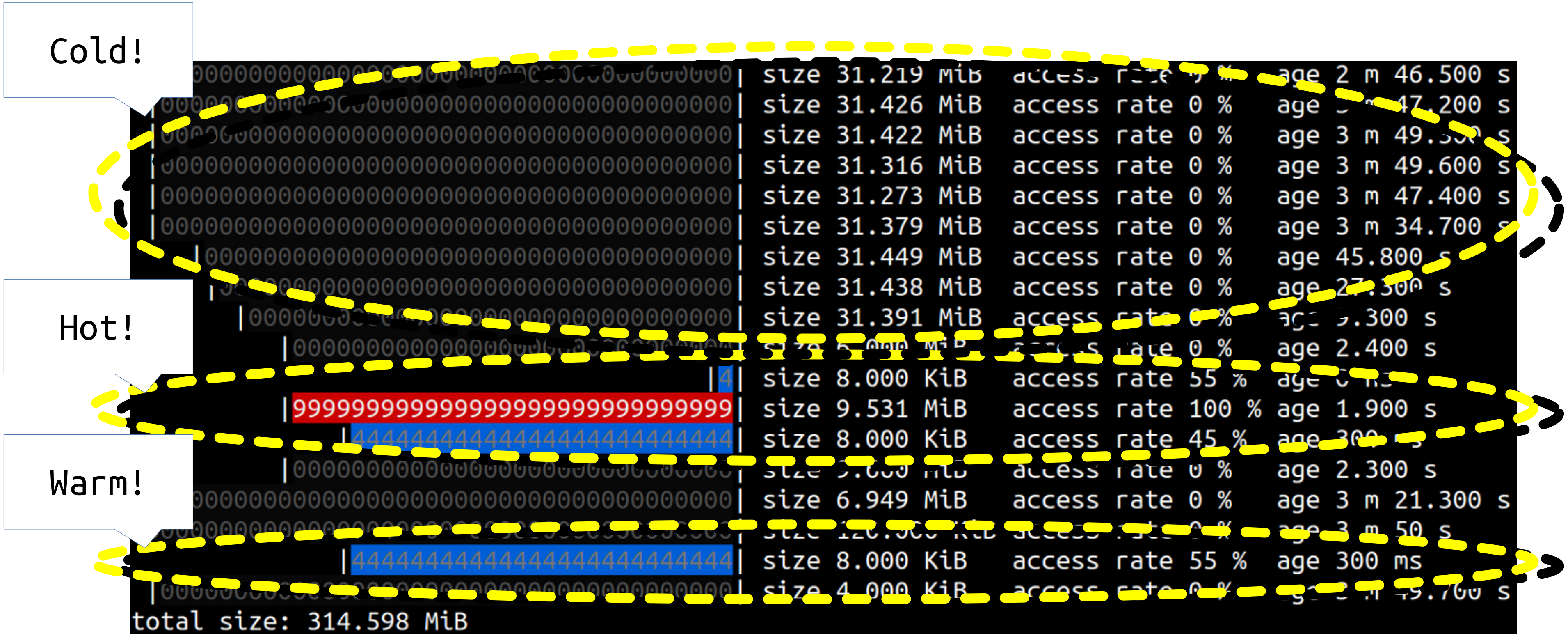
DAMON: Access Pattern Snapshot Generator

- Inform 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



```
    0000000000000000000000000000000000000| size 31.219 MiB   access rate 0 %   age 2 m 46.500 s
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          |000000000000000000000000000000| size 5.000 MiB    access rate 0 %   age 2.300 s
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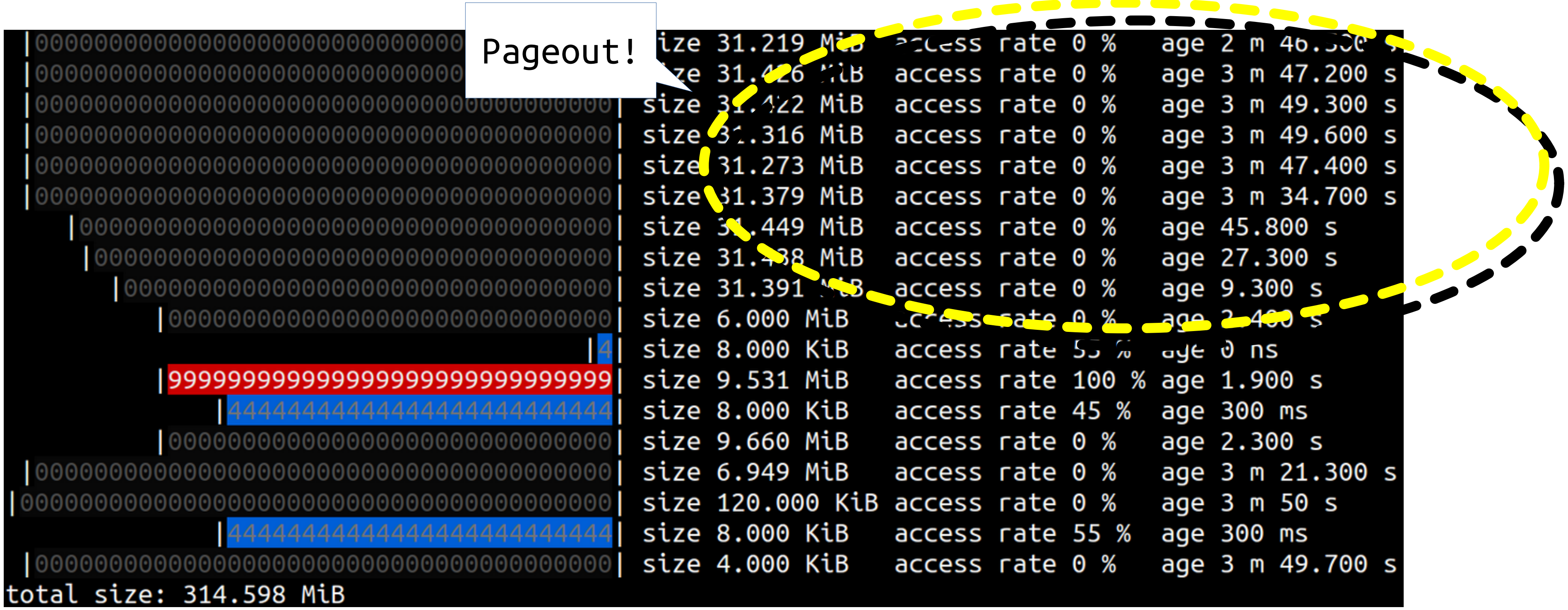
 |000000000000000000000000000000000000000| size 4.000 KiB    access rate 0 %   age 3 m 49.700 s
total size: 314.598 MiB
```

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
```



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```

Features for Product Quality DAMOS Control

- *“One does not simply control DAMOS with only access pattern”*
- Quota: 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

Usages, To One’s Best Knowledge

- Products
  - Proactive memory reclamation for memory overcommit systems
  - CXL-based tiered memory management software development kit
- Researches
  - DAMON paper got 20 citations
- Distros having `CONFIG_DAMON=y`
  - Amazon Linux (>=5.4), Android (>=5.10), CentOS (>=4.18), Fedora (>=6.2), UEK (>=5.15)
- Package repos providing DAMON user-space tool
  - AUR, Debian, EPEL, Fedora, Kali, PyPI, Raspian, Ubuntu

Community

- *“Strive to be Earth’s best community”*
- Public mailing list (lore.kernel.org-archived)
- Bi-weekly meetup series (on Google Meet in usual)
  - Occasional/regular private meetings on demand
- Project website (https://damonitor.github.io)
  - Starting point for DAMON users and developers
  - Daily performance test results archive

Scan to visit the project website

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

DAMON Updates

Answer to LSFMM 2023 Feedbacks

- “Some good documentation would be appreciated”
  - Improving `Documentation/.../damon/`
- “Adding DAMON user-space tool in-tree sounds not a good idea”
  - The goal was test coverage and easy DAMON interface understanding
  - Implementing DAMON functionality selftests

```
v6.5-rc1
    Patch series "Docs/{mm,admin-guide}damon: update design and usage docs".
    Patch series "Docs/mm/damon: Minor fixes and design doc update".
v6.8-rc1
    Patch series "selftests/damon: add Python-written DAMON functionality
v6.9-rc1
    Patch series "Docs/mm/damon: misc readability improvements".
    Patch series "selftests/damon: add more tests for core functionalities and
```

More Features

- New filter types
  - “address range”: Specific NUMA nodes or zones
  - “young page”: Per-page access double check
- Fast snapshot generation
  - Generate per “aggregation interval” -> “sampling interval”
  - Faster monitoring, faster DAMOS with large aggregation interval

```
v6.6-rc1
    Patch series "Extend DAMOS filters for address ranges and DAMON monitoring
v6.7-rc1
    Patch series "mm/damon: implement DAMOS apply intervals".
    Patch series "mm/damon: provide pseudo-moving sum based access rate".
```

Aim-oriented Feedback-driven DAMOS Aggressiveness Auto-tuning

- *“One does not manually control DAMOS”*
- Auto-tune effective DAMOS quota using a proportional feedback loop
- Arbitrary value can be fed by user
  - E.g., Main workload’s latency as feedback score
- System metrics based target can be set so DAMOS self-feed/auto-tune
  - Supporting memory PSI-based target (will add more target metrics)
  - *“Reclaim cold pages aiming 0.1% memory pressure stall rate”*

```
f(n) = max(f(n - 1) * ((target_score - current_score) / target_score + 1), 1)
```

```
v6.8-rc1
    Patch series "mm/damon: let users feed and tame/auto-tune DAMOS".
v6.9-rc1
    Patch series "mm/damon: let DAMOS feeds and tame/auto-tune itself".
```

DAMON Future Plans

DAMOS Auto-tuning Based Tiered Memory Management

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

Existing DAMON-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, merged in `damon/next` tree)
  - 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 implement only mechanisms, not the policy
  - HMSDK v2 open-source their 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)  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

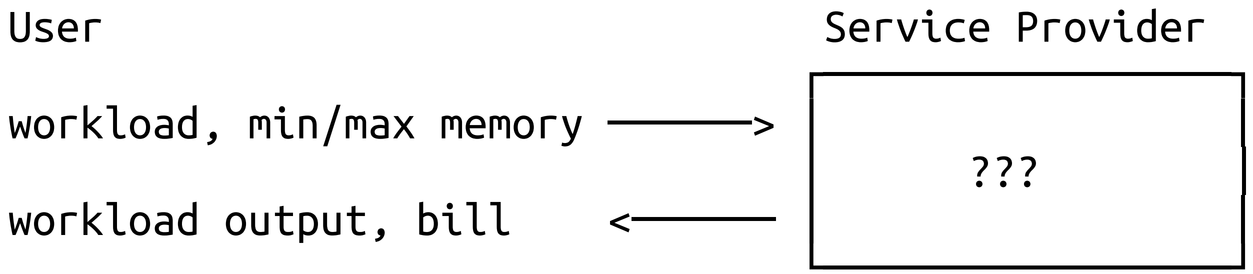
- Detailed RFC idea is sent to the mailing list
- No test setup, no implementation

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

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

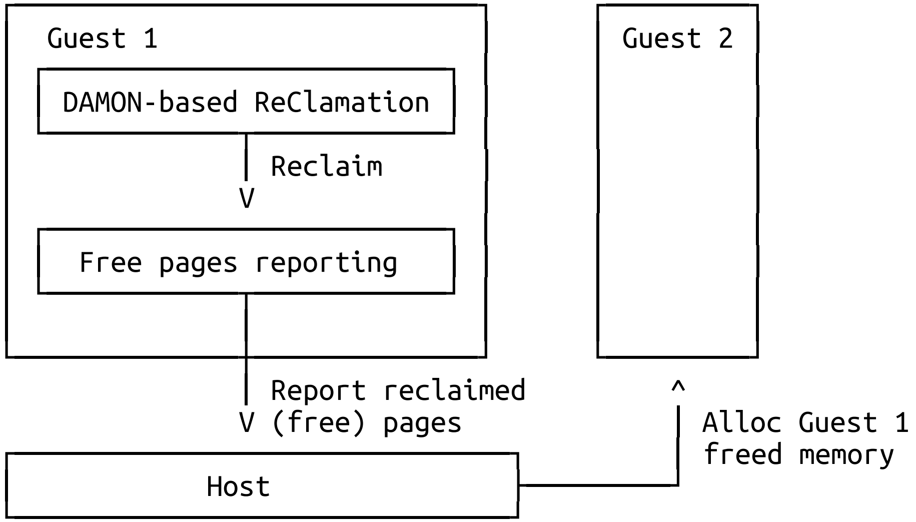
Motive Business Model

- User: specify workload and min/max memory requirements
- Service Provider: run it somewhere, charge as they gone
  - Achieving high performance and low price is the provider’s duty, and benefits both



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

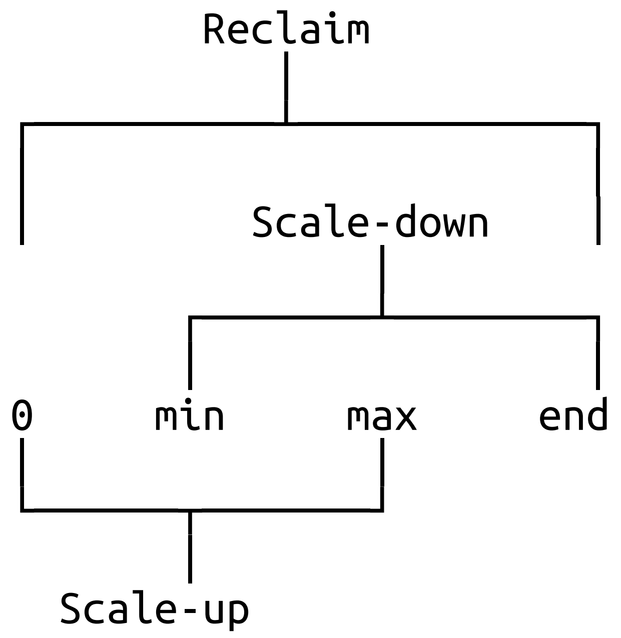
- Complexity of user-space driven multiple kernel features orchestration
- Memory hot-unplugging is slow and easy to fail
  - Due to coarse granularity and access obliviousness
- System-level compaction is wasteful and access oblivious
- Lack of after-report pages control
  - Any reported pages can be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



Access-aware Ballooning: Control non-collaborative guests

- Adjust ACMA’s max-mem parameter for baloon {in,de}flating
- Reuse virtio-balloon interface (no host-side change)

```
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);
```

Limitations (Hopefully) Mitigated

- Complexity of user-space driven multiple kernel features orchestration
  - ACMA: single module asking three parameters
- Memory hot-unplugging is slow and easy to fail,
  System-level compaction is wasteful and access oblivious
  - ACMA scales down (isolate/migrate) memory in 2 MiB granularity, colder regions first
- Lack of after-report pages control
  - ACMA returns pages on demand but keeping maximum contiguity
- Lack of non-collaborative guests control
  - Host can just use virtio-balloon

More Hopeful Usages of Access-aware Contiguous Memory Allocation

- Dynamic contiguous memory allocation pool
- 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

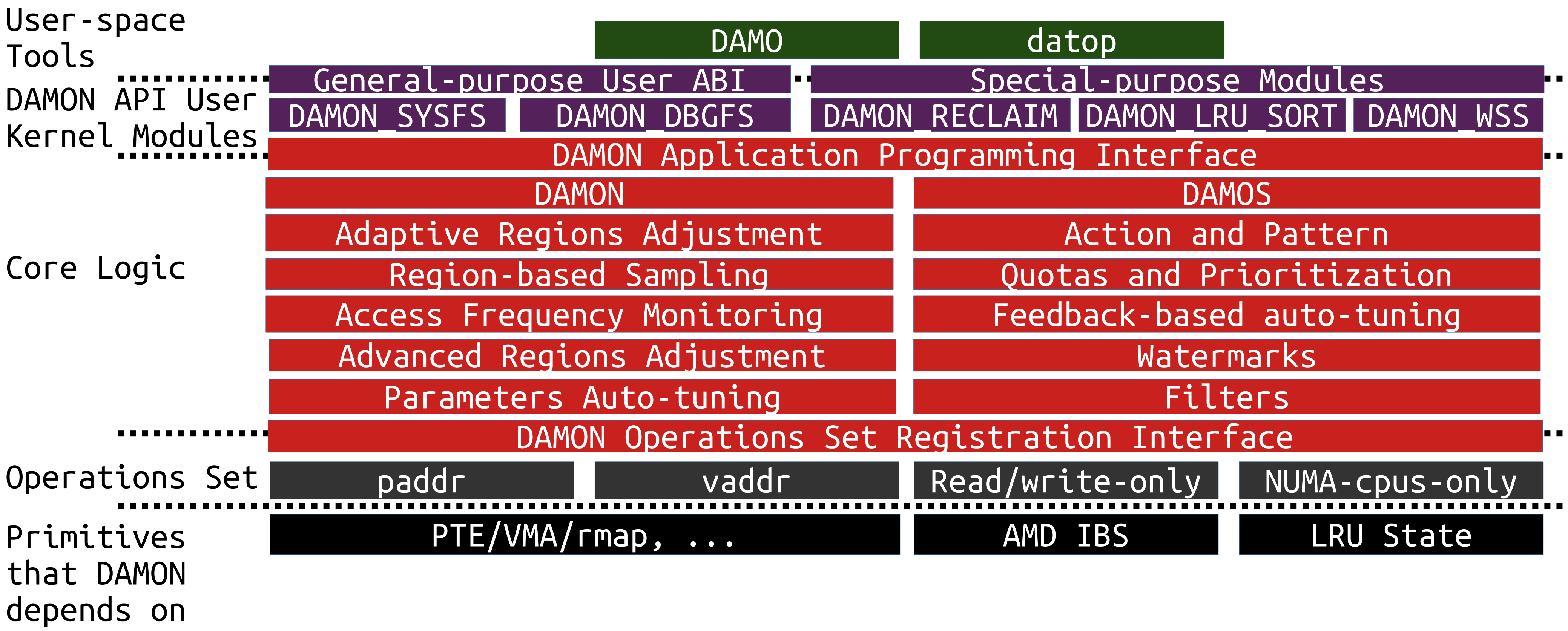
- Monitoring improvements
  - Auto-tuning
  - higher accuracy
- Write-only monitoring
- LRU-sort auto-tuning
- Access-aware THP assistant
- CPU-aware monitoring and NUMA-balancing

Discussion Time!

- 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 Access-aware 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?
- Questions or comments on updated features and other future plans
- Don’t forget sj@kernel.org, damon@lists.linux.dev, and DAMON Beer/Coffee/Tea Chat

Backup Slides

DAMON Stack, In a Future



ACMA and Unmovable/Long-pinned Pages

- Unmovable pages or long-pinned pages can interfere ACMA scale down
  - ACMA apply DAMOS_ALLOC to only not-yet-completely DAMOS_ALLOC-ed memory block of highest address
- Solution: Allow limited amount of not-DAMOS_ALLOC-ed regions in scaling window
- If the ‘struct page’ reduction mechanism can be applied in only memory block granularity (e.g., memory hot-unplugging), ‘struct page’ reduction rate can be reduced
  - Hugetlb vmemmap optimization (HVO)-like approach could be applied instead
  - For DRAM power saving, HVO-like approach cannot help, though