The International ACM Symposium on High-Performance Parallel and Distributed Computing (HPDC),
Minneapolis, Minnesota, United States, June 27 – July 1, 2022

DAOS:
Data Access-aware Operating System

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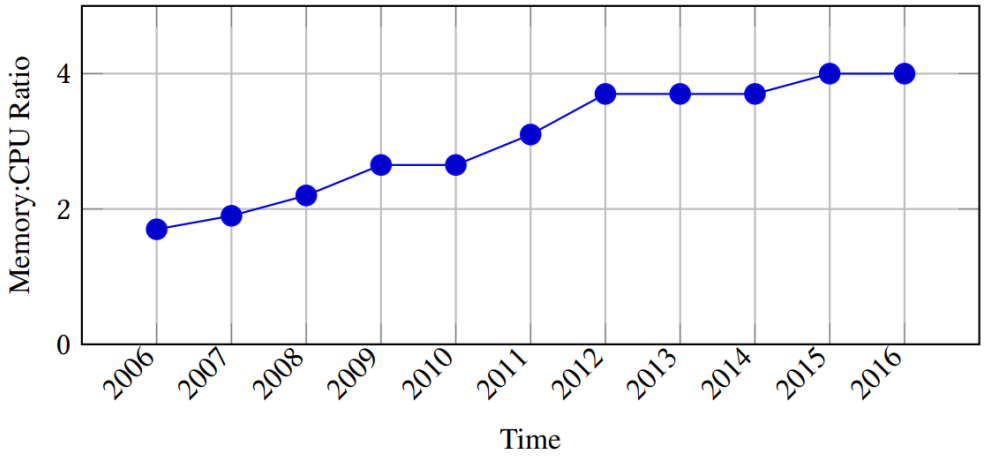
Disclaimer

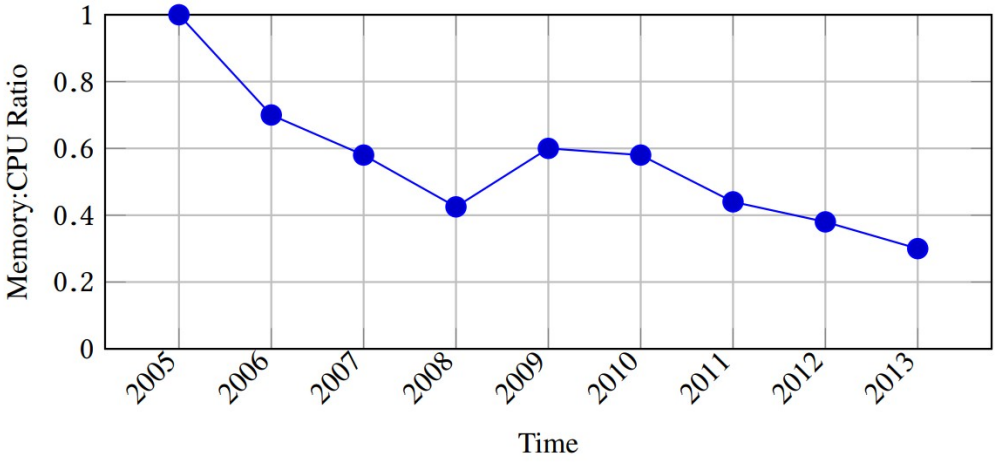
- The views expressed herein are those of the speaker; they do not reflect the views of his employers

The Trends

- Demands for memory is increasing
  - Modern workloads (e.g., cloud, big data, ML, …) use larger working set
- Size of DRAM in each machine is growing slower than that
  - Due to issues including heat/power/cost/supply
  - Tiered memory is available
- DRAM over-committed systems becoming prevalent



For AWS instances of m* types
(virtual machines: demand)



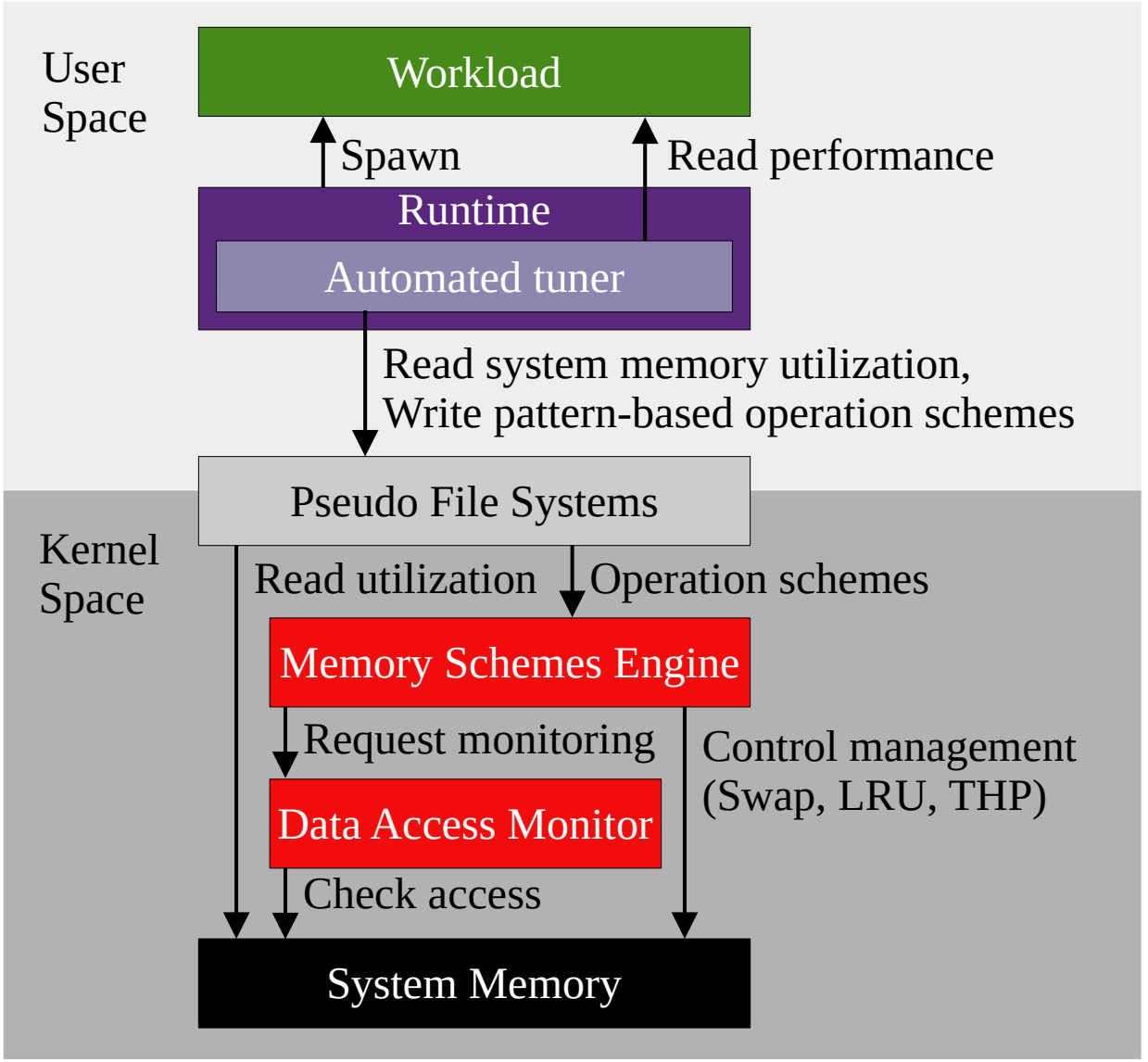
For multiple server generations
(physical machines: supply)

(Images retrieved from https://oatao.univ-toulouse.fr/24818/1/nitu_24818.pdf)

We Need Data Access-aware Operating System (DAOS)

- Because DAOS can predict future memory usage better
- Because it helps making better data management decision
- Because it can improve memory efficiency and performance
- Because DRAM is a major infrastructure expense

DAOS: Three Simple Pieces



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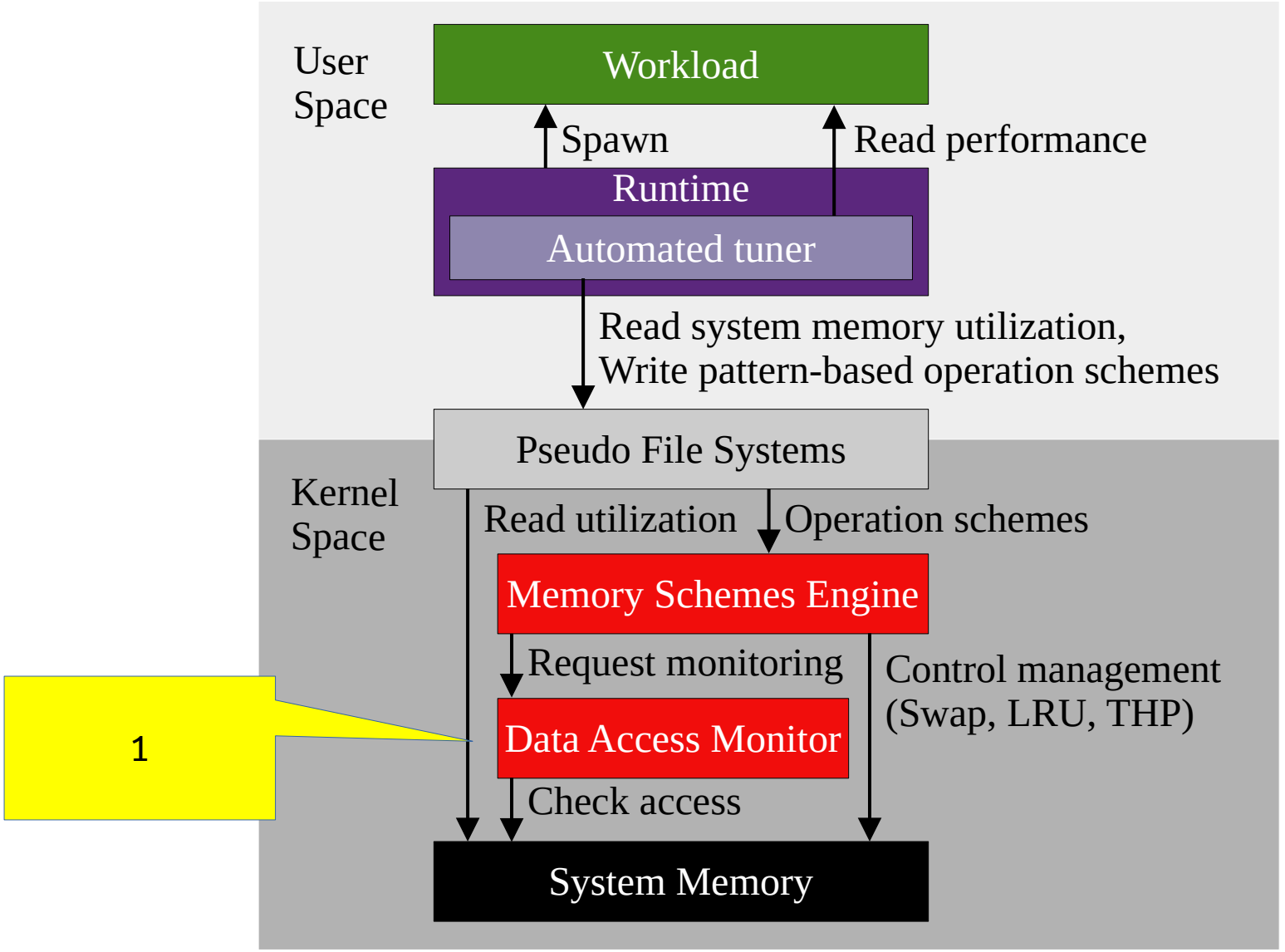

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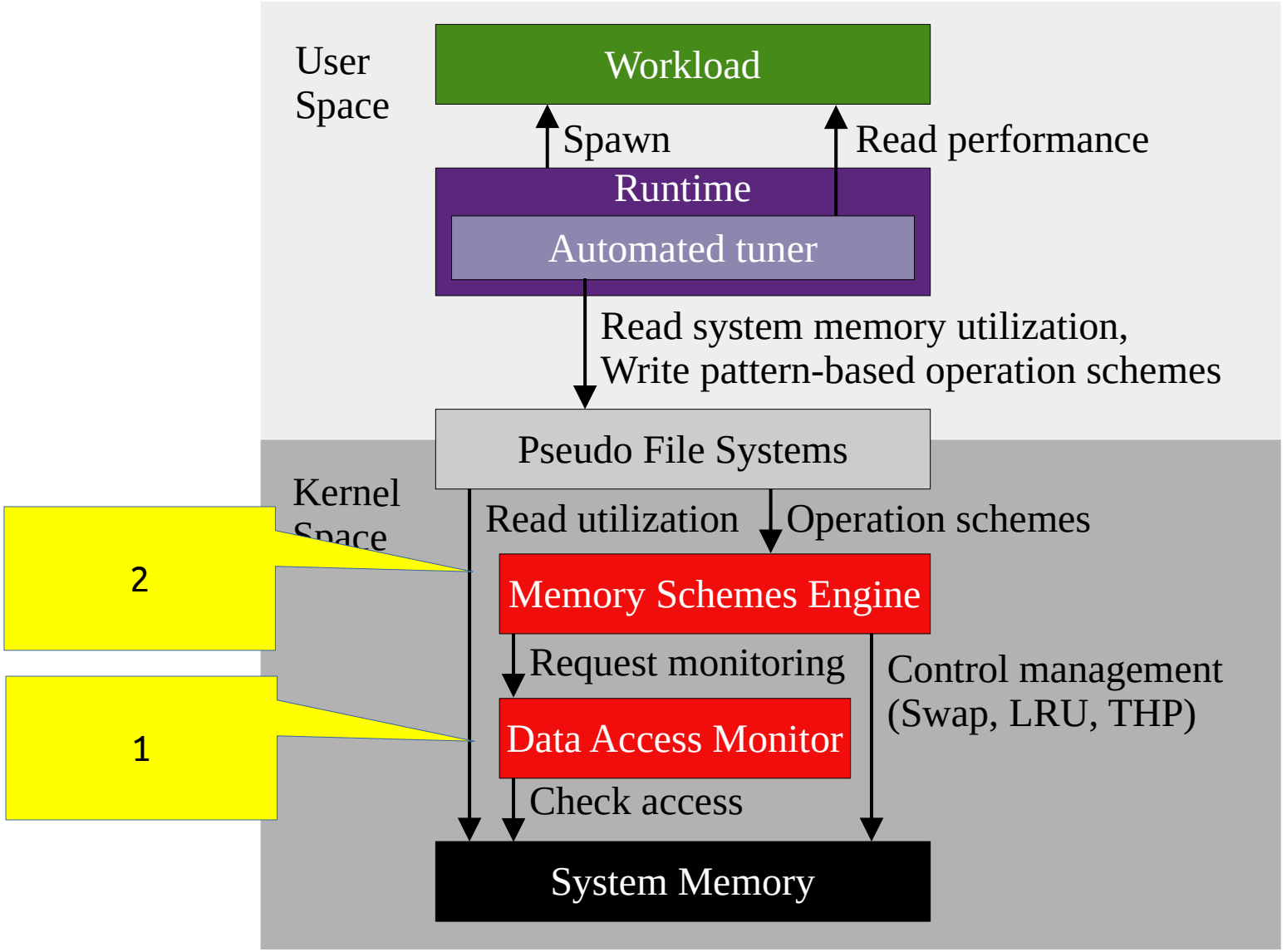

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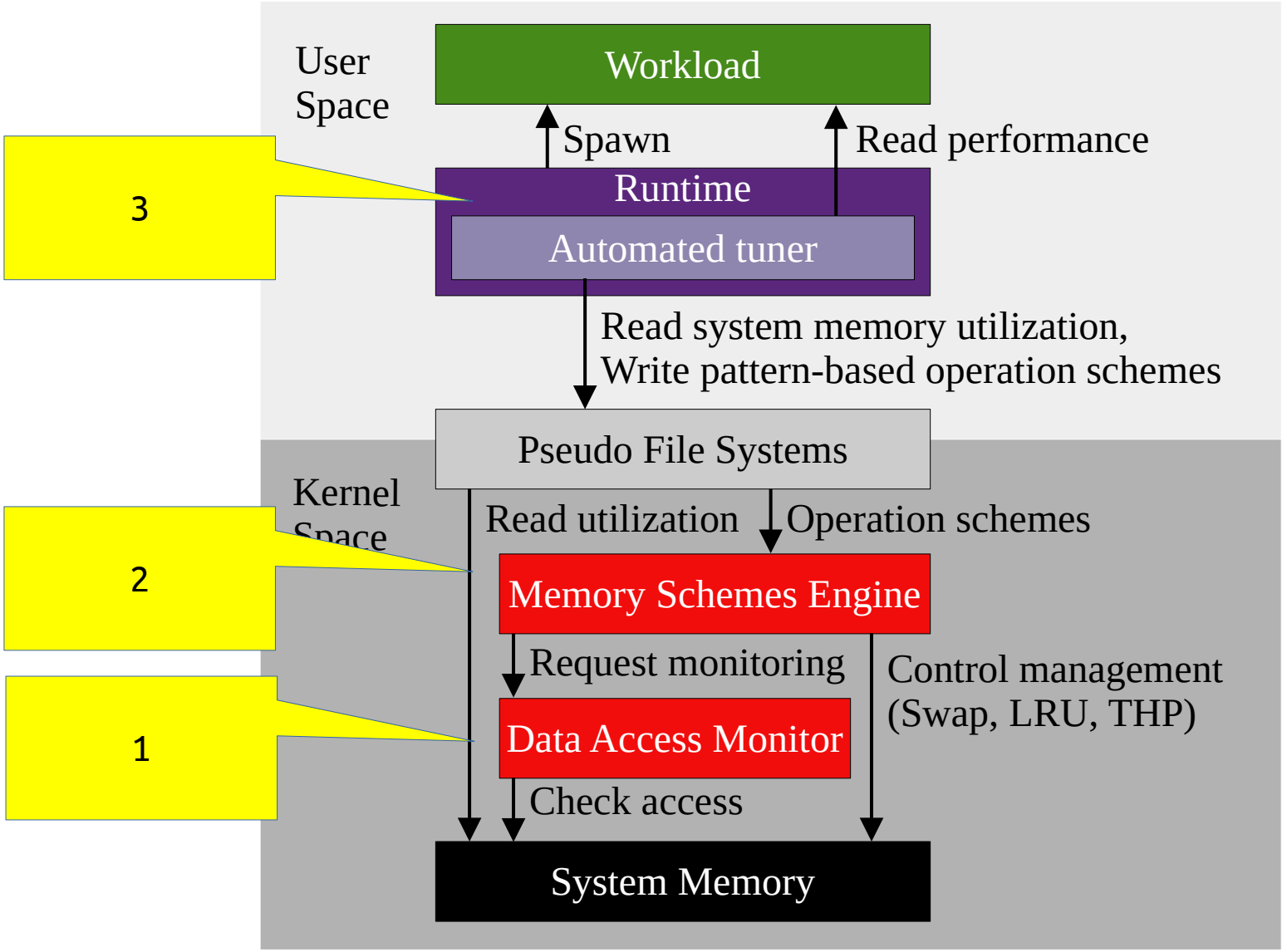
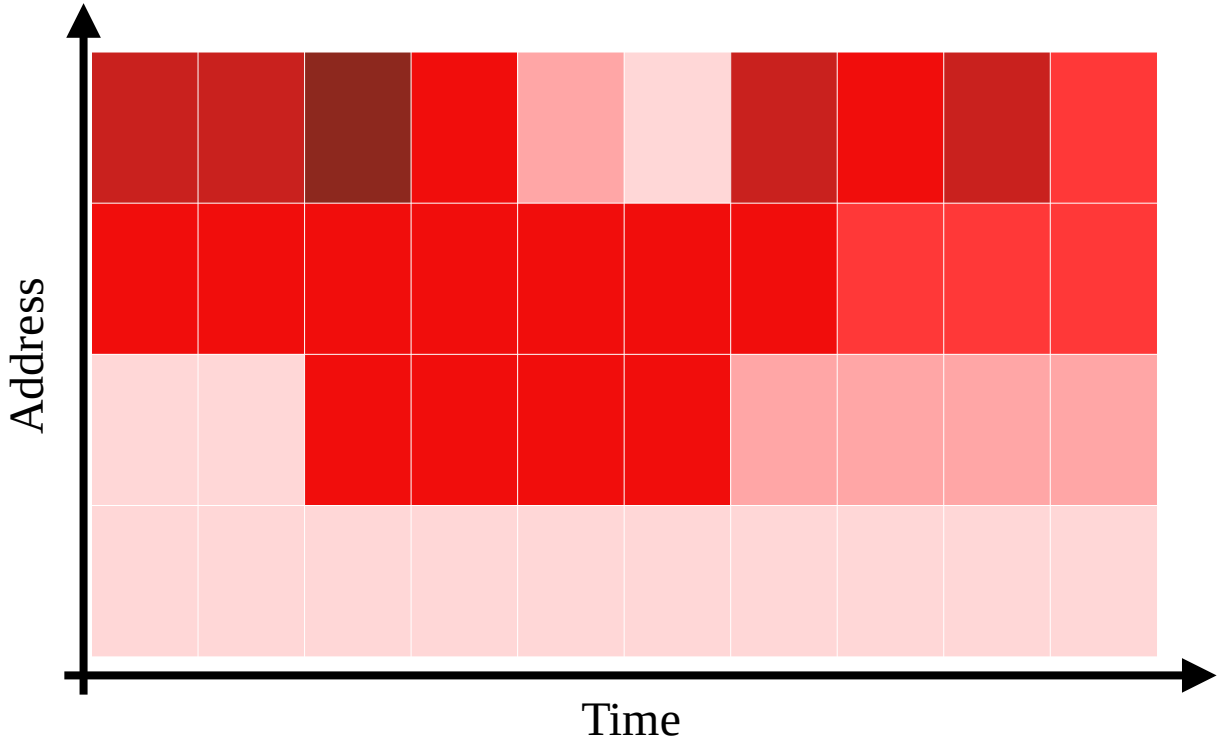


DAMON: Data Access MONitor

- Data access monitoring component for DAOS
  - Provides access frequency of each address range
  - DAOS gets data access patterns of the system online using this component



Existing Data Access Monitoring Techniques

- Instrumentation-based
  - Hook/trace every memory access
  - Incur unacceptably high overhead for unnecessarily precise information
  - Some static analysis based technique reduces the overhead but recompiling is required
- Page table access bit tracking
  - Repeatedly clear and read page table entries' accessed bits
  - The overhead is not negligible and arbitrarily grows as the size of the target memory increases
- None of them would fit well for DAOS

The Design Requirements for DAMON

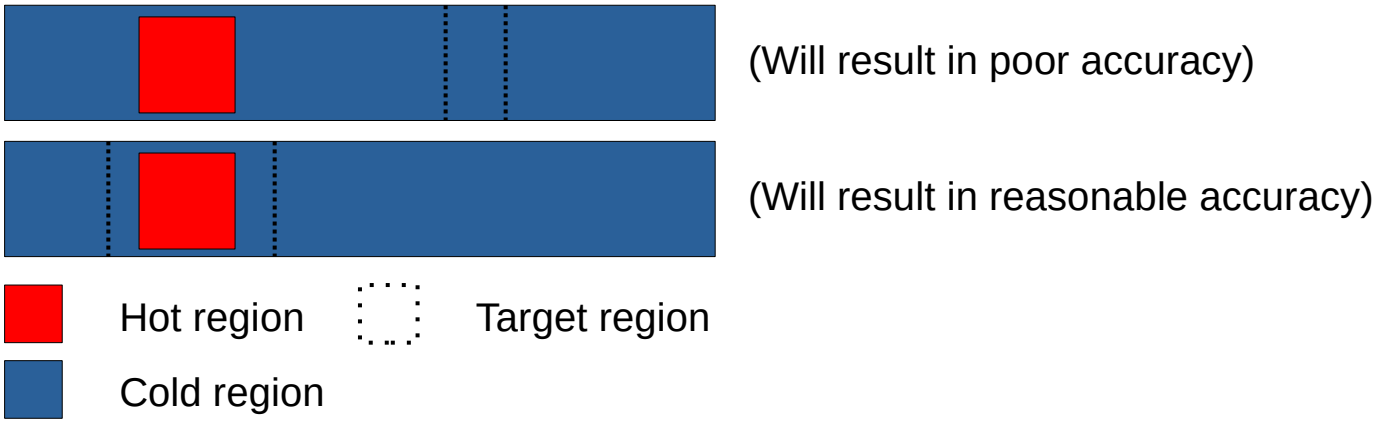
- To be used for DAOS, DAMON needs to fulfill below requirements
  - Accuracy: The monitoring result should be useful for DRAM level MM
  - Overhead: Should light-weight enough for online monitoring
  - Scalability: The upper-bound overhead should be controllable regardless of the size of the monitoring target systems and workloads
- DAMON fulfills the requirements in below steps
  - Straightforward Access Monitoring (collect basic information)
  - Region-based Sampling (optimize overhead)
  - Adaptive Regions Adjustment (make best-effort accuracy)

Straightforward Access Monitoring

- Periodically checks if each monitoring target page is accessed
  - The period is called ‘sampling interval’
- Aggregates the observations into access frequencies
  - Count number of observed accesses and periodically reset the counter
  - The period is called ‘aggregation interval’
- By notifying the users just before the reset of the counter, we can provide the access frequency of the pages to the users
- Pros: Fine-grained (page size) monitoring
  - Might not strictly required in some performance-centric optimizations
- Cons: High and unscalable monitoring overhead
  - The overhead arbitrarily increases as the target size grows

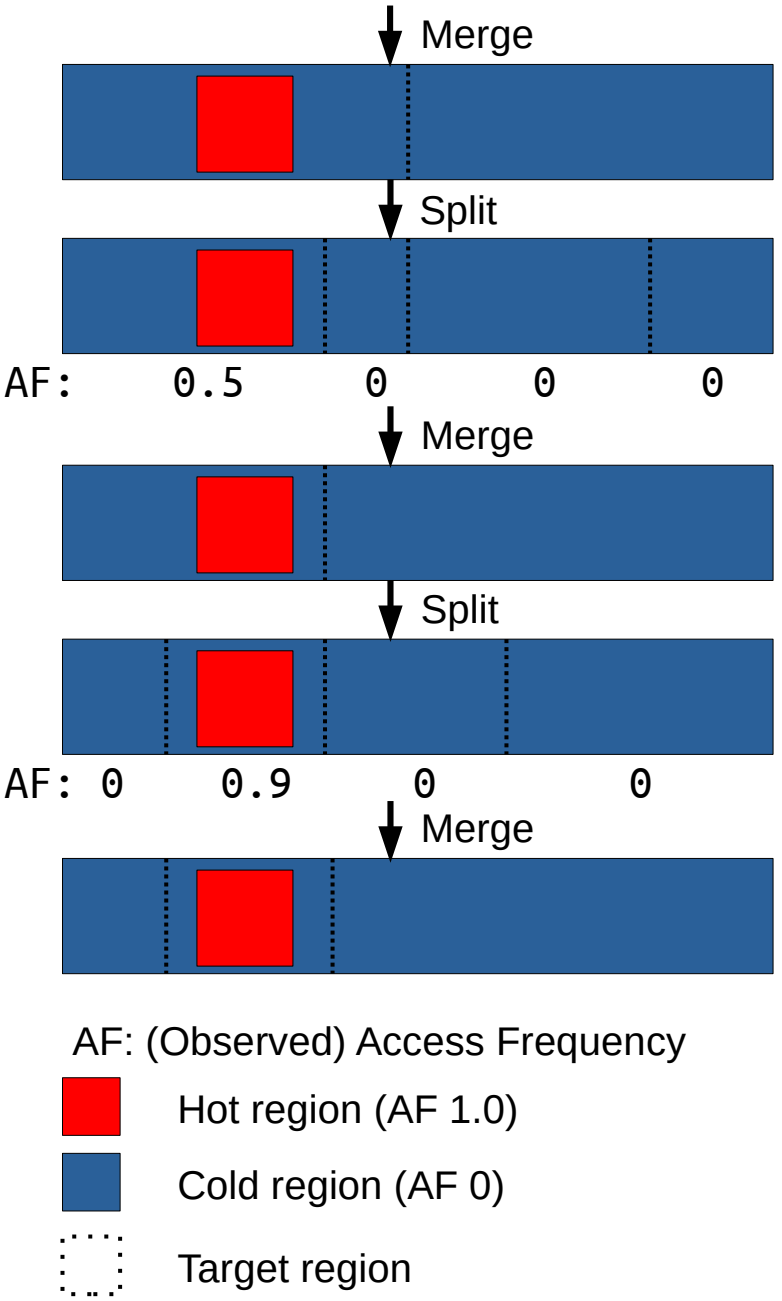
Region-based Sampling

- 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



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



DAMON-based Manual Memory Management Schemes

- Now DAMON-based optimizations are available in below steps
  - Step 1: Run DAMON
  - Step 2: Analyze the monitoring results offline or online
  - Step 3: Make some changes in the kernel or the app
    - e.g., page out cold regions, THP-collapse hot regions, …
  - Could be done inside kernel or from user space
  - Could be effective, but has some risks

Risks of Manual DAMON-based Optimizations

- It could be difficult, dangerous, dirty, and/or restrictive
- Optimizations in the kernel space could be difficult and dangerous
  - No every sysadmin is an experienced kernel programmer
  - Every kernel bug is dangerous
- Optimizations in the user space could be dirty and restrictive
  - Receiving and analyzing the results require some lines of code
    - It also incur overheads for context switches
  - User space apps can do only limited memory management actions
- Most of the basic works would be repetitive

DAMOS: DAMON-based Operation Schemes

- DAMON-based memory management schemes engine for DAOS
- Receives ‘schemes’; each scheme is constructed with
  - Target access pattern: ranges of size, access frequency, and age
  - 1 memory management action
    - Currently supported actions include:
      `WILLNEED, COLD, PAGEOUT, HUGEPAGE, NOHUGEPAGE`
- DAMOS automatically finds the memory region of the target pattern from DAMON results and applies the action to the region
- Now users can make DAMON-based optimizations with no-code

```
# format is:
# <min/max size> <min/max frequency (0-100)> <min/max age> <action>
#
# if a region of size >=4KB didn’t accessed for >=2mins, page out
4K max       0 0       2m max       pageout
```

DAMOS: Example Schemes

- Core concepts of some state-of-the-art works can be implemented using DAMOS again as simple as below
- Proactive reclamation (software-defined far memory, ASPLOS'19)

```
$ cat prcl.damos
# page out memory regions that not accessed >=2 minutes
4K  max     0 0      2m max     page_out
```

- Data Access-aware THP (Ingens, OSDI'16)

```
$ cat ethp.damos
# Use THP for >=2MiB regions having >=80% frequency ratio for >=1 minute
2MB max     80% max     min max     thp
# Don't use THP for regions having <=5% frequency ratio for >=1 minute
min max     min 5%      1m max      nothp
```

Evaluation Questions for DAMON/DAMOS

- How lightweight DAMON is?
- How accurate DAMON is?
- How useful DAMOS-based optimizations are?

Evaluation Environment

- Test machine
  - QEMU/KVM virtual machine on AWS EC2 i3.metal instance
  - 3.0 GHz x 36 vCPUs, 128 GB memory, 4 GB zram swap device
  - Ubuntu 18.04, THP turned off by default
  - Linux v5.10 + DAOS changes
- Workloads: 25 realistic benchmark workloads
  - 13 workloads from PARSEC3
  - 12 workloads from SPLASH-2X
- DAMON monitoring attributes: The default values
  - sampling interval: 5ms, aggregation interval: 100ms
  - Number of regions: [10, 1000]

Evaluation Targets

- Six variants
  - orig: All DAOS features turned off (same to vanilla v5.10 Linux)
  - rec: orig + DAMON for virtual address of the workload turned on
  - prec: orig + DAMON for entire physical address of the system turned on
  - thp: orig + THP enabled with `always` policy (to be compared with ethp)
  - ethp: orig + ethp DAMON-based operation scheme is applied

```
$ cat ethp.damos
# for regions having 5/100 access frequency, apply MADV_HUGEPAGE
min max     5 max       min max     hugepage
# for regions >=2MB and not accessed for >=7 seconds, apply MADV_NOHUGEPAGE
2M max      min min     7s max      nohugepage
```

  - prcl: orig + prcl DAMON-based operation scheme is applied

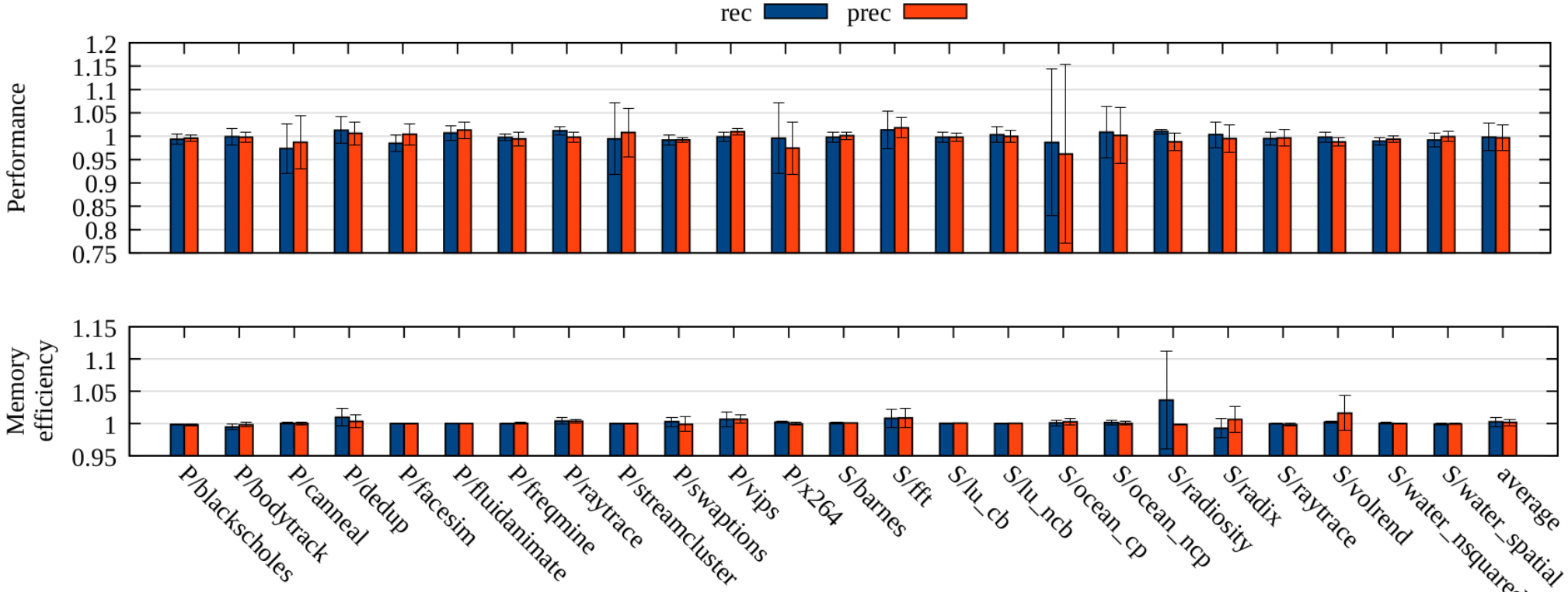
```
$ cat prcl.damos
# for regions >=4KB and not accessed for >=5 seconds, apply MADV_PAGEOUT
4K  max     0 0     5s max      pageout
```

Evaluation Methodology

- Measurement
  - DAMON/DAMOS' CPU consumption
  - Runtime speedup compared to the 'orig'
  - Memory efficiency compared to the 'orig'
    - System entire memory usage for 'prec', RSS of the workload for others
  - For each of the workload x variant combinations
- Every following data is average of 5 different runs

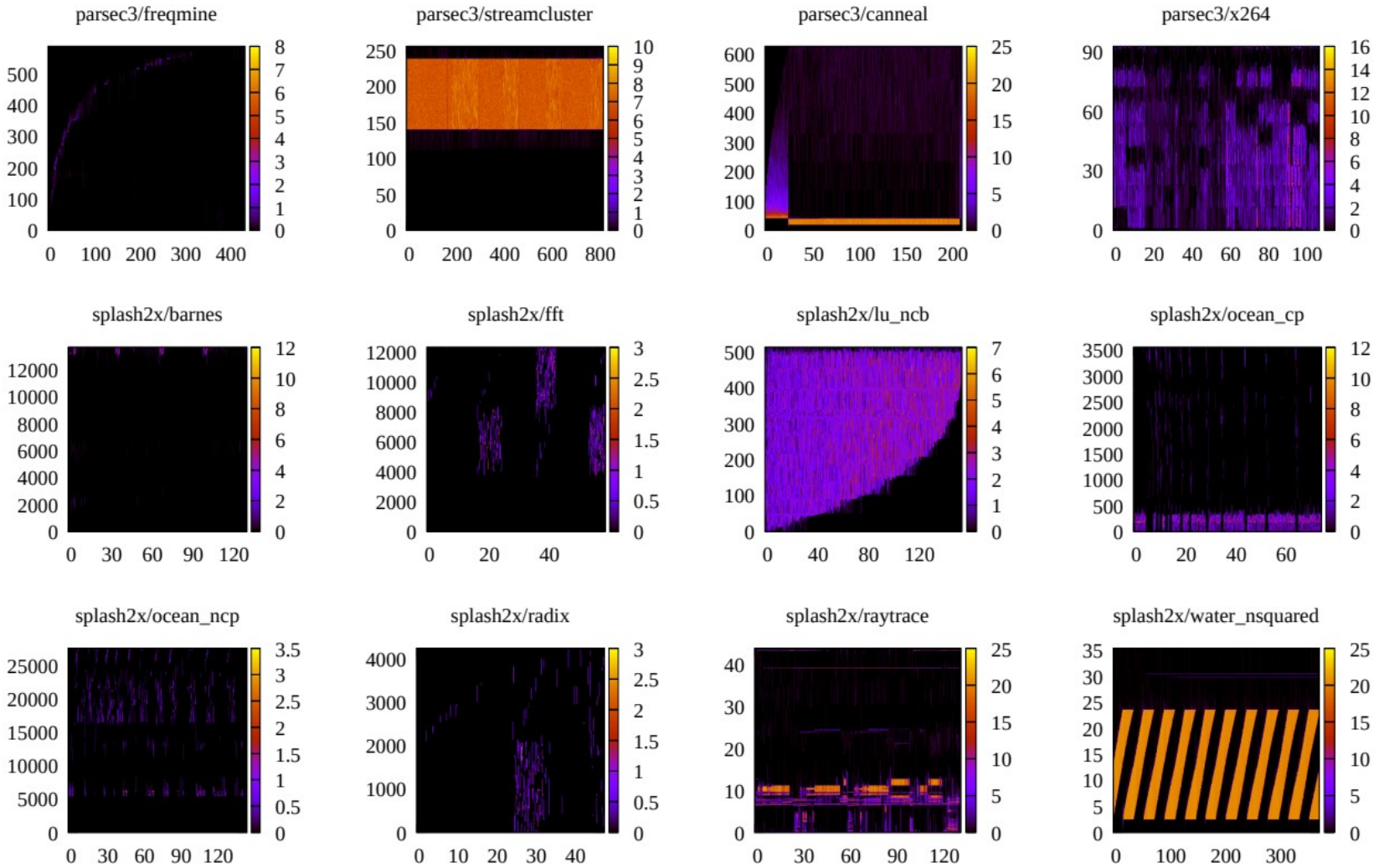
DAMON Overhead

- For both ‘rec’ and ‘prec’ (note: ‘prec’ covers entire system memory)
  - Consumes <2% of a single CPU time
  - Incurs about 1% on average and up to 4% slowdown to the workload
  - Memory overhead is also negligible
- DAMON keeps upper-limit of the overhead regardless of target size



DAMON Accuracy

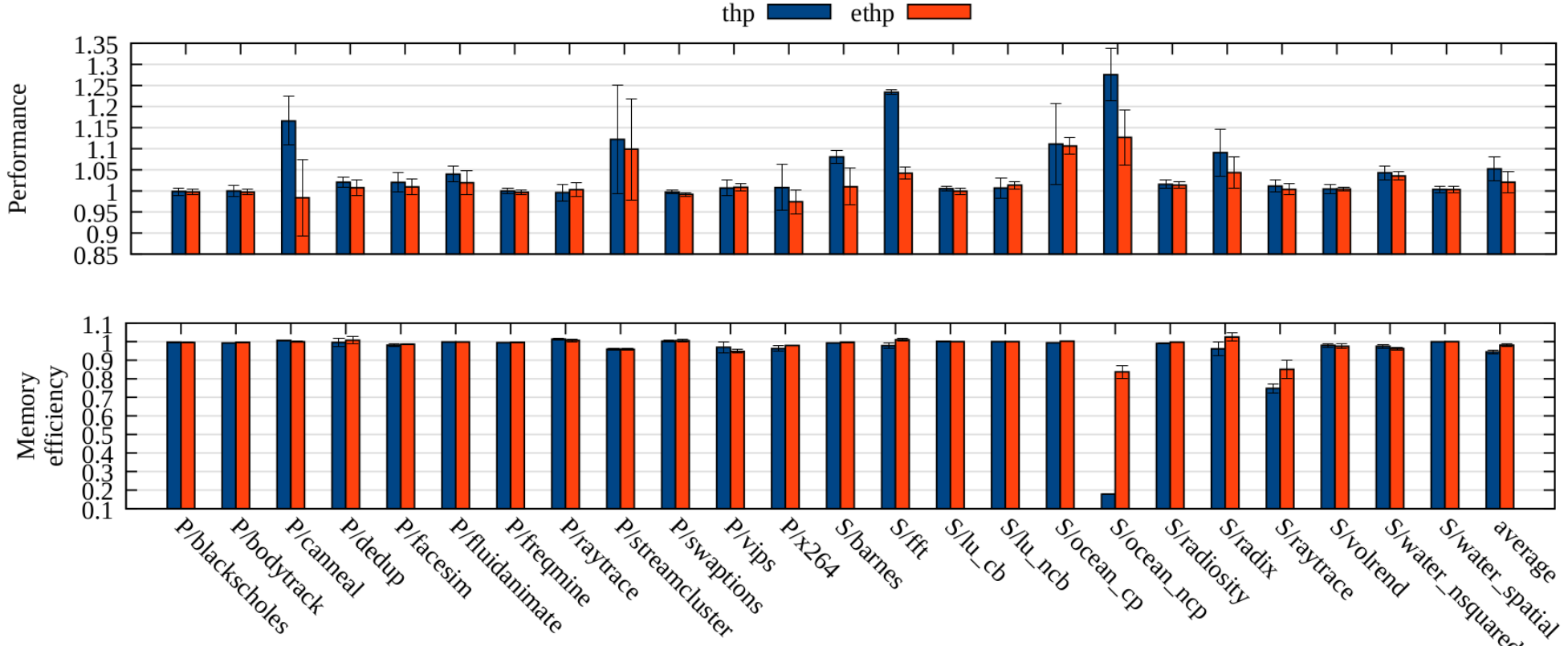
- DAMON results in heatmap visualization shows reasonable results



Data access patterns of the workloads in heatmap format. Each heatmap shows when (x-axis, in seconds) what memory regions of specific address (y-axis, in MiB) is how frequently (color) accessed.

DAMON Accuracy and DAMOS ‘ethp’ Effectiveness

- On average, ‘ethp’ preserves 39% of ‘thp’ speedup while removing 64.28% of ‘thp’ memory overhead
- For splash-2x/ocean_ncp
  - ‘thp’ shows up to 27.54% speedup with 82.18% memory overhead
  - ‘ethp’ provides 12.67% speedup with only 16.3% memory overhead



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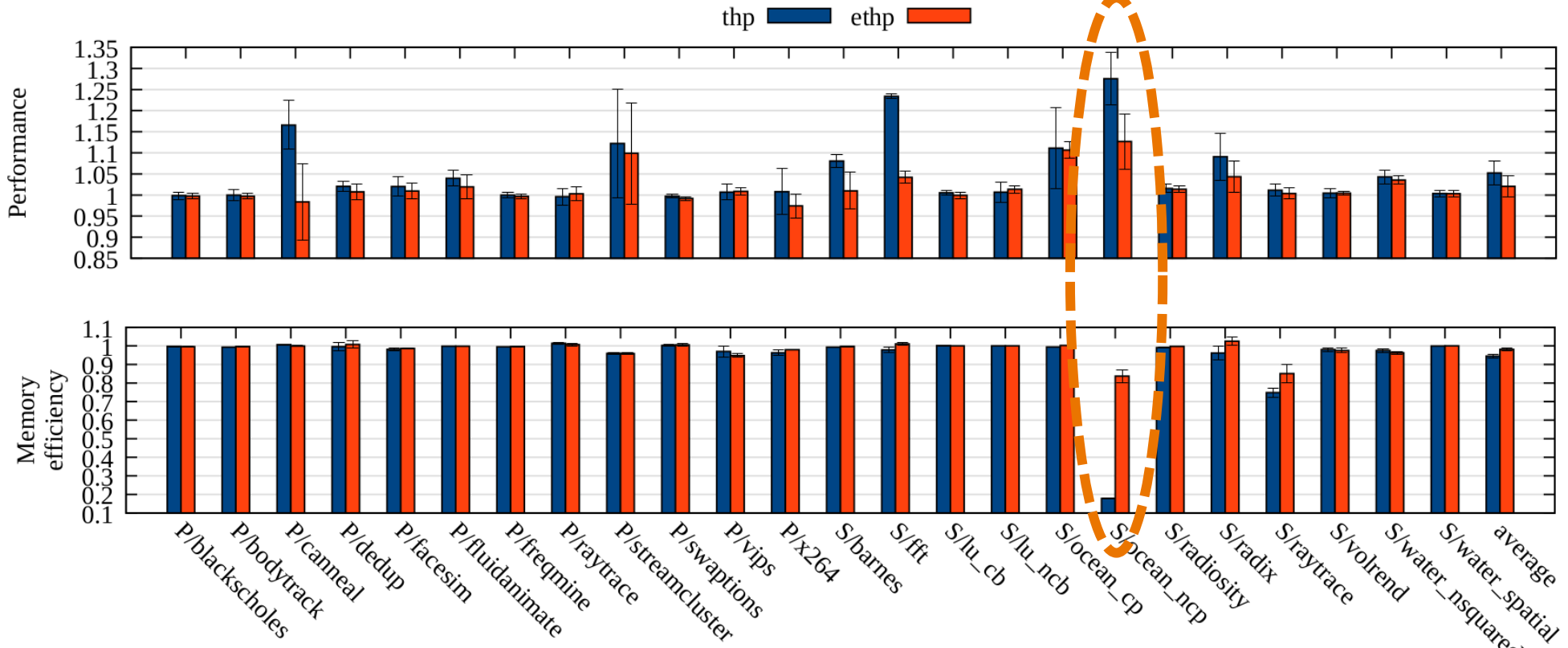
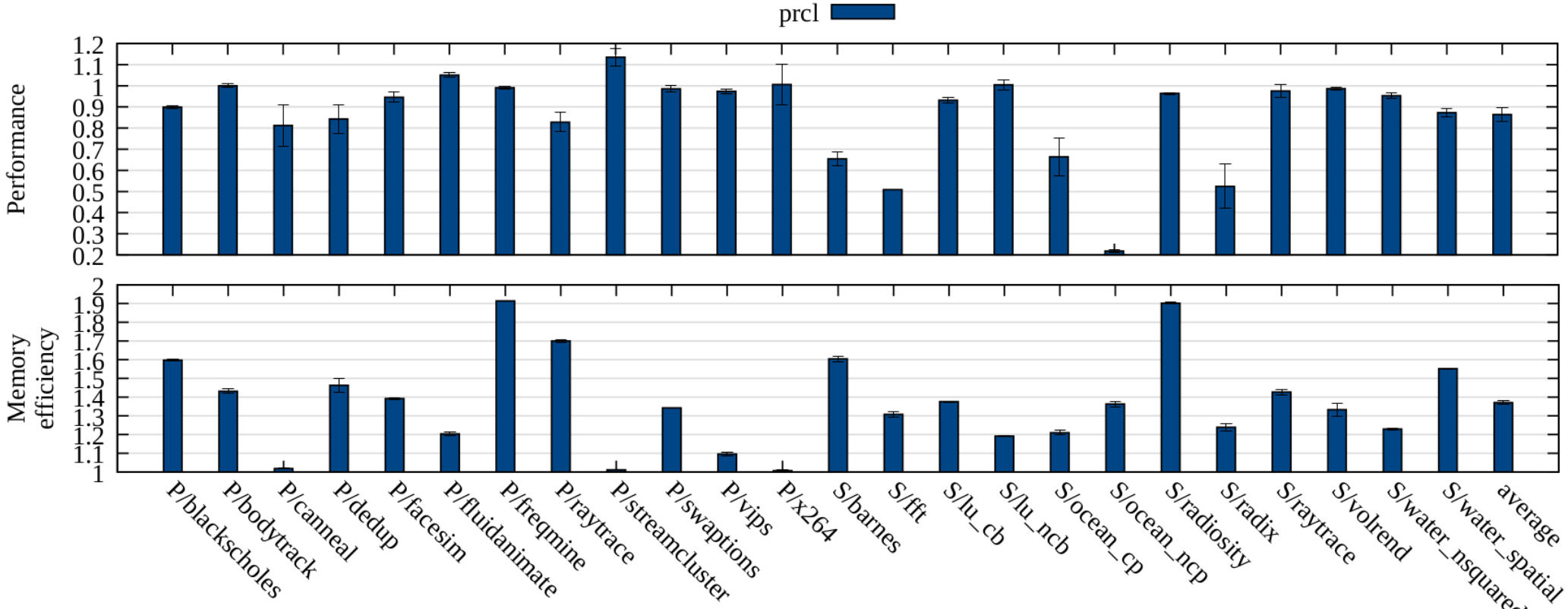


DAMON Accuracy and DAMOS ‘prcl’ Effectiveness

- On average, ‘prcl’ saves 37.10% memory with 13.66% slowdown
  - On the best case (‘parsec3/freqmine’), 91.34% memory saving with 0.91% slowdown
  - On the worst case (‘splash-2x/ocean_ncp’), 36.29% memory saving with 78.16% slowdown; coldness threshold would need to be longer



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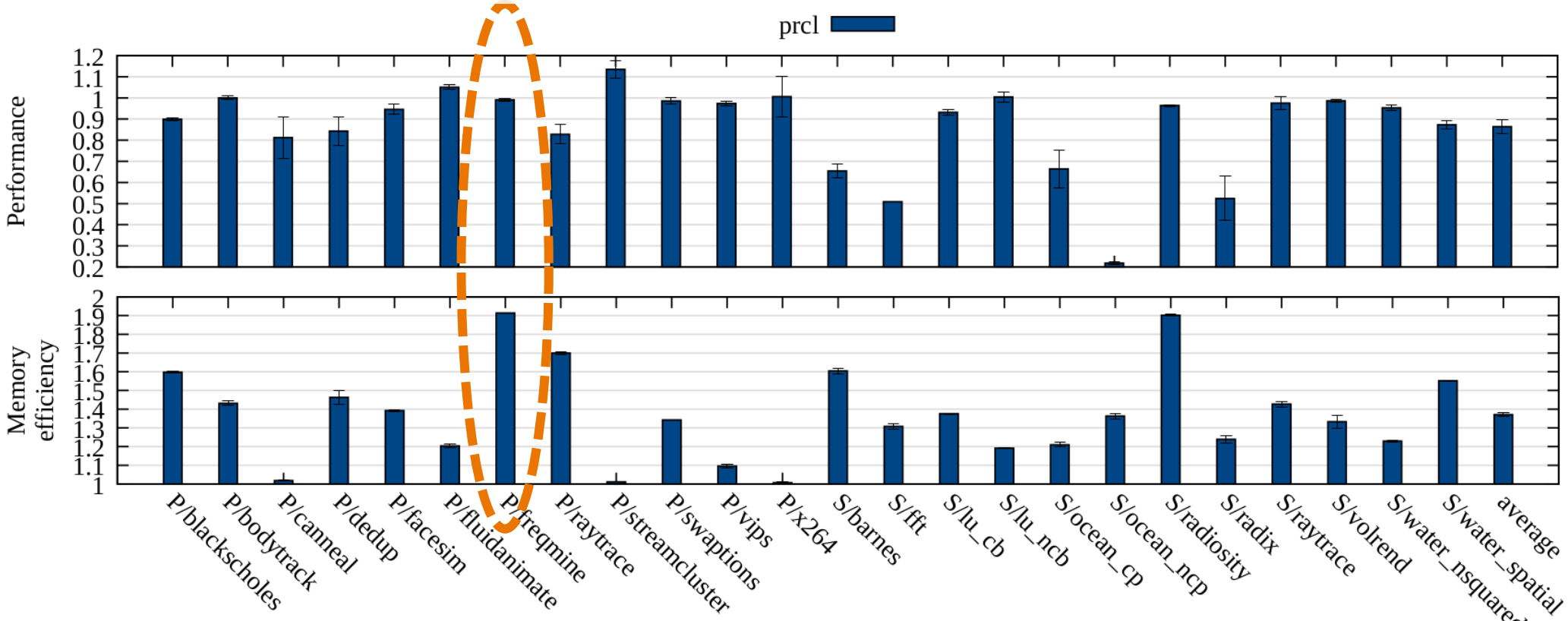

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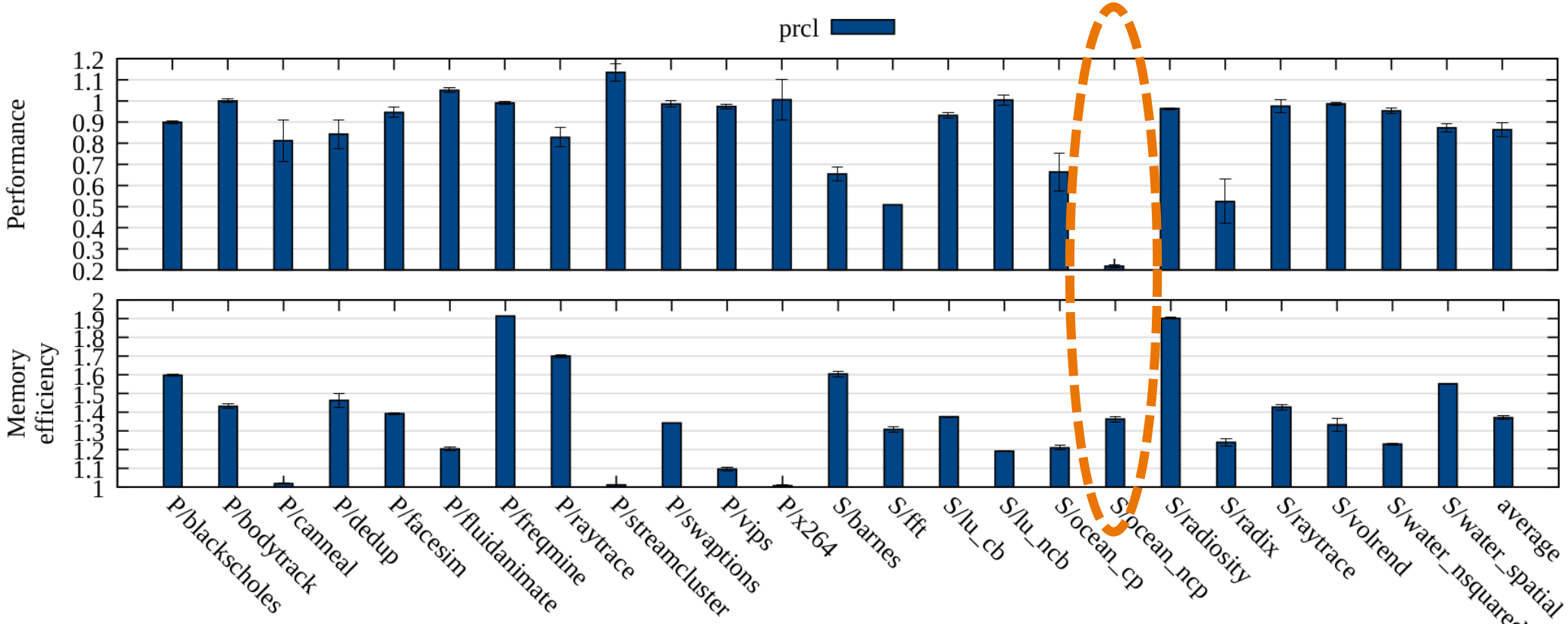


Conclusion from DAMON/DAMOS Evaluation

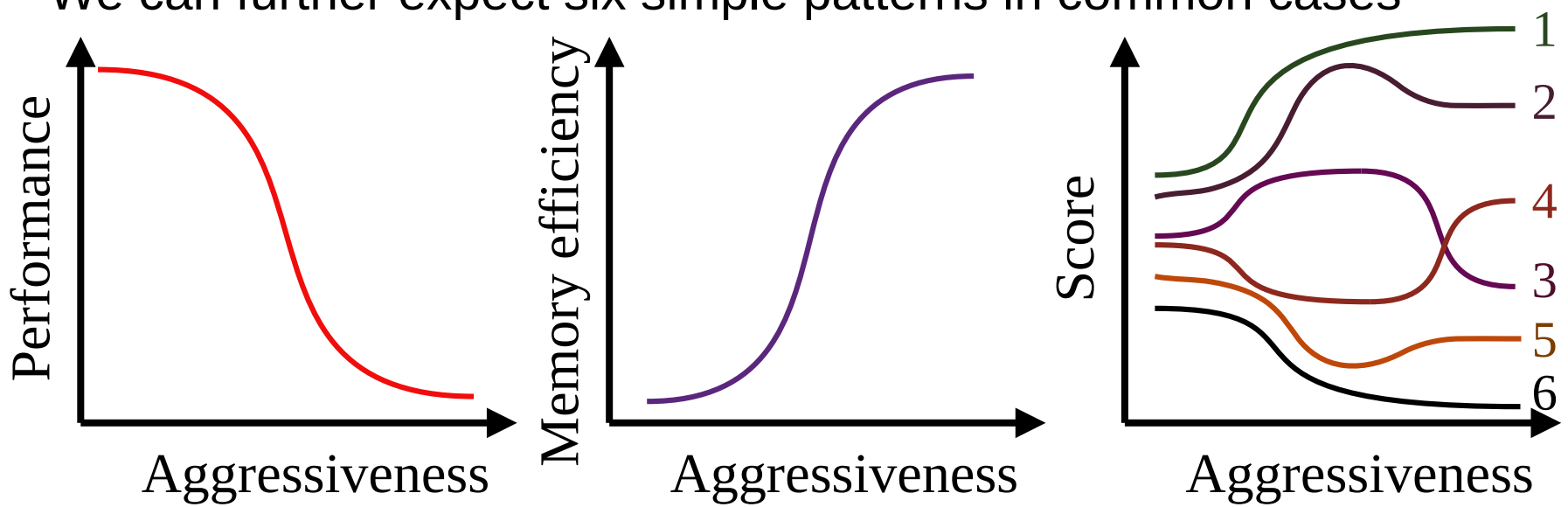
- DAMON is lightweight, scalable, and accurate for DRAM level optimization
- DAMOS is effective, but needs fine tuning for each workload
  - This would be not trivial works; Should we do that every time?

Why Searching Optimal Operation Schemes Is Difficult

- Depends on both h/w and s/w characteristics
  - Need to tune for each application on each system
- Many parameters to consider and tune
  - TLB miss, pgmajfaults, CPU usage, swap i/o, PSI, …
    - Target access pattern itself is constructed with six data points
  - Essentially this problem is multi-dimensional search problem

Simplifying The Problem

- We care only memory efficiency and performance at last
  - These can be consolidated into one metric (score) with different priorities
  - Giving the metrics and priorities could be easy for users (like SLO)
- The target access pattern is only the aggressiveness of the scheme
- The multi-dimension search space can be reduced to 2-dimension
  - Aggressiveness as X-axis, Score as Y-axis
- We can further expect six simple patterns in common cases



DAMOOS: Auto-tuning Runtime for DAOS

- Receives
  - A workload to run
  - Methods for measuring the performance and memory efficiency
  - The score function for the workload
  - Unit work time of the workload
    - The time to wait before getting performance and memory efficiency
  - Time limit for the tuning
- Finds the best DAMOS scheme for the score function in the time limit and starts the workload with the scheme

DAMOOS: Sampling (Example: ‘prcl’)

- Calculate how many times we can measure the score for different aggressiveness (‘nr_samples’)
  - The user-specified tuning time limit divided by the unit work time
- Run the workload with 60% of ‘nr_samples’ schemes having random aggressiveness and measure one score for each scheme
- Run the workload with 40% of ‘nr_samples’ schemes having random but near to the best of the 60% sample results aggressiveness

‘prcl’ example. Measured line is what we measured later (DAMOOS don’t know it)

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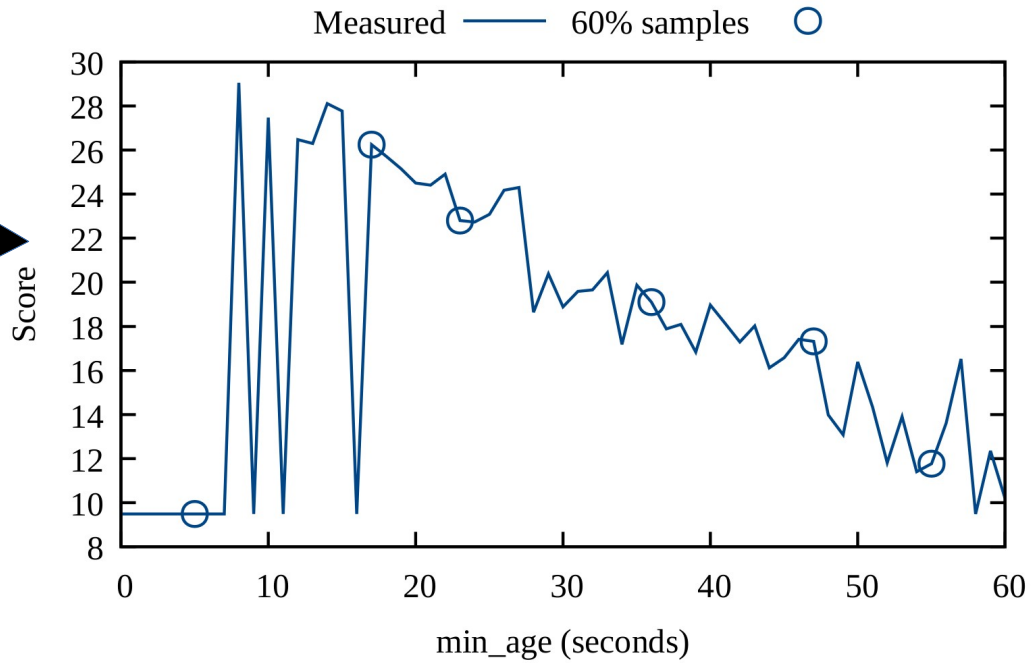

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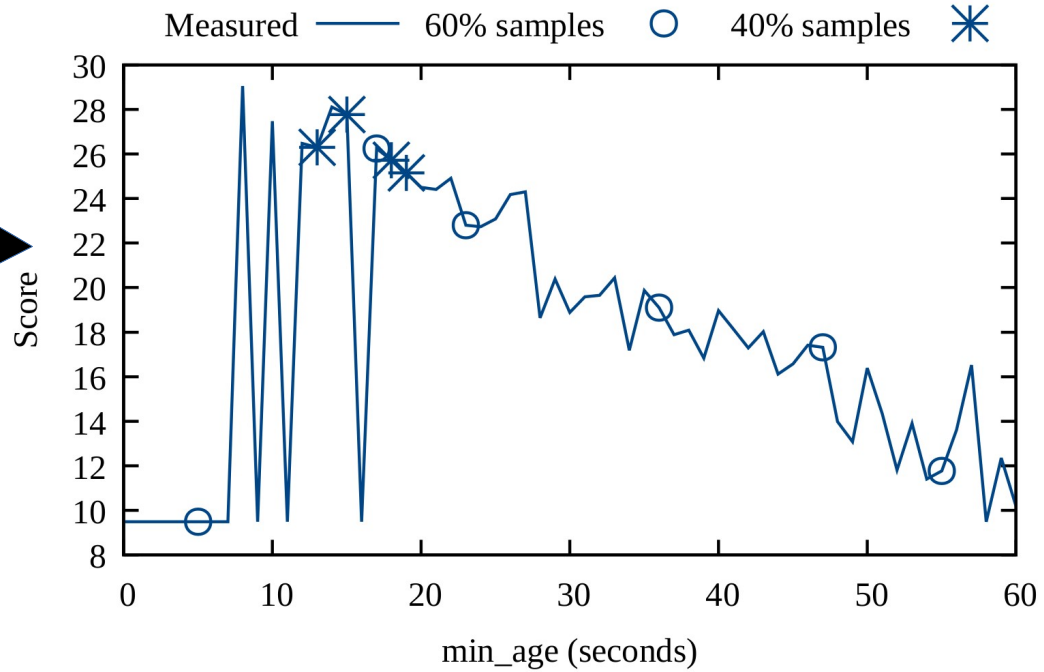

DAMOOS: Estimation and Best Scheme Selection

- Find the relationship between the aggressiveness and score by applying Polynomial curve fitting to the ‘nr_samples’ data points
- On the curve, we find an aggressiveness value that generates maximum score and use it as the best scheme aggressiveness

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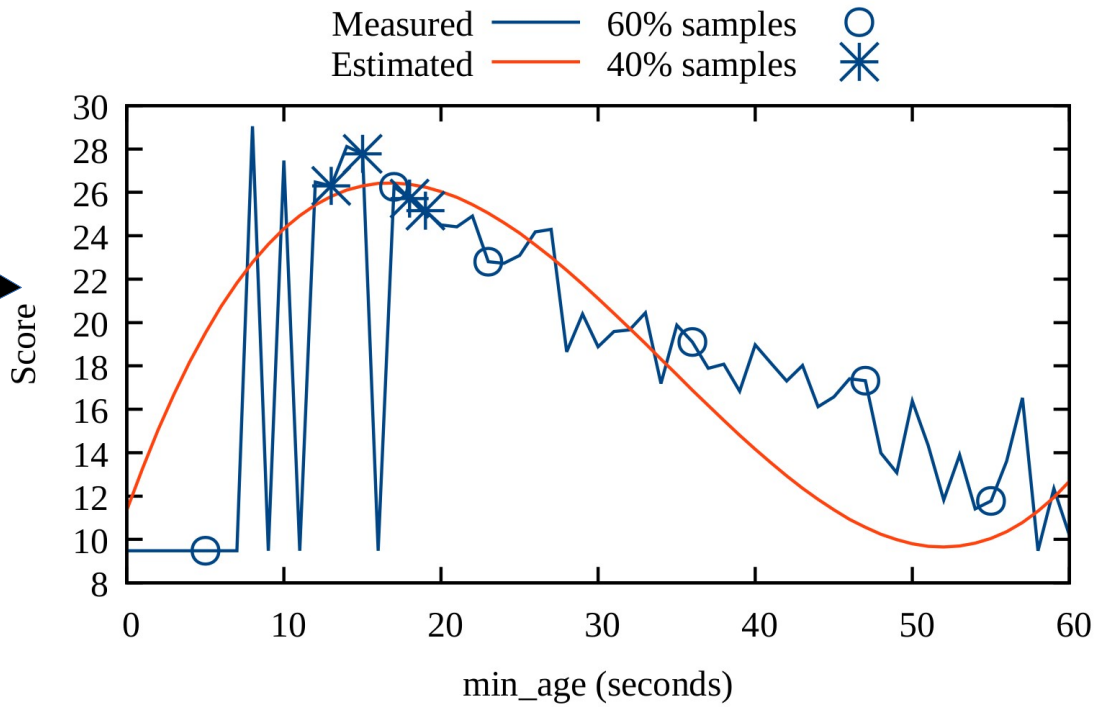
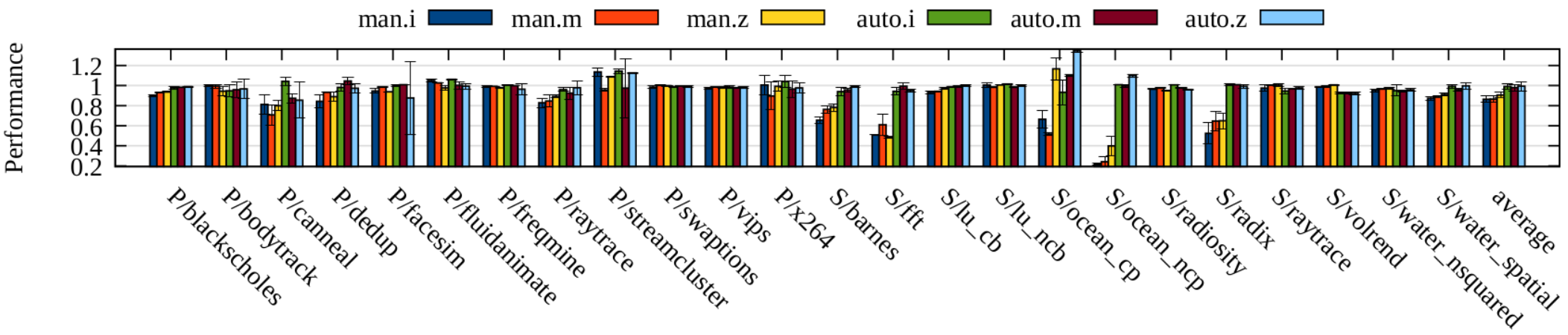


DAMOOS Evaluation Setup

- Basically same to the DAMON/DAMOS evaluation setup
- Adds two more AWS EC2 instance types to show if DAMOOS works for different hardware types
- In total, three types of hardware are used
  - I3.metal: 3 GHz x 36 vCPUs, 128 GiB DRAM (i/o optimized)
  - M5d.metal: 3.1 GHz x 48 vCPUs, 96 GiB DRAM (general purpose optimized)
  - Z1d.metal: 4.0 GHz x 24 vCPUs, 96 GiB DRAM (computing optimized)
- Use ‘prcl’ only
- The score function is focused on avoiding >10% performance drop
  - For detail, please read the paper

DAMOOS Evaluation Results for ‘prcl’: Performance

- Average performance drops on the three h/w
  - Manual-tuned: 13.65%, 13.45%, 9.54%
  - Auto-tuned: 0.91%, 2.04%, 0.59%
- DAOS’s auto-tuning removes 93.33%, 84.83%, and 93.81% of the slowdown of manual version on the three h/w, respectively
  - The 10% performance drop SLO is almost always kept



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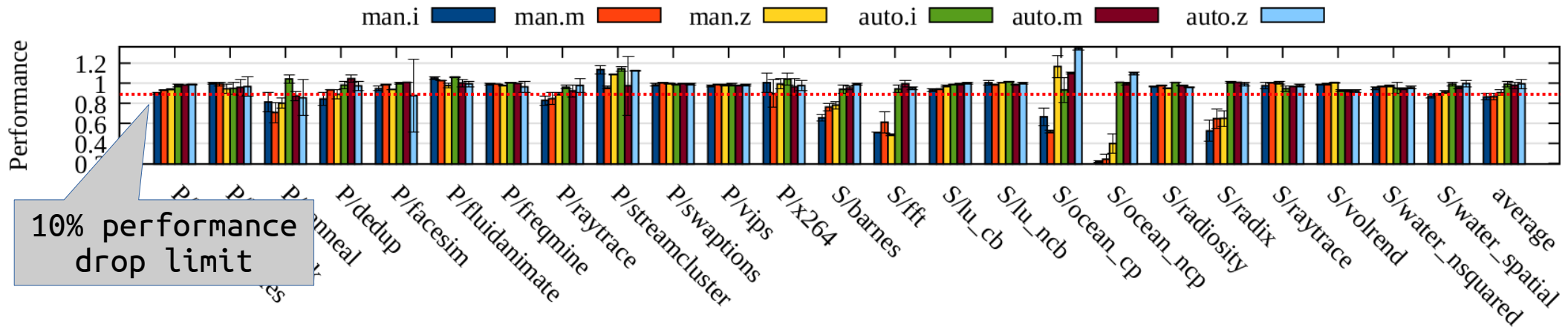
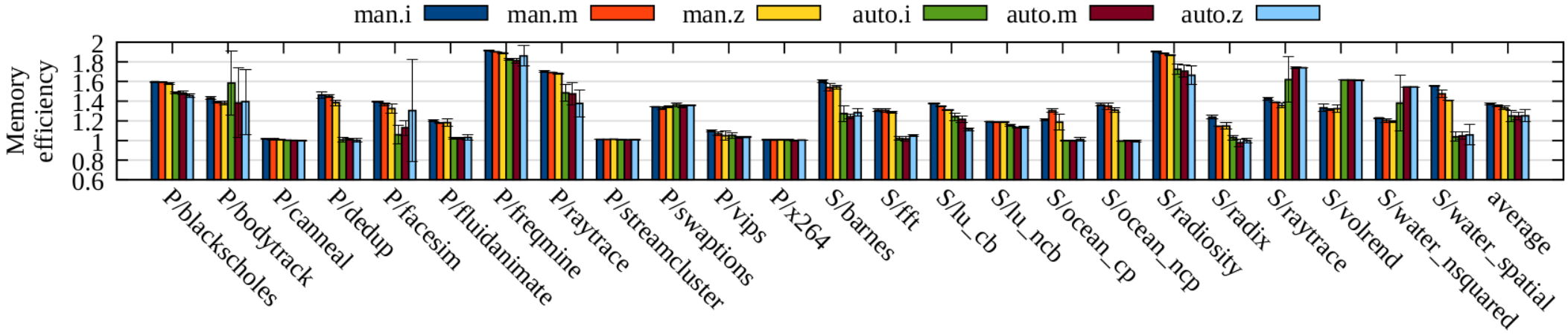


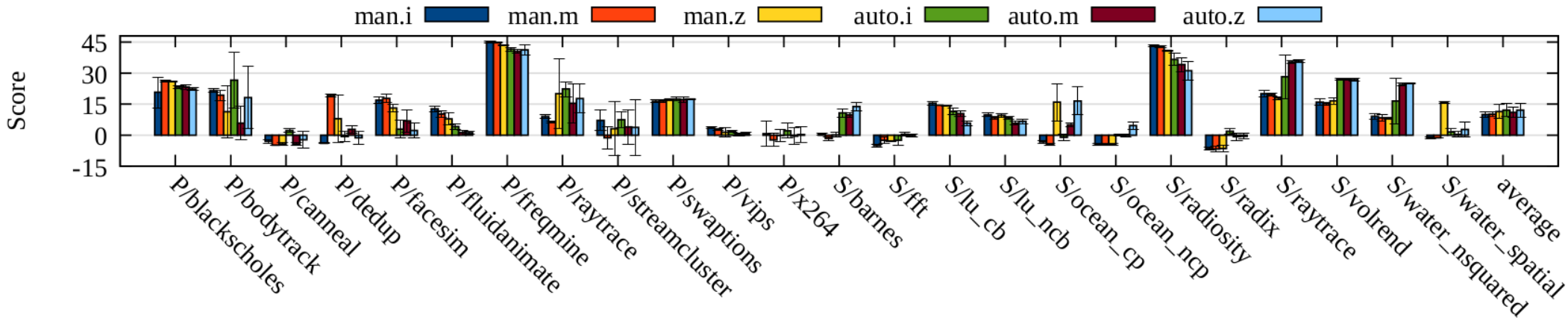
DAMOOS Evaluation Results for ‘prcl’: Memory Saving

- Average memory saving on the three h/w types
  - Manually-tuned: 37.10%, 35.21%, 33.22%
  - Auto-tuned: 24.97%, 24.73%, 25.10%
- Auto-tuned version’s memory saving is lower than those of manual version
  - Because the score function gives more priority to performance
  - Memory saving could increase if we adjust the priorities



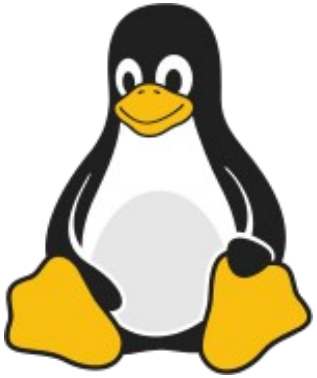
DAMOOS Evaluation Results for ‘prcl’: Score

- Average score on the three h/w types
  - Manually-tuned: 9.99, 10.09, 11.35
  - Auto-tuned: 12.08, 11.01, 12.06
- Auto-tuning runtime obtains score improvements of 20.02%, 6.16%, and 6.25%



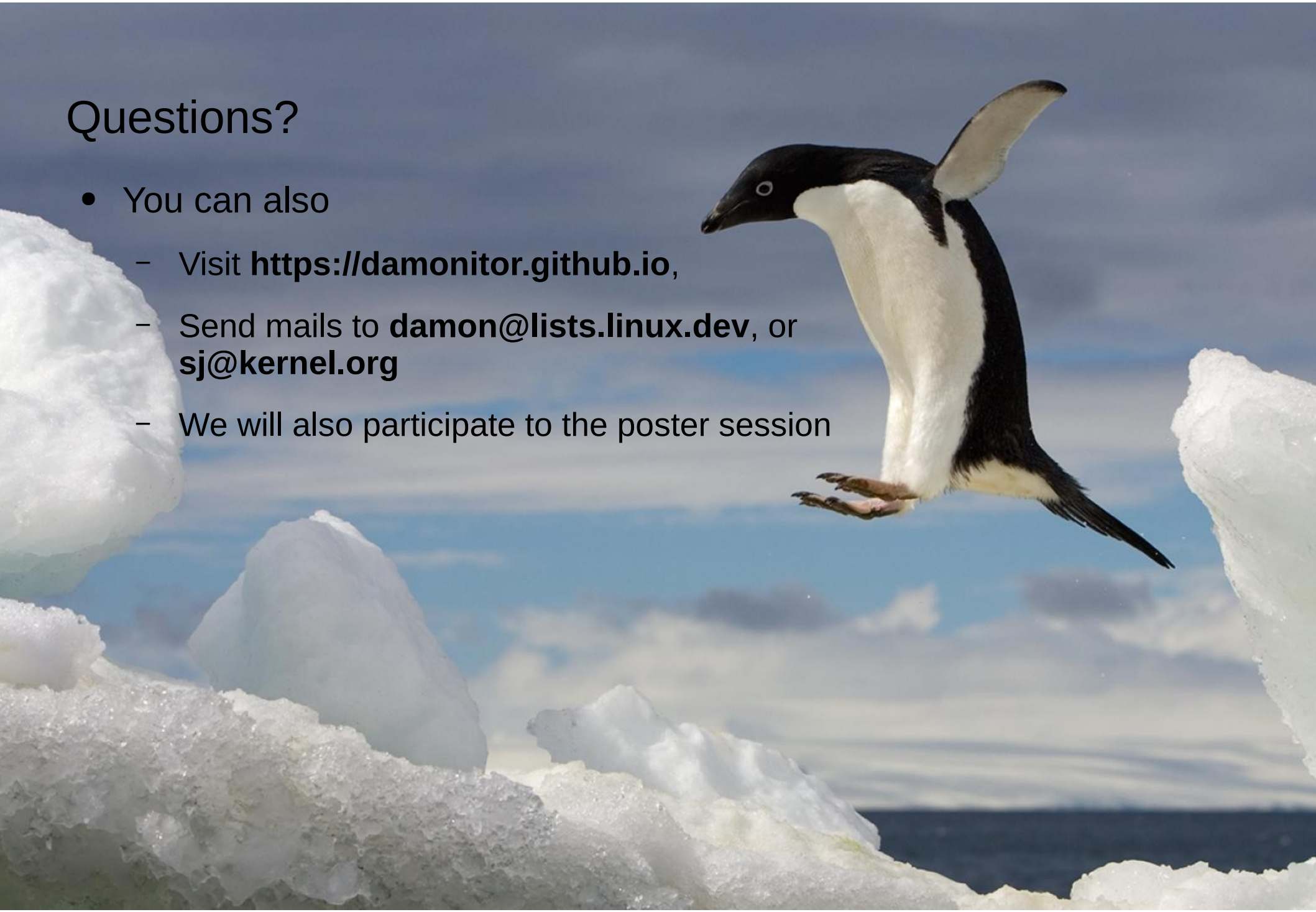
Conclusion

- DAOS is a data access-aware operating system that constructed with three simple pieces
  - DAMON provides best-effort accurate access patterns with lightweight and upper-bound-limited overhead
  - DAMOS allows general access-aware memory management with no difficult, danger, dirty code
  - DAMOOS provides a runtime that provides auto-tuned data access-aware memory management scheme within a finite time
- All parts of DAOS are opensource
  - DAMON and DAMOS are merged in the mainline Linux kernel
  - DAMOOS is available at github
  - Visit https://github.com/damonitor for quick start



Questions?

- You can also
  - Visit **https://damonitor.github.io**,
  - Send mails to **damon@lists.linux.dev**, or **sj@kernel.org**
  - We will also participate to the poster session



https://kids.nationalgeographic.com/content/dam/kids/photos/animals/Birds/A-G/adelie-penguin-jumping-ocean.ngsversion.1396530997321.adapt.1900.1.jpg

Backup Slides

DAMON: Resulting Architecture

- Core logic and monitoring operations layer are separated
  - Multiple address spaces and usages can easily supported
  - Current version of DAMON supports virtual address spaces and the physical address space