Expanding CXL Software Ecosystem through HMSDK on Linux

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Expanding CXL Software Ecosystem through HMSDK on Linux

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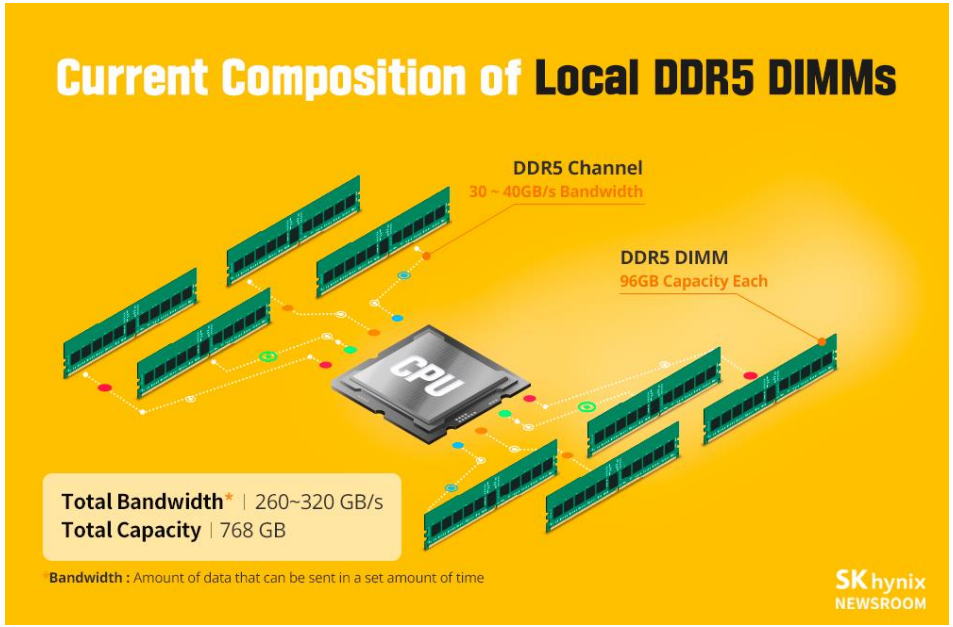
SK hynix

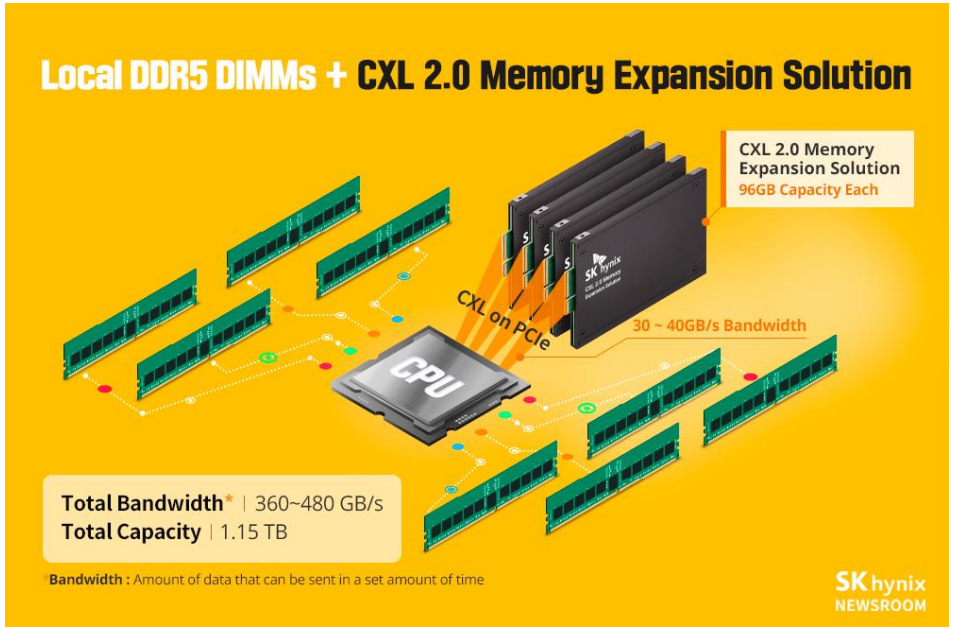
Conventional (Homogeneous) Memory System

- Most systems have the same type of memory in their DIMM slots.
  - It just works without software support.



Heterogeneous Memory System

- CXL memory allows bandwidth/capacity expansion beyond DIMM slot limits.
  - But it requires software support for efficient use.



Software Support for CXL Memory

- CXL driver level support.
  - In Linux kernel, CXL device driver is at ***linux/drivers/cxl***.

- Memory management(mm) support for the efficient use.
  - Based on NUMA abstraction
    - CXL memory is detected as a cpuless NUMA node.
  - We're working on this under HMSDK project.

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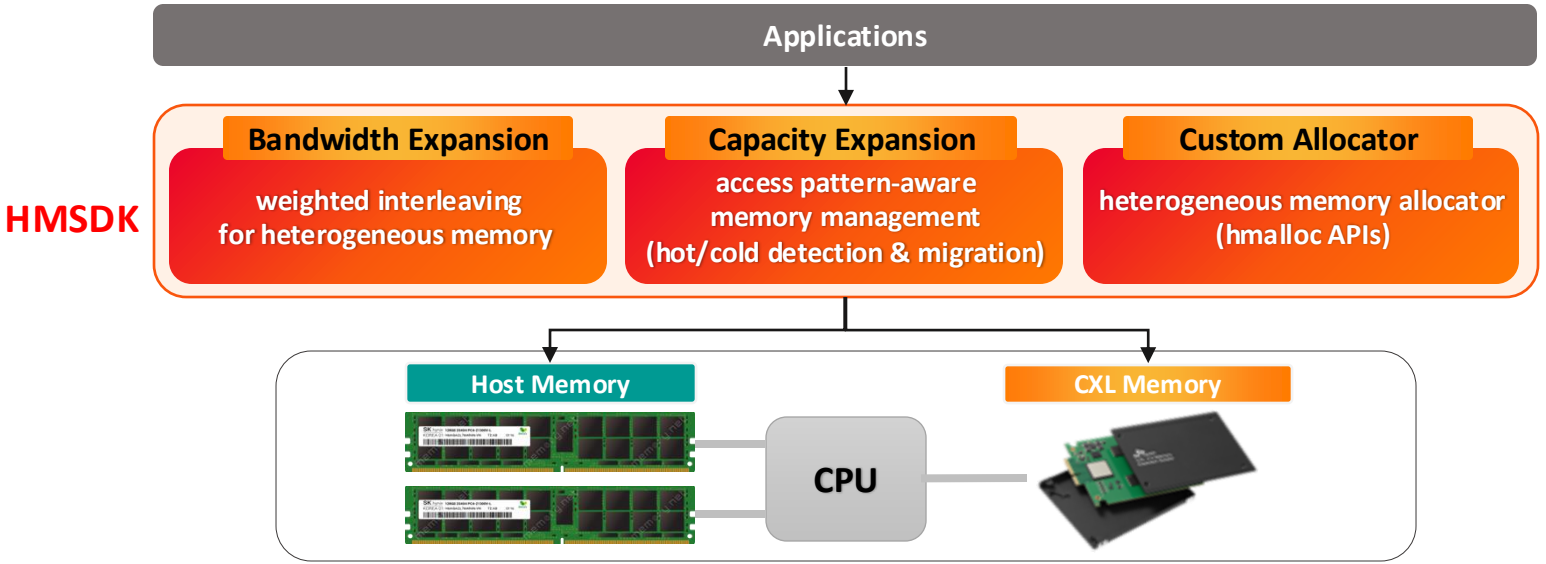
- Heterogeneous Memory Software Development Kit



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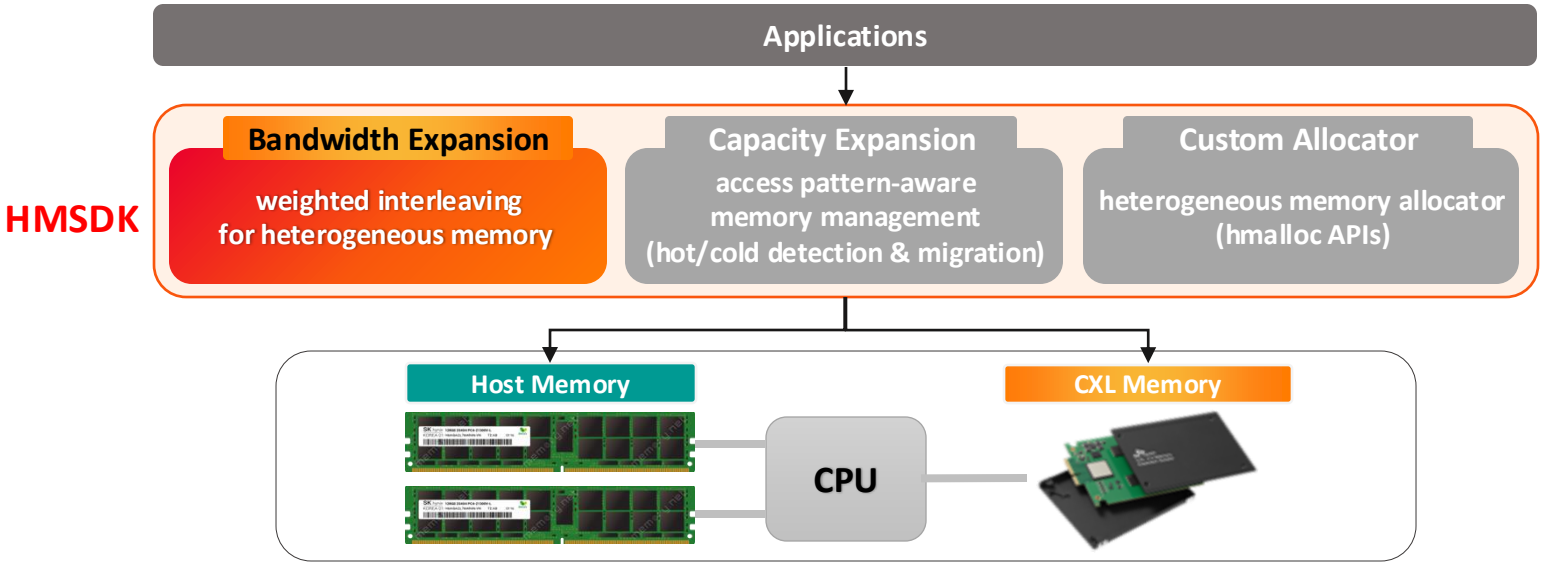
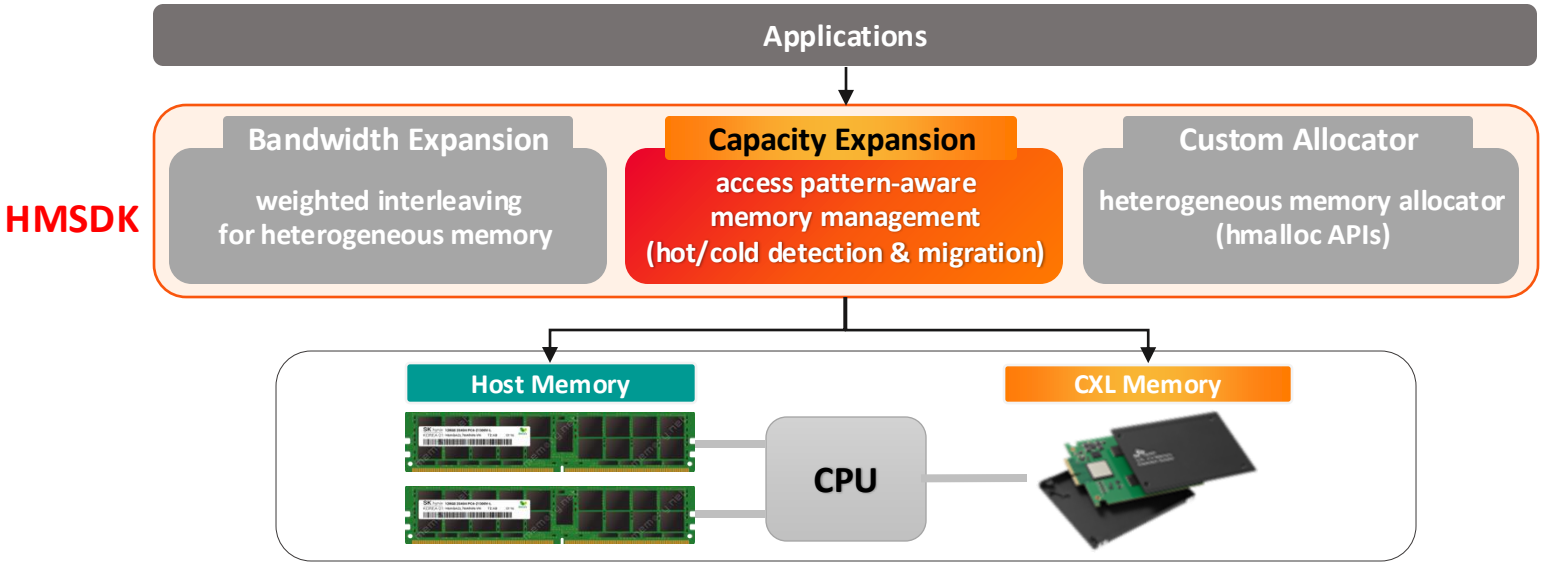
- **Bandwidth Expansion** is used when target workloads are **bandwidth hungry**.
  - Achieve speed up for bandwidth-intensive workloads.



HMSDK

- **Capacity Expansion** is used when target workloads **needs more capacity**.
  - Expand capacity with CXL memory minimizing the additional latency issue.



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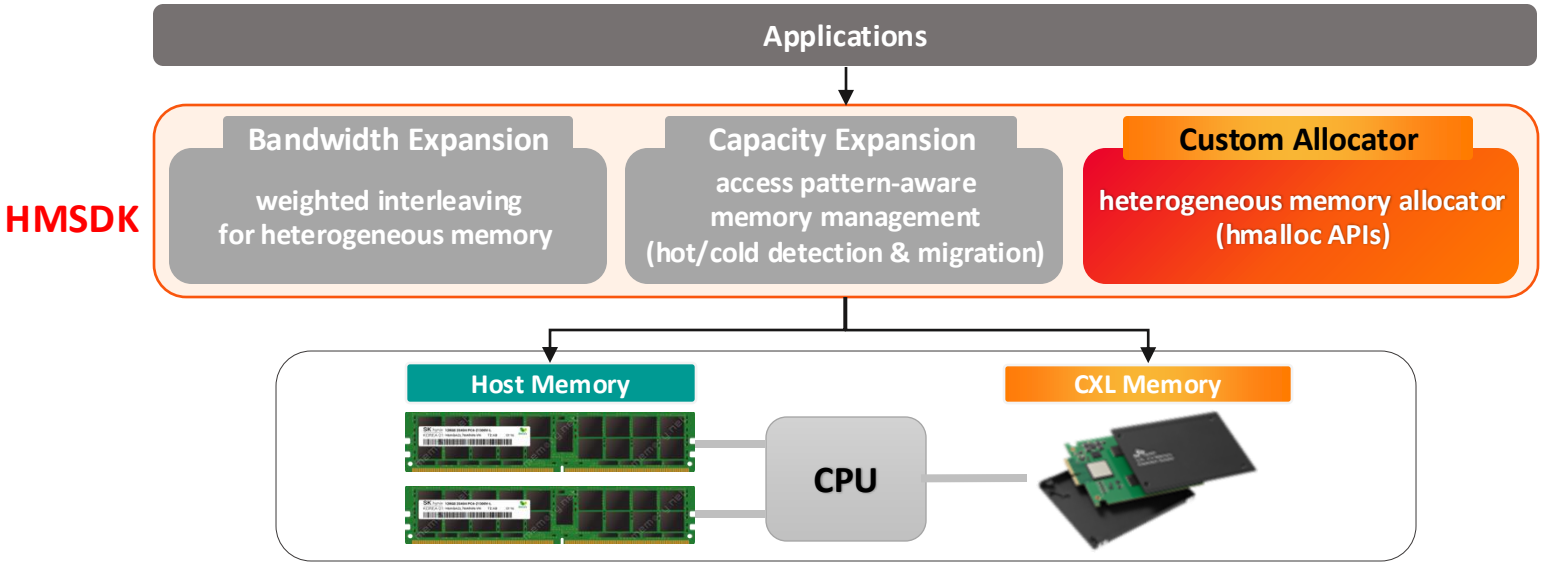
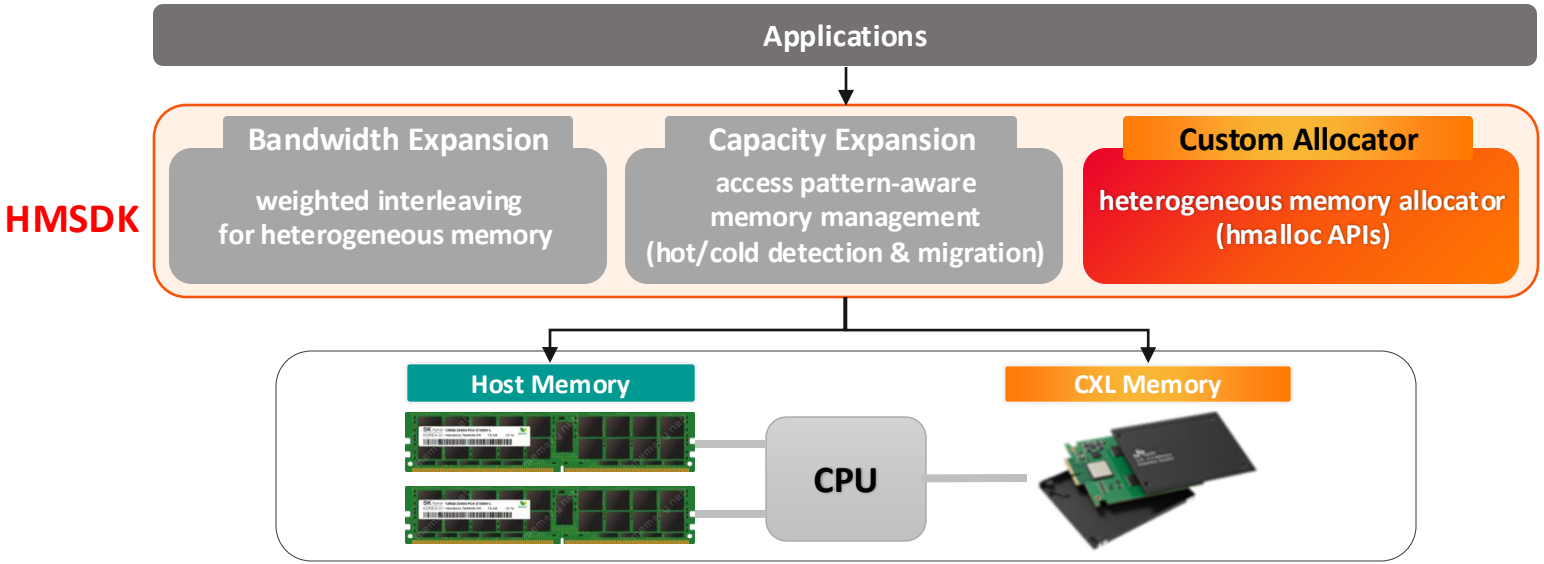
- **Custom Allocator** is used when **users have knowledge of their programs**.
  - With customized programs using **hmalloc APIs** such as ***hmalloc()***, ***hfree()***, etc.



HMSDK

- Custom allocator **requires software modification**.



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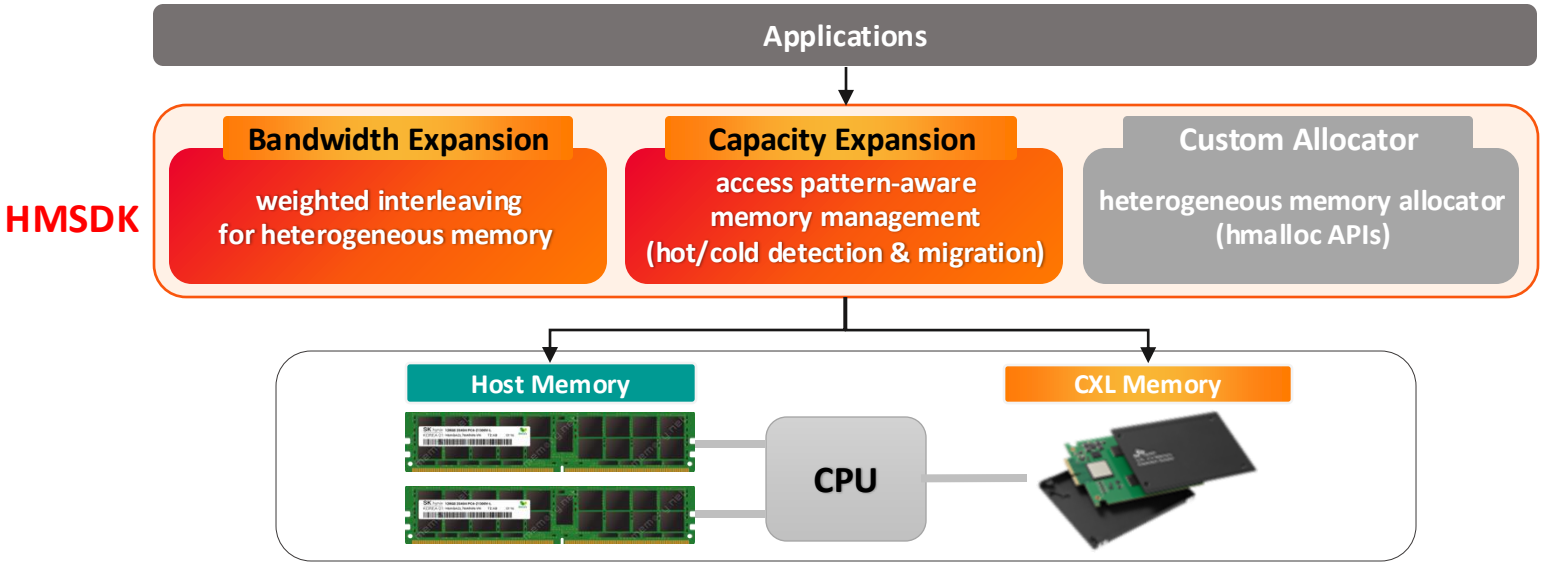
- Bandwidth and capacity expansion **DO NOT require software modification**.
  - Those are OS level techniques.



Bandwidth and Capacity Expansion

- No free lunch for bandwidth and capacity expansion.
  - Unlike DIMM attached host memory.

- Bandwidth can be expanded with default 1:1 interleaving.
  - But may not utilize the full bandwidth of host memory.

- Capacity can be expanded but there can be performance issues.
  - Frequently accessed data might stay in CXL memory.

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    -> Weighted interleave

- Capacity can be expanded but there can be performance issues.
  - Frequently accessed data might stay in CXL memory.

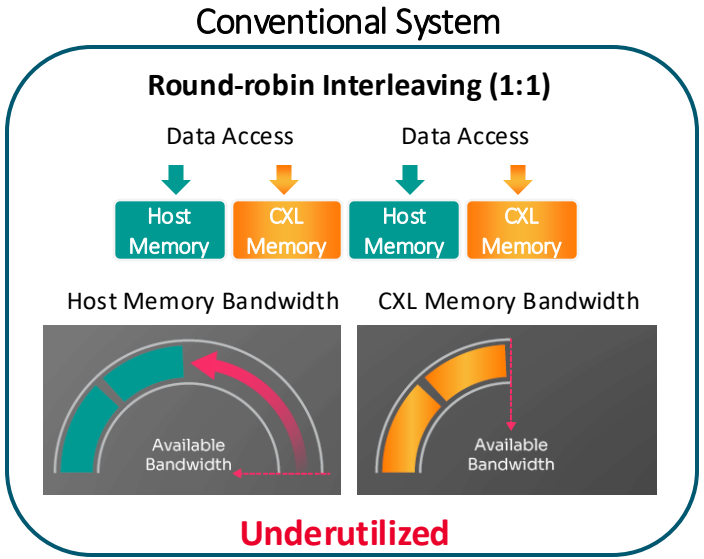
    -> Memory access pattern based migration

Bandwidth Expansion

Achieve speed up for bandwidth-intensive workloads

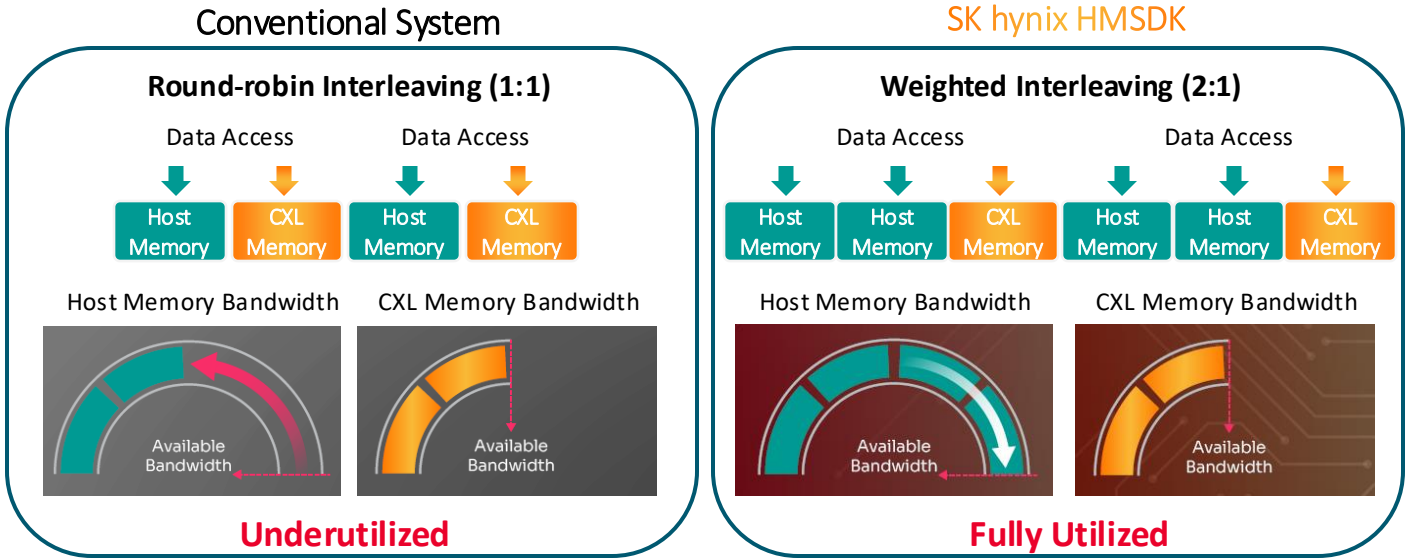
Bandwidth Expansion (via round-robin interleave)

- Bandwidth can be expanded with conventional 1:1 interleaving.
  - But it may not utilize the full bandwidth of host memory.



Bandwidth Expansion (via weighted interleave)

- Bandwidth can be expanded with conventional 1:1 interleaving.
  - But it may not utilize the full bandwidth of host memory.
  - Weighted interleaving is needed to handle the bandwidth difference.



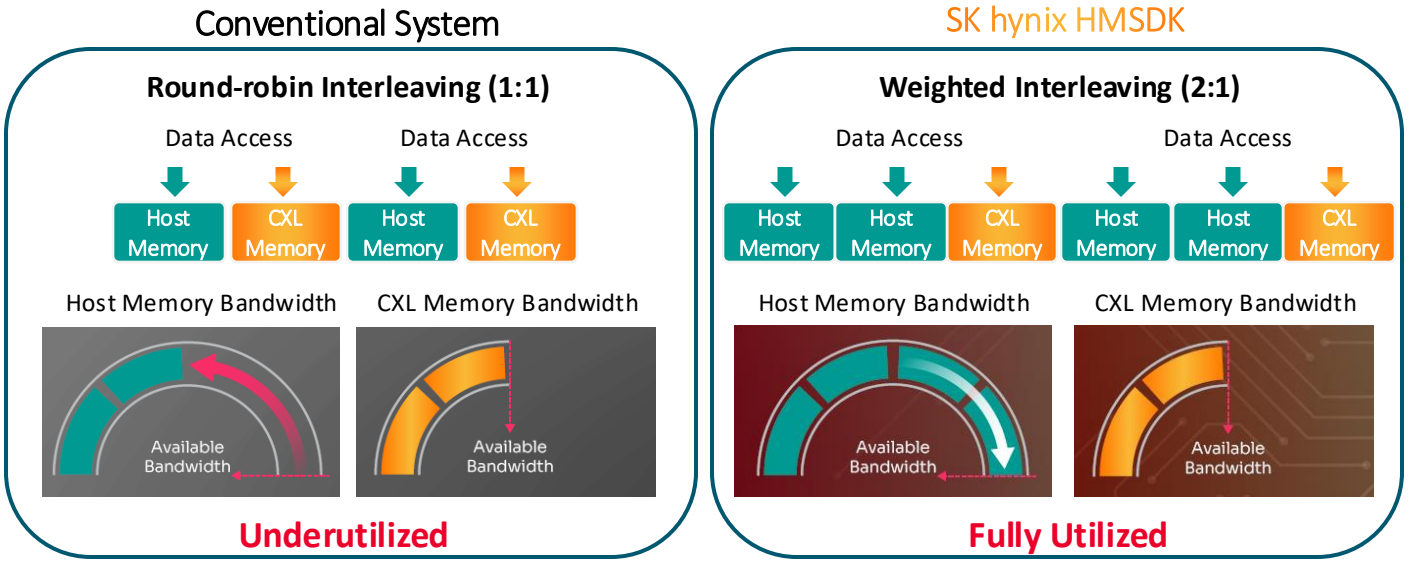
Bandwidth Expansion (via weighted interleave)

- The kernel interface: sysfs interface (**available from v6.9**)
  - ***/sys/kernel/mm/mempolicy/weighted_interleave/nodeN***
    - Where ***N*** is a node number.
    - It stores a value for weight.

- The user interface: ***numactl -w/--weighted-interleave <nodes>*** option.
  - Set the mempolicy to ***MPOL_WEIGHTED_INTERLEAVE***.
  - Set ***nodemask*** for the given NUMA ***nodes***.

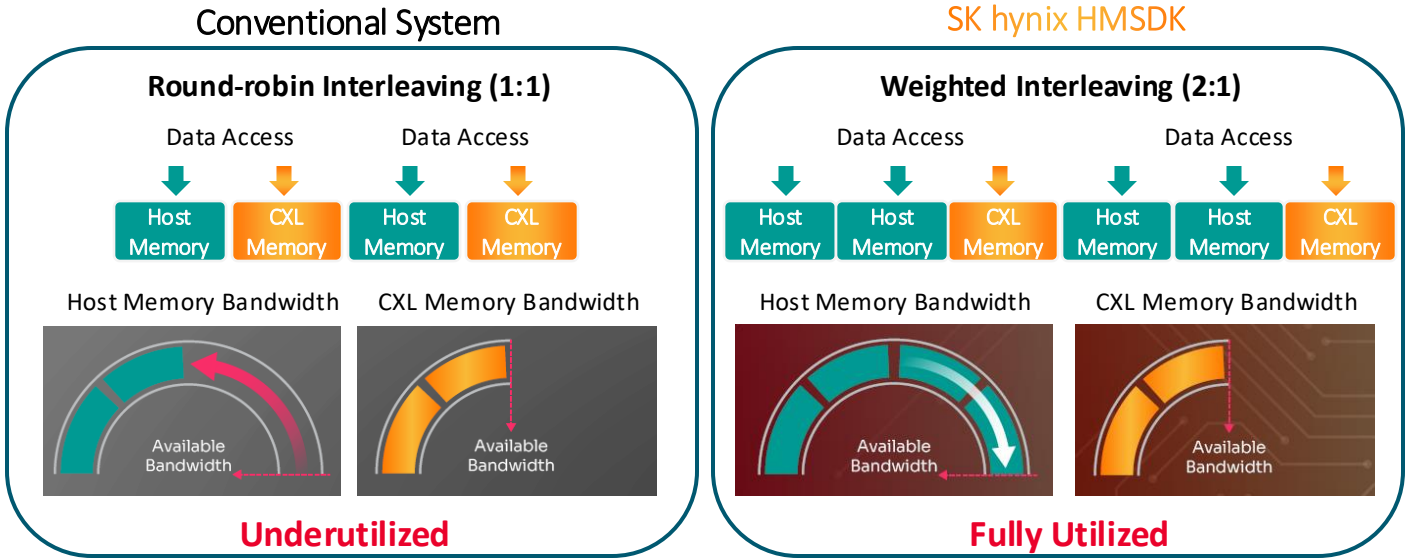
Bandwidth Expansion (via weighted interleave)

- Bandwidth can be expanded with weighted interleaving. (e.g. 2:1 interleaving)
  - `echo 2 > /sys/kernel/mm/mempolicy/weighted_interleave/node0  # DRAM node`
  - `echo 1 > /sys/kernel/mm/mempolicy/weighted_interleave/node1  # CXL node`



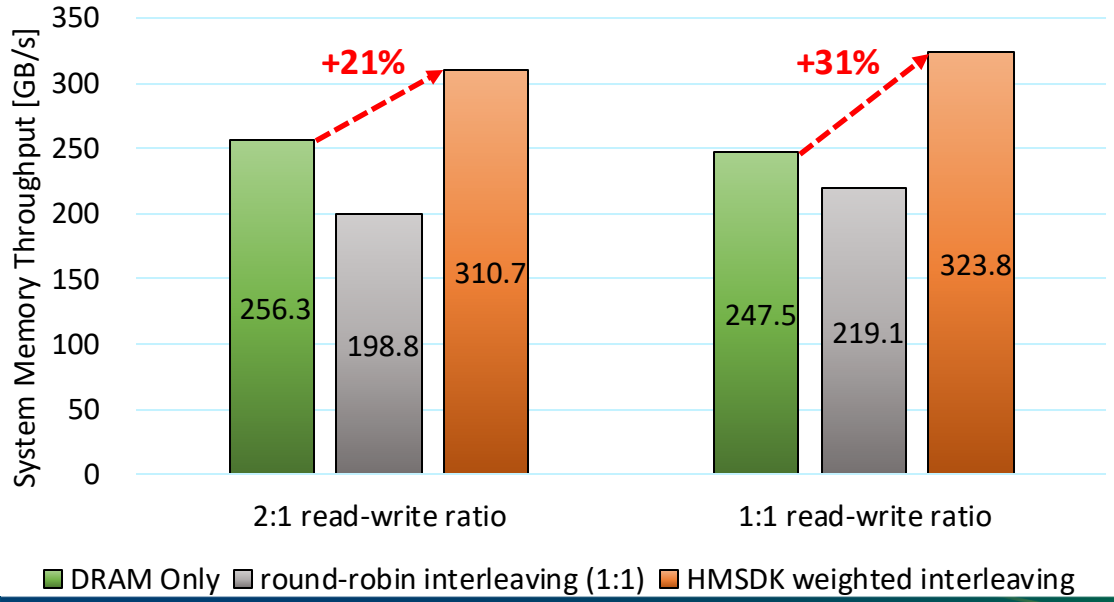
Bandwidth Expansion (via weighted interleave)

- Then run the target program, ***<prog>***, with ***numactl*** as follows.
  - ***numactl --weighted-interleave 0,1 <prog>***
    - It reads weights for **node0** and **node1** then run ***<prog>*** in weighted interleave mode.



Bandwidth Expansion (via weighted interleave)

- Experimental result using Intel MLC tool.
  - 8:3 weighted interleaving for 8ch DDR5 DRAM + 4ch CMM-DDR5

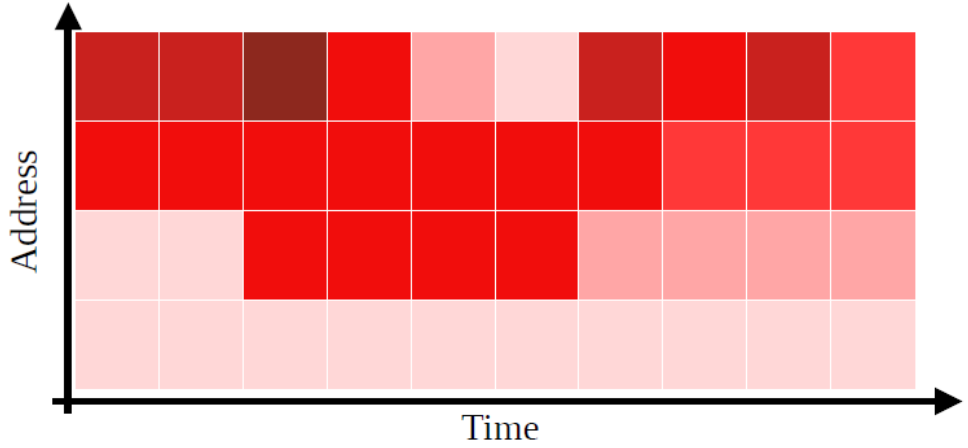


Capacity Expansion

Expand capacity with CXL memory
minimizing the additional latency overhead.

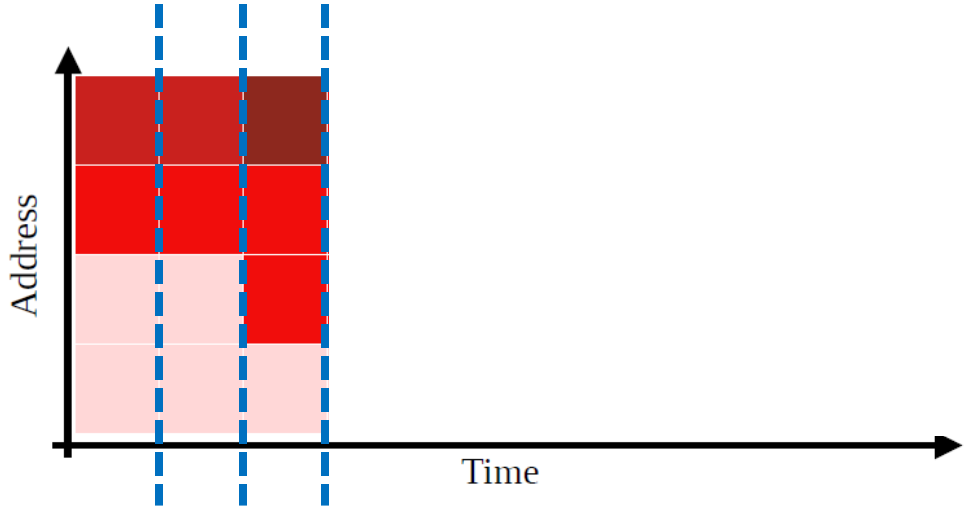
DAMON: Data Access MONitor

- DAMON is a data access monitoring framework in the Linux kernel.
  - Supported from Linux v5.15, released on Nov 2021.
- DAMON allows memory access checks in upper bounded overhead for scalability.
  - But scarifies some accuracy.



DAMOS: DAMON based Operation Schemes

- DAMOS is an access-aware system optimizations engine.
  - Make memory management decision based on DAMON.



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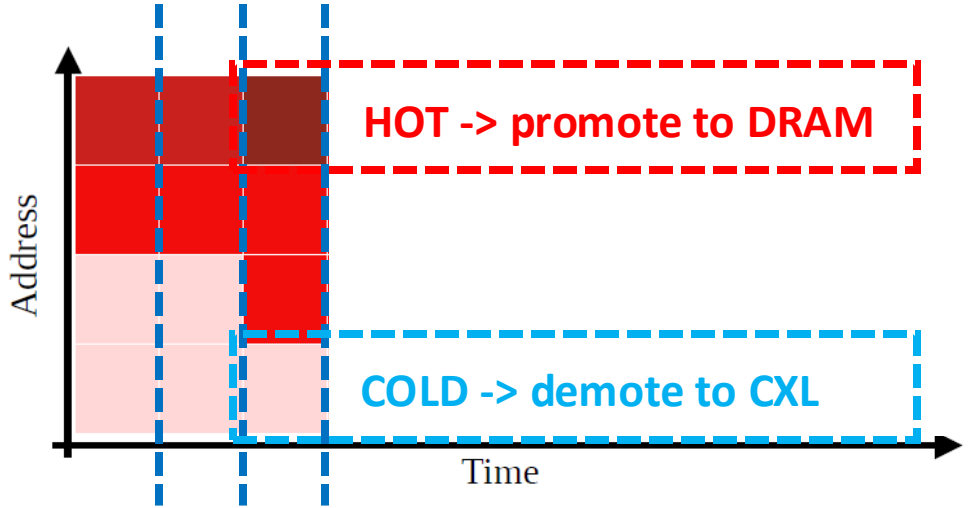

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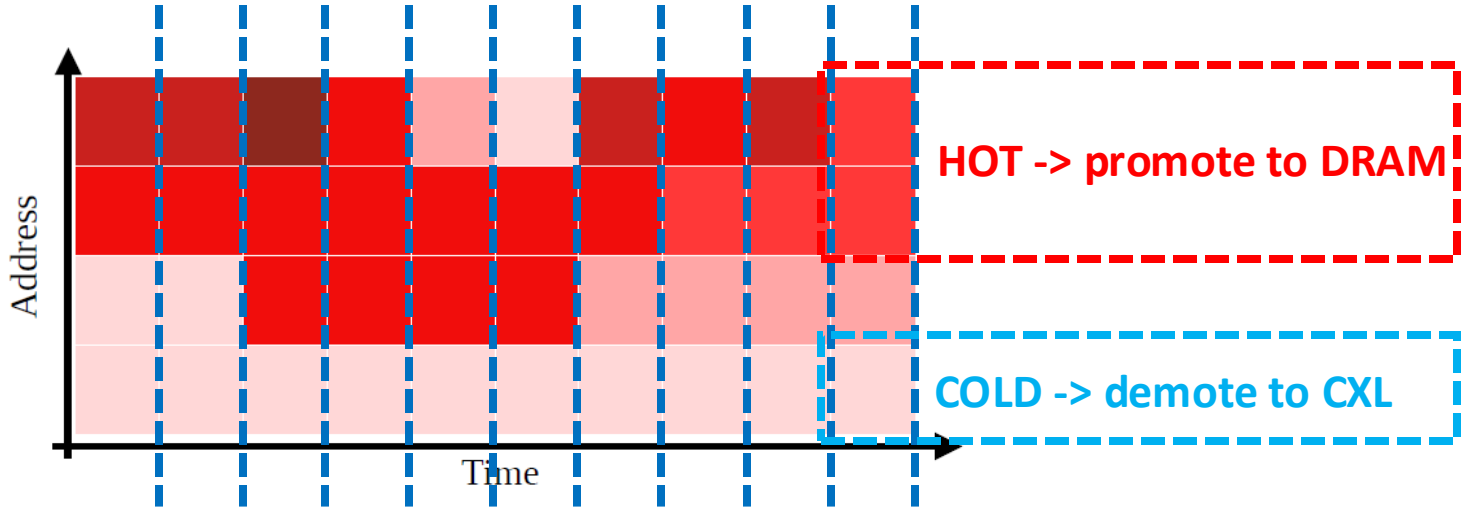

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```
enum damos_action {
    DAMOS_WILLNEED,
    DAMOS_COLD,
    DAMOS_PAGEOUT,
    DAMOS_HUGEPAGE,
    DAMOS_NOHUGEPAGE,
    DAMOS_LRU_PRIO,
    DAMOS_LRU_DEPRIO,


    DAMOS_STAT,
    NR_DAMOS_ACTIONS,
};
```

DAMOS: DAMON based Operation Schemes

- DAMOS is an access-aware system optimizations engine.
  - Make memory management decision based on DAMON.
  - HMSDK implemented migration actions. (**available from Linux v6.11**)

```
enum damos_action {
    DAMOS_WILLNEED,
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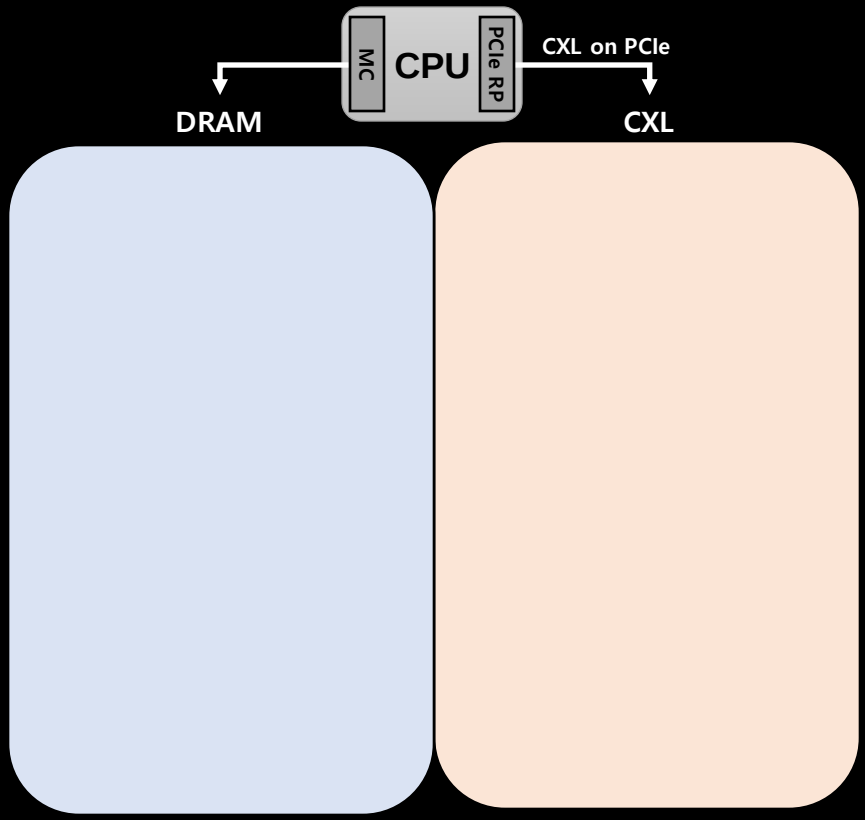
    DAMOS_PAGEOUT,
    DAMOS_HUGEPAGE,
    DAMOS_NOHUGEPAGE,
    DAMOS_LRU_PRIO,
    DAMOS_LRU_DEPRIO,
    DAMOS_MIGRATE_HOT,  // promotion
    DAMOS_MIGRATE_COLD, // demotion
    DAMOS_STAT,
    NR_DAMOS_ACTIONS,
};
```

HMSDK Capacity Expansion



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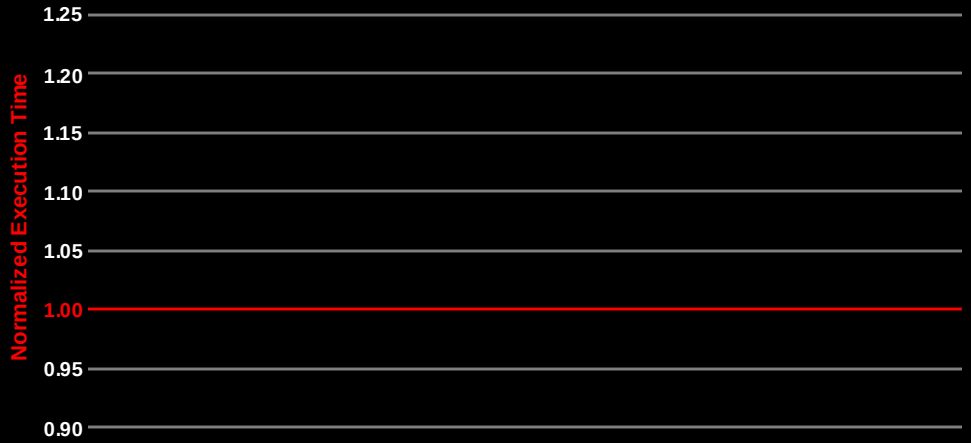

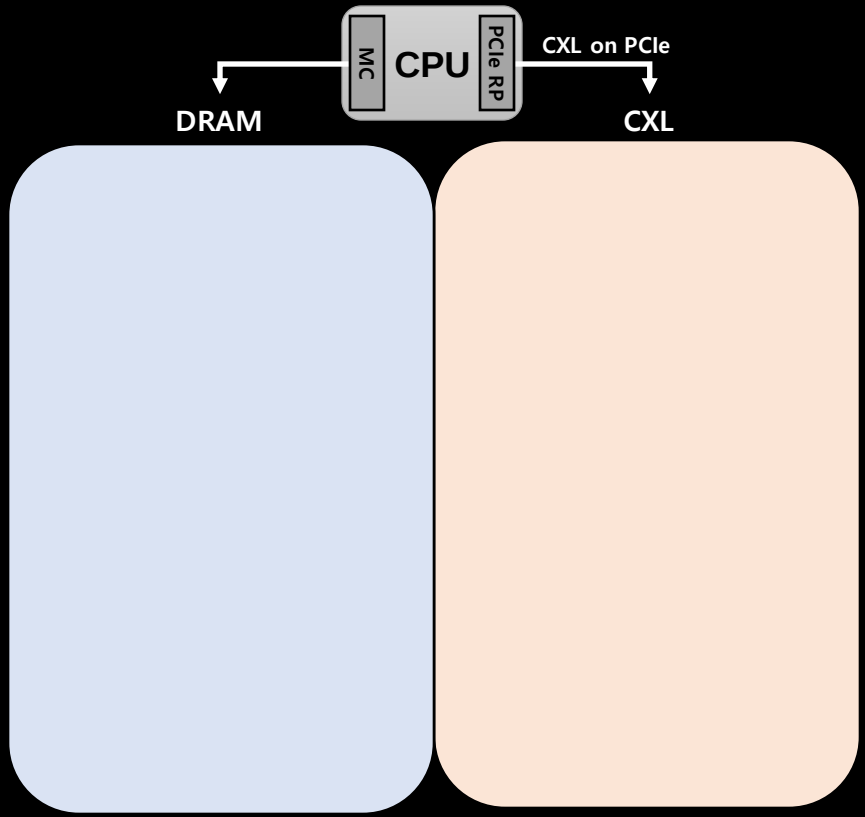

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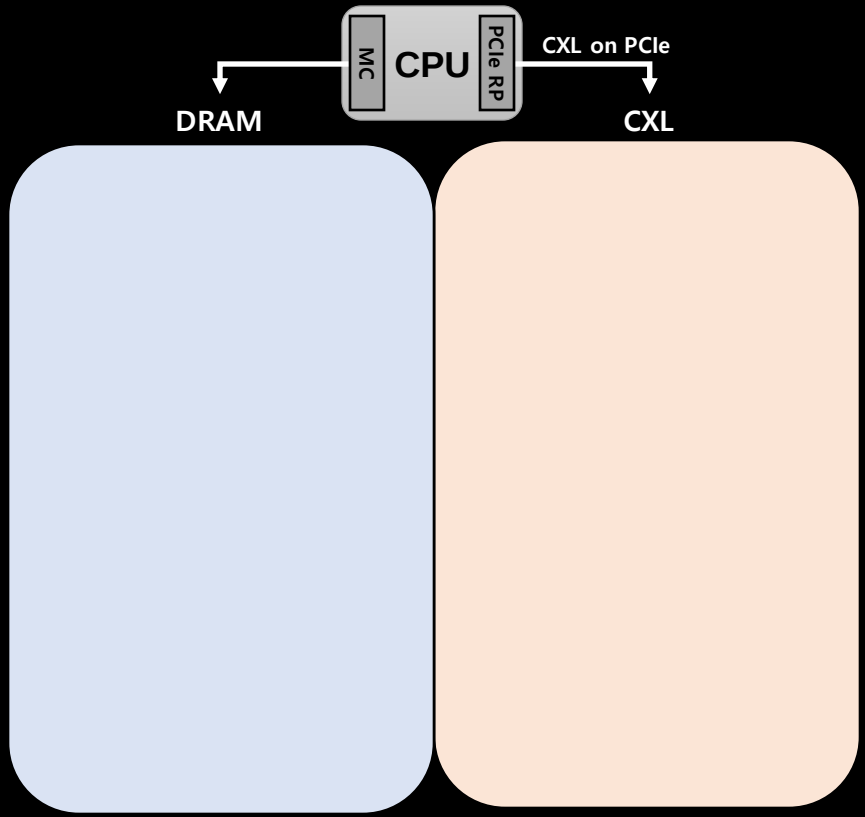

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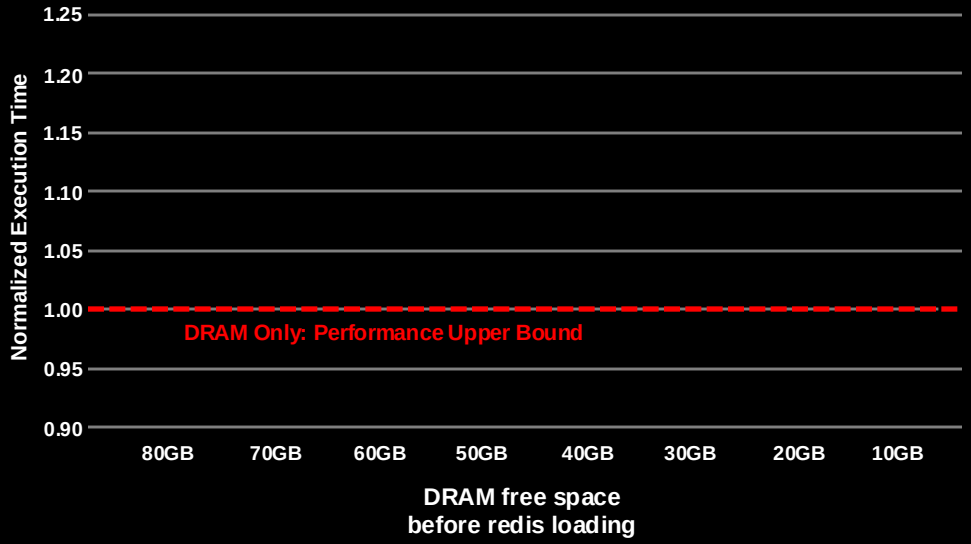

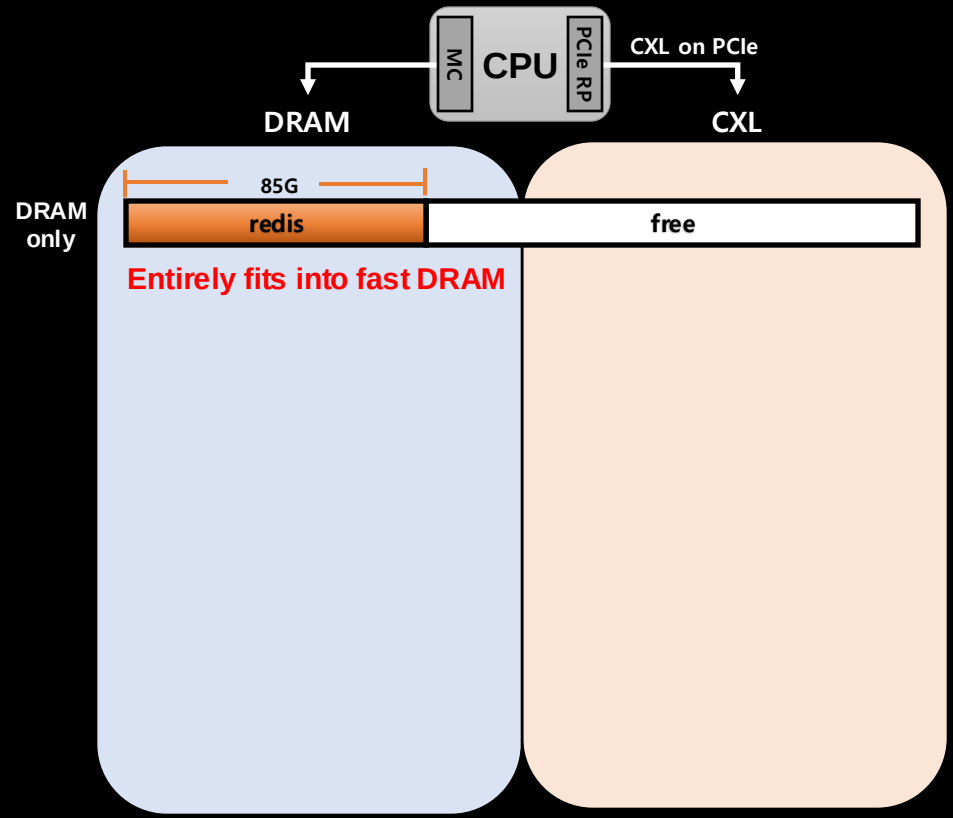

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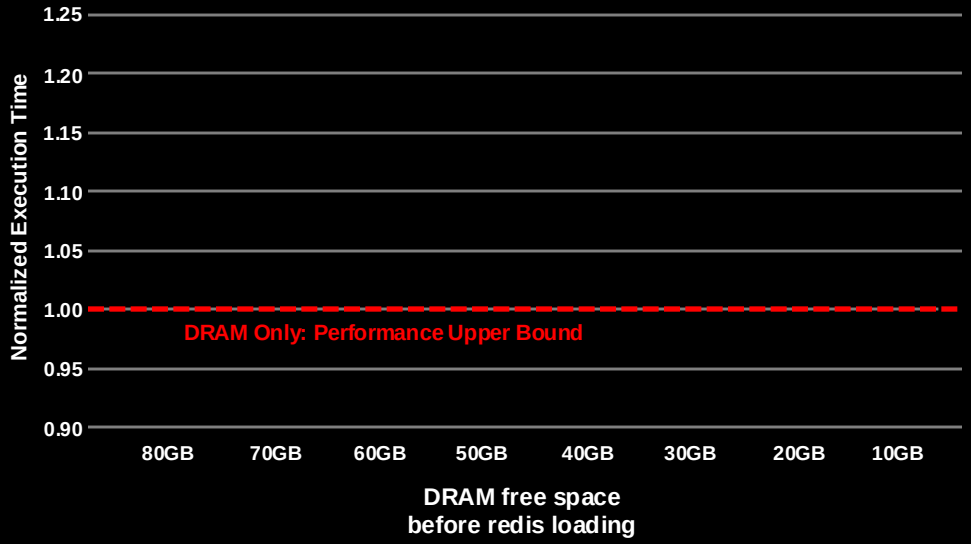

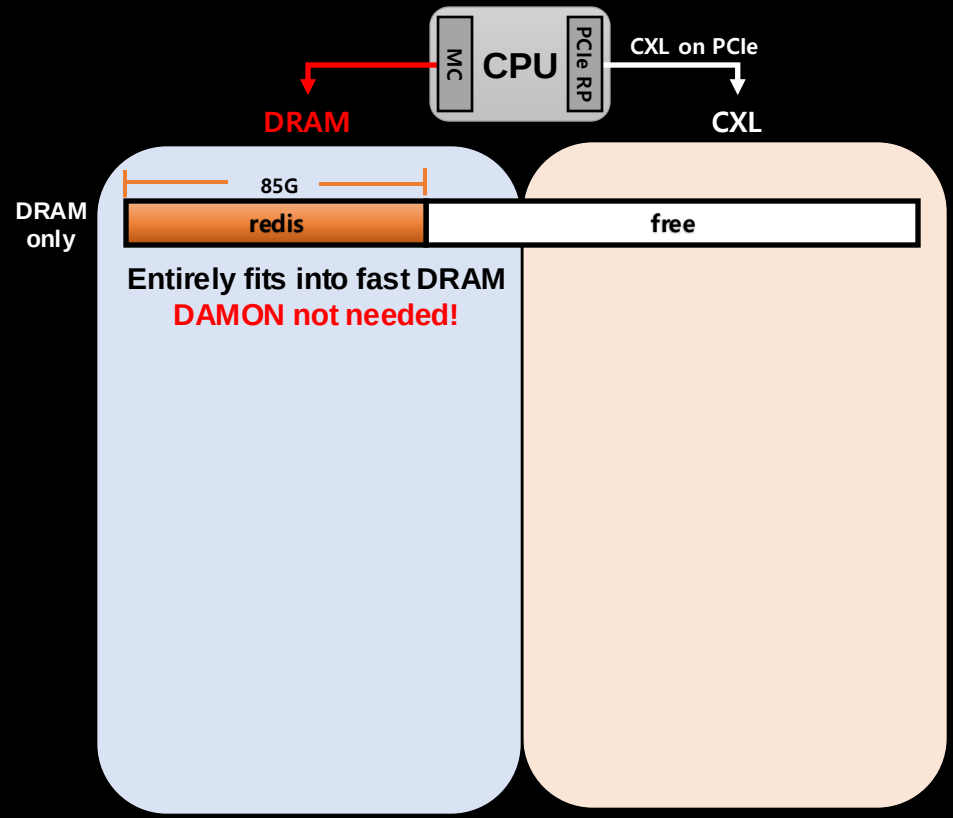

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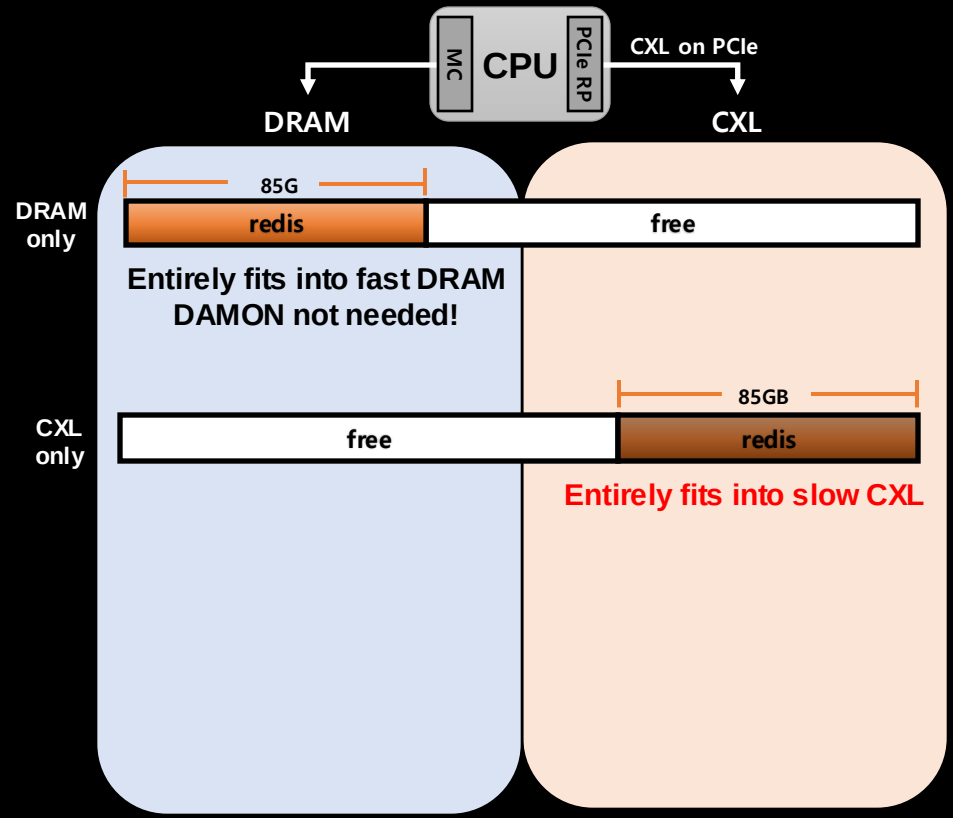

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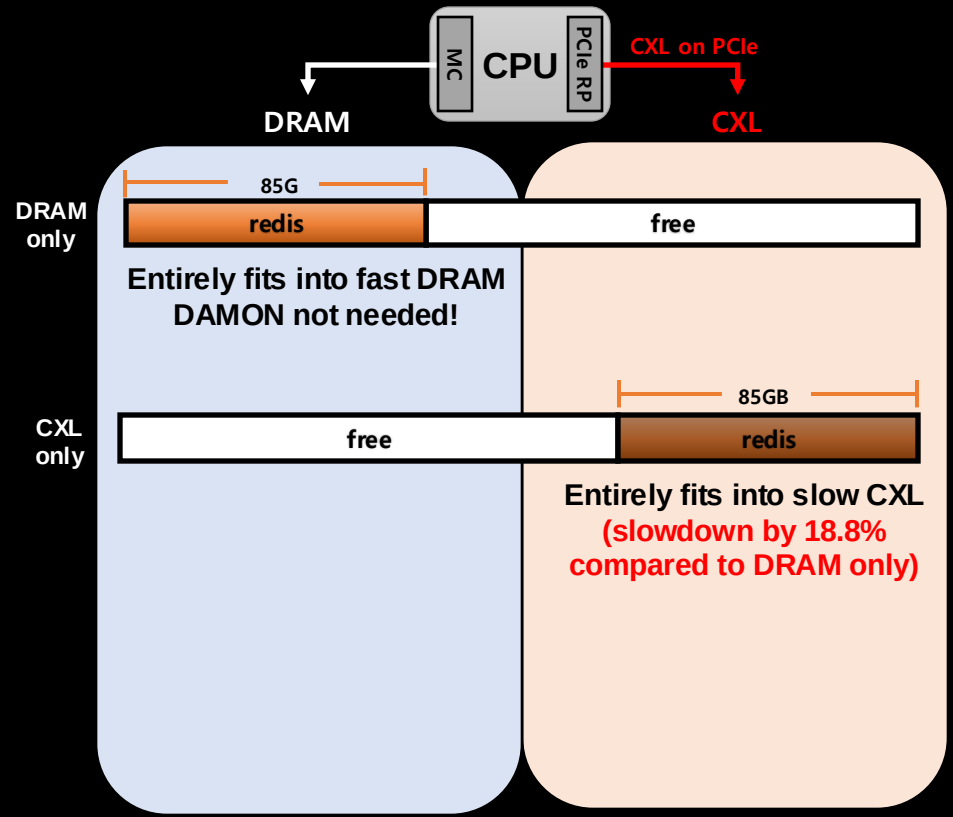

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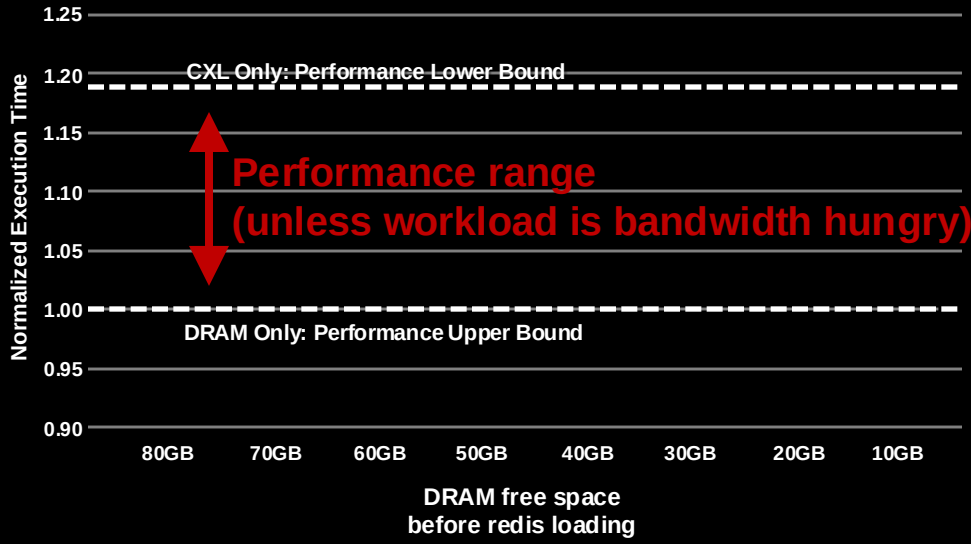

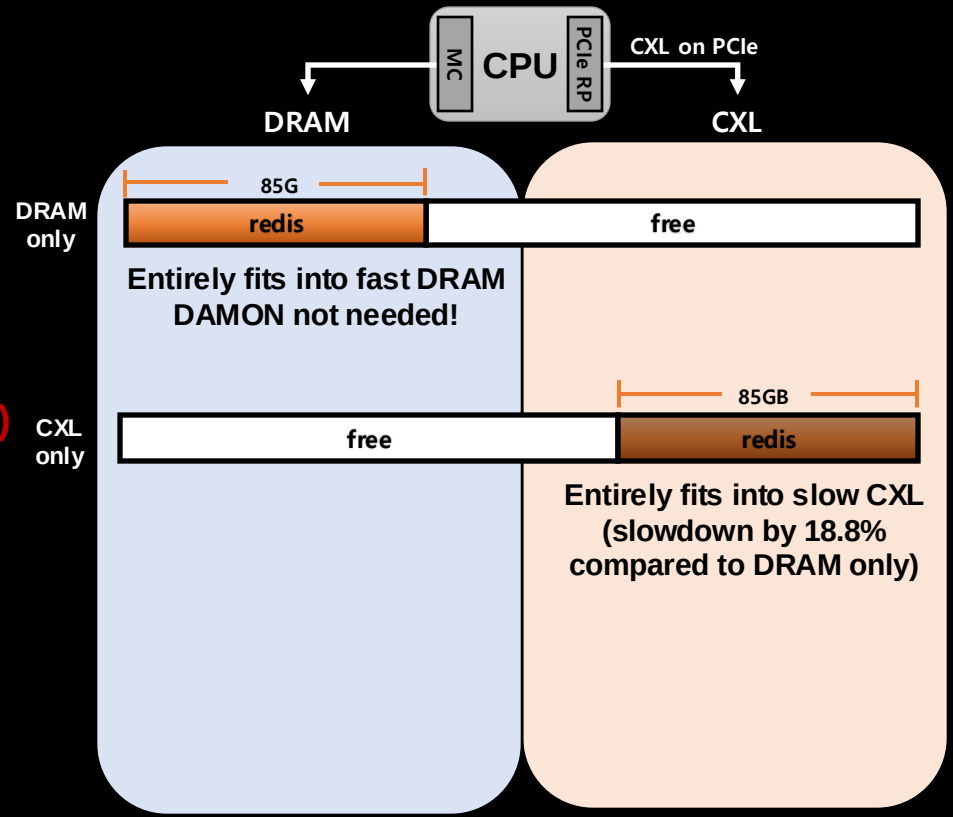

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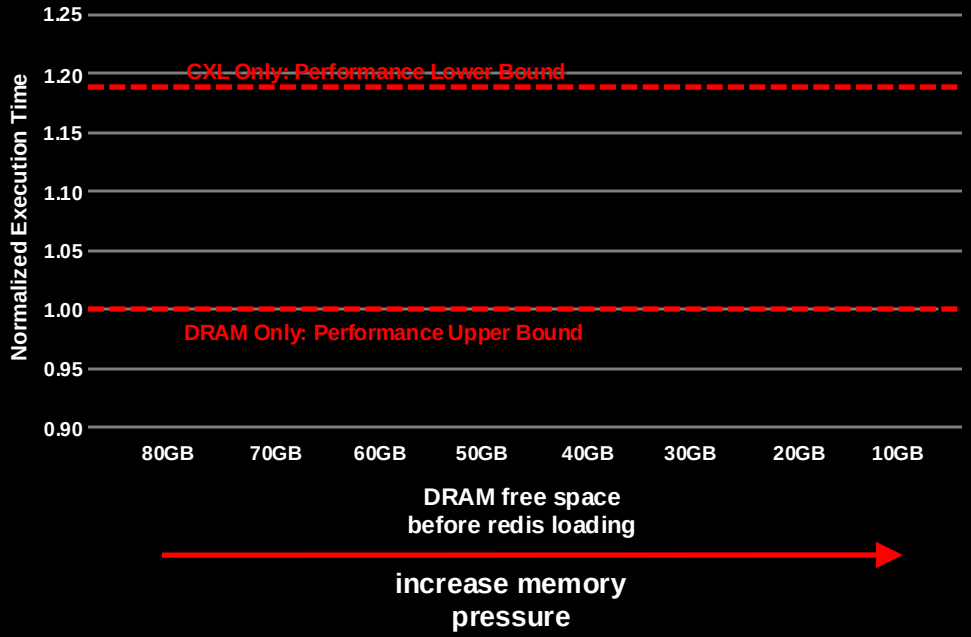

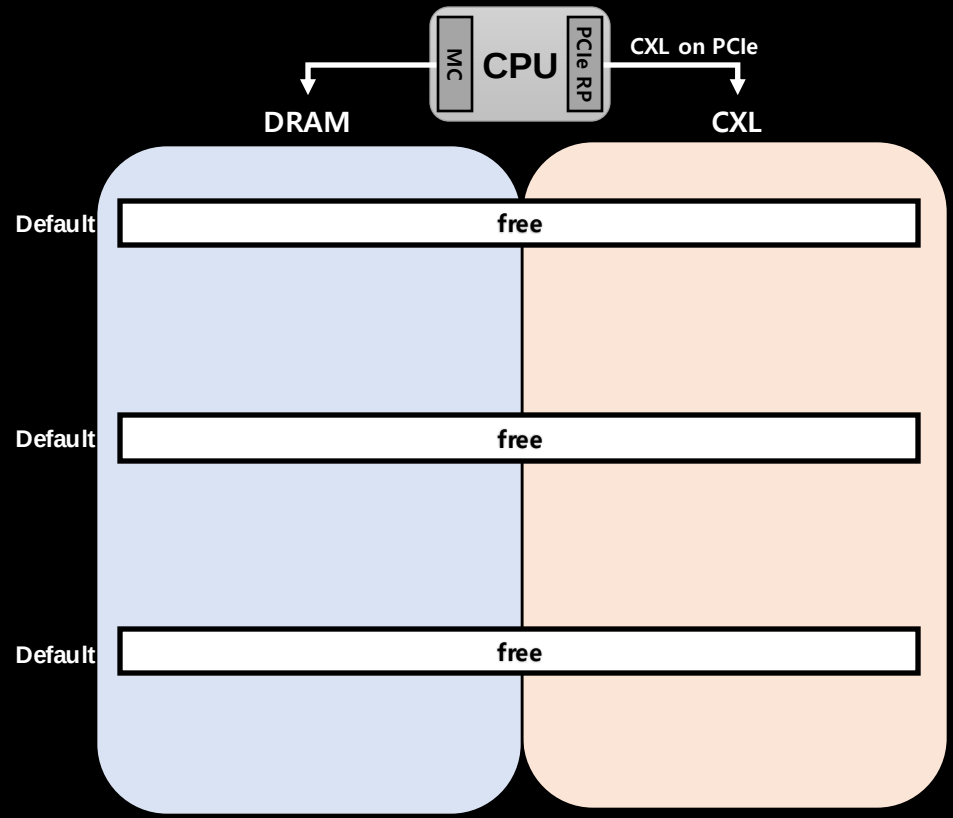

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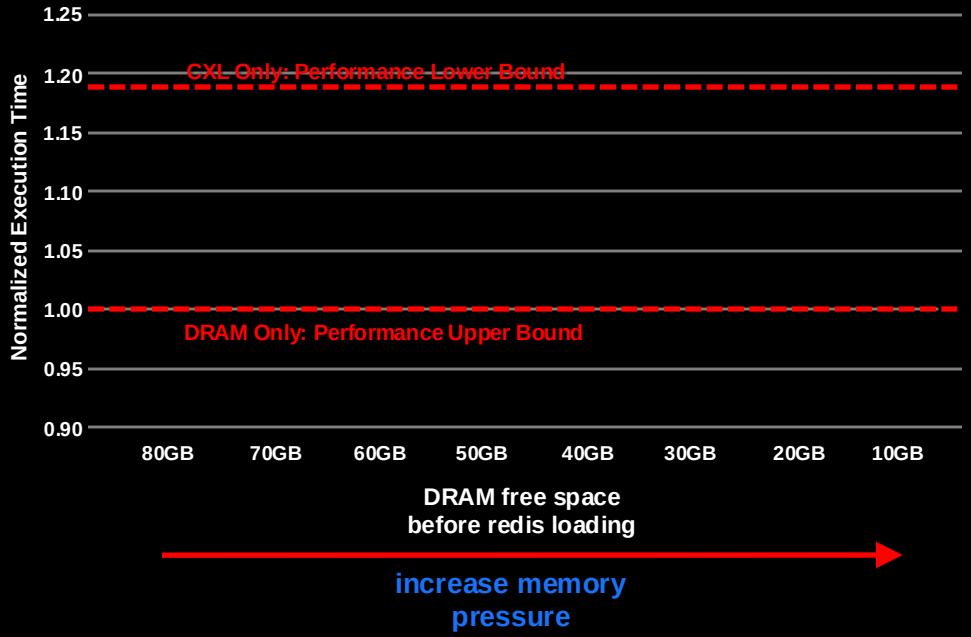

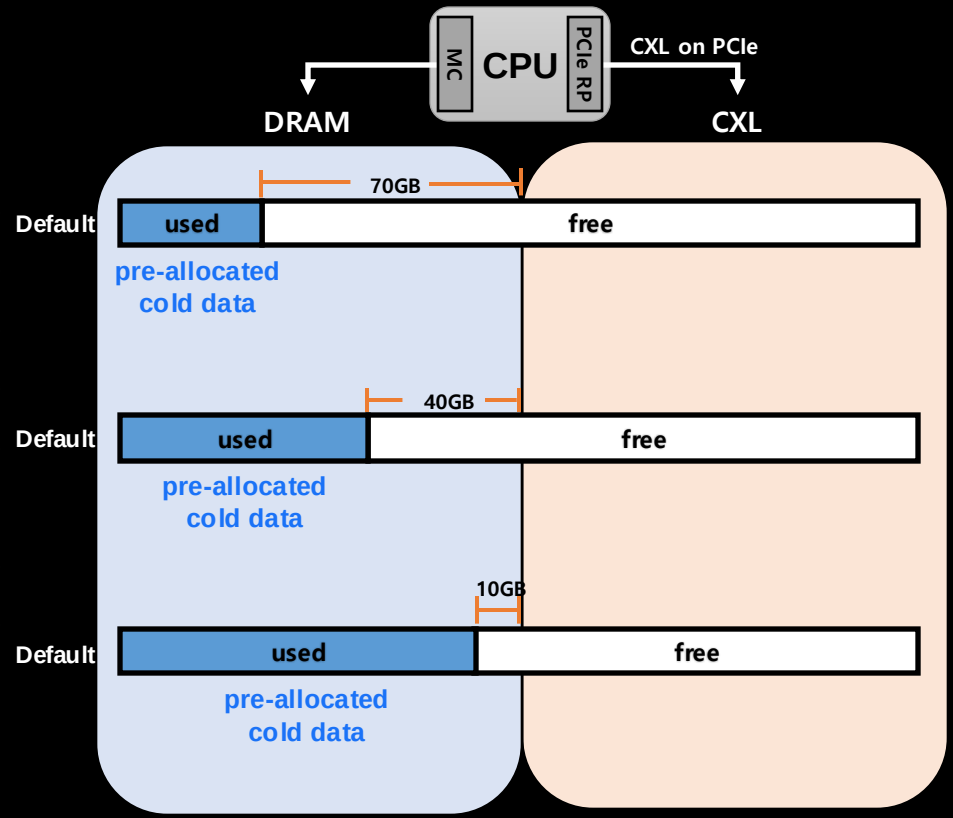

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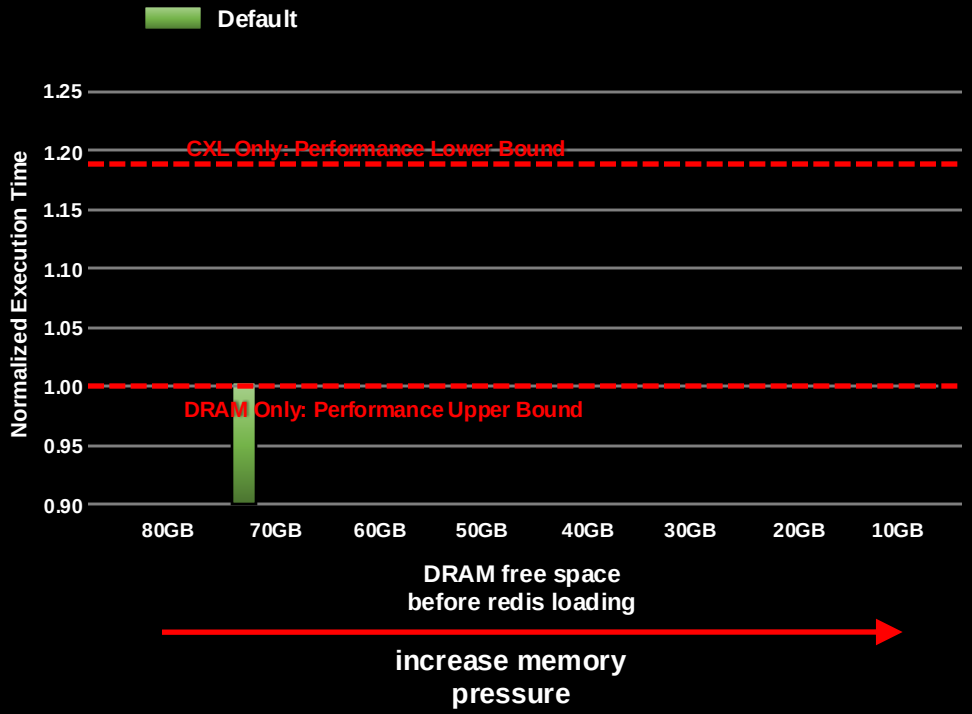
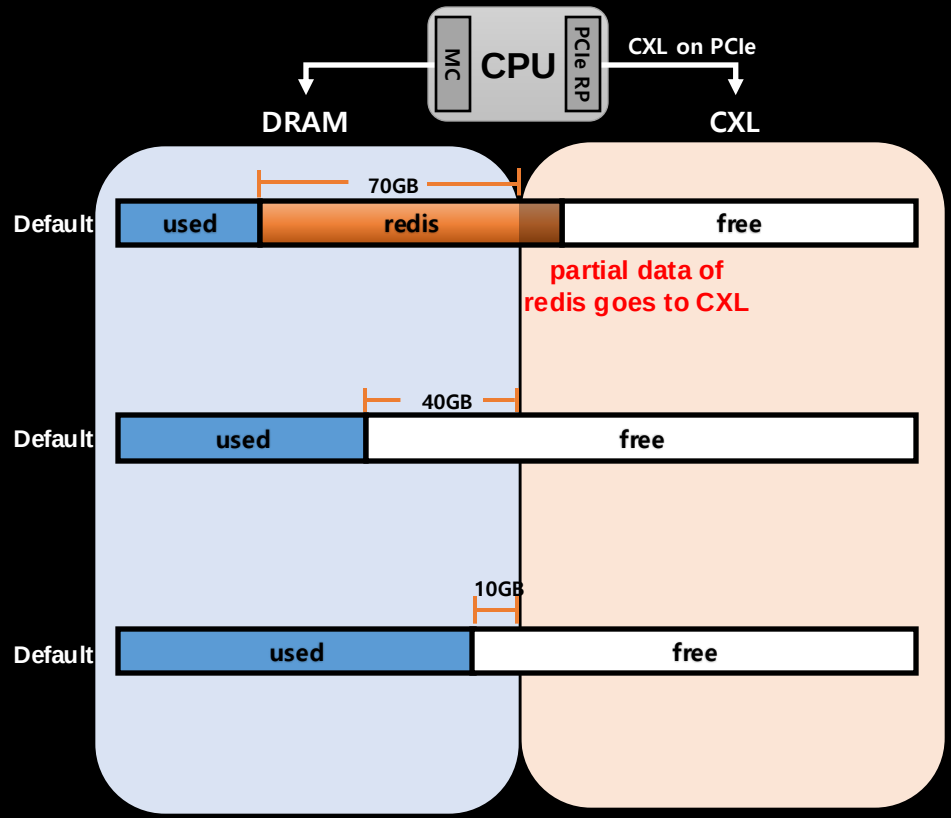
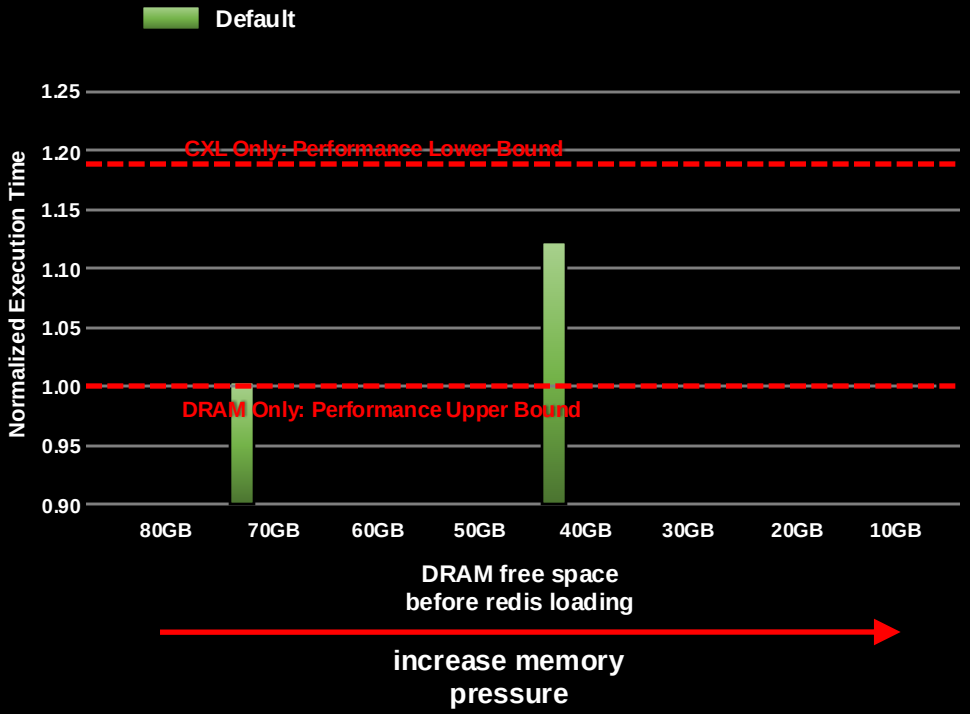


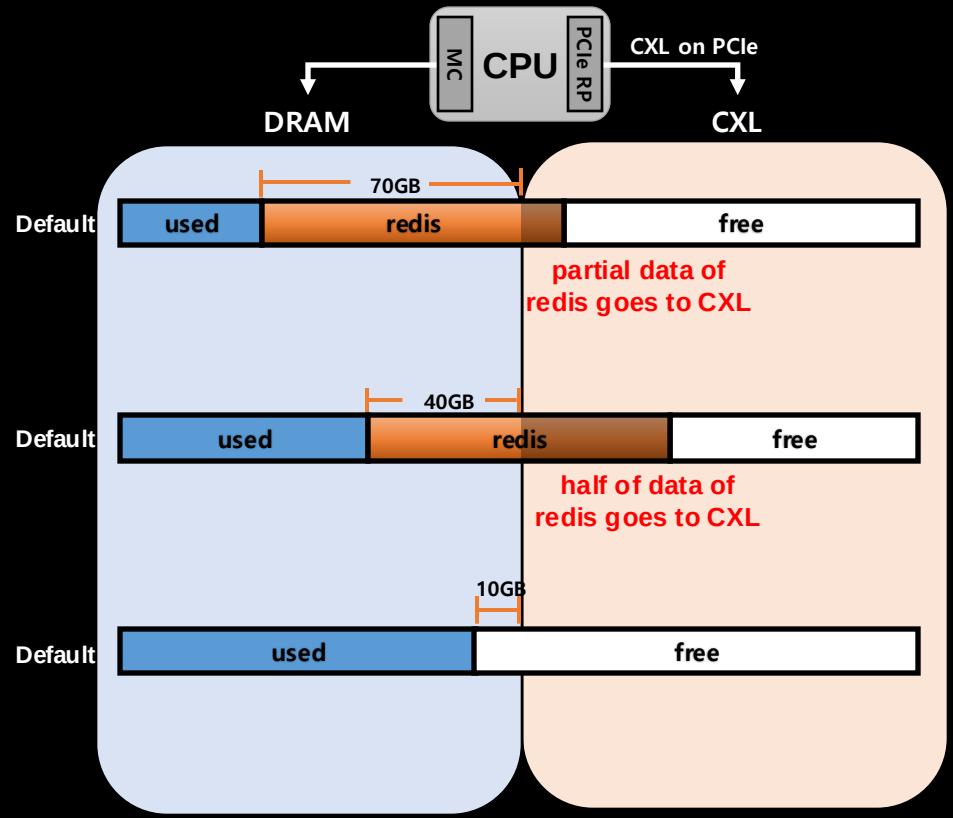


<Default>

1. DRAM is partially used by non-redis cold data.
2. Partial redis data is allocated on CXL memory.
   (due to insufficient space on DRAM)

HMSDK Capacity Expansion





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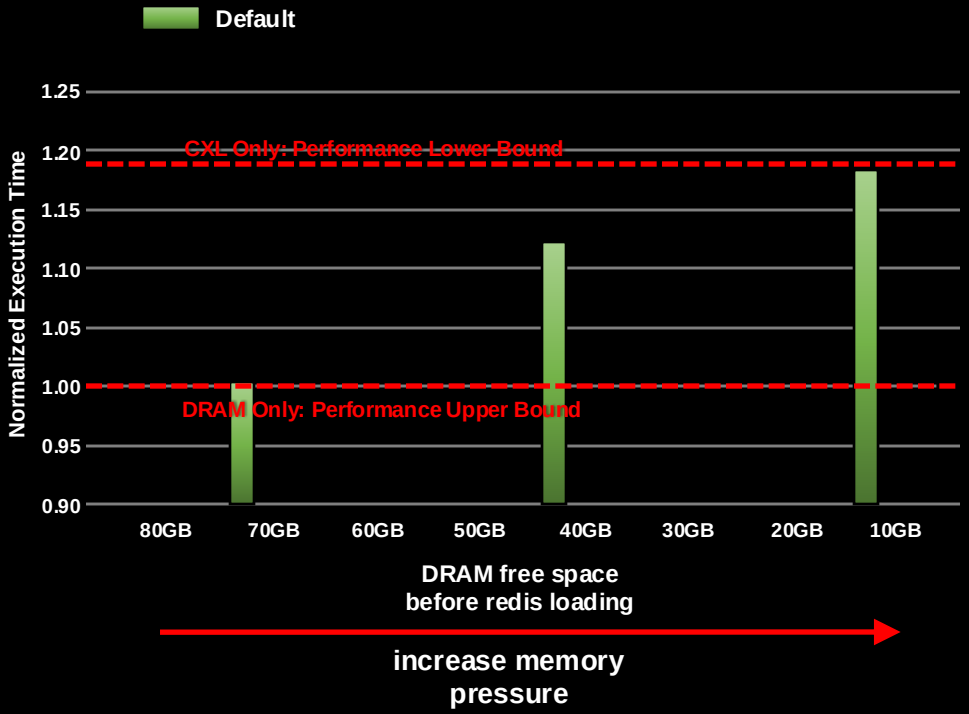

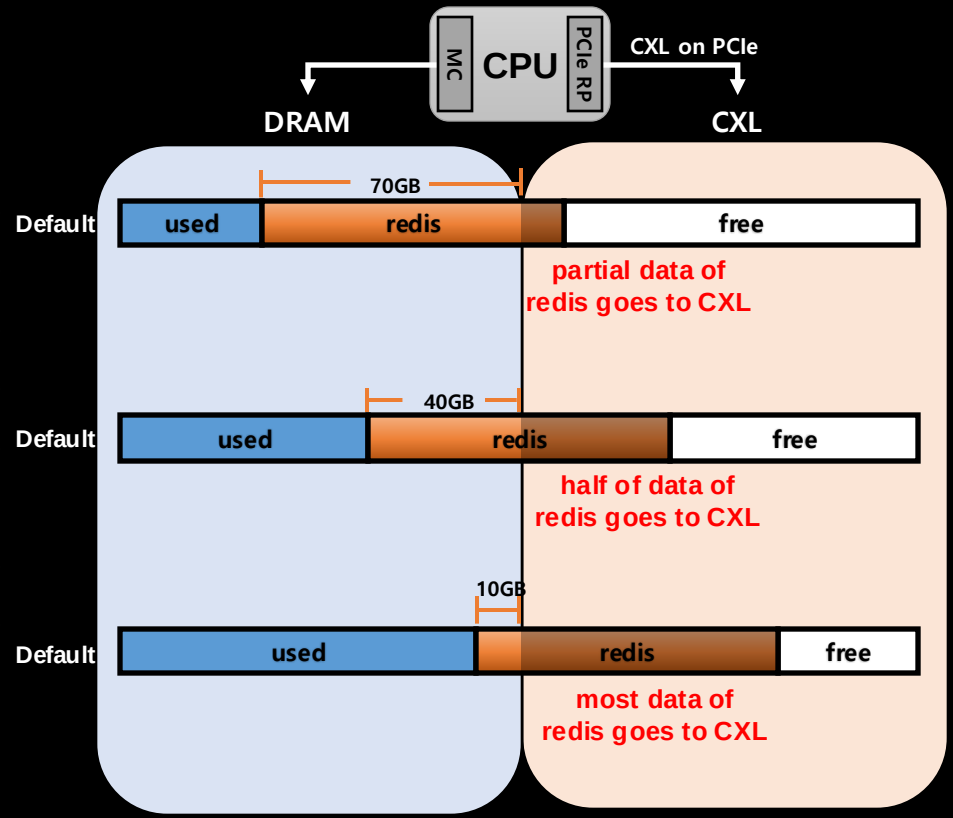

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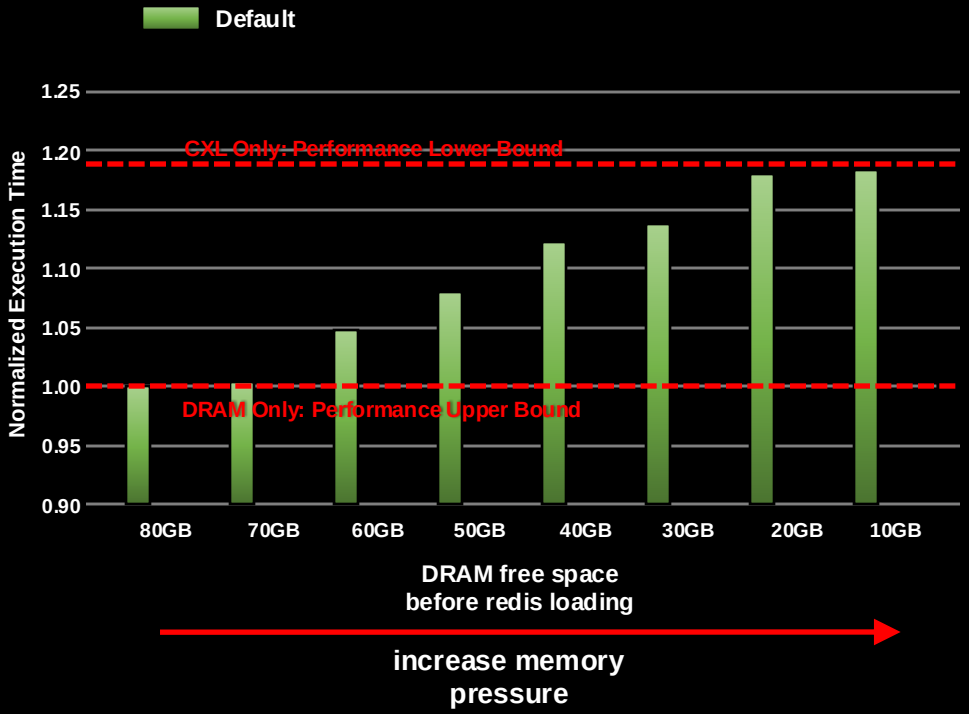

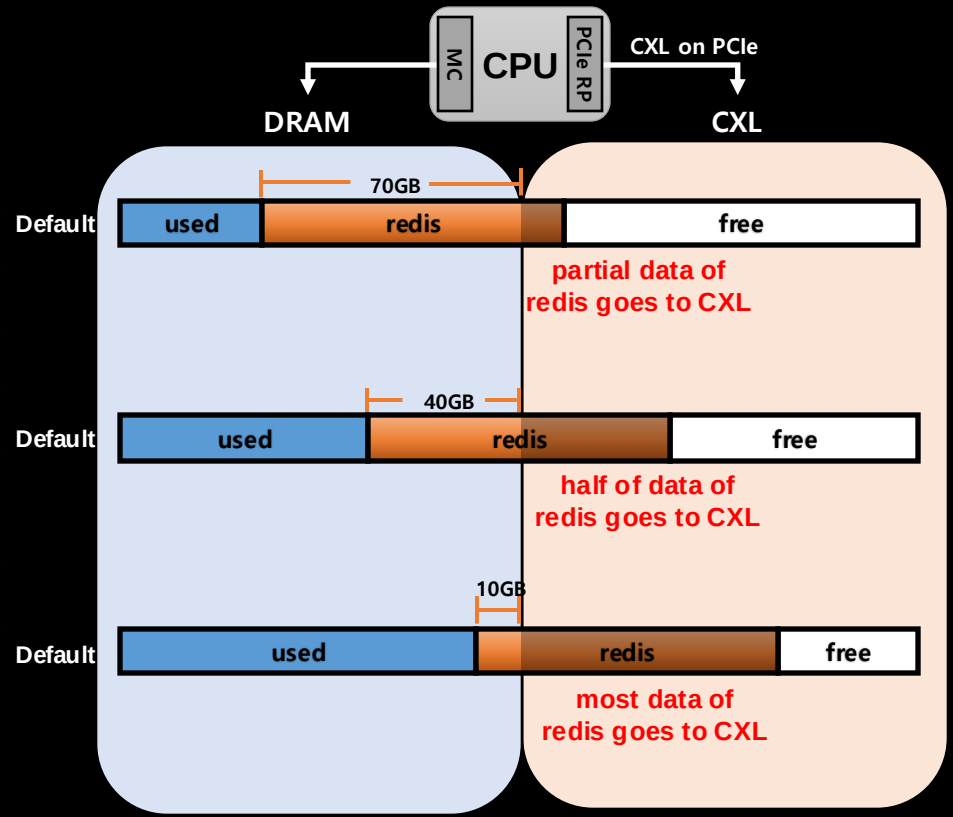

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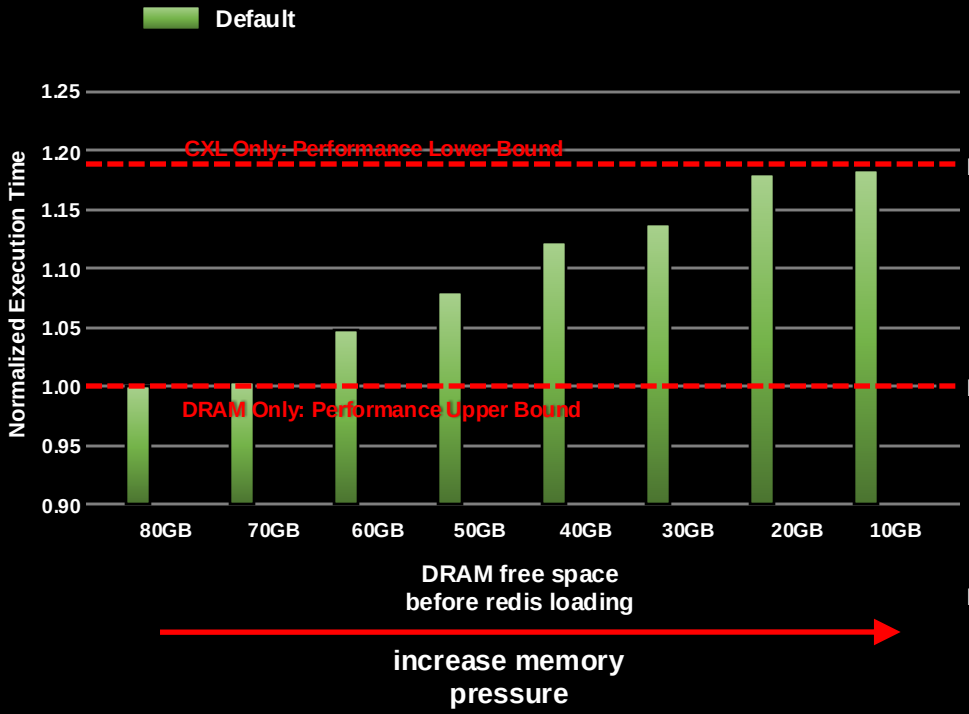
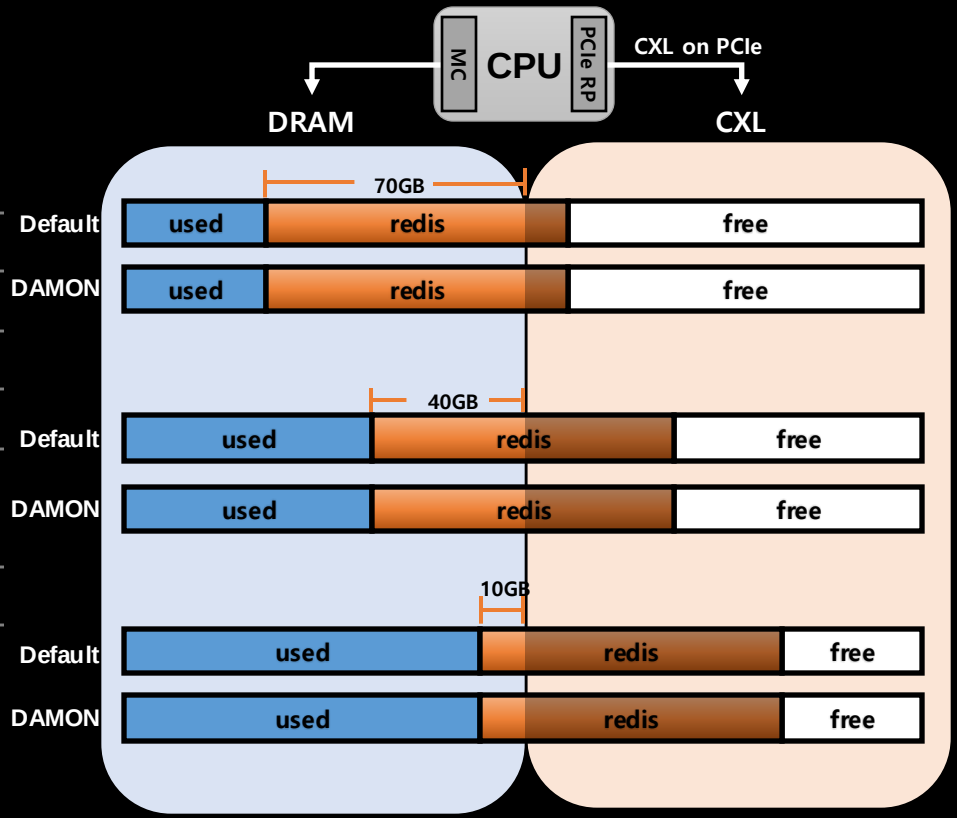
HMSDK Capacity Expansion





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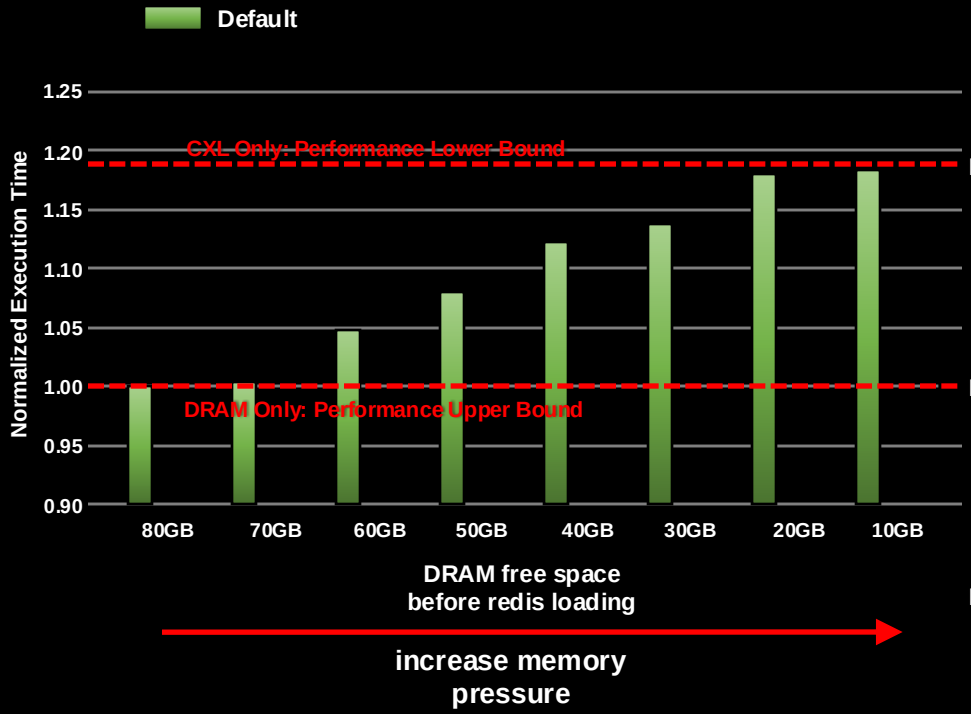

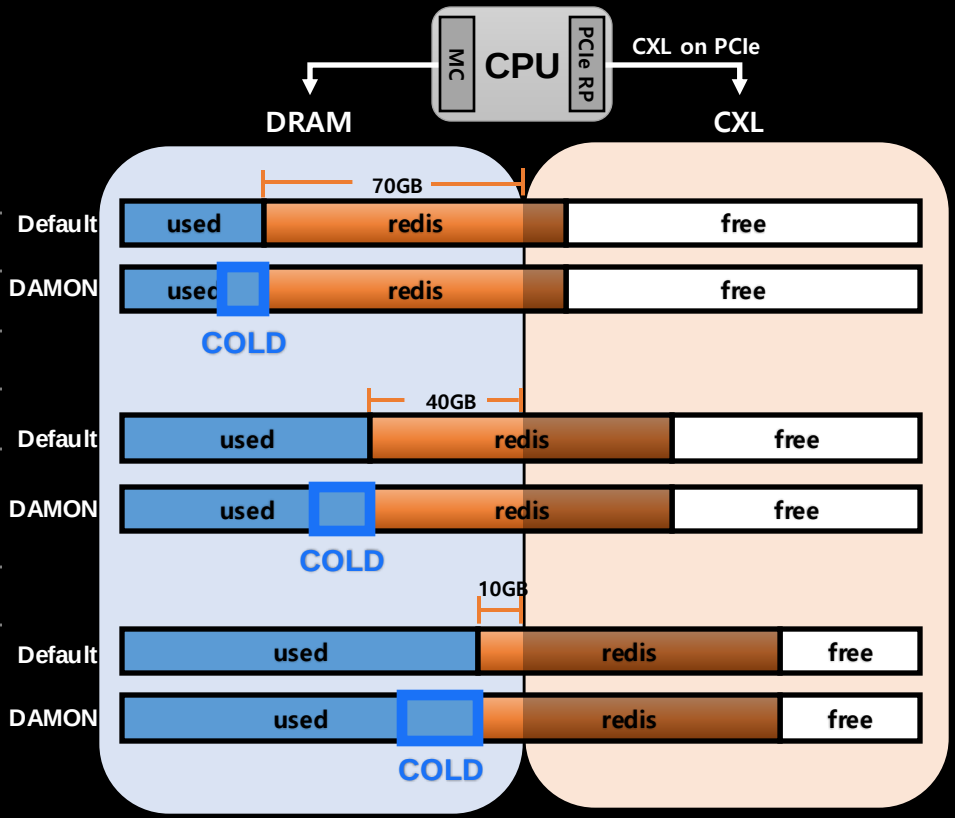

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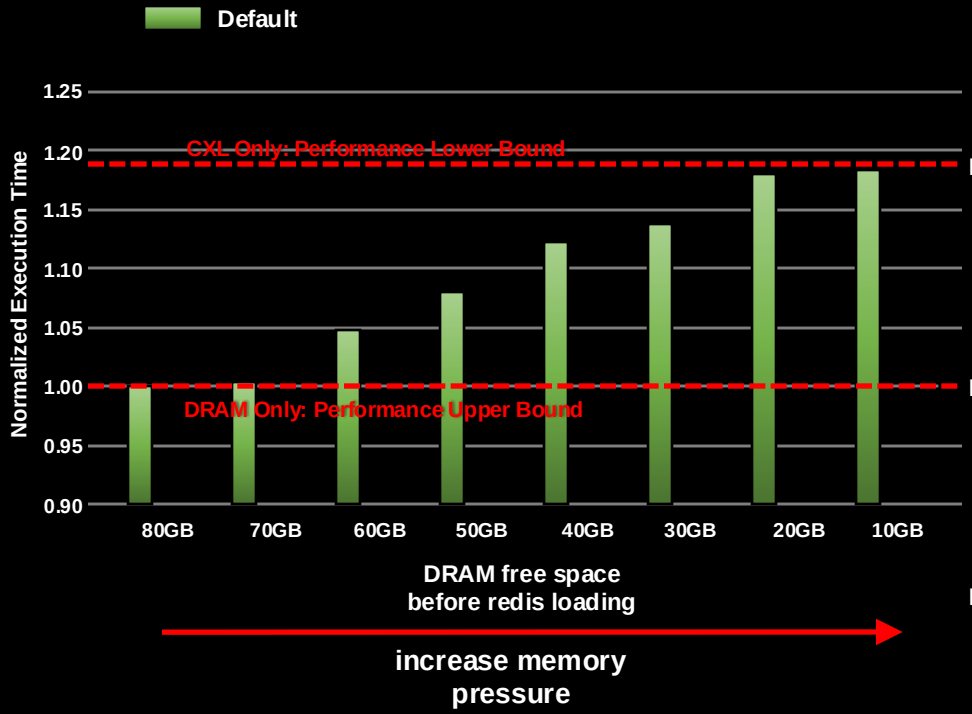
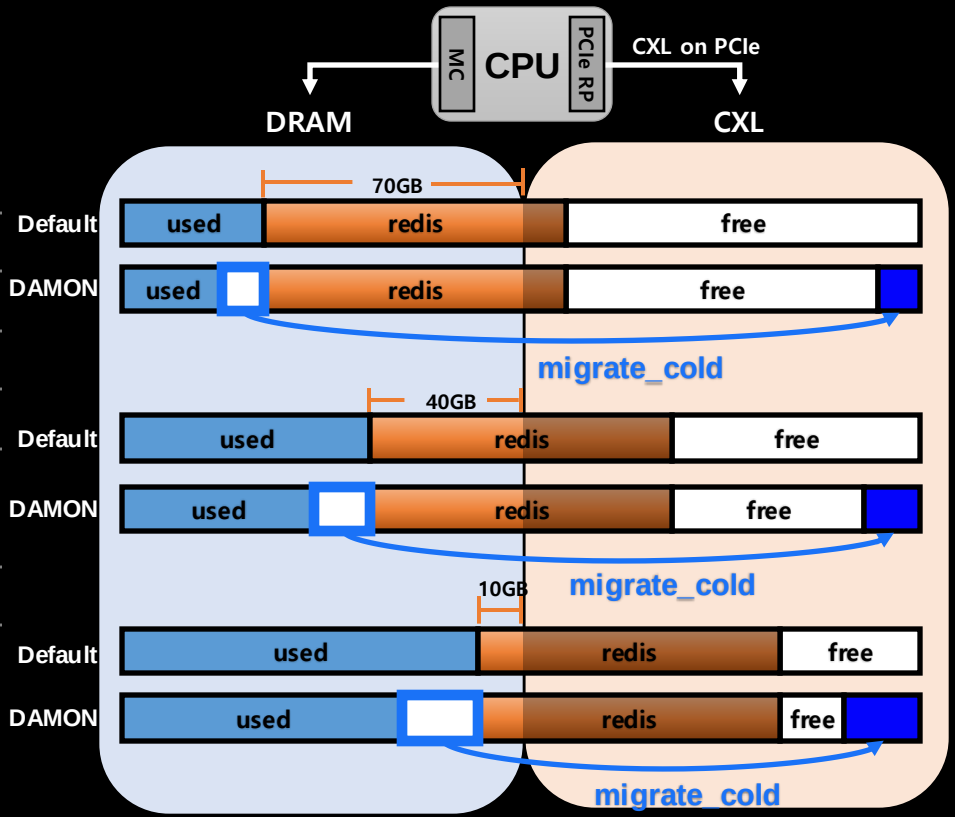
<HMSDK>

1. Demote cold data from DRAM to CXL memory.

HMSDK Capacity Expansion





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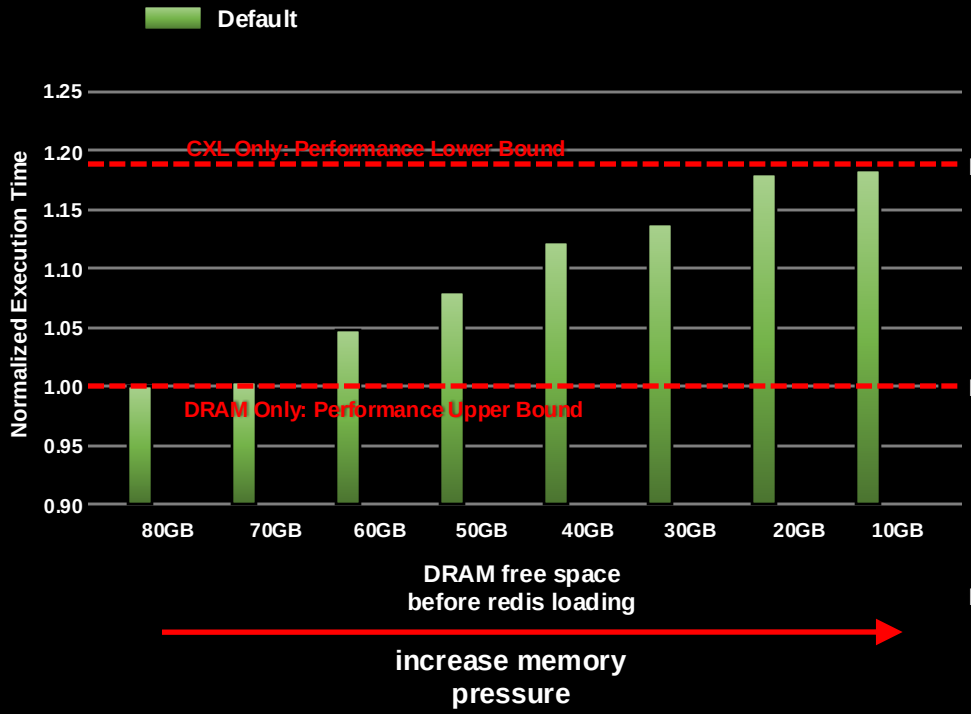
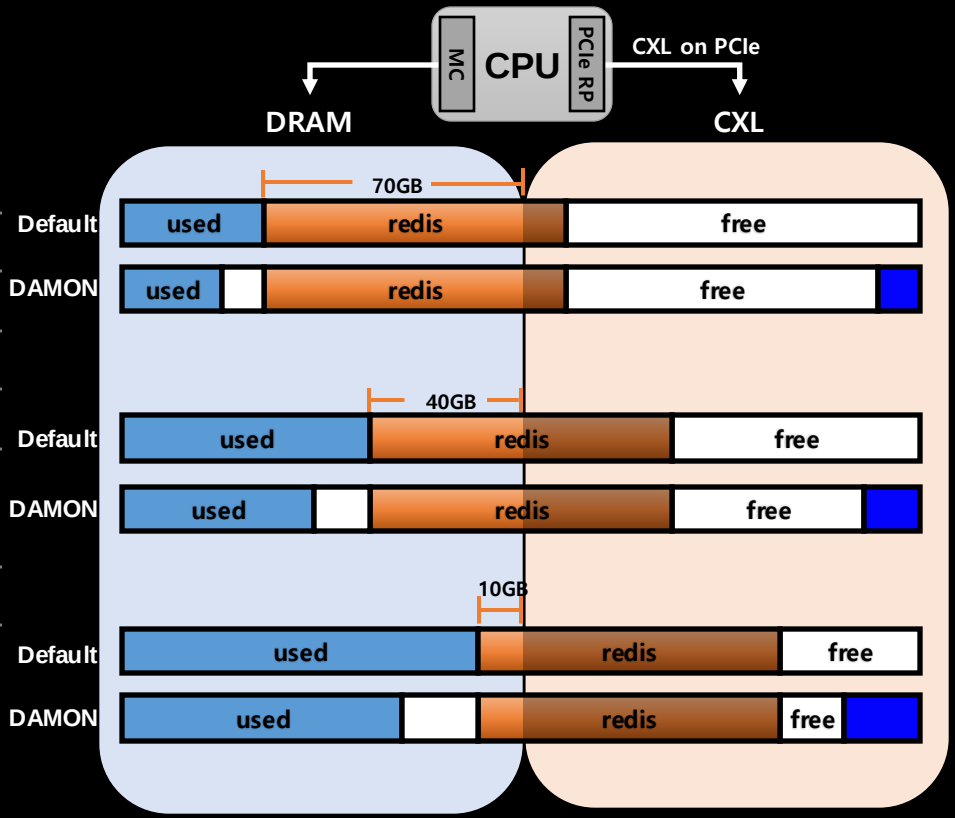
<HMSDK>

1. Demote cold data from DRAM to CXL memory.

HMSDK Capacity Expansion





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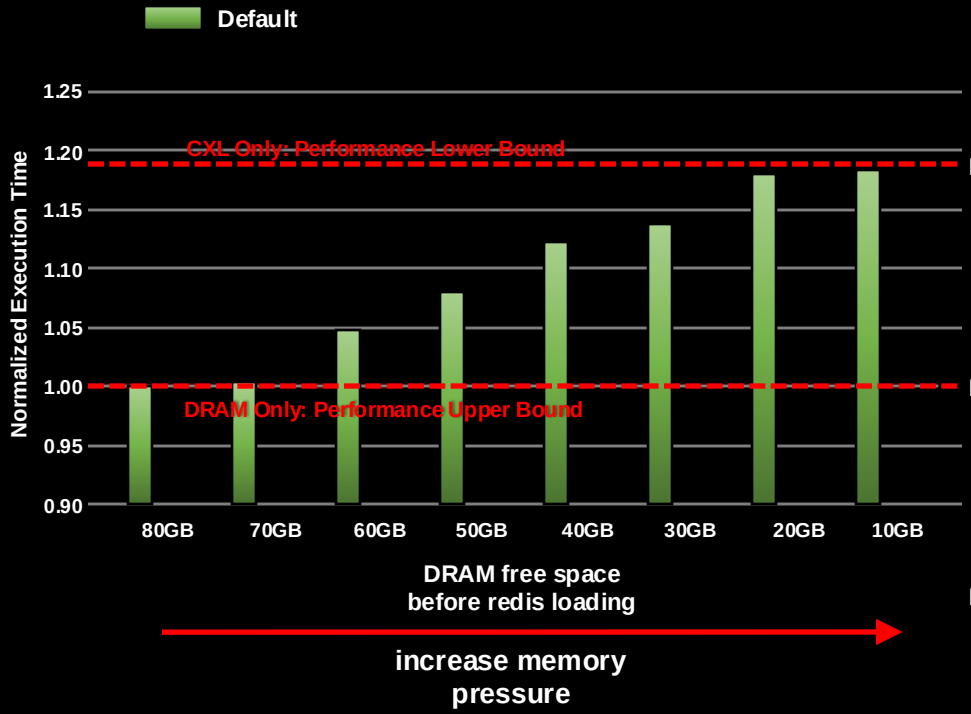

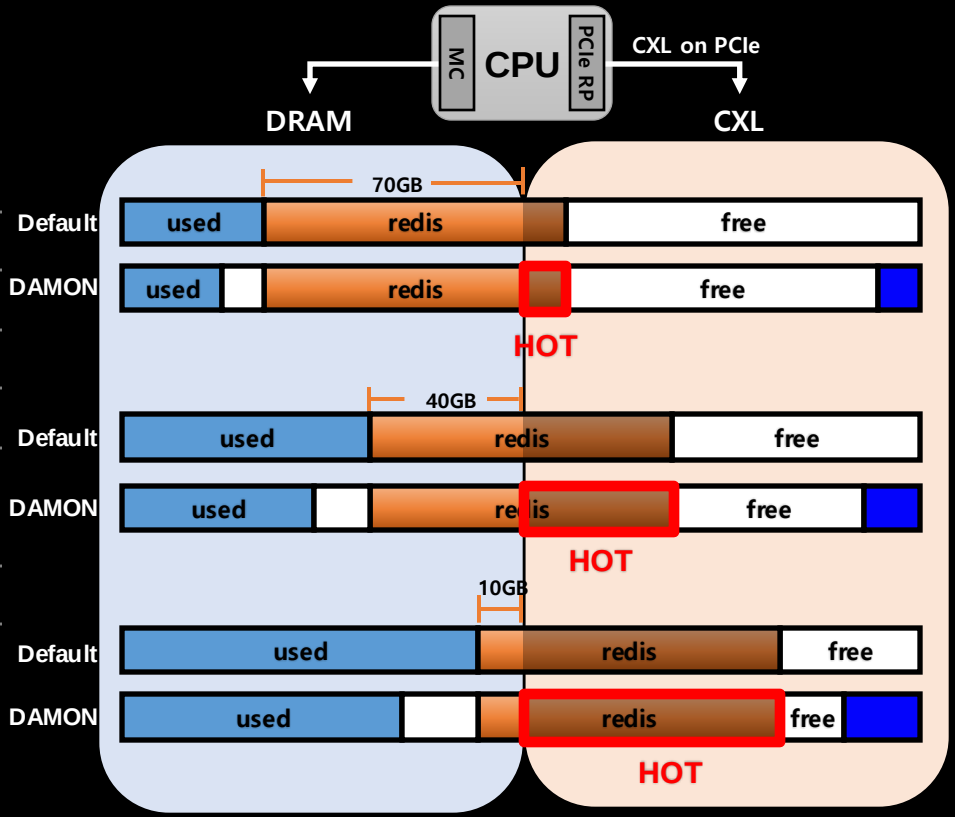

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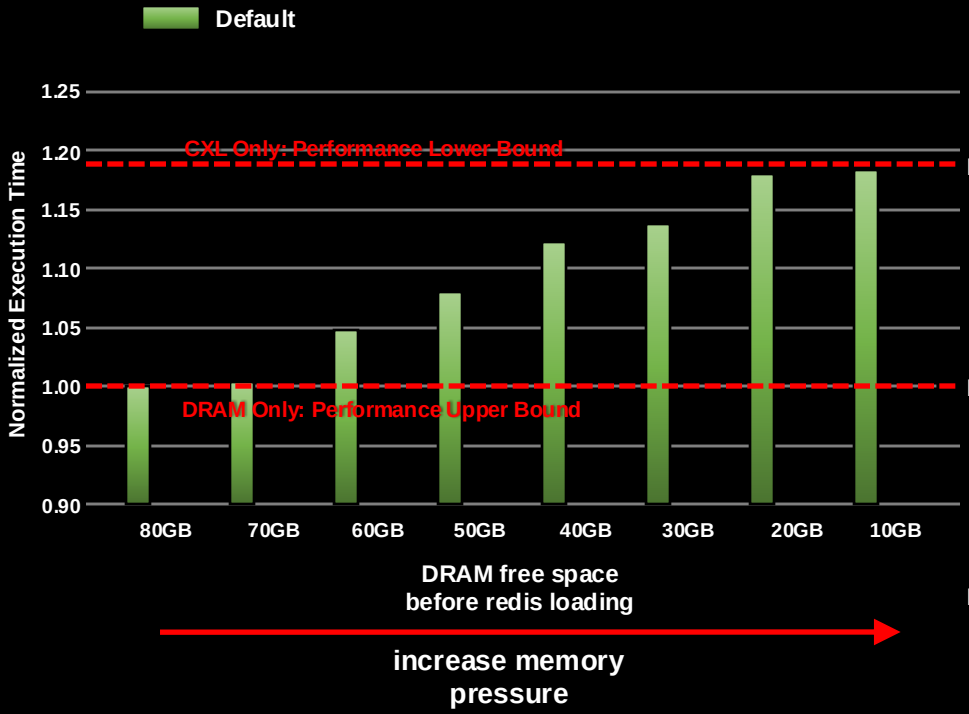
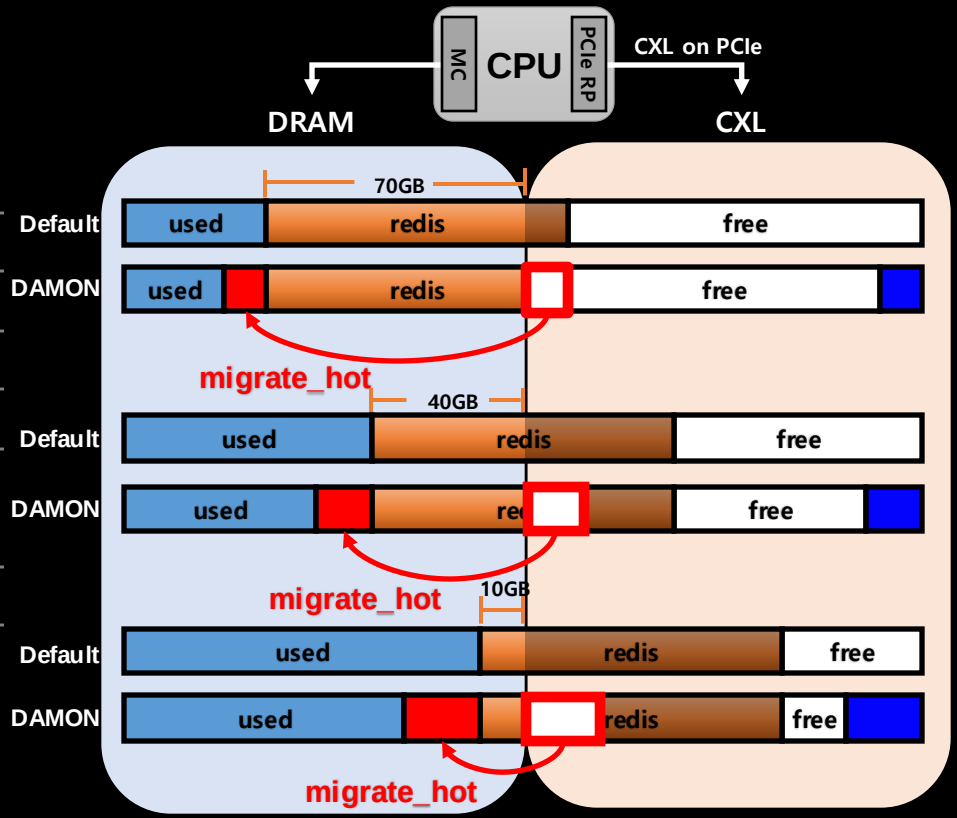
<HMSDK>

1. Demote cold data from DRAM to CXL memory.
2. Promote more redis data to fast DRAM.
   (while keeping cold data on CXL memory)

HMSDK Capacity Expansion





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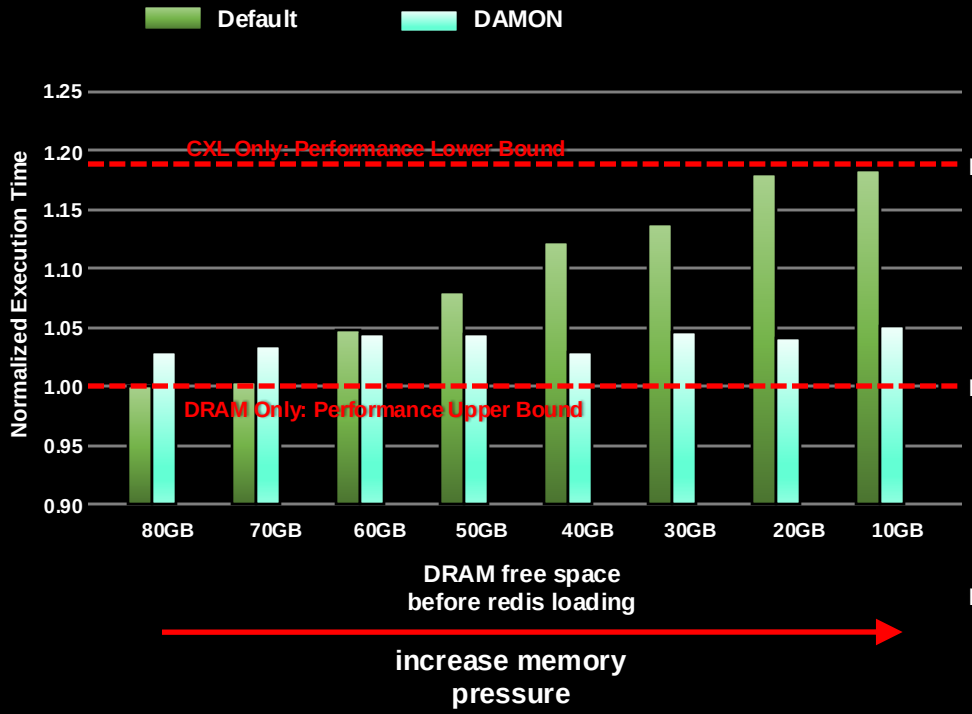

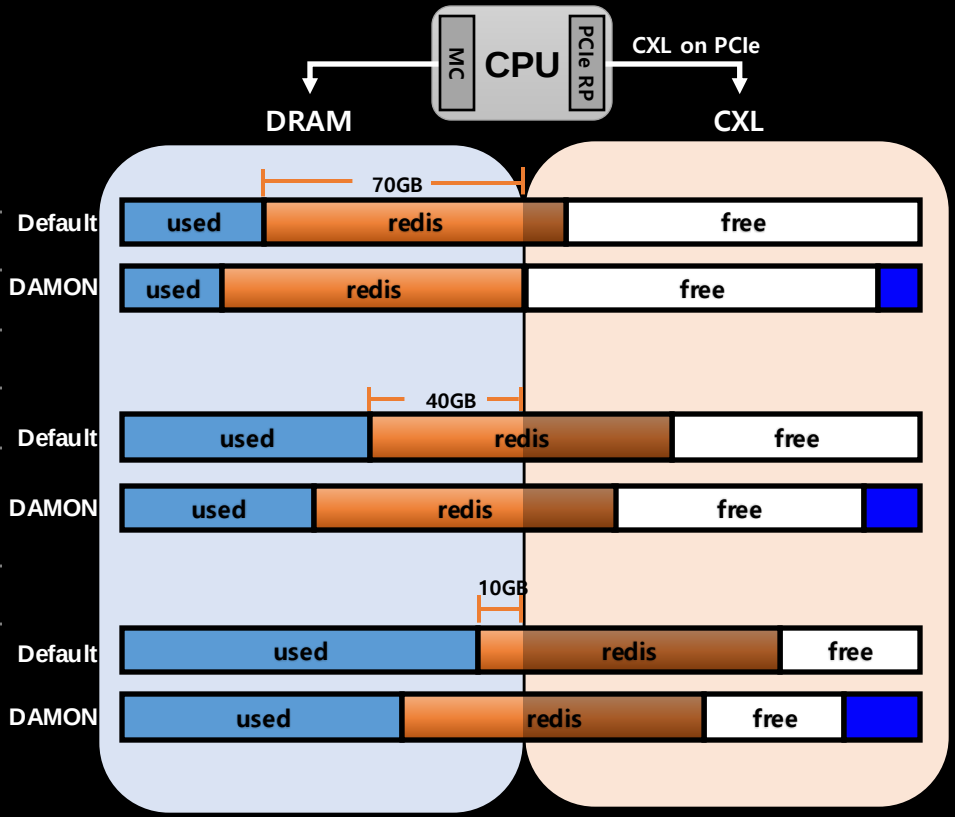

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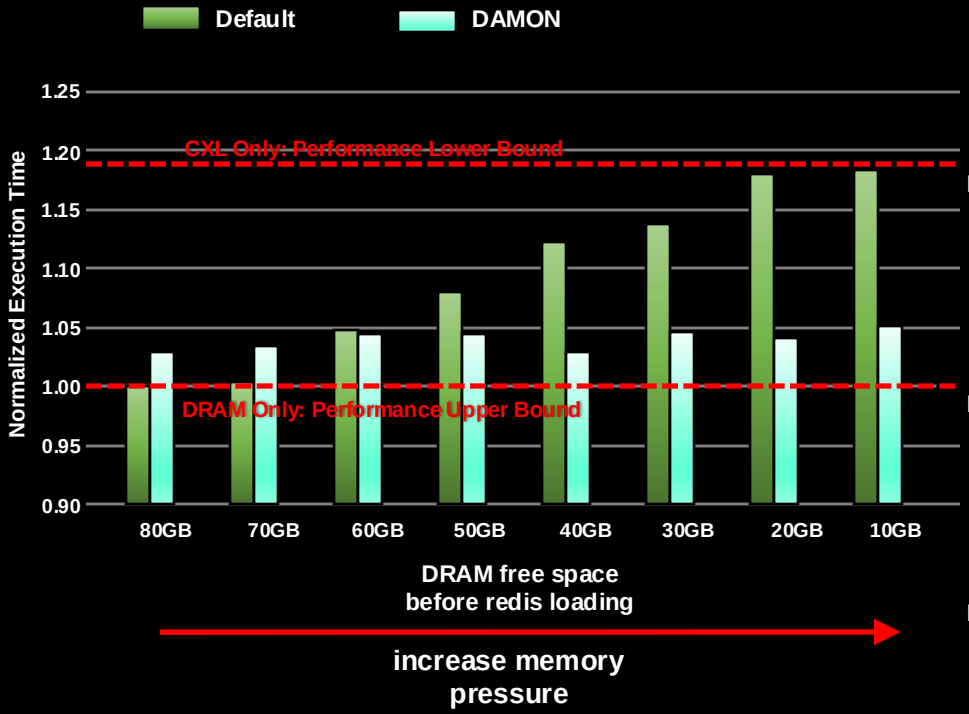
   (while keeping cold data on CXL memory)

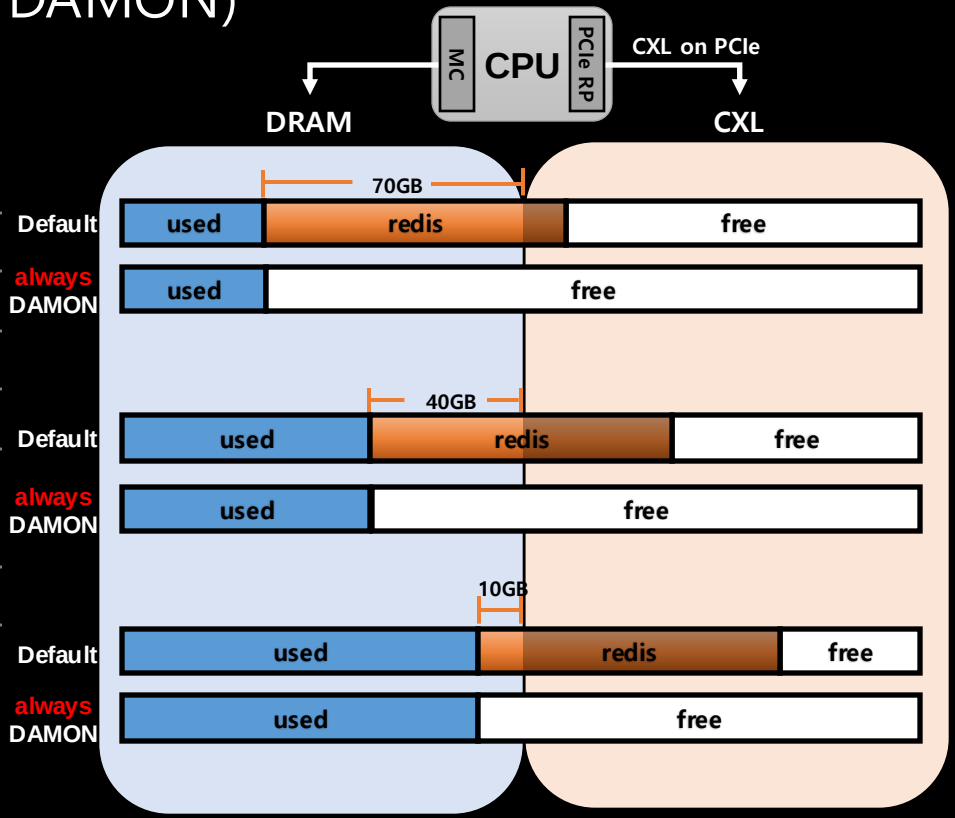
HMSDK Capacity Expansion Evaluation

- The DAMON was turned on just before the memory accesses via YCSB.
  - This is more for evaluation.

- In the real world, the DAMON will be running always on the system.
  - So other cold data can be demoted earlier.
  - Even before the workload(redis) was loaded.

HMSDK Capacity Expansion (always DAMON)





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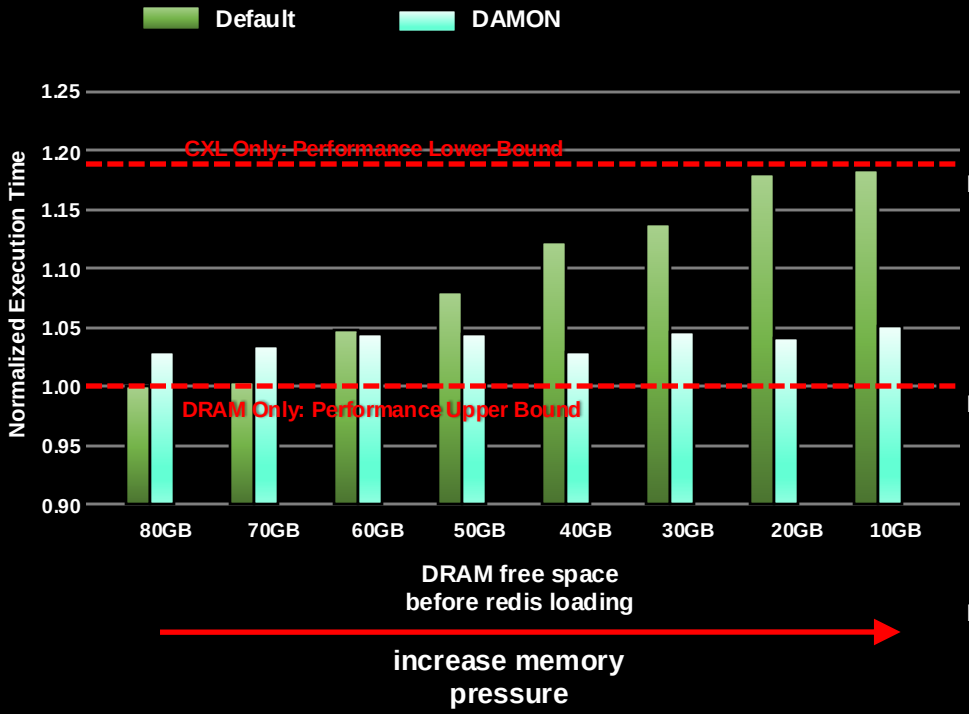

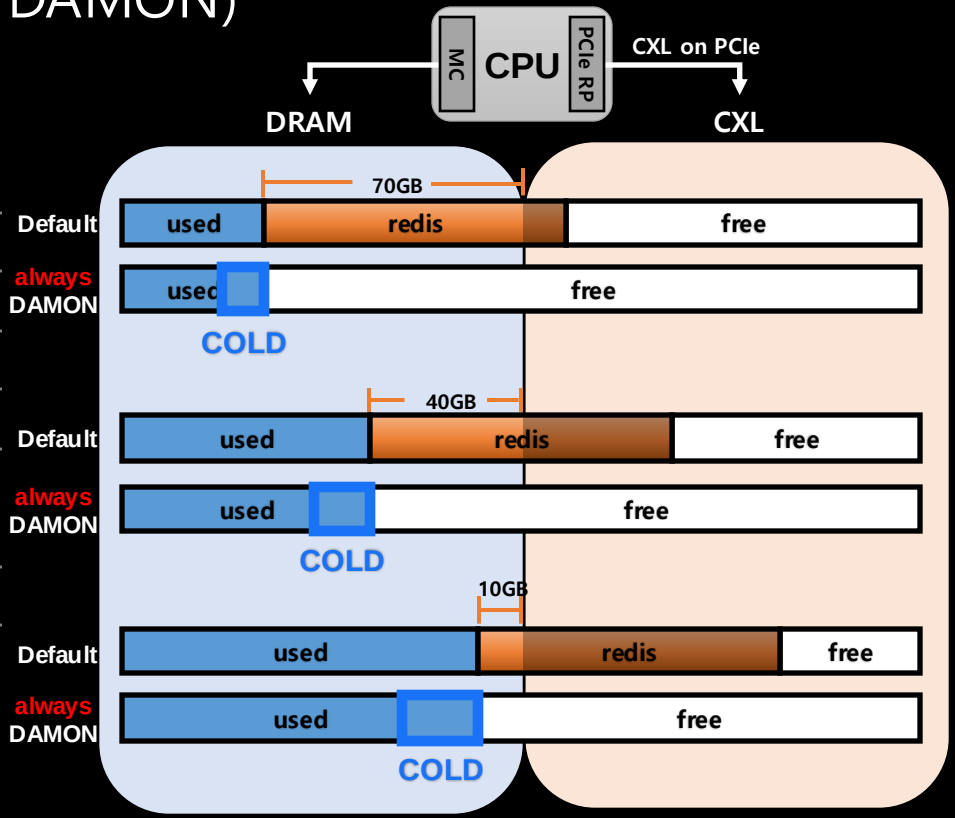

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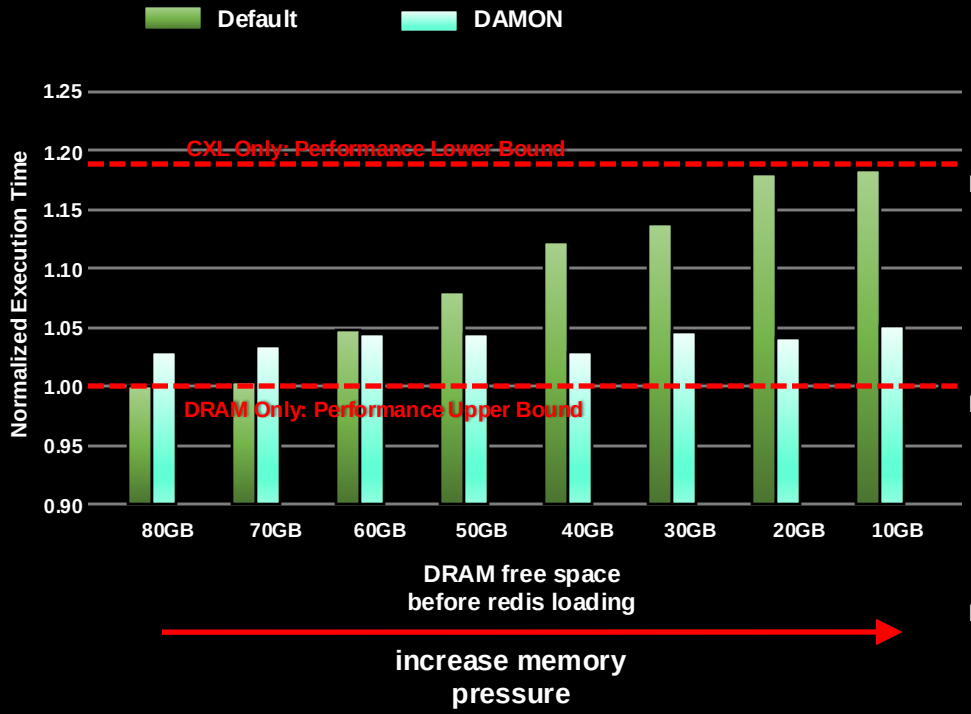

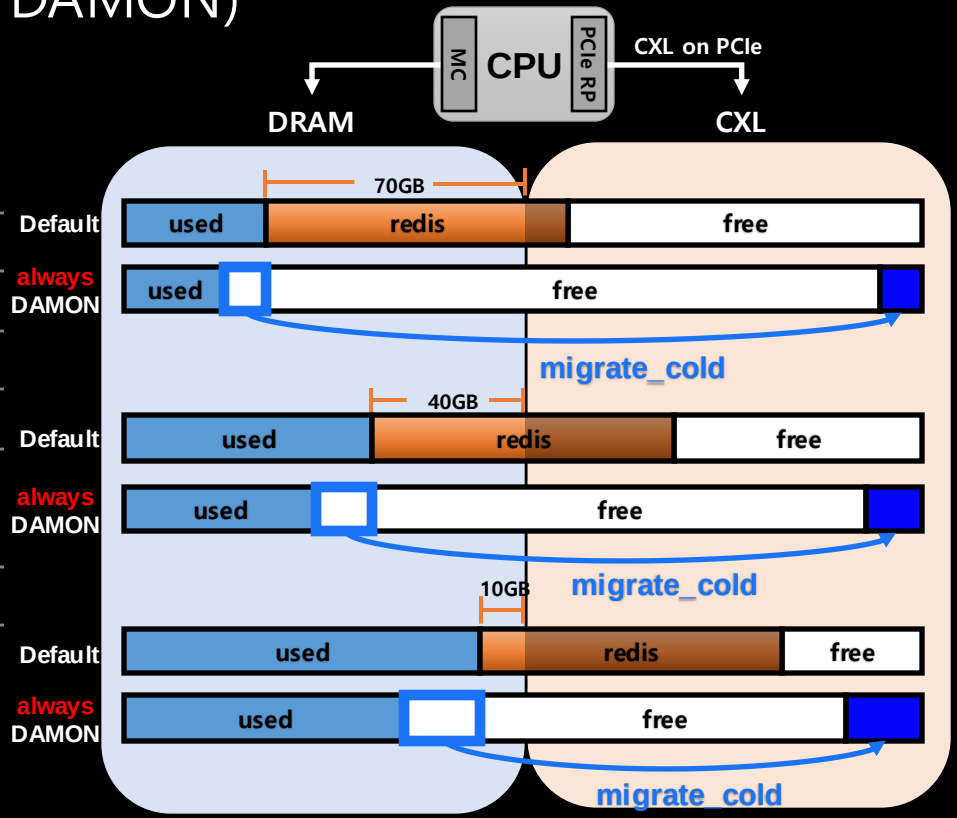

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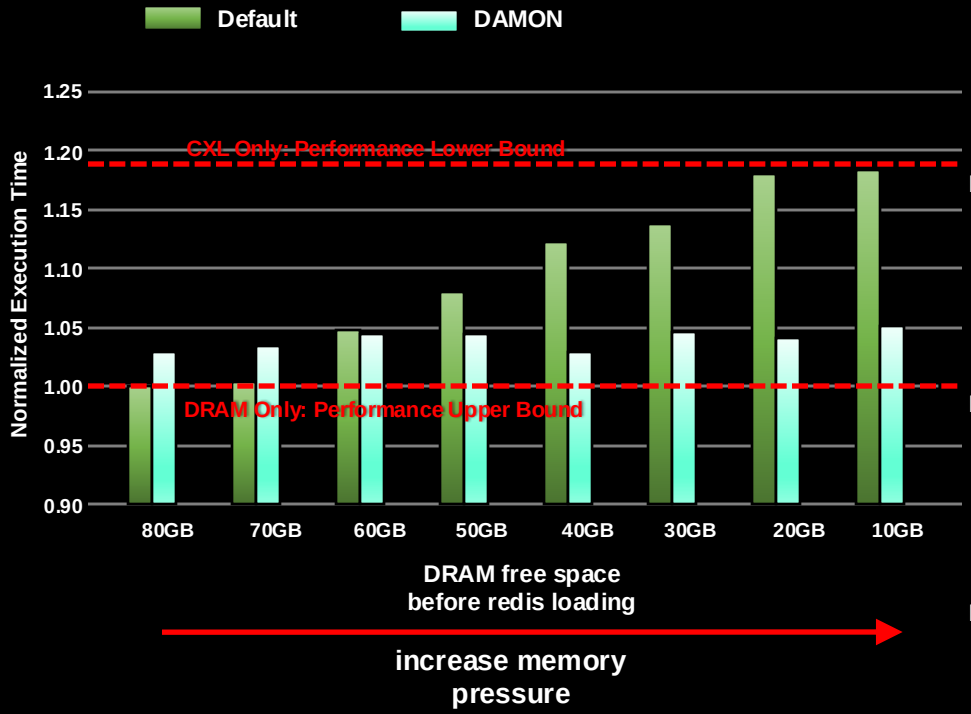

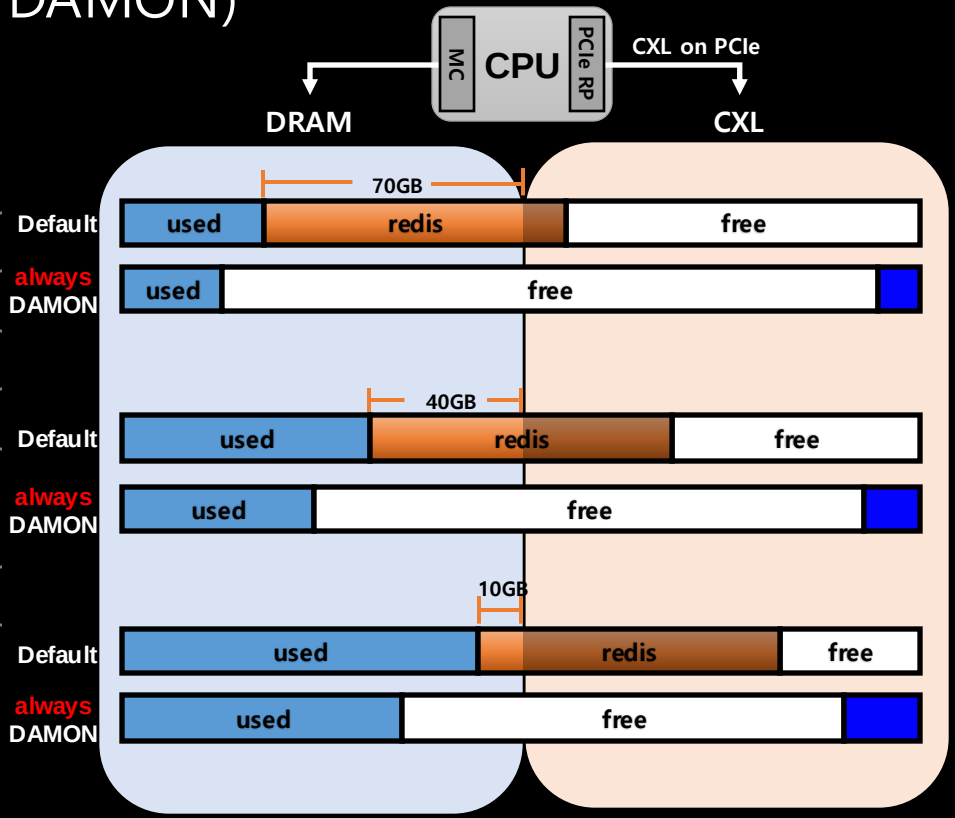

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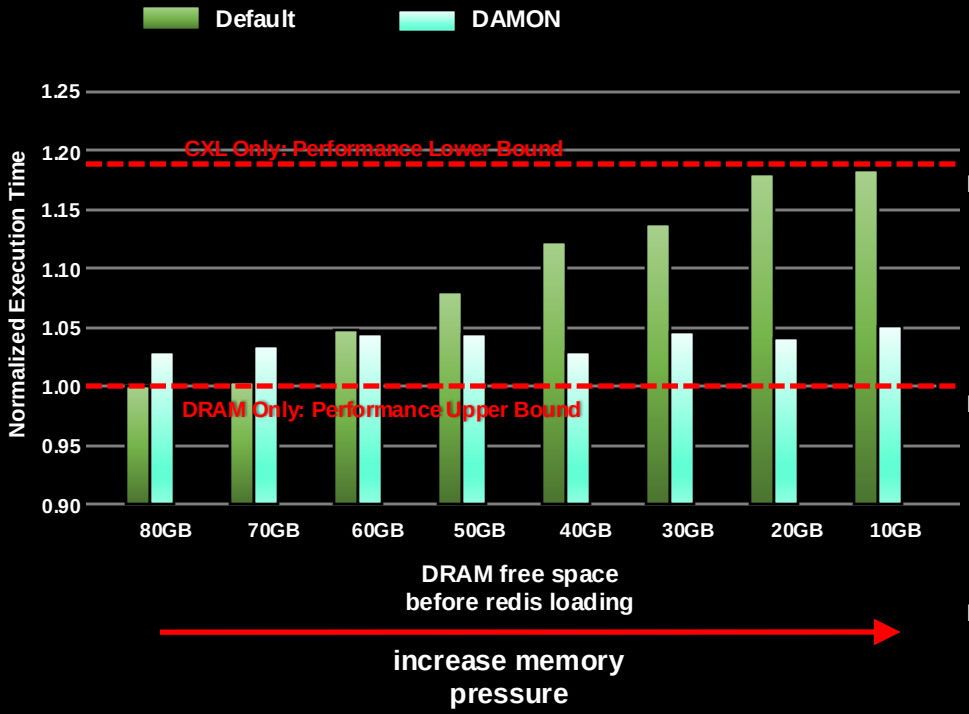

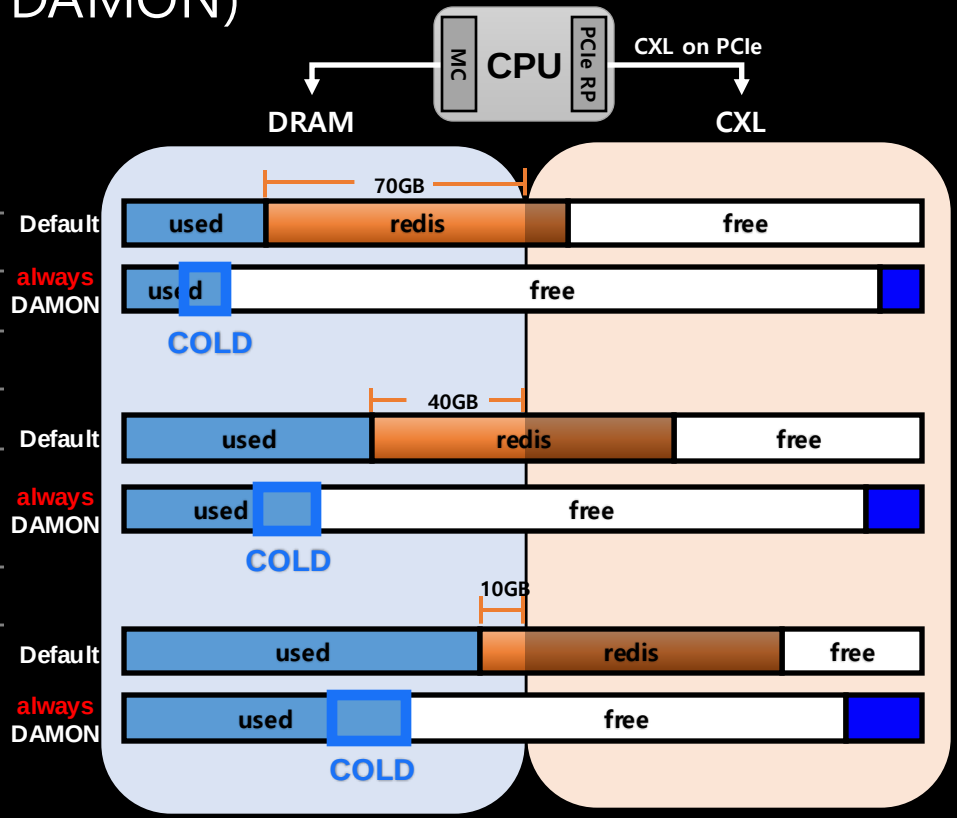

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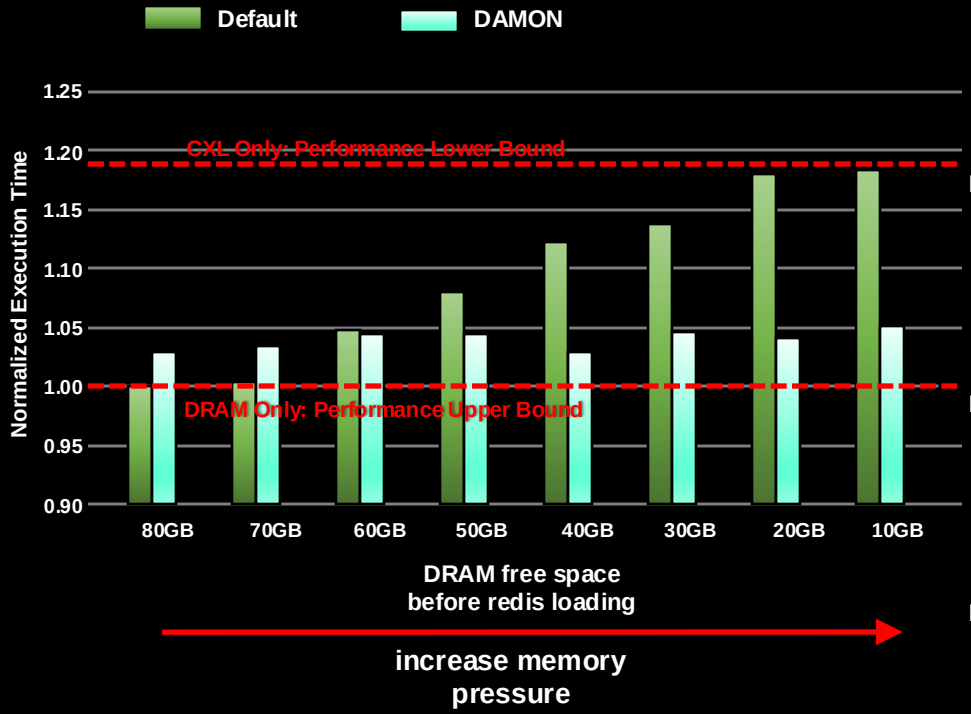

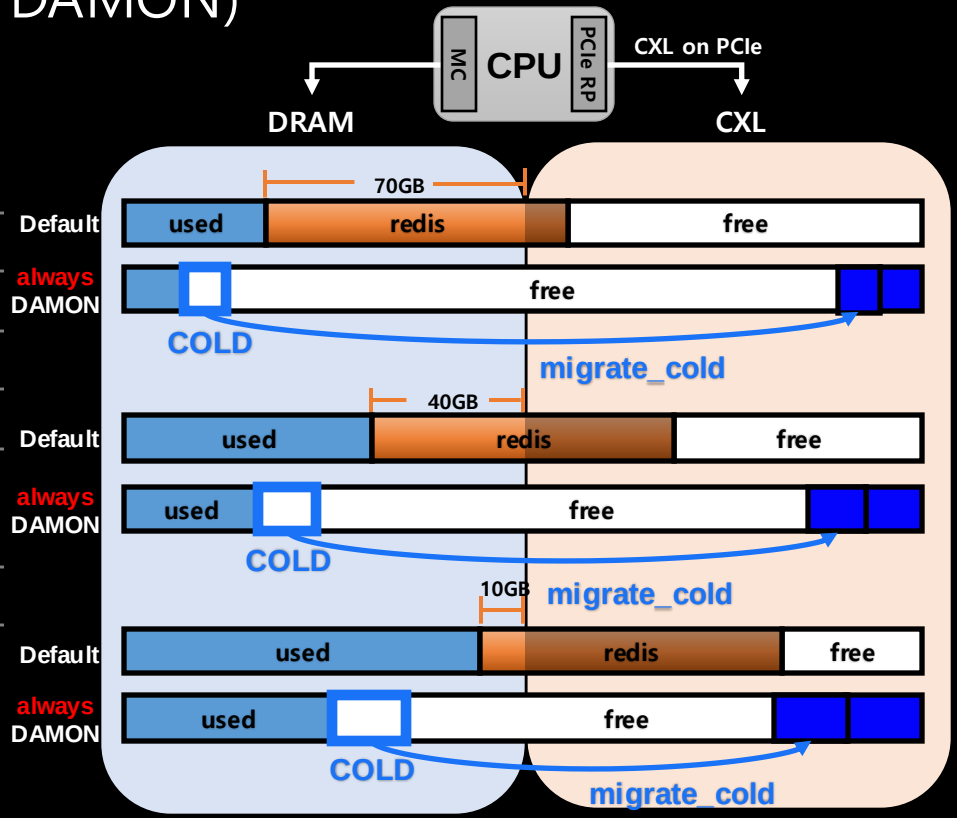

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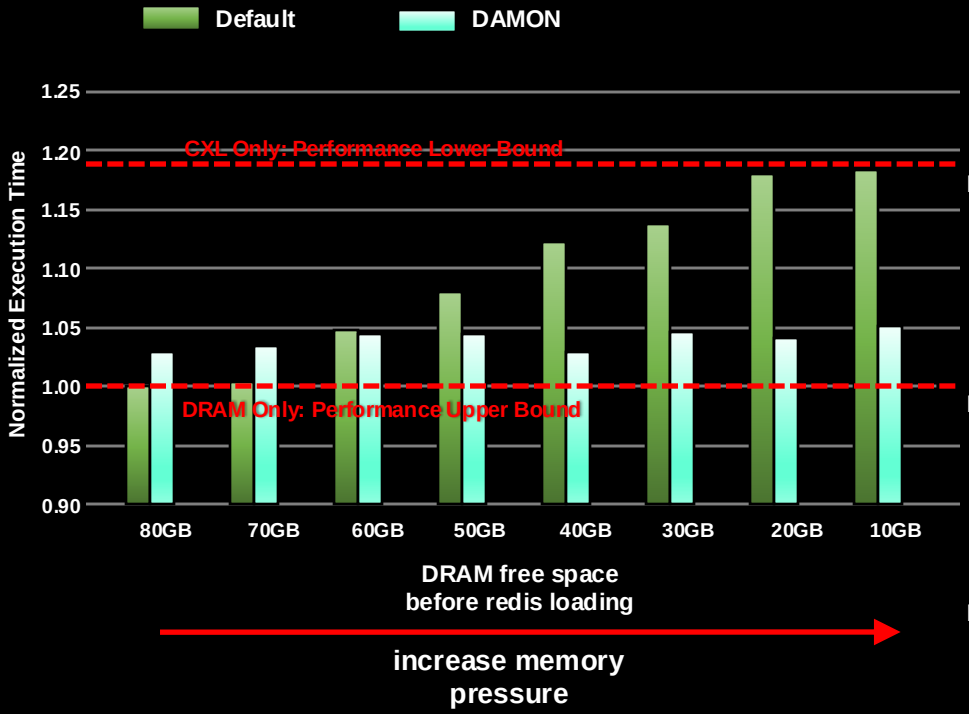

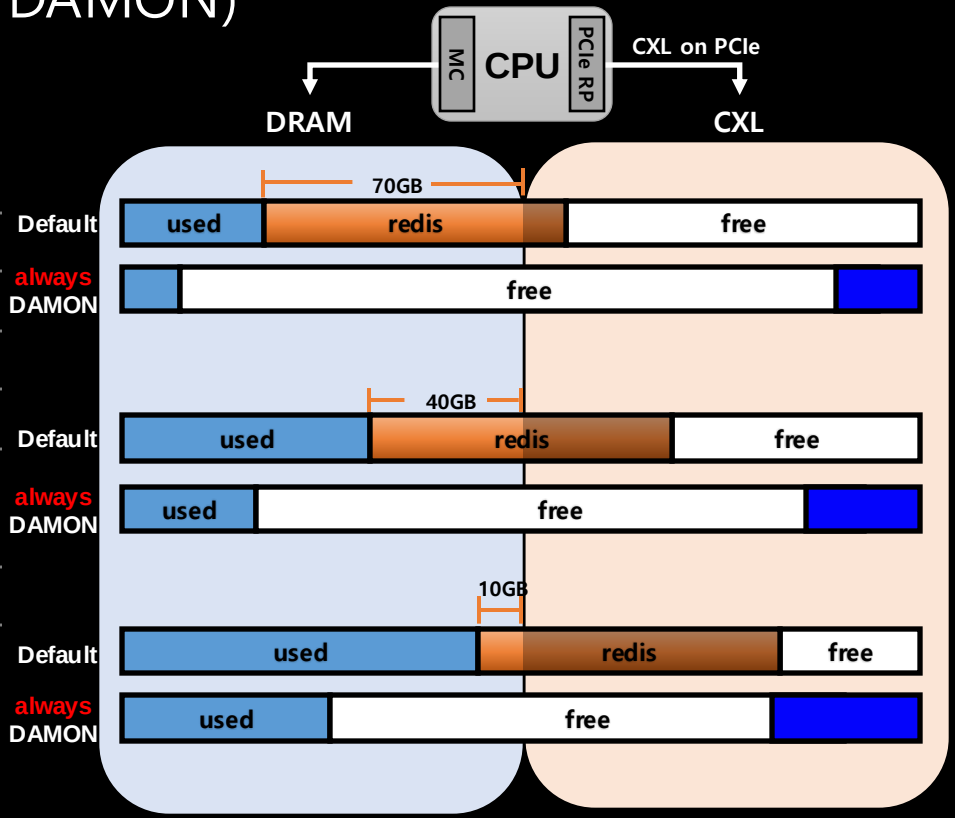

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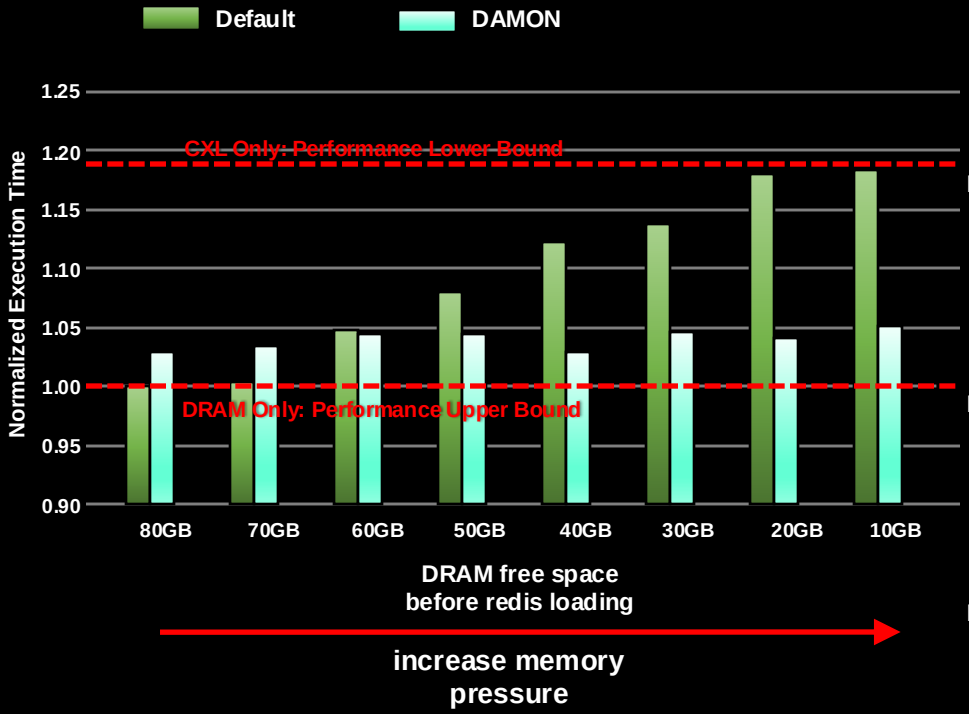

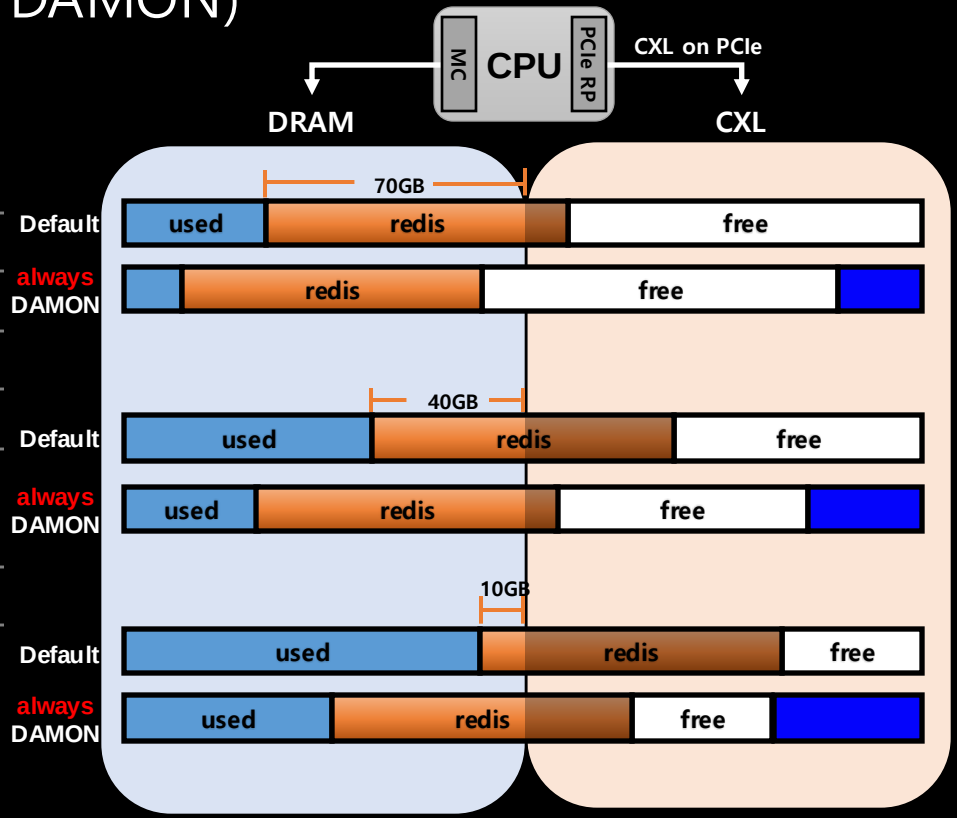

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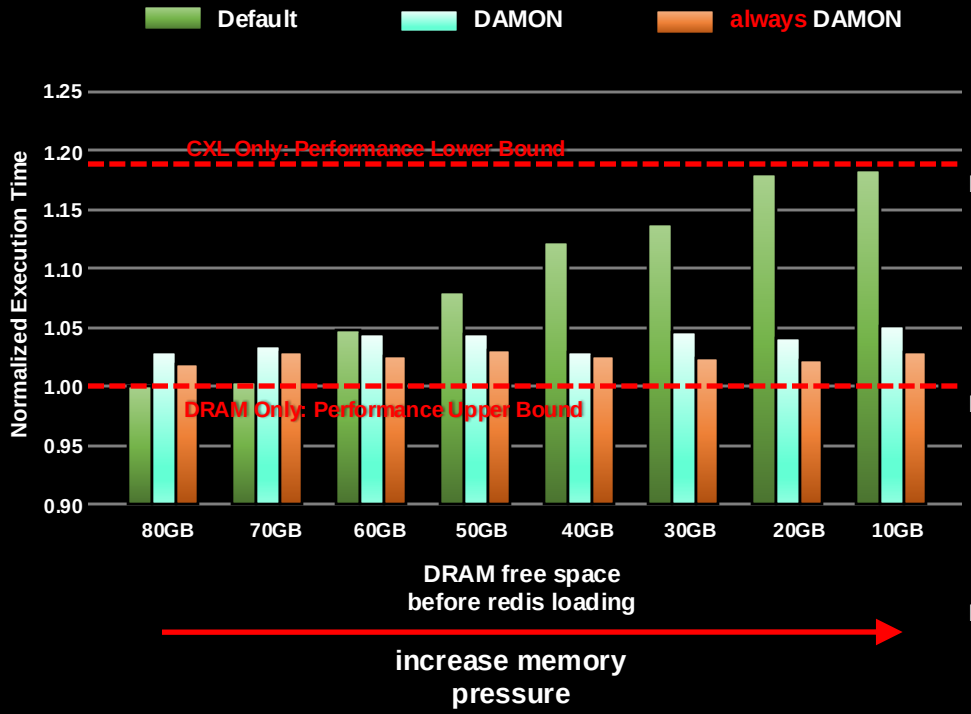

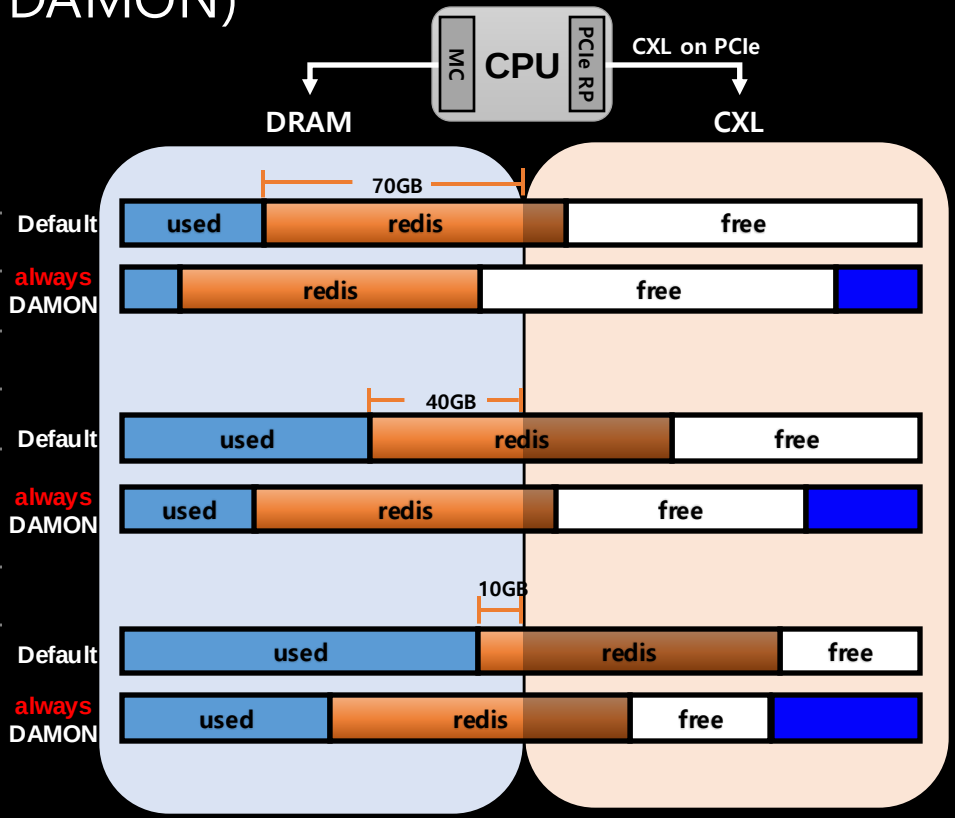

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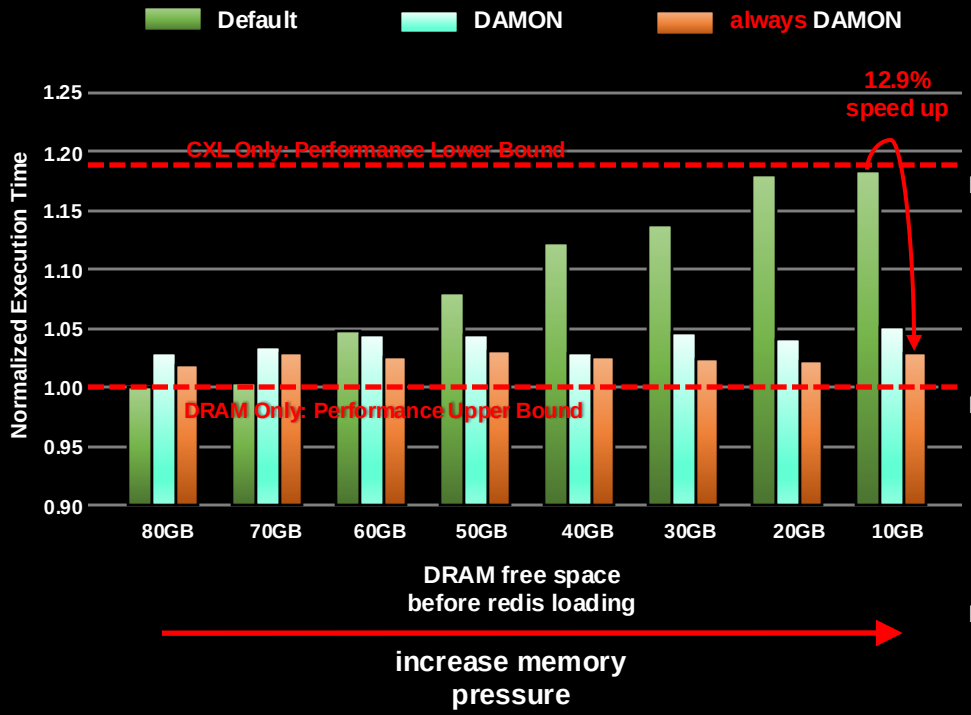

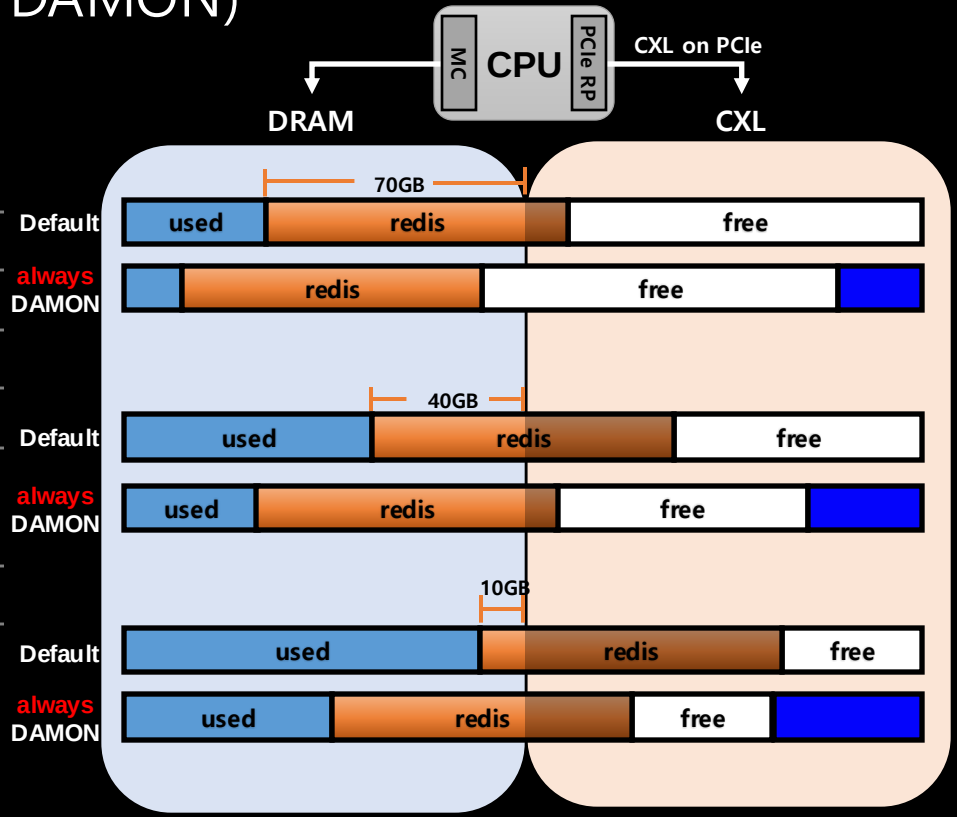

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Collaboration with DAMON community

- This work was done and presented at Open Source Summit Europe 2024.
  - DAMON Recipes: Ways to Save Memory Using a Linux Kernel Subsystem in the Real World
    - Presented by DAMON maintainer SeongJae Park@Meta and Honggyu Kim@SK hynix.

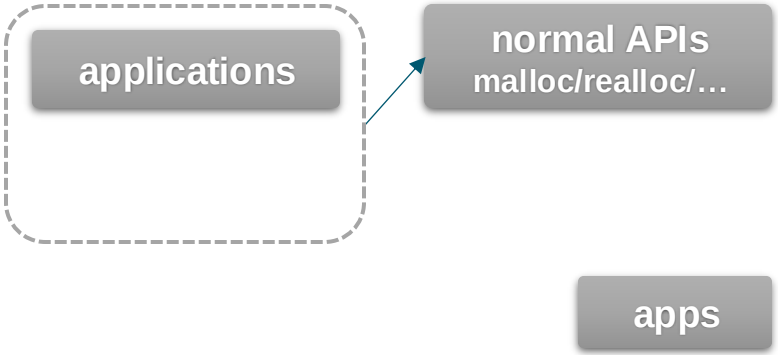
- The slide and video are available at
  - https://osseu2024.sched.com/event/1ej2S

Heterogeneous Memory Allocator (Custom Allocator)

With customized programs using hmalloc APIs.

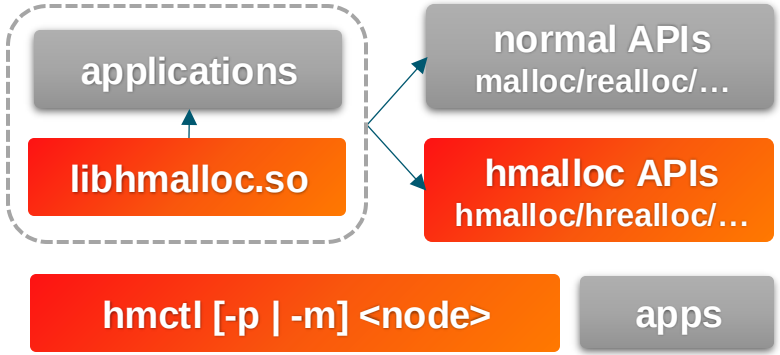
Heterogeneous Memory Allocator

- This can be used when users have knowledge of their program.
  - If users know which memory objects are cold,
    - then explicitly replace normal allocation APIs to hmalloc APIs.



Heterogeneous Memory Allocator

- This can be used when users have knowledge of their program.
  - If users know which memory objects are cold,
    - then explicitly replace normal allocation APIs to hmalloc APIs.
- HMSDK library usage (libhmalloc.so)
  - explicit allocation to a specific NUMA node (e.g. CXL memory)
    - e.g. ***hmalloc()***, ***hcalloc()***, ***hfree()***, etc.
  - ***numactl*** like ***hmctl*** tool
    - ***numactl*** applies process level mempolicy.
    - but ***hmctl*** applies mempolicy only to hmalloc area.
    - support ***--preferred*** and ***--membind*** modes.



Heterogeneous Memory Allocator

```
#include <hmalloc.h>
    ...
int main() {
    char *p = malloc(256 * MiB);
    char *hp = hmalloc(512 * MiB);
    memset(p, 'x', sz * MiB);
    memset(hp, 'x', hsz * MiB);
        ...
    getchar();  /* wait here */

    hfree(hp);
    free(p);
    return 0;
}
```

```
$ ./example &
[1] 49288
255 MiB is allocated by malloc().
511 MiB is allocated by hmalloc().
Press enter to stop.


$ numastat -c -p $!
Per-node process memory usage (in MBs) for PID 49288
(example)
         Node 0 Node 1 Node 2 Node 3 Total
         ------ ------ ------ ------ -----
Total       773      0      0      0   773
```

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}
```

```
$ hmctl -m 2 ./example &
[1] 49288
255 MiB is allocated by malloc().
511 MiB is allocated by hmalloc().
Press enter to stop.


$ numastat -c -p $!
Per-node process memory usage (in MBs) for PID 49288
(example)
         Node 0 Node 1 Node 2 Node 3 Total
         ------ ------ ------ ------ -----
Total       261      0    512      0   773
```

Heterogeneous Memory Allocator

```
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        ...
    getchar();  /* wait here */

    hfree(hp);
    free(p);
    return 0;
}
```

```
$ hmctl -m 3 ./example &
[1] 49288
255 MiB is allocated by malloc().
511 MiB is allocated by hmalloc().
Press enter to stop.


$ numastat -c -p $!
Per-node process memory usage (in MBs) for PID 49288
(example)
         Node 0 Node 1 Node 2 Node 3 Total
         ------ ------ ------ ------ -----
Total       261      0      0    512   773
```

Heterogeneous Memory Allocator

```c
#include <hmalloc.h>
    ...
int main() {
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    memset(p, 'x', sz * MiB);
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        ...
    getchar();  /* wait here */

    hfree(hp);
    free(p);
    return 0;
}
```

```
$ numactl -p 1 hmctl -m 3 ./example &
[1] 49288
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Press enter to stop.


$ numastat -c -p $!
Per-node process memory usage (in MBs) for PID 49288
(example)
         Node 0 Node 1 Node 2 Node 3 Total
         ------ ------ ------ ------ -----
Total         3    258      0    512   773
```
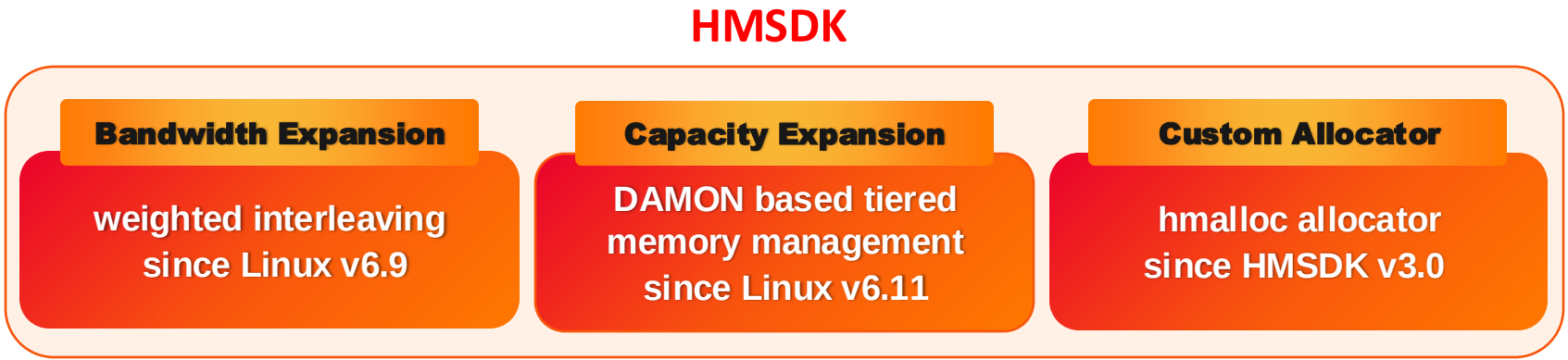

Conclusion

HMSDK v3.0 release

- HMSDK v3.0 was released Sep 2024 based on Linux v6.11!
  - Fully aligned with various open-source projects.
  - The official Linux kernel can directly be used for HMSDK.
  - https://github.com/skhynix/hmsdk/releases/tag/hmsdk-v3.0



HMSDK v3.0 release

- Linux kernel
  - weighted interleave (available from v6.9)
  - DAMON based tiered memory management (available from v6.11)

- numactl
  - -w/--weighted-interleave option (available on master)

- damo (DAMON user-space tool)
  - Interface for hot/cold migration (available from v2.4.0)
  - Support multiple kdamonds with yaml format.

Other Projects

- hwloc (Hardware locality)
  - Support HWLOC_MEMBIND_WEIGHTED_INTERLEAVE (available from hwloc-2.11.0)

- UMF (Unified Memory Framework)
  - Support UMF_NUMA_MODE_WEIGHTED_INTERLEAVE (proposed)

Conclusion

- We’re trying to expand CXL software ecosystem on Linux.
  - To make CXL memory usable by end users.
  - Such as software developers and system admins.

- New memory system requires software changes.
  - Especially for major open-source projects such as Linux kernel, etc.
  - Need to lower the huddle of using software techniques.

Thank You!

https://github.com/skhynix/hmsdk