Evaluation of Intel Memory Drive Technology Performance for Scientific Applications

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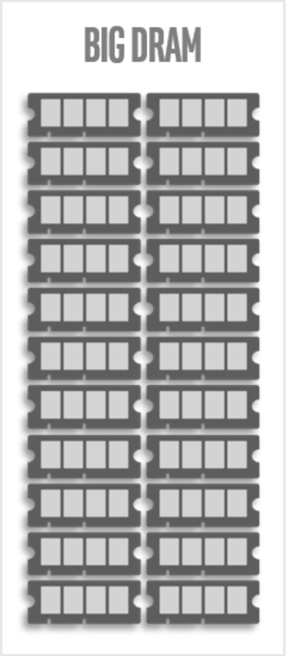
Introducing Intel® Memory Drive Technology

- Use Intel® Optane™ SSD DC P4800X **transparently as memory**
- Grow **beyond system DRAM capacity**, or **replace high-capacity DIMMs** for lower-cost alternative, with **similar performance**
- **Leverage storage**-class memory today!
  - **No change to software** stack: unmodified Linux* OS, applications, and programming
  - **No change to hardware**: runs bare-metal, loaded before OS from BIOS or UEFI
- **Aggregated single volatile memory pool**

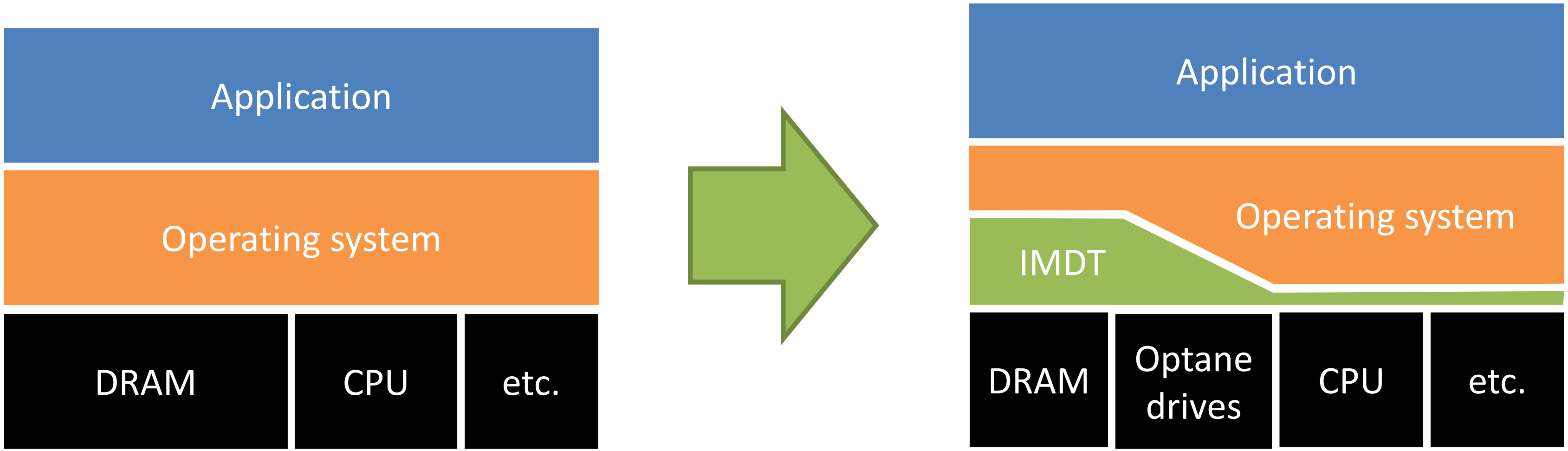


OLD

NEW

*Other names and brands may be claimed as the property of others

How Intel® Memory Drive Technology works



- IMDT operates on hypervisor level
- Requires CPU with virtualization support
- Supports any Linux distribution

- Store unused memory pages to Optane drives and load to DRAM when needed
- **Analyzes memory access patterns to prefetch data on local to CPU DRAM slot**

When to use and when not to use Intel® Memory Drive Technology

✓ Your application is designed to use very large amount of memory

- Benefits from the large memory pool
- Virtually no performance decrease on benchmarks with high arithmetic intensity

✓ Your application does not handle memory-locality/NUMA well

- Benefits from the intelligent control of NUMA memory access

✗ Your application is bound by the memory bandwidth

- The memory-bandwidth of Xeon is >50GB/s; Optane is 2GB/s per SSD
- Up to ~50% efficiency is expected, not more

What is important for Intel® Memory Drive Technology?

- Predictable accesses
  - If there is a pattern to the memory access, be it simple such as “sequential”, mid-complex like “fetch 1K every 72K”, or entirely complex like “if going to an ID field in a record in a table, fetch the whole record”
- High arithmetic intensity (FLOPs/byte ratio)
  - For every fetch from memory (in average) many compute cycles done
- High concurrency
  - Using at least 50% of the cores in a server platform concurrently, preferably more and even over-subscribed

IMDT BENCHMARKS

Hardware description

- Dual-socket Intel® Xeon® E5-2699 v4 (2x22 cores, 2.2 GHz)
  - First configuration (MDT):
    - 256 GB ECC DDR4
    - 4x320 GB Intel® Optane™ SSD (≈10 GB/s aggregated bandwidth)
  - Second configuration (lot of DRAM):
    - 1536 GB ECC DDR4
- Dual-socket Intel Xeon Gold 6154 (2x18 cores, 3.0 GHz)
  - First configuration:
    - 192 GB ECC DDR4
    - 8x Intel® Optane™ SSD
  - Second configuration
    - 1536 GB ECC DDR4
  - Only few benchmarks have been run yet

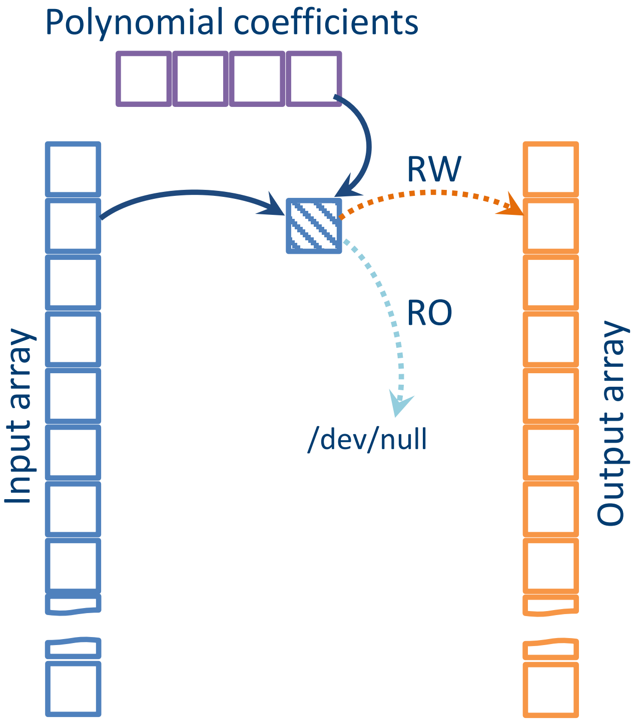
Polynomial benchmark

- Sequential-memory access benchmark
  - Compute polynomial values over a large array of input data
- Types of memory access patterns:
  - Read only (RO)
  - Read and write to another array (RW)
- Adjustable degree of polynomials
- Polynomials are computed using Horner method:

$$P(x) = (\dots((a_n x + a_{n-1})x + a_{n-2})\dots)x + a_0$$

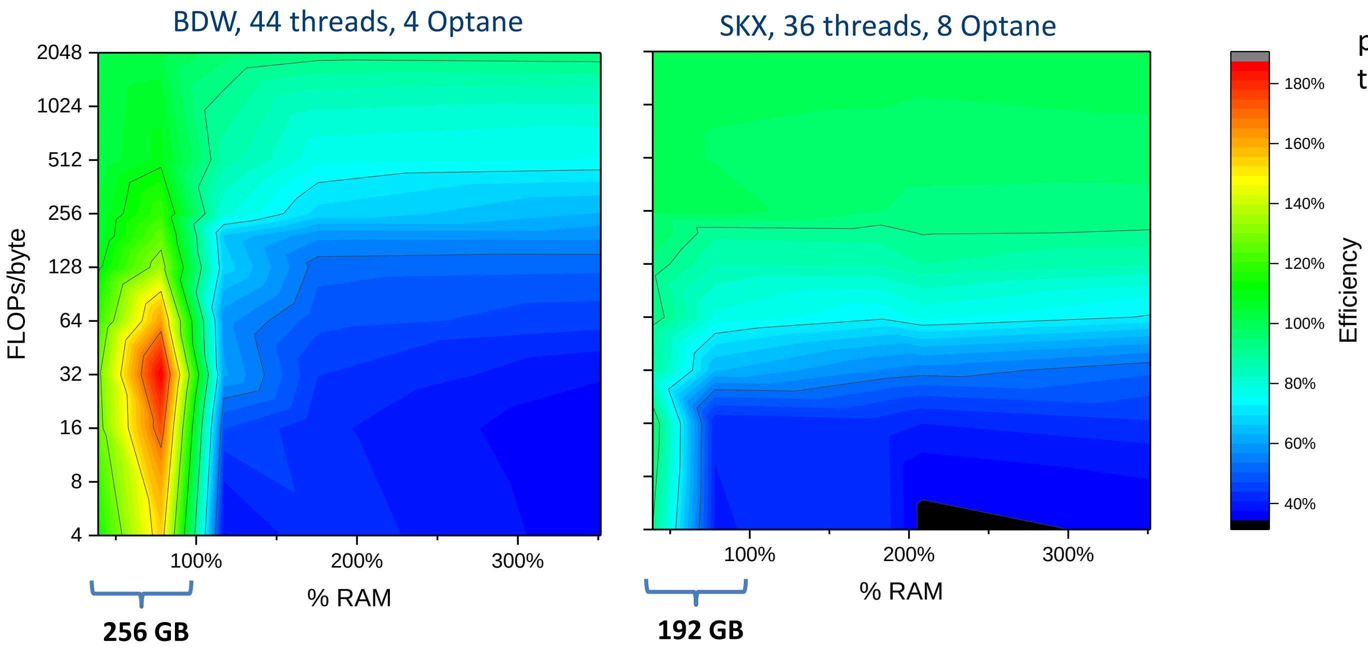
$$N_{FLOP} = (2 \cdot degree) \cdot N_{data}$$

$$\frac{FLOPs}{byte} = \frac{2 \cdot degree}{sizeof(real\_t)}$$



Polynomial benchmark (Read Only)

Efficiency: Intel® Memory Drive technology vs RAM



SKX results are preliminary – not all test cases have been sampled yet

% RAM – workload size, FLOPs/byte – workload complexity, color – efficiency

Polynomial benchmark (Read Only)

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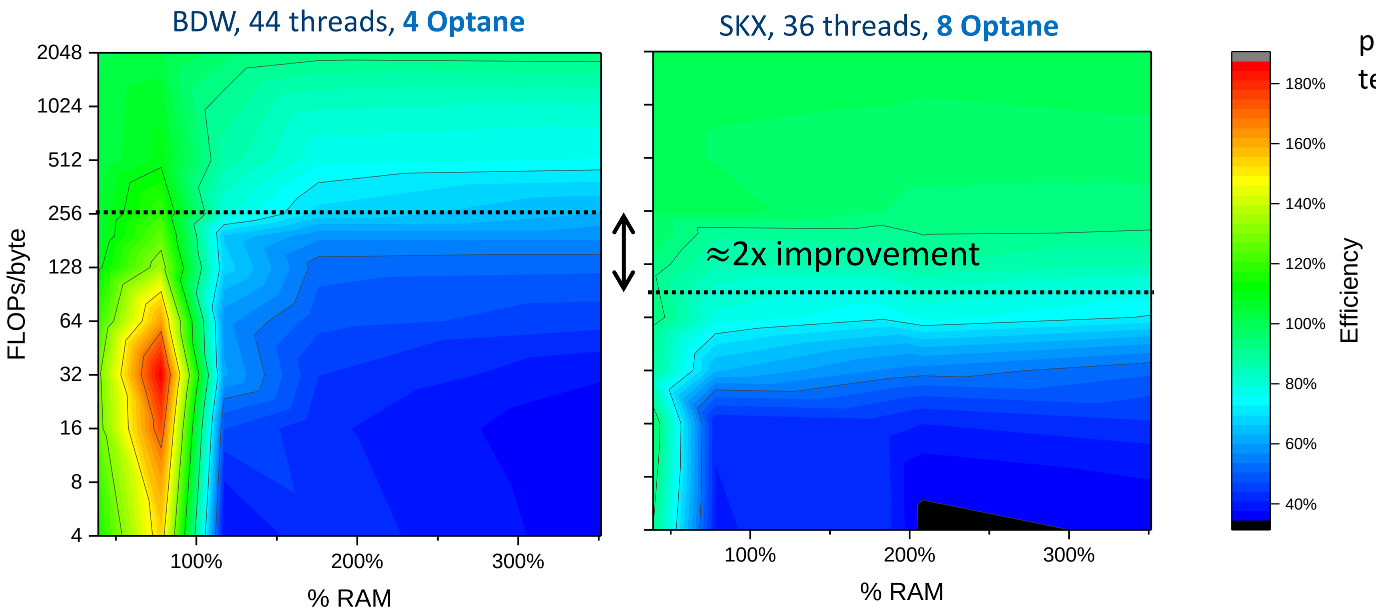

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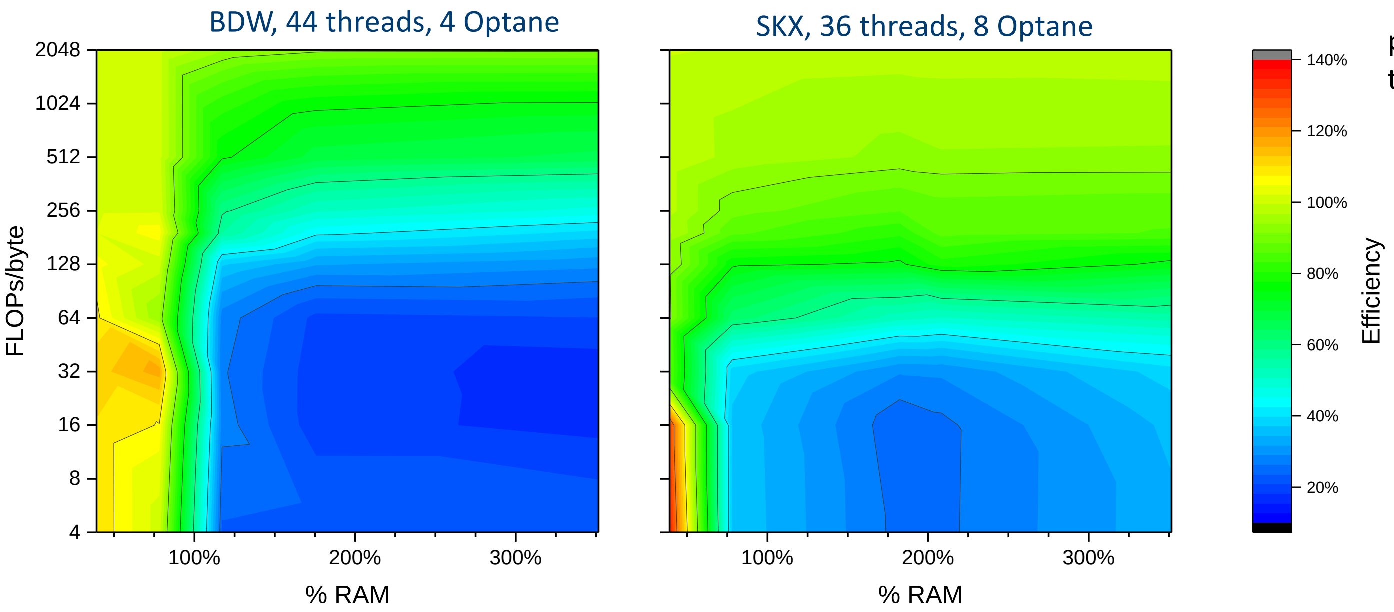
Polynomial benchmark (Read&Write)

Efficiency: Intel® Memory Drive technology vs RAM



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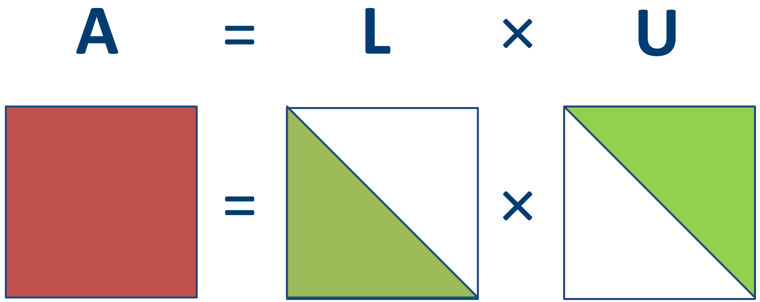
Polynomial benchmark summary

- If data size is larger than DRAM:
  - Arithmetic intensity (AI) requirements to get efficiency >80% depends on the workload, number of drives and CPU:
    - RO: 128-256 FLOPs/byte
    - RW: 256-512 FLOPs/byte
  - AI should be measured on DRAM-LLC level
- If data fits in DRAM:
  - No performance degradation
  - MDT can be faster for NUMA non-aware applications
- Arithmetic intensity requirements decrease linearly with the number of Intel Optane drives

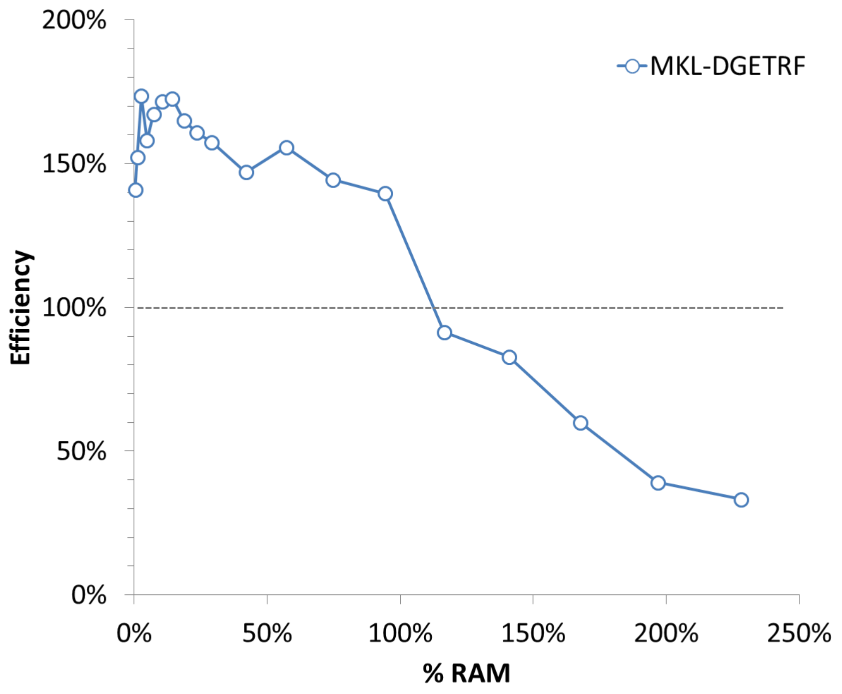
LU decomposition

- Factorization of matrix A into product of lower triangular (L) and upper triangular (U) matrices
- A commonly used kernel in many scientific codes:
  - Solving systems of linear equations
  - Matrix inversion
  - Computing determinants
- A kernel in LINPACK benchmark



LU decomposition

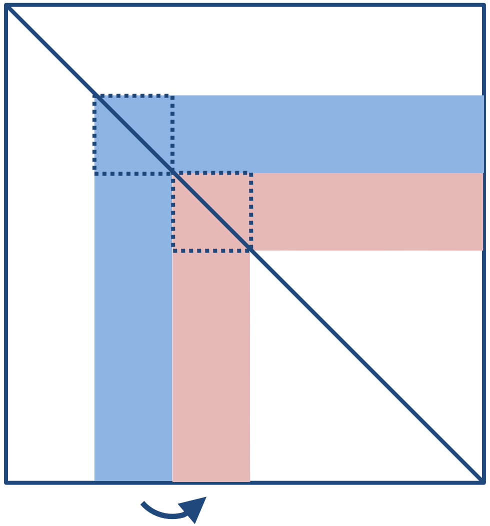
- Performance results
  - DRAM maximum performance: 850 GFLOPs/s
  - Intel® Memory Drive Technology maximum performance: 1,250 GFLOPs/s
  - A huge performance degradation beyond ≈150% RAM utilization
- Can we improve the results?



LU decomposition

- Memory access pattern is by column blocks
- Nearby elements are scattered throughout different memory pages
  - 4KB page = 512 double precision numbers
  - A huge data traffic for large matrices ($2 \cdot 10^5$ and above)
- There are tiled LU algorithms (e.q. PLASMA)

LU memory access pattern



LU decomposition

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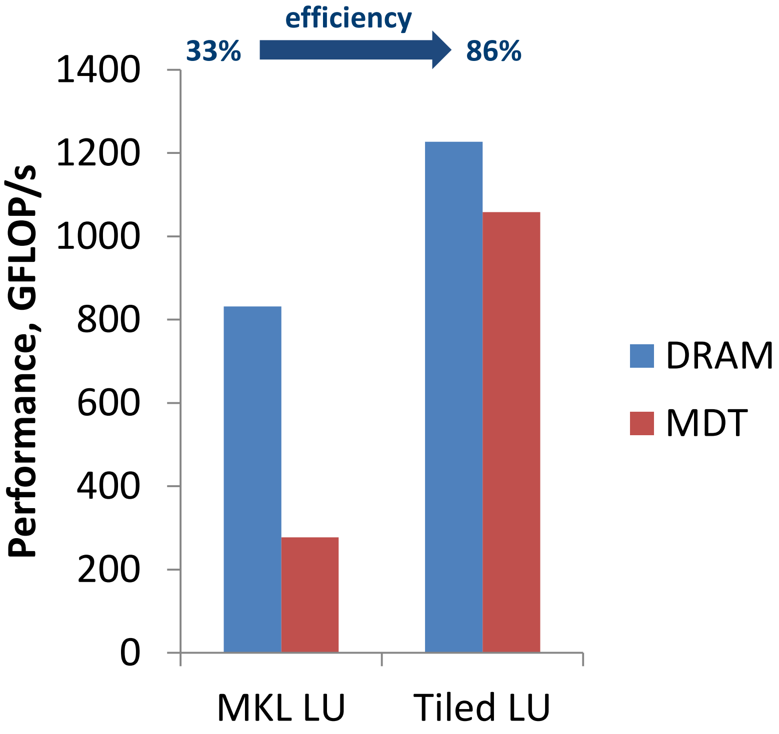
- Nearby elements are scattered throughout different memory pages
  - 4KB page = 512 double precision numbers
  - A huge data traffic for large matrices ($2 \cdot 10^5$and above)
- There are tiled LU algorithms (e.q. PLASMA)
- We used a simple implementation from *hetero-streams* code base
- Little performance degradation beyond 100% RAM usage



$N = 280000$, 230% RAM

Lessons learned from benchmarks with Intel® Memory Drive Technology

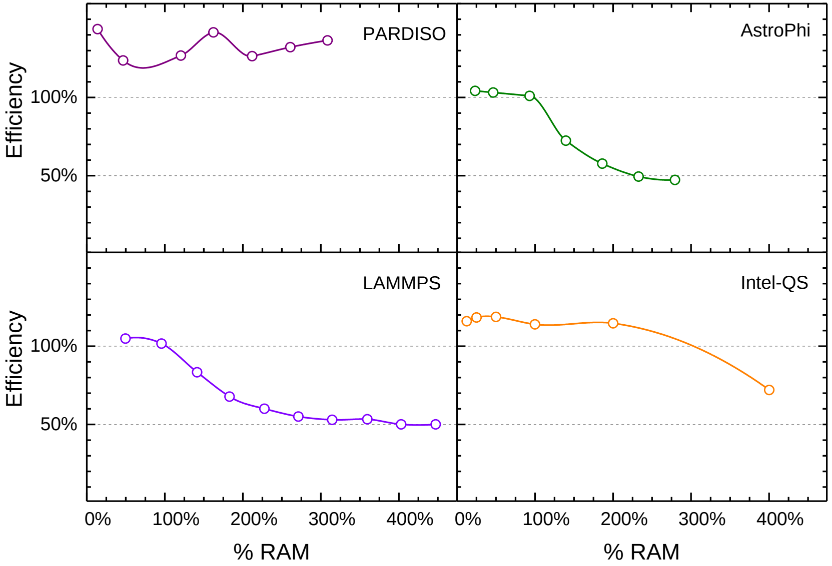
- Data moving between Intel® Optane™ SSDs and RAM is very expensive (10-20 GB/s max):
  - Reuse data as much as possible
    - Arithmetic intensity on DRAM↔MDT level should be ≥200-500 FLOPs/byte depending on the number of Optane
  - Redesign data structures in you program for locality
  - Work with large data chunks
  - Think about DRAM as a large L4 cache for MDT
- Same optimization principles as on NUMA architectures
- Data-oriented programming is a must
  - It benefits another modern hardware as well

Scientific applications

- Computational chemistry:
  - LAMMPS* (molecular dynamics)
  - GAMESS (two-electron integral kernel)
- Astrophysics:
  - AstroPhi* (hyperbolic partial differential equation solver)
- Sparse linear algebra problems:
  - Intel® Math Kernel Library PARDISO
- Quantum computing simulator:
  - Intel-QS, formerly known as qHipster

Scientific applications

- Results:
  - Efficiency is slightly higher than 100% within DRAM
  - Efficiency beyond DRAM varies from 50% up to >100%
  - LAMMPS, AstroPhi and Intel-QS are memory bound apps, efficiency tends to 50% when memory growth



Conclusions

- Efficiency of optimized applications is close to 100% with Intel® Memory Drive Technology
- Efficiency of non-optimized applications can vary from 20% to more than 100%. Typical efficiency of bandwidth-bound applications is up to 50%.
- Optimal performance is expected on next generation of Intel® Optane™ SSDs

Future work

– Scaling of IMDT performance vs number of Optane SSDs
– Comparing Intel Optane-powered fat-memory node with distributed memory on scientific applications
– Testing Intel® Optane™ DC Persistent memory

Our paper at SC’18 workshop

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Acknowledgements

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  - Justin Hogaboam (Intel) for Intel QS code
  - all of you for your attention!