Performance of PGAS Models on Emerging Multi-/Many-core Architectures using MVAPICH2-X

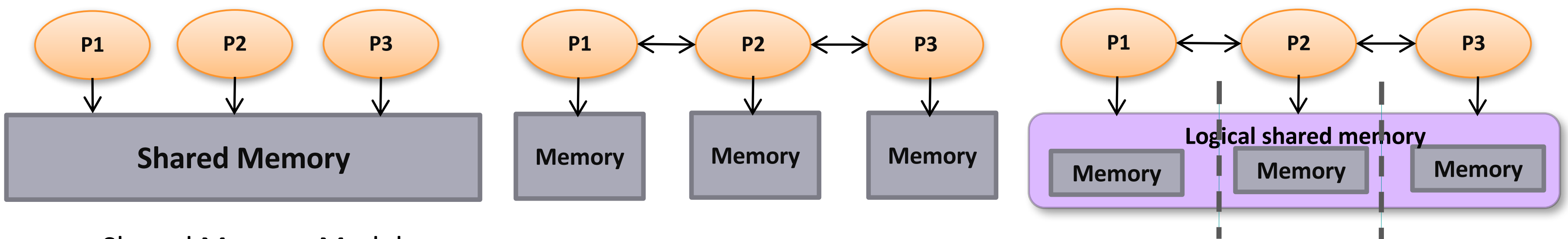
Supercomputing’17 OSU Booth Talk

J. Hashmi, H. Subramoni and DK Panda

The Ohio State University

E-mail: {hashmi.29, Subramoni.1, panda.2}@osu.edu

Parallel Programming Models Overview



Shared Memory Model | Distributed Memory Model | Partitioned Global Address Space (PGAS)

SHMEM, DSM | MPI (Message Passing Interface) | Global Arrays, UPC, Chapel, X10, CAF, …

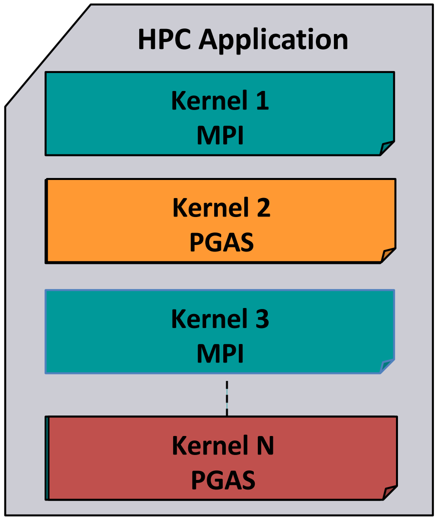
- Programming models provide abstract machine models
- Models can be mapped on different types of systems
  - e.g. Distributed Shared Memory (DSM), MPI within a node, etc.
- PGAS models and Hybrid MPI+PGAS models are gradually receiving importance

Partitioned Global Address Space (PGAS) Models

- Key features
  - Simple shared memory abstractions
  - Light weight one-sided communication
  - Easier to express irregular communication
- Different approaches to PGAS
  - Languages
    - Unified Parallel C (UPC)
    - Co-Array Fortran (CAF)
    - X10
    - Chapel
  - Libraries
    - OpenSHMEM
    - UPC++
    - Global Arrays

Hybrid (MPI+PGAS) Programming

- Application sub-kernels can be re-written in MPI/PGAS based on communication characteristics
- Benefits:
  - Best of Distributed Computing Model
  - Best of Shared Memory Computing Model
- Cons
  - Two different runtimes
  - Need great care while programming
  - Prone to deadlock if not careful



Overview of the MVAPICH2 Project

- High Performance open-source MPI Library for InfiniBand, Omni-Path, Ethernet/iWARP, and RDMA over Converged Ethernet (RoCE)
  - MVAPICH (MPI-1), MVAPICH2 (MPI-2.2 and MPI-3.0), Started in 2001, First version available in 2002
  - MVAPICH2-X (MPI + PGAS), Available since 2011
  - Support for GPGPUs (MVAPICH2-GDR) and MIC (MVAPICH2-MIC), Available since 2014
  - Support for Virtualization (MVAPICH2-Virt), Available since 2015
  - Support for Energy-Awareness (MVAPICH2-EA), Available since 2015
  - Support for InfiniBand Network Analysis and Monitoring (OSU INAM) since 2015
  - **Used by more than 2,825 organizations in 85 countries**
  - **More than 432,000 (> 0.4 million) downloads from the OSU site directly**
  - Empowering many TOP500 clusters (June '17 ranking)
    - **1st, 10,649,600-core (Sunway TaihuLight) at National Supercomputing Center in Wuxi, China**
    - 15th, 241,108-core (Pleiades) at NASA
    - 20th, 462,462-core (Stampede) at TACC
    - 44th, 74,520-core (Tsubame 2.5) at Tokyo Institute of Technology
  - Available with software stacks of many vendors and Linux Distros (RedHat and SuSE)
  - **http://mvapich.cse.ohio-state.edu**
- Empowering Top500 systems for over a decade
  - System-X from Virginia Tech (3rd in Nov 2003, 2,200 processors, 12.25 TFlops) ->
  - Sunway TaihuLight (1st in Jun'17, 10M cores, 100 PFlops)

MVAPICH2 Software Family

High-Performance Parallel Programming Libraries	
MVAPICH2	Support for InfiniBand, Omni-Path, Ethernet/iWARP, and RoCE
MVAPICH2-X	Advanced MPI features, OSU INAM, PGAS (OpenSHMEM, UPC, UPC++, and CAF), and MPI+PGAS programming models with unified communication runtime
MVAPICH2-GDR	Optimized MPI for clusters with NVIDIA GPUs
MVAPICH2-Virt	High-performance and scalable MPI for hypervisor and container based HPC cloud
MVAPICH2-EA	Energy aware and High-performance MPI
MVAPICH2-MIC	Optimized MPI for clusters with Intel KNC
Microbenchmarks	
OMB	Microbenchmarks suite to evaluate MPI and PGAS (OpenSHMEM, UPC, and UPC++) libraries for CPUs and GPUs
Tools	
OSU INAM	Network monitoring, profiling, and analysis for clusters with MPI and scheduler integration
OEMT	Utility to measure the energy consumption of MPI applications

Performance of PGAS Models using MVAPICH2-X

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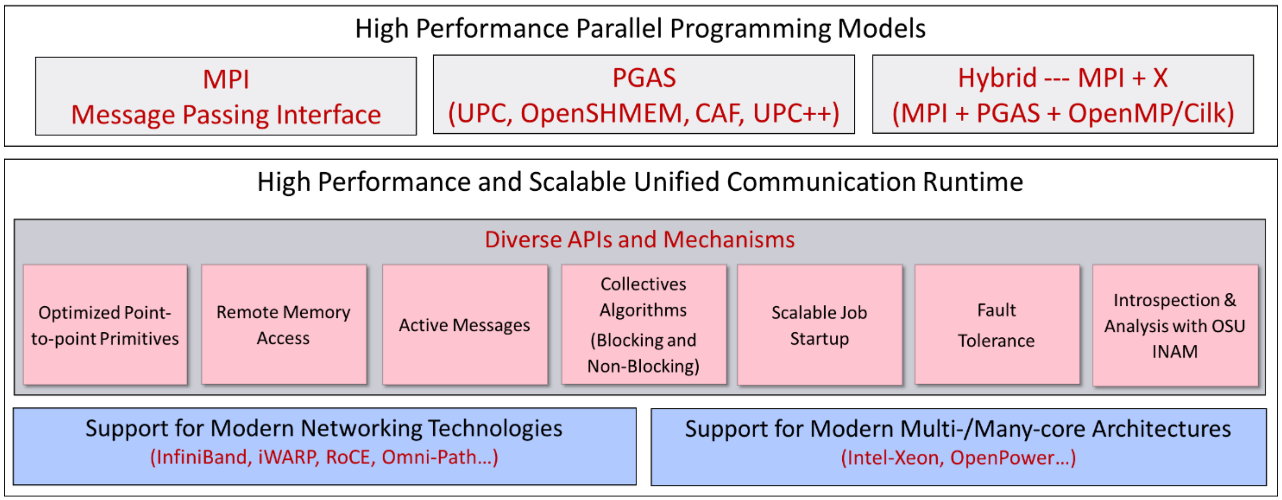
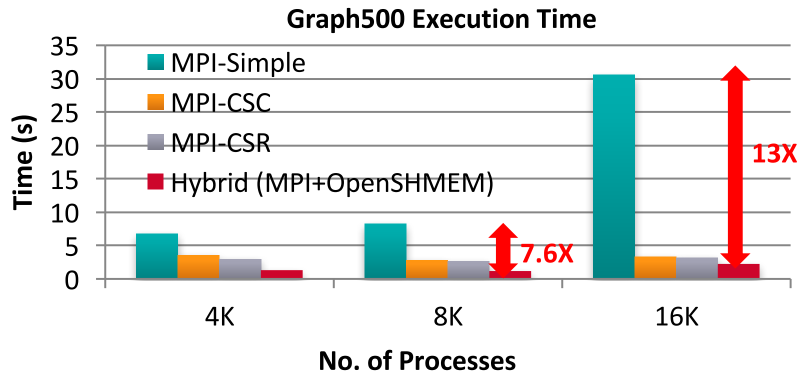
  - Performance of Put and Get with OpenSHMEM, UPC, and UPC++
  - Comparison on KNL and Broadwell for OpenSHMEM point-to-point, collectives, and atomics Operations
  - Impact of AVX-512 Vectorization and MCDRAM on OpenSHMEM Application Kernels
  - Performance of UPC++ Application kernels on MVAPICH2-X communication runtime

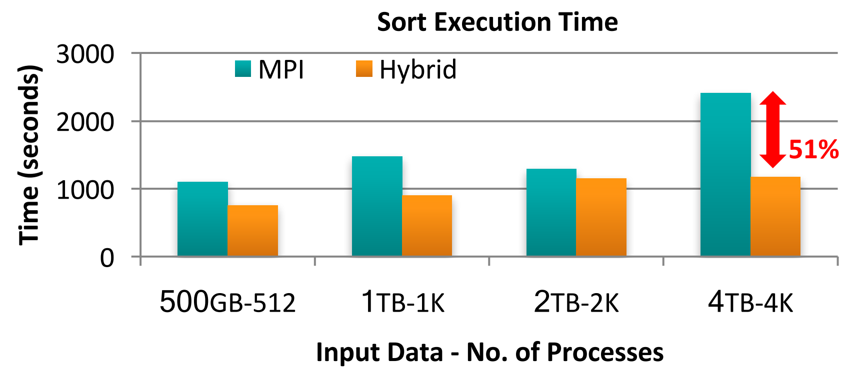
MVAPICH2-X for Hybrid MPI + PGAS Applications



- Current Model – Separate Runtimes for OpenSHMEM/UPC/UPC++/CAF and MPI
  - Possible deadlock if both runtimes are not progressed
  - Consumes more network resource
- Unified communication runtime for MPI, UPC, UPC++, OpenSHMEM, CAF
  - Available with since 2012 (starting with MVAPICH2-X 1.9)
  - http://mvapich.cse.ohio-state.edu

Application Level Performance with Graph500 and Sort





- Performance of Hybrid (MPI+ OpenSHMEM) Graph500 Design
  - 8,192 processes
    - **2.4X** improvement over MPI-CSR
    - **7.6X** improvement over MPI-Simple
  - 16,384 processes
    - **1.5X** improvement over MPI-CSR
    - **13X** improvement over MPI-Simple

- Performance of Hybrid (MPI+OpenSHMEM) Sort Application
  - 4,096 processes, 4 TB Input Size
    - MPI – 2408 sec; 0.16 TB/min
    - Hybrid – 1172 sec; 0.36 TB/min
    - **51%** improvement over MPI-design

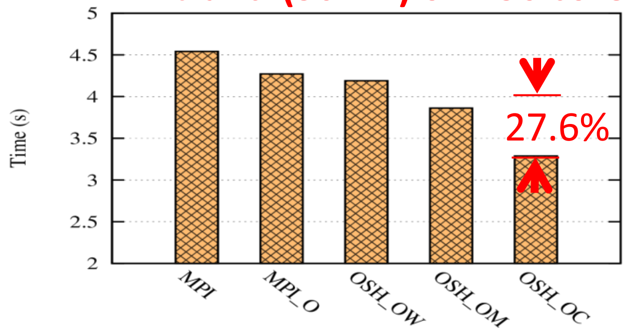
J. Jose, S. Potluri, H. Subramoni, X. Lu, K. Hamidouche, K. Schulz, H. Sundar and D. Panda Designing Scalable Out-of-core Sorting with Hybrid MPI+PGAS Programming Models, PGAS'14

J. Jose, S. Potluri, K. Tomko and D. K. Panda, Designing Scalable Graph500 Benchmark with Hybrid MPI+OpenSHMEM Programming Models, International Supercomputing Conference (ISC'13), June 2013

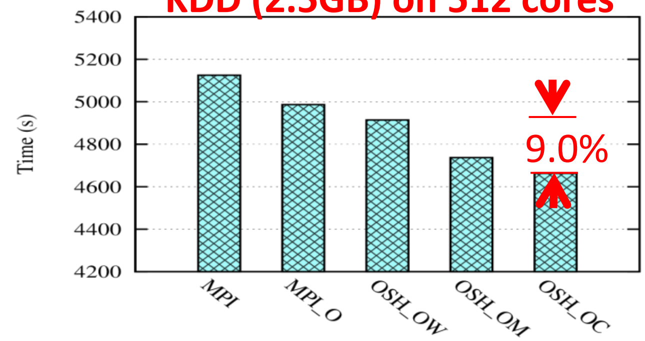
Accelerating MaTEx k-NN with Hybrid MPI and OpenSHMEM

- **MaTEx:** MPI-based Machine learning algorithm library
- **k-NN:** a popular supervised algorithm for classification
- **Hybrid designs:**
  - Overlapped Data Flow; One-sided Data Transfer; Circular-buffer Structure

KDD-tranc (30MB) on 256 cores



KDD (2.5GB) on 512 cores



- Benchmark: KDD Cup 2010 (8,407,752 records, 2 classes, k=5)
- For truncated KDD workload on 256 cores, reduce 27.6% execution time
- For full KDD workload on 512 cores, reduce 9.0% execution time

J. Lin, K. Hamidouche, J. Zhang, X. Lu, A. Vishnu, D. Panda. Accelerating k-NN Algorithm with Hybrid MPI and OpenSHMEM, OpenSHMEM 2015

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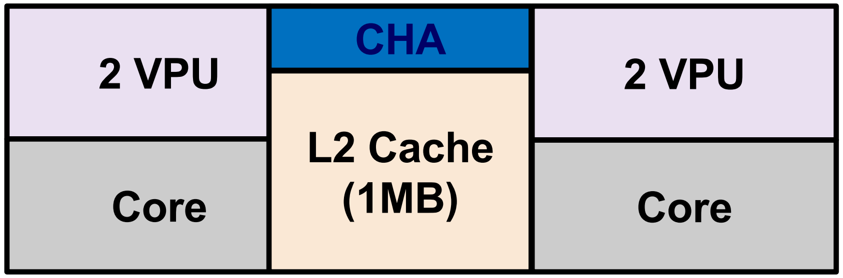
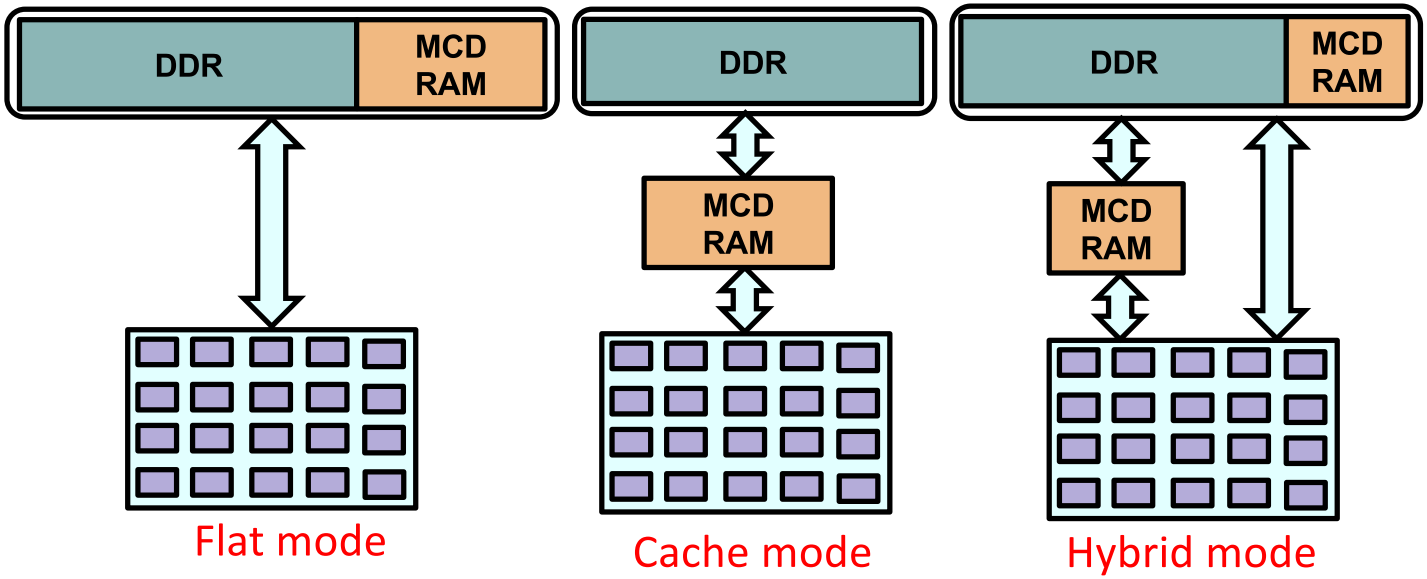
Intel Knights Landing (KNL) Processor Architecture

- Hardware Multi-threaded cores
  - Up to 72 cores (model 7290)
- All cores divided into 36 Tiles
- Each tile contains two core
  - 2 VPU per core
  - 1MB shared L2 cache
- 512-bit wide vector registers
  - AVX-512 extension



A single Tile of KNL

Intel Knights Landing (KNL) Processor - MCDRAM



- On-package Multi Channel DRAM (MCDRAM)
  – 450 GB/s of theoretical bandwidth (4x of DDR)
  – Configurable in Flat, Cache, and Hybrid modes

Motivation

- Optimizing HPC programming models and runtimes on emerging multi-/many-cores is of great research interest
- Exploring benefits of the architectural features of modern architectures for PGAS models and applications
- Characterizing and understanding
  - the impact of vectorization on application kernels
  - MCDRAM vs. DDR performance
  - Exploiting hardware multi-threading

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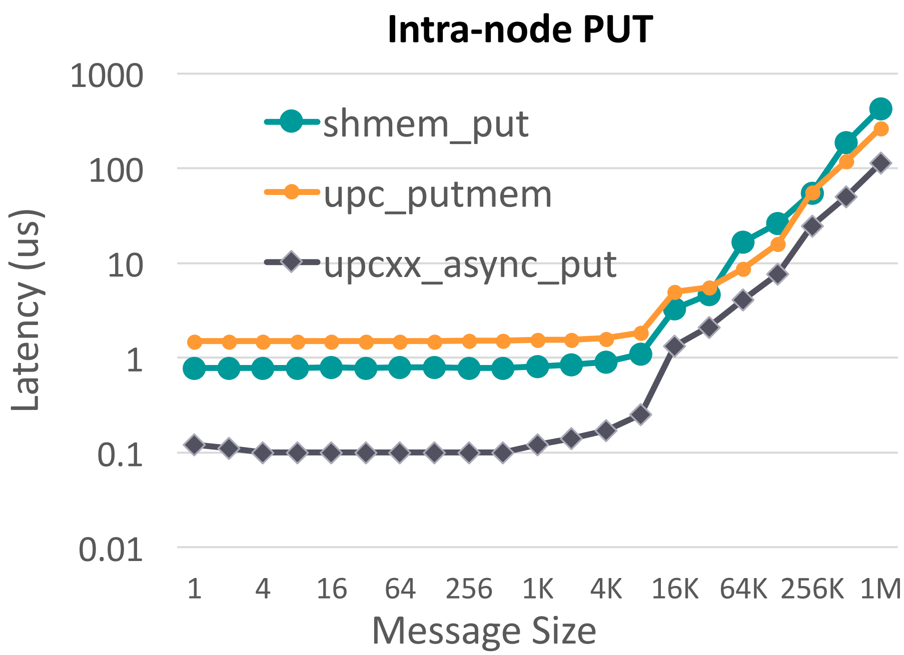
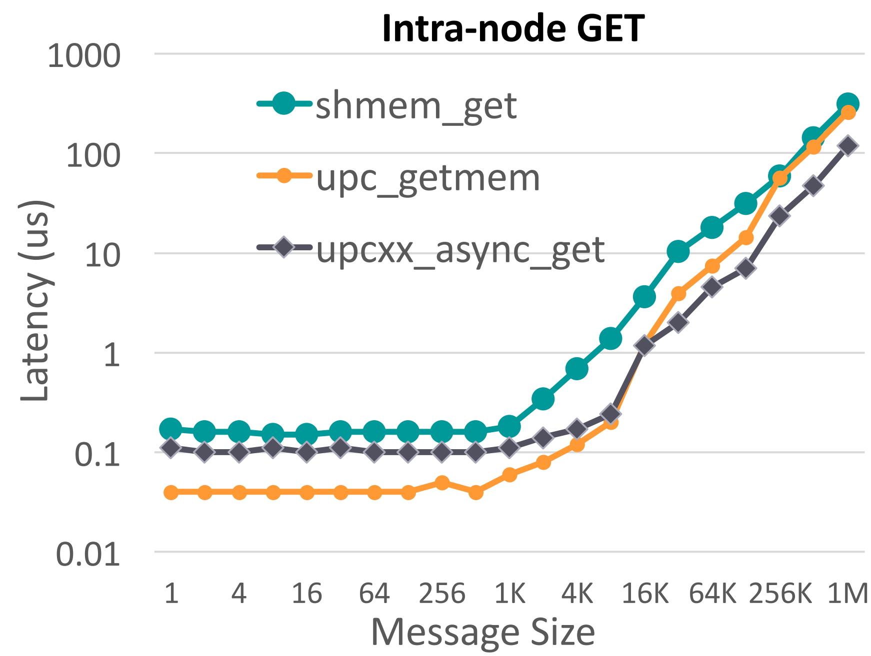
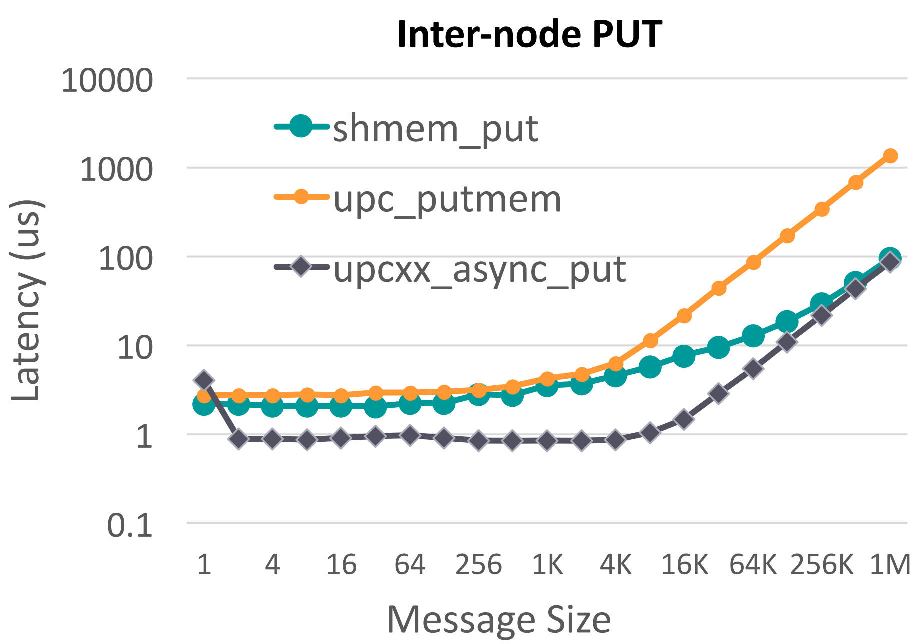
Performance of PGAS Models on KNL using MVAPICH2-X

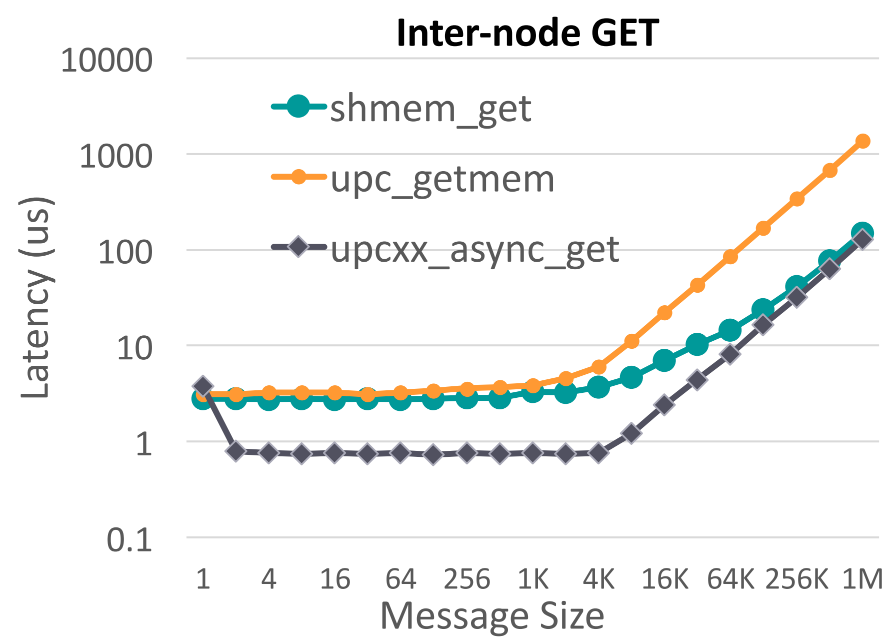




- Intra-node performance of one-sided Put/Get operations of PGAS libraries/languages using MVAPICH2-X communication conduit
- Near-native communication performance is observed on KNL

Performance of PGAS Models on KNL using MVAPICH2-X





- Inter-node performance of one-sided Put/Get operations using MVAPICH2-X communication conduit with InfiniBand HCA (MT4115)
- Native IB performance for all three PGAS models is observed.

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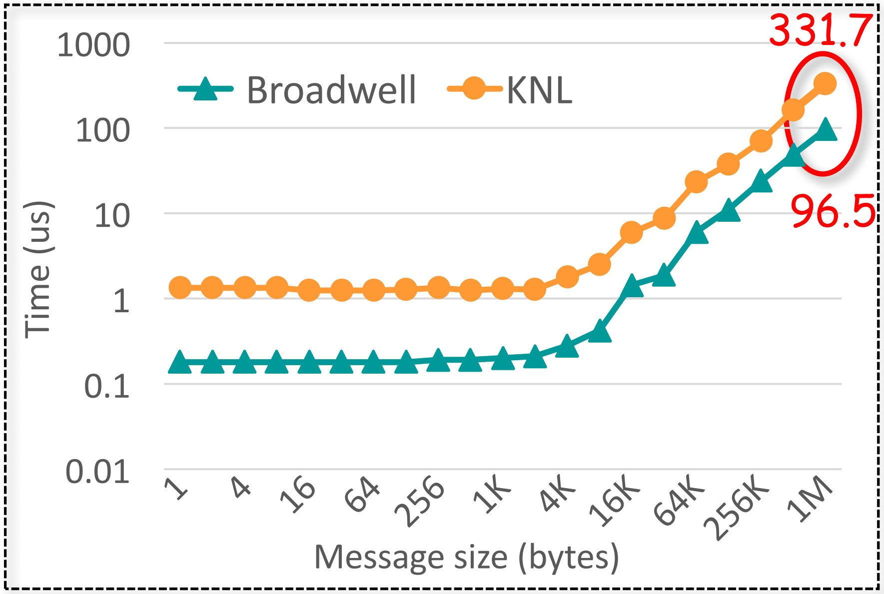
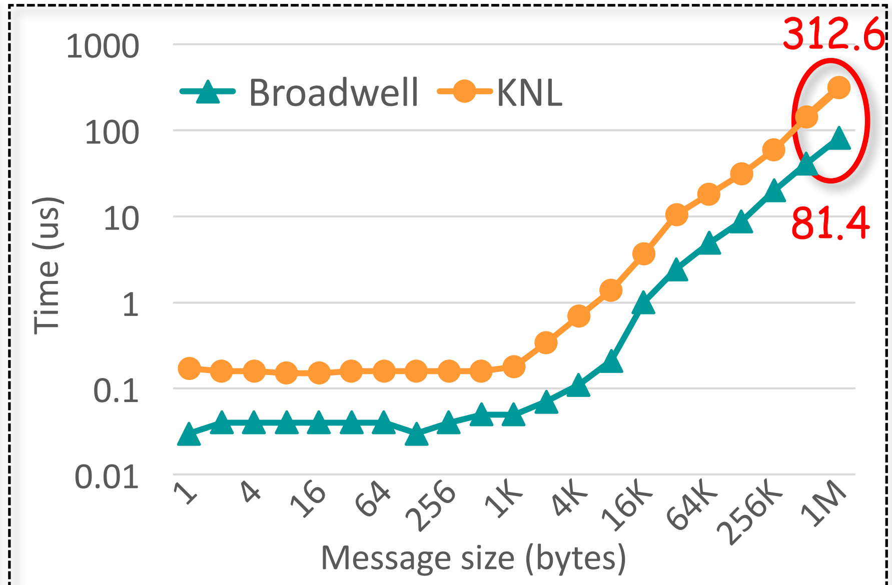
Microbenchmark Evaluations (Intra-node Put/Get)



Shmem_putmem

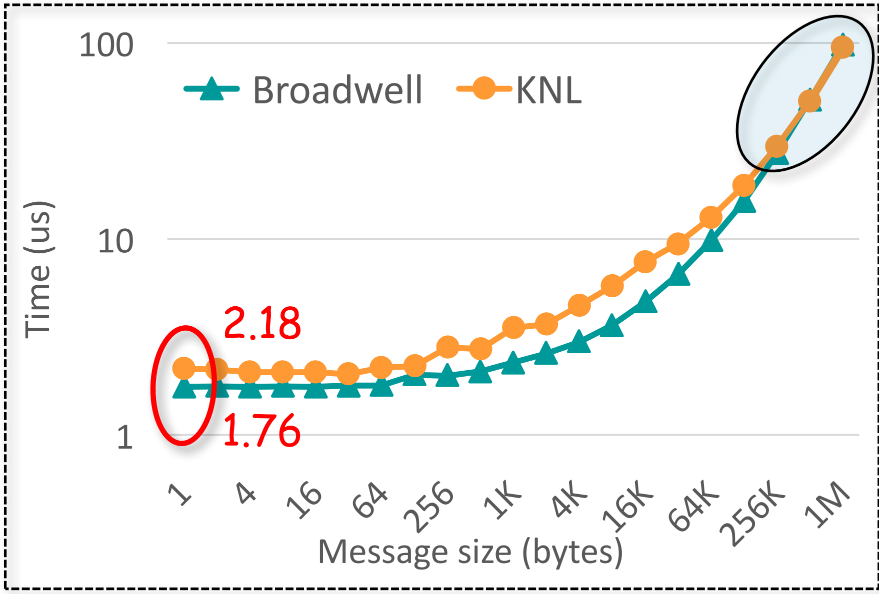


Shmem_getmem

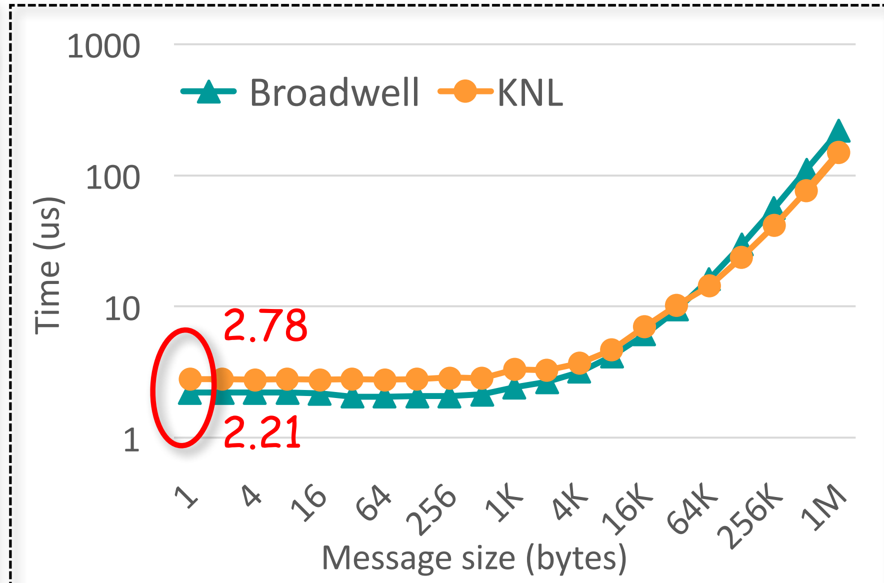
- Broadwell shows about 3X better performance than KNL on large message
- Muti-threaded memcpy routines on KNL could offset the degradation caused by the slower core on basic Put/Get operations

J. Hashmi, M. Li, H. Subramoni, D. Panda. Exploiting and Evaluating OpenSHMEM on KNL Architecture, OpenSHMEM 2017.

Microbenchmark Evaluations (Inter-node Put/Get)



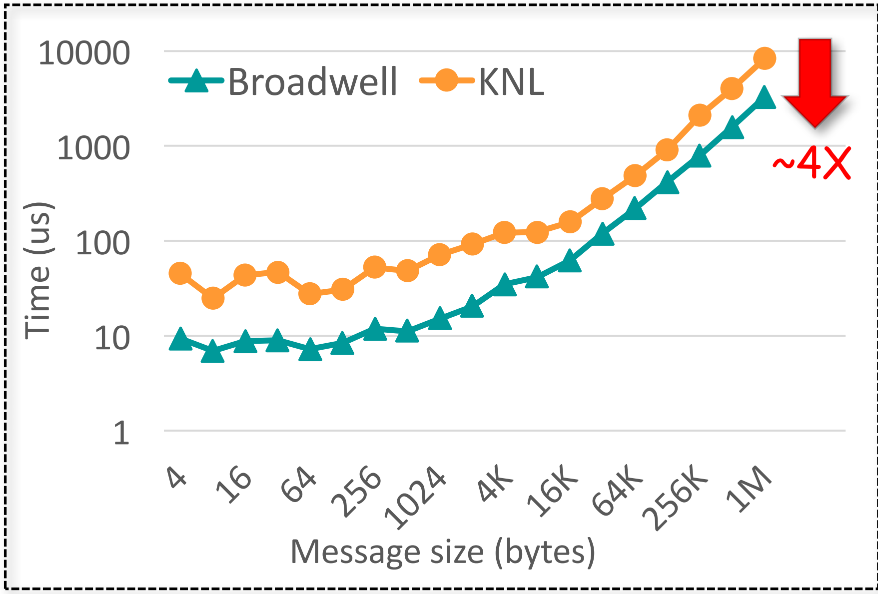
Shmem_putmem



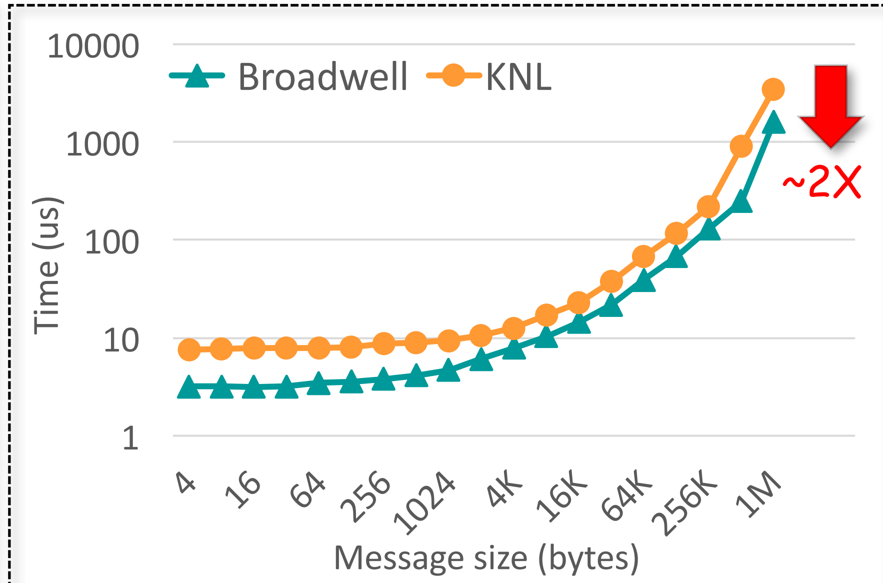
Shmem_getmem

- Inter-node small message latency is only 2X worse on KNL. While large message performance is almost similar on both KNL and Broadwell.

Microbenchmark Evaluations (Collectives)



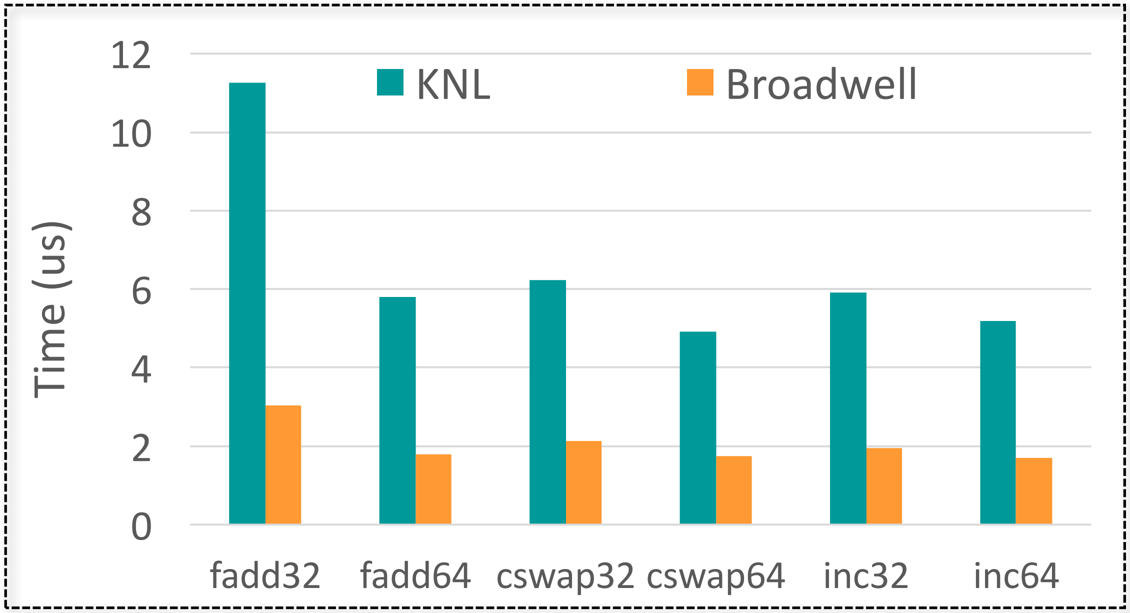
Shmem_reduce on 128 processes



Shmem_broadcast on 128 processes

- 2 KNL nodes (64 ppn) and 8 Broadwell nodes (16 ppn).
- 4X degradation is observed on KNL using collective benchmarks.
- Basic point-to-point performance difference is reflected in collectives as well

Microbenchmark Evaluations (Atomics)



OpenSHMEM atomics on 128 processes

- Using multiple nodes of KNL, atomic operations showed about 2.5X degradation on compare-swap, and Inc atomics
- Fetch-and-add (32-bit) showed up to 4X degradation on KNL

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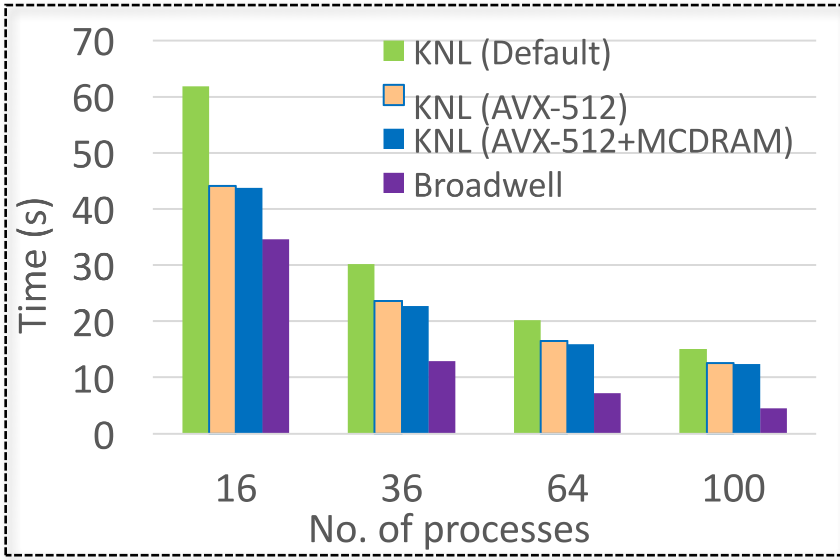
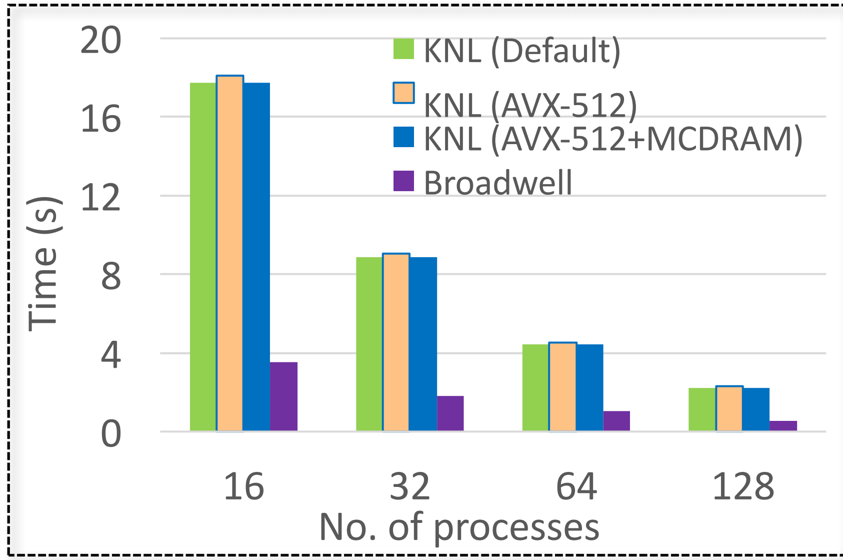
NAS Parallel Benchmark Evaluation

NAS-BT (PDE solver), CLASS=B

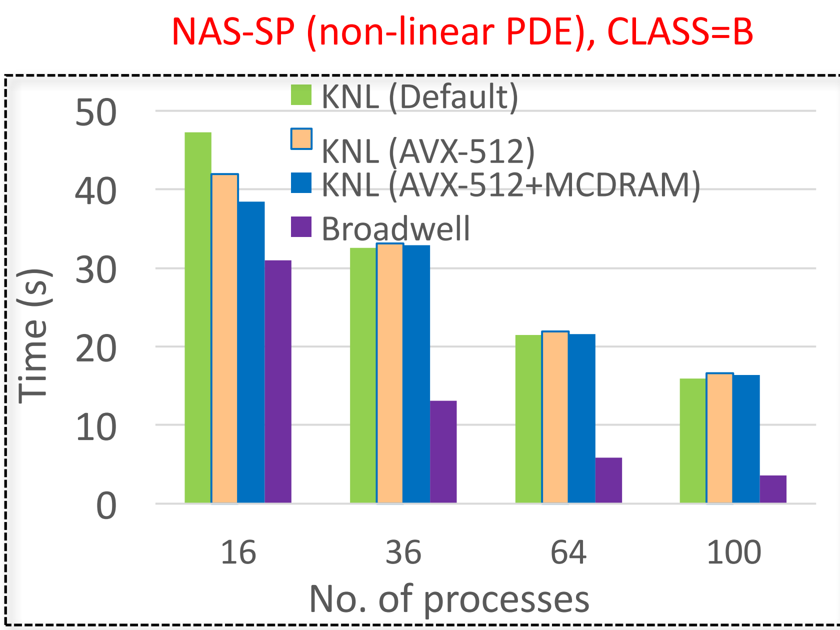


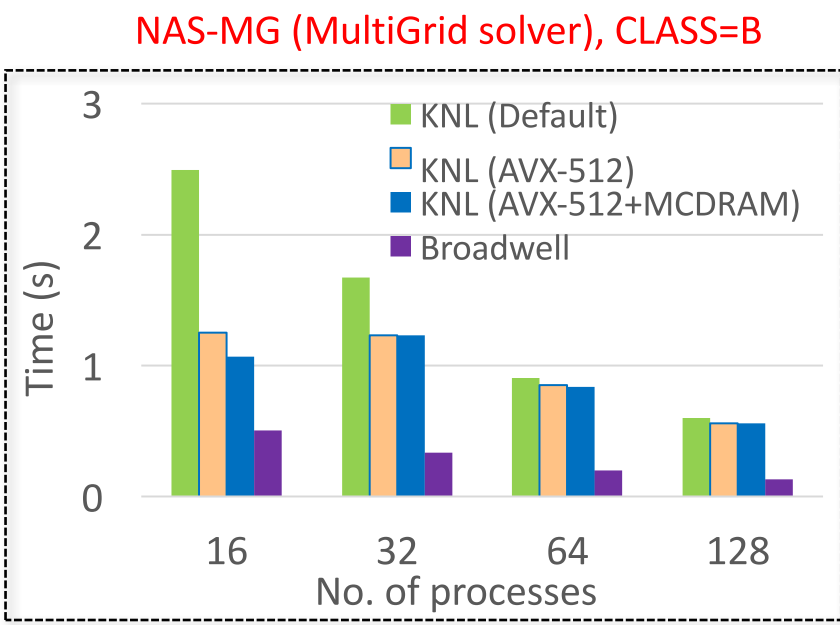
NAS-EP (RNG), CLASS=B



- AVX-512 vectorized execution of BT kernel on KNL showed 30% improvement over default execution while EP kernel didn't show any improvement
- Broadwell showed 20% improvement over optimized KNL on BT and 4X improvement over all KNL executions on EP kernel (random number generation).

NAS Parallel Benchmark Evaluation (contd.)

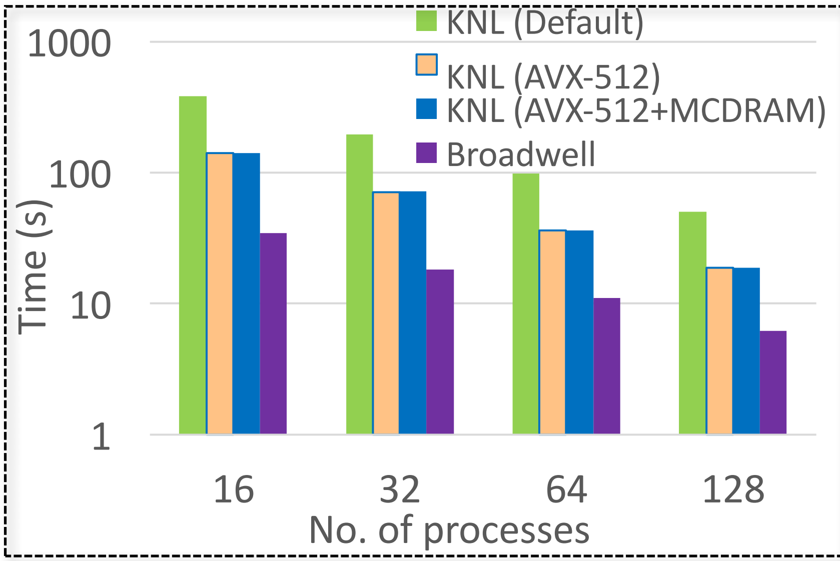




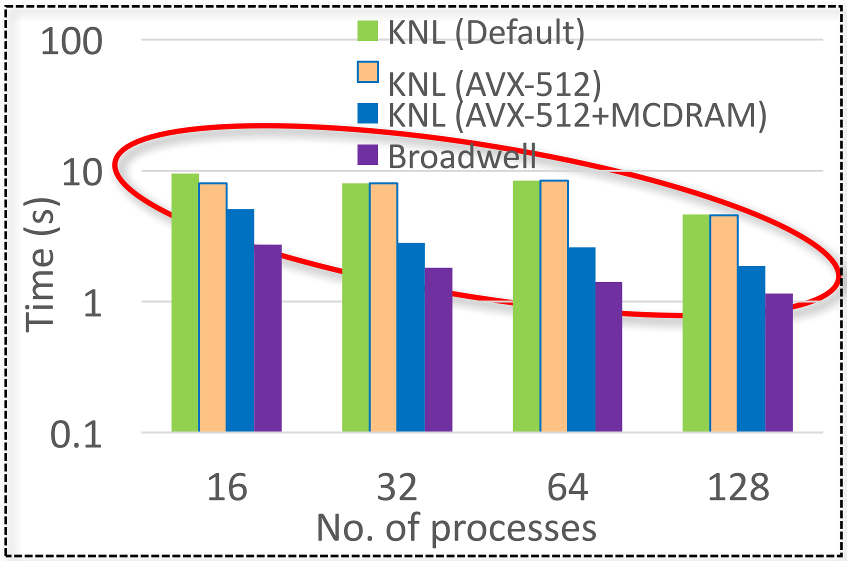
- Similar performance trends are observed on BT and MG kernels as well
- On SP kernel, MCDRAM based execution showed up to 20% improvement over default at 16 processes.

Application Kernels Evaluation

Heat-2D Kernel using Jacobi method



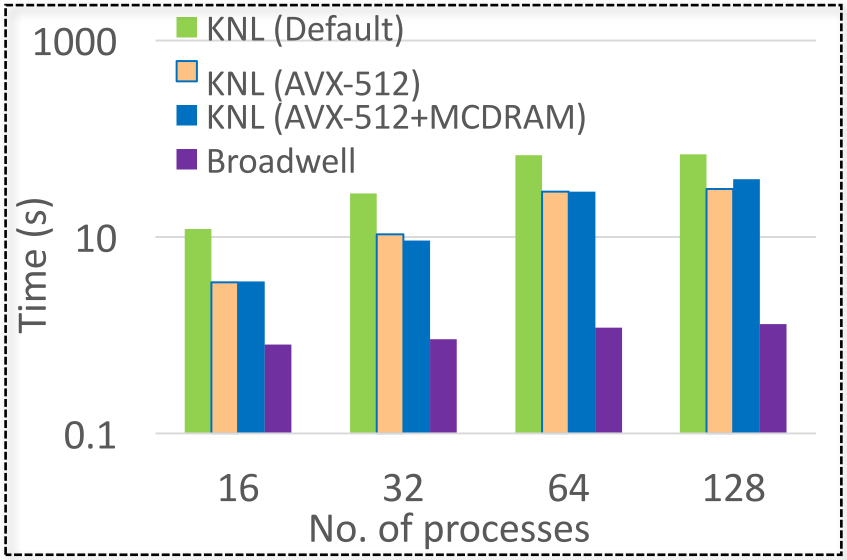
Heat Image Kernel



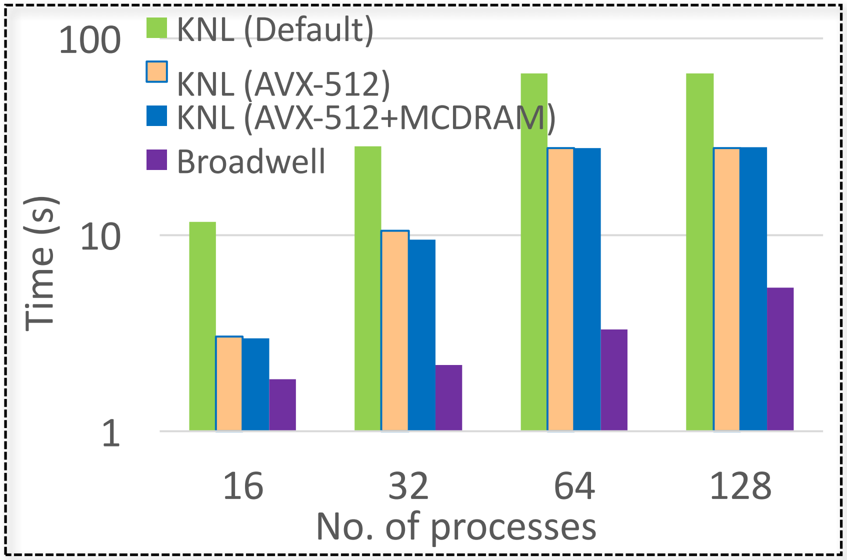
- On heat diffusion based kernels AVX-512 vectorization showed better performance
- MCDRAM showed significant benefits on Heat-Image kernel for all process counts. Combined with AVX-512 vectorization, it showed up to 4X improved performance

Application Kernels Evaluation (contd.)

Matrix Multiplication kernel



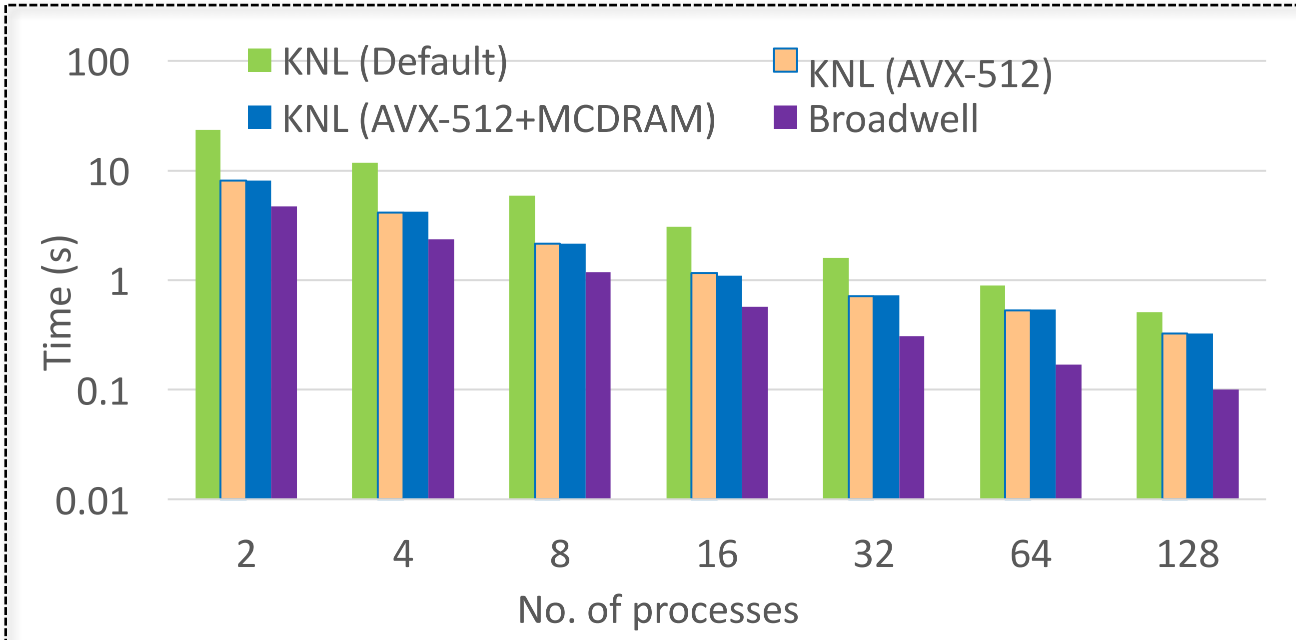
DAXPY kernel



- Vectorization helps in matrix multiplication and vector operations.
- Due to heavily compute bound nature of these kernels, MCDRAM didn't show any significant performance improvement.

Application Kernels Evaluation (contd.)

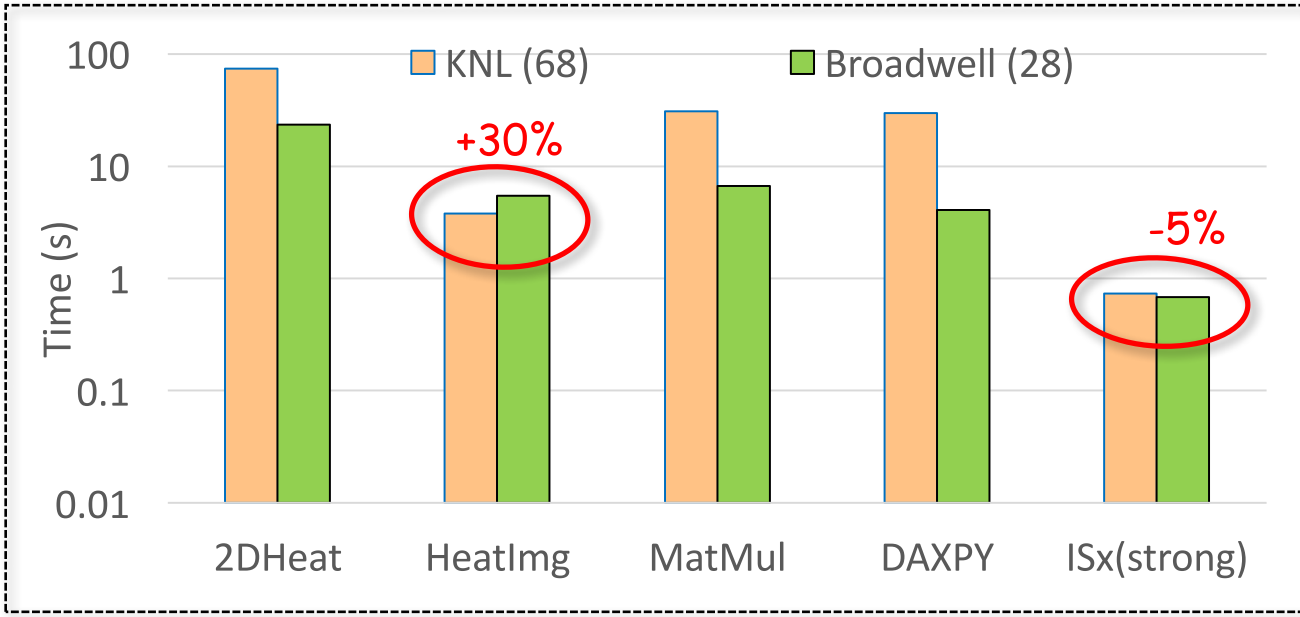
Scalable Integer Sort Kernel (ISx)



- Up to 3X improvement on un-optimized execution is observed on KNL
- Broadwell showed up to 2X better performance for core-by-core comparison

Node-by-node Evaluation using Application Kernels

Application Kernels on a single KNL vs. single Broadwell node



- A single node of KNL is evaluated against a single node of Broadwell using all the available physical cores
- HeatImage and ISx kernels, showed better performance than Intel Xeon

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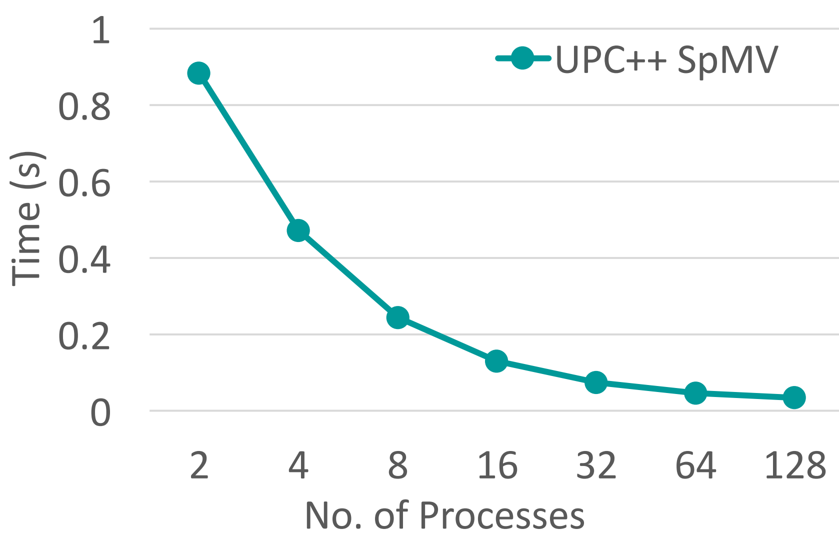
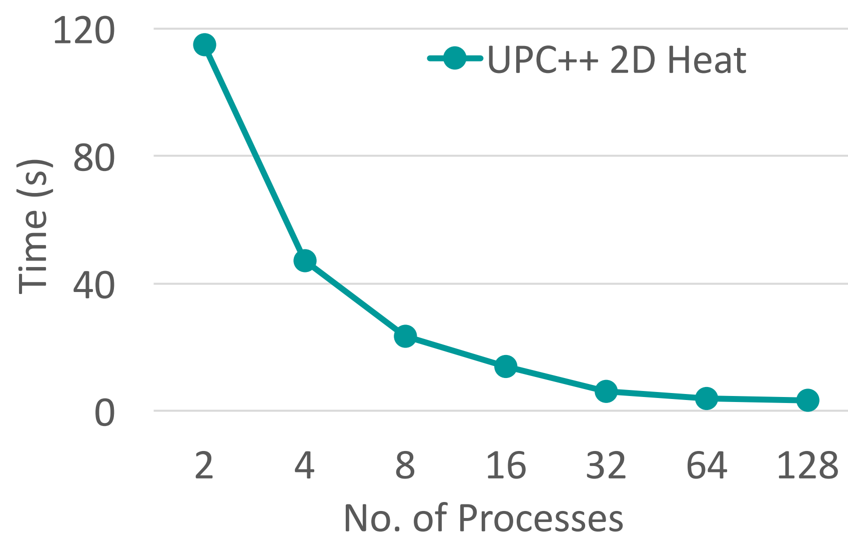
UPC++ Application Kernels Performance on KNL

- We used two application kernels to evaluate UPC++ model using MVAPICH2-X as communication runtime
- Sparse Matrix Vector Multiplication (SpMV)
- Adaptive Mesh Refinement (AMR) kernel
  - 2D-Heat conduction using Jacobi iterative
- We designed 2D-Heat kernel using pure UPC++ asynchronous primitives and provide MVAPICH2-X based communication support to achieve near-native peroformance.
- We observed near optimal speed-up for these kernels on two KNL nodes

Application Kernels Performance of UPC++ on MVAPICH2-X



Strong-scaling Performance of SpMV kernel (2Kx2K)

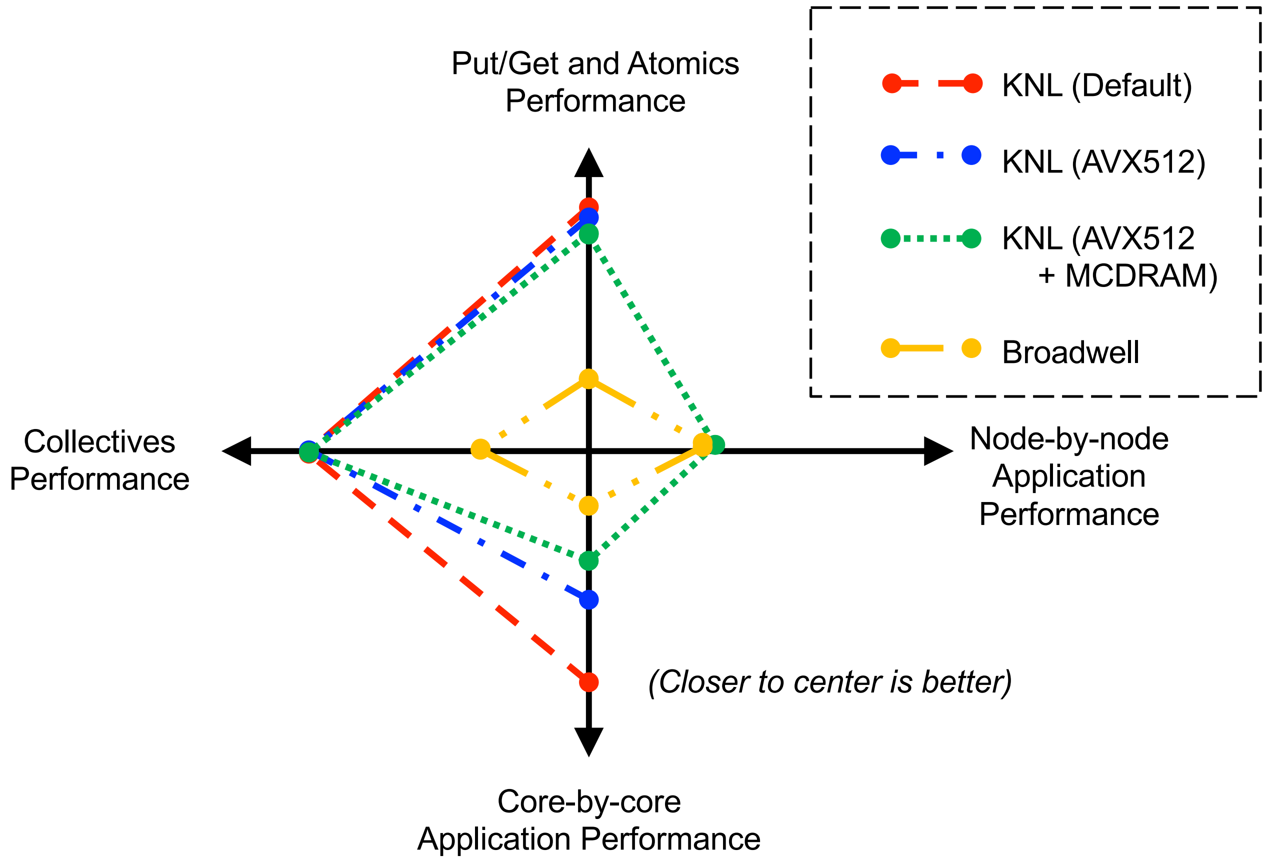


Strong-scaling Performance of 2D-Heat kernel (512x512)

- Implemented 2D Heat application kernels in UPC++
- SpMV and 2D Heat kernels using MVAPICH2-X showed good scalability on increasing number of processes of KNL

J. Hashmi, M. Li, H. Subramoni, D. Panda. Performance of PGAS Models on KNL: A Comprehensive Study with MVAPICH2-X, IXPUG 2017.

Performance Results Summary



Conclusion

- Comprehensive performance evaluation of MVAPICH2-X based OpenSHMEM, UPC, and UPC++ models over the KNL architecture
- Observed significant performance gains on application kernels when using AVX-512 vectorization
  - 2.5x performance benefits in terms of execution time
- MCDRAM benefits are not prominent on most of the application kernels
  - Lack of memory bound operations
- KNL showed up to 3X worse performance than Broadwell for core-by-core evaluation
- KNL showed better or on-par performance than Broadwell on Heat-Image and ISx kernels for Node-by-Node evaluation
- The runtime implementations need to take advantage of the concurrency of KNL cores

Thank You!

hashmi.29@osu.edu

Network-Based Computing Laboratory
http://nowlab.cse.ohio-state.edu/

The High-Performance MPI/PGAS Project
http://mvapich.cse.ohio-state.edu/

The High-Performance Big Data Project
http://hibd.cse.ohio-state.edu/

The High-Performance Deep Learning Project
http://hidl.cse.ohio-state.edu/