PGAS Programming Models: My 20-year Perspective

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Outline

I. My early career or “why I drank the PGAS Kool-Aid”

II. The PGAS community 2001 to 2017

III. 2017 to the present

IV. Closing

Early Career 1

- Summer 1999 I had no funding from my Ph.D. adviser
- Was working in computational solid state physics
- Met Bill Saphire of LBNL† through a job fair
- Bill needed somebody to work on Linux networking, including kernel drivers
- I had good background in operating systems and hobbyist experience in the Linux kernel
- Summer position became career track a year later

† LBNL: Lawrence Berkeley National Laboratory. Will mostly be read as “Berkeley Lab” from here forward.

Early Career 2

- Worked on “M-VIA”
  - Modular Virtual Interface Architecture
  - VIA was a precursor to today’s InfiniBand standard
- Most details not terribly relevant, other than two:
  - RDMA: the ability of network hardware to move data in or out of address spaces of a user process without CPU participation in the critical path (also known as “zero copy”)
  - OS Bypass: the ability for network hardware to accept work from a user process without going through a system call

Early Career 3

- MVICH was a LBNL port of MPICH over VIPL
  - Work by Mike Welcome under the same funding
- As M-VIA funding came to a close, proposed LDRD† to port MVICH to InfiniBand
  - Was declined
  - Was told vendors would do the work if it was really needed
  - Ironically, D.K. Panda at OSU did the work instead: MVAPICH
- Instead joined Kathy Yelick's UPC project at LBNL
  - Ported GASNet to InfiniBand

†LDRD: Laboratory Directed R&D. Research funding managed at the Lab level, funded out of overhead

Early Career 4

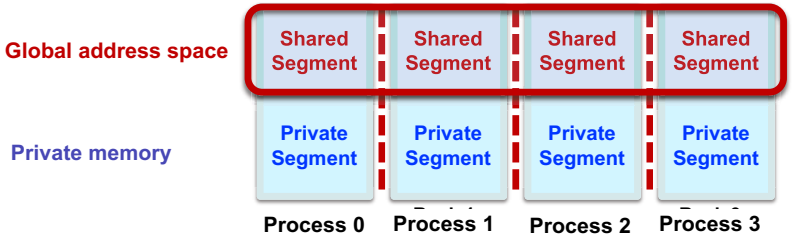
- PGAS was already an active area by this time with three languages having emerged in the late 1990s
  - UPC, C based
  - Co-array Fortran (CAF), Fortran based
  - Titanium (Ti), Java based

- GASNet began as a common network runtime for these
  - Topic of my talk at CHIUW'22 last year
- But what is "PGAS"?

The PGAS model

Partitioned **G**lobal **A**ddress **S**pace

- Support global memory abstraction
  - leveraging the network's RDMA capability
- Often distinguish private and shared memory
- Separate synchronization from data movement



Languages that provide PGAS:

Chapel, UPC, Fortran coarrays (Fortran 2008+), X10, Titanium…

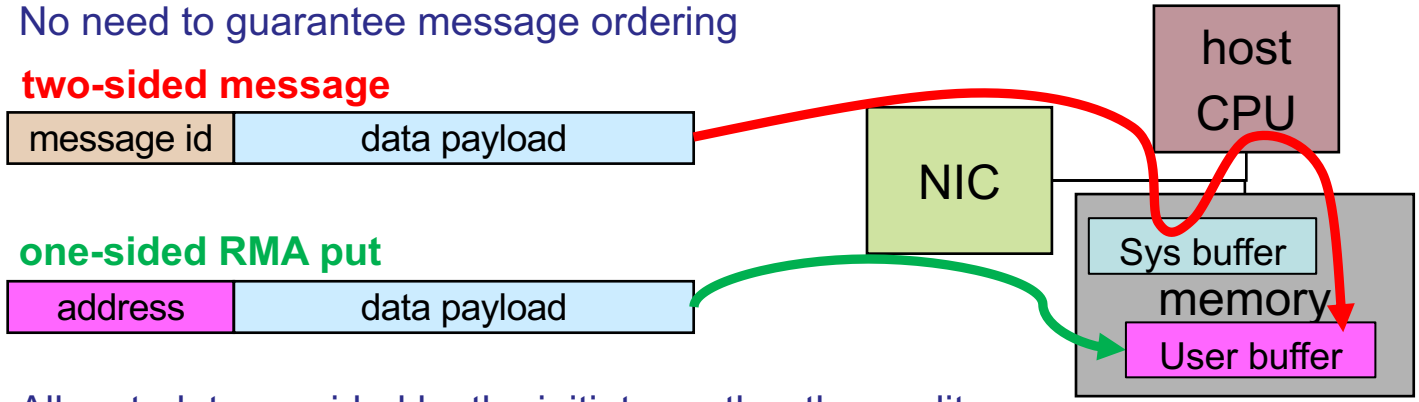
Libraries that provide PGAS:

UPC++, OpenSHMEM, Co-Array C++, Global Arrays, DASH…

A key semantic property is support for one-sided RMA

Reducing communication overhead using one-sided RMA

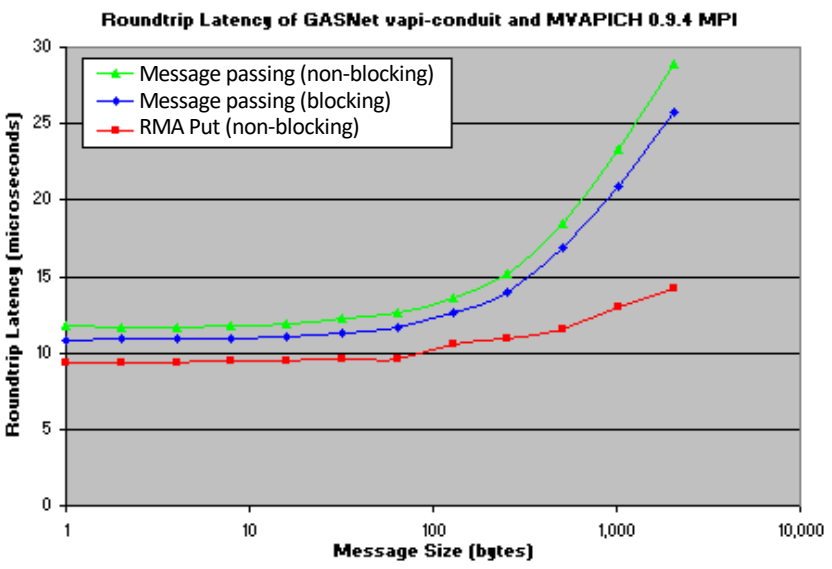
- Idea: Let each process directly access another's memory via a global pointer
- Communication is **one-sided :** there is no "receive" operation
  - No need to match sends to receives
  - No unexpected messages
  - No need to guarantee message ordering

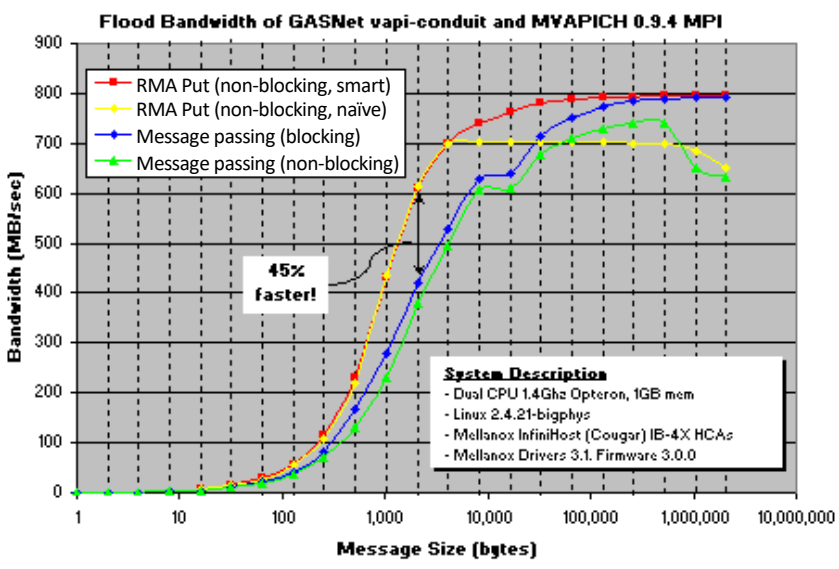


  - All metadata provided by the initiator, rather than split between sender and receiver
  - Supported in hardware through RDMA (Remote Direct Memory Access)
- Looks like shared memory: shared data structures with asynchronous access

November 2004 GASNet vs MVAPICH

Our oldest RMA vs message passing comparison I could find:





Among the things that helped me feel I'd "found my calling"

https://gasnet.lbl.gov/performance-2004/#lambda

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SCxy (Supercomputing) Booth

- UPC and PGAS booths
  - Began as SC01 UPC booth run by Tarek El-Ghazawi of GWU
  - I became involved in booth operations starting at SC05
  - Name changed from “UPC” to “PGAS” at SC07
  - LBNL took over operation from SC10 to SC17
- Booth features
  - Poster gallery highlighting work in the field
  - Flyers and CD/DVD in the early years
  - Gathering place for folks working in the field
- UPC and PGAS BOFs at SC as well

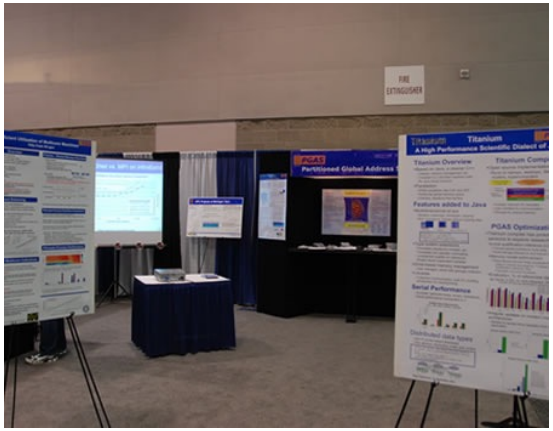


Image credit: George Washington University https://hpcl.gwu.edu/2017/10/11/pgas-research-booth-at-sc09/

Burton Smith and PGAS

- Co-founded Tera Computer Company in 1987
- In 2000, Tera bought Cray Research business unit from SGI to form Cray Inc.
- P.I. on Cray's DARPA HPCS project "Cascade"
- Left Cray for Microsoft in 2005
- Became an annual visitor to UPC/PGAS booth at SC

Image credit:
By Dimitrij Krepis - Taken by Dimitrij Krepis at Supercomputing 2007, CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=3152007

DARPA HPCS Project

- High *Productivity* Computing Systems
- 2002 through 2012
- Goals included:
  - Multi-petaflops system(s)
  - 10x improvement in user productivity
  - Recognizes that “time to solution” involves both factors
- Three PGAS programming languages emerged
  - Chapel, X10, and Fortress
  - Chapel remains the most active today

Selected Chapel History

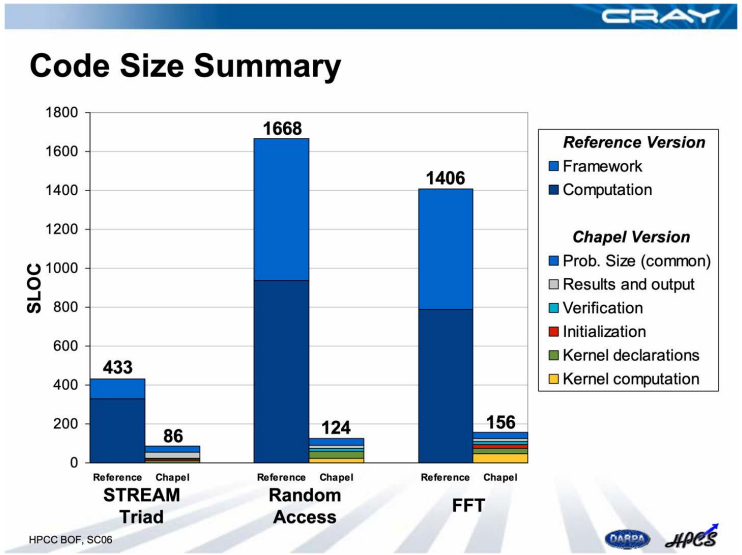
- April 2004
  - "The Cascade High Productivity Language" at HIPS04 https://doi.org/10.1109/HIPS.2004.1299190
  - Random observation:
    - The immediately preceding paper in those proceedings is on ZPL, co-authored by Brad Chamberlain and its Related Work section reviews UPC, CAF & Ti
- December 2006
  - Chapel 0.4 released with only single-locale support
- March 2008
  - Chapel 0.7 released with multi-locale support based on GASNet 1.10.0
- GASNet remains Chapel's recommended backend for InfiniBand

HPC Challenge (HPCC) Awards

- Product of the HPCS Project
  - Ran 2005 through 2014
- Application kernels and communications benchmarks
- In spirit of HPCS goals, annual award in two classes
  - Class 1: Best Performance
  - Class 2: Most Productive (a subjective “beauty contest”)
- Class 1 winners mostly non-portable hand-tuned codes
  - Example of what happens when absolute performance is the goal
- Class 2 winners mostly PGAS models
  - Chapel received Class 2 recognition in five of ten years

Chapel and HPCC Awards

Chapel in 2006



Chapel in 2012

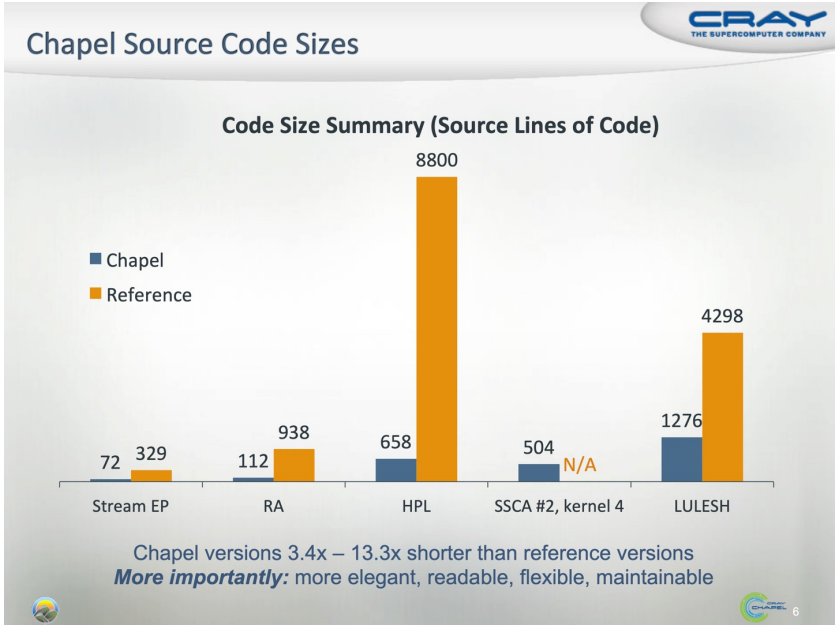


Image credits: Cray's slides at HPCC BOFs at SC06 and SC12
https://hpcchallenge.org/presentations/sc2006/chamberlain-slides.pdf
https://hpcchallenge.org/presentations/sc2012/ChapelHPCC2012.pdf

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PGAS Publication Venues 2007 - present

- Conference on Partitioned Global Address Space Programming Models
  - 2007 - 2015, as PGAS'xy
- PAW / PAW-ATM https://go.lbl.gov/paw
  - Held annually at SC
  - 2016 & 2017: PGAS Applications Workshop
  - 2018: Parallel Applications Workshop, Alternatives To MPI
  - Since 2019: Parallel Applications Workshop, Alternatives To MPI+X
  - Current call: submissions due July 24

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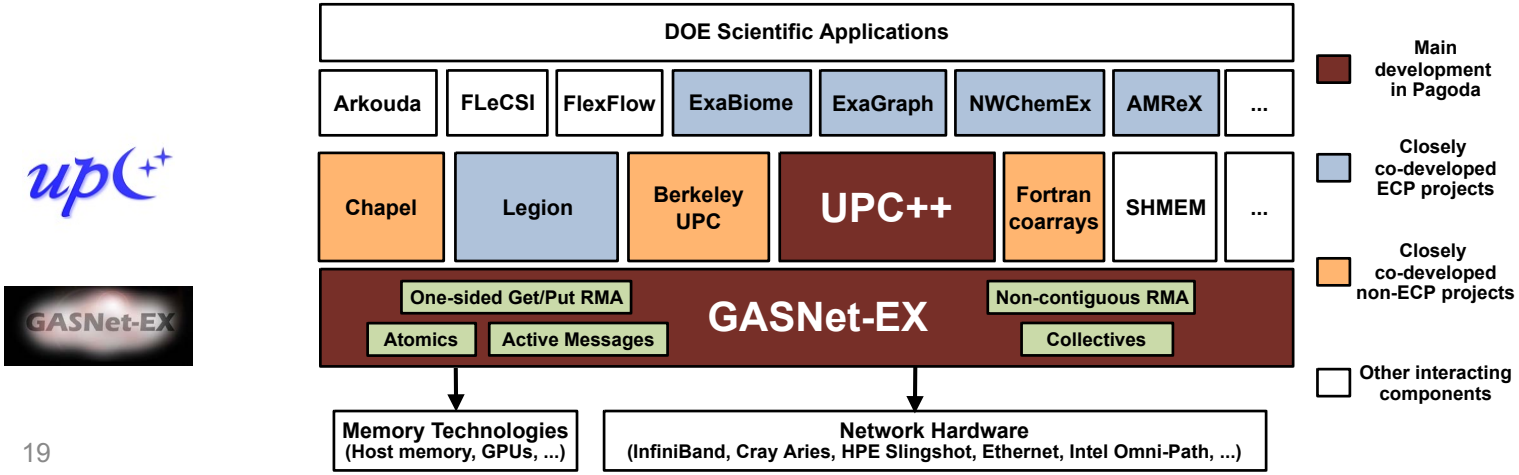
The Pagoda Project

https://go.lbl.gov/pagoda

Support for lightweight communication for exascale applications, frameworks and runtimes

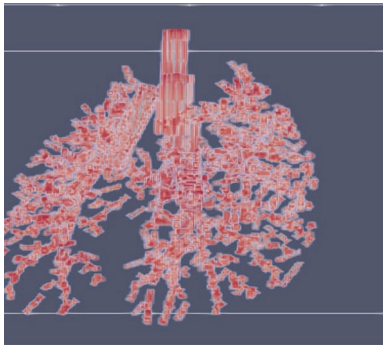
- **GASNet-EX** middleware layer providing a network-independent interface suitable for Partitioned Global Address Space (PGAS) runtime developers
- **UPC++** C++ PGAS library for application, framework and library developers, a productivity layer over GASNet-EX

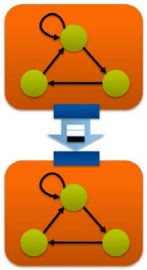


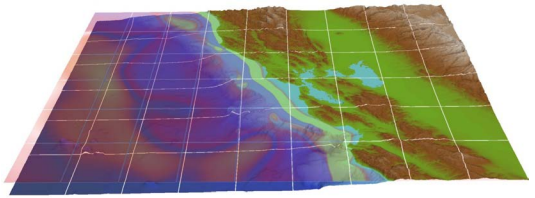
UPC++ Application Examples

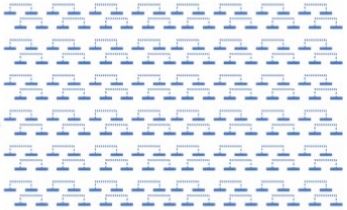
Several applications have been written using UPC++, resulting in improved programmer productivity and runtime performance. Examples include:

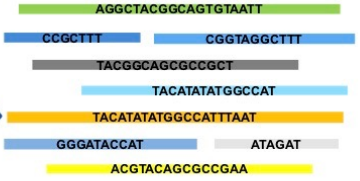
- Actor-UPCXX, used in the Pond tsunami simulator
- A UPC++ backend for NWChemEx/TAMM
- MetaHipMer, a genome assembler
- UPC++ DepSpawn, a library for data-flow computing
- Mel-UPX, half-approximate graph matching solver
- SIMCoV, agent-based simulation of lungs with COVID

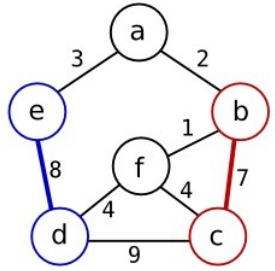












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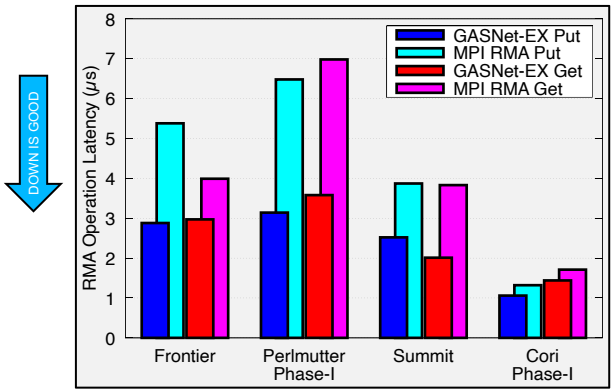
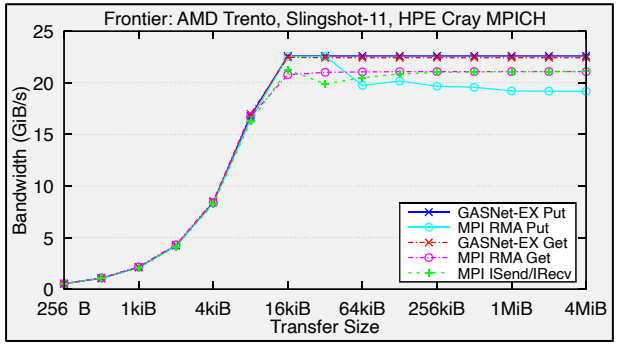
GASNet-EX RMA Performance versus MPI RMA and Isend/Irecv

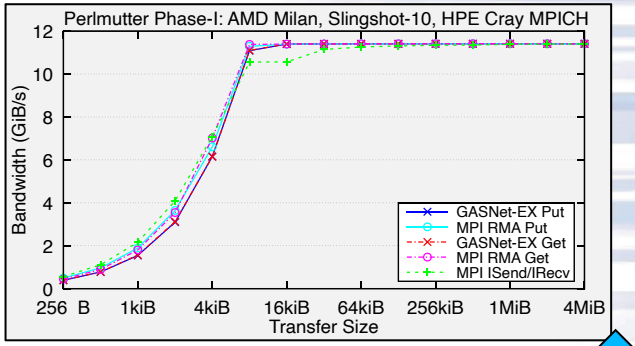
- Four distinct network hardware types
- The performance of GASNet-EX matches or exceeds that of MPI RMA and message-passing:
  - 8-byte Put latency 19 - 52% better
  - 8-byte Get latency 16 - 49% better
  - Better flood bandwidth efficiency: often reaching same or better peak at ½ or ¼ the transfer size

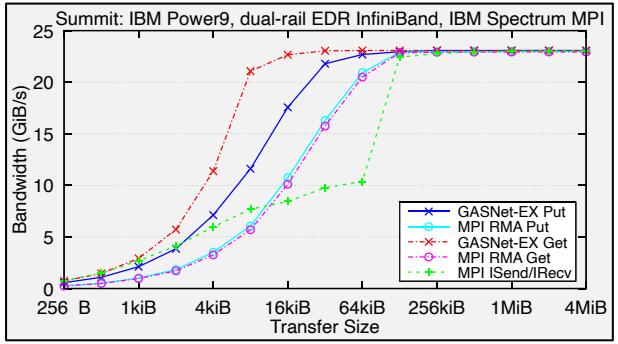
8-Byte RMA Operation Latency (one-at-a-time)

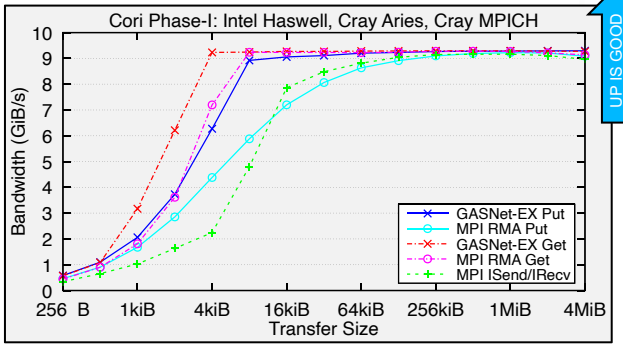


Uni-directional Flood Bandwidth (many-at-a-time)

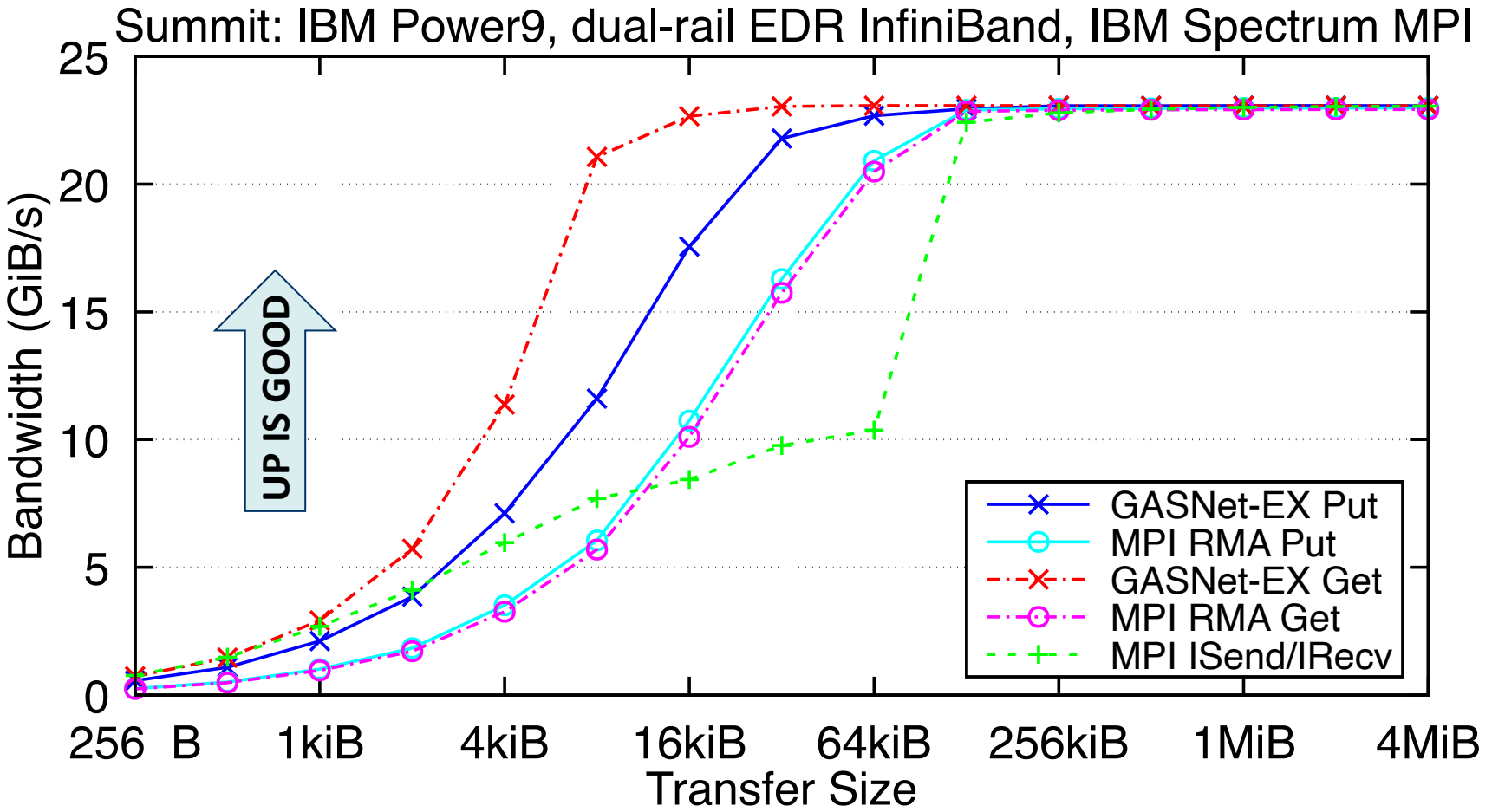








Perlmutter Phase-I results collected July 2022, all others collected April 2023.
GASNet-EX tests were run using then-current GASNet library and its tests.
MPI tests were run using then-current center default MPI version and Intel MPI Benchmarks.
All tests use two nodes and one process per node.
For details see LCPC'18 doi.org/10.25344/S4QP4W and PAW-ATM'22 doi.org/10.25344/S40C7D
See also: gasnet.lbl.gov/performance



#5 System on June 2023 Top500

A comparison of uni-directional point-to-point host-memory flood bandwidth benchmarks, run April 2023 on OLCF's Summit system.
Shows the performance of RMA (Put and Get) operations using GASNet-EX and both RMA and message-passing (Isend/Irecv) using IBM Spectrum MPI.
Results were obtained using current GASNet tests and Intel MPI Benchmarks, respectively.

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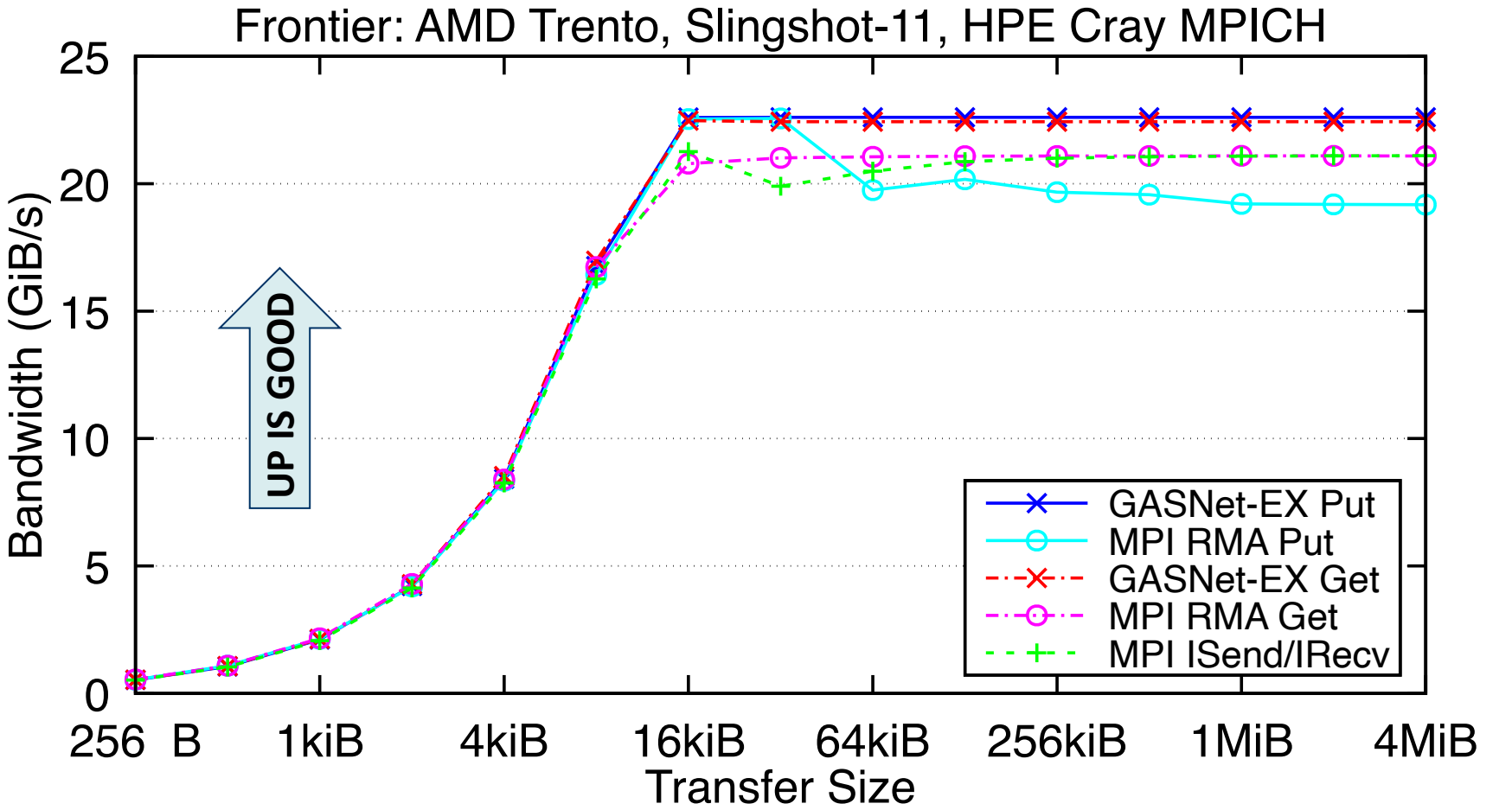

#1 System on June 2023 Top500

A comparison of uni-directional point-to-point host-memory flood bandwidth benchmarks, run April 2023 on OLCF's Frontier system.
Shows the performance of RMA (Put and Get) operations using GASNet-EX and both RMA and message-passing (Isend/Irecv) using HPE Cray MPI.
Results were obtained using current GASNet tests and Intel MPI Benchmarks, respectively.

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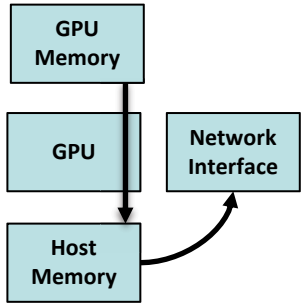
Accelerated RMA to/from GPU memory

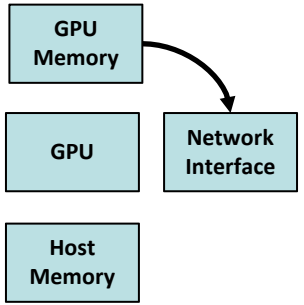
Modern GPUs and NICs can support peer-to-peer data transfers

Example: Put with source on GPU

- In the absence of necessary hardware and OS support:
  1. Data must be copied from GPU memory to host memory
  2. RDMA from host memory's copy
- With support:
  1. RDMA directly from GPU memory (no copies)



Data movement without acceleration



Data movement with acceleration

Accelerated RMA to/from GPU Memory

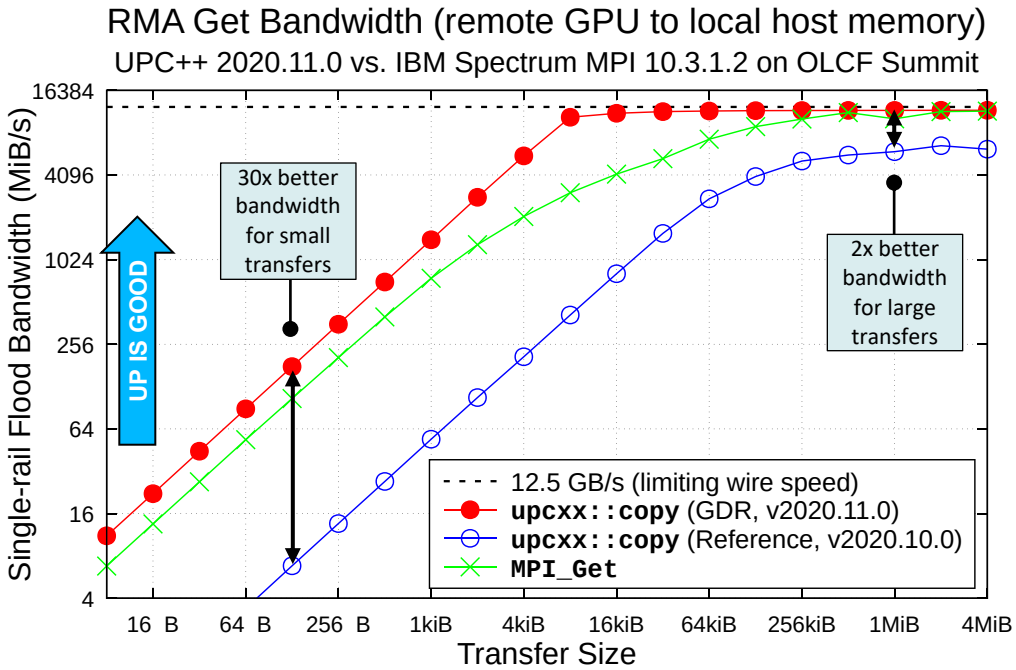
Measurements of flood bandwidth of **`upcxx::copy()`** on OLCF's Summit

Difference between two consecutive releases shows benefit of GASNet-EX's support for accelerated transfers via Nvidia's "GDR".

- No longer staging through host memory
- Large xfers: 2x better bandwidth
- Small xfers: up to 30x better bandwidth

Get operations to/from GPU memory now perform comparably to host memory

Comparisons to MPI RMA in GDR-enabled IBM MPI show UPC++ saturating more quickly to the peak



GASNet-EX

upc++

The Ohio State University

IBM Spectrum MPI

OAK RIDGE National Laboratory | LEADERSHIP COMPUTING FACILITY

UPC++ results were collecting using the version of the **`cuda_benchmark`** test that appears in the 2020.11.0 release.
MPI results are from **`osu_get_bw`** test in a CUDA-enabled build of OSU Micro-Benchmarks 5.6.3.
All tests were run on OLFC Summit, between two nodes with one process per node, over its EDR InfiniBand network.

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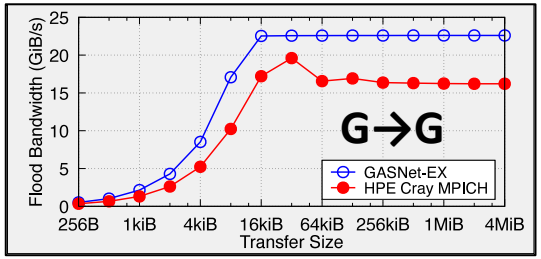
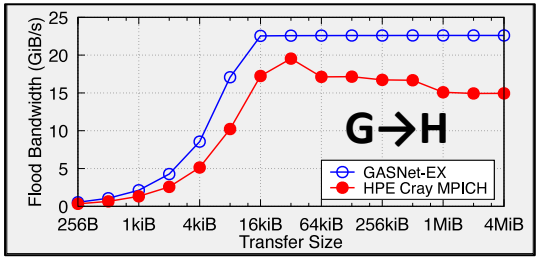
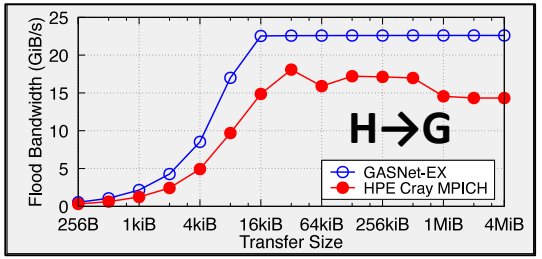
GPU memory RMA on OLCF's Frontier

Recent comparison of GASNet-EX and Cray MPICH performance on internode flood bandwidth benchmarks for six distinct combinations of (H)ost versus (G)PU memory and direction of transfer (Put or Get)

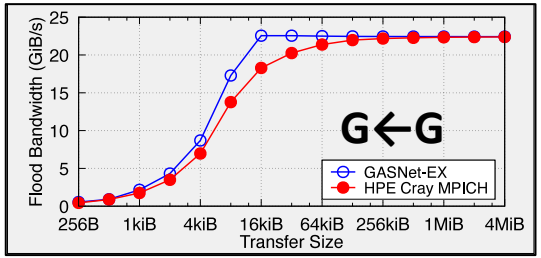
Put:

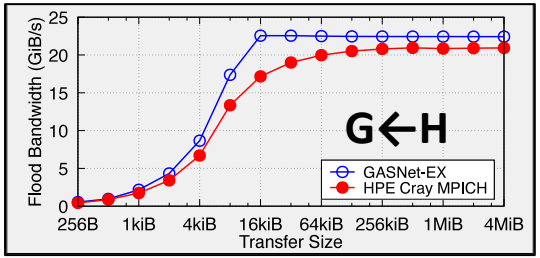


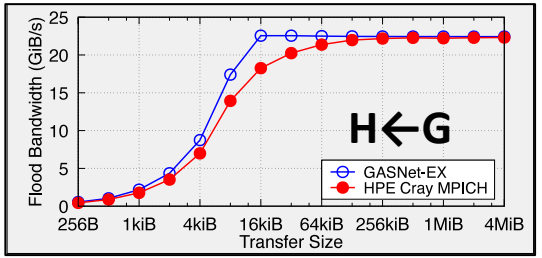




Get:







GASNet results were collecting using the **`testlarge`** benchmark that appears in the 2023.3.0 release.
MPI results are from **`osu_put_bw`** and **`osu_get_bw`** tests in a ROCM-enabled build of OSU Micro-Benchmarks 7.1-1.
All tests were run on OLCF Frontier in April 2023, between two nodes with one process per node, over its Slingshot-11 network.

Informal Survey of GPU RMA Support

	G→G	G→H	H→G	G←G	G←H	H←G
GASNet-EX (IB, SS10, SS11)	✔	✔	✔	✔	✔	✔
Cray MPICH (SS11)	✔	✔	✔	✔	✔	✔
Cray MPICH (SS10)	✘	✘	✔	✘	✔	✘
IBM Spectrum MPI (IB)	✘	✘	✘	✘	✘	✔
MVAPICH2-GDR (IB)*	✔	✔	✔	✔	✔	✔

Looking at three networks representative of top DOE systems.
Each ✔ or ✘ represent the (in)ability to complete the benchmarks by the best-behaving example of a given MPI *found by the author on DOE systems* in April and May 2023.

* Not provided by the center or vendor. Used OSU's binary distribution for Summit.

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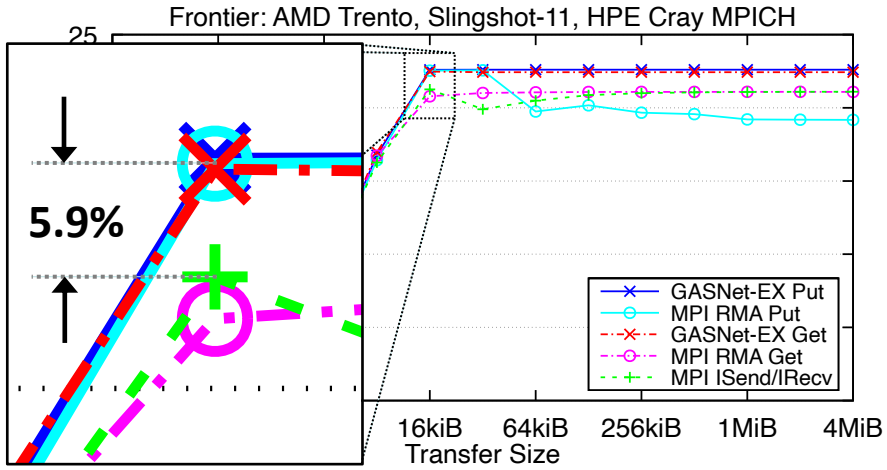
Thoughts on the Future (1 of 2)

- GASNet has helped programming model developers show that one need not sacrifice high performance to achieve high productivity
  - A good semantic fit to network capabilities has historically provided a performance advantage over message-passing
- However, modern systems have narrowed some of the performance gaps for host memory RMA
  - RMA versus message passing
  - GASNet versus MPI RMA



Thoughts on the Future (2 of 2)

- Current GASNet and UPC++ comparisons to MPI show there is *still* a network performance advantage for RMA to/from GPU memory
  - At least for now
- Nothing has changed in 20+ years to erode the productivity arguments for PGAS over message passing
  - And the prospects look good for extending this to GPUs as well
- I look forward to taking part in another decade of PGAS

Acknowledgements

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This research used resources of the **Oak Ridge Leadership Computing Facility** at the Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

THANK YOU!

go.lbl.gov/paul-hargrove

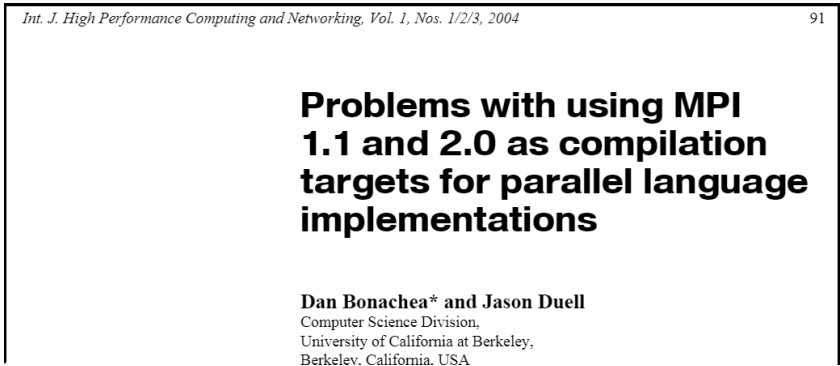
gasnet.lbl.gov

upcxx.lbl.gov

BACKUP SLIDES USED IN Q&A

GASNet-1: Historical Overview

- Started in 2002 to provide a portable network communication runtime for three PGAS languages:
  - UPC, Titanium and CAF
- Primary features:
  - Non-blocking RMA (one-sided Put and Get)
  - Active Messages (simplification of Berkeley AM-2)
- Motivated by semantic issues in (then current) MPI-2.0
  - https://doi.org/10.1504/IJHPCN.2004.007569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Problems with using MPI 1.1 and 2.0 as compilation targets for parallel language implementations

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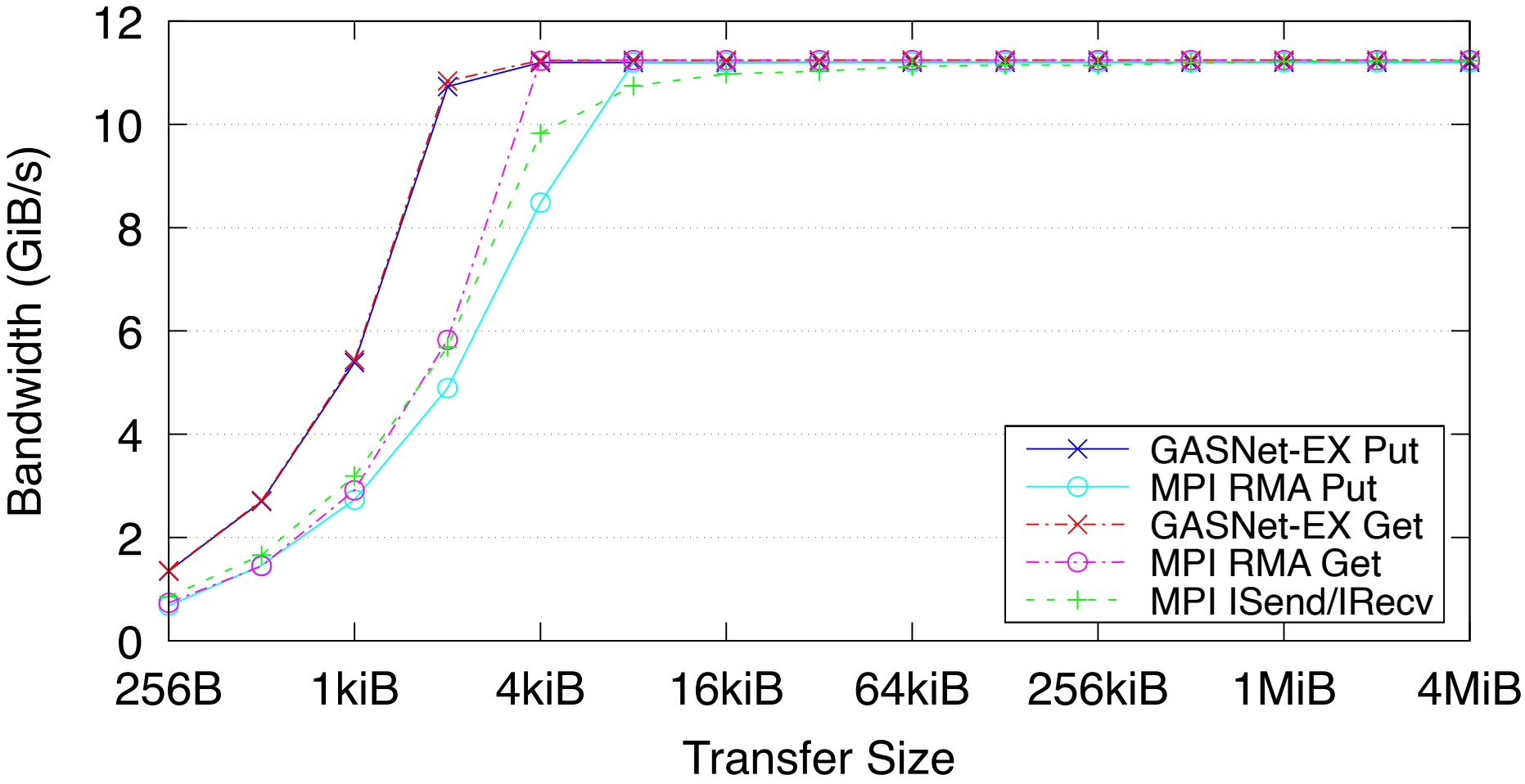
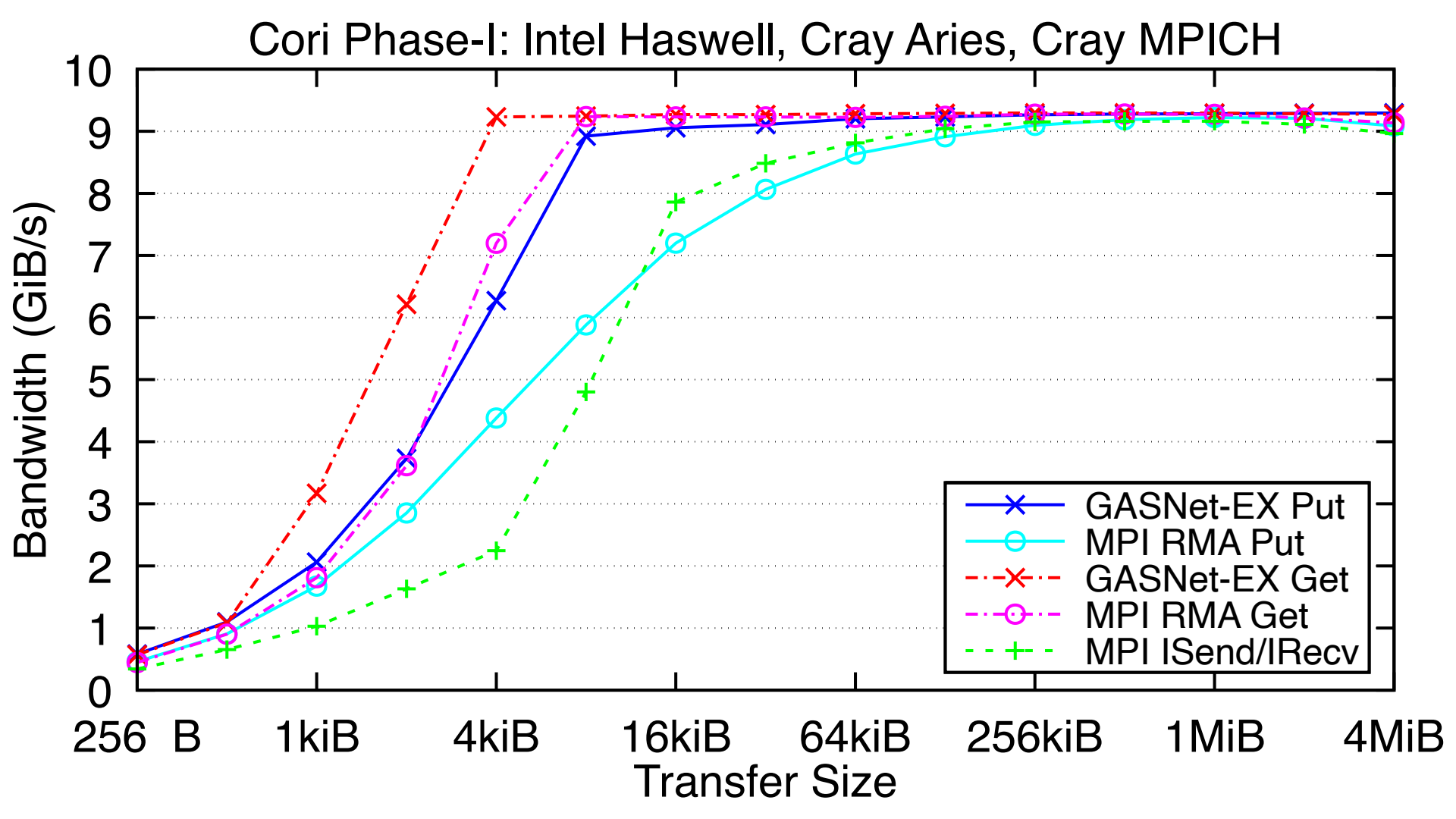

JLSE Arcticus: Intel Ice Lake, EDR InfiniBand, Intel MPI
Bandwidth (GiB/s)
0
2
4
6
8
10
12
256B
1kiB
4kiB
16kiB
64kiB
256kiB
1MiB
4MiB
Transfer Size
GASNet-EX Put
MPI RMA Put
GASNet-EX Get
MPI RMA Get
MPI ISend/IRecv


Cori Phase-I: Intel Haswell, Cray Aries, Cray MPICH
Bandwidth (GiB/s)
0
1
2
3
4
5
6
7
8
9
10
256 B
1kiB
4kiB
16kiB
64kiB
256kiB
1MiB
4MiB
Transfer Size
GASNet-EX Put
MPI RMA Put
GASNet-EX Get
MPI RMA Get
MPI ISend/IRecv