MVAPICH

MPI, PGAS and Hybrid MPI+PGAS Library

Scalable and Distributed DNN Training on Modern HPC Systems

Talk at Deep Learning Workshop (SC '18)

by

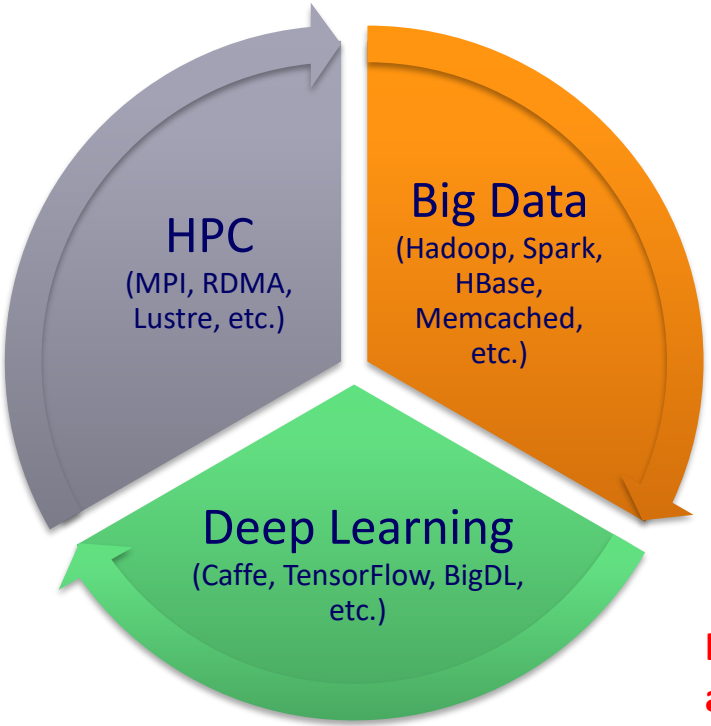
Dhabaleswar K. (DK) Panda

The Ohio State University

E-mail: panda@cse.ohio-state.edu

http://www.cse.ohio-state.edu/~panda

Increasing Usage of HPC, Big Data and Deep Learning



Convergence of HPC, Big Data, and Deep Learning!

Increasing Need to Run these applications on the Cloud!!

Drivers of Modern HPC Cluster Architectures

Multi-core Processors

High Performance Interconnects - InfiniBand
<1usec latency, 100Gbps Bandwidth>

Accelerators / Coprocessors high compute density, high performance/watt
>1 TFlop DP on a chip

SSD, NVMe-SSD, NVRAM

- Multi-core/many-core technologies
- Remote Direct Memory Access (RDMA)-enabled networking (InfiniBand and RoCE)
- Solid State Drives (SSDs), Non-Volatile Random-Access Memory (NVRAM), NVMe-SSD
- Accelerators (NVIDIA GPGPUs and Intel Xeon Phi)
- Available on HPC Clouds, e.g., Amazon EC2, NSF Chameleon, Microsoft Azure, etc.

Summit

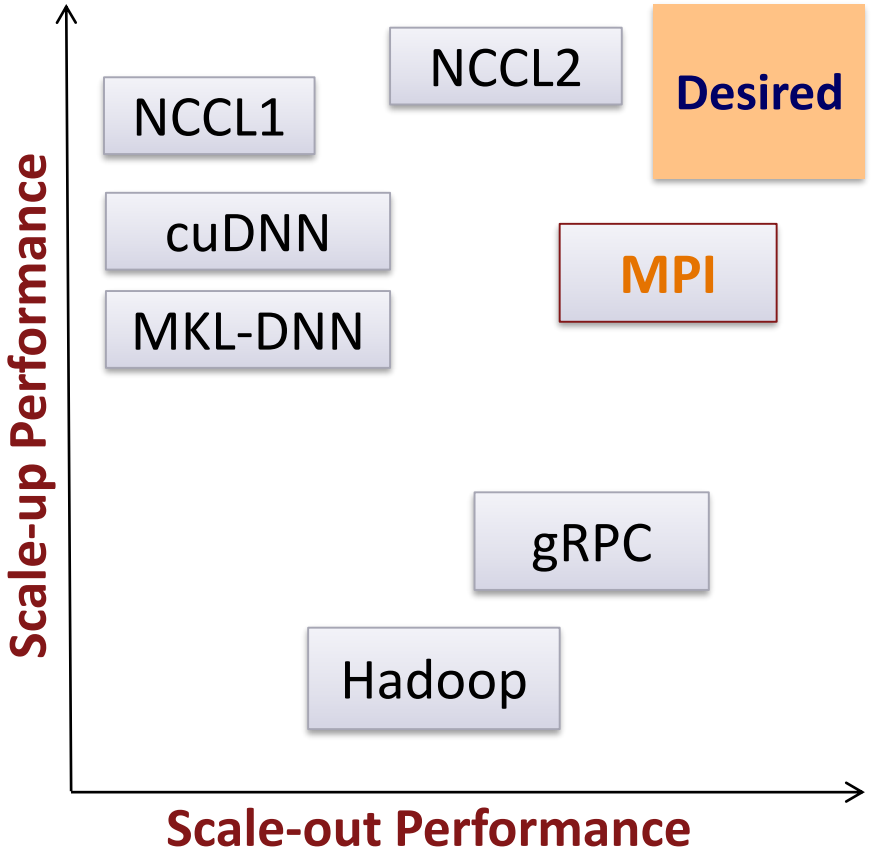
Sierra

Sunway TaihuLight

K - Computer

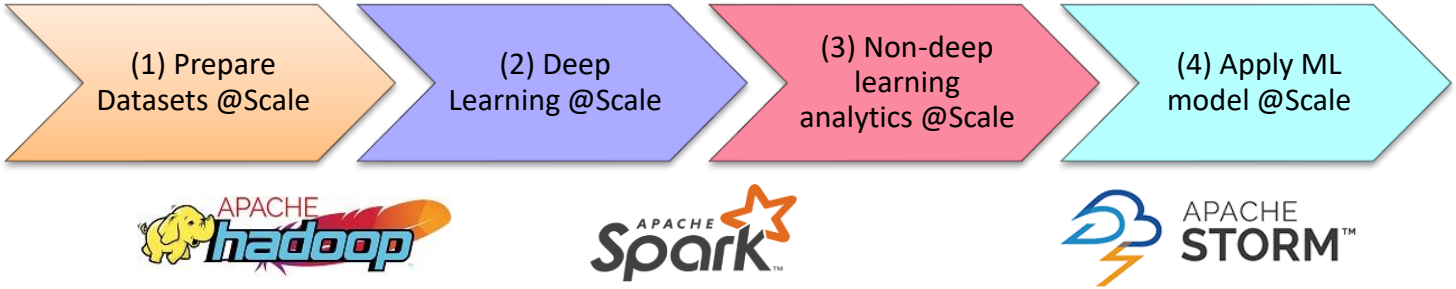
Scale-up and Scale-out

- **Scale-up**: Intra-node Communication
  - Many improvements like:
    - NVIDIA cuDNN, cuBLAS, NCCL, etc.
    - CUDA 9 Co-operative Groups
- **Scale-out**: Inter-node Communication
  - DL Frameworks – most are optimized for single-node only
  - Distributed (Parallel) Training is an emerging trend
    - **OSU-Caffe – MPI-based**
    - Microsoft CNTK – MPI/NCCL2
    - Google TensorFlow – gRPC-based/MPI/NCCL2
    - Facebook Caffe2 – Hybrid (NCCL2/Gloo/MPI)



Deep Learning over Big Data (DLoBD)

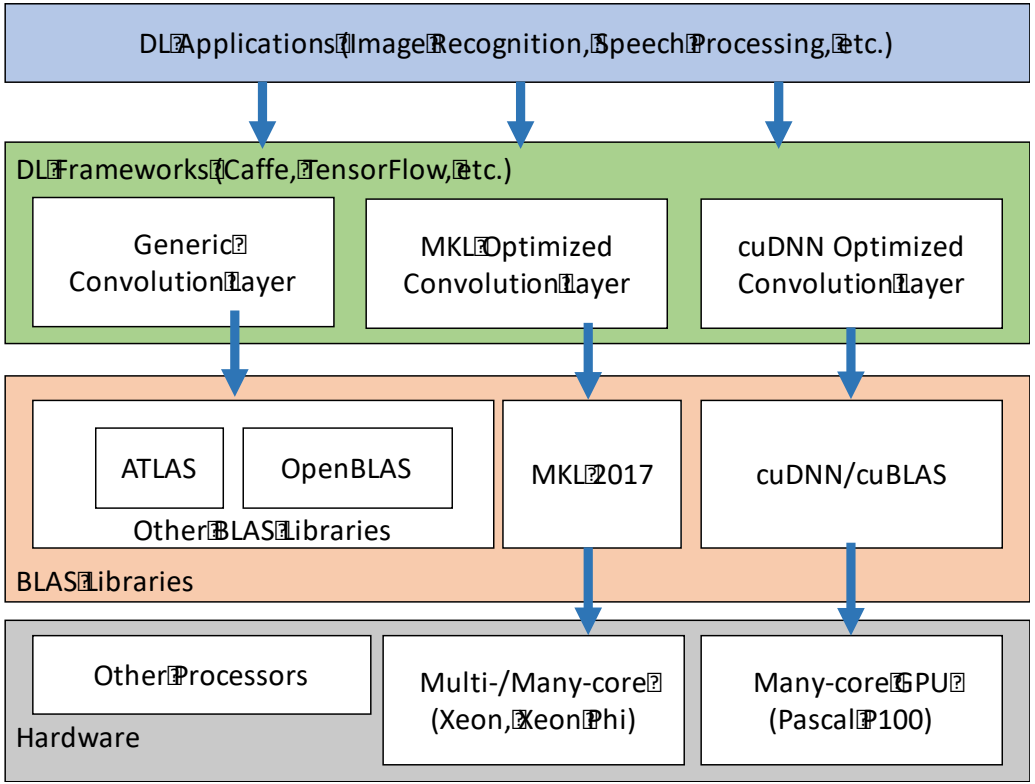
- Deep Learning over Big Data (**DLoBD**) is one of the most efficient analyzing paradigms
- More and more deep learning tools or libraries (e.g., Caffe, TensorFlow) start running over big data stacks, such as Apache Hadoop and Spark
- **Benefits** of the DLoBD approach
  - Easily build a powerful data analytics **pipeline**
    - E.g., Flickr DL/ML Pipeline, "*How Deep Learning Powers Flickr*", http://bit.ly/1KIDfof



  - Better data **locality**
  - Efficient resource sharing and **cost effective**

Holistic Evaluation is Important!!

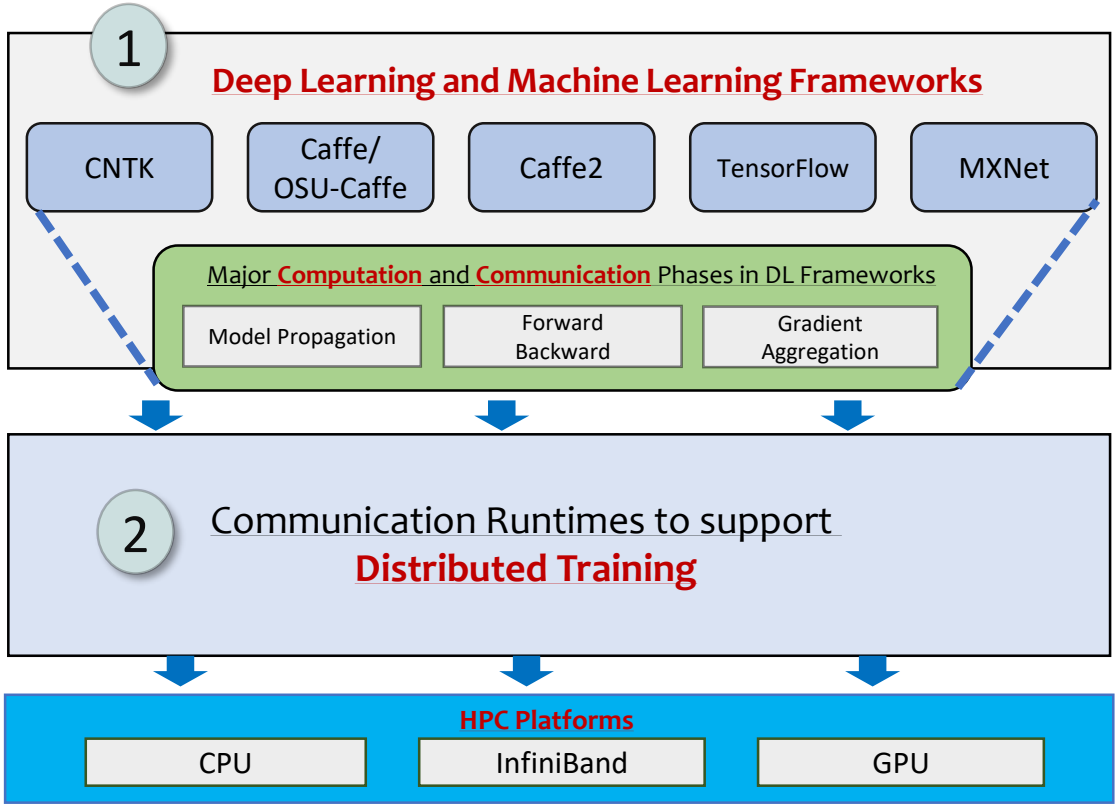
- My framework is faster than your framework!
- This needs to be understood in a holistic way.
- Performance depends on the entire execution environment (the full stack)
- Isolated view of performance is not helpful



A. A. Awan, H. Subramoni, and Dhabaleswar K. Panda. "An In-depth Performance Characterization of CPU- and GPU-based DNN Training on Modern Architectures", In Proceedings of the Machine Learning on HPC Environments (MLHPC'17). ACM, New York, NY, USA, Article 8.

Research Challenges to Exploit HPC Technologies

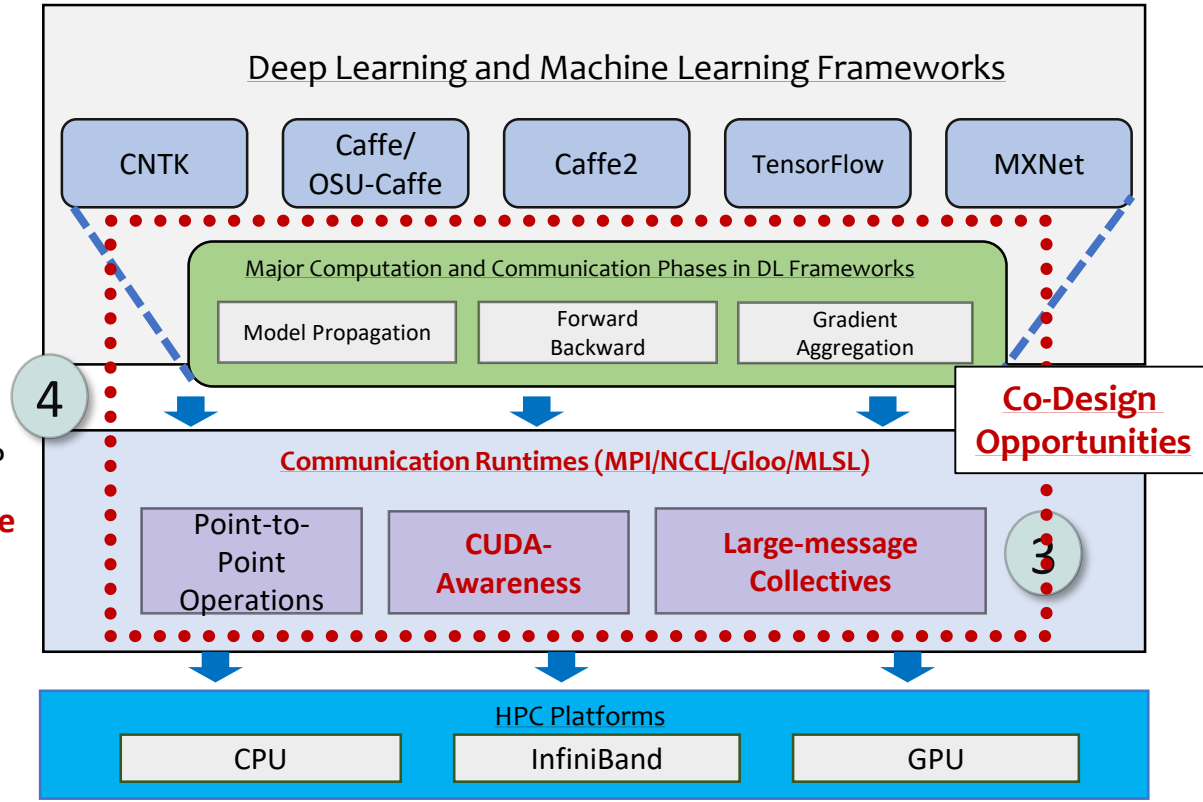
1. What are the fundamental issues in designing **DL frameworks**?
   - Memory Requirements
   - **Computation** Requirements
   - **Communication** Overhead
2. Why do we need to support **distributed training**?
   - To overcome the limits of single-node training
   - To better utilize hundreds of existing HPC Clusters



Research Challenges to Exploit HPC Technologies (Cont'd)

3. What are the **new design challenges** brought forward by DL frameworks for Communication runtimes?
   - Large Message **Collective Communication** and Reductions
   - GPU Buffers (**CUDA-Awareness**)

4. Can a **Co-design** approach help in achieving Scale-up and Scale-out efficiently?
   - **Co-Design** the support at **Runtime level** and Exploit it at the **DL Framework level**
   - What performance benefits can be observed?
   - What needs to be fixed at the **communication runtime** layer?

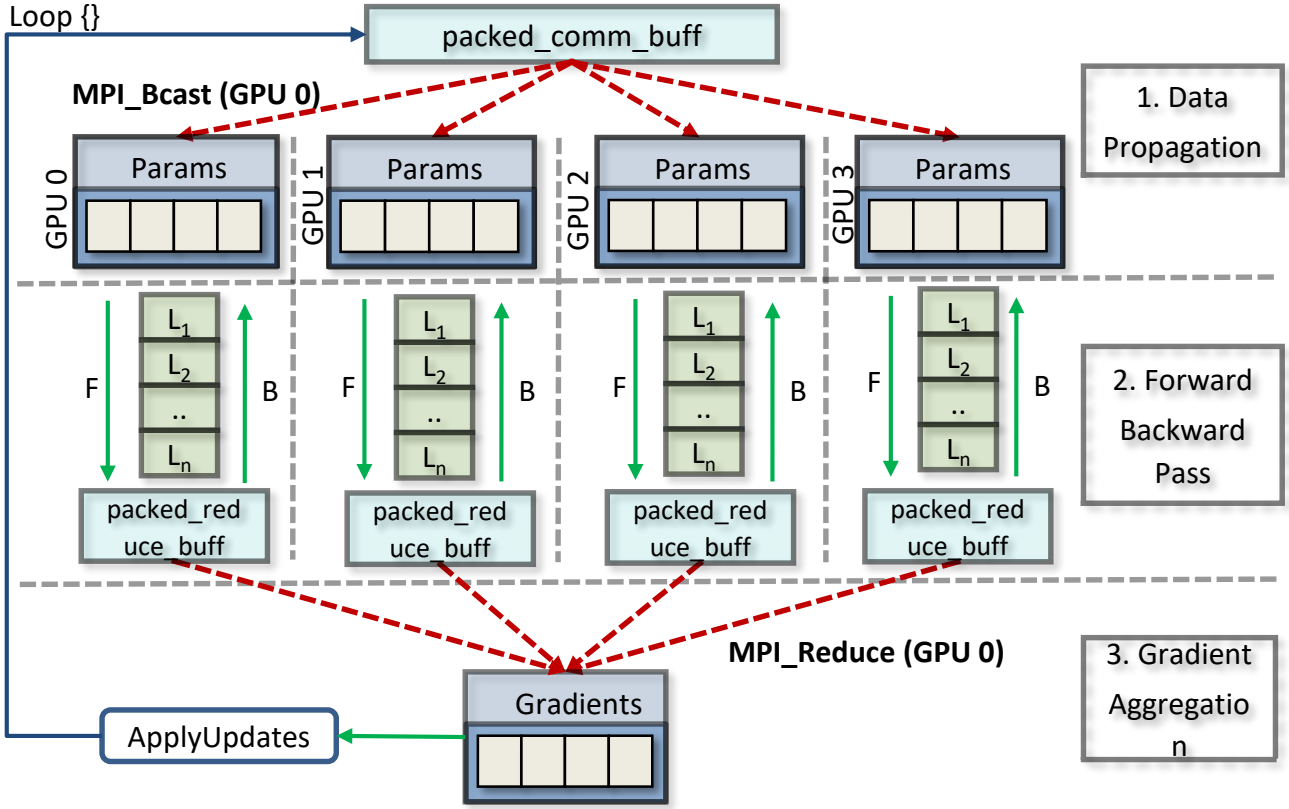


Multiple Approaches taken up by OSU

- MPI-driven Deep Learning
- Co-designing Deep Learning Stacks with High-Performance MPI
- Out-of-core DNN training
- Accelerating TensorFlow on HPC Systems
- Accelerating Big Data Stacks
- Efficient Deep Learning over Big Data

Data Parallel Deep Learning and MPI Collectives

- Major **MPI Collectives** involved in Designing distributed frameworks
- **MPI_Bcast** – required for DNN parameter exchange
- **MPI_Reduce** – needed for gradient accumulation from multiple solvers
- **MPI_Allreduce** – use just one Allreduce instead of Reduce and Broadcast



A. A. Awan, K. Hamidouche, J. M. Hashmi, and D. K. Panda, S-Caffe: Co-designing MPI Runtimes and Caffe for Scalable Deep Learning on Modern GPU Clusters. In *Proceedings of the 22nd ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming* (PPoPP '17)

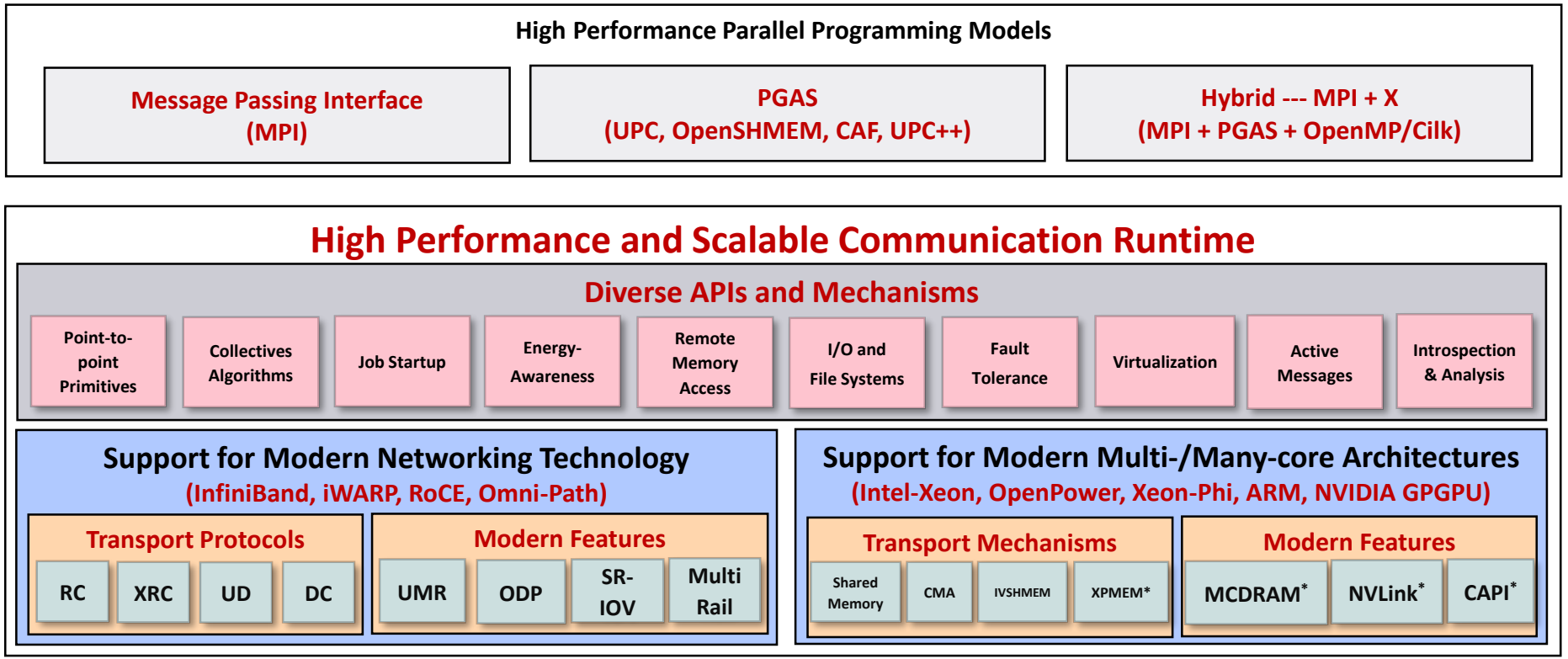
Overview of the MVAPICH2 Project

- 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-3.1), 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 2,950 organizations in 86 countries**
  - **More than 506,000 (> 0.5 million) downloads from the OSU site directly**
  - Empowering many TOP500 clusters (Nov '18 ranking)
    - 3rd ranked 10,649,640-core cluster (Sunway TaihuLight) at NSC, Wuxi, China
    - 14th, 556,104 cores (Oakforest-PACS) in Japan
    - 17th, 367,024 cores (Stampede2) at TACC
    - 27th, 241,108-core (Pleiades) at NASA and many others
  - Available with software stacks of many vendors and Linux Distros (RedHat, SuSE, and OpenHPC)
  - **http://mvapich.cse.ohio-state.edu**

Partner in the upcoming TACC Frontera System

- Empowering Top500 systems for over a decade

Architecture of MVAPICH2 Software Family



* Upcoming

GPU-Aware (CUDA-Aware) MPI Library: MVAPICH2-GPU

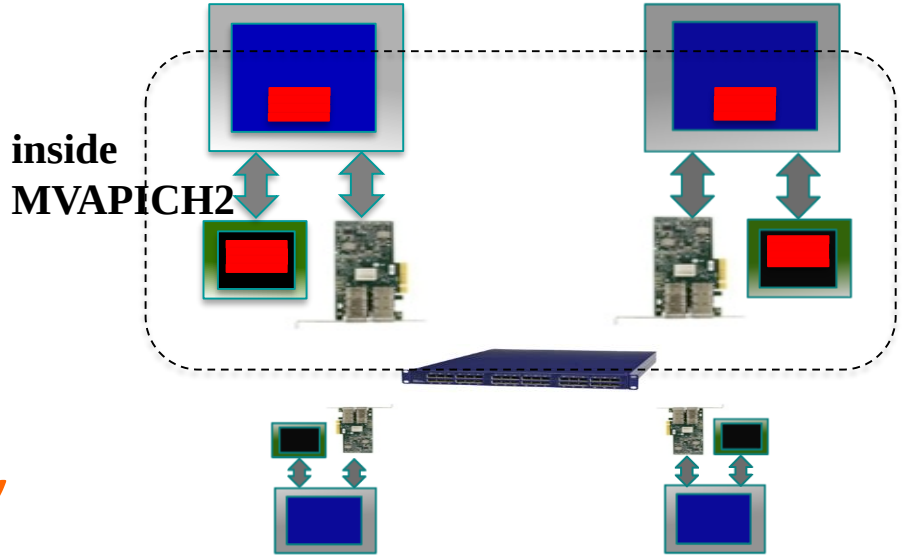
- Standard MPI interfaces used for unified data movement
- Takes advantage of Unified Virtual Addressing (>= CUDA 4.0)
- Overlaps data movement from GPU with RDMA transfers

At Sender:

```
MPI_Send(s_devbuf, size, …);
```

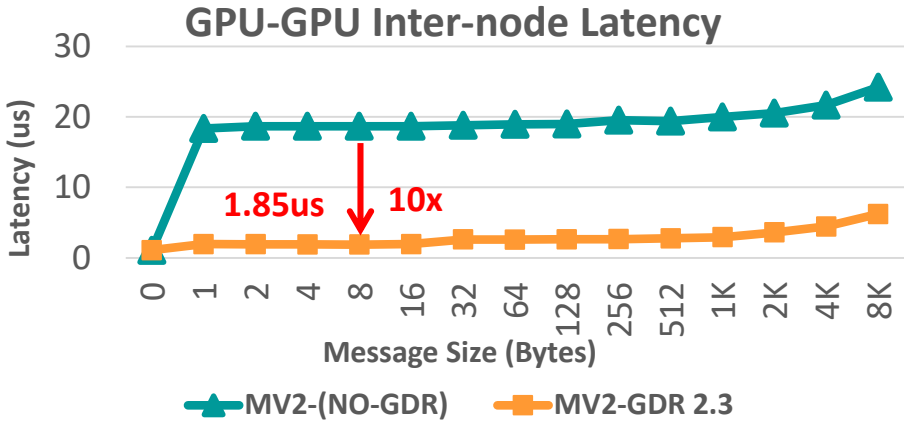
At Receiver:

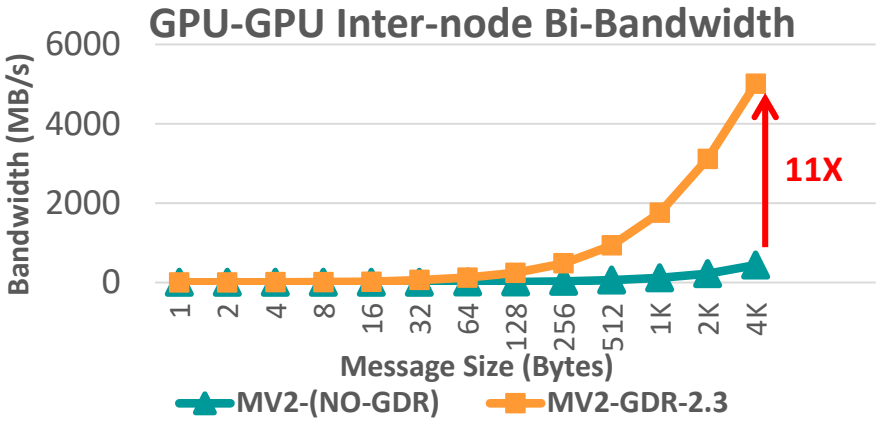
```
MPI_Recv(r_devbuf, size, …);
```

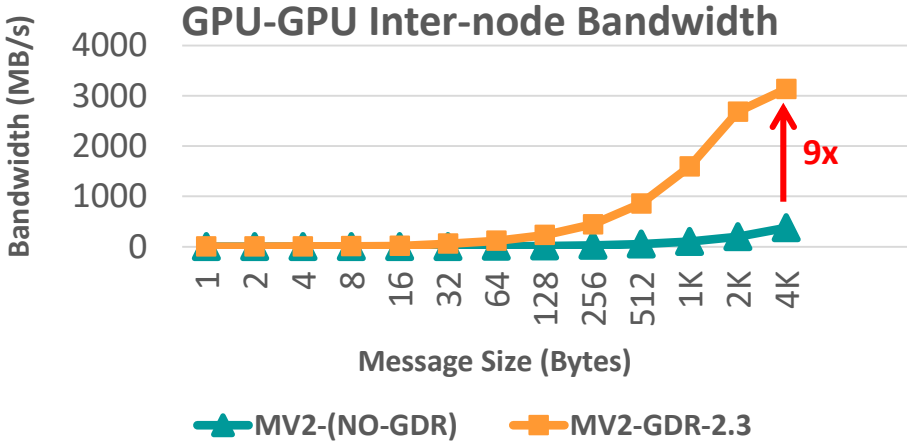


High Performance and High Productivity

Optimized MVAPICH2-GDR Design



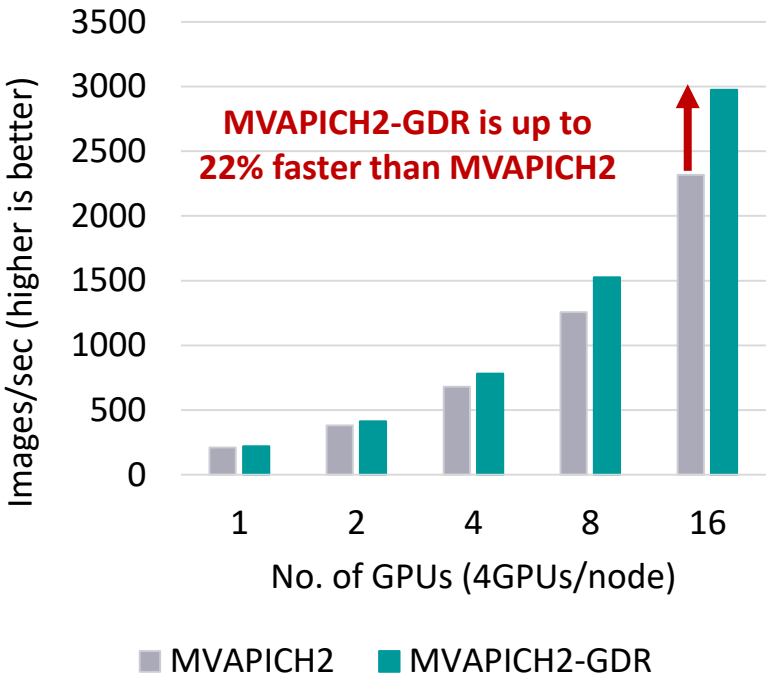




MVAPICH2-GDR-2.3
Intel Haswell (E5-2687W @ 3.10 GHz) node - 20 cores
NVIDIA Volta V100 GPU
Mellanox Connect-X4 EDR HCA
CUDA 9.0
Mellanox OFED 4.0 with GPU-Direct-RDMA

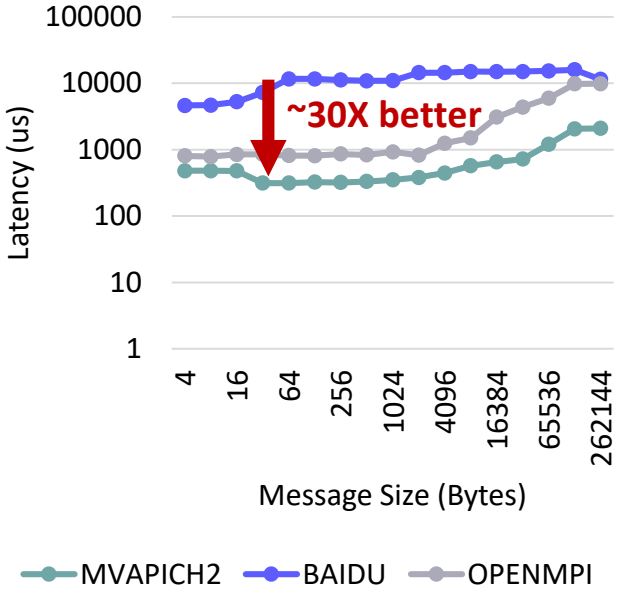
Exploiting CUDA-Aware MPI for TensorFlow (Horovod)

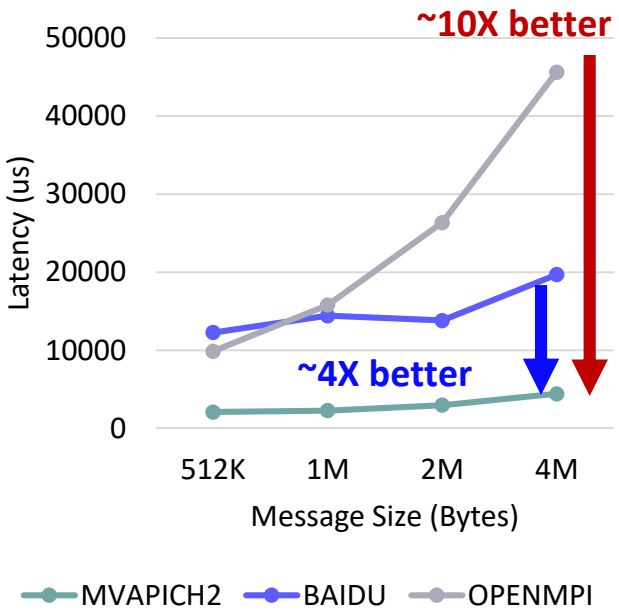
- MVAPICH2-GDR offers excellent performance via advanced designs for MPI_Allreduce.
- Up to **22% better** performance on Wilkes2 cluster (16 GPUs)

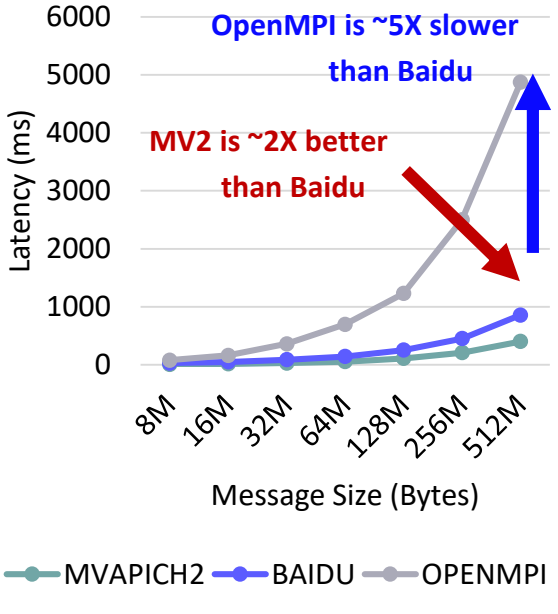


MVAPICH2-GDR: Allreduce Comparison with Baidu and OpenMPI

- 16 GPUs (4 nodes) MVAPICH2-GDR vs. Baidu-Allreduce and OpenMPI 3.0



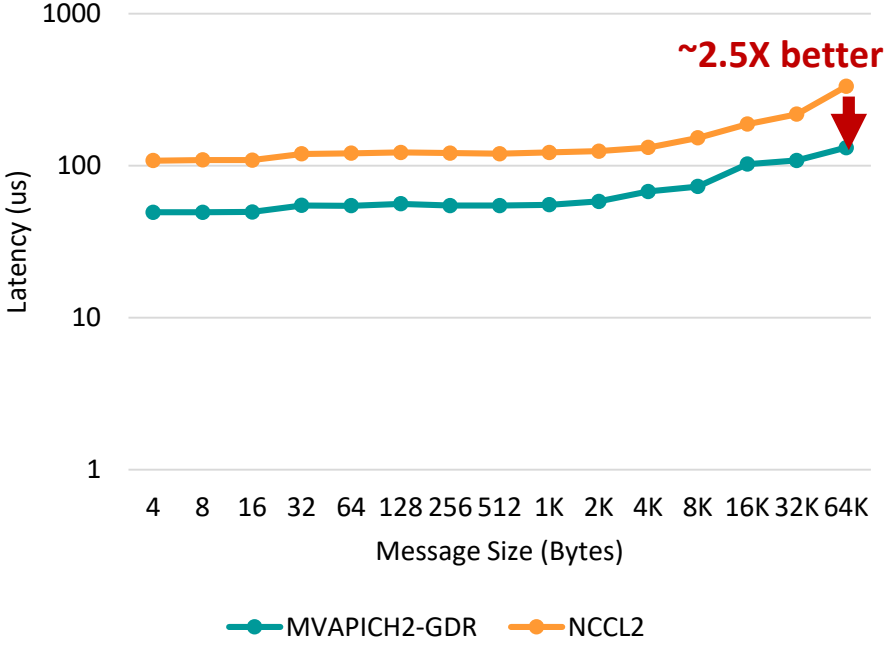


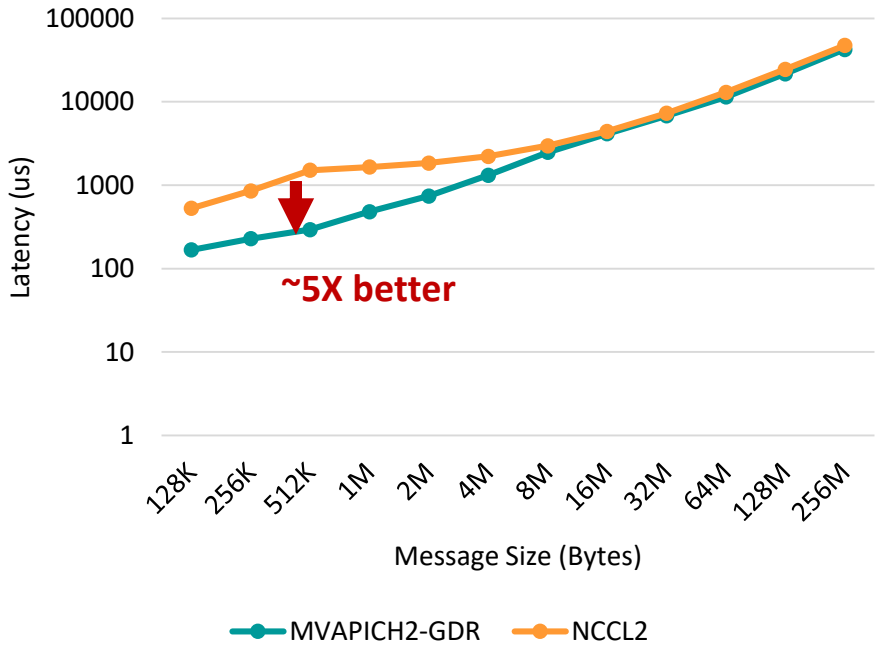


**Available since MVAPICH2-GDR 2.3a*

MVAPICH2-GDR vs. NCCL2 – Reduce Operation

- Optimized designs in MVAPICH2-GDR 2.3b* offer better/comparable performance for most cases
- MPI_Reduce (MVAPICH2-GDR) vs. ncclReduce (NCCL2) on 16 GPUs



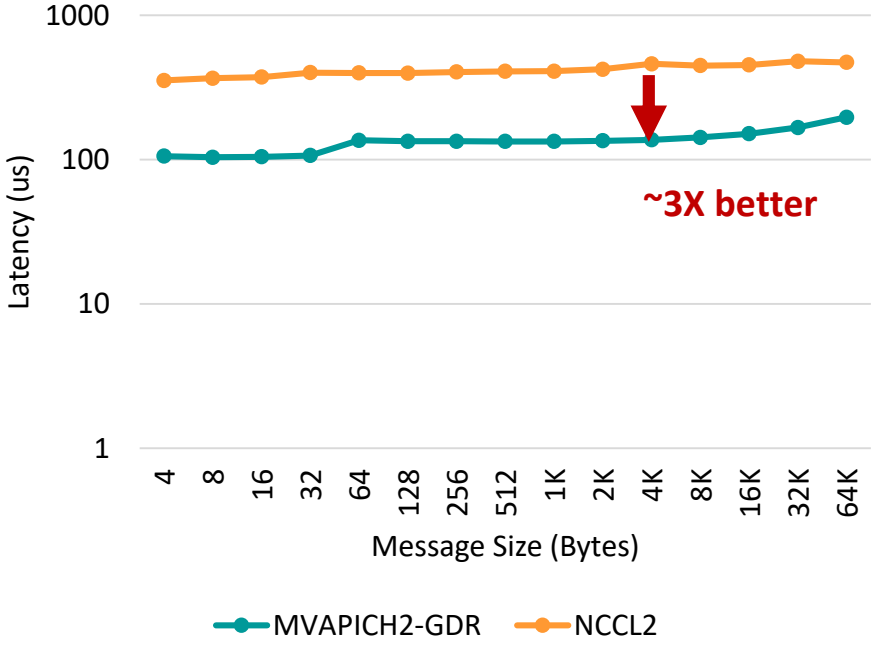


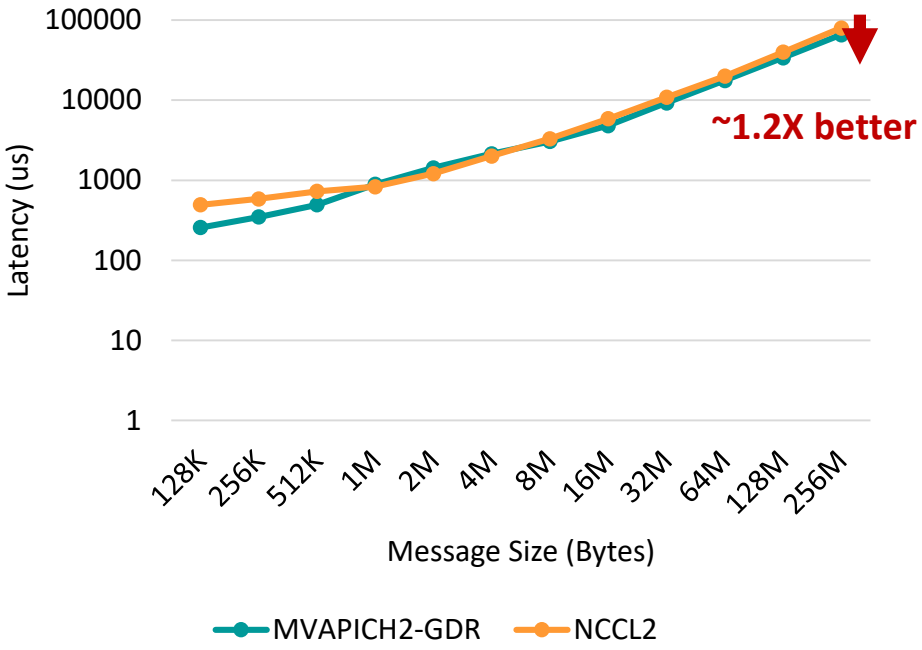
*Will be available with upcoming MVAPICH2-GDR 2.3b

Platform: Intel Xeon (Broadwell) nodes equipped with a dual-socket CPU, 1 K-80 GPUs, and EDR InfiniBand Inter-connect

MVAPICH2-GDR vs. NCCL2 – Allreduce Operation

- **Optimized designs in MVAPICH2-GDR 2.3rc1 offer better/comparable performance for most cases**
- **MPI_Allreduce (MVAPICH2-GDR) vs. ncclAllreduce (NCCL2) on 16 GPUs**





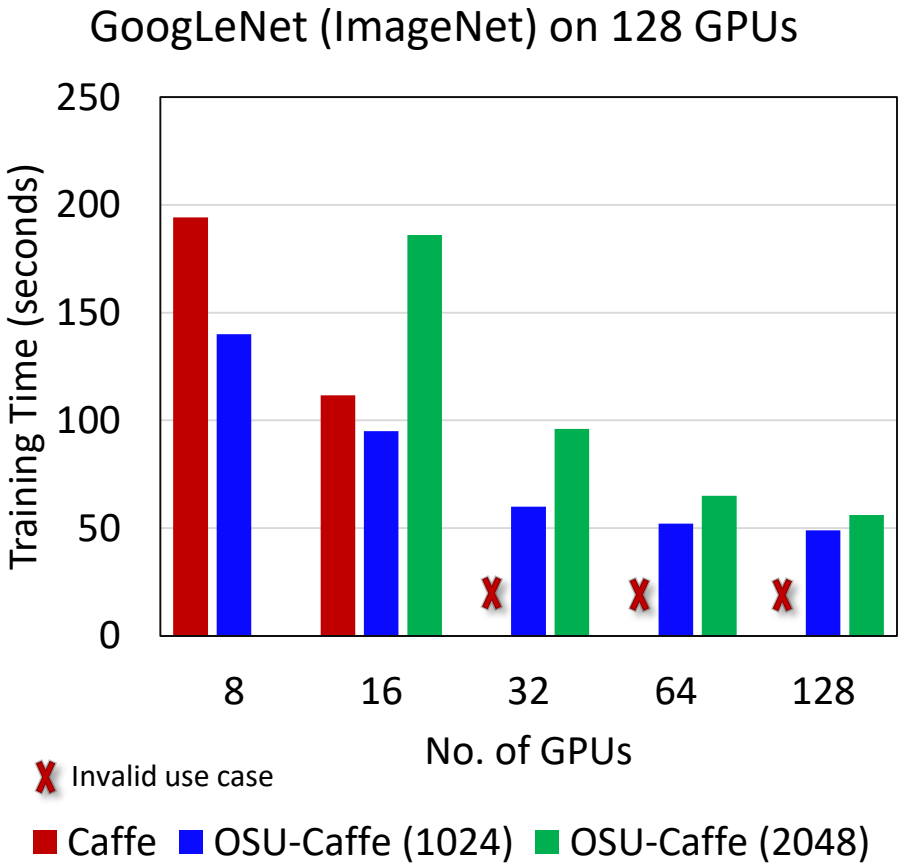
Platform: Intel Xeon (Broadwell) nodes equipped with a dual-socket CPU, 1 K-80 GPUs, and EDR InfiniBand Inter-connect

OSU-Caffe: Scalable Deep Learning

- Caffe : A flexible and layered Deep Learning framework.
- Benefits and Weaknesses
  - Multi-GPU Training within a single node
  - Performance degradation for GPUs across different sockets
  - Limited Scale-out
- OSU-Caffe: MPI-based Parallel Training
  - Enable Scale-up (within a node) and Scale-out (across multi-GPU nodes)
  - Scale-out on 64 GPUs for training CIFAR-10 network on CIFAR-10 dataset
  - Scale-out on 128 GPUs for training GoogLeNet network on ImageNet dataset

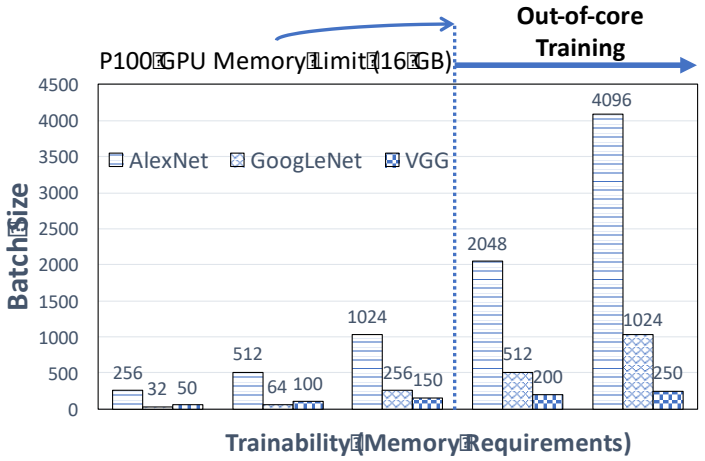
OSU-Caffe publicly available from

http://hidl.cse.ohio-state.edu/



Out-of-Core Deep Neural Network Training with Caffe

- Large DNNs cannot be trained on GPUs due to memory limitation!
  - ResNet-50 is the state-of-the-art DNN architecture for Image Recognition but current frameworks can only go up to a small batch size of 45
  - Next generation models like Neural Machine Translation (NMT) are ridiculously large, consists of billions of parameters, and require even more memory
  - Can we design Out-of-core DNN training support using new software features in CUDA 8/9 and hardware mechanisms in Pascal/Volta GPUs?
- General intuition is that managed allocations "will be" slow!
  - The proposed framework called OC-Caffe (Out-of-Core Caffe) shows the potential of managed memory designs that can provide performance with negligible/no overhead.
  - In addition to Out-of-core Training support, productivity can be greatly enhanced in terms of DL framework design by using the new Unified Memory features.

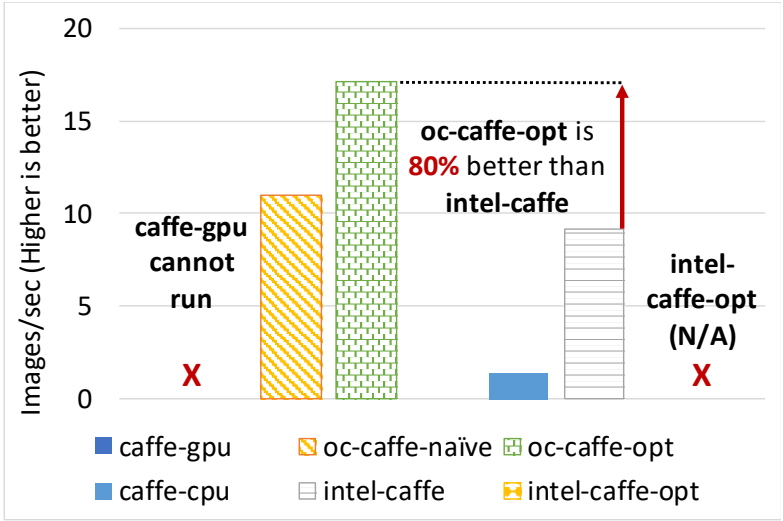


A. Awan, C. Chu, H. Subramoni, X. Lu, and D. K. Panda, OC-DNN: Exploiting Advanced Unified Memory Capabilities in CUDA 9 and Volta GPUs for Out-of-Core DNN Training, HiPC '18

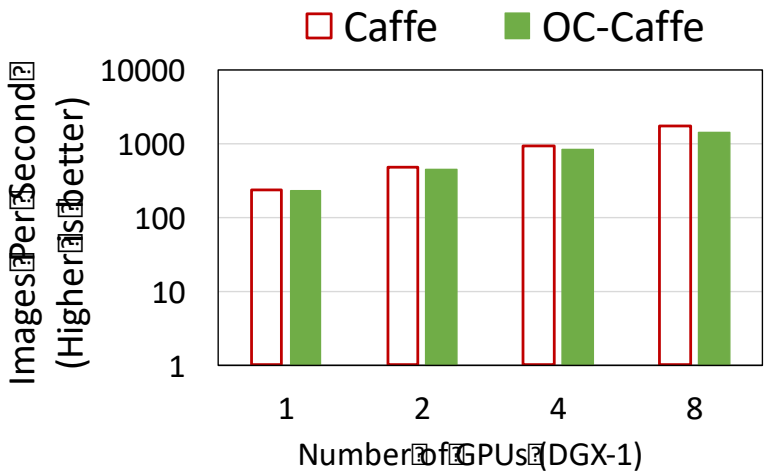
Performance Trends for OC-Caffe

- OC-Caffe-Opt: up to **80% better** than Intel-optimized CPU Caffe for ResNet-50 training on the Volta V100 GPU with CUDA9 and CUDNN7
- OC-Caffe allows efficient scale-up on DGX-1 system with Pascal P100 GPUs with CUDA9 and CUDNN7

Out-of-core (over-subscription)



Scale-up on DGX-1



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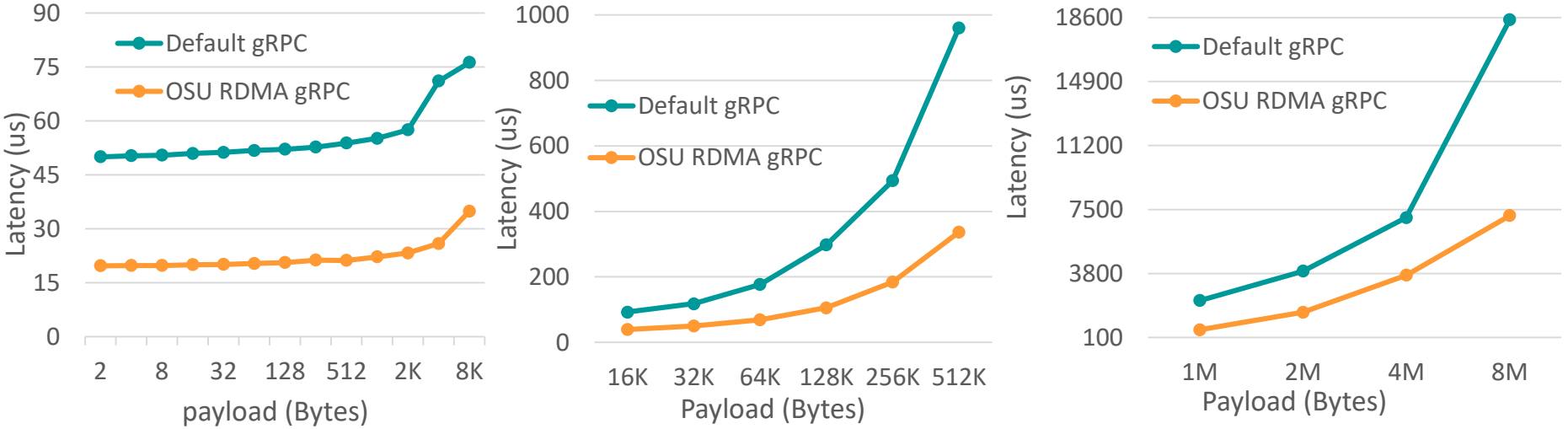
Performance Benefits for RDMA-gRPC with Micro-Benchmark

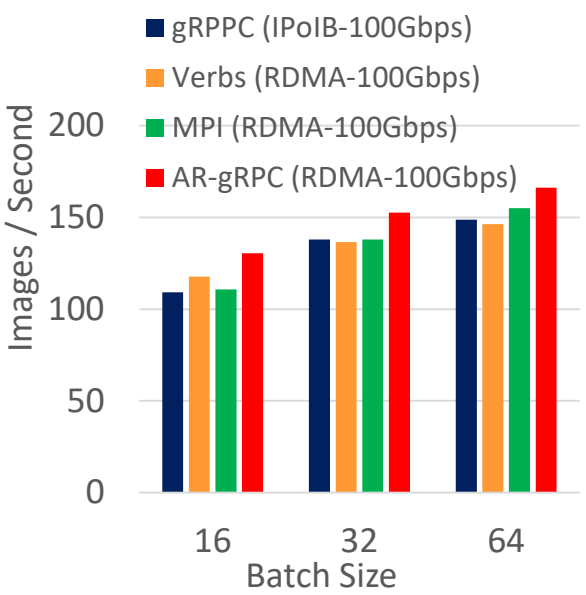


RDMA-gRPC RPC Latency

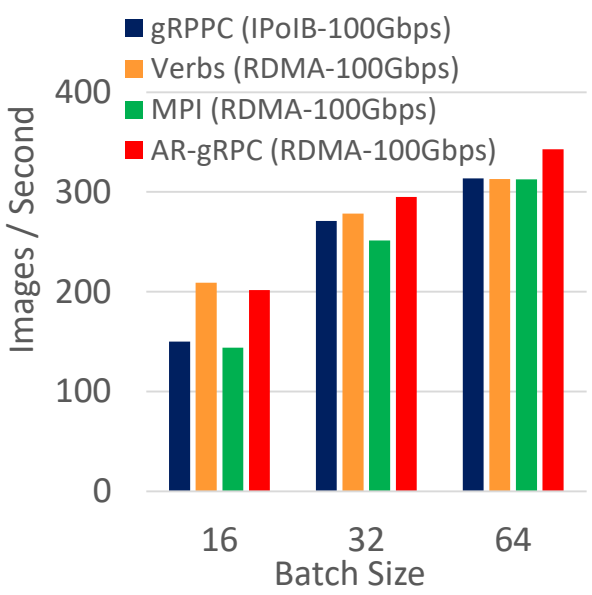
- **gRPC-RDMA Latency on SDSC-Comet-FDR**
  - **Up to 2.7x** performance speedup over IPoIB for Latency for small messages
  - **Up to 2.8x** performance speedup over IPoIB for Latency for medium messages
  - **Up to 2.5x** performance speedup over IPoIB for Latency for large messages

R. Biswas, X. Lu, and D. K. Panda, Accelerating gRPC and TensorFlow with RDMA for High-Performance Deep Learning over InfiniBand, HiPC '18.

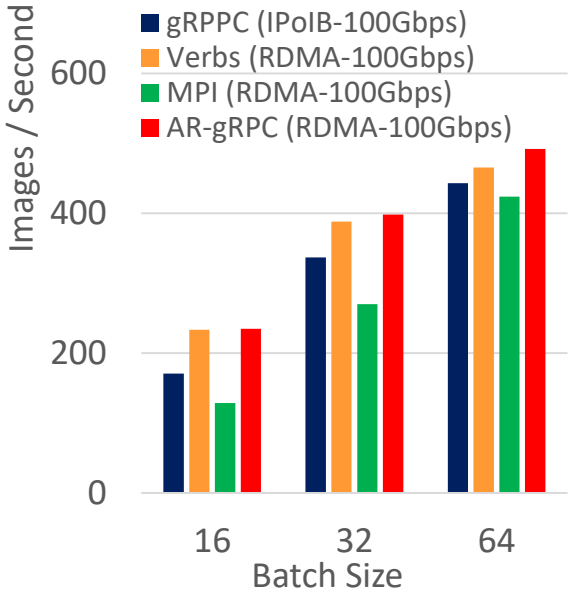
Performance Benefit for RDMA-TensorFlow (Inception3)



4 Nodes (8 GPUS)



8 Nodes (16 GPUS)



12 Nodes (24 GPUS)

- TensorFlow Inception3 performance evaluation on an IB EDR cluster
  - Up to 20% performance speedup over Default gRPC (IPoIB) for 8 GPUs
  - Up to 34% performance speedup over Default gRPC (IPoIB) for 16 GPUs
  - Up to 37% performance speedup over Default gRPC (IPoIB) for 24 GPUs

R. Biswas, X. Lu, and D. K. Panda, Accelerating TensorFlow with Adaptive RDMA-based gRPC. HiPC '18

RDMA-TensorFlow Distribution

- High-Performance Design of TensorFlow over RDMA-enabled Interconnects
  - High performance RDMA-enhanced design with native InfiniBand support at the verbs-level for gRPC and TensorFlow
  - RDMA-based data communication
  - Adaptive communication protocols
  - Dynamic message chunking and accumulation
  - Support for RDMA device selection
  - Easily configurable for different protocols (native InfiniBand and IPoIB)
- Current release: 0.9.1
  - Based on Google TensorFlow 1.3.0
  - Tested with
    - Mellanox InfiniBand adapters (e.g., EDR)
    - NVIDIA GPGPU K80
    - Tested with CUDA 8.0 and CUDNN 5.0
  - http://hidl.cse.ohio-state.edu

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The High-Performance Big Data (HiBD) Project

- RDMA for Apache Spark
- RDMA for Apache Hadoop 3.x (RDMA-Hadoop-3.x)
- RDMA for Apache Hadoop 2.x (RDMA-Hadoop-2.x)
  - Plugins for Apache, Hortonworks (HDP) and Cloudera (CDH) Hadoop distributions
- RDMA for Apache Kafka
- RDMA for Apache HBase
- RDMA for Memcached (RDMA-Memcached)
- RDMA for Apache Hadoop 1.x (RDMA-Hadoop)
- OSU HiBD-Benchmarks (OHB)
  - HDFS, Memcached, HBase, and Spark Micro-benchmarks
- http://hibd.cse.ohio-state.edu
- Users Base: 295 organizations from 34 countries
- More than 28,300 downloads from the project site

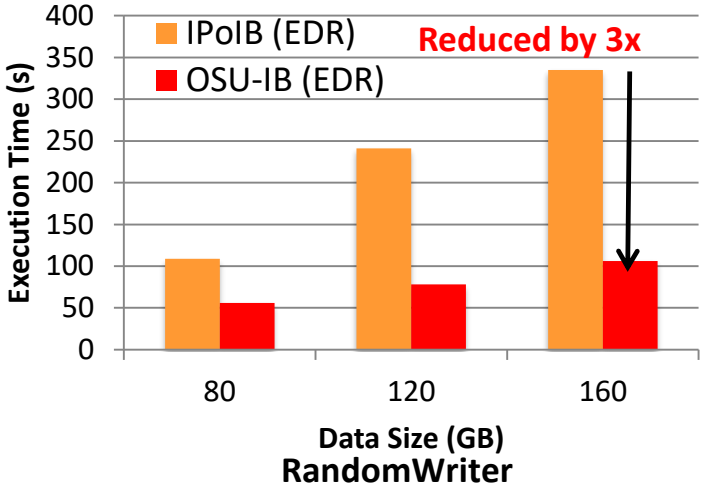
Available for InfiniBand and RoCE

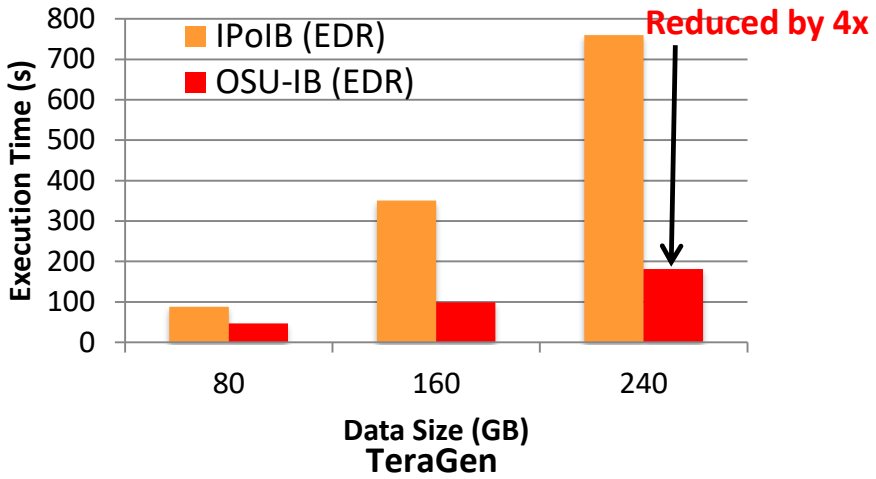
Also run on Ethernet

Available for x86 and OpenPOWER

Support for Singularity and Docker

Performance Numbers of RDMA for Apache Hadoop 2.x – RandomWriter & TeraGen in OSU-RI2 (EDR)

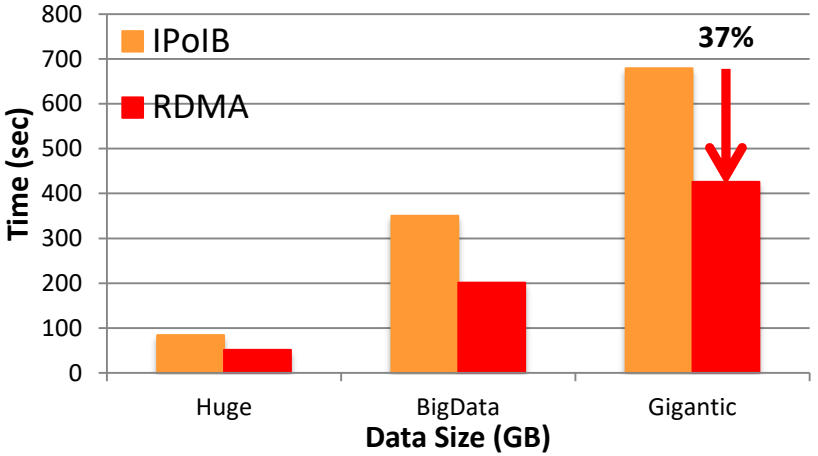




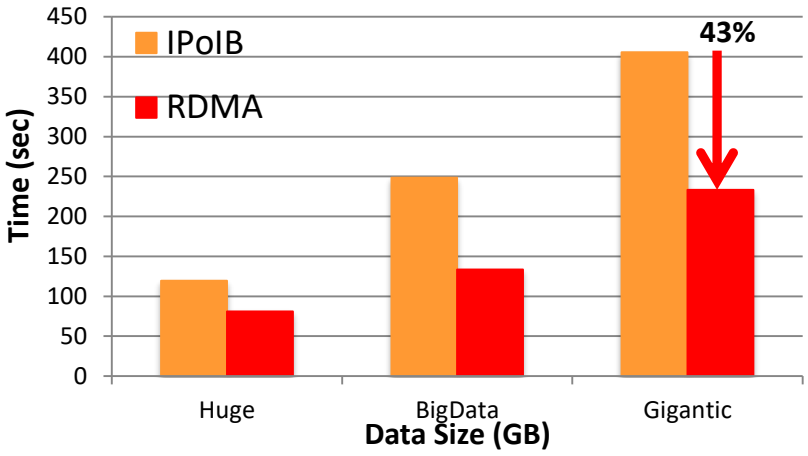
Cluster with 8 Nodes with a total of 64 maps

- RandomWriter
  - **3x** improvement over IPoIB for 80-160 GB file size
- TeraGen
  - **4x** improvement over IPoIB for 80-240 GB file size

Performance Evaluation on SDSC Comet – HiBench PageRank



32 Worker Nodes, 768 cores, PageRank Total Time

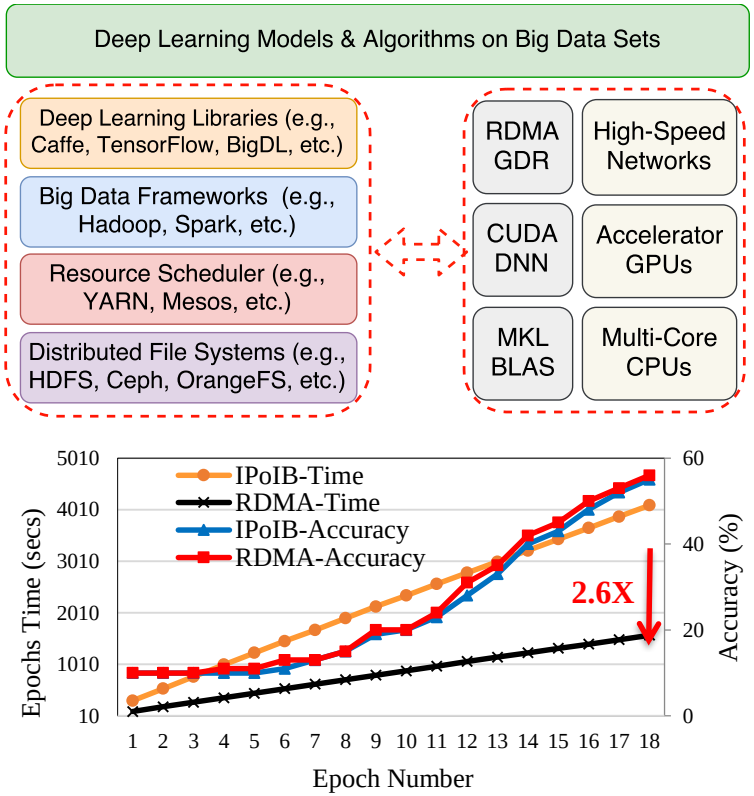


64 Worker Nodes, 1536 cores, PageRank Total Time

- InfiniBand FDR, SSD, 32/64 Worker Nodes, 768/1536 Cores, (768/1536M 768/1536R)
- RDMA-based design for Spark 1.5.1
- RDMA vs. IPoIB with 768/1536 concurrent tasks, single SSD per node.
  - 32 nodes/768 cores: Total time reduced by 37% over IPoIB (56Gbps)
  - 64 nodes/1536 cores: Total time reduced by 43% over IPoIB (56Gbps)

High-Performance Deep Learning over Big Data (DLoBD) Stacks

- Challenges of Deep Learning over Big Data (DLoBD)
  - Can RDMA-based designs in DLoBD stacks improve performance, scalability, and resource utilization on high-performance interconnects, GPUs, and multi-core CPUs?
  - What are the performance characteristics of representative DLoBD stacks on RDMA networks?
- Characterization on DLoBD Stacks
  - CaffeOnSpark, TensorFlowOnSpark, and BigDL
  - IPoIB vs. RDMA; In-band communication vs. Out-of-band communication; CPU vs. GPU; etc.
  - Performance, accuracy, scalability, and resource utilization
  - RDMA-based DLoBD stacks (e.g., BigDL over RDMA-Spark) can achieve 2.6x speedup compared to the IPoIB based scheme, while maintain similar accuracy



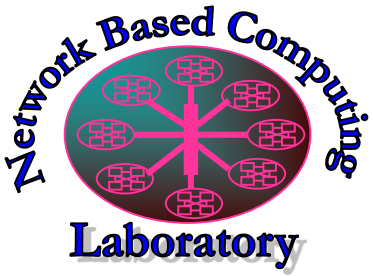
X. Lu, H. Shi, M. H. Javed, R. Biswas, and D. K. Panda, Characterizing Deep Learning over Big Data (DLoBD) Stacks on RDMA-capable Networks, HotI 2017.

Conclusions

- Scalable distributed training is getting important
- Requires high-performance middleware designs while exploiting modern interconnects
- Provided a set of different solutions to achieve scalable distributed training
  - CUDA-aware MPI with optimized collectives
  - TensorFlow-gRPC with RDMA support
  - Efficient DL support over Big Data
- Will continue to enable the DL community to achieve scalability and high-performance for their distributed training

Thank You!

panda@cse.ohio-state.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/