MVAPICH
MPI, PGAS and Hybrid MPI+PGAS Library

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HiBD
High-Performance Big Data

2023 OFA Virtual Workshop

HIGH-PERFORMANCE AND SCALABLE SUPPORT FOR BIG DATA STACKS WITH MPI

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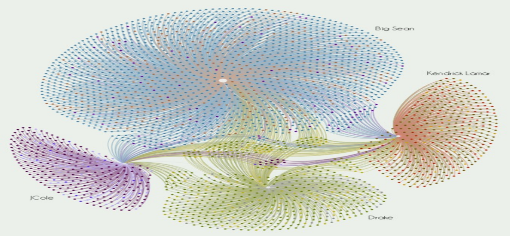
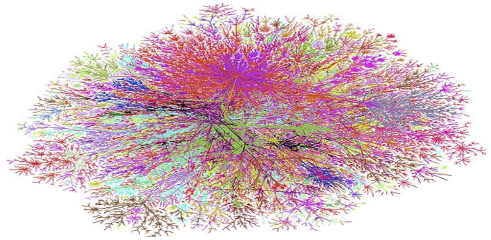
Presentation Outline

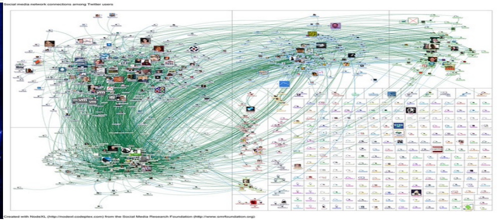
- **Introduction to Big Data Analytics and MVAPICH2**
- Overview, Design and Implementation
  - MPI4Spark
  - MPI4Dask
- Performance Evaluation
  - MPI4Spark
  - MPI4Dask
- Related Publications and Summary

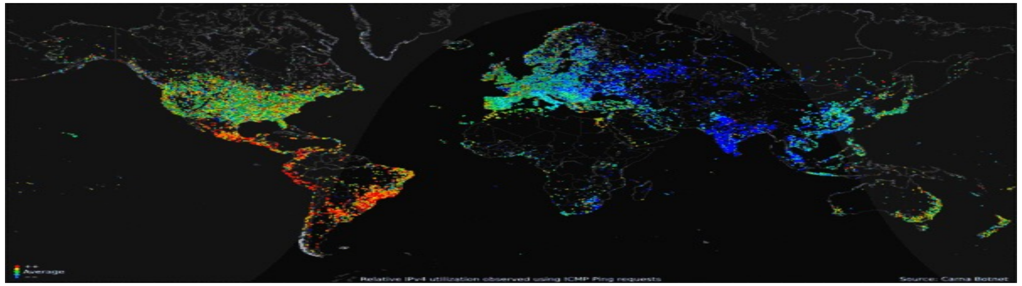
Introduction to Big Data Analytics

- Big Data has changed the way people understand and harness the power of data, both in the business and research domains
- Big Data has become one of the most important elements in business analytics
- Big Data and High Performance Computing (HPC) are converging to meet large scale data processing challenges
- Dask and Spark are two popular Big Data processing frameworks
- Sometimes also called Data Science

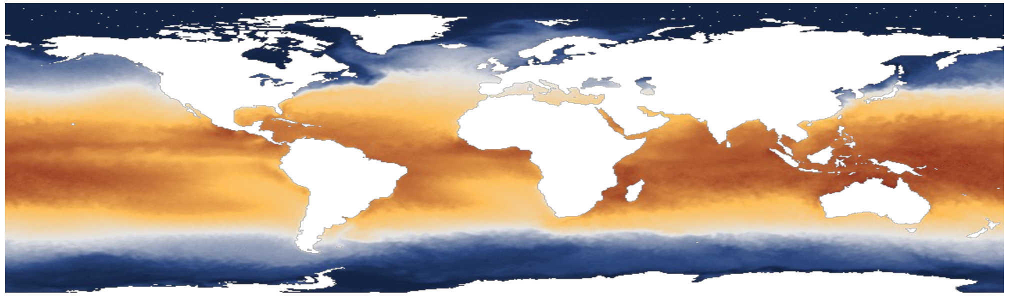








http://www.coolinfographics.com/blog/tag/data?currentPage=3



http://www.climatecentral.org/news/white-house-brings-together-big-data-and-climate-change-17194

Overview of the MVAPICH Project

- High Performance open-source Message Passing Interface (MPI) Library
- Support for multiple interconnects
  - InfiniBand, Omni-Path, Ethernet/iWARP, RDMA over Converged Ethernet (RoCE), AWS Elastic Fabric Adapter, Omni-Path Express, Broadcom RoCE, Intel Ethernet, Rockport Networks, Slingshot 10/11
- Support for multiple platforms
  - x86, OpenPOWER, ARM, Xeon-Phi, GPGPUs (NVIDIA and AMD)
- Started in 2001, first open-source version demonstrated at SC ‘02
- Supports the latest MPI-3.1 standard
- http://mvapich.cse.ohio-state.edu
- Additional optimized versions for different systems/environments:
  - MVAPICH2-X (Advanced MPI + Partitioned Global Address Space), since 2011
  - MVAPICH2-GDR with support for NVIDIA (since 2014) and AMD (since 2020) GPUs
  - MVAPICH2-MIC with support for Intel Xeon-Phi, since 2014
  - MVAPICH2-Virt with virtualization support, since 2015
  - MVAPICH2-EA with support for Energy-Awareness, since 2015
  - MVAPICH2-Azure for Azure HPC InfiniBand instances, since 2019
  - MVAPICH2-X-AWS for AWS HPC+Elastic Fabric Adapter instances, since 2019
- Tools:
  - OSU MPI Micro-Benchmarks (OMB), since 2003
  - OSU InfiniBand Network Analysis and Monitoring (INAM), since 2015

- **Used by more than 3,300 organizations in 90 countries**
- **More than 1.66 Million downloads from the OSU site directly**
- Empowering many TOP500 clusters (Nov ‘22 ranking)
  - 7^{th} , 10,649,600-core (Sunway TaihuLight) at NSC, Wuxi, China
  - 19^{th}, 448, 448 cores (Frontera) at Texas Advanced Computing Center
  - 34^{th}, 288,288 cores (Lassen) at Lawrence Livermore National Lab
  - 46^{th}, 570,020 cores (Nurion) in South Korea and many others
- Available with software stacks of many vendors and Linux Distros (RedHat, SuSE, OpenHPC, and Spack)
- Partner in the 19^{th} ranked TACC Frontera system
- **Empowering Top500 systems for more than 17 years**

Architecture of MVAPICH2 Software Family for HPC, DL/ML, and Data Science

High Performance Parallel Programming Models

- Message Passing Interface (MPI)
- PGAS (UPC, OpenSHMEM, CAF, UPC++)
- Hybrid --- MPI + X (MPI + PGAS + OpenMP/Cilk)

High Performance and Scalable Communication Runtime

Diverse APIs and Mechanisms

- Point-to-point Primitives
- Collectives Algorithms
- Job Startup
- Energy-Awareness
- Remote Memory Access
- I/O and File Systems
- Fault Tolerance
- Virtualization
- Active Messages
- Introspection & Analysis

Support for Modern Networking Technology
(InfiniBand, iWARP, RoCE, Omni-Path, EFA, Rockport, Slingshot)

Transport Protocols: RC, SRD, UD, DC

Modern Features: UMR, ODP, SR-IOV, Multi Rail

Support for Modern Multi-/Many-core Architectures
(Intel-Xeon, AMD, OpenPOWER, ARM, GPU (NVIDIA, AMD), DPU)

Transport Mechanisms: Shared Memory, CMA, IVSHMEM, XPMEM

Modern Features: Optane*, NVLink, CAPI*

* Upcoming

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  - **MPI4Dask**
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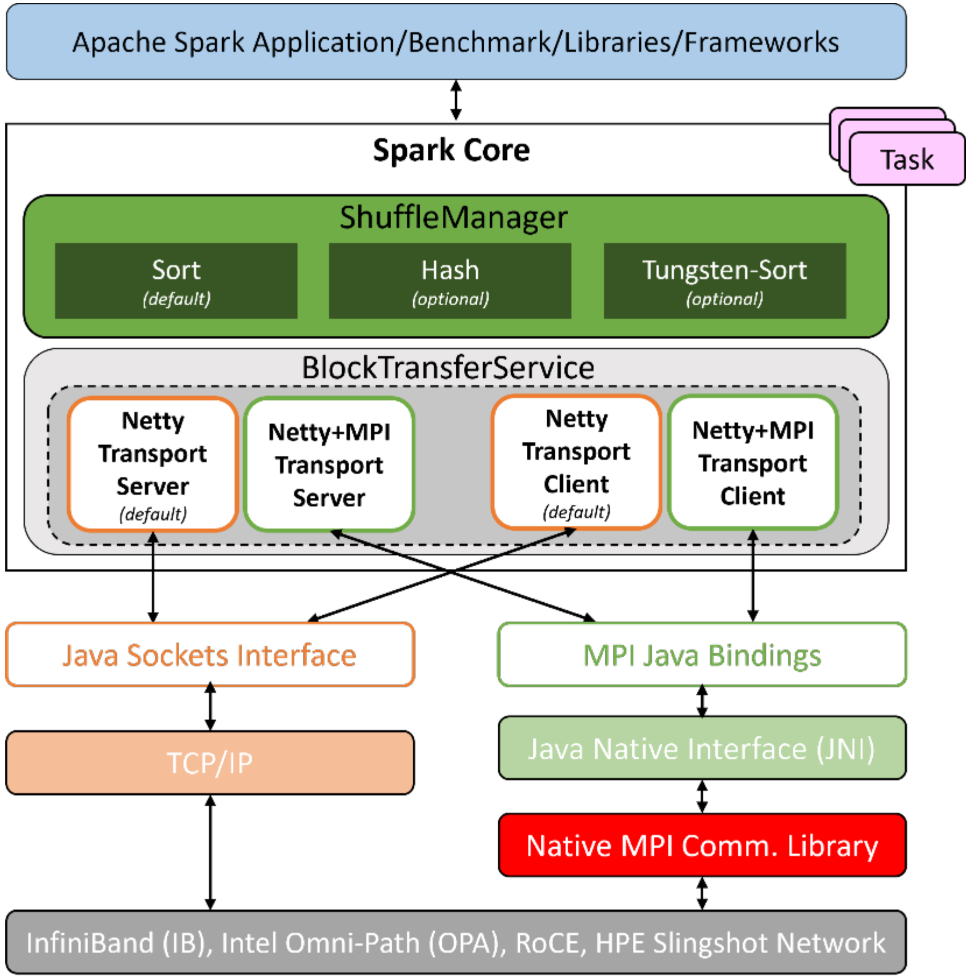
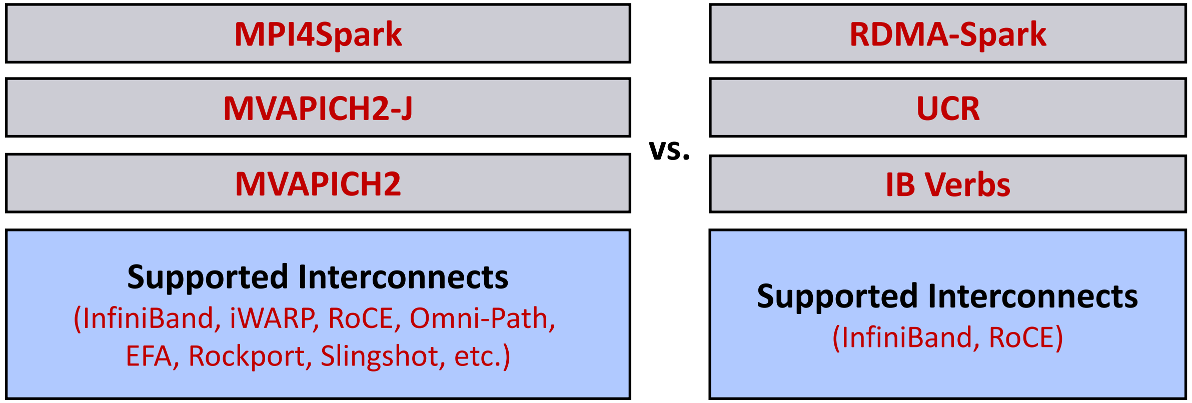
MPI4Spark: Using MVAPICH2 to Optimize Apache Spark

- The main motivation of this work is to utilize the communication functionality provided by MVAPICH2 in the Apache Spark framework
- MPI4Spark relies on Java bindings of the MVAPICH2 library
- Spark's default Shuffle Manager relies on Netty for communication:
  - Netty is a Java New I/O (NIO) client/server framework for event-based networking applications
  - The key idea is to utilize MPI-based point-to-point communication inside Netty



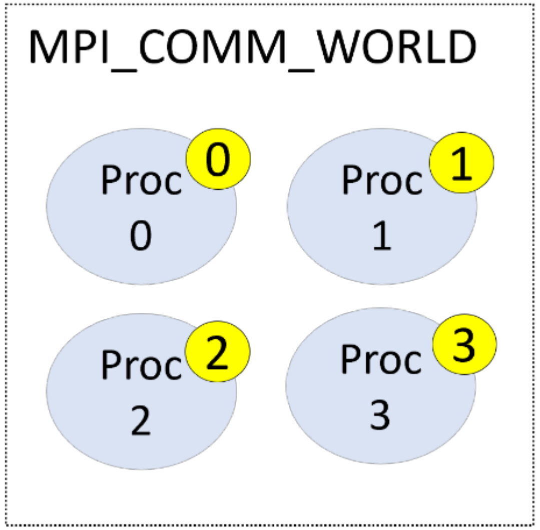
MPI4Spark Interconnect Support

- The current approach is different from its predecessor design, RDMA-Spark (http://hibd.cse.ohio-state.edu)
  - RDMA-Spark supports only InfiniBand and RoCE
  - Requires new designs for new interconnect
- MPI4Spark supports multiple interconnects/systems through a common MPI library
  - Such as InfiniBand (IB), Intel Omni-Path (OPA), HPE Slingshot, RoCE, and others
  - No need to re-design the stack for a new interconnect as long as the MPI library supports it

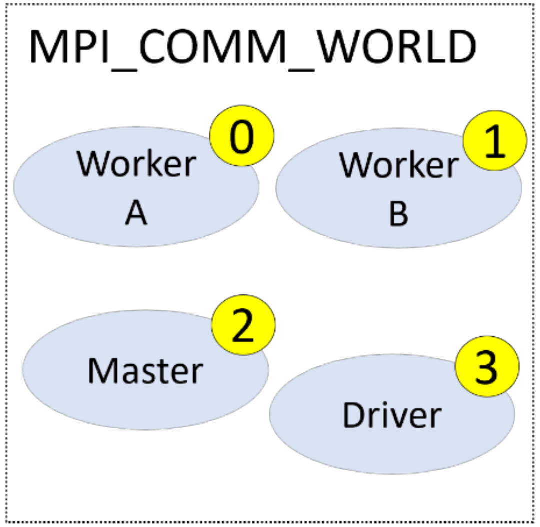


Launching Spark using MPI with Dynamic Process Management

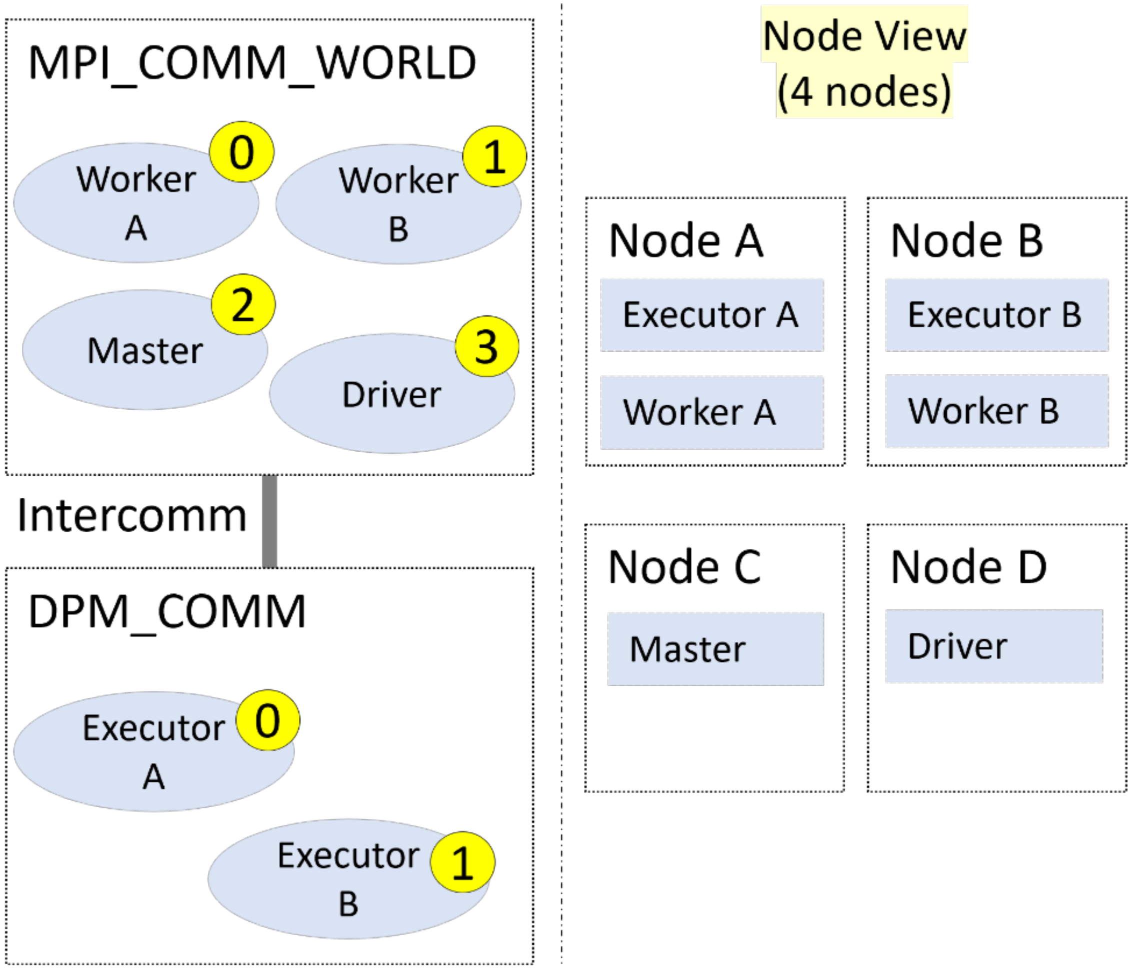
Step A: Launch 4 Wrapper Processes
(for e.g. mpiexec –np 4 .. SparkMPI.java)



Step B: Each Wrapper Process Forks Spark Processes

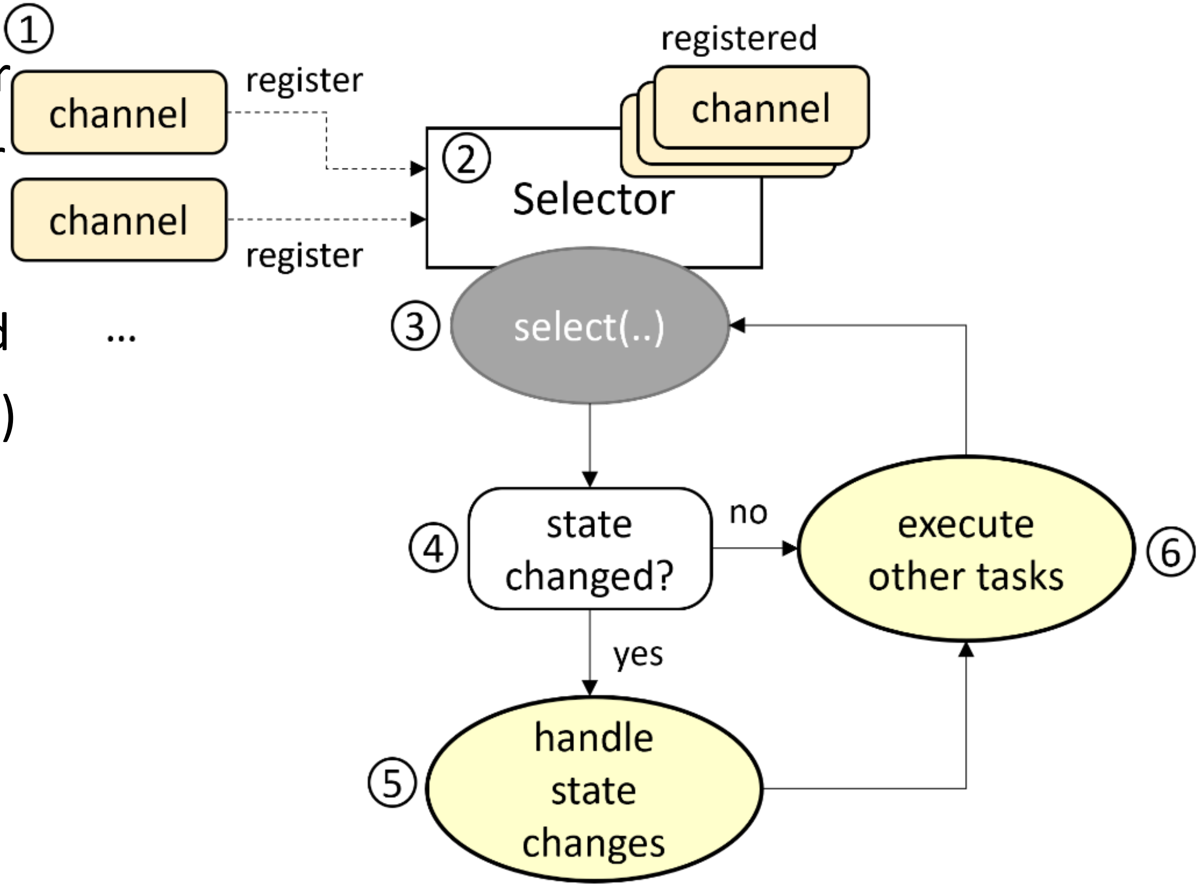


Step C: Launch 2 Executor Processes
MPI_Comm_spawn_multiple()



MPI4Spark-Basic Design

- Modified the Netty NIO selector loop, which polls for channel state changes based on connection, read, or write events
- Inside of the selector loop checks were implemented with MPI non-blocking probing method (MPI_Iprobe) for MPI_recv calls matching MPI_sends
- Netty Channels or simply Java sockets were still being used but only for connection establishment
- Too CPU-intensive, performed badly

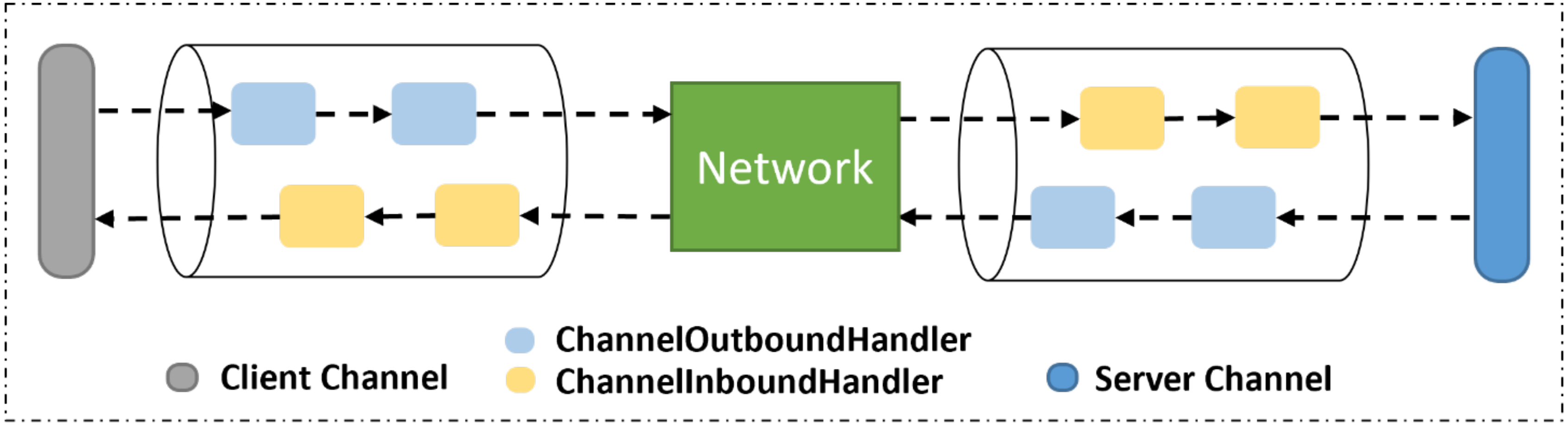


Types of Messages Communicated by Spark

Message Type	Function
StreamRequest	A request to stream data from the remote end
StreamResponse*	A response to a StreamRequest when the stream has been successfully opened
RpcRequest	A request to perform a generic Remote Procedure Call (RPC)
RpcResponse	A response to a RpcRequest for a successful RPC
ChunkFetchRequest	A request to fetch a sequence of a single chunk of a stream
ChunkFetchSuccess*	A response to ChunkFetchRequest when a chunk exists and has been successfully fetched
OneWayMessage	A RPC that does not expect a reply

MPI4Spark-Optimized Design

- The MPI4Spark-Optimized design avoids the pitfalls of the MPI4Spark-Basic design and is a lot simpler
- In this design, we only target shuffle messages, Knowing that the shuffle phase was a performance bottleneck and can account for 80% of total execution time
  - non-blocking MPI probes are avoided
  - the idea was now to trigger MPI_recv calls by parsing the headers of shuffle messages inside of ChannelHandlers that reside in ChannelPipelines in Netty



MPI4Spark Release

- MPI4Spark 0.1 release adds support for high-performance MPI communication to Spark:
  - Can be downloaded from: http://hibd.cse.ohio-state.edu
- Features:
  - (NEW) Based on Apache Spark 3.3.0
  - (NEW) Compliant with user-level Apache Spark APIs and packages
  - (NEW) High performance design that utilizes MPI-based communication
    - Utilizes MPI point-to-point operations
    - Relies on MPI Dynamic Process Management (DPM) features for launching executor processes
  - (NEW) Built on top of the MVAPICH2-J Java bindings for MVAPICH2 family of MPI libraries
  - (NEW) Tested with
    - OSU HiBD-Benchmarks, GroupBy and SortBy
    - Intel HiBench Suite, Micro Benchmarks, Machine Learning and Graph Workloads
    - Mellanox InfiniBand adapters (EDR and HDR 100G and 200G)
    - HPC systems with Intel OPA interconnects
    - Various multi-core platforms

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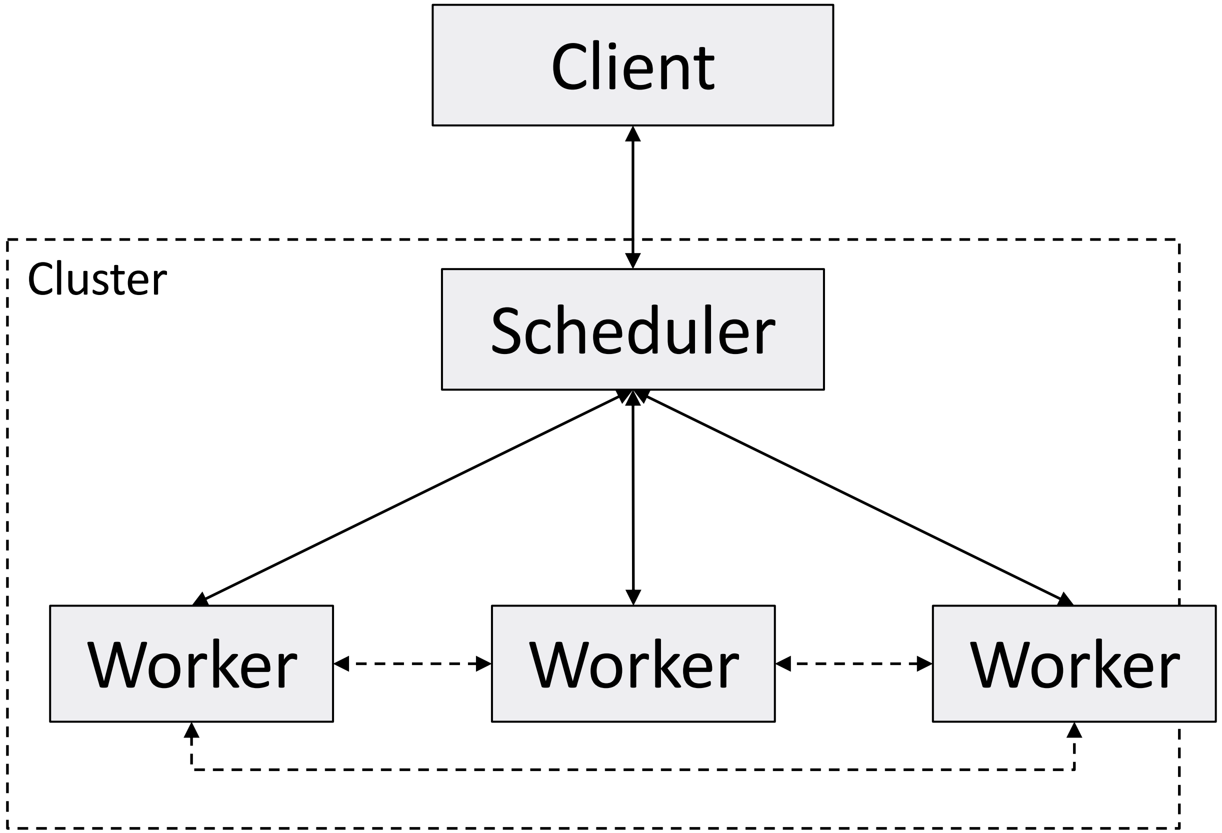
MPI4Dask: MPI backend for Dask

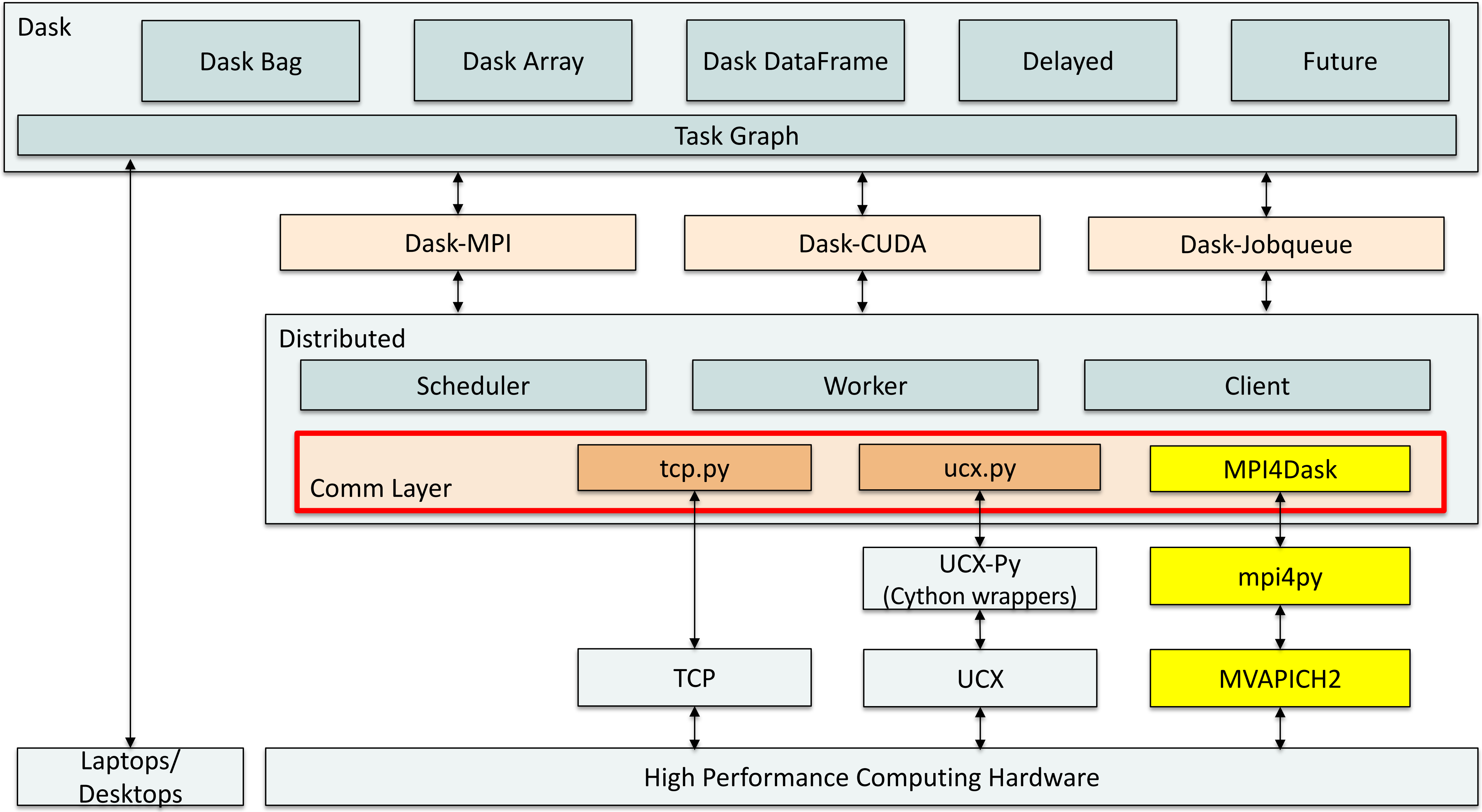
- Dask is a popular task-based distributed computing framework:
  - Scales Python applications from laptops to high-end systems
  - Builds a task-graph that is executed lazily on parallel hardware
- Dask Distributed library historically had two communication backends:
  - TCP: Tornado-based
  - UCX: Built using a GPU-aware Cython wrapper called UCX-Py
- Designed and implemented MPI4Dask communication device:
  - MPI-based backend for Dask
  - Implemented using mpi4py (Cython wrappers) and MVAPICH2
  - Uses Dask-MPI to bootstrap execution of Dask programs

Dask Distributed Execution Model

- Key characteristics:
  1. Scalability
  2. Elasticity
  3. Support for coroutines
  4. Serialization/De-serialization to data to/from GPU memory

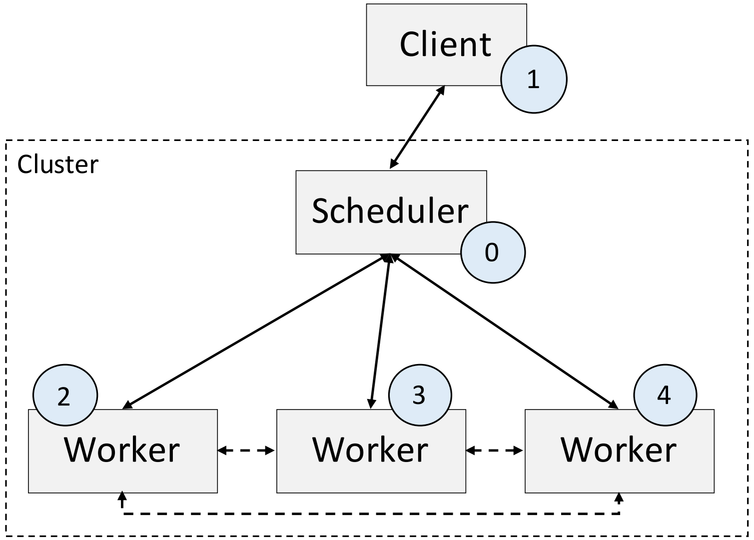


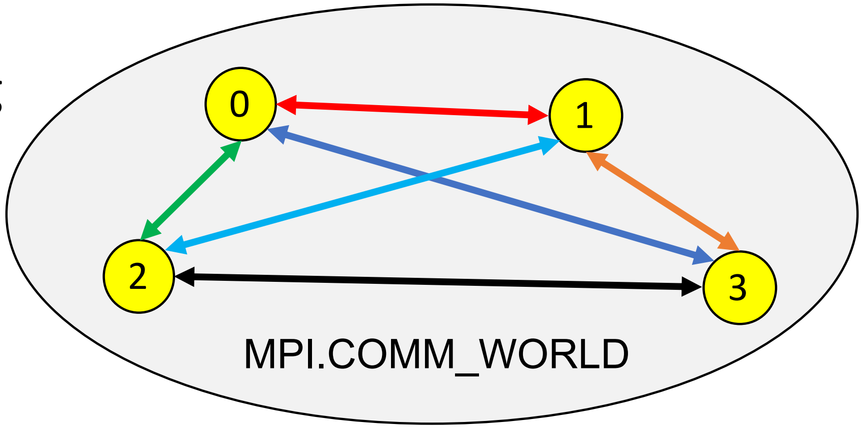
MPI4Dask in the Dask Architecture



MPI4Dask: Bootstrapping and Dynamic Connectivity

- Several ways to start Dask programs:
  - Manual
  - Utility classes:
    - LocalCUDACluster, SLURMCluster, SGECluster, PBCCluster, and others
- MPI4Dask uses the Dask-MPI to bootstrap execution of Dask programs
- Dynamic connectivity is established using the asyncio package in MPI4Dask:
  - Scheduler and workers listen for incoming connections by calling asyncio.start_server()
  - Workers and client connect using asyncio.open_connection()





MPI4Dask: Point-to-point Communication Coroutines

- Implements communication coroutines for point-to-point MPI functions:
  - Using mpi4py (Cython wrappers) and MVAPICH2-GDR
- mpi4py provides two flavors of point-to-point communication functions:
  - Send()/Recv() – for exchanging data in buffers (faster and used in MPI4Dask)
  - send()/recv() – for communicating Python objects (pickle/unpickle)
  - GPU buffers implement the __cuda_array_interface__
- Implemented chunking mechanism for large messages
- The send and receive communication coroutines are as follows:

```
request = comm.Isend([buf, size], dest, tag)
status = request.Test()

while status is False:
   await asyncio.sleep(0)
   status = request.Test()
```

```
request = comm.Irecv([buf, size], src, tag)
status = request.Test()

while status is False:
   await asyncio.sleep(0)
   status = request.Test()
```

MPI4Dask Release

- MPI4Dask 0.3 was released in Feb ‘23 adding support for high-performance MPI communication to Dask:
  – Can be downloaded from: http://hibd.cse.ohio-state.edu
- Features:
  – (NEW) Based on Dask Distributed 2022.8.1
  – Compliant with user-level Dask APIs and packages
  – Support for MPI-based communication in Dask for cluster of GPUs
    - Implements point-to-point communication co-routines
    - Efficient chunking mechanism implemented for large messages
  – Built on top of mpi4py over the MVAPICH2-GDR library
  – Supports starting execution of Dask programs using Dask-MPI
  – Tested with
    - Mellanox InfiniBand adapters (FDR, EDR, and HDR)
    - (NEW) Various benchmarks used by the community (MatMul, Slicing, Sum Transpose, cuDF Merge, etc.)
    - (NEW) Various multi-core platforms
    - (NEW) NVIDIA V100 and A100 GPUs

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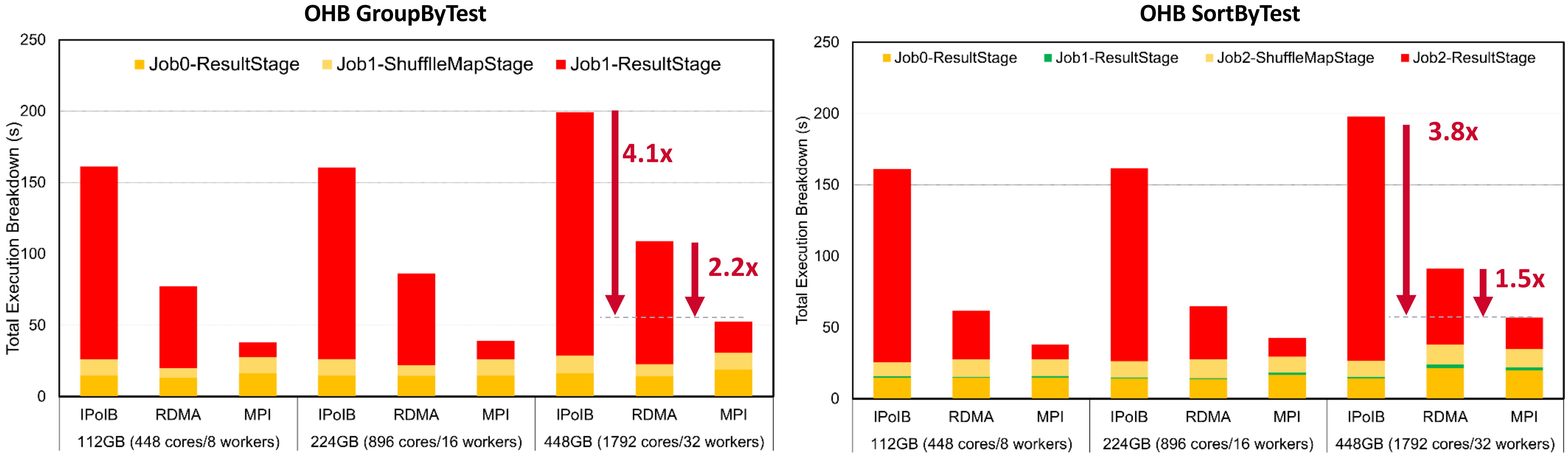
Weak Scaling Evaluation with OSU HiBD Benchmarks (OHB)

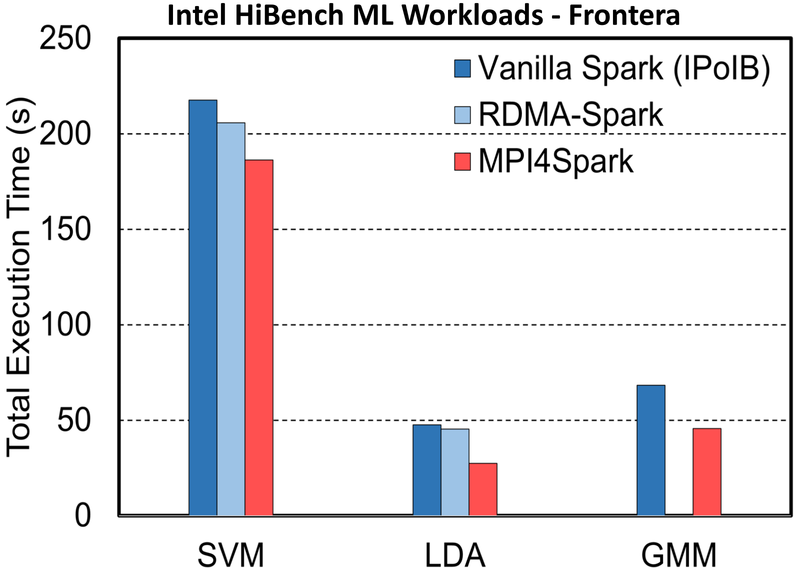


- The above are **weak-scaling** performance numbers of OHB benchmarks (GroupByTest and SortByTest) executed on the TACC Frontera system
- Speed-ups for the overall total execution time for 448GB with GroupByTest is **4.1x** and **2.2x** compared to IPoIB and RDMA, and for SortByTest the speed-ups are **3.8x** and **1.5x**, respectively
- Speed-ups for the shuffle read stage for 112GB with GroupByTest are **13x** compared with IPoIB and **5.6x** compared to RDMA, while for SortByTest the speed-ups are **12.8x** and **3.2x**, respectively

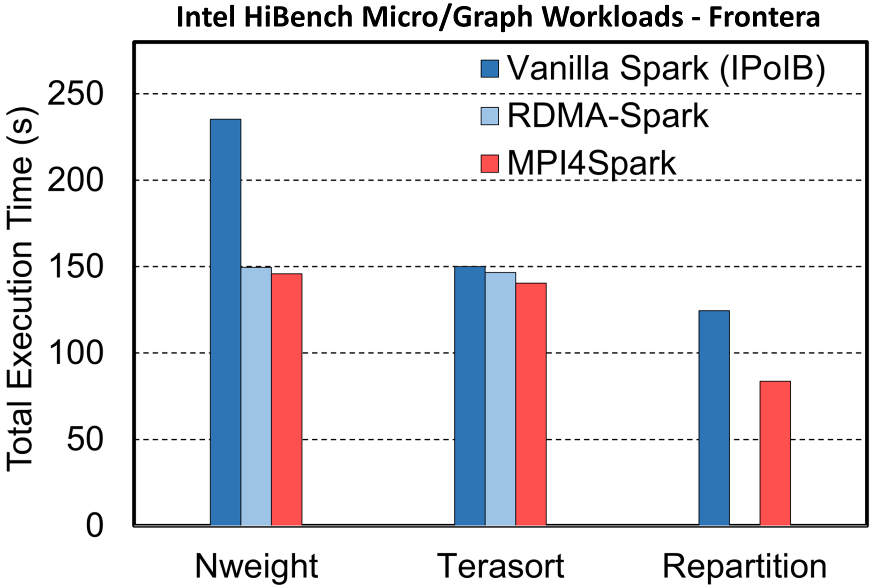
K. Al Attar, A. Shafi, M. Abduljabbar, H. Subramoni, D. Panda, Spark Meets MPI: Towards High-Performance Communication Framework for Spark using MPI, IEEE Cluster '22, Sep 2022.

Performance Evaluation with Intel HiBench Workloads

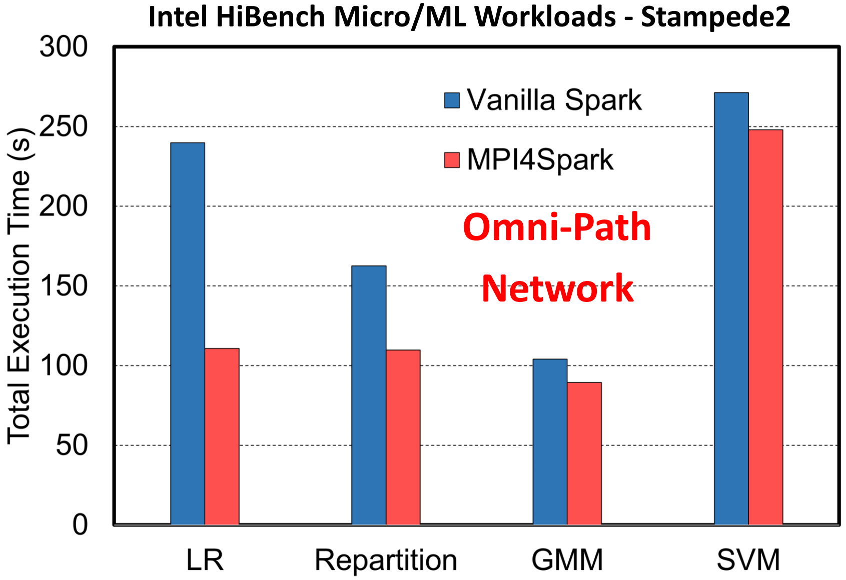
1.4x on average than RDMA-Spark



1.4x on average than Vanilla Spark



1.5x on average than Vanilla Spark



- This evaluation was done on the TACC Frontera (IB) and the TACC Stampede2 (OPA) Systems
- This illustrates the portability of MPI4Spark on different interconnects
- We see a speed-up for the LR machine learning workload on Stampede2 of about **2.2x**
- Speed-ups for the LDA machine learning workload on Frontera are **1.7x** for both IPoIB and RDMA

K. Al Attar, A. Shafi, M. Abduljabbar, H. Subramoni, D. Panda, Spark Meets MPI: Towards High-Performance Communication Framework for Spark using MPI, IEEE Cluster '22, Sep 2022.

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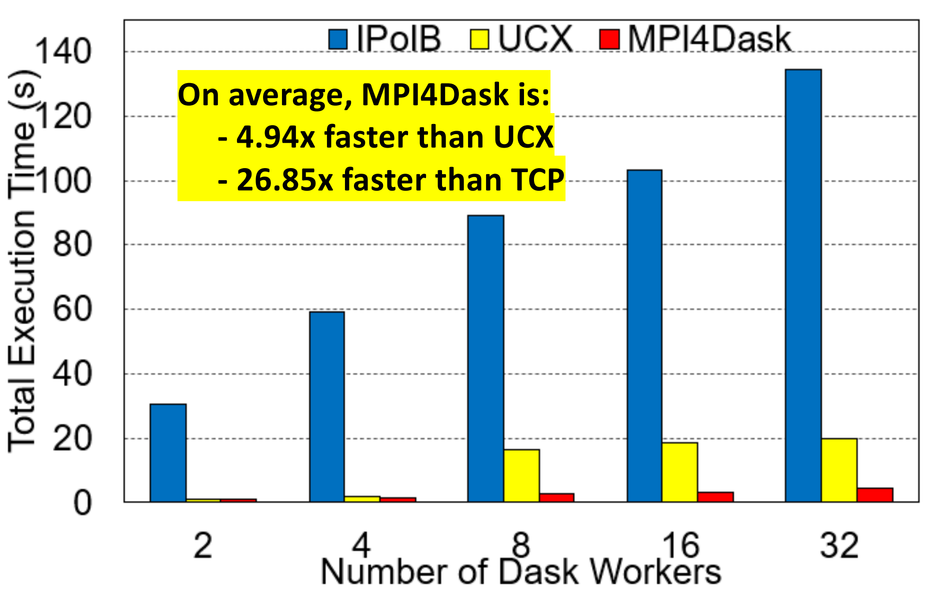
cuDF Merge Benchmark on the Cambridge Wilkes-3 System

- GPU-based Operation: $ddf1.merge(ddf2)$, using persist
  - Merge two GPU data frames, each with length of 32*1e8
  - Compute() will gather the data from all worker nodes to the client node, and make a copy on the host memory.
  - Persist() will leave the data on its current nodes without any gathering

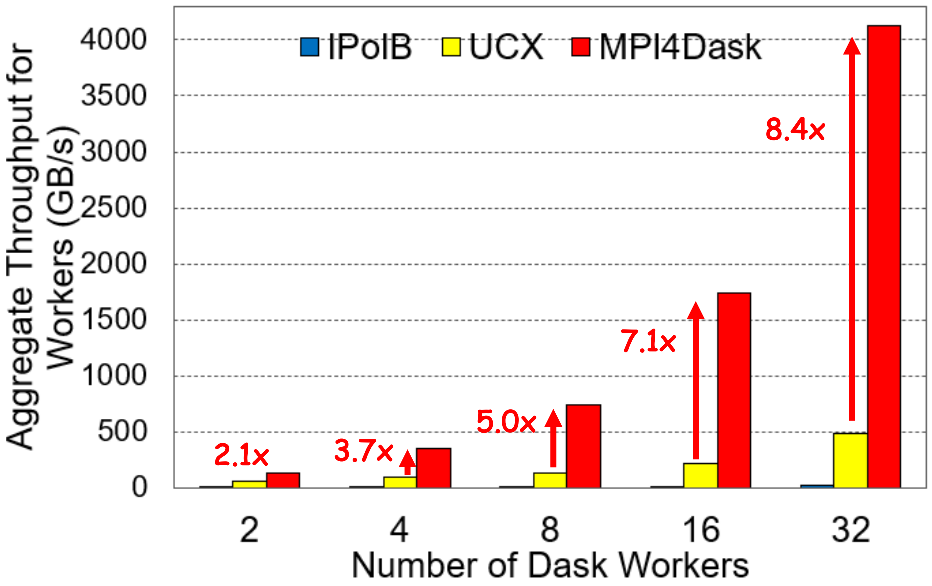
Wilke3 GPU System:

- 80 nodes
- 2x AMD EPYC 7763 64-core Processors
- 1000 GiB RAM
- Dual-rail Mellanox HDR200 IB
- 4x NVIDIA A100 SXM4 80 GB

Execution Time



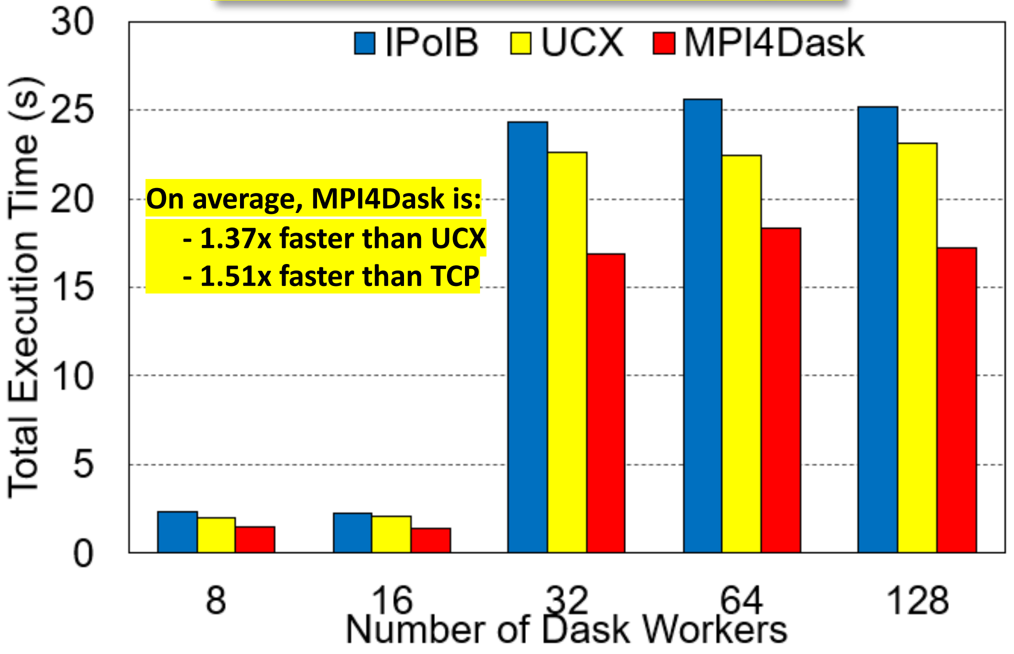
Aggregated Throughput



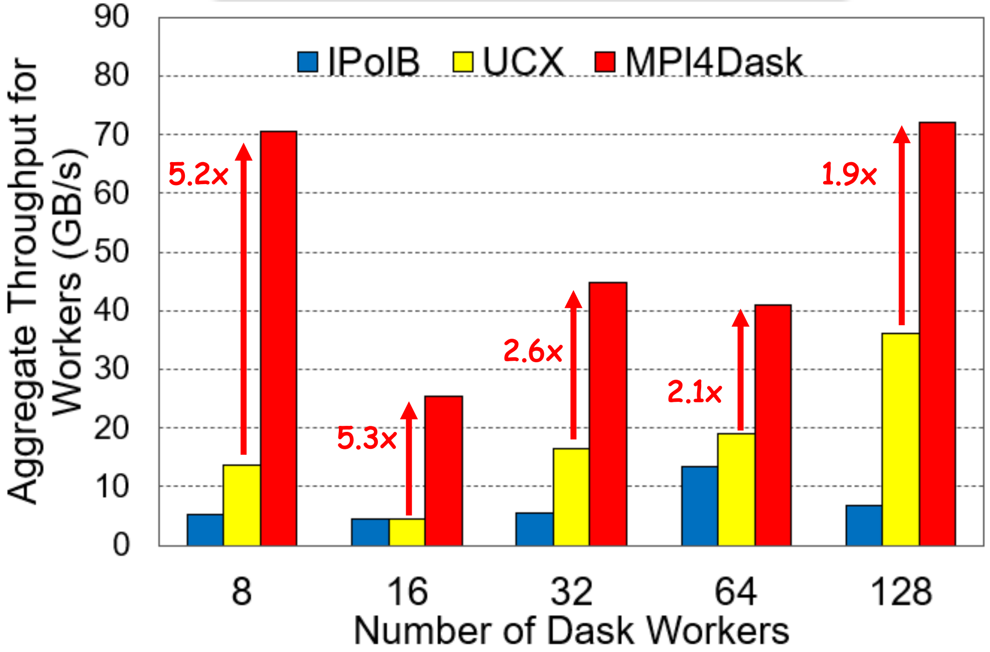
MPI4Dask 0.3, Dask 2022.8.1, Distributed, 2022.8.1, MVAPICH2-GDR 2.3.7, UCX v1.13.1, UCX-py 0.27.00

NumPy Array Slicing Benchmark on TACC Frontera CPU System

1.26x better on average



3.17x better on average



From 32 workers, we increase array size by 16 times

A. Shafi , J. Hashmi , H. Subramoni , and D. K. Panda, Efficient MPI-based Communication for GPU-Accelerated Dask Applications, CCGrid '21
https://arxiv.org/abs/2101.08878

MPI4Dask 0.3 release

(http://hibd.cse.ohio-state.edu)

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Related Publications

- Spark Meets MPI: Towards High-Performance Communication Framework for Spark using MPI K. Al Attar, A. Shafi, M. Abduljabbar, H. Subramoni, D. Panda IEEE Cluster '22, Sep 2022.

- Towards Java-based HPC using the MVAPICH2 Library: Early Experiences K. Al Attar, A. Shafi, H. Subramoni, D. Panda HIPS '22 (IPDPSW), May 2022.

- Efficient MPI-based Communication for GPU-Accelerated Dask Applications A. Shafi, J. Hashmi, H. Subramoni, D. Panda, The 21st IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing, May 2021. https://arxiv.org/abs/2101.08878

- Blink: Towards Efficient RDMA-based Communication Coroutines for Parallel Python Applications A. Shafi, J. Hashmi, H. Subramoni, D. Panda, 27th IEEE International Conference on High Performance Computing, Data, and Analytics, Dec 2020.

Summary

- Apache Spark and Dask are two popular Big Data processing frameworks
- There is existing support for parallel and distributed on HPC systems:
  - One bottleneck is the lack of support for low-latency and high-bandwidth interconnects
- This talk presented latest developments in the MPI4Dask (MPI-based Dask ecosystem) and MPI4Spark (MPI-based Spark ecosystem)
- Provided an overview of issues, challenges, and opportunities for designing efficient communication runtimes
  - Efficient, scalable, and hierarchical designs are crucial for Big Data/Data Science frameworks
  - Co-design of communication runtimes and BigData/Data Science frameworks will be essential

Thank You!

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The MVAPICH2 Project
http://mvapich.cse.ohio-state.edu/

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