Sandia National Laboratories

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LATENCY AND BANDWIDTH MICROBENCHMARKS OF US DEPARTMENT OF ENERGY SYSTEMS IN THE JUNE 2023 TOP500 LIST

Christopher M. Siefert, Carl Pearson, Stephen L. Olivier, [1]Andrey Prokopenko, Jonathan J. Hu, Timothy J. Fuller

Sandia National Laboratories [1]Oak Ridge National Laboratory

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U.S. DEPARTMENT OF ENERGY

NNSA

SAND2023-13518C

MOTIVATION

- These slides: **carlpearson.net/talk/20231113_pmbs/**

- Portable application codes
  - Performance on a variety of machines

- "Acceptance Testing" inadequate for community knowledge base
  - Part of the supercomputer procurement process
  - Performance (and stability) of **one machine**
  - Varying degrees of public release

- Our goal: provide a one-stop shop for key intra-node performance measures on representative machines

Any subjective views or opinions that might be expressed do not necessarily represent the views of the U.S. Government.

SYSTEM SELECTION

- Top500[1] is a biannual list of the 500 computers with the fastest LINPACK performance
  - June 2023 was the most recent at the time of the work
- US Department of Energy has a wide variety of machines
- Some machines have been decommissioned since June 2023
  - Summit will stop accepting batch jobs in December
- Arbitrary cutoff at #150

[1] TOP500 June 2023. [Online]. Available: https://www.top500.org/lists/top500/2023/06/

SELECTED SYSTEMS (HARDWARE)

Name	Top500 Rank	Loc.	CPU	GPU
Frontier	1	ORNL	AMD EPYC	AMD MI250X
Summit	5	ORNL	IBM POWER9	NVIDIA V100
Sierra	6	LLNL	IBM POWER9	NVIDIA V100
Perlmutter	8	NERSC	AMD EPYC 7763	NVIDIA A100[1]
Polaris	19	ANL	AMD EPYC 7532	NVIDIA A100
Trinity	27	LANL	Intel Xeon Phi 7250	--
Lassen	36	LLNL	IBM Power9	NVIDIA V100
Theta	94	ANL	Intel Xeon Phi 7230	--
Sawtooth	109	INL	Intel Xeon Platinum 8268	--
RZVernal	116	LLNL	AMD EPYC	AMD MI250X
Eagle	127	NREL	Intel Xeon Gold 6154	--
Tioga	132	LLNL	AMD EPYC	AMD MI250X
Manzano	141	SNL	Intel Xeon Platinum 8268	--

[1]40GB

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[1]40GB

IBM, Intel, and AMD CPUs

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[1] 40GB

multi-core CPUs

Intel Knight's Landing

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[1] 40GB

With and without GPUS

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[1] 40GB

AMD and Nvidia GPUs

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[1]40GB

Similar nodes

Frontier / RZVernal / Tioga

Summit / Sierra / Lassen

Perlmutter / Polaris

Trinity / Theta

SELECTED SYSTEMS (SOFTWARE)

- Multiple versions and vendors for compilers and MPI available on each system
- We stick with as default an experience as possible
  - ”log in and compile”
  - Our expectation is that defaults should be well-behaved
  - Sometimes, defaults are too old to compile benchmarks (e.g. gcc 4.9.3 on Lassen)

SELECTED SYSTEMS (SOFTWARE)

Name	Top500 Rank	Compiler	Acc. Toolchain	MPI
Frontier	1	amd-mixed/5.3.0		cray-mpich/8.1.23
Summit	5	xl/16.1.1-10	cuda/11.0.3	spectrum-mpi/10.4.0.3-20210112
Sierra	6	gcc/8.3.1	cuda/10.1.243	spectrum-mpi/rolling-release
Perlmutter	8	gcc/11.2.0	cuda/11.7	cray-mpich/8.1.25
Polaris	19	nvhpc/21.9	cuda/11.4	cray-mpich/8.1.16
Trinity	27	intel/2022.0.2	--	cray-mpich/7.7.20
Lassen	36	gcc/8.3.1	cuda/10.1.243	spectrum-mpi/rolling-release
Theta	94	intel/19.1.0.166	--	cray-mpich/7.7.14
Sawtooth	109	intel/19.0.5	--	intel-mpi/2019.0.117
RZVernal	116	amd/5.6.0		cray-mpich/8.1.26
Eagle	127	gcc/8.4.0	--	openmpi/4.1.0
Tioga	132	amd/5.6.0		cray-mpich/8.1.26
Manzano	141	intel/16.0	--	openmpi/1.10

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Theta	94	intel/19.1.0.166	--	cray-mpich/7.7.14
Sawtooth	109	intel/19.0.5	--	intel-mpi/2019.0.117
RZVernal	116	amd/5.6.0		cray-mpich/8.1.26
Eagle	127	gcc/8.4.0	--	openmpi/4.1.0
Tioga	132	amd/5.6.0		cray-mpich/8.1.26
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GNU, LLVM, and vendor compilers

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OpenMPI, Cray/MPICH, IBM, and Intel MPIs

BENCHMARK SELECTION

- Used pre-existing open-source microbenchmarks
  - Chosen based on portability, familiarity, and established use in the community

- BabelStream [1]
  - serial, OpenMP, CUDA, and HIP (among others)
  - STREAM bandwidth for serial, OpenMP, CUDA, and HIP
- OSU MPI Microbenchmarks [2]
  - MPI
  - Point-to-point latency
- Comm|Scope [3]
  - CUDA and HIP
  - CPU/GPU and GPU/GPU memcpy bandwidth, GPU control latencies

We only use MPI intra-node

- Measures mirror how many DOE applications are written
  - MPI to communicate between processes
  - GPU/GPU communication handled by GPU-aware MPI or by staging through host

[1] T. Deakin, J. Price, M. Martineau, and S. McIntosh-Smith, "Evaluating attainable memory bandwidth of parallel programming models via BabelStream," International Journal of Computational Science and Engineering, vol. 17, no. 3, pp. 247–262, 2018.
[2] OSU micro-benchmarks. [Online]. Available: http://mvapich.cse.ohio-state.edu/benchmarks/
[3] C. Pearson, A. Dakkak, S. Hashash, C. Li, I.-H. Chung, J. Xiong, and W.-M. Hwu, "Evaluating characteristics of CUDA communication primitives on high-bandwidth interconnects," in Proceedings of the 2019 ACM/SPEC International Conference on Performance Engineering, 2019, pp. 209–218

CPU MEMORY BANDWIDTH AND MPI LATENCY

	Memory Bandwidth (GB/s)			MPI Latency (us)	
Rank. Name	One Core	All Cores	Peak (all cores)	On-Socket	On-Node
29. Trinity	12.36 ± 0.16	347.28 ± 5.76	> 450	0.67 ± 0.01	0.99 ± 0.01
94. Theta	18.76 ± 0.58	119.72 ± 0.54	> 450	5.95 ± 0.01	6.25 ± 0.05
109. Sawtooth	13.06 ± 0.35	238.70 ± 8.39	281.50	0.48 ± 0.01	0.48 ± 0.01
127. Eagle	13.45 ± 0.03	208.24 ± 0.92	255.91	0.17 ± 0.00	0.38 ± 0.01
141. Manzano	15.27 ± 0.05	234.86 ± 0.12	281.50	0.32 ± 0.00	0.56 ± 0.01

theoretical

Ranks on same socket

Ranks on different sockets

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- Peak number is MCDRAM bandwidth
  - Our working set fits in MCDRAM
- MCDRAM configured as a transparent cache

- These two systems are very similar on paper

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- Whether same-socket or cross-socket impacts performance varies

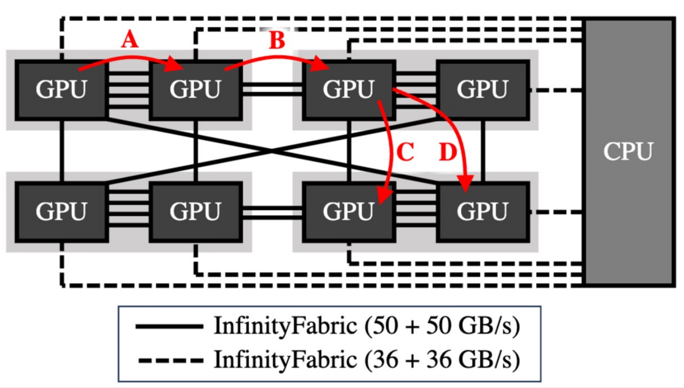
MEASUREMENTS FOR ACCELERATOR SYSTEMS

	Acc. Memory Bandwidth (GB/s)		MPI Latency (us)	MPI Latency (us) Acc.-to-Acc.			
Rank. Name	Measured	Peak	Host-to-Host	A	B	C	D
1. Frontier	1336.35 ± 1.11	1600	0.45 ± 0.01	0.44 ± 0.00	0.44 ± 0.00	0.44 ± 0.00	0.44 ± 0.00
5. Summit	786.43 ± 0.11	900	0.34 ± 0.07	18.10 ± 0.22	19.30 ± 0.15		
6. Sierra	861.40 ± 0.65	900	0.38 ± 0.01	18.72 ± 0.12	19.76 ± 0.37		
8. Perlmutter	1363.74 ± 0.23	1555.2	0.46 ± 0.06	13.50 ± 0.13			
19. Polaris	1362.75 ± 0.17	1555.2	0.21 ± 0.00	10.42 ± 0.03			
36. Lassen	861.03 ± 0.53	900	0.37 ± 0.00	18.68 ± 0.20	19.72 ± 0.13		
116. RZVernal	1291.38 ± 0.77	1600	0.49 ± 0.00	0.50 ± 0.01	0.50 ± 0.01	0.50 ± 0.00	0.49 ± 0.01
132. Tioga	1336.81 ± 0.97	1600	0.49 ± 0.00	0.50 ± 0.00	0.50 ± 0.00	0.50 ± 0.00	0.49 ± 0.01

theoretical

Two ranks on same CPU socket

Two ranks on different accelerators near/fast (A) … to … far/slow (D) (more details on coming slides)



	MPI Latency (us) Acc.-to-Acc.			
Rank. Name	A	B	C	D
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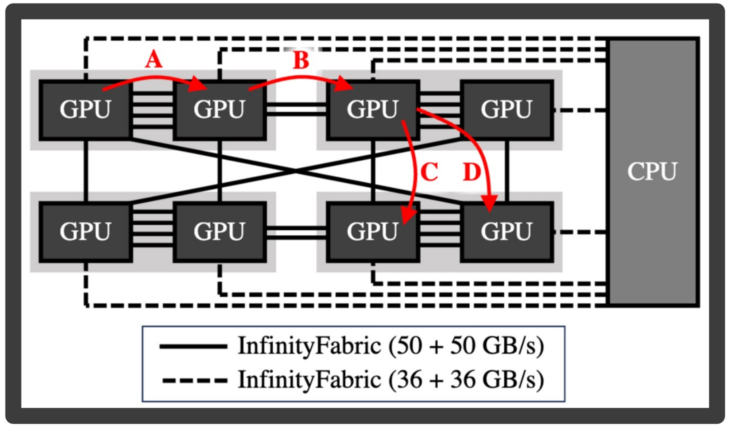
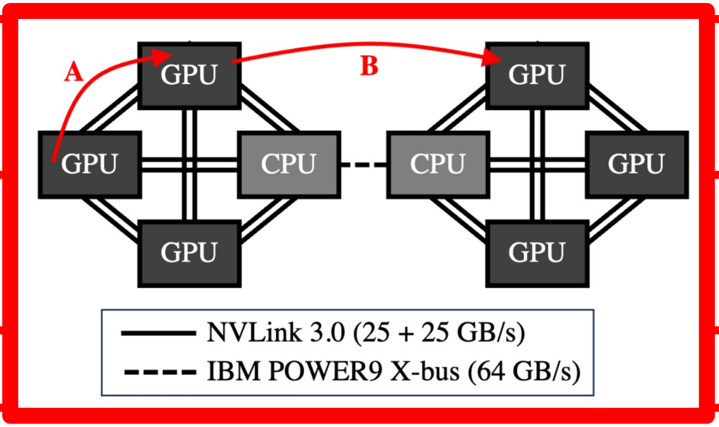
No measurable MPI latency difference on this node type





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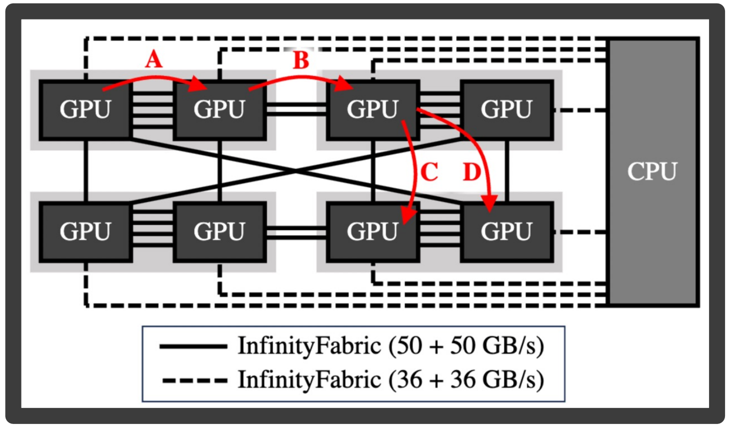
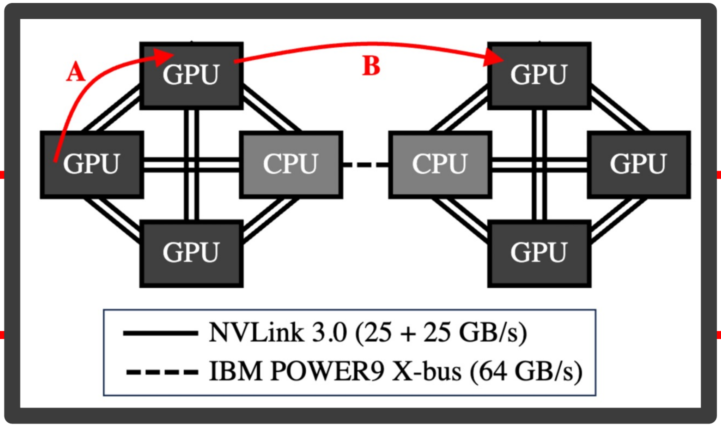
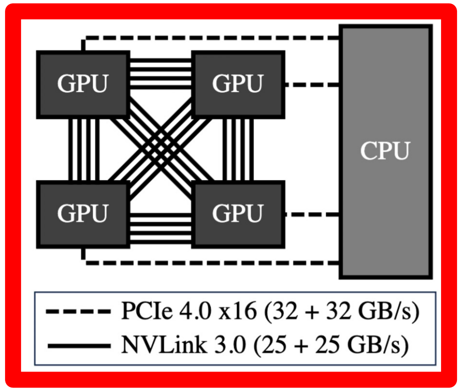
Although Summit / Sierra / Lassen have different numbers of GPUs connected by different lanes, A/B have the same meaning

Going across X-bus has a measurable latency penalty







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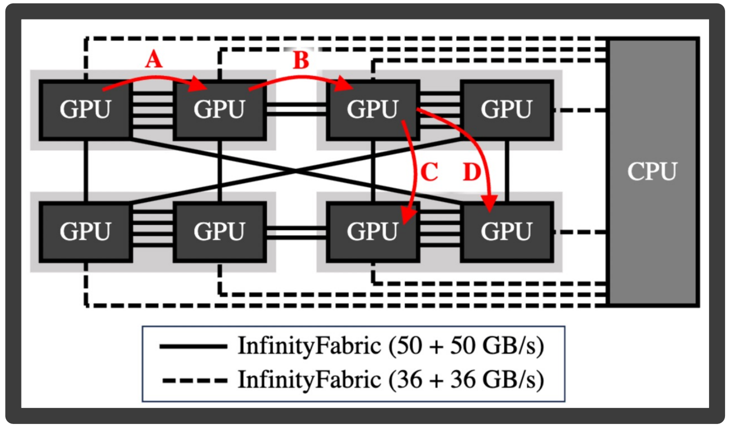
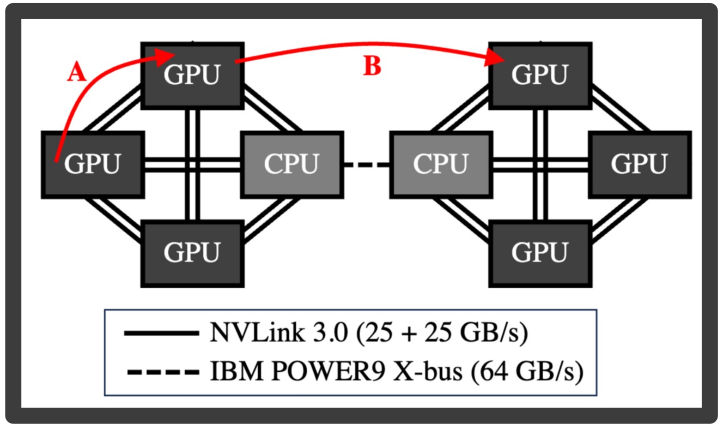
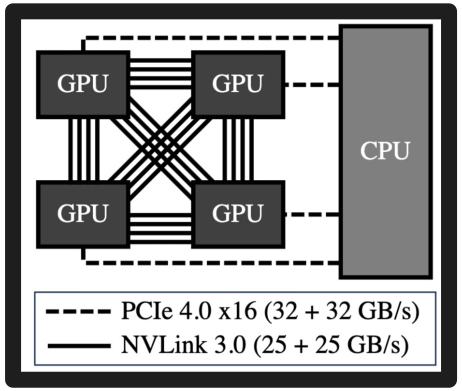
Identical all-to-all GPU connections







	MPI Latency (us) Acc.-to-Acc.			
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5. Summit	18.10 ± 0.22	19.30 ± 0.15		
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116. RZVernal	0.50 ± 0.01	0.50 ± 0.01	0.50 ± 0.00	0.49 ± 0.01
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Extremely low latency for small ($\leq 2^8$) messages.

ACCELERATOR CONTROL LATENCIES

	Kernel (us)		(H -> D + D -> H) / 2		D -> D Latency (us)			
Rank. Name	Launch	Wait	Latency (us)	Bandwidth (GB/s)	A	B	C	D
1. Frontier	1.51 ± 0.00	0.14 ± 0.00	12.91 ± 0.02	24.87 ± 0.01	12.02 ± 0.05	12.56 ± 0.03	12.68 ± 0.02	12.02 ± 0.10
5. Summit	4.84 ± 0.01	4.31 ± 0.01	7.82 ± 0.07	44.88 ± 0.00	24.97 ± 0.16	27.44 ± 0.14		
6. Sierra	4.13 ± 0.01	5.59 ± 0.02	7.27 ± 0.23	63.40 ± 0.01	23.91 ± 0.16	27.70 ± 0.12		
8. Perlmutter	1.77 ± 0.01	0.98 ± 0.00	4.24 ± 0.01	24.74 ± 0.00	14.74 ± 0.41			
19. Polaris	1.83 ± 0.00	1.32 ± 0.01	5.33 ± 0.02	23.71 ± 0.00	32.84 ± 0.30			
36. Lassen	4.56 ± 0.00	5.52 ± 0.01	7.76 ± 0.32	63.34 ± 0.02	24.56 ± 0.28	27.69 ± 0.10		
116. RZVernal	2.16 ± 0.01	0.12 ± 0.00	12.20 ± 0.07	24.88 ± 0.00	9.85 ± 0.01	12.58 ± 0.00	12.45 ± 0.02	10.21 ± 0.01
132. Tioga	2.15 ± 0.01	0.12 ± 0.00	12.19 ± 0.04	24.88 ± 0.00	9.85 ± 0.02	12.59 ± 0.01	12.46 ± 0.01	10.12 ± 0.02

launch empty kernel

sync empty queue

async memcpy

A/B/C/D same as previous slides

ACCELERATOR CONTROL LATENCIES

	Kernel (us)		(H -> D + D -> H) / 2		D -> D Latency (us)			
Rank. Name	Launch	Wait	Latency (us)	Bandwidth (GB/s)	A	B	C	D
1. Frontier	1.51 ± 0.00	0.14 ± 0.00	12.91 ± 0.02	24.87 ± 0.01	12.02 ± 0.05	12.56 ± 0.03	12.68 ± 0.02	12.02 ± 0.10
5. Summit	4.84 ± 0.01	4.31 ± 0.01	7.82 ± 0.07	44.88 ± 0.00	24.97 ± 0.16	27.44 ± 0.14		
6. Sierra	4.13 ± 0.01	5.59 ± 0.02	7.27 ± 0.23	63.40 ± 0.01	23.91 ± 0.16	27.70 ± 0.12		
8. Perlmutter	1.77 ± 0.01	0.98 ± 0.00	4.24 ± 0.01	24.74 ± 0.00	14.74 ± 0.41			
19. Polaris	1.83 ± 0.00	1.32 ± 0.01	5.33 ± 0.02	23.71 ± 0.00	32.84 ± 0.30			
36. Lassen	4.56 ± 0.00	5.52 ± 0.01	7.76 ± 0.32	63.34 ± 0.02	24.56 ± 0.28	27.69 ± 0.10		
116. RZVernal	2.16 ± 0.01	0.12 ± 0.00	12.20 ± 0.07	24.88 ± 0.00	9.85 ± 0.01	12.58 ± 0.00	12.45 ± 0.02	10.21 ± 0.01
132. Tioga	2.15 ± 0.01	0.12 ± 0.00	12.19 ± 0.04	24.88 ± 0.00	9.85 ± 0.02	12.59 ± 0.01	12.46 ± 0.01	10.12 ± 0.02

AMD kernel latencies

ACCELERATOR CONTROL LATENCIES

	Kernel (us)		(H -> D + D -> H) / 2		D -> D Latency (us)			
Rank. Name	Launch	Wait	Latency (us)	Bandwidth (GB/s)	A	B	C	D
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AMD X86 + NVIDIA A100

IBM POWER9 + NVIDIA V100

ACCELERATOR CONTROL LATENCIES

	Kernel (us)		(H -> D + D -> H) / 2		D -> D Latency (us)			
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PCIE 4.0 between CPU and GPU

NVLink between CPU and GPU

ACCELERATOR CONTROL LATENCIES

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Similar systems – configuration differences?

ACCELERATOR CONTROL LATENCIES

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Similar systems – configuration differences?

ACCELERATOR SUMMARY

Acc.	Memory BW (GB/s)	MPI Latency (us)	Kernel (us)		H2D / D2H		D2D
			Launch	Wait	Latency (us)	BW (GB/s)	Latency (us)
V100	786.43–861.40	18.10–18.72	4.13–4.84	4.31–5.59	7.27–7.82	44.88–63.40	23.91–24.97
A100	1362.75–1363.74	10.42–13.50	1.77–1.83	0.98–1.32	4.24–5.33	23.71–24.74	14.74–32.84
MI250X	1291.38–1336.81	0.44–0.50	1.51–2.16	0.12–0.14	12.19–12.91	24.87–24.88	9.85–12.02

CONCLUSION

- 2x-10x difference in key measures across contemporaries
  - event 50x across active systems (0.12us vs 5.59us kernel wait latency MI250X vs V100)
- Newer systems tend to be faster
  - Not across the board
- Intra-node topologies are complicated
  - Physical and/or manufacturing reasons
  - Does not always impact simple measurements
- Software and/or system configuration introduces significant differences in similar hardware
  - e.g. Memory Bandwidth on Theta and Trinity
  - Difficult to predict what your software will actually achieve

CURRENT GAPS AND FUTURE WORK

- Working on open-sourcing the benchmark scripts
- Not a *completely* representative sample
  - Focused on machines used by DOE
  - Missing interesting machines, e.g. Fugaku (Top500 #2, RIKEN)
- No inter-node measurements
  - Very important to application performance
  - Has all the complexity of intra-node measures, combined with network performance
    - Actually increases intra-node complexity too – e.g. GPU-to-NIC mapping
  - Thinking about a digestible set of key inter-node measures
- Cloud
  - Cloud-native HPC clusters, or spillover
  - Intra-node measurement approach could be similar
  - Maybe additional challenges for inter-node measures
- Enough interest to regenerate results and iterate on the approach every year?

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LATENCY AND BANDWIDTH MICROBENCHMARKS OF US DEPARTMENT OF ENERGY SYSTEMS IN THE JUNE 2023 TOP500 LIST

Christopher M. Siefert, Carl Pearson, Stephen L. Olivier, [1]Andrey Prokopenko, Jonathan J. Hu, Timothy J. Fuller

Sandia National Laboratories [1]Oak Ridge National Laboratory

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Questions?

cwpears@sandia.gov

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