



Sandia
National
Laboratories

Offloading Data Management Services to SmartNICS

Craig Ulmer, Sandia National Labs, California

Jianshen Liu, Aldrin Montana, & Carlos Maltzahn, University of California Santa Cruz

Matthew L. Curry, Scott Levy, & Whit Schonbein, Sandia National Labs, New Mexico



U.S. DEPARTMENT OF
ENERGY

Office of
Science

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OPEN SOURCE SOFTWARE



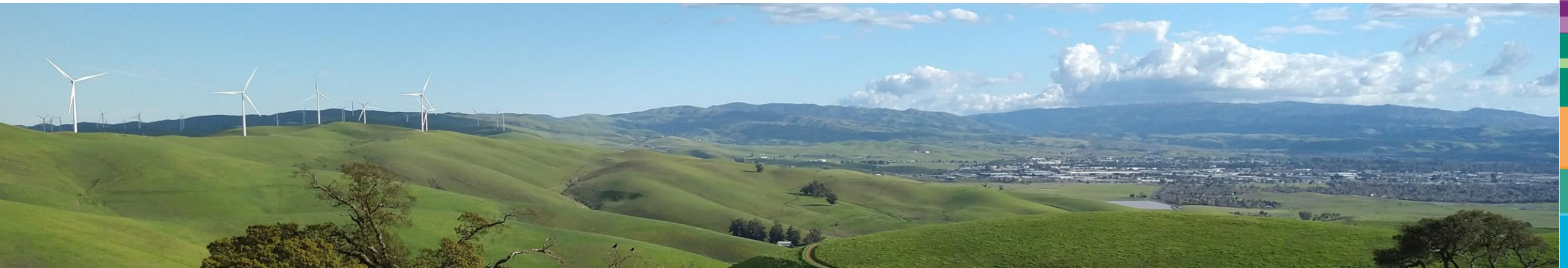
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About Craig Ulmer



- Computer Engineer from Georgia Tech
 - Ph.D. for parallel computing communication software
 - Internships at IBM, Eastman Kodak, and NASA JPL
- Joined Sandia National Labs in Livermore, California (2003)
 - **FPGA Accelerators**: Network packet filters
 - **Scientific Computing**: Connecting simulations & analytics
 - **Nonproliferation**: Sifting through large geospatial datasets
 - **SmartNICs**: Leveraging SmartNICs for data management services



Outline for Today



- What is the Department of Energy? What does Sandia do?
- How do researchers use High-Performance Computing to solve problems?
- How can SmartNICs improve workflows on HPC Platforms?
 - SmartNICs
 - Creating an environment for hosting services on SmartNICs
 - Particle sifting example
- Jobs at the labs
 - <https://www.energy.gov/jobs-national-labs>
 - <https://www.sandia.gov/careers/>



What is the Department of Energy? What does Sandia do?



The Department of Energy



Manhattan Project
1942



Atomic Energy
Commission 1946



Department of
Energy 1977



The mission of the Energy Department is to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.

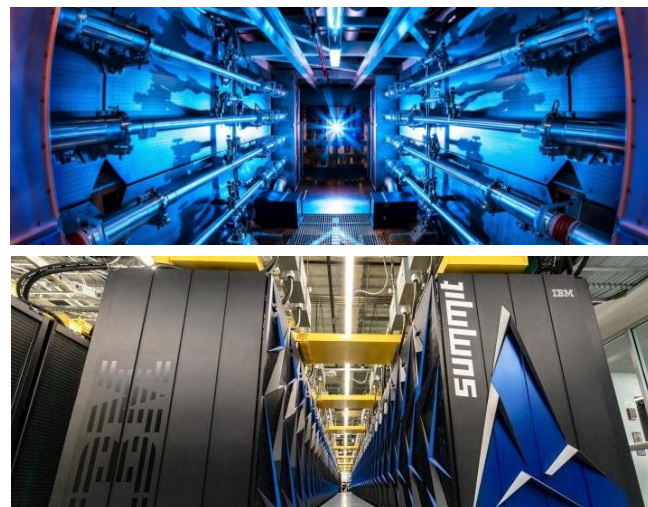
Energy

Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in energy technologies.



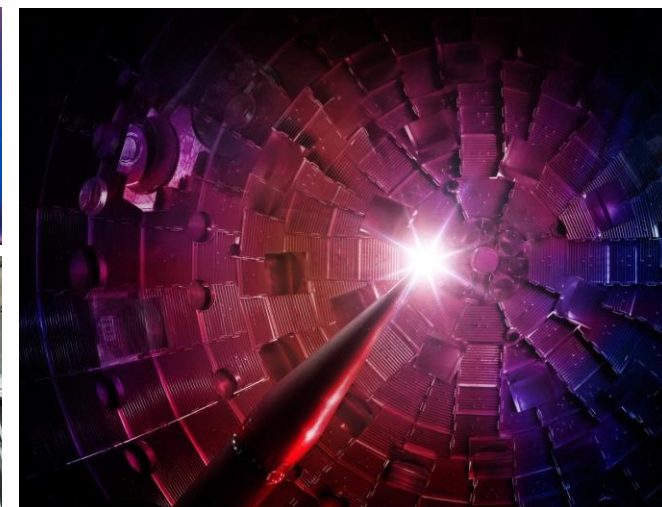
Science & Innovation

Maintain a vibrant U.S. effort in science and engineering as a cornerstone of our economic prosperity with clear leadership in strategic areas.



Nuclear Safety & Security

Enhance nuclear security through defense, nonproliferation, and environmental efforts.



The DOE has 17 National Laboratories



Office of Science Laboratories

- 1 Ames Laboratory
Ames, Iowa
- 2 Argonne National Laboratory
Argonne, Illinois
- 3 Brookhaven National Laboratory
Upton, New York
- 4 Fermi National Accelerator Laboratory
Batavia, Illinois
- 5 Lawrence Berkeley National Laboratory
Berkeley, California
- 6 Oak Ridge National Laboratory
Oak Ridge, Tennessee
- 7 Pacific Northwest National Laboratory
Richland, Washington
- 8 Princeton Plasma Physics Laboratory
Princeton, New Jersey
- 9 SLAC National Accelerator Laboratory
Menlo Park, California
- 10 Thomas Jefferson National Accelerator Facility
Newport News, Virginia

Other DOE Laboratories

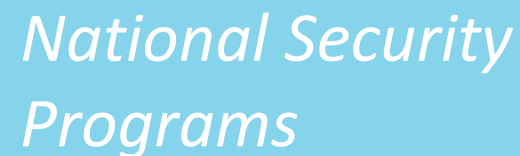
- 1 Idaho National Laboratory
Idaho Falls, Idaho
- 2 National Energy Technology Laboratory
Morgantown, West Virginia
Pittsburgh, Pennsylvania
Albany, Oregon
- 3 National Renewable Energy Laboratory
Golden, Colorado
- 4 Savannah River National Laboratory
Aiken, South Carolina

NNSA Laboratories

- 1 Lawrence Livermore National Laboratory
Livermore, California
- 2 Los Alamos National Laboratory
Los Alamos, New Mexico
- 3 Sandia National Laboratory
Albuquerque, New Mexico
Livermore, California



14,000 Federal Employees
95,000 Contractors

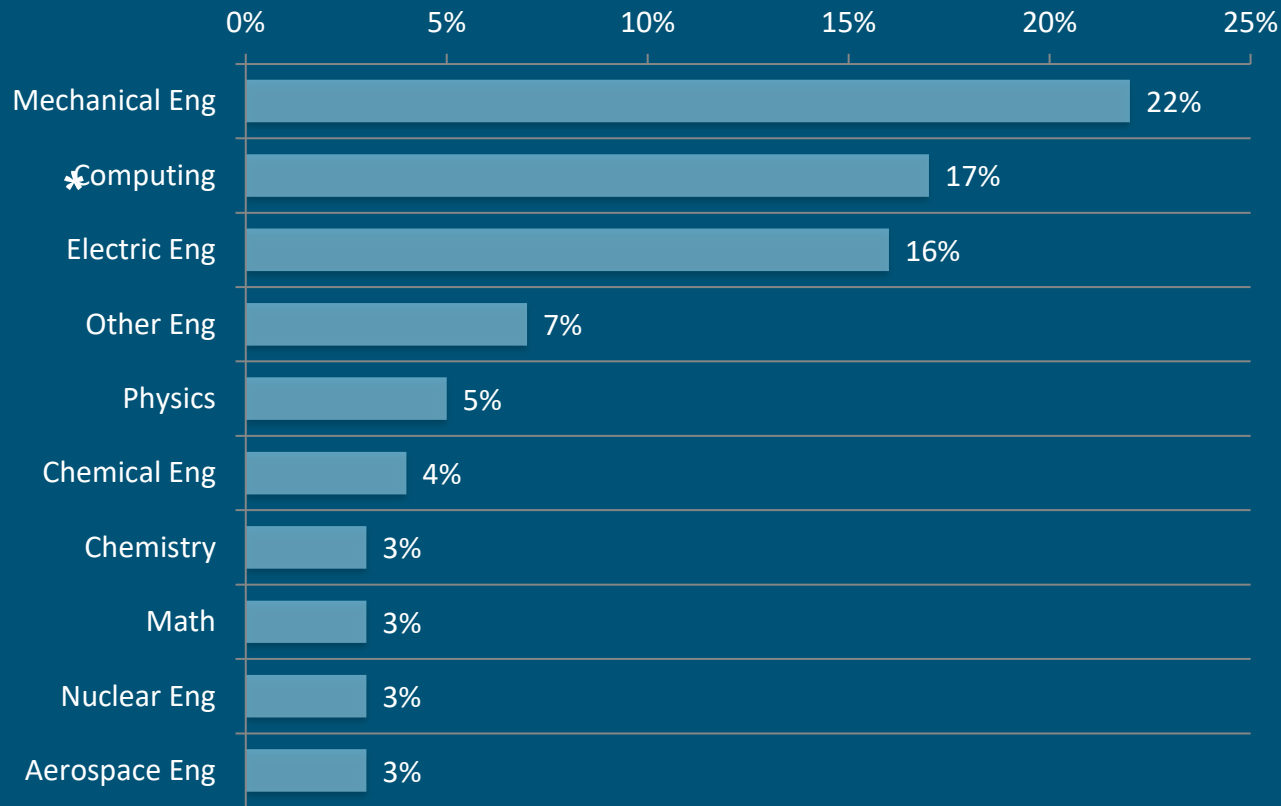


Some of the critical national security issues that we address lie in the cyber area.

Sandia: R&D by Discipline & Degree

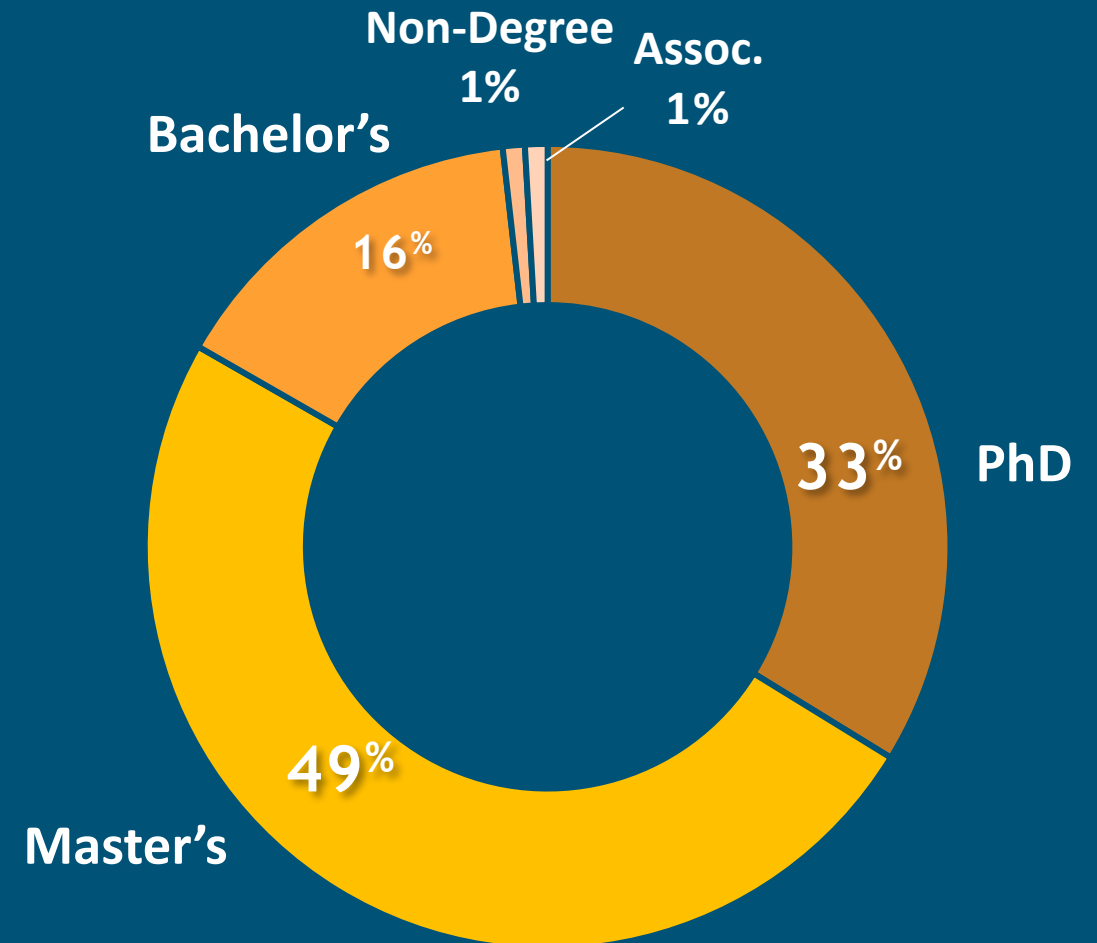


Sandia has approximately 16,000 Employees
14,000 NM, 2,000 CA



Top 10 job descriptions shown, Regular exempt non-management employees only

(*) Computing includes disciplines such as High Performance Computing, Cybersecurity, Machine Learning, Autonomous Sensing and Perception





How do researchers use
High-Performance Computing
to solve problems?



Stakeholders Have Difficult Questions



How far apart should windmills be placed?

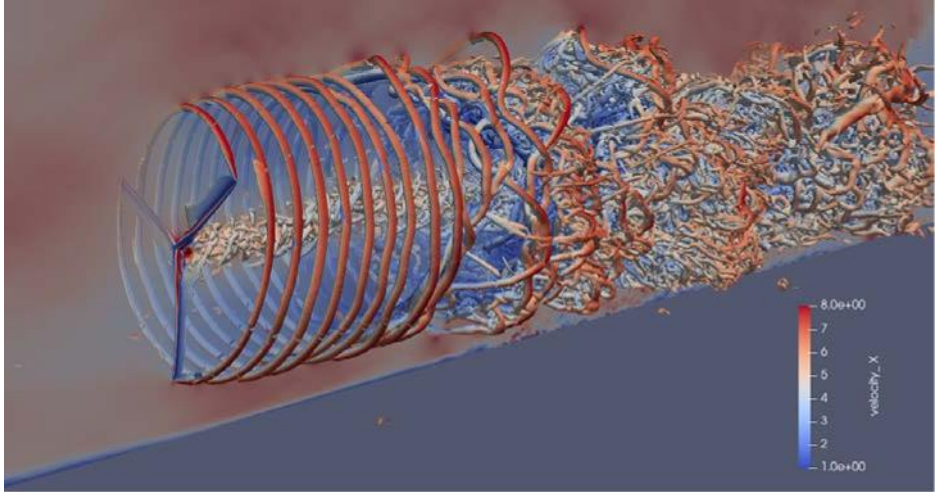
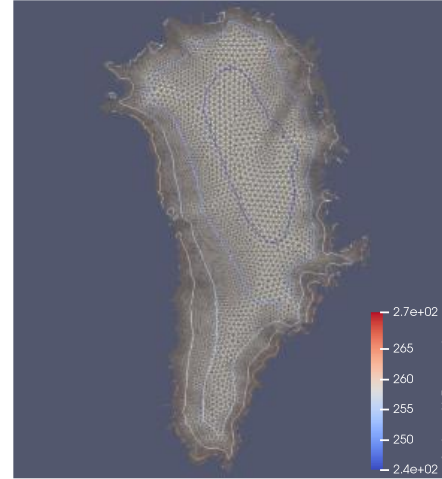
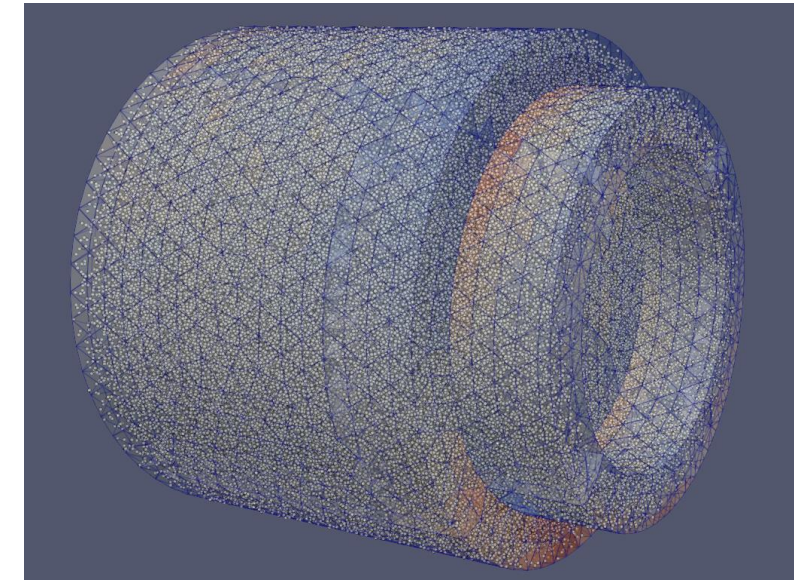


Image from G. Vijaykumar

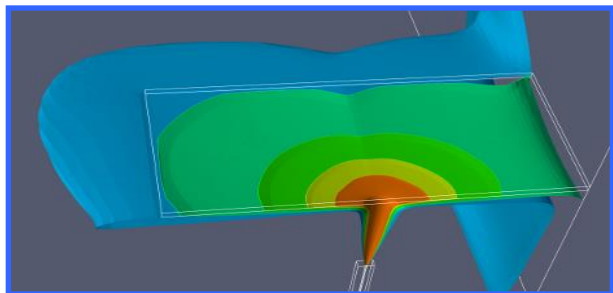
Where will fractures in ice sheets occur?



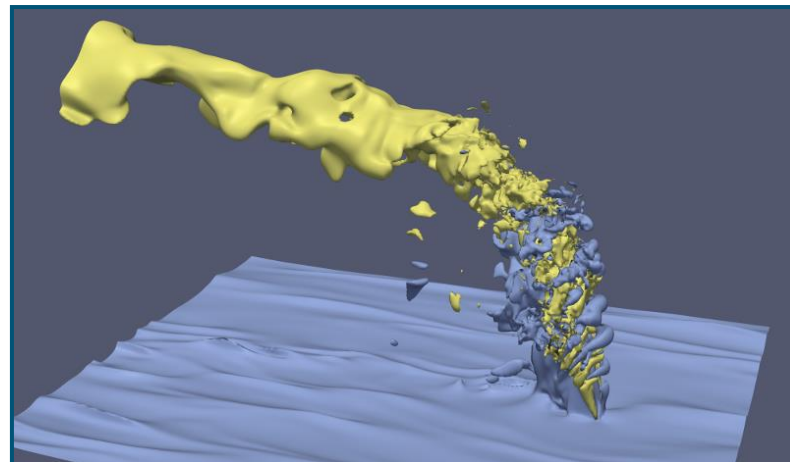
How much charge will accumulate on this surface?



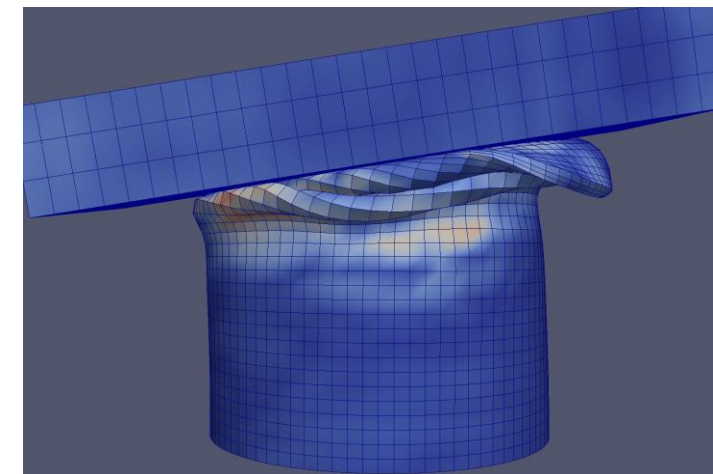
How much hydrogen would leak before detection?



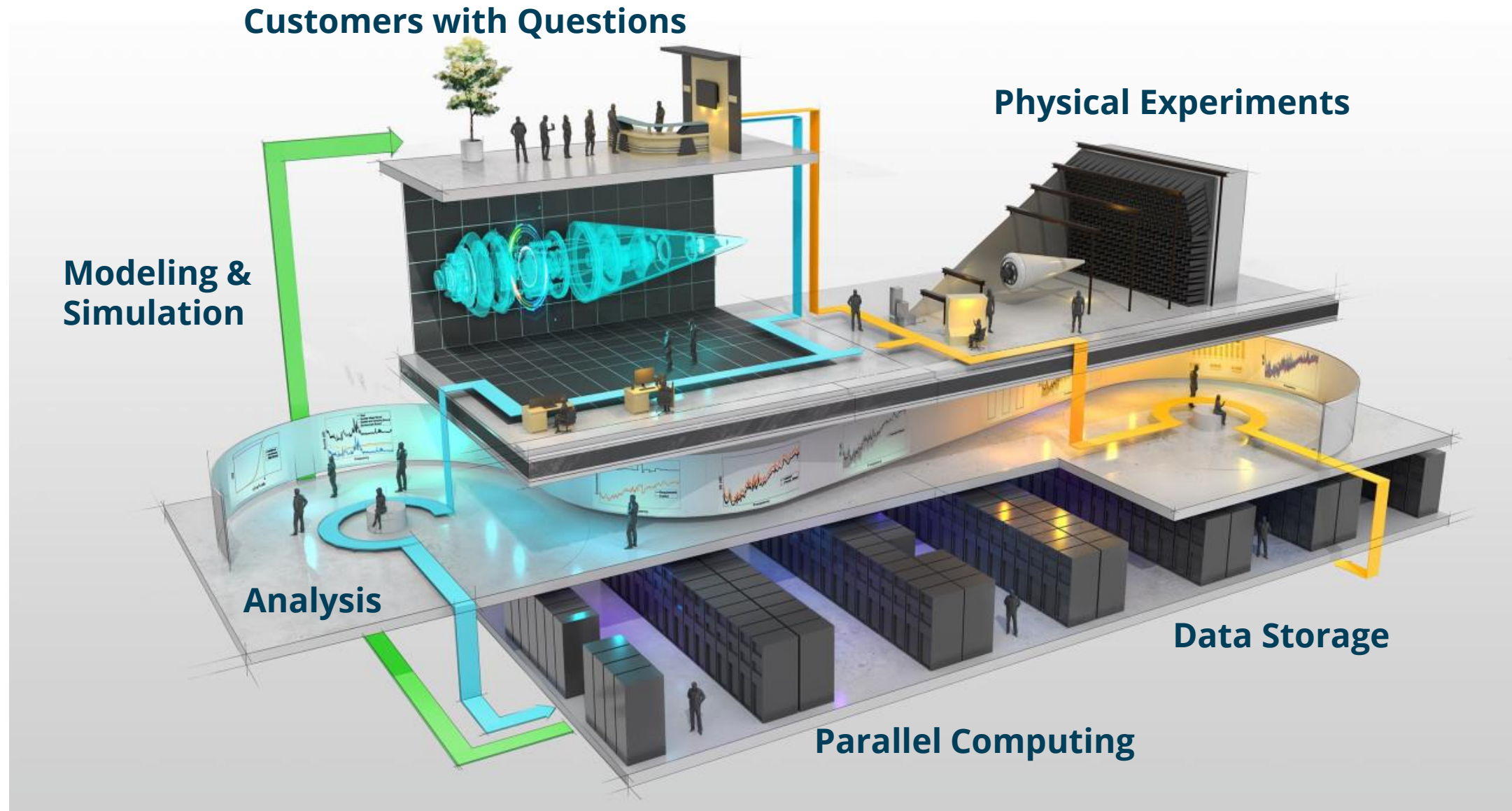
How does mixture ratio affect combustion?



Will this part still function if damaged?



What is the Vision for Computing at the Labs?





How can SmartNICs improve workflows on HPC Platforms?

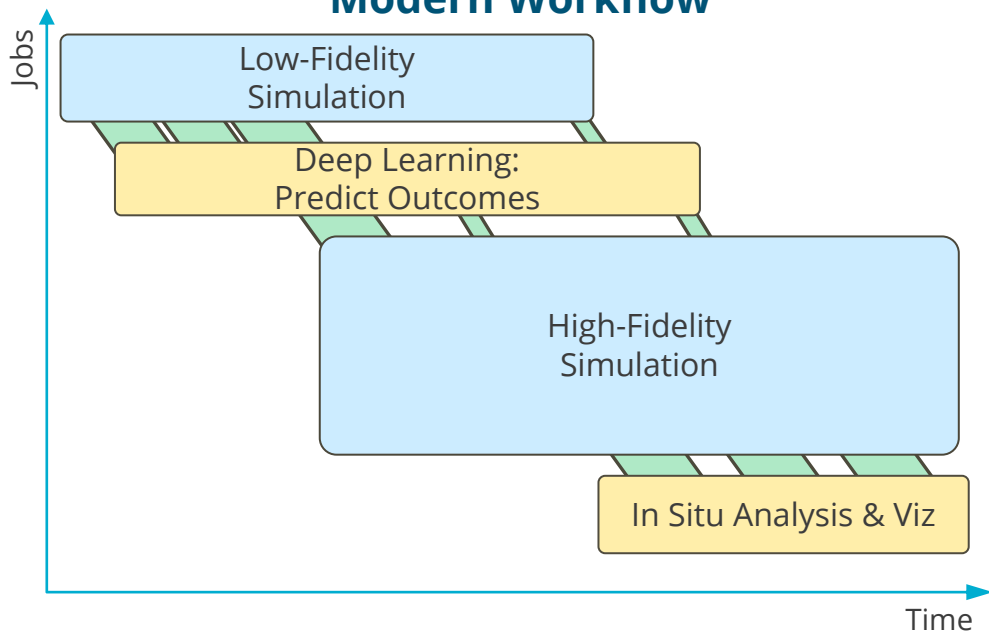


High-Performance Computing Workflows

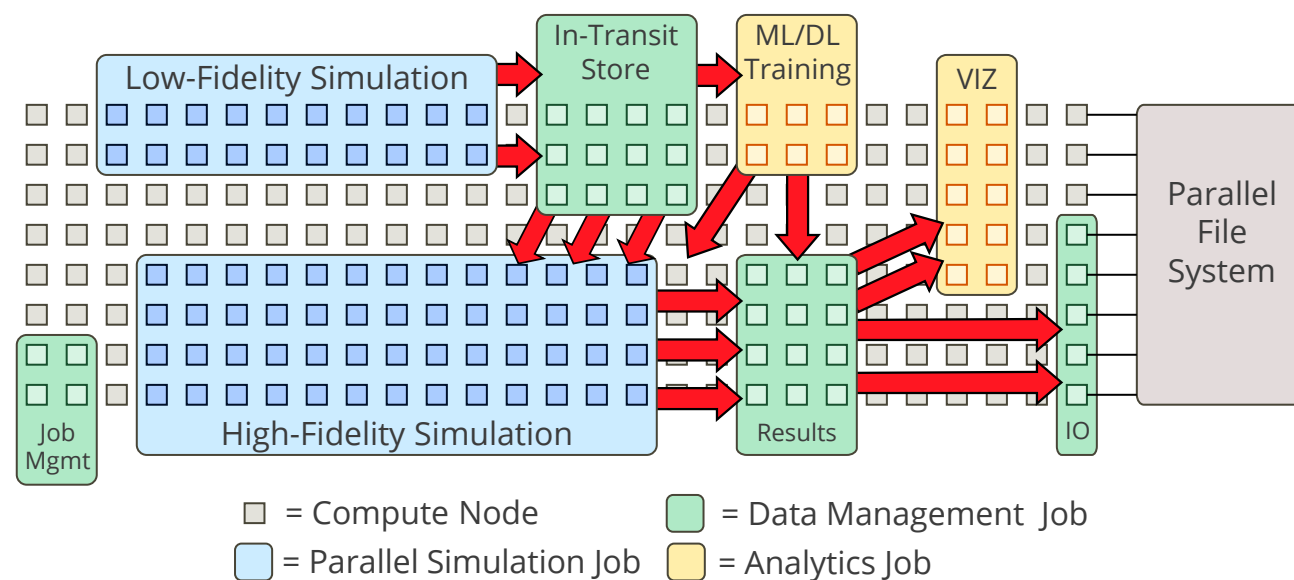


- Scientists run massively-parallel simulations to answer difficult research questions
 - Runtime datasets are too large to store (Summit ~3PB of RAM)
 - Couple different analysis tools to simulations to harvest information
- Modern workflows involve multiple parallel applications

Modern Workflow



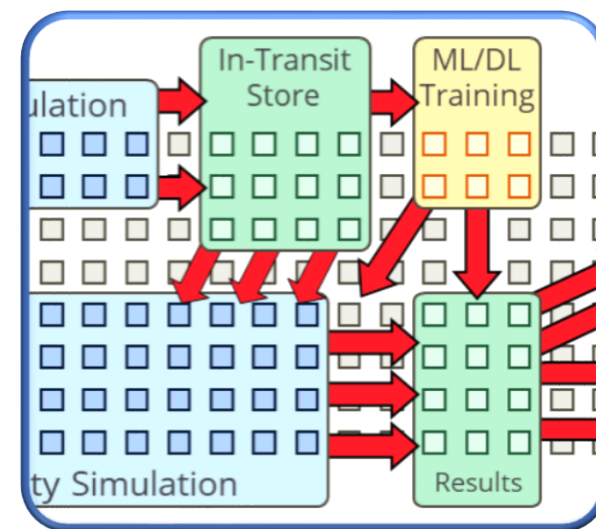
Parallel Jobs on HPC Platform



Data Management and Storage Services



- HPC community has multiple data management libraries for routing data between jobs
 - DataSpaces, Mochi, Conduit, FAODEL
- Distributed memory services
 - Dedicate a number of nodes to serve as a pool for housing objects in memory
 - Use RDMA methods and event-driven semantics to move objects efficiently
- Problem: Services consume resources
 - Simulation Nodes: Steal cycles/memory from simulations
 - Memory Pool Nodes: Underutilize compute resources
- How can we insert cheaper memory pools?
- How can we create an environment for in-transit computations?



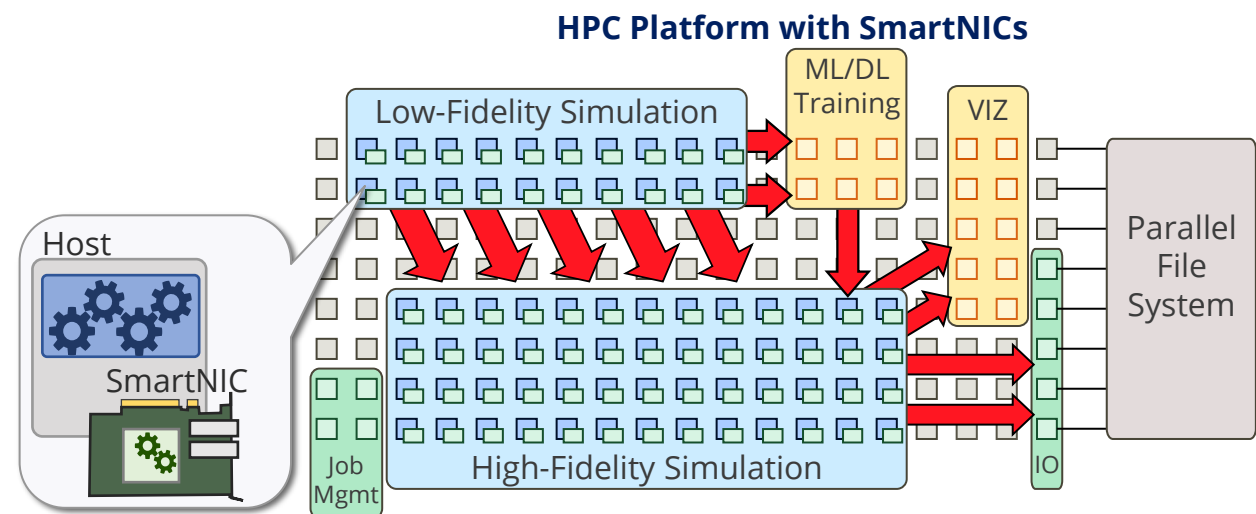
Smart Network Interface Cards (SmartNICs)



- Network vendors now offer SmartNICs with *user-programmable* resources
 - Examples: NVIDIA BlueField-2 DPU, Intel IPU, and FPGA
 - Embedded processors provide isolated space for caching and processing in-transit data
- Emerging HPC platforms include SmartNICs
 - How do we make an environment for hosting data services in SmartNICs?



BlueField-2 DPU SmartNIC



= Compute Node with a *SmartNIC* for offloading data services



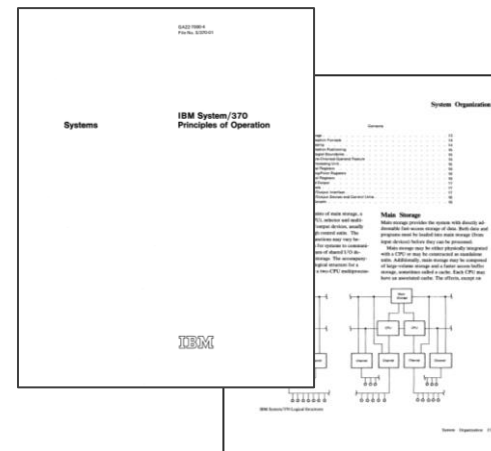
SmartNICs



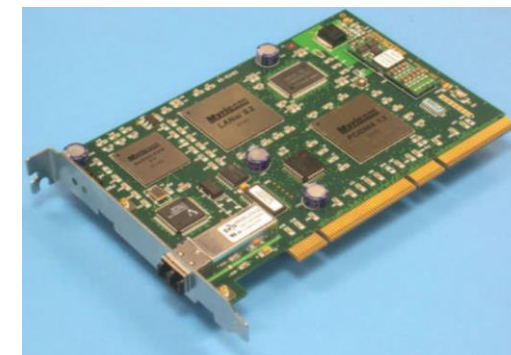
SmartNIC Timeline



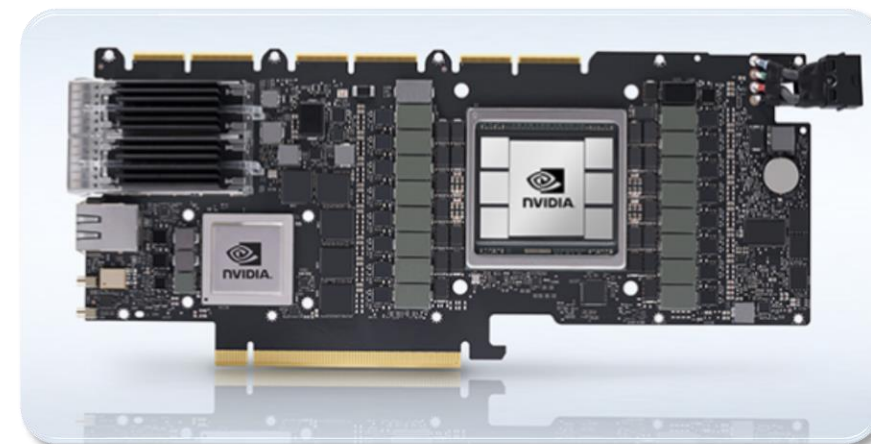
- 1957-1980s: IBM Channel I/O Processors
- 1990s: The Golden Age of Programmable NICs
 - Caltech Mosaic → Myrinet LANai NIC
- 2000s: Queue-based NICs
- 2010s: Security & Data Center NICs
 - Tilera: 64-100 cores for network pattern matching
 - Cloud vendors (AWS, Azure): Secure Networks
- 2016: Mellanox BlueField SmartNICs and DPUs
 - 2020: BlueField-2 Ethernet (InfiniBand in 2021)
 - 2023: BlueField-3: "10x improvement"
 - 202x: BlueField-4: "100x improvement" (GPU)



IBM Channel I/O

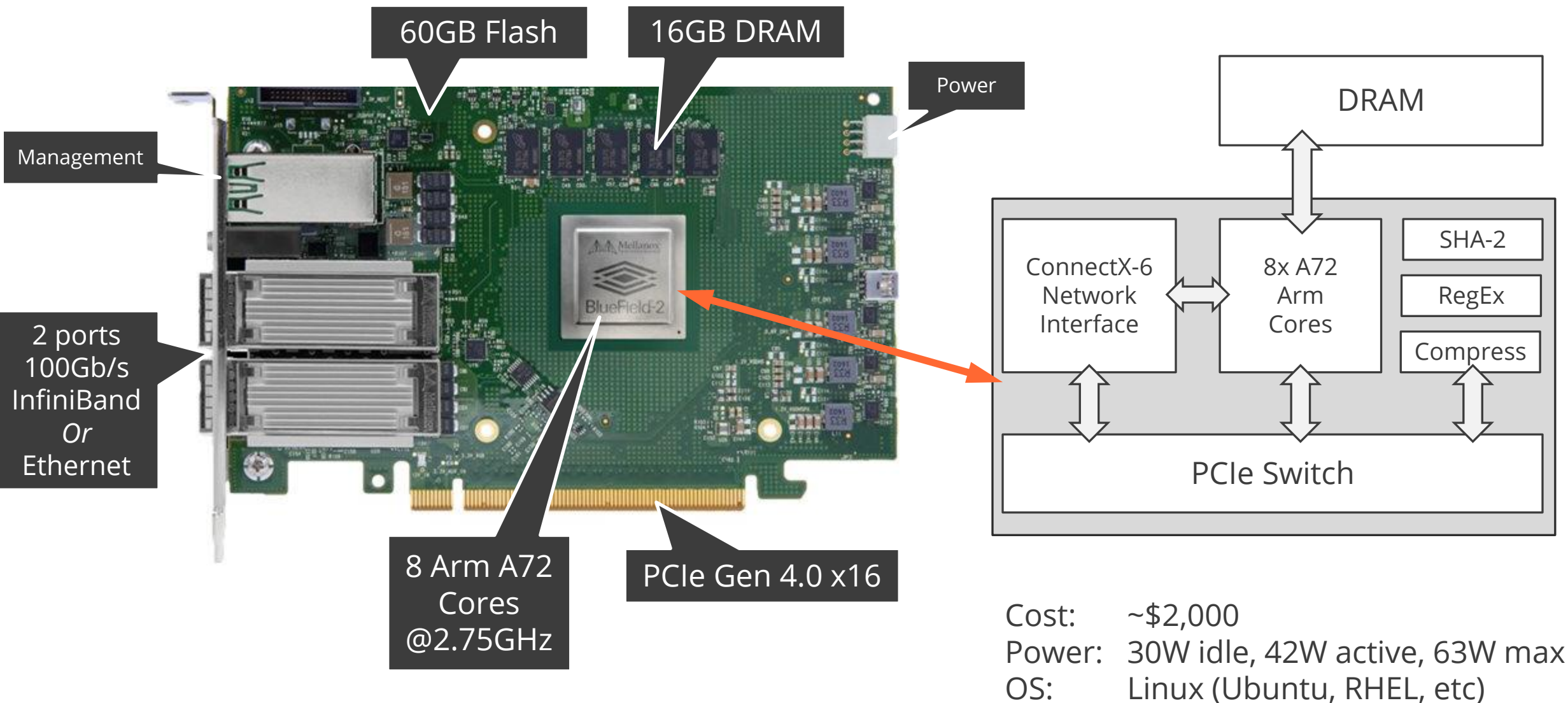


Myricom LANai



NVIDIA Converged

Today: NVIDIA BlueField-2 VPI SmartNICs





```
ubuntu@localhost: ~  
ubuntu@192.168.100.2's password:  
Welcome to Ubuntu 20.04.3 LTS (GNU/Linux 5.4.0-1017.17.gf565efa-bluefield aarch64)  
  
* Documentation:  https://help.ubuntu.com  
* Management:    https://landscape.canonical.com  
* Support:       https://ubuntu.com/advantage  
  
System information as of Fri Jan 21 03:58:10 UTC 2022  
  
System load:  0.0           Users logged in:      0  
Usage of /:   9.5% of 58.05GB IPv4 address for ibp3s0f0: 172.17.9.198  
Memory usage: 6%           IPv4 address for oob_net0: 10.60.7.76  
Swap usage:   0%           IPv4 address for tmfifo_net0: 192.168.100.2  
Processes:    220  
  
11 updates can be applied immediately.  
4 of these updates are standard security updates.  
To see these additional updates run: apt list --upgradable  
  
The list of available updates is more than a week old.  
To check for new updates run: sudo apt update  
Failed to connect to https://changelogs.ubuntu.com/meta-release-lts. Check your Internet connection or proxy settings  
  
Last login: Fri Jan 21 03:00:14 2022 from 192.168.100.1  
ubuntu@localhost:~$
```

Expect Embedded Processor Performance

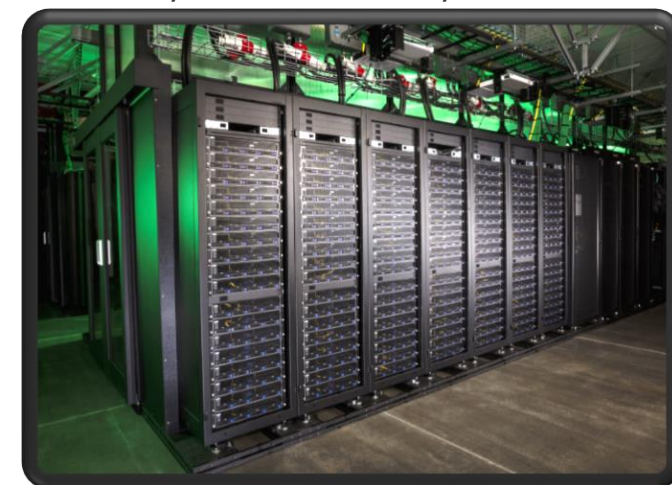


- SmartNIC designers face multiple constraints
 - Cost: Niche market, price sensitive
 - PCIe card: limited space, power, and cooling
- Embedded processors: 4-10x slower, but better power efficiency

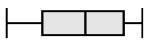


	SmartNIC	Host CPU	GPU
Processor	Arm A72	AMD EPYC 7543P	Ampere A100
Cores	8	32	108 SMs
Clock	2.75GHz	2.8GHz	0.765 – 1.41GHz
L1 Cache	256KB	1MB	192KB
L2 Cache	6MB	256MB	-
Memory Capacity	16GB	512GB	40GB
Memory Bandwidth	25GB/s	204GB/s	1,555GB/s
TDP	63W	225W	250W

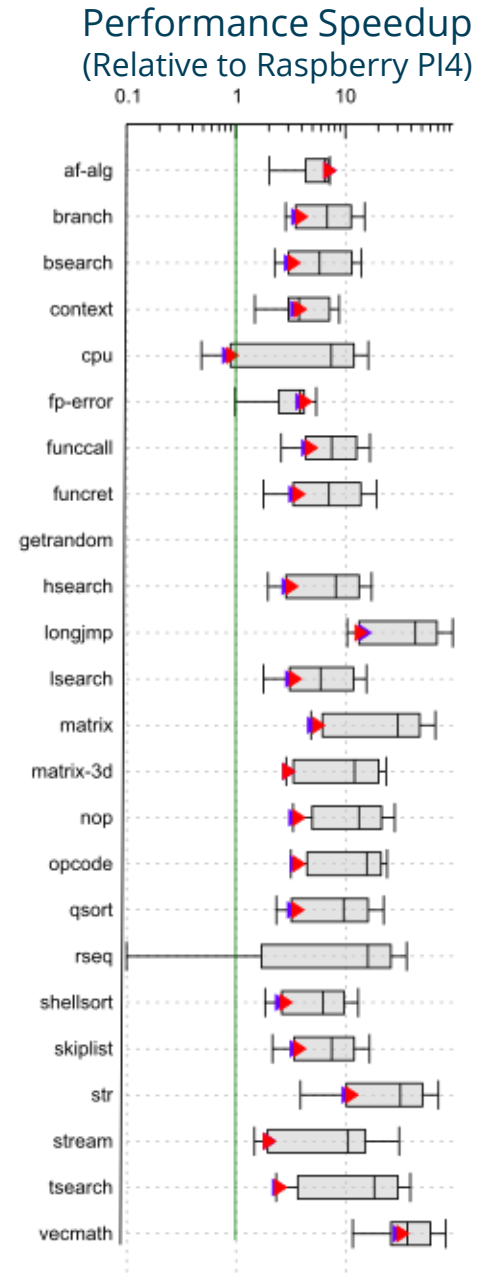
Sandia's Glinda Cluster (2021)

- 126 Compute Nodes
- Zen3, BlueField-2, A100



Microbenchmarks

- **stress-ng** from Colin Ian King (Canonical)
 - Suite of 218 stressors for kernel burn-in
 - Normalize results to Raspberry Pi 4B
- Comparison of BlueField-2 to 12 servers
 -  Performance range of different servers
 -  BlueField-2 2.50 GHz (Ethernet)
 -  BlueField-2 2.75 GHz (Ethernet/InfiniBand)
- BlueField-2's Arms order of magnitude slower than hosts
 - *...but still good enough for data management tasks*

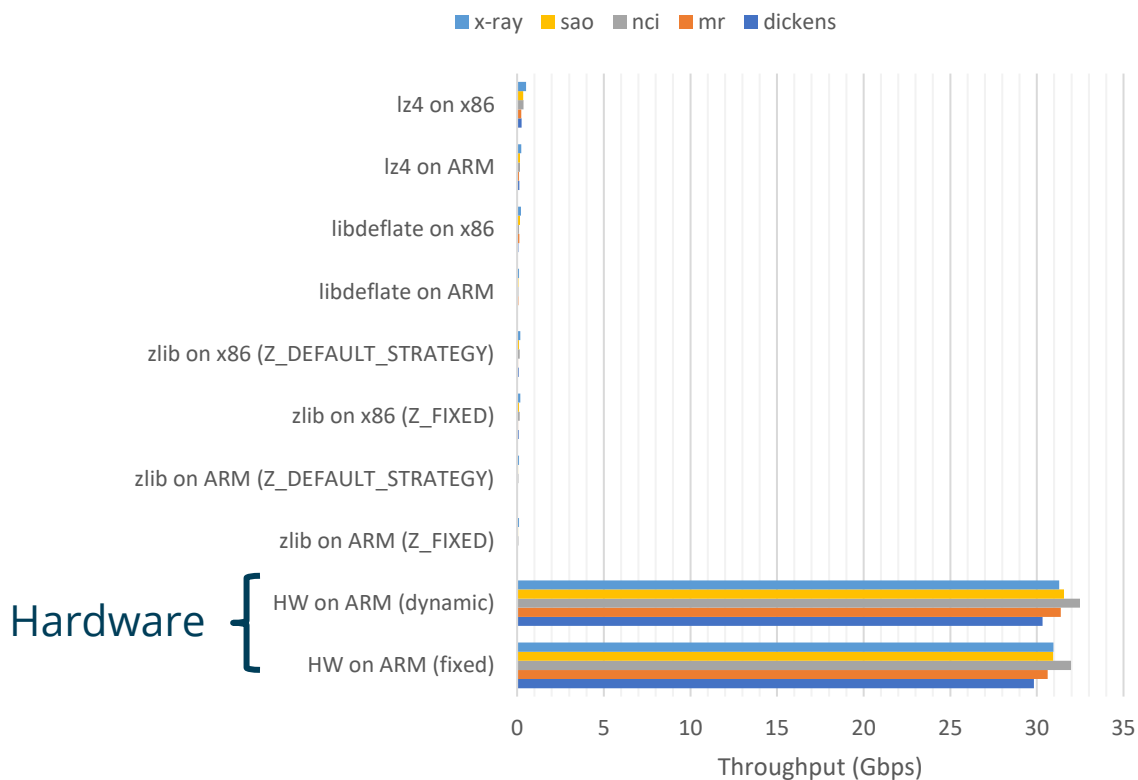


BlueField-2's Compression is Significantly Faster than Host

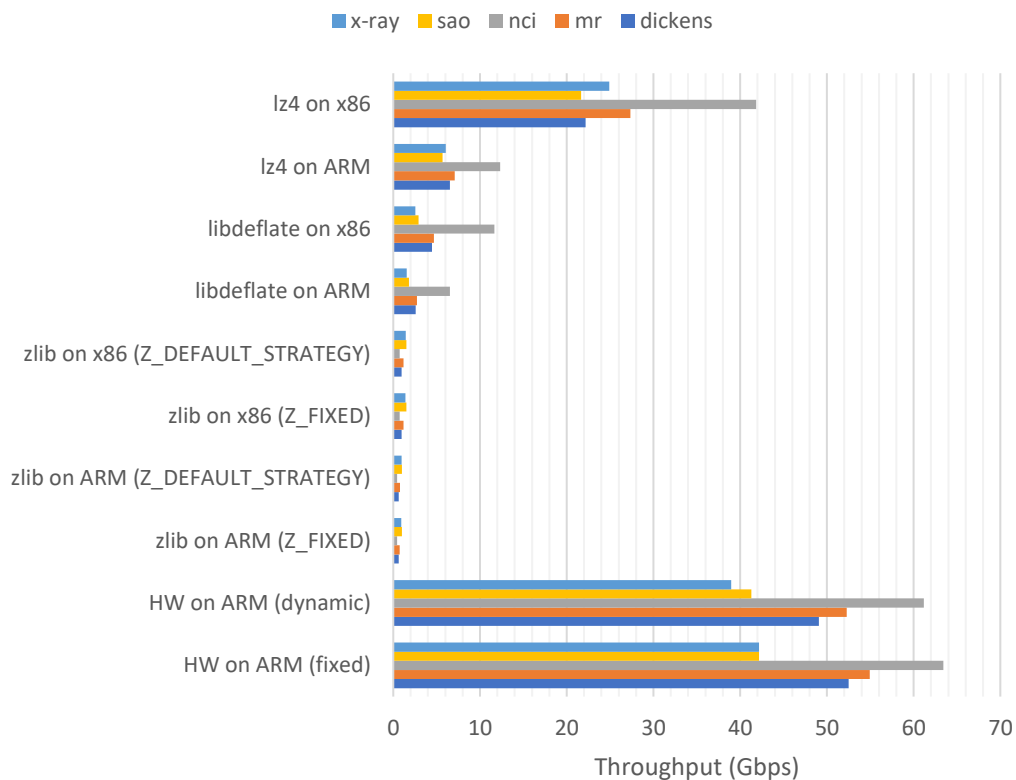


- BlueField-2 features compression hardware for the DEFLATE algorithm (e.g., gzip)

Compression Throughput



Decompression Throughput





Creating an Environment for Data Services on SmartNICs

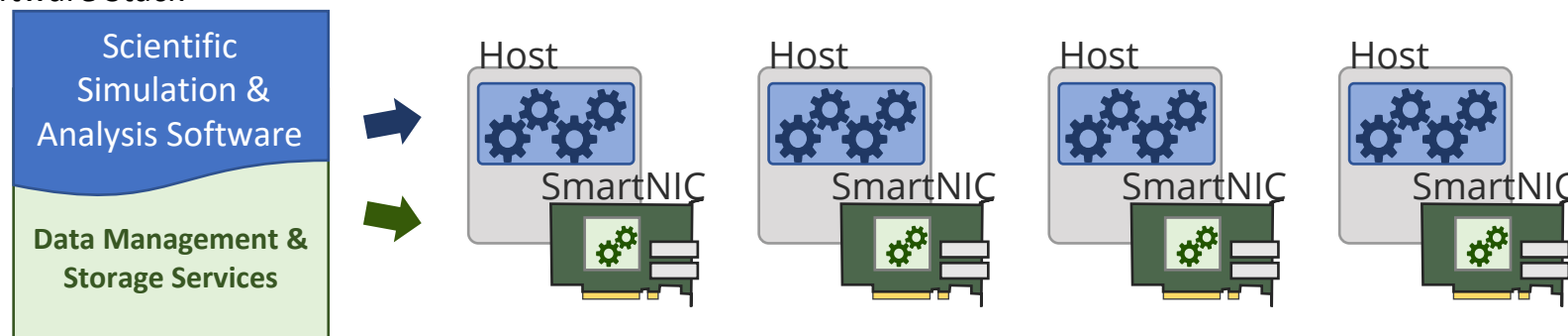


Create an Environment for Hosting Data Services on SmartNICs



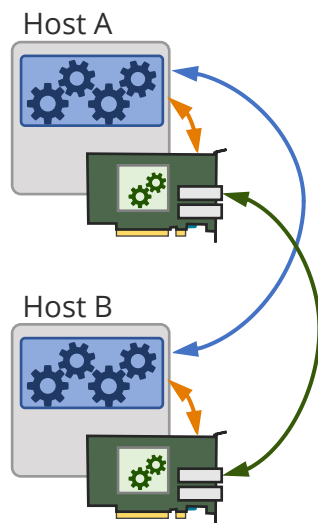
- We define five requirements (R1-R5) for creating this environment
 - Three communication, Two computation
- Leverage existing libraries as much as possible
- Prototype environment
 - Communication via **Faodel**: C++ library with distributed-memory Key/Blob API built on RDMA
 - Computation via **Apache Arrow**: C++ library for processing in-memory tabular data

Software Stack



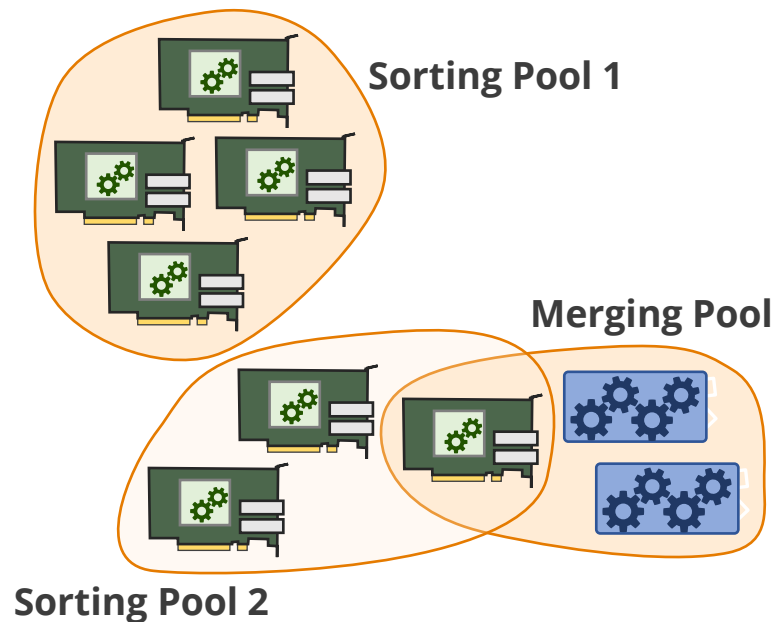
R1: Any-to-Any Transfers

- Faodel has globally accessible endpoints
- Host and SmartNICs can be endpoints
- Put/Get remote objects
- RDMA for point-to-point transfers



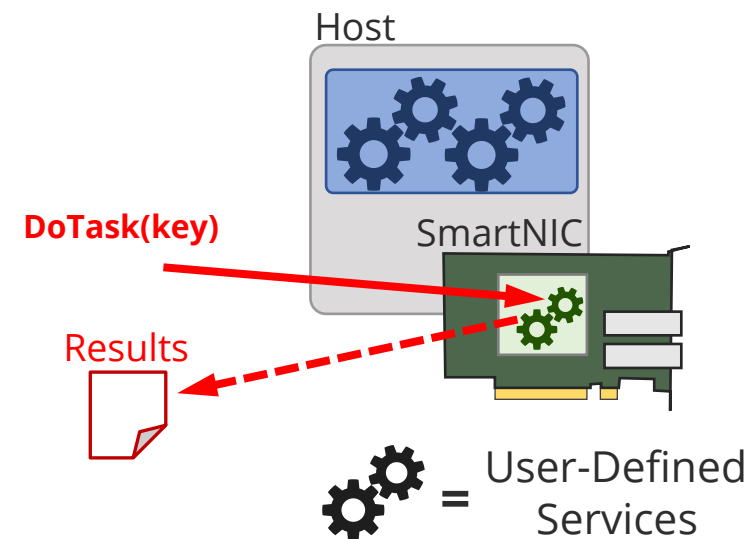
R2: Group Resources

- Faodel uses a Pool abstraction
- Pool has endpoints & distribution policy
- Work mapped to resources at run time



R3: Dispatch Computations

- Faodel primarily moves data
- Invoke remote operation on object
- Local main can also make decisions





R4: Common Data Representation

- Arrow provides robust data structures for 2D data
- Efficient in-memory storage
- Built-in functions to serialize



ID	Time	Pos _{xyz}	Vel _{xyz}
100	7	XYZ	XYZ
714	7	XYZ	XYZ
867	7	XYZ	XYZ
943	7	XYZ	XYZ
483	7	XYZ	XYZ
...			

Simulation

ID	Time	Pos _{xyz}	Vel _{xyz}
100	7	XYZ	XYZ
714	7	XYZ	XYZ
867	7	XYZ	XYZ
943	7	XYZ	XYZ
483	7	XYZ	XYZ
...			



Serialized Data

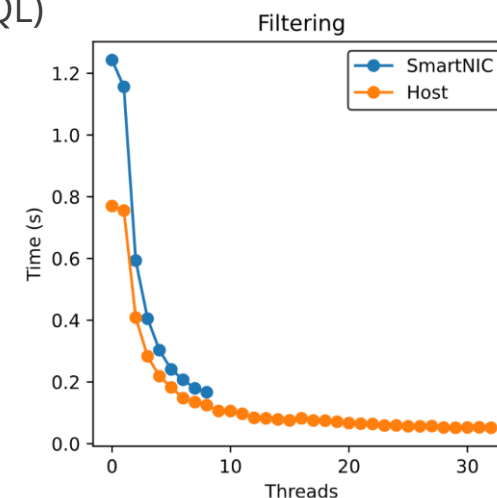
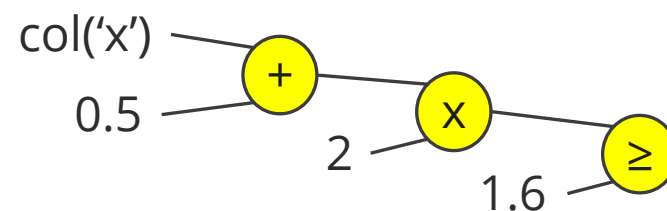


ID	Time	Pos _{xyz}	Vel _{xyz}
100	7	XYZ	XYZ
714	7	XYZ	XYZ
867	7	XYZ	XYZ
943	7	XYZ	XYZ
483	7	XYZ	XYZ
...			

Analysis

R5: Data-Parallel Computations

- Arrow includes compute functions for tables
- Target for higher-level languages (SQL)
- Thread- and SIMD-Aware



```
// 2 * (0.5 + x) >= 1.6
auto filter_expression = arrow::compute::greater_equal(
    arrow::compute::call(
        "multiply",
        {arrow::compute::literal(2),
         arrow::compute::call("add_checked", {arrow::compute::literal(0.5),
                                                arrow::compute::field_ref("x")})}),
    arrow::compute::literal(1.6));
```



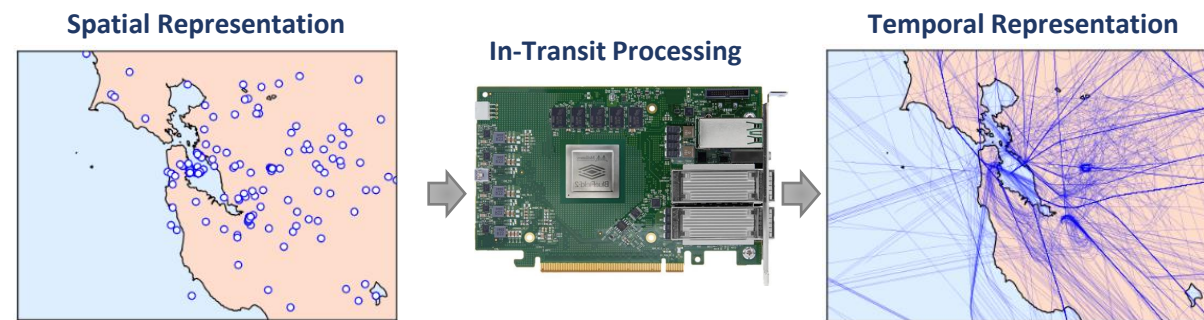

Particle Sifting Example



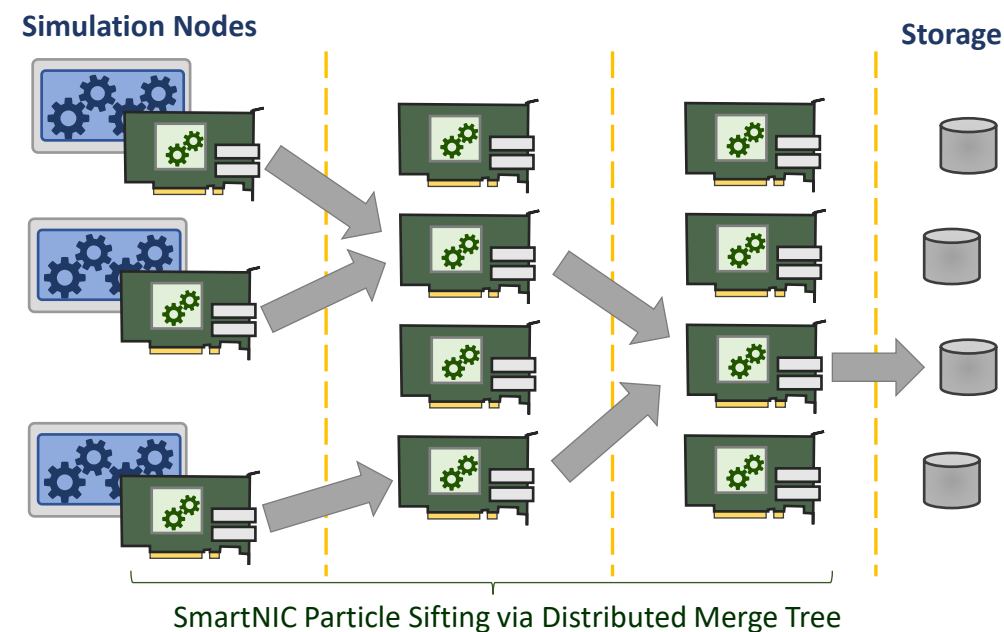
Example: Reorganizing Particle Simulation Results



- Particle simulations track billions of particles
- Mismatch between producers/consumers
 - Simulations: Sorted by position and time
 - Analytics: Sorted by ID and time
- Particle sifting service
 - Periodically sample current data
 - Use distributed SmartNICs to reorganize
 - Distributed merge tree sorts data by ID
- Implementation
 - Faodel Pools/Keys to control data flow
 - Arrow compute to split data
- Experiments on 100-node Cluster w/ BlueField-2 DPUs



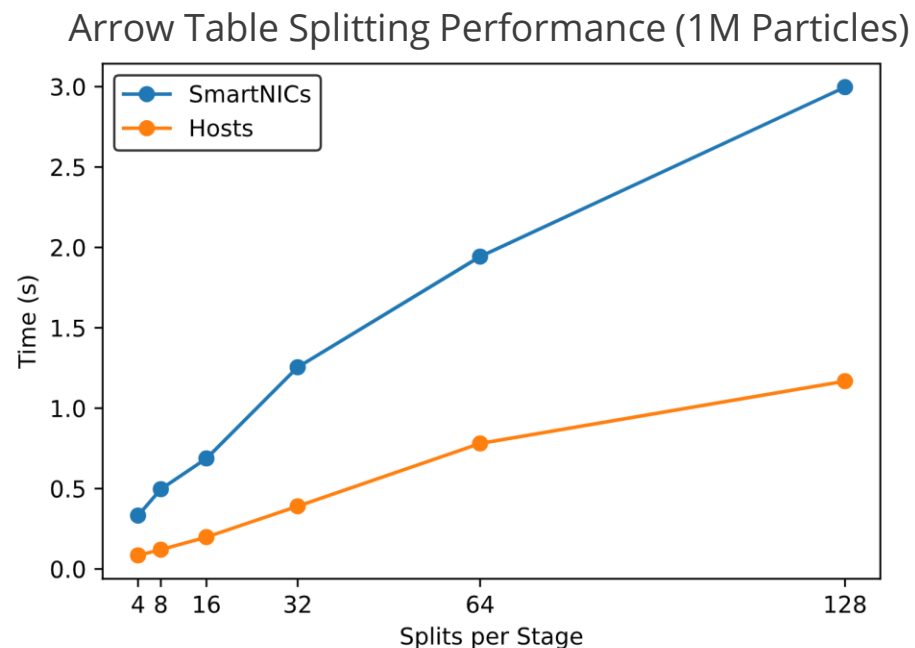
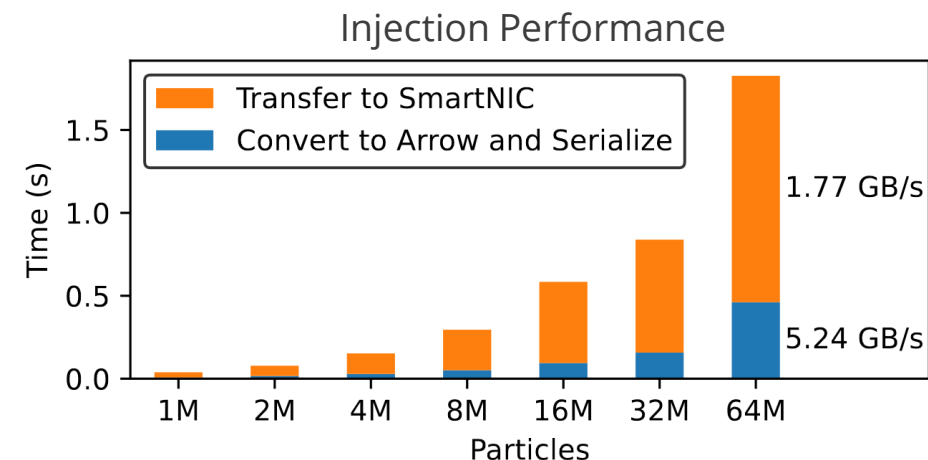
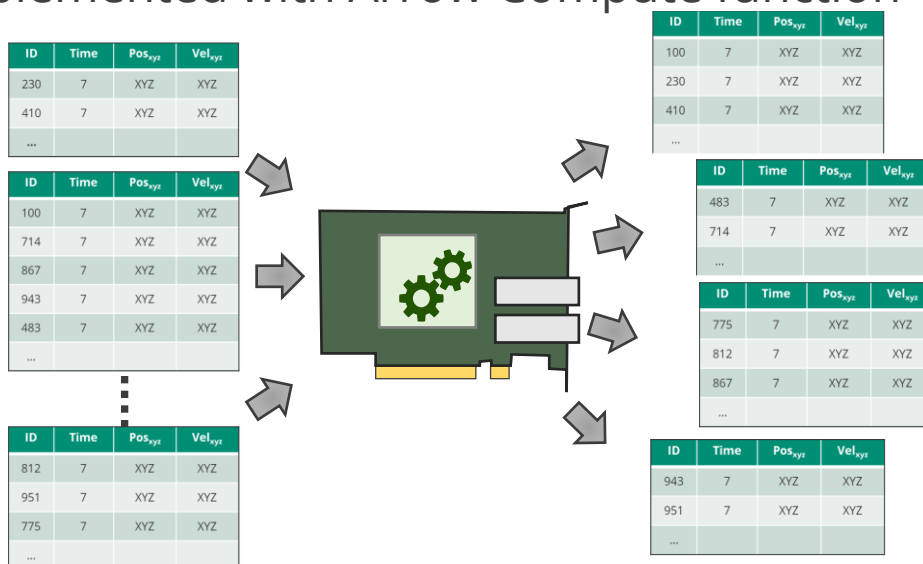
SmartNICs enable simulation results to be transformed while in transit to storage.



Performance Measurements



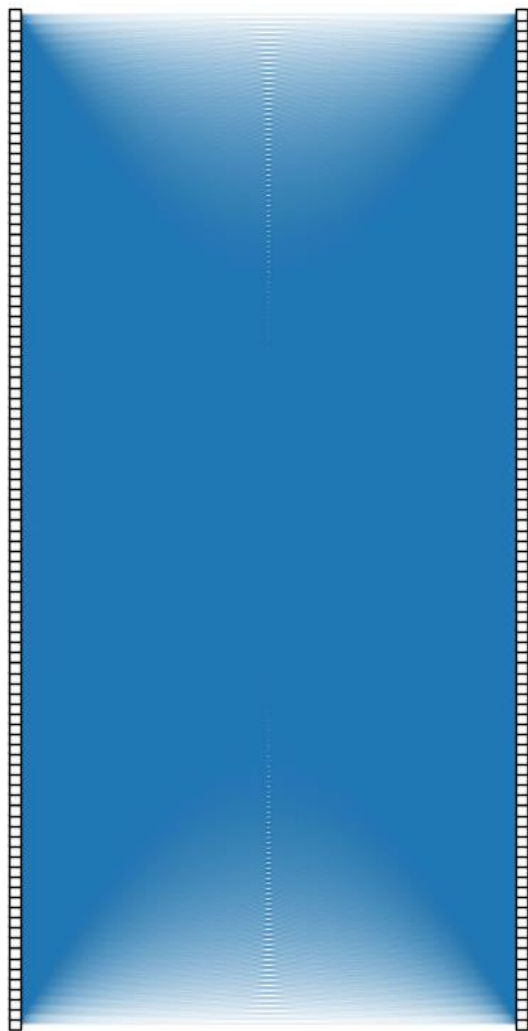
- Injection
 - Convert to Apache Arrow's serialized IPC format
 - Transfer to local SmartNIC
 - 1M-64M Particles (37MB-2.4GB), Overall: 1.32GB/s
 - **New Work:** 10GB/s for "Serialize-on-Transfer"
- Splitting Tables
 - Merge incoming tables and split based on particle IDs
 - Implemented with Arrow Compute function



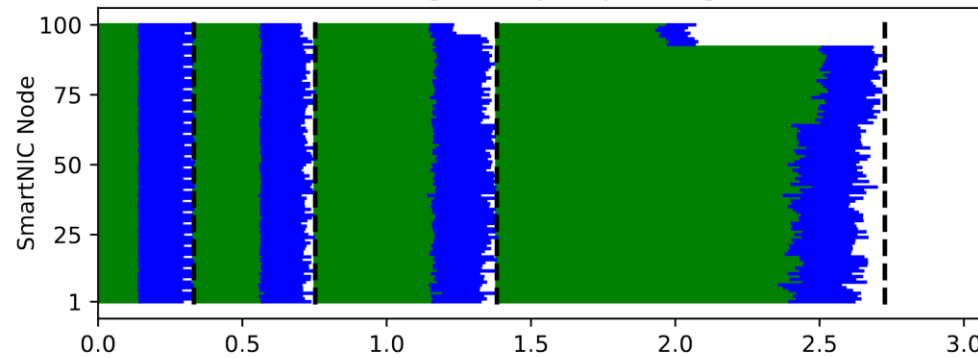
Overall Sifting Performance: 100M Particles on 100 SmartNICs



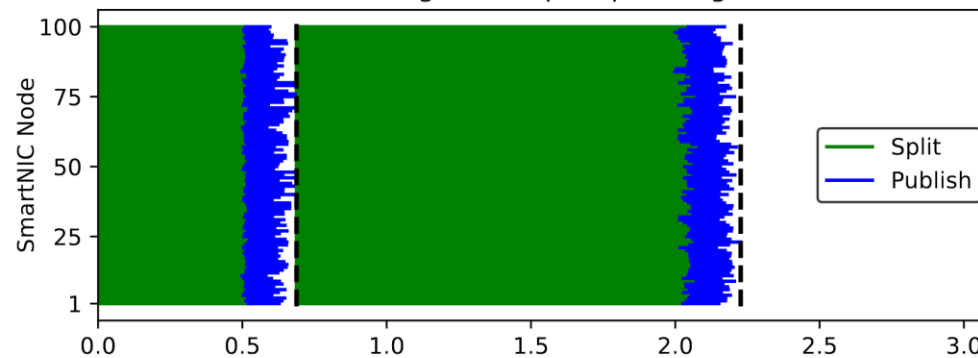
1-Stage, 128-Splits/Stage



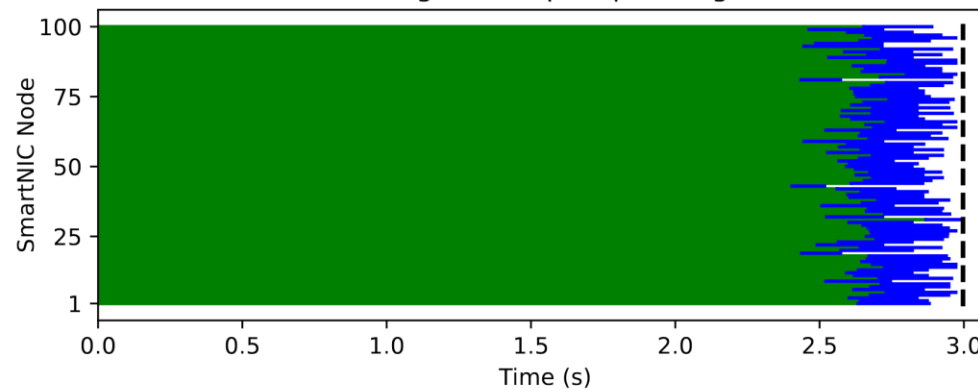
4 Stages, 4 Splits per Stage



2 Stages, 16 Splits per Stage



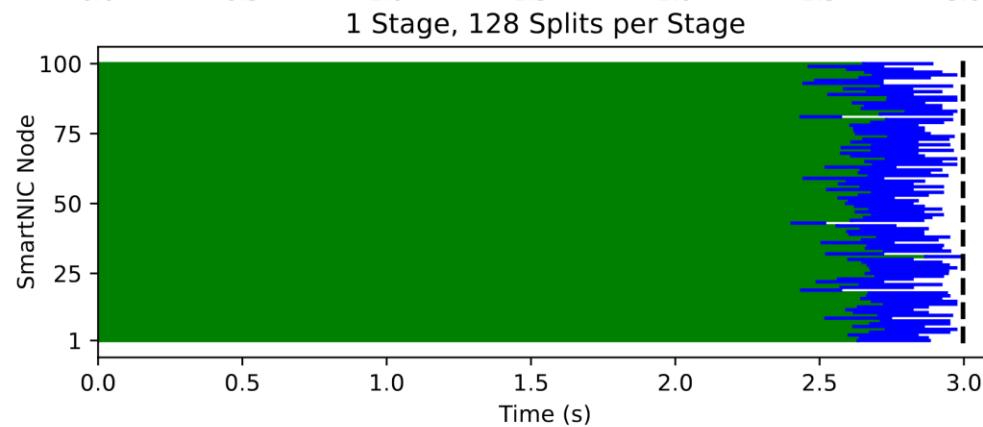
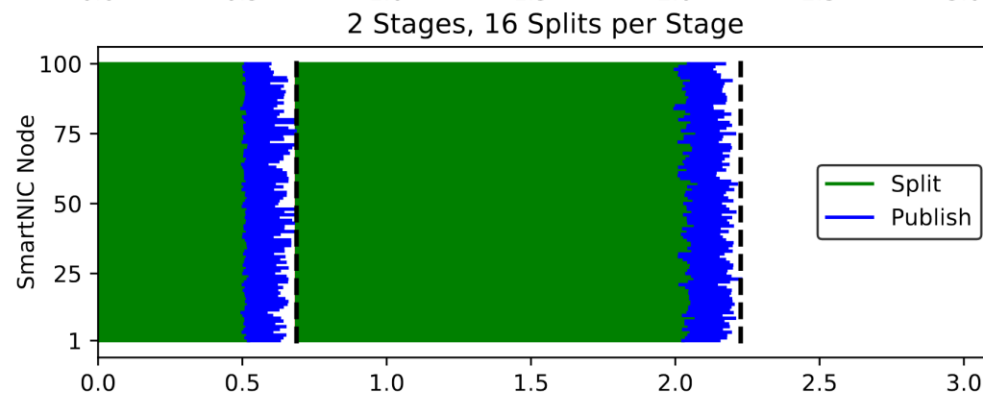
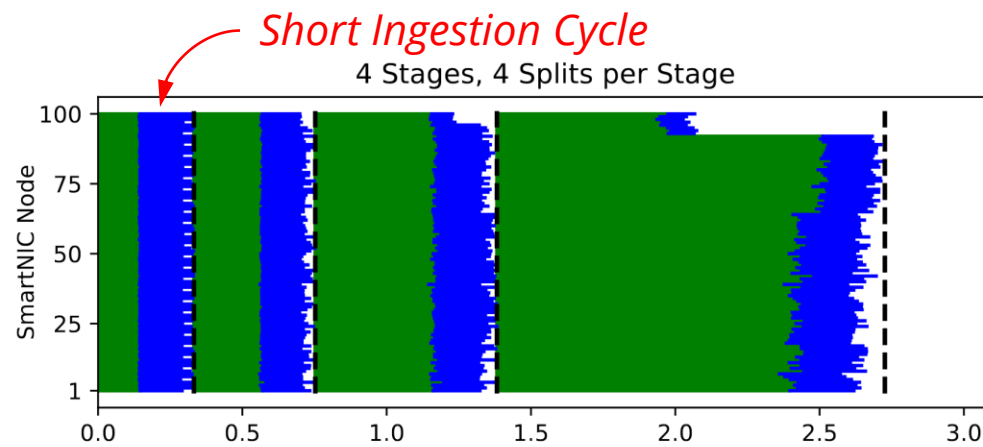
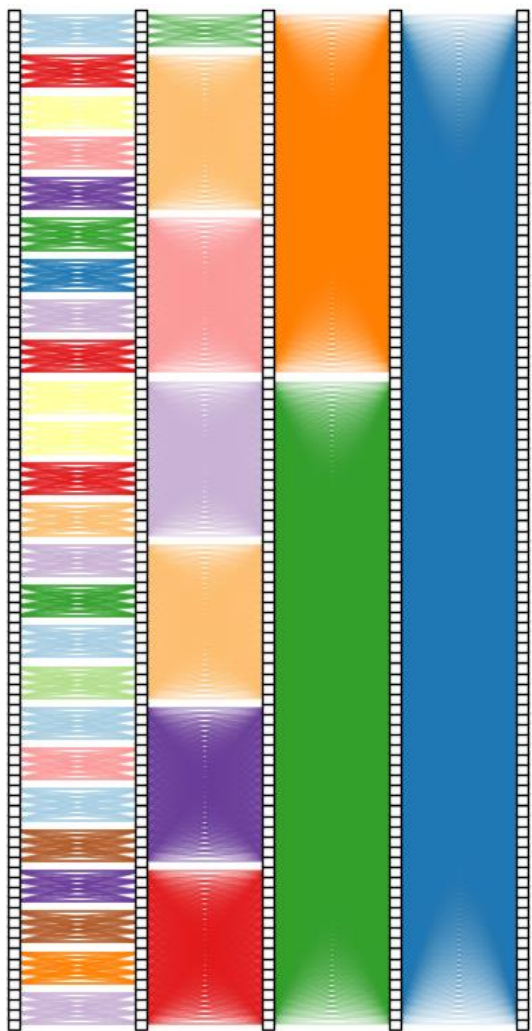
1 Stage, 128 Splits per Stage



Overall Sifting Performance: 100M Particles on 100 SmartNICs



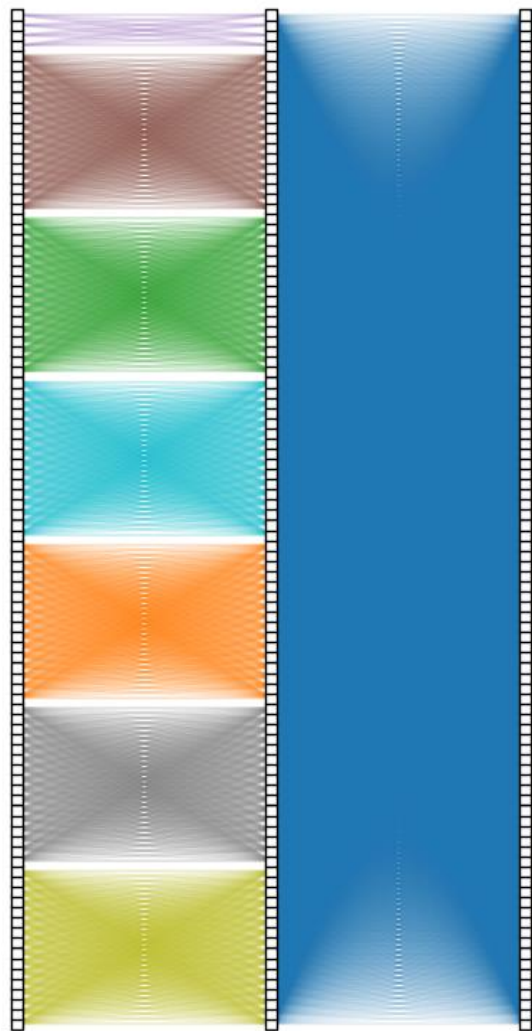
4-Stages, 4-Splits/Stage



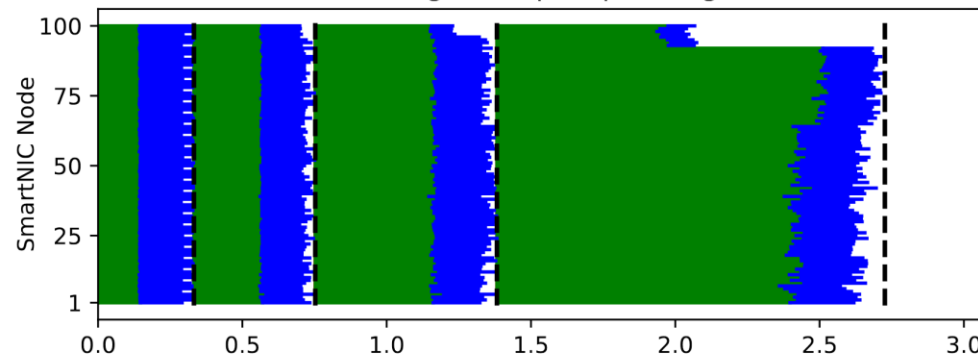
Overall Sifting Performance: 100M Particles on 100 SmartNICs



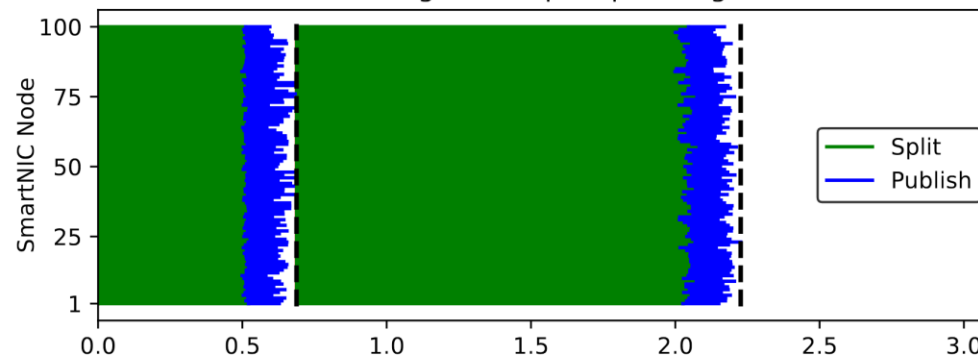
2-Stages, 16-Splits/Stage



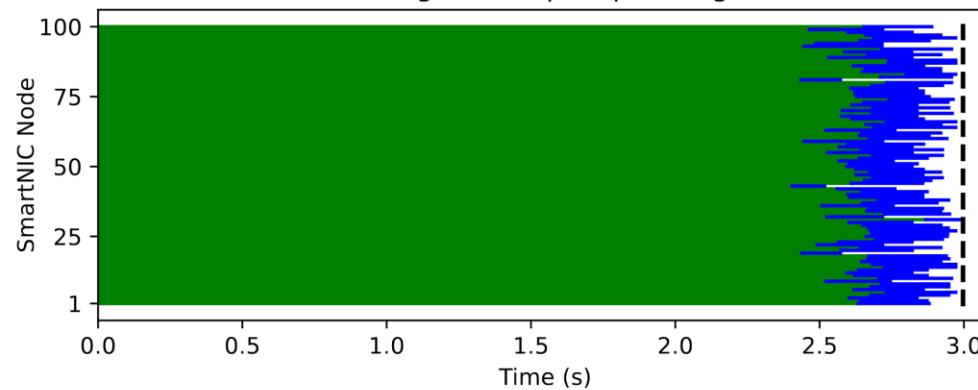
4 Stages, 4 Splits per Stage



2 Stages, 16 Splits per Stage



1 Stage, 128 Splits per Stage



Summary and Future Work



- SmartNICs offer a new space for hosting data management services
 - Positive: Isolated space for operations near producers
 - Negative: Host processors 4x faster, Vendor-specific libraries, extra costs (\$, power)
- Can build a functional environment for hosting services from existing libraries
 - Faodel and Arrow provided primitives we needed
- Recent work: Implemented query service for in-transit data
- Future Work
 - Evaluating BlueField-3 and competing SmartNICs
 - Connect with computational storage devices
 - Extend work to other workflows

<https://github.com/sandialabs/faodel>

<https://github.com/apache/arrow>



Jobs at the National Labs



- **Students:** The national labs have large, summer jobs programs (paid)
 - Apply in December/January
 - <https://www.energy.gov/jobs-national-labs>
 - <https://www.sandia.gov/careers/>
- **Faculty:** Student interns are a great way to develop collaborations with the labs

