Offloading Data Management Services to SmartNICS

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This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research under Field Work Proposal Number 20-023266.

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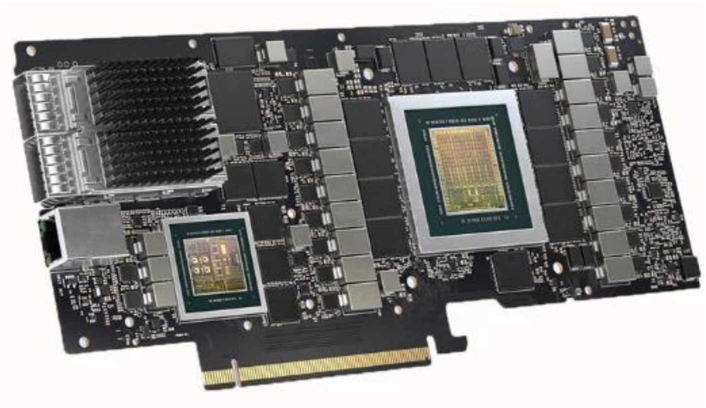
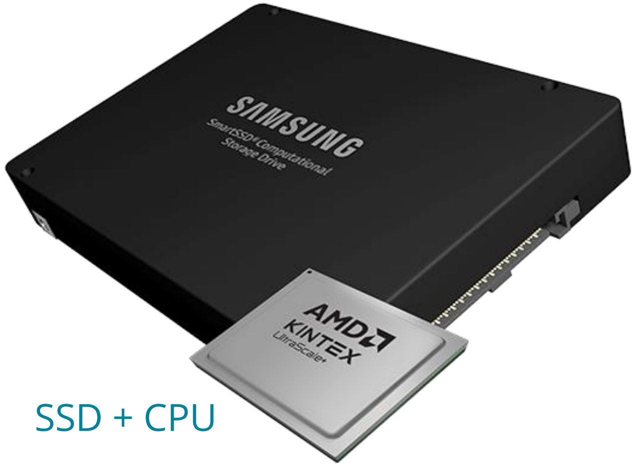
SAND2024-03874PE

Overview

- Hardware vendors are adding *embedded processors* to network & storage products
  - Enables users to execute code on in-transit or in-storage data
  - Use cases: infrastructure security, resilience, embedded queries
- How can we leverage these devices in scientific computing workflows?
- DOE ASCR Project: Offloading Data Management Services to SmartNICs (FY20-23)
  - Focus on *data services* used for moving data in HPC workflows
  - Leverage Apache Arrow as a data standard, Sandia's Faodel for communication



Network Interface Card + CPU (+ GPU)



SSD + CPU

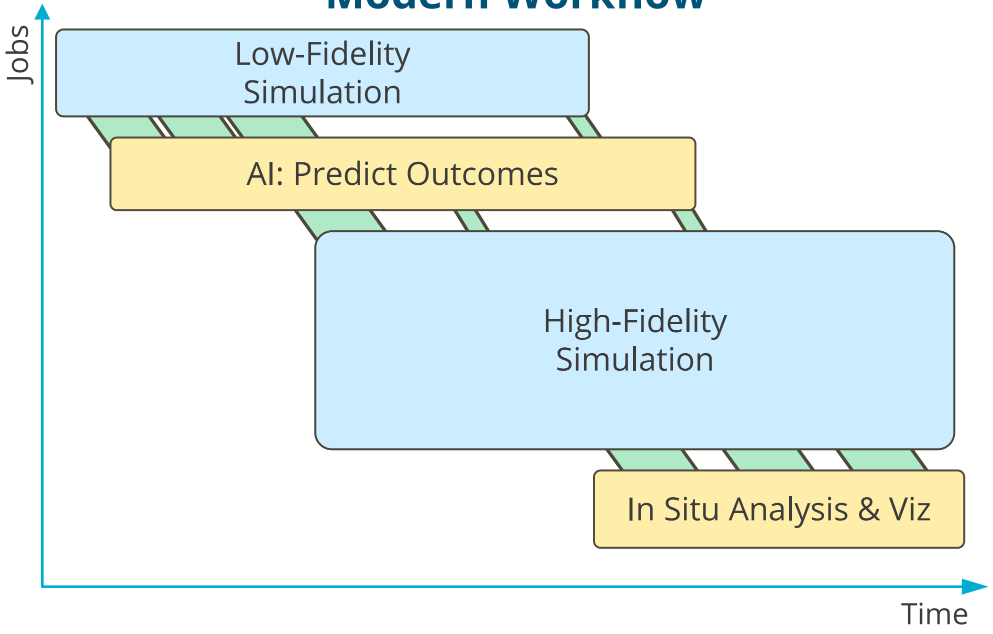
APACHE ARROW

Motivation

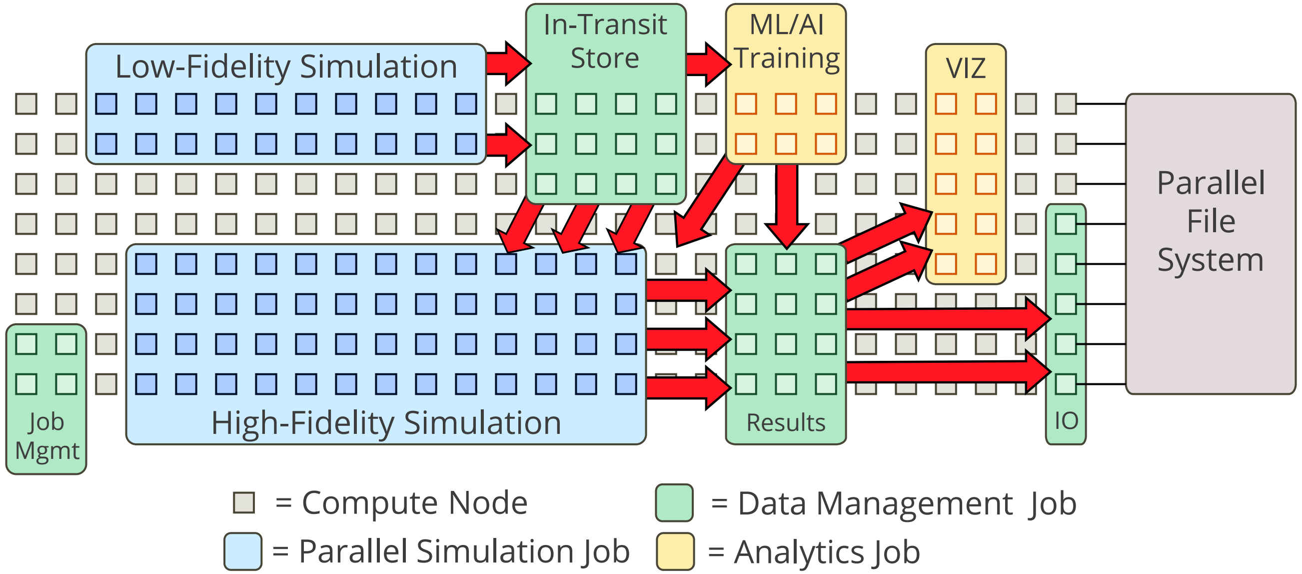
High-Performance Computing Workflows

- ECP/ATDM: Advanced workflows involve many parallel tools
  - Use *data management services* to implement data flow between jobs, hide I/O costs
  - Multiple library options: DataSpaces, Mochi, Conduit, Faodel
- Problem: Data management services consume host resources

Modern Workflow



Parallel Jobs on HPC Platform

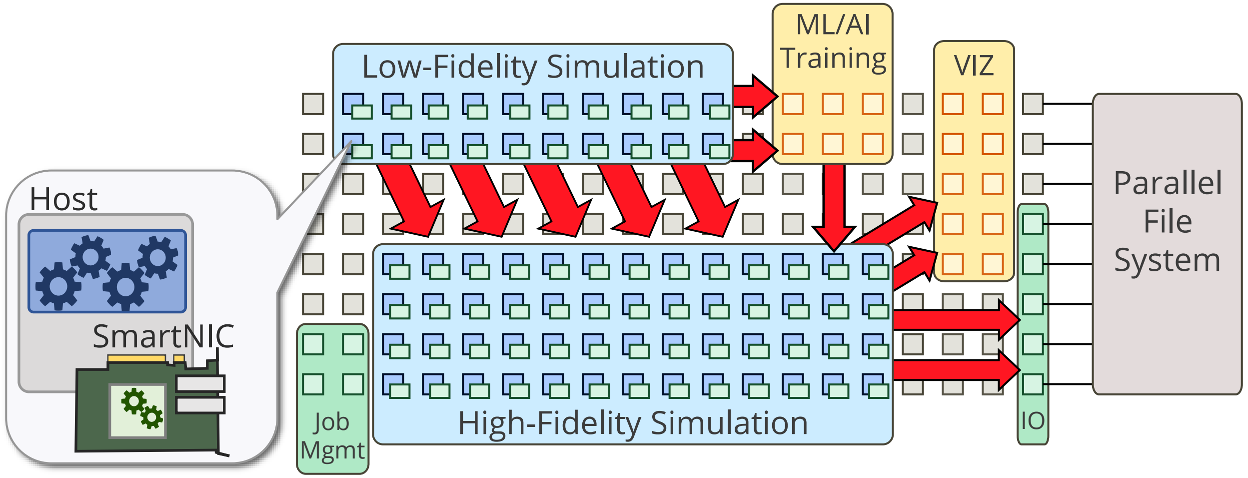


Smart Network Interface Cards (SmartNICs)

- 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

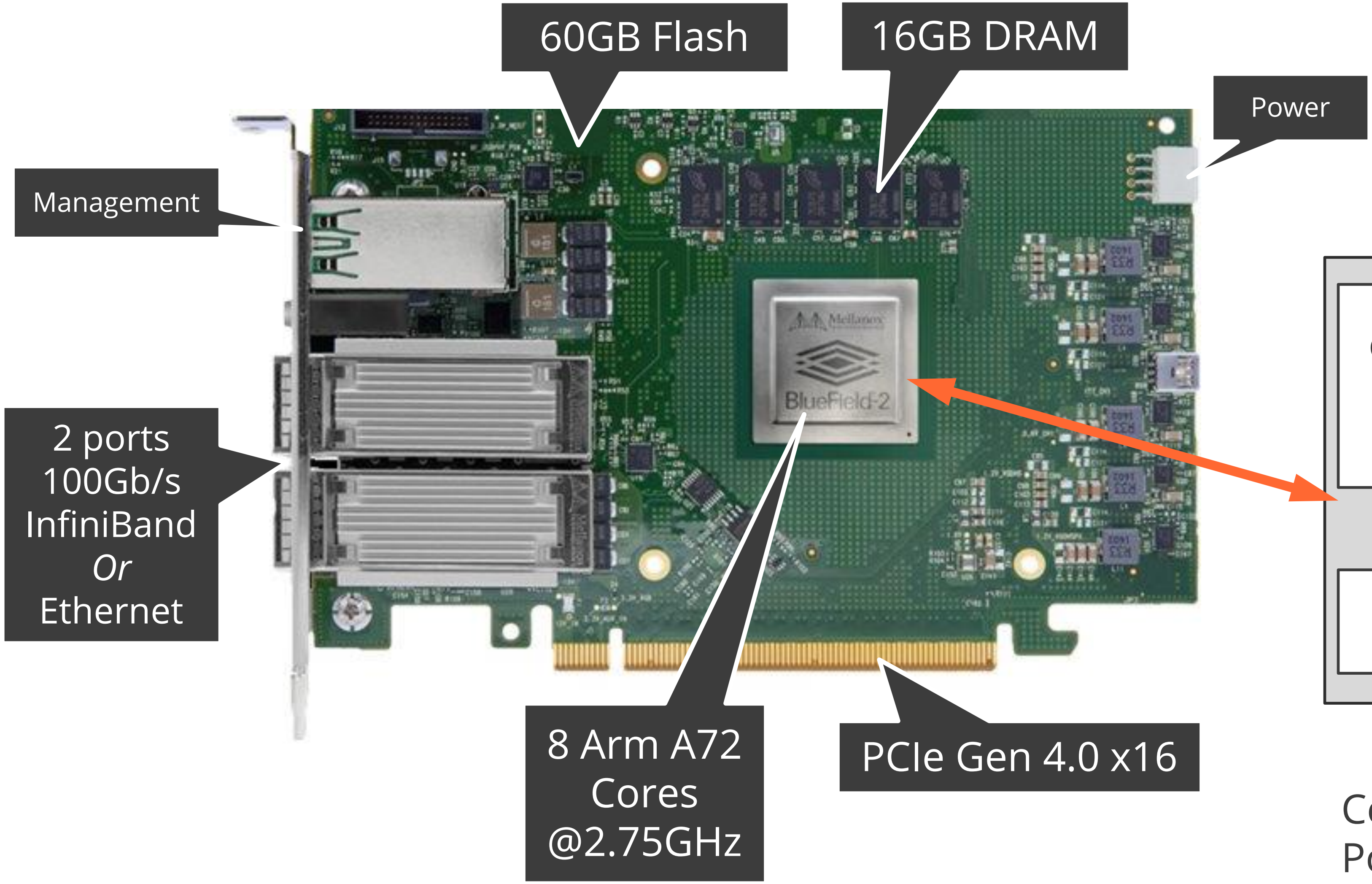
HPC Platform with SmartNICs

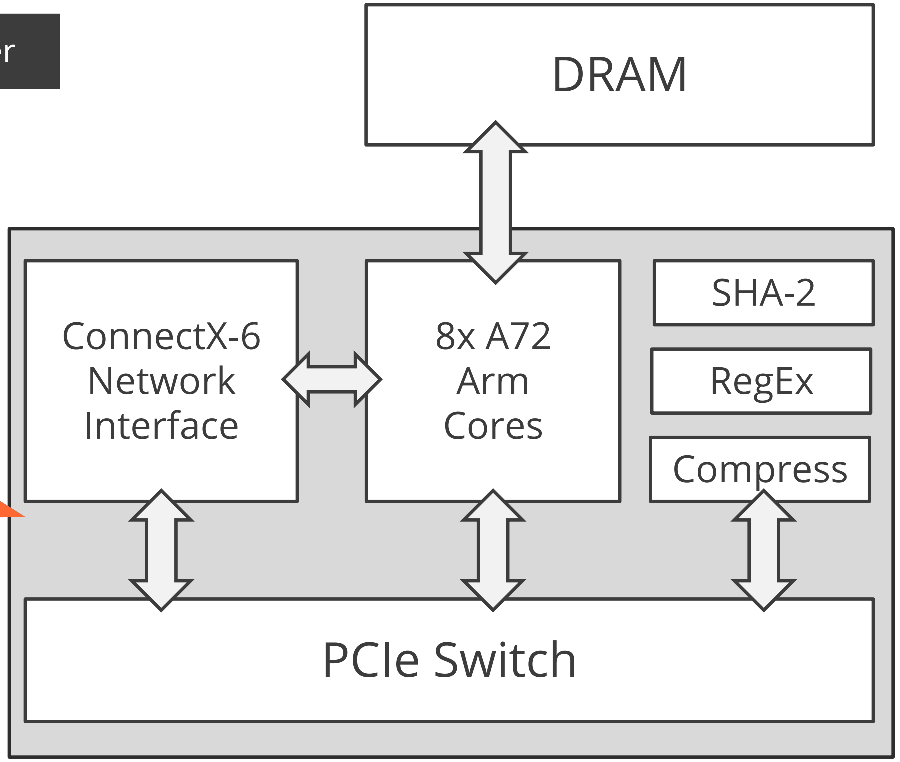


= Compute Node with a *SmartNIC* for offloading data services

Characterizing the BlueField-2 SmartNIC

NVIDIA BlueField-2 VPI SmartNICs



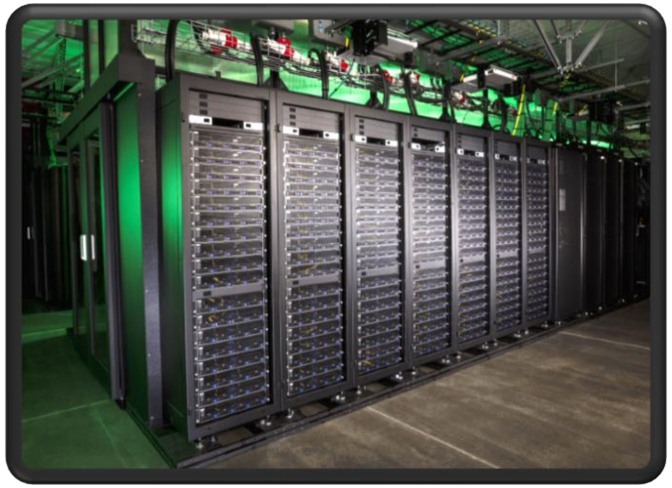


Cost: ~$2,000
Power: 30W idle, 42W active, 63W max
OS: Linux (Ubuntu, RHEL, etc)

Sandia's Glinda Cluster (2021)

- Heterogenous architecture for Data Analytics
  - BlueField-2 DPU, AMD Zen 3 CPUs, NVIDIA A100
  - 126 Nodes
- BlueField-2's Embedded processors
  - 4-10x slower, but better power efficiency

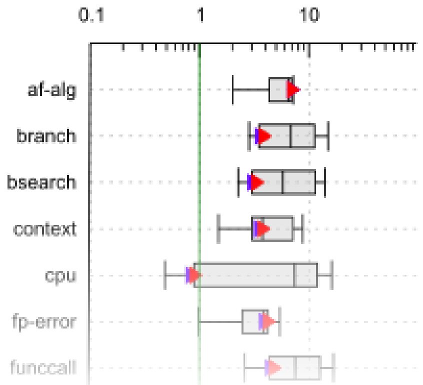
	SmartNIC	Host CPU	GPU
Processor	Arm A72	AMD EPYC 7543P	Ampere A100
Cores	**8**	**32**	**108 SMs**
Clock	2.75GHz	2.8GHz	0.765 – 1.41GHz
L1 Cache	256KB	1MB	192KB
L2 Cache	6MB	256MB	-
Memory Capacity	16GB	512GB	40GB
Memory Bandwidth	**25GB/s**	**204GB/s**	**1,555GB/s**
TDP	63W	225W	250W



Glinda

stress-ng microbenchmarks

- BF2 vs 12 servers in 200 tests
- BF2 lower, but within order of magnitude

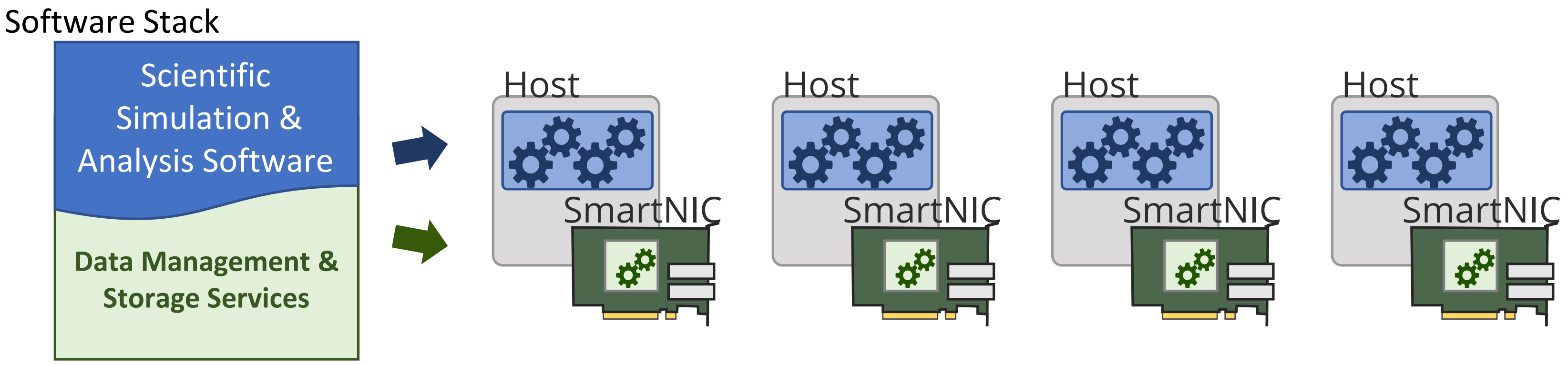


"Performance Characteristics of the BlueField-2 SmartNIC"

Creating an Environment for Data Services on SmartNICs

Create an Environment for Hosting Data Services on SmartNICs

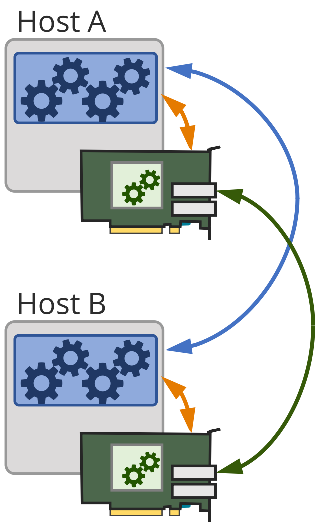
- We define five requirements (R1-R5) for creating this environment
  - Three communication, Two computation
- Leverage existing libraries as much as possible
- Prototype environment
  - Communication via **Faodel**: C++ library with distributed-memory Key/Blob API built on RDMA
  - Computation via **Apache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



Resolving Communication Requirements with Faodel

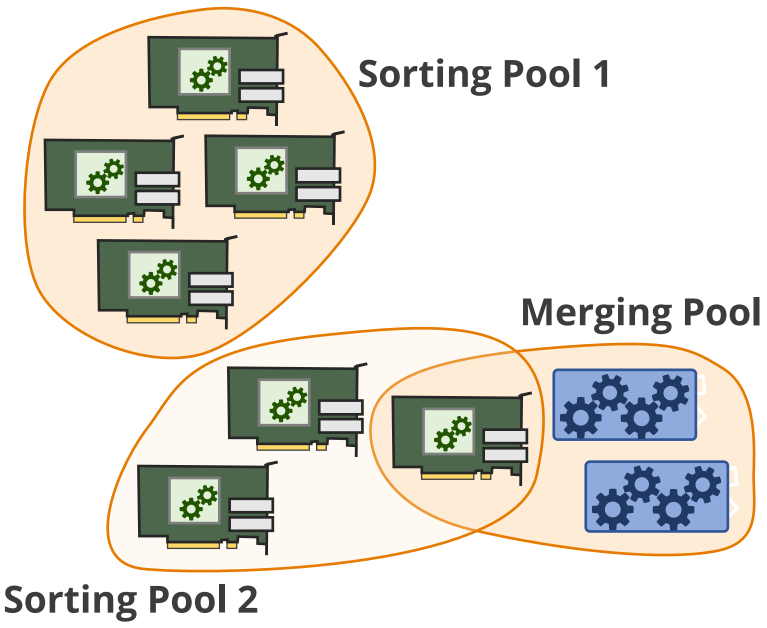
R1: Any-to-Any Transfers

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



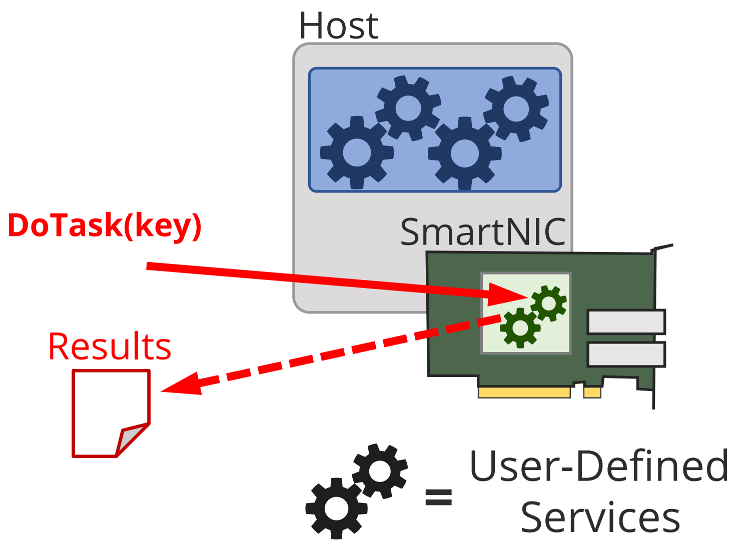
R2: Group Resources

- 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



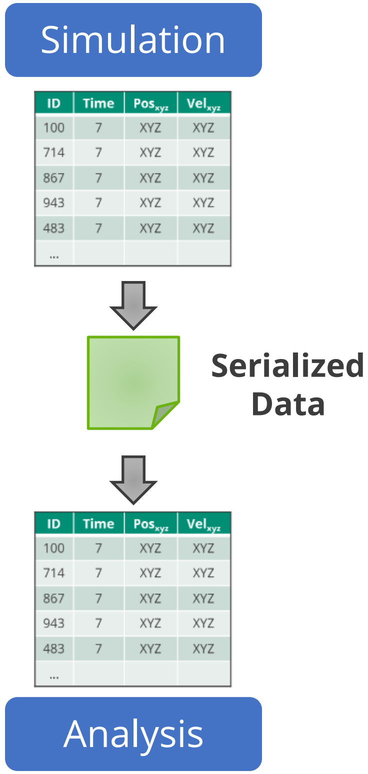
Resolving Computational Requirements with Apache Arrow

R4: Common Data Representation

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

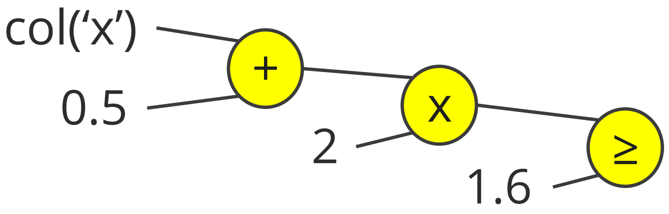
APACHE ARROW

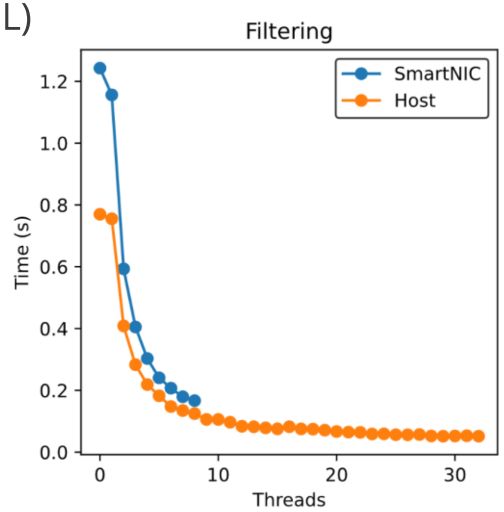
ID	Time	Pos_{xyz}	Vel_{xyz}
100	7	XYZ	XYZ
714	7	XYZ	XYZ
867	7	XYZ	XYZ
943	7	XYZ	XYZ
483	7	XYZ	XYZ
…			



R5: Data-Parallel Computations

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



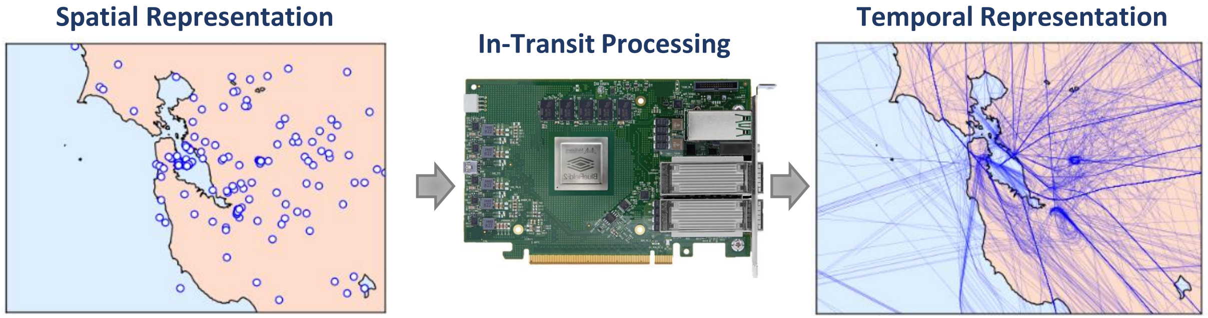



```
// 2 * (0.5 + x) >= 1.6
auto filter_expression = arrow::compute::greater_equal(
    arrow::compute::call(
        "multiply",
        {arrow::compute::literal(2),
         arrow::compute::call("add_checked", {arrow::compute::literal(0.5),
                                              arrow::compute::field_ref("x")})}),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

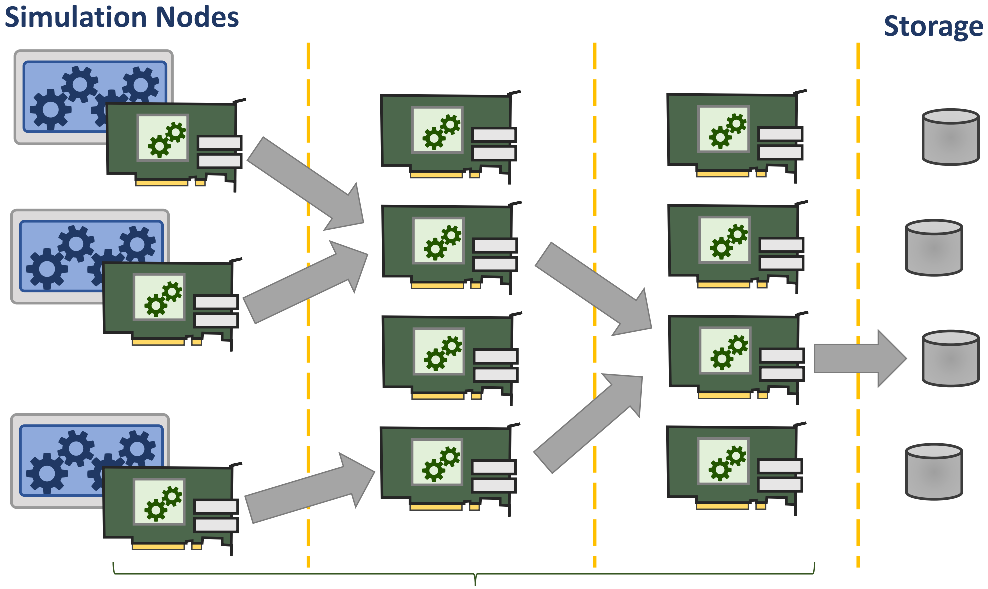
Particle Sifting Example

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



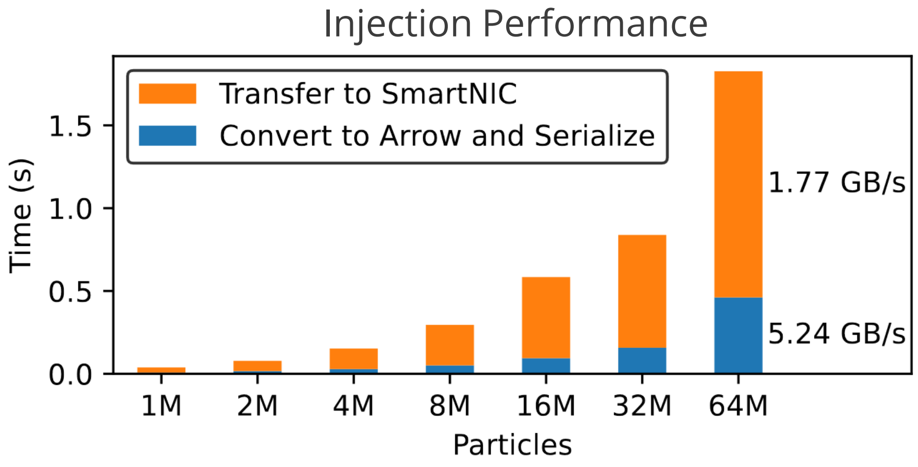
SmartNICs enable simulation results to be transformed while in transit to storage.

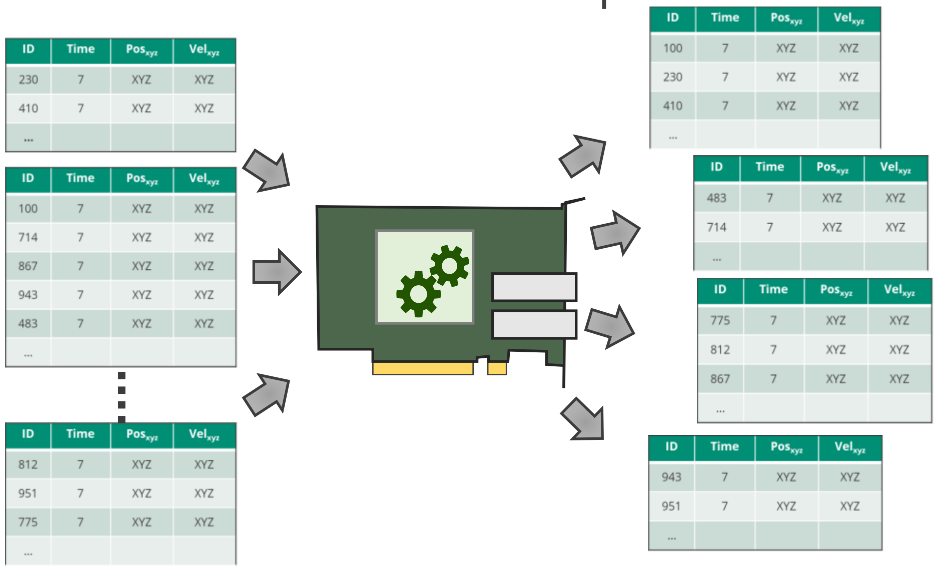


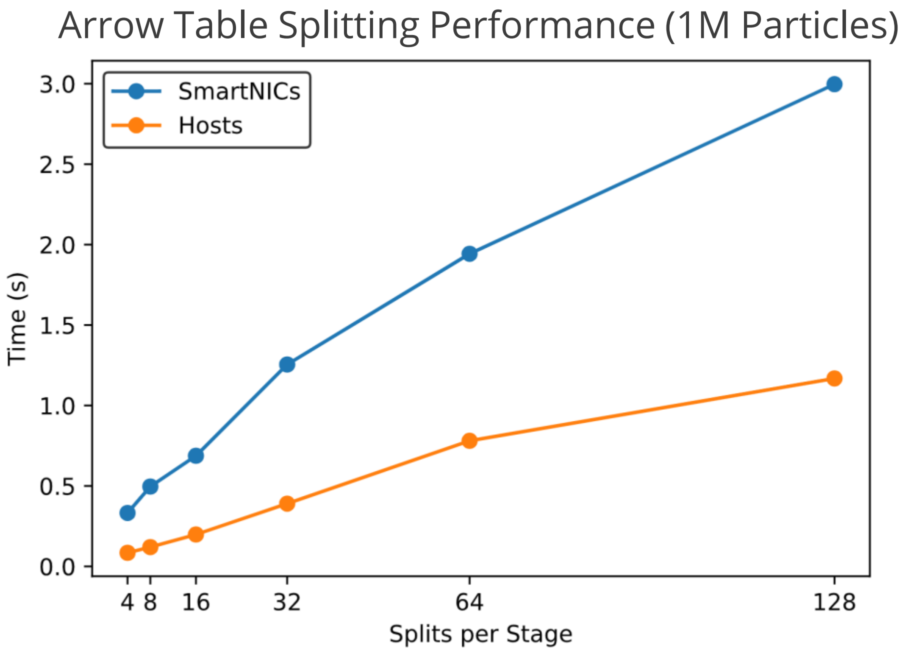
SmartNIC Particle Sifting via Distributed Merge Tree

Performance Measurements

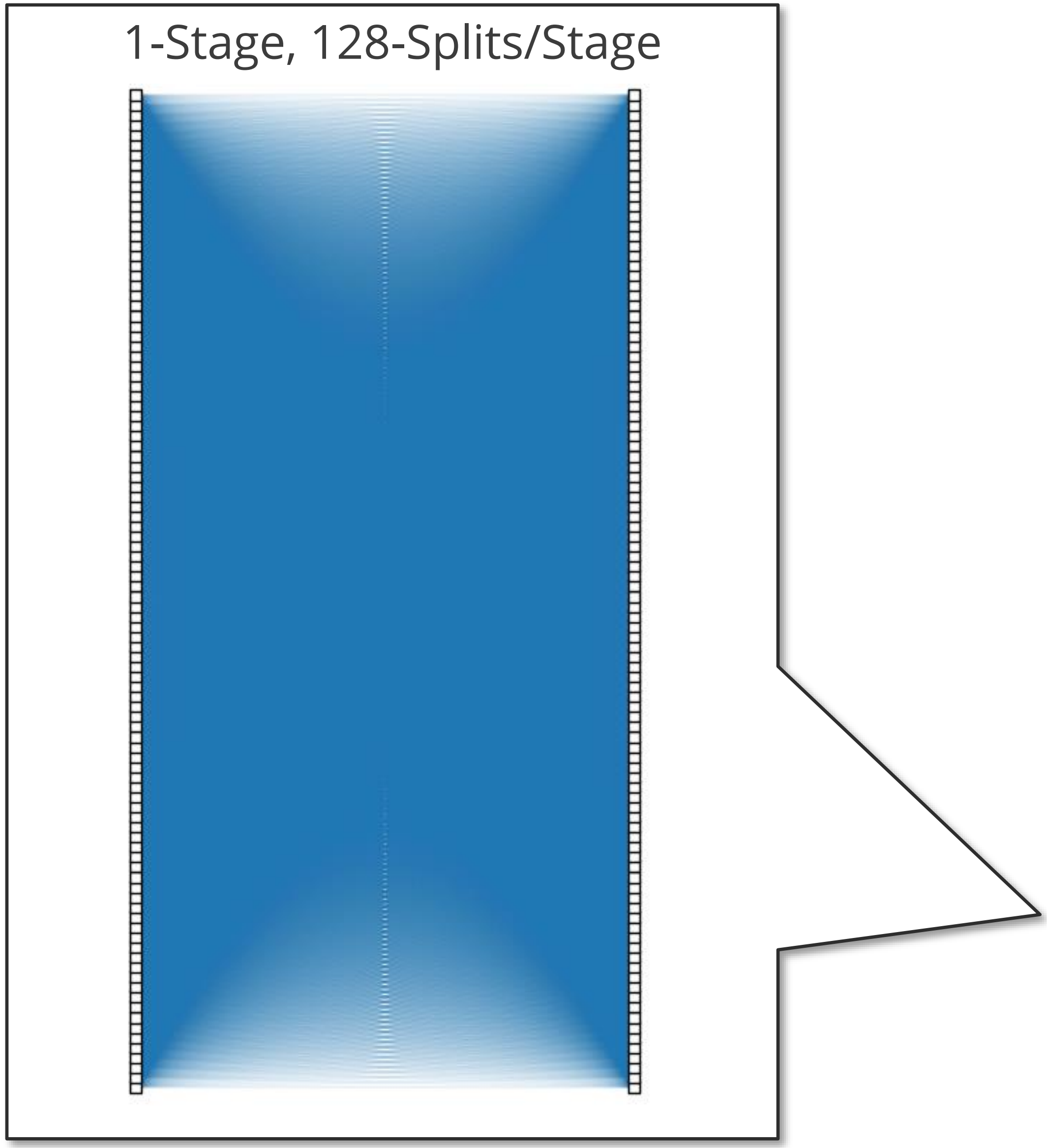
- Injection
  - Convert to Apache Arrow's serialized IPC format
  - Transfer to local SmartNIC
  - 1M–64M Particles (37MB-2.4GB), Overall: 1.32GB/s
  - ***New Work**:* 10GB/s for "Serialize-on-Transfer"
- Splitting Tables
  - Merge incoming tables and split based on particle IDs
  - Implemented with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

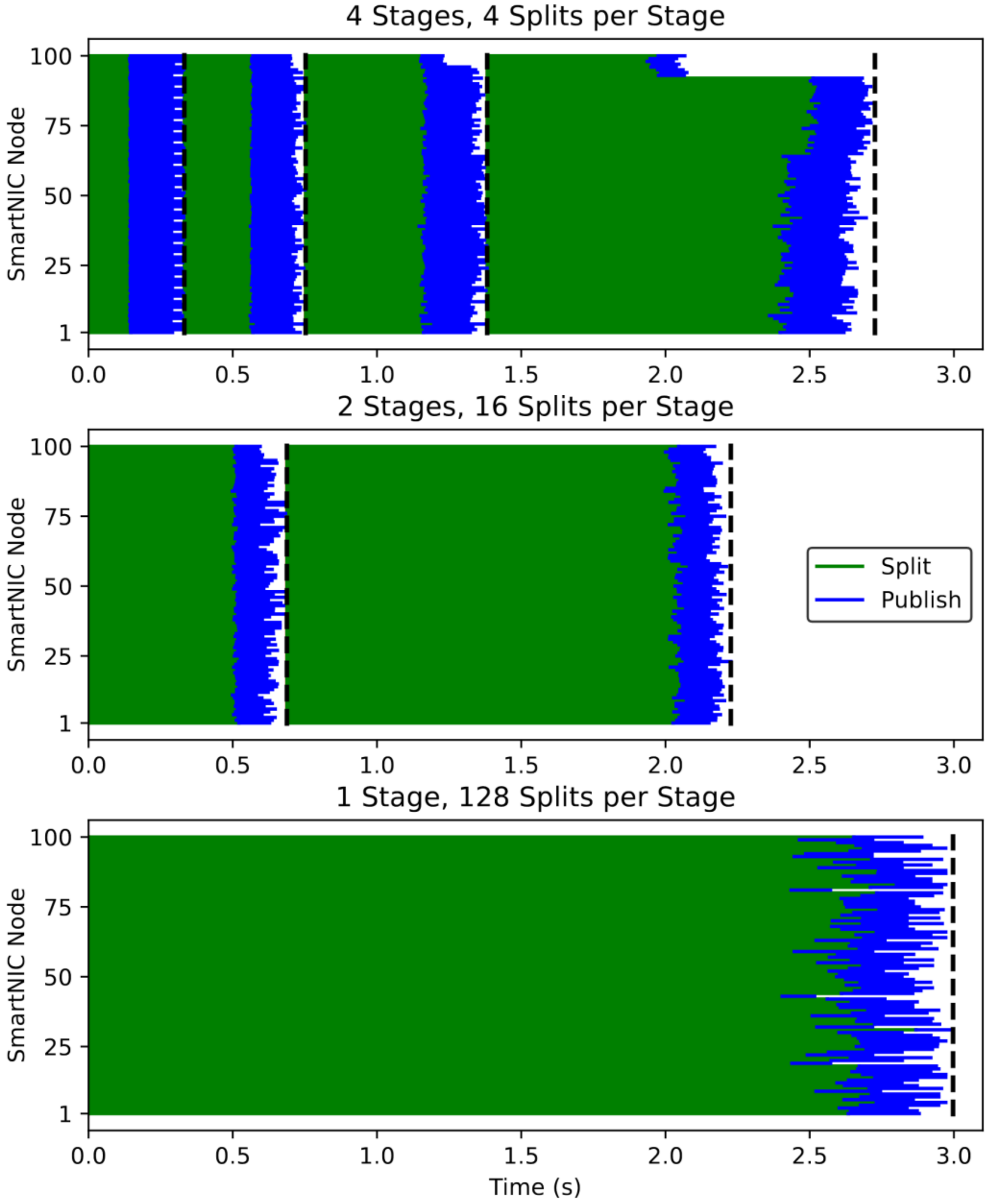




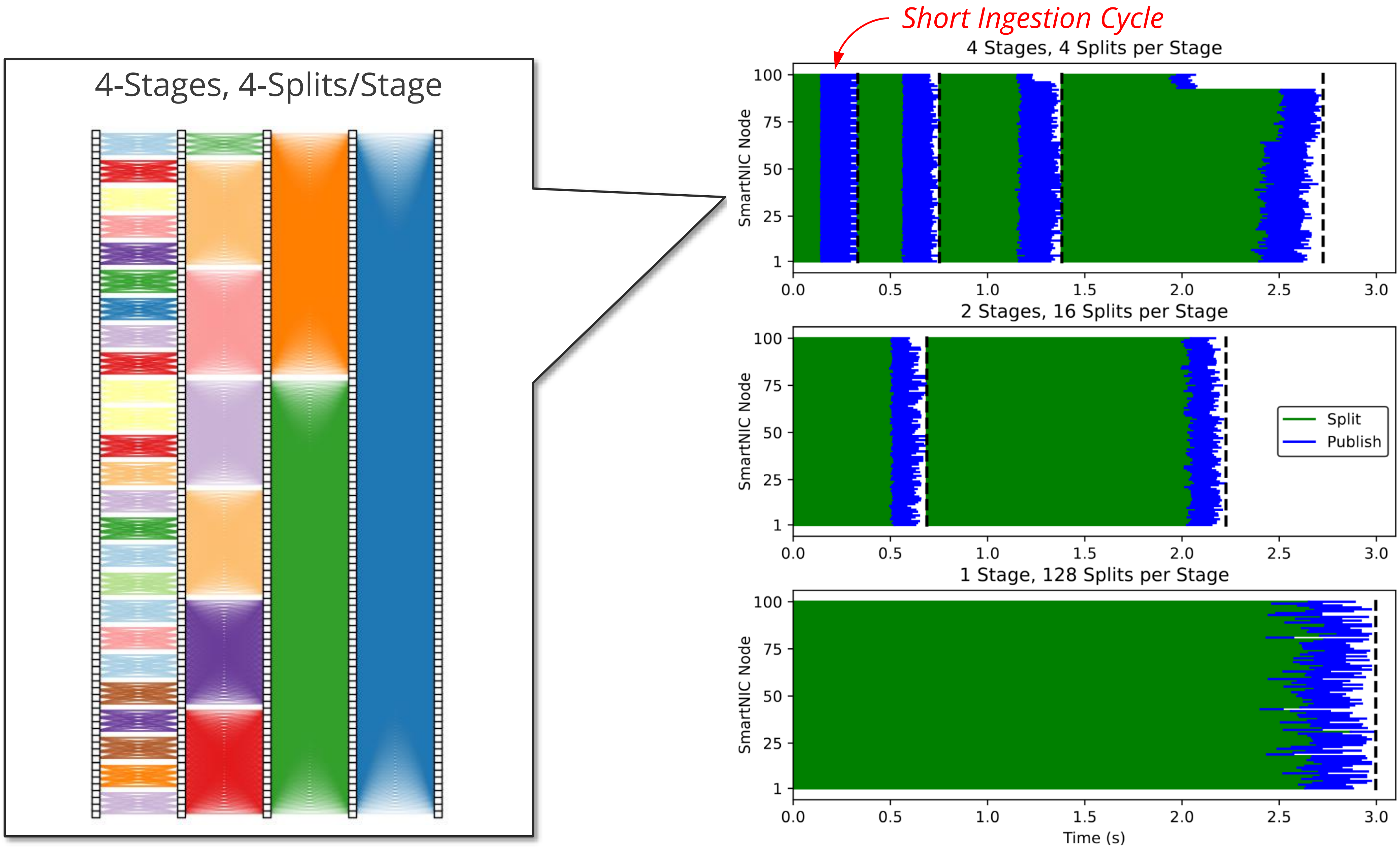


Overall Sifting Performance: 100M Particles on 100 SmartNICs

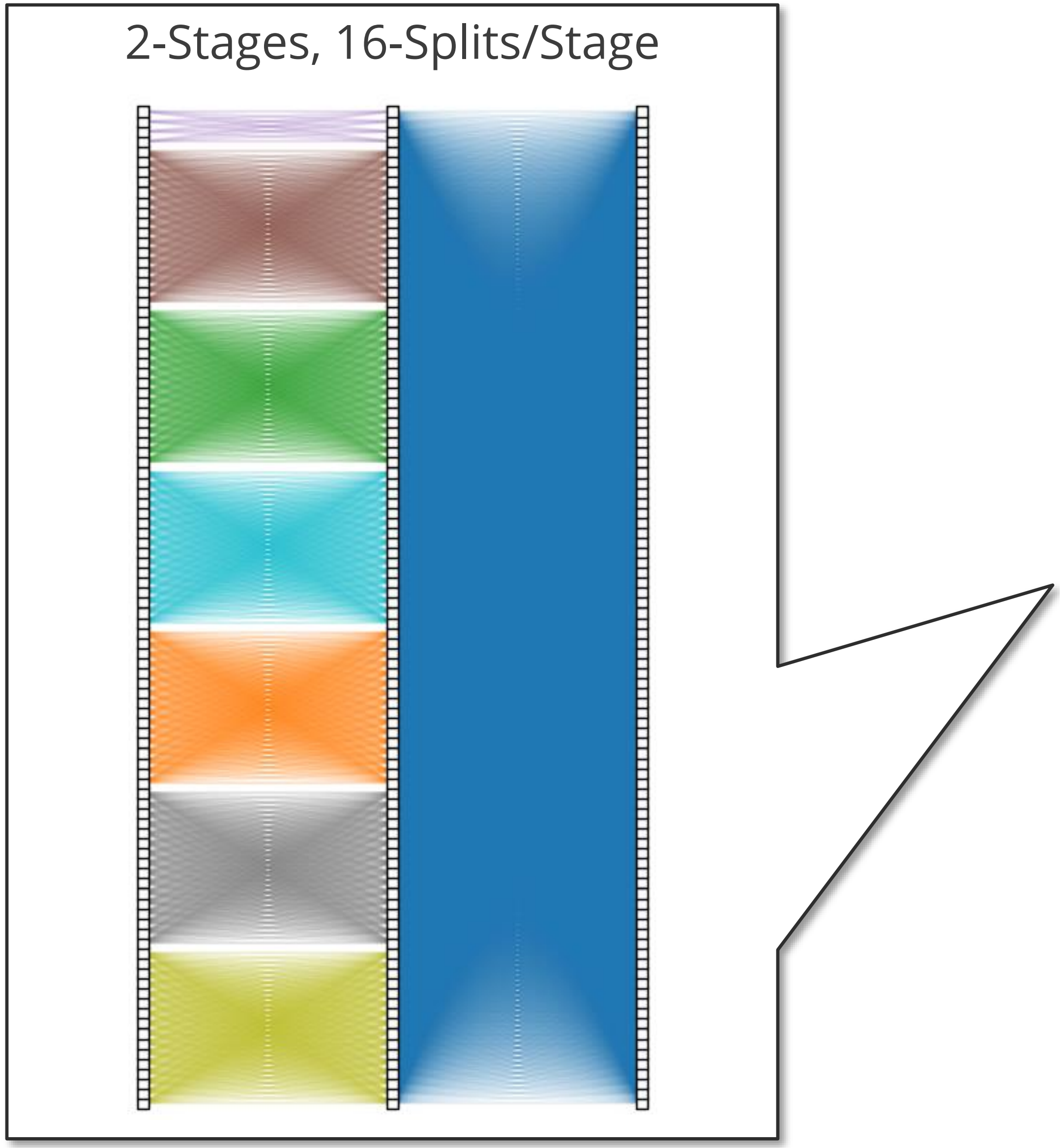


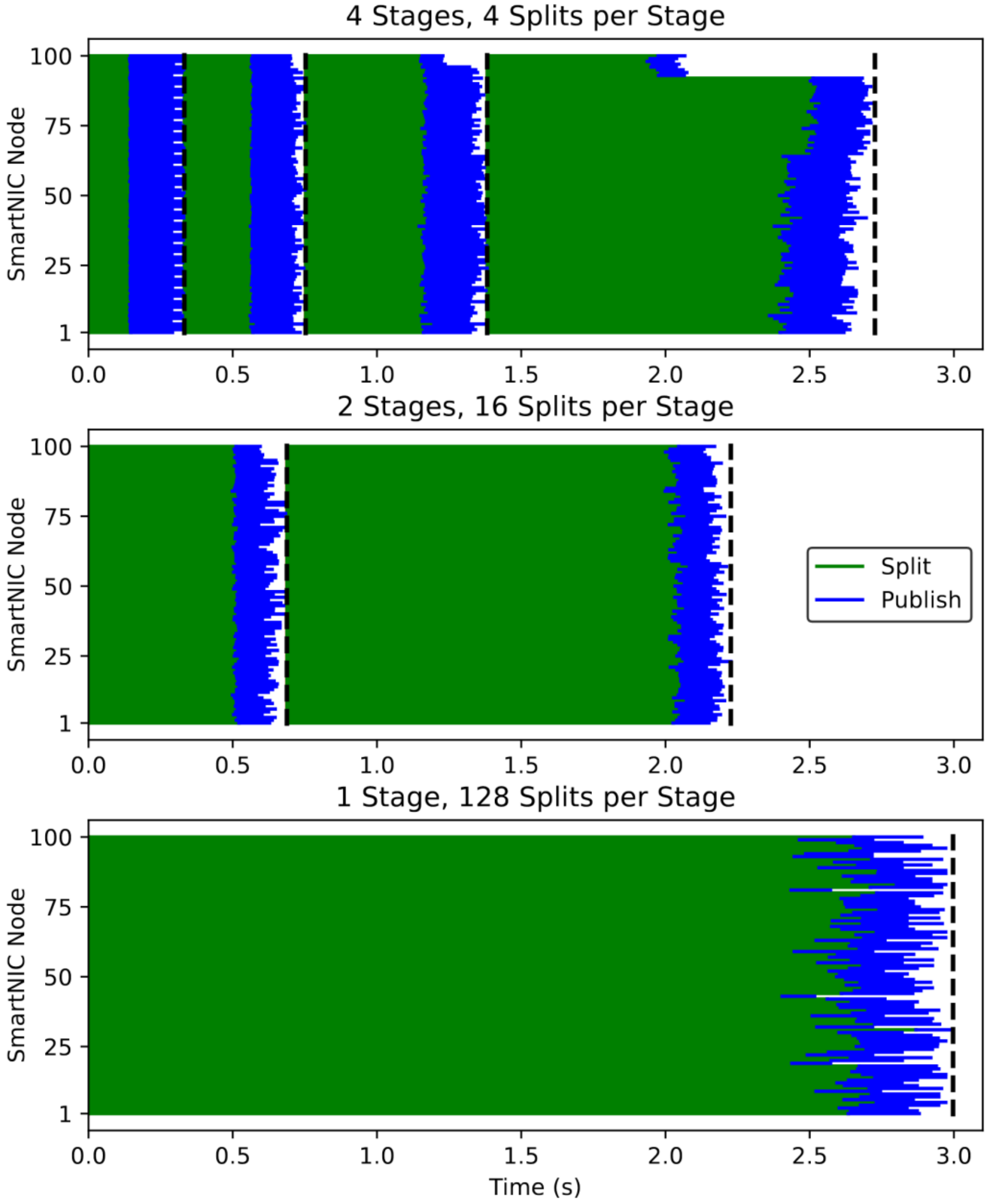


Overall Sifting Performance: 100M Particles on 100 SmartNICs



Overall Sifting Performance: 100M Particles on 100 SmartNICs



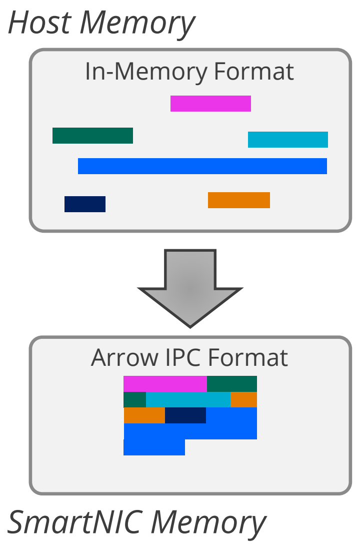


Additional Research Threads Explored

Injection Optimizations

- **Problem**: Serialization is expensive
- **Goal**: Minimize output time

- Defer serialization to SmartNIC
  - Reorganize on SmartNIC *or*
  - Align fragments on transfer



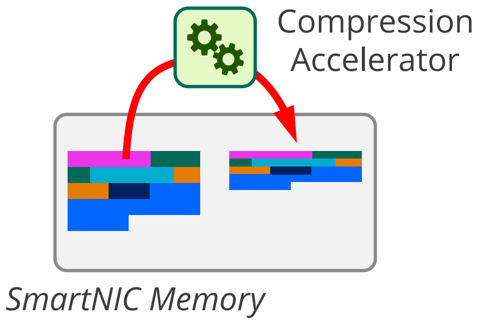
Scott Levy & Whit Schonbein

Leveraging high-performance data transfer to offload data management tasks to SmartNICs

Compression

- **Problem**: Compression is expensive
- **Goal**: Dynamic data compression

- Leverage BF2 compression unit
  - DEFLATE standard
  - Block or Streaming
- 30x faster than host



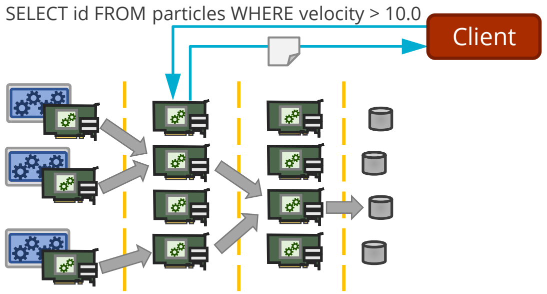
Jianshen Liu

Processing particle data flows with SmartNICs

Dynamic Data Queries

- **Problem**: Poor dataflow visibility
- **Goal**: Dynamic query in-transit data

- Dynamic queries w/ Arrow
  - User generates query plan
  - SmartNIC applies locally
  - Push-down vs Push-back



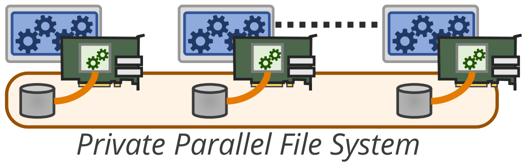
Jianshen Liu

Opportunistic query execution on SmartNICs for analyzing in-transit data

Node-Local Storage

- **Problem**: Platform storage is noisy
- **Goal**: Private, Parallel FS

- Implement PFS in SmartNICs
  - Attach to host's NVMe via NVMe-over Fabric
  - BeeGFS



Matthew L. Curry & John Shawger

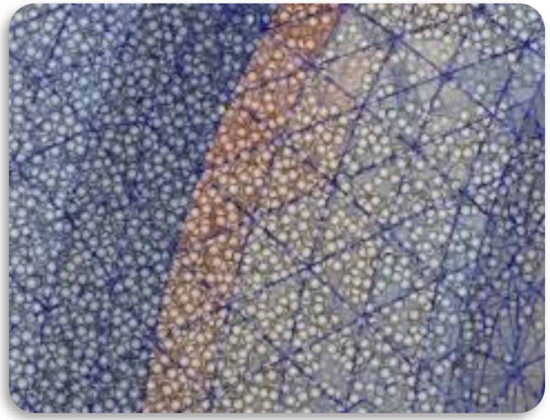
Offloading node-local filesystems in high performance computing environments

Summary and Future Work

- SmartNICs offer a new space for hosting data management services
  - Positive: Isolated space for operations near producers, Cheap nodes
  - 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
- Opportunities
  - Scheduling use of network link to avoid contention
  - Connect with computational storage devices
  - Low-cost metric collection, resilience

https://github.com/sandialabs/faodel

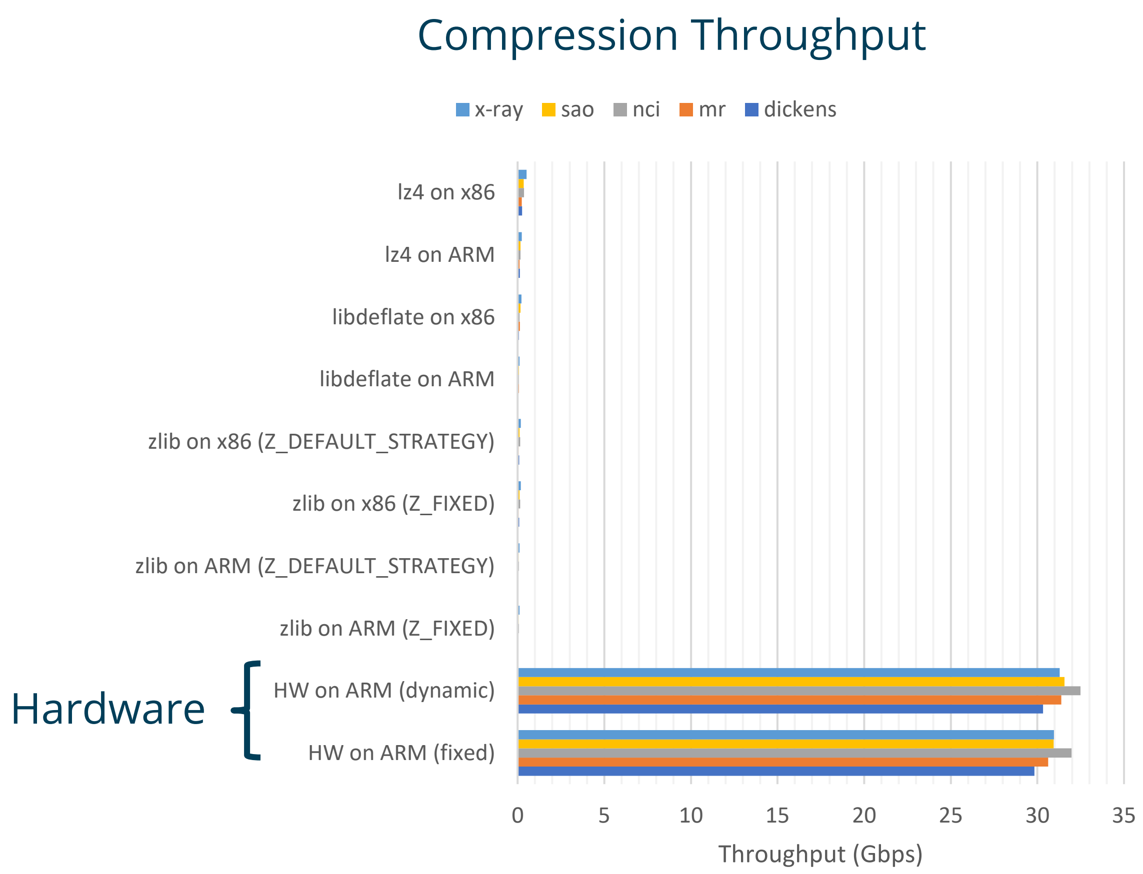
https://github.com/apache/arrow

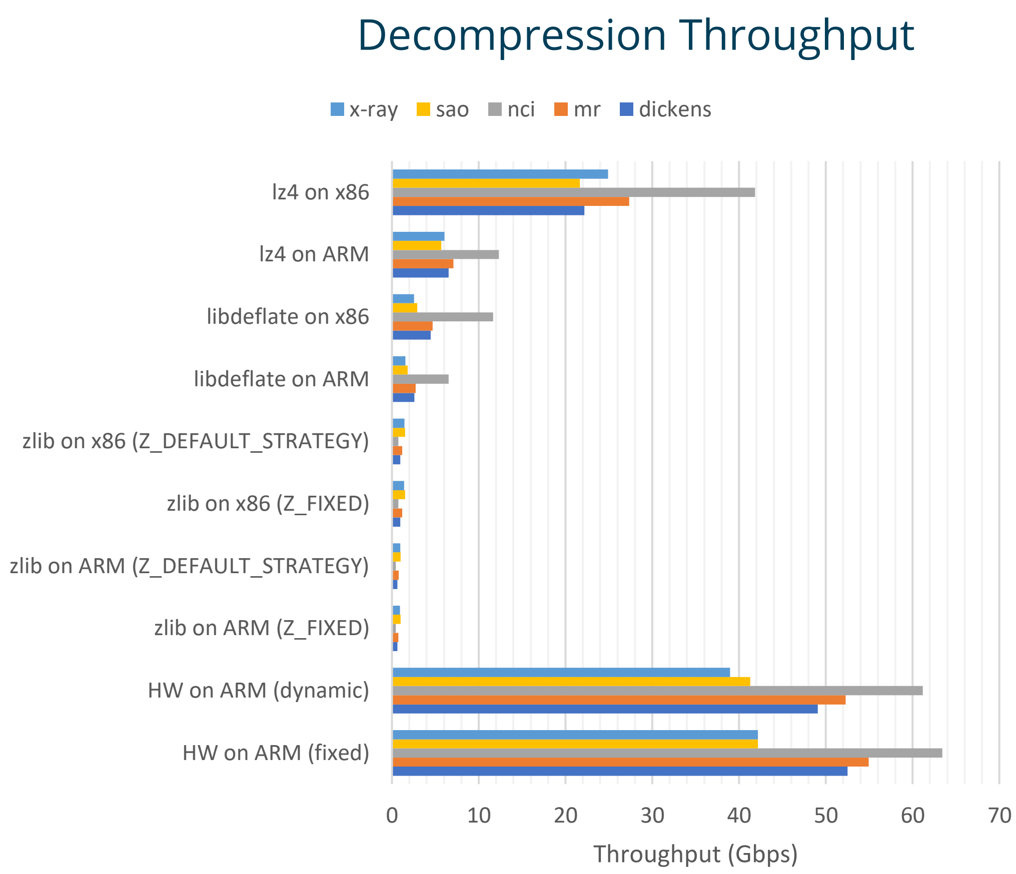


Backup Slides

BlueField-2's Compression is Significantly Faster than Host

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

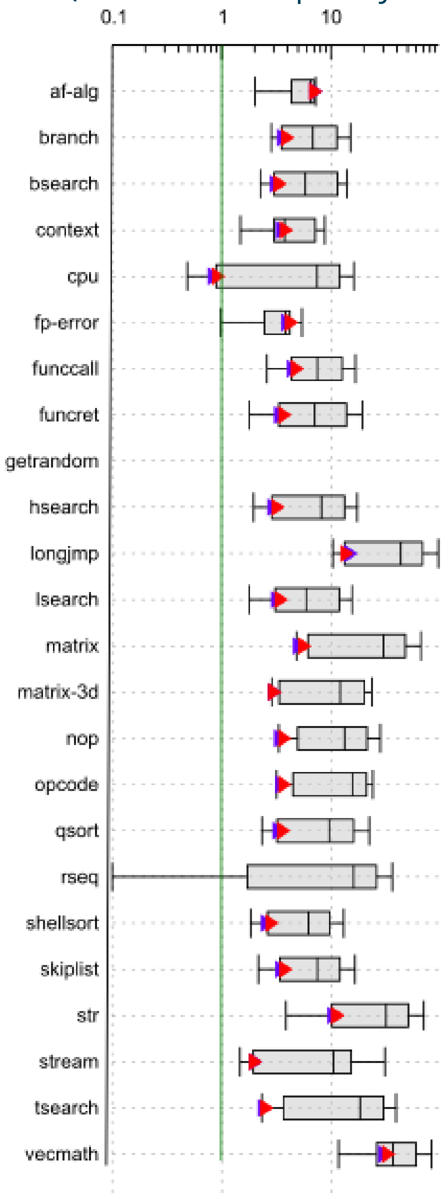




Microbenchmarks

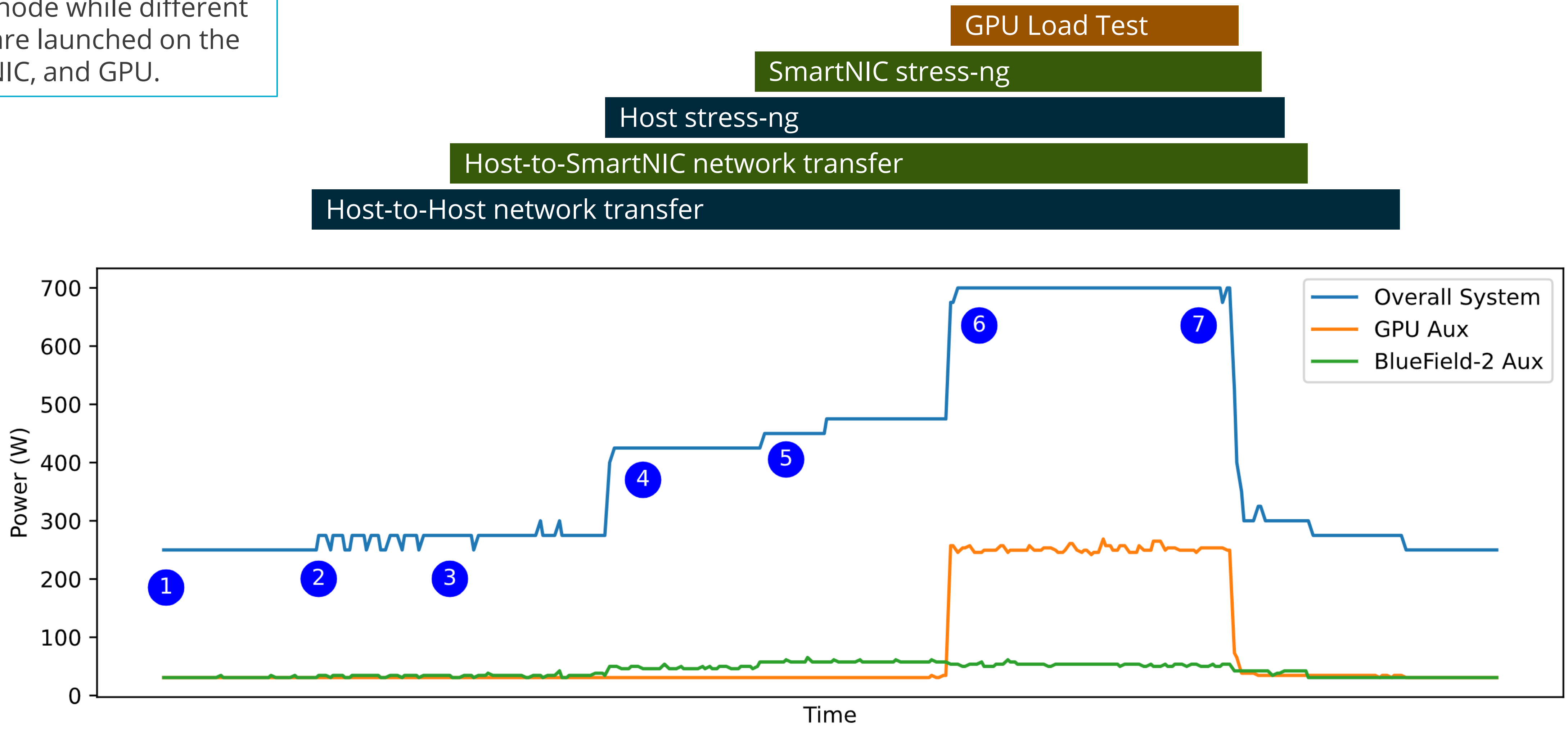
- **stress-ng** from Colin Ian King (Canonical)
  - Suite of 218 stressors for kernel burn-in
  - Normalize results to Raspberry Pi 4B
- Comparison of BlueField-2 to 12 servers
  - Performance range of different servers
  - BlueField-2 2.50 GHz (Ethernet)
  - BlueField-2 2.75 GHz (Ethernet/InfiniBand)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

Performance Speedup
(Relative to Raspberry PI4)



Glinda Power Use in Stress Tests

Internal power measurements for a Glinda node while different stress tests are launched on the host, SmartNIC, and GPU.



Evolution of Network Interface Cards

- NIC hardware is often surprisingly simple
  - FIFO queues to move packets between CPU and Wire
- 1990s: Golden Age of programmable NICs
  - Caltech Mosaic → Myricom, Intel IXP, I2O
  - User-programmable CPU at NIC to control messaging
  - Customize to HPC, multicast, collectives, route to PCI devices
- 2000s: InfiniBand, back to (better) hardware queues
- 2020s: Multiple vendors developing SmartNICs
  - Mellanox/NVIDIA BlueField, Intel IPU, Chelsio
  - Processor for On-Path or Off-Path processing