Extending Composable Data Services into SmartNICs

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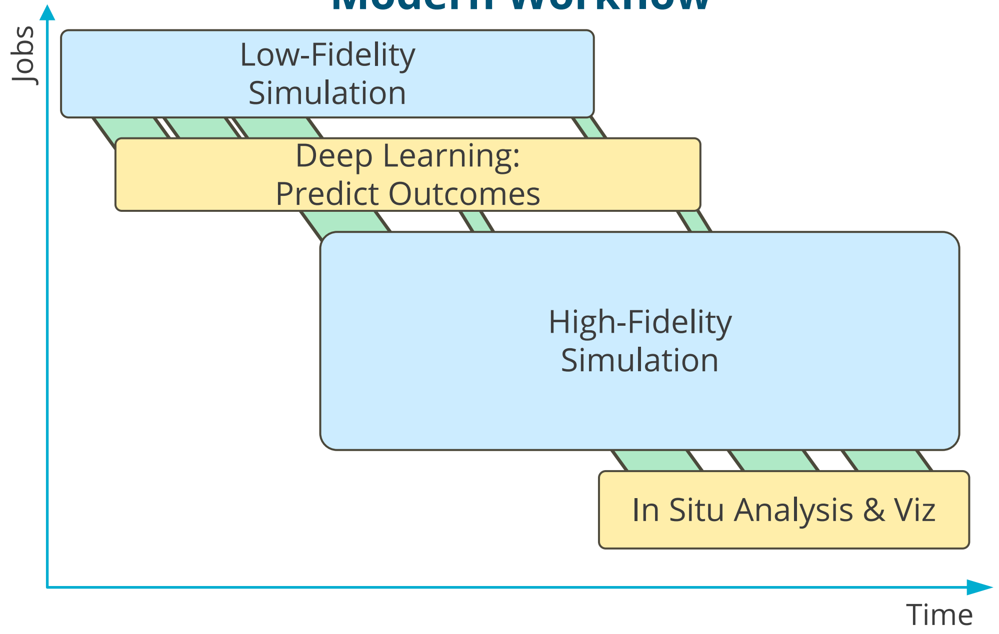
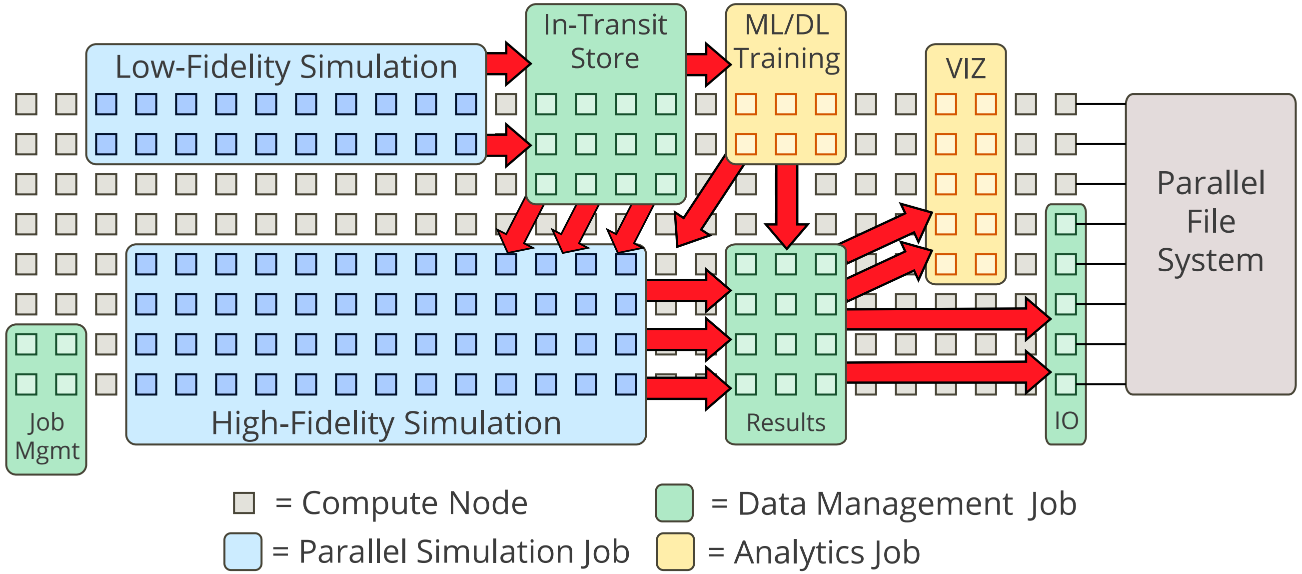
Background: High-Performance Computing Workflows

- Scientific Computing workflows involve multiple applications that run in parallel
- *Composable Data Services* responsible for moving data between applications
- ***Problem***: Data services consume compute-node resources

Modern Workflow



Parallel Jobs on HPC Platform



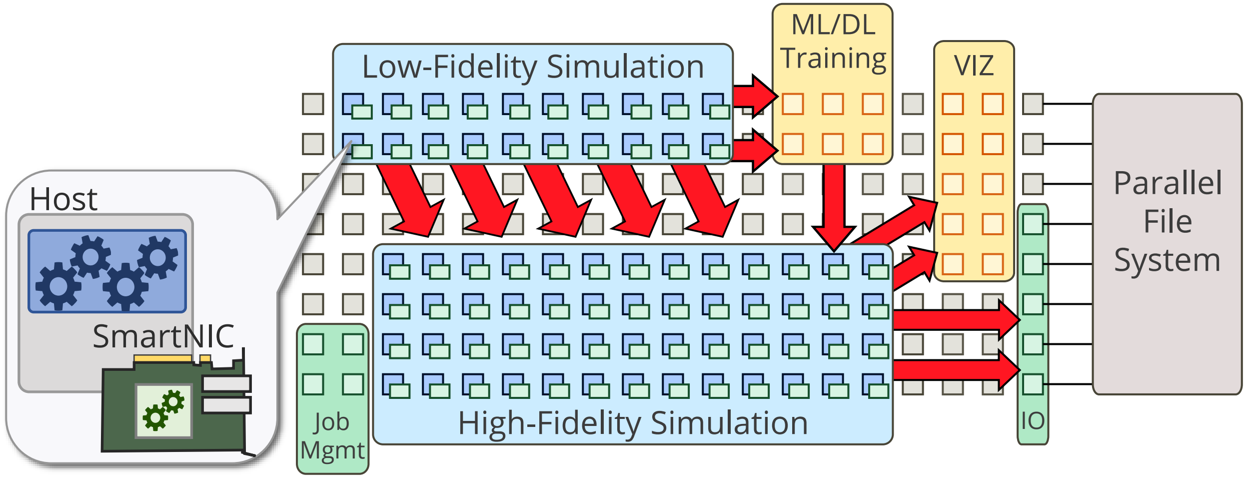
Smart Network Interface Cards (SmartNICs)

- Network vendors now offer SmartNICs with *user-programmable* resources
  - Example: NVIDIA BlueField-2 DPU
  - Embedded processors are an order of magnitude slower than hosts
  - 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

- 100Gb/s InfiniBand
- 8 Arm Cores
- 16GB DRAM
- 60GB Flash

HPC Platform with SmartNICs

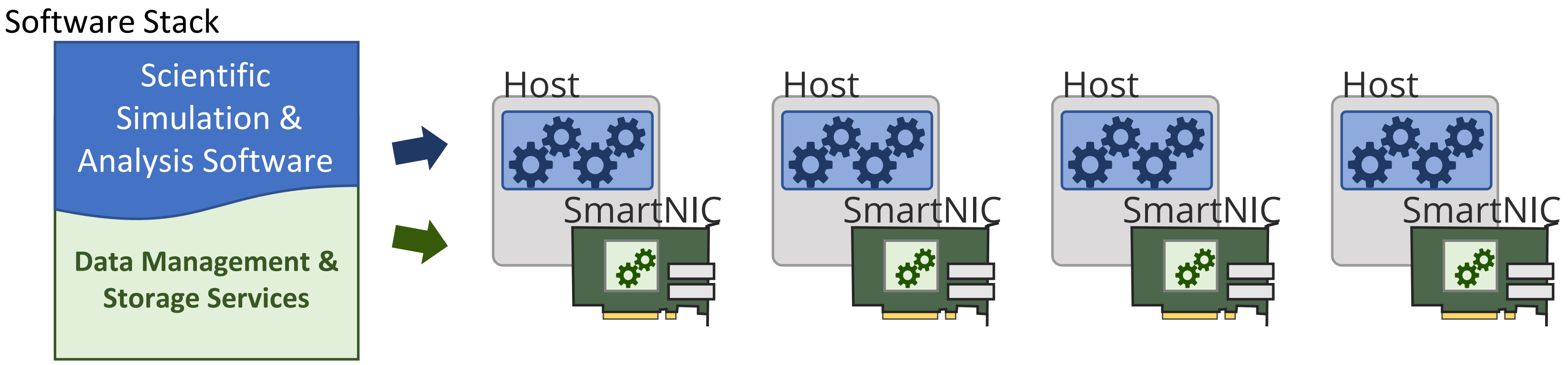


= Compute Node with a *SmartNIC* for offloading data services

Creating an Environment for Data Services on SmartNICs

Create an Environment for Hosting Data Services on SmartNICs

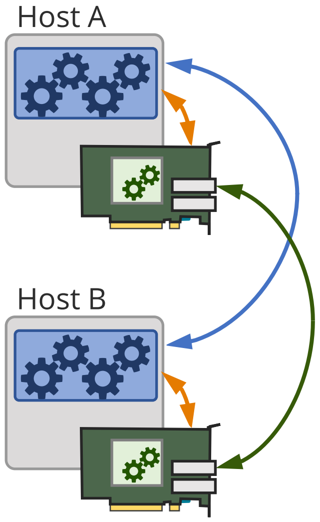
- We define five requirements (R1-R5) for creating this environment
  - Three communication, Two computation
- Existing composable data service libraries for hosts are a good starting point
  - High-level APIs: Remote Procedure Calls, Key/Value stores, Async Tasking, RDMA primitives
- Prototype environment
  - 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

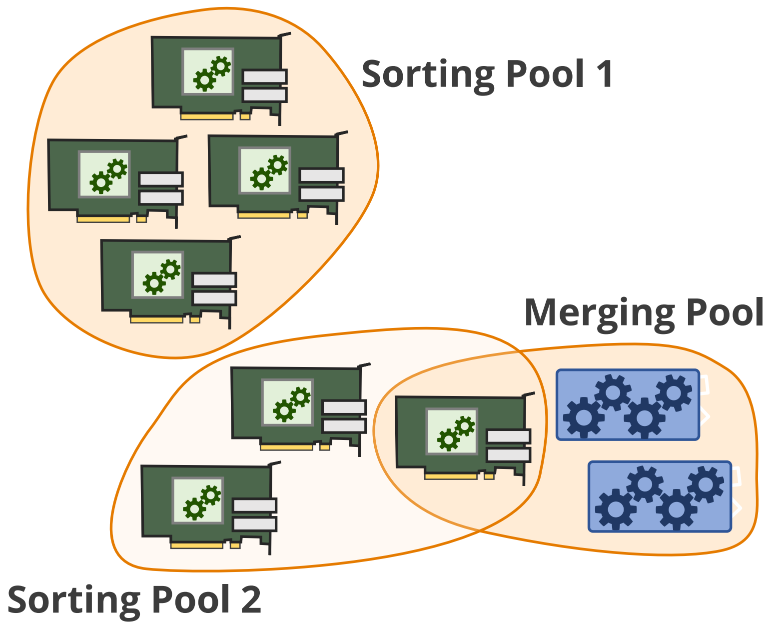
R1: Any-to-Any Transfers

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



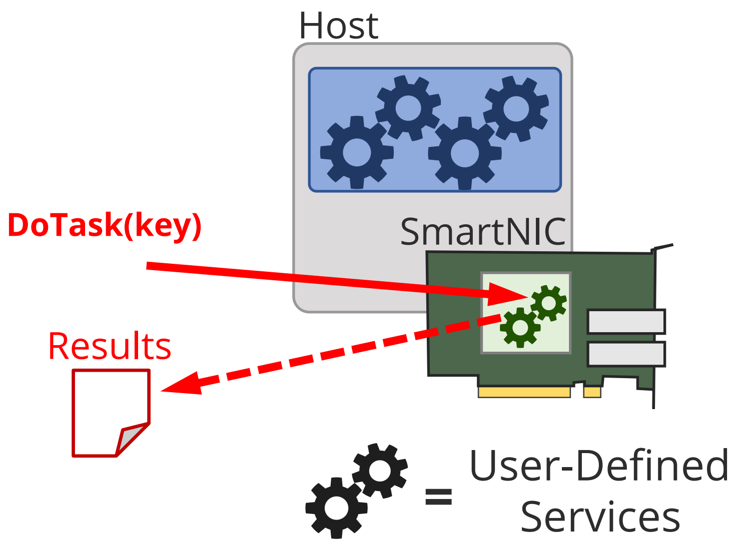
R2: Group Resources

- 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



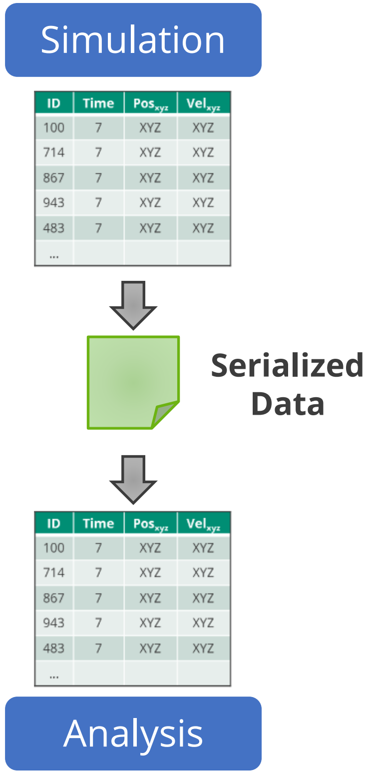
Resolving Computational Requirements with Apache Arrow

R4: Common Data Representation

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

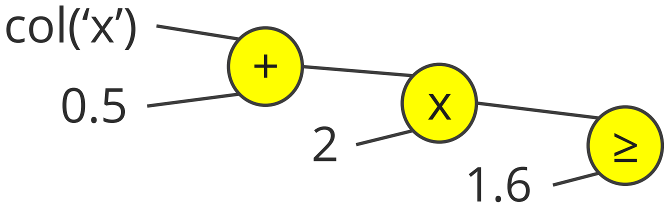
APACHE ARROW

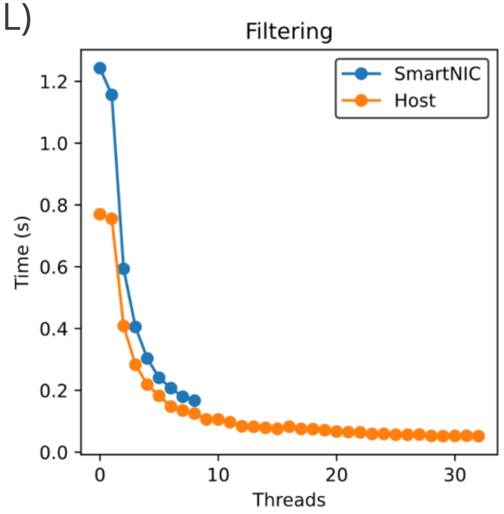
ID	Time	Pos_{xyz}	Vel_{xyz}
100	7	XYZ	XYZ
714	7	XYZ	XYZ
867	7	XYZ	XYZ
943	7	XYZ	XYZ
483	7	XYZ	XYZ
…			



R5: Data-Parallel Computations

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



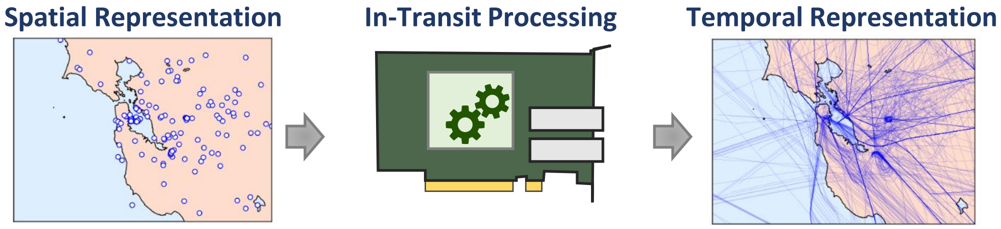



```
// 2 * (0.5 + x) >= 1.6
auto filter_expression = arrow::compute::greater_equal(
    arrow::compute::call(
        "multiply",
        {arrow::compute::literal(2),
         arrow::compute::call("add_checked", {arrow::compute::literal(0.5),
                                              arrow::compute::field_ref("x")})}),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

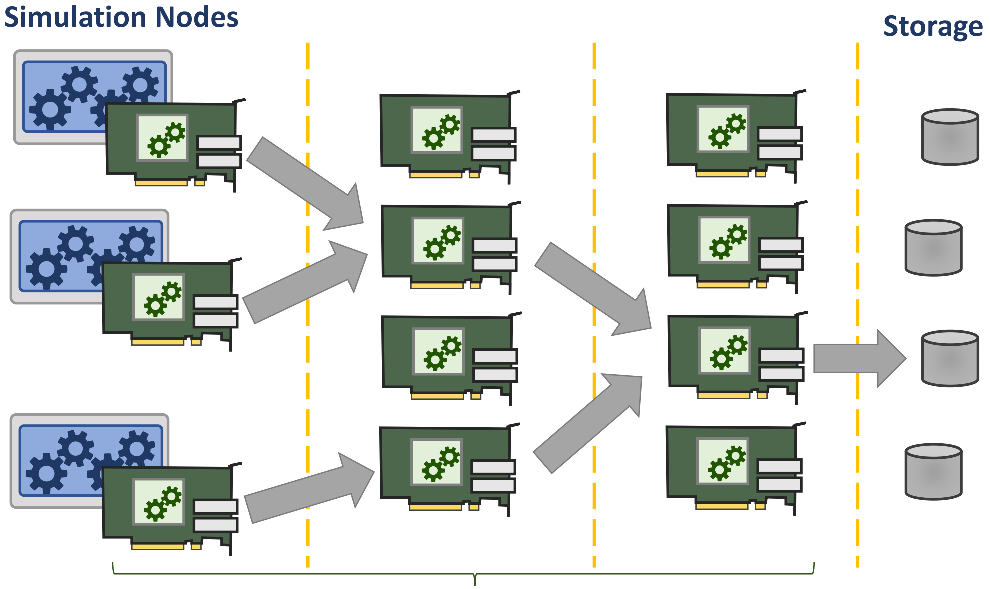
Particle-Sifting Example

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
  - Log-structured merge (LSM) 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



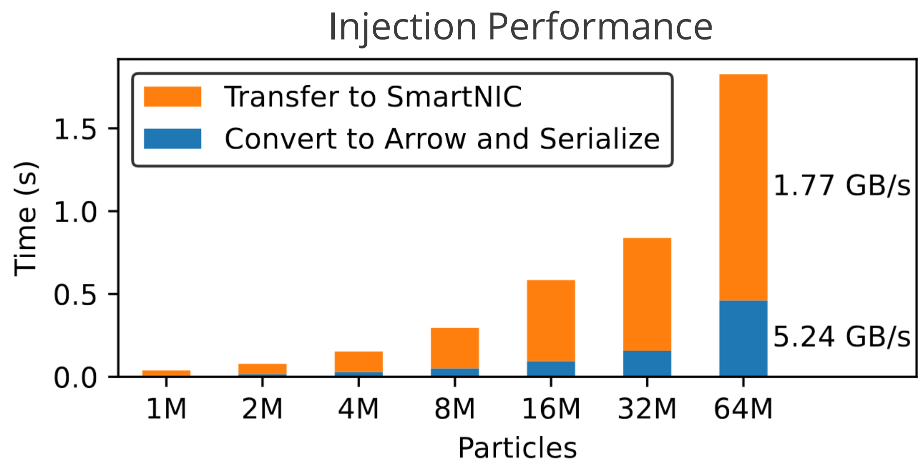
SmartNICs enable simulation results to be transformed while in transit to storage.

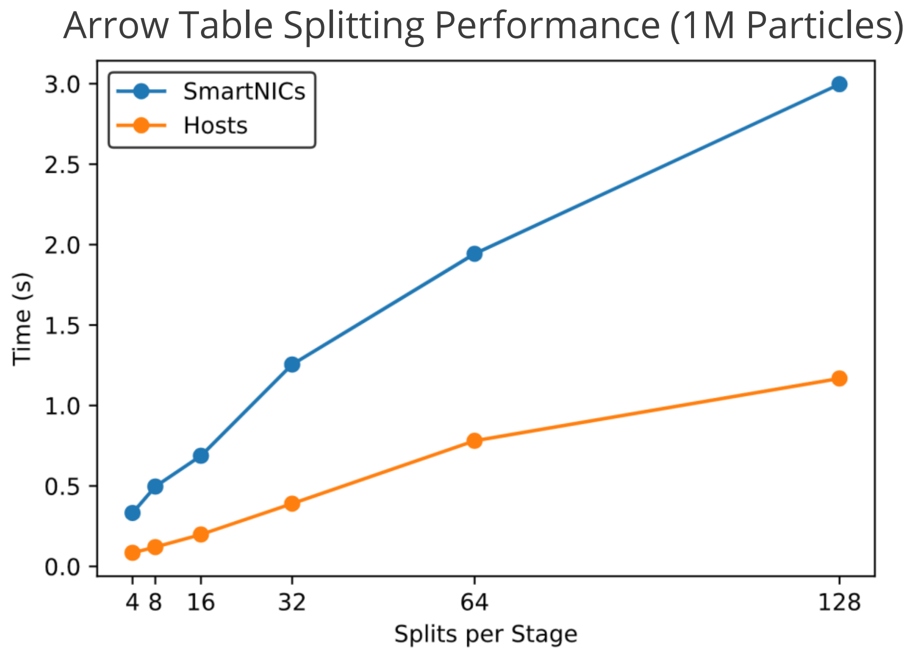


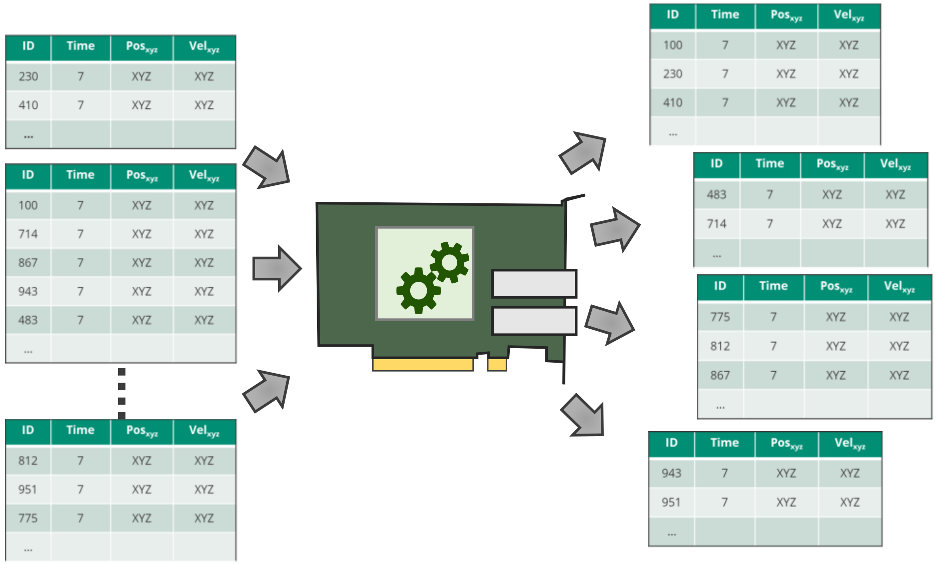
SmartNIC Particle Sifting via Log-Structured Merge Tree

Performance Measurements

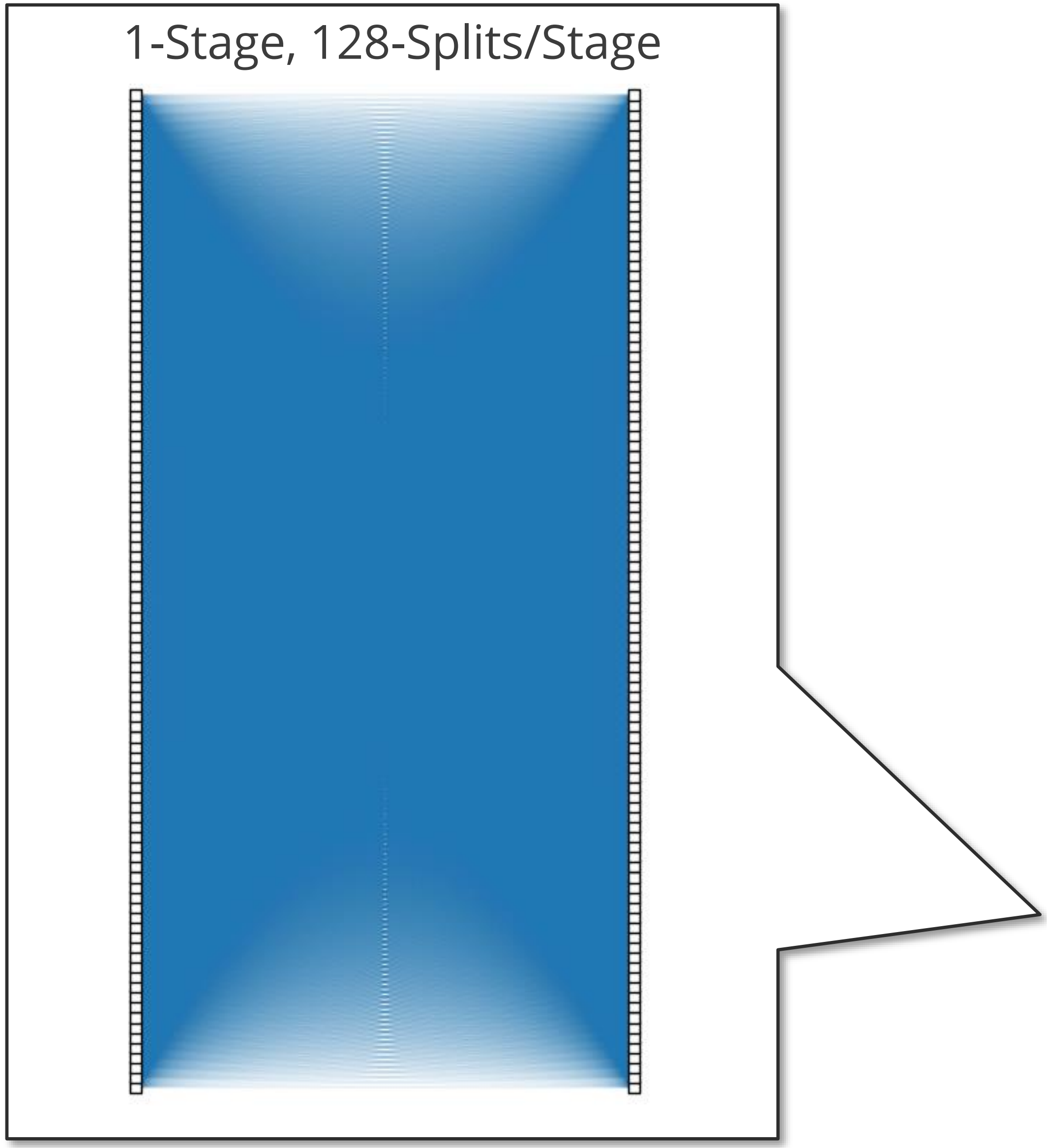
- Injection
  - Convert to Apache Arrow's serialized IPC format
  - Transfer to local SmartNIC
  - 1M–64M Particles (37MB-2.4GB), Overall: 1.32GB/s
- Splitting Tables
  - Merge incoming tables and split based on particle IDs
  - Implemented with Arrow Compute function

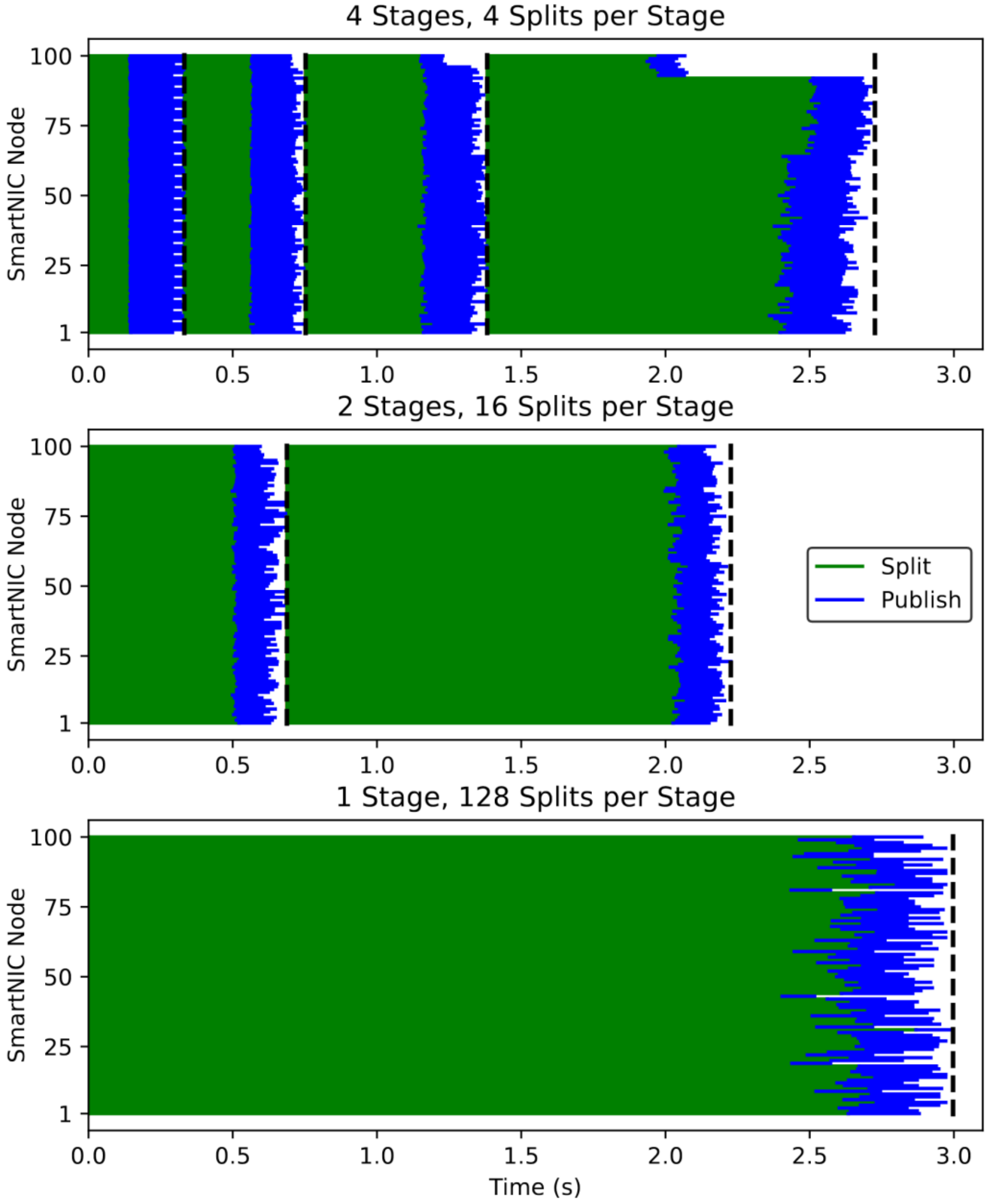






Overall Sifting Performance: 100M Particles on 100 SmartNICs





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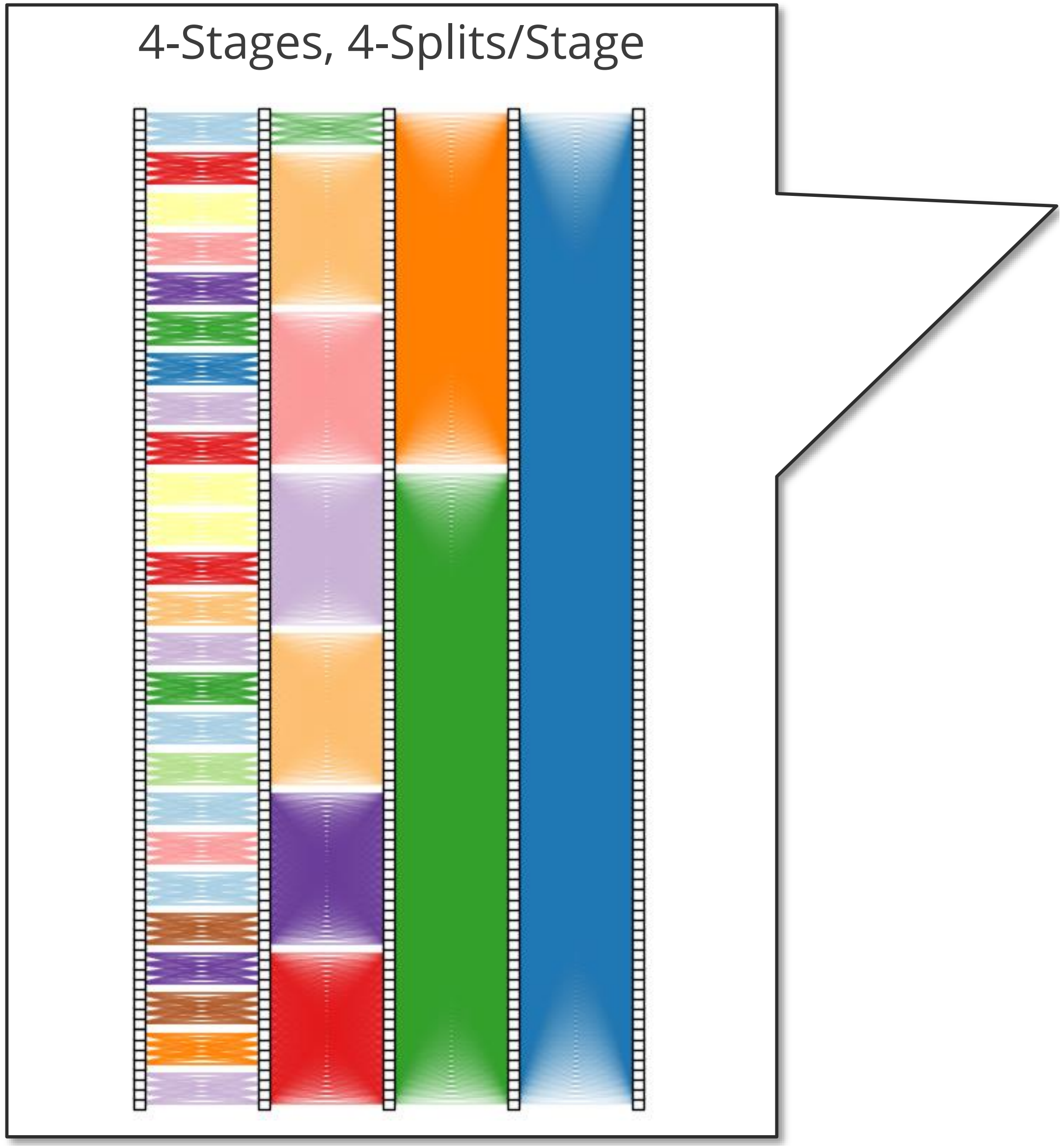

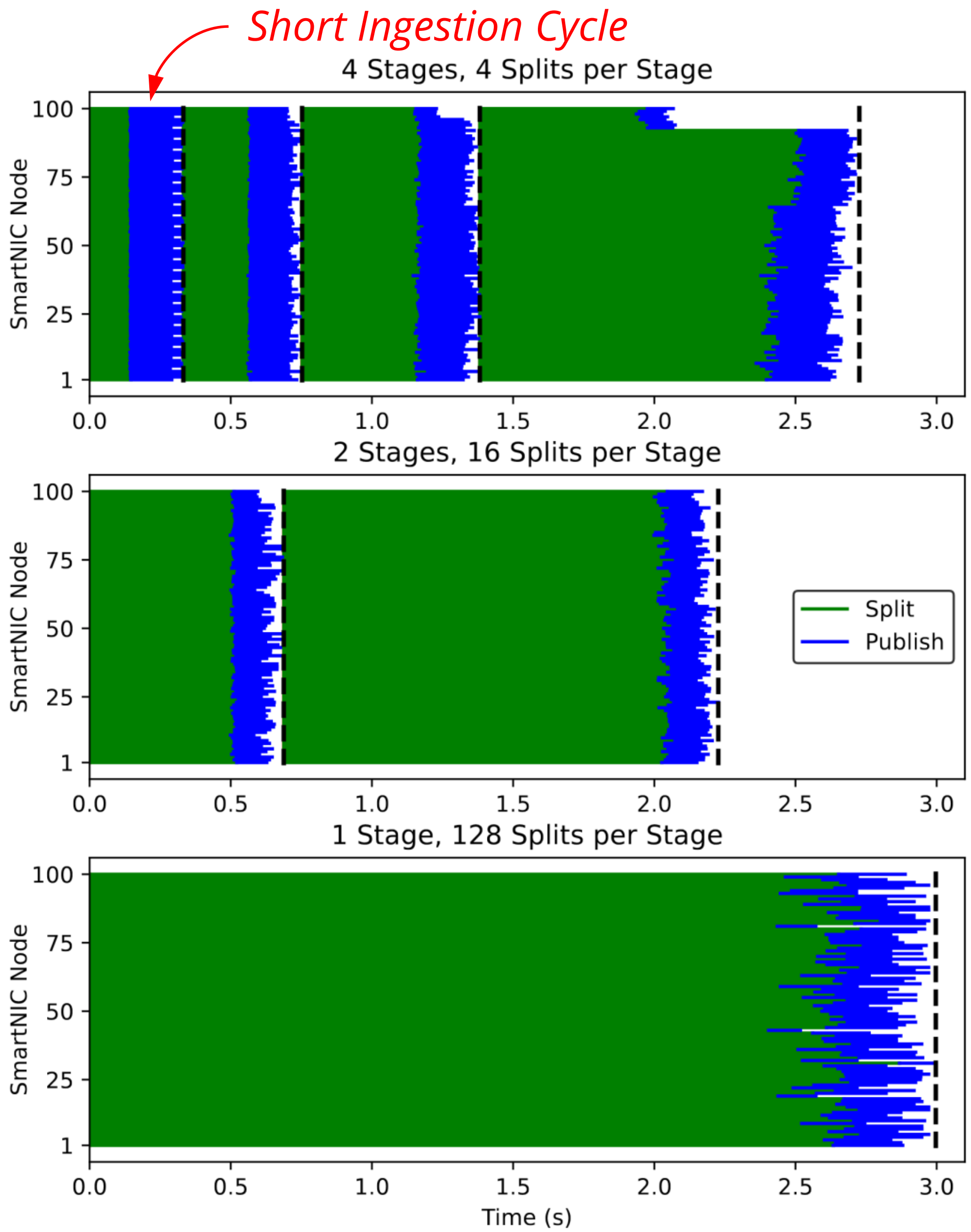

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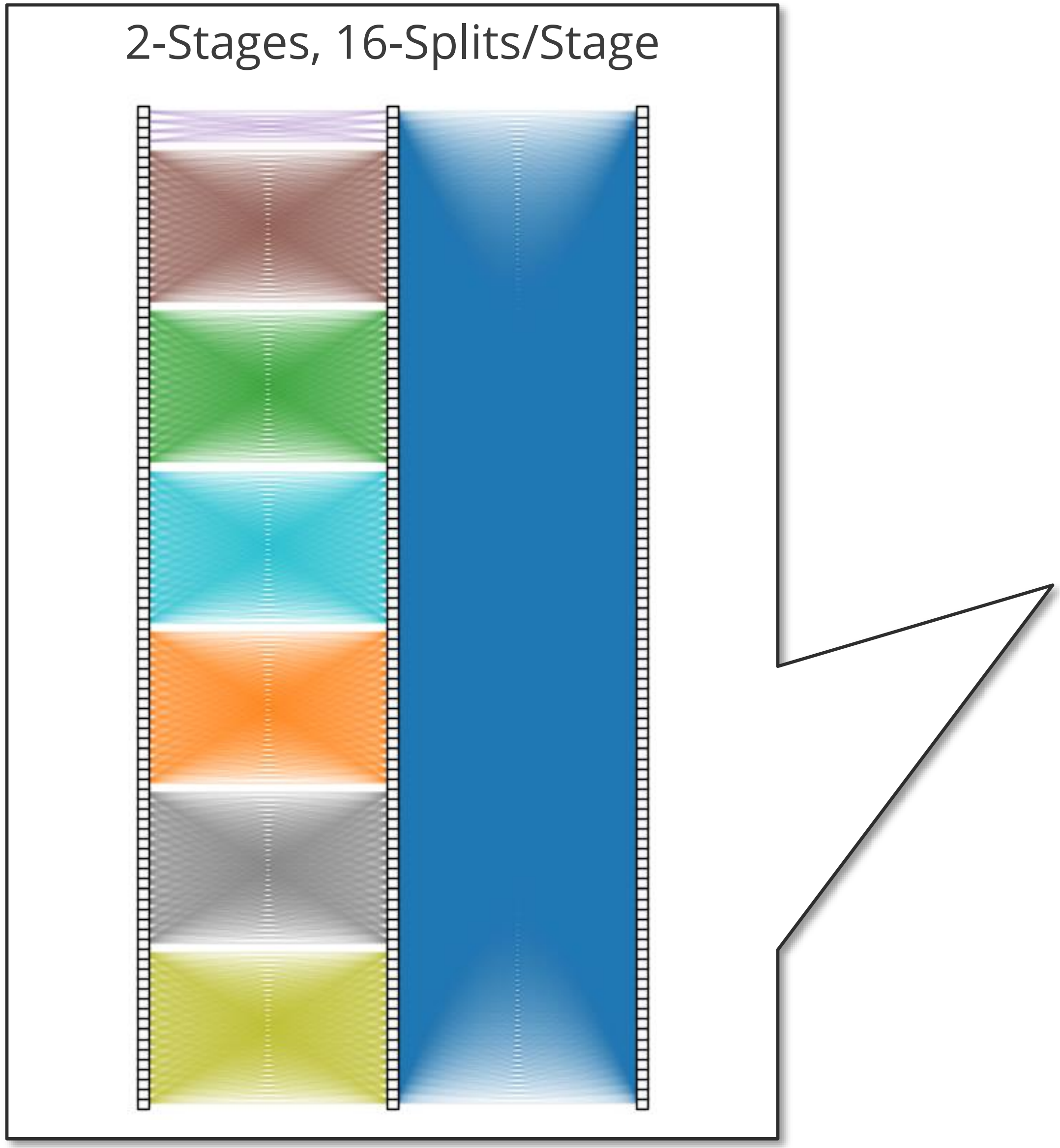
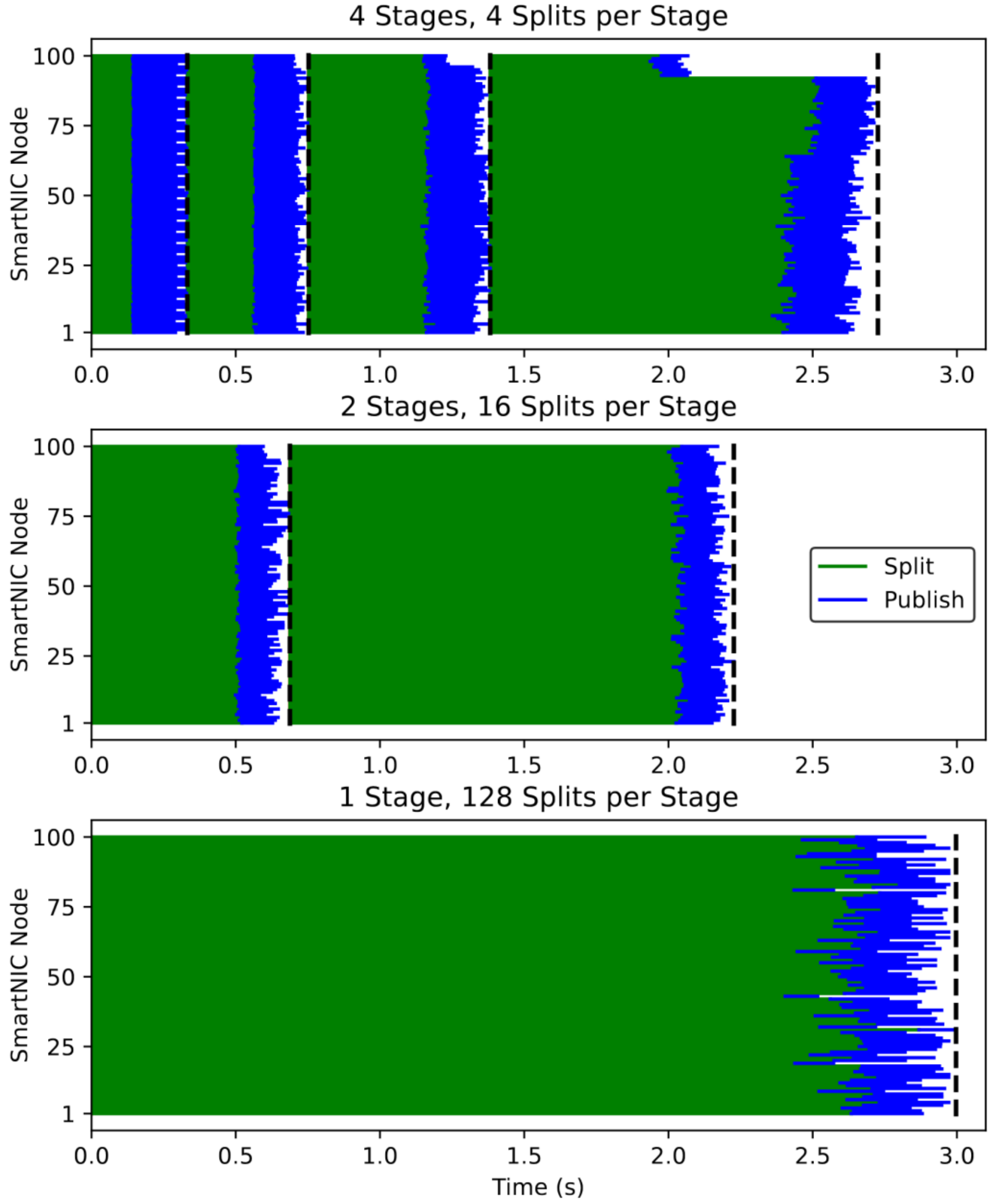
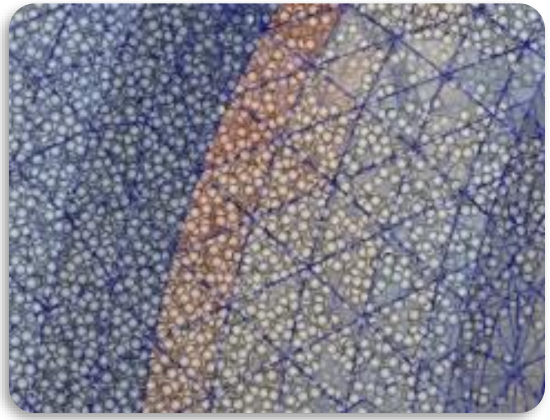




Summary and Future Work

- 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 offers flexible primitives for workflows
  - Apache Arrow simplified development and leveraged parallel hardware
- Future directions
  - Improving injection performance through DOCA and serialization pipelining
  - Embedding query engines in SmartNICs to support push-down queries
  - Evaluate emerging BlueField-3 hardware



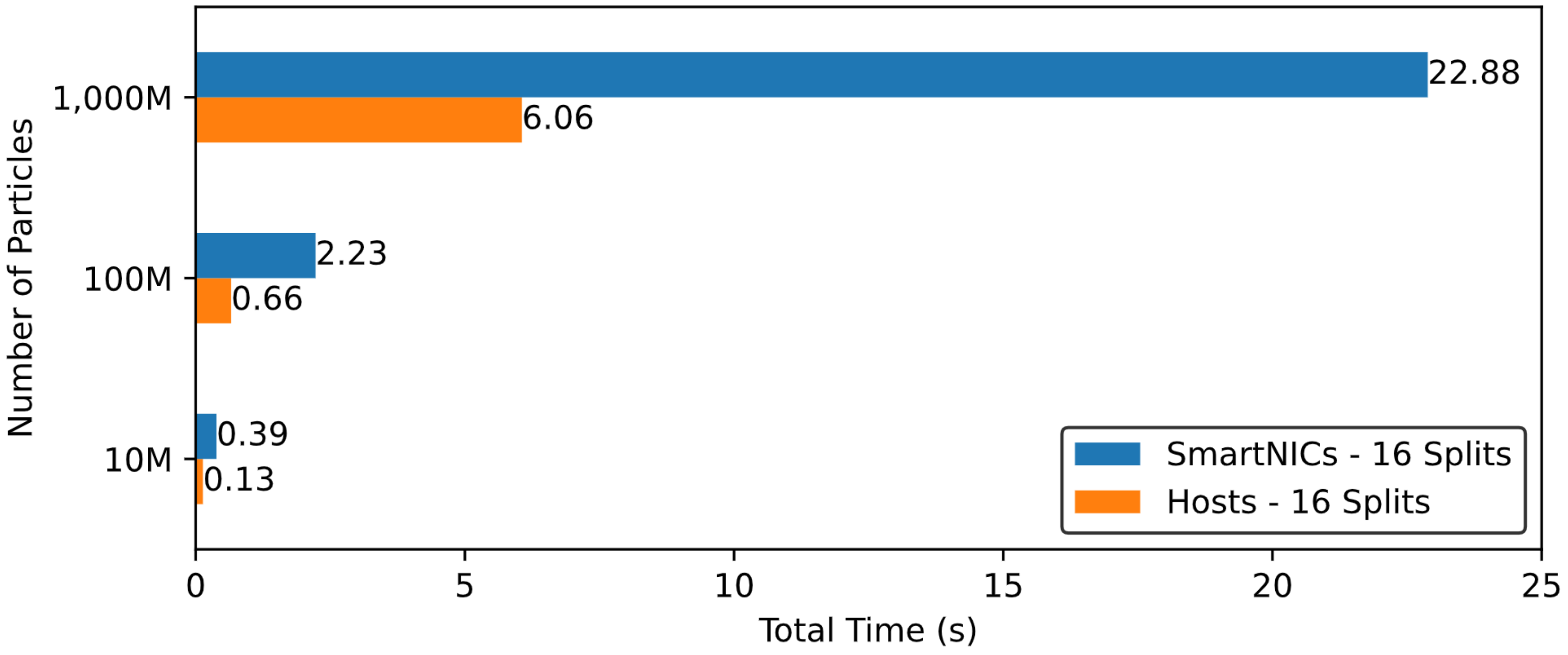
https://github.com/faodel/faodel

https://github.com/apache/arrow

Extras

SmartNIC vs Host Performance for Particle Sifting

- Scaled number of particles from 10M to 1B
  - Selected the best approach for each implementation
  - Hosts roughly 3-4x faster than SmartNICs



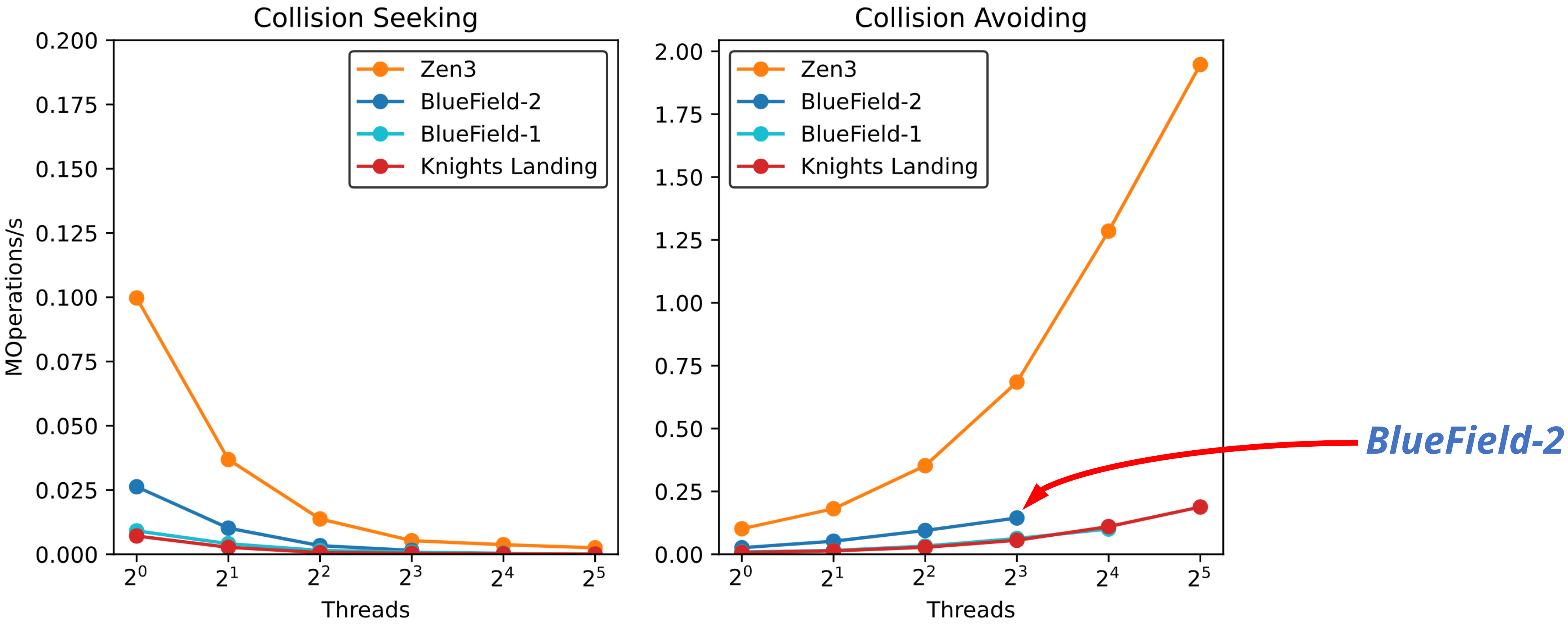
FAODEL Stress Experiments

- How are data management tasks impacted by embedded processors?
  - Stress-ng benchmark inspired us to create **faodel-stress** tool
  - Generating/sorting keys, serializing data, allocating network memory, hash maps, …
  - Compared BlueField to a variety of servers used today in HPC
- Examples Local Key/Blob store

Processor	Year	Architecture	Cores	Frequency	Memory
Zen3	2021	AMD EPYC 7543p	1x32	2.8 GHz	512 GB
BlueField-2	2021	ARMv8 A72	1x8	2.5 GHz	16 GB
BlueField-1	2018	ARMv8 A72	1x16	800 MHz	16 GB
Knights Landing (KNL)	2016	Intel Phi 7250	1x68	1.4 GHz	16+96 GB

FAODEL Stress Experiments: In-memory Key/Blob Store

- Data structure for organizing objects and scaffolding for event-driven operations
  - Perform put/get/drop operations in rapid succession
  - Use key names that either create or avoid contention



Takeaway: BF2 actually faster than some data-parallel processors.