SCALABLE COMPUTING
SOFTWARE LABORATORY

ILLINOIS INSTITUTE
OF TECHNOLOGY

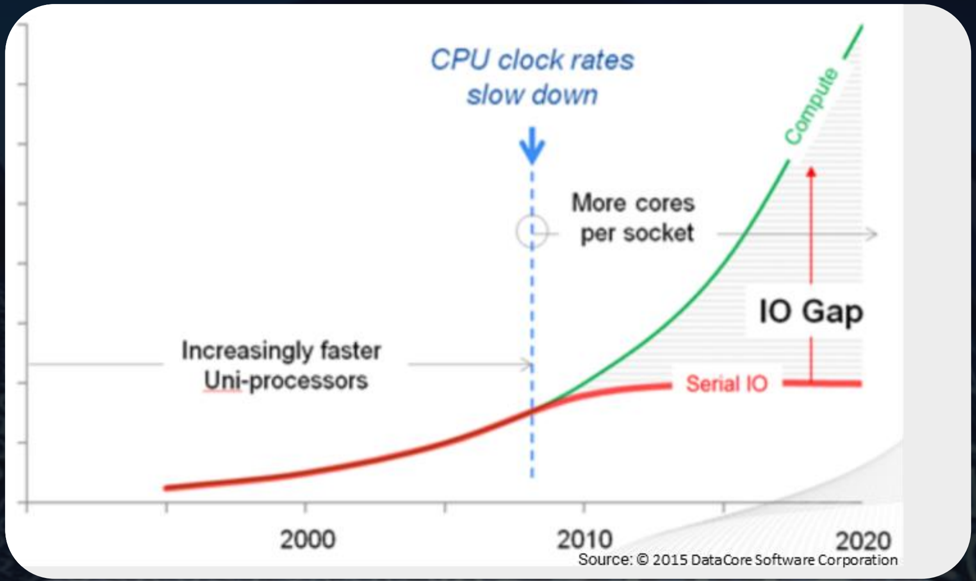
dLABEL:

A Label-Based Data Representation & its Application on Big Data I/O Systems

Xian-He Sun
Illinois Institute of Technology

Keynote Speech at HPBD&IS International Conference, May 23, 2020

The Data Access Bottleneck



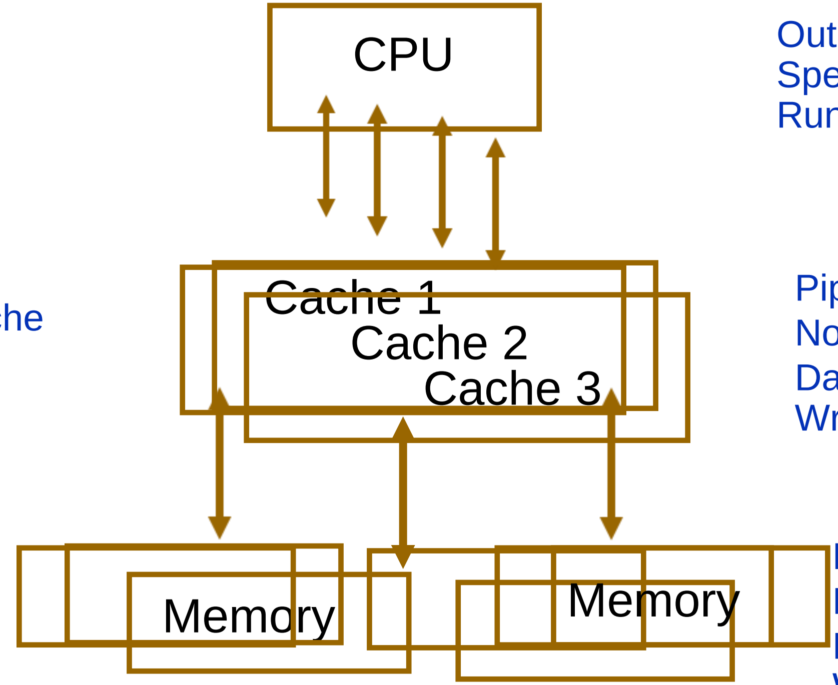
The Memory Wall & I/O Wall

- Super-parallel Computers, Accelerators, Big Data applications
- Many data requests
- Many different data requests
- Many small data requests

System Complicity: Hierarchy, Concurrent, Remote, Heterogeneity

Multi-core
Multi-threading
Multi-issue

Out-of-order Execution
Speculative Execution
Runahead Execution



Multi-banked Cache
Multi-level Cache

Pipelined Cache
Non-blocking Cache
Data Prefetching
Write buffer

Multi-channel
Multi-rank
Multi-bank

Pipeline
Non-blocking
Prefetching
Write buffer

Input-Output (I/O)

Parallel File System

Disks

Diversity of Data Requirements

Feature	Data Requirement	HPC	Cloud/bigdata	Optimizations
Data consistency	Data must be consistent between operations.	Strong, POSIX	Eventual, Immutable	Tunable consistency
Data access	Multiple processes must be able to operate on the same data concurrently.	Shared concurrent	Multiple replicas	Concurrent handlers, Complex locks, Collective access
Global namespace	Data identifiers must be resolved and recognizable in a global namespace that can be accessed from anywhere.	Hierarchical, Directory, Nesting	Flat	Namespace partitioning, Cache & Client-side caching, Decoupling data-metadata, Connectors
Fault tolerance	Data must be protected against faults and errors.	Special hardware, check-pointing	Replication, Data partitioning	Erasure coding
Scale	Support for extreme scale and multi-tenancy	Few large jobs, Batch processing	Many small jobs, Iterative	Job scheduling, buffering, Scale-out
Locality	Jobs are spawned where data reside.	Remote memory & storage	Node local	Data aggregations
Ease of use	Interface, user-friendliness	High-level	Simple data	Amazon S3,

Challenges of a System Solution

- **System Requirement**
  - System Malleability
  - Asynchronous Request
  - Resource Heterogeneity
  - Data Provisioning
  - Storage Bridging

A out-of-box thinking

How retailer giants handle their online order today?

A simple analogy of shopping

- Sending a gift (before)
  - Drive to three different retailers
  - Purchase items independently
  - Decide what package to use
  - Decide which delivery provider
  - Decide options (priority, etc)

- Accessing data (today)
  - Three different data sources
  - Acquire data elements
  - Data representation (file, object, etc)
  - Storage device (SSD, HDD, etc)
  - Storage semantics

A simple analogy of online shopping

- Sending a gift via an online retailer
  - Add items to cart
  - Specify details (payment info, etc.)
  - Submit order
  - The gift is shipped from the warehouse

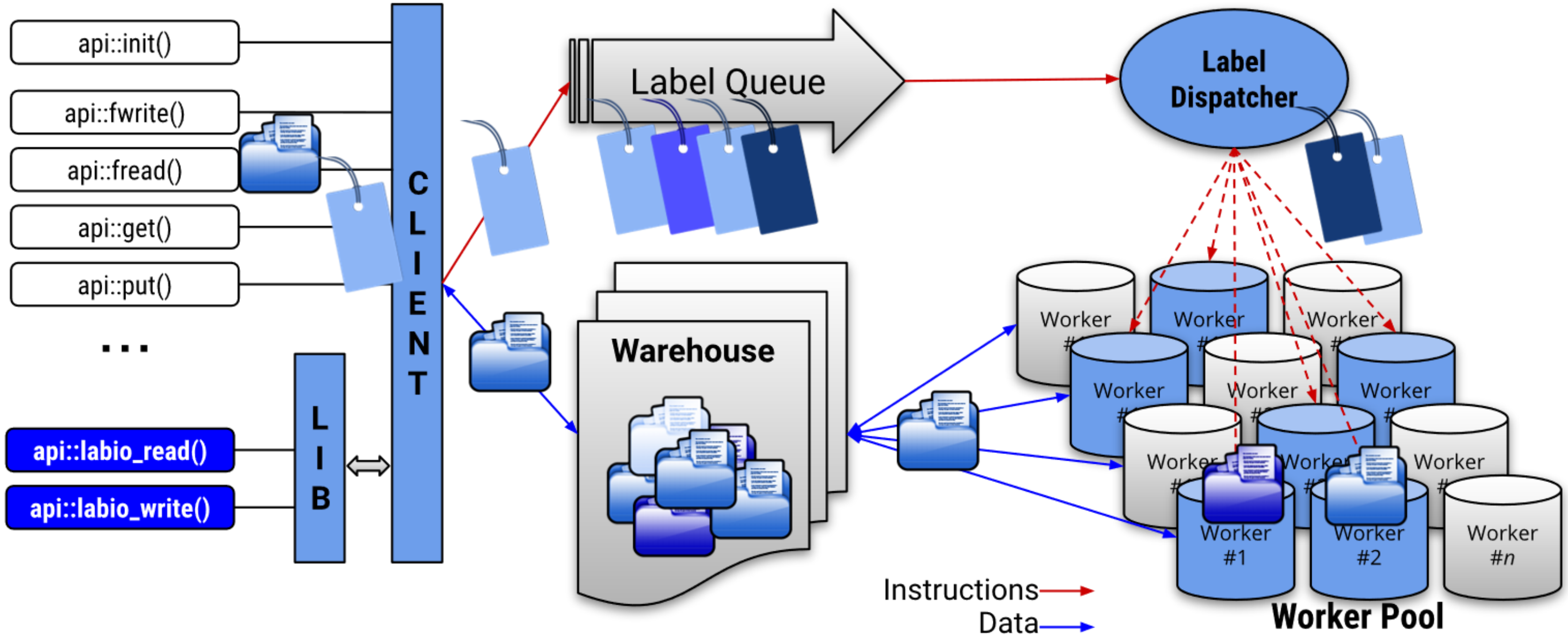
- Similar data management
  - Create labels for data
  - Define label attributes (feature, operation, etc.)
  - Push labels to queue
  - Data operation is carried at the data Wearhouse

The Data Label Representation

- Location-independent abstraction expressing data intent.
- A tuple of one or more operations and a pointer to the physical data.
- Exclusive to each application.
- Immutable, independent of one another, and cannot be re-used.
- Data Label structure includes:
  - Type
  - Unique identifier
  - Source and destination
    - memory address, file path, server IP, network port
  - Function pointer (user-defined or pre-defined)
    - all functions are store in a shared program repository
  - Set of flags indicating label's state
    - queued, scheduled, pending, cached, invalidated, etc.,

A Logical Overview of Data Operation with Label

- Data requests are transformed into a configurable unit, called a (data) ***Label.***
  - A label is a tuple of an operation and a pointer to the data.
  - Resembles a shipping label following a Post Office package.
- Labels are pushed to a distributed queue.
- Data or contents are pushed into a warehouse.
- A dispatcher distributes labels to the workers.
- Workers execute labels independently (i.e., fully decoupled).



The Key Question

Don't have good ideas if you aren't willing to be responsible for them.

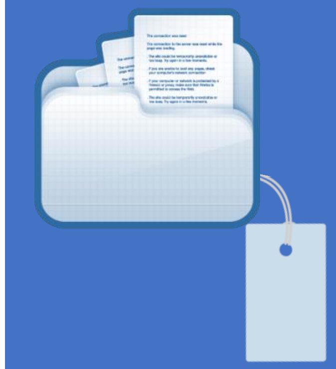
Alan Perlis

Our Solution

LABIOS: A Label-Based I/O System

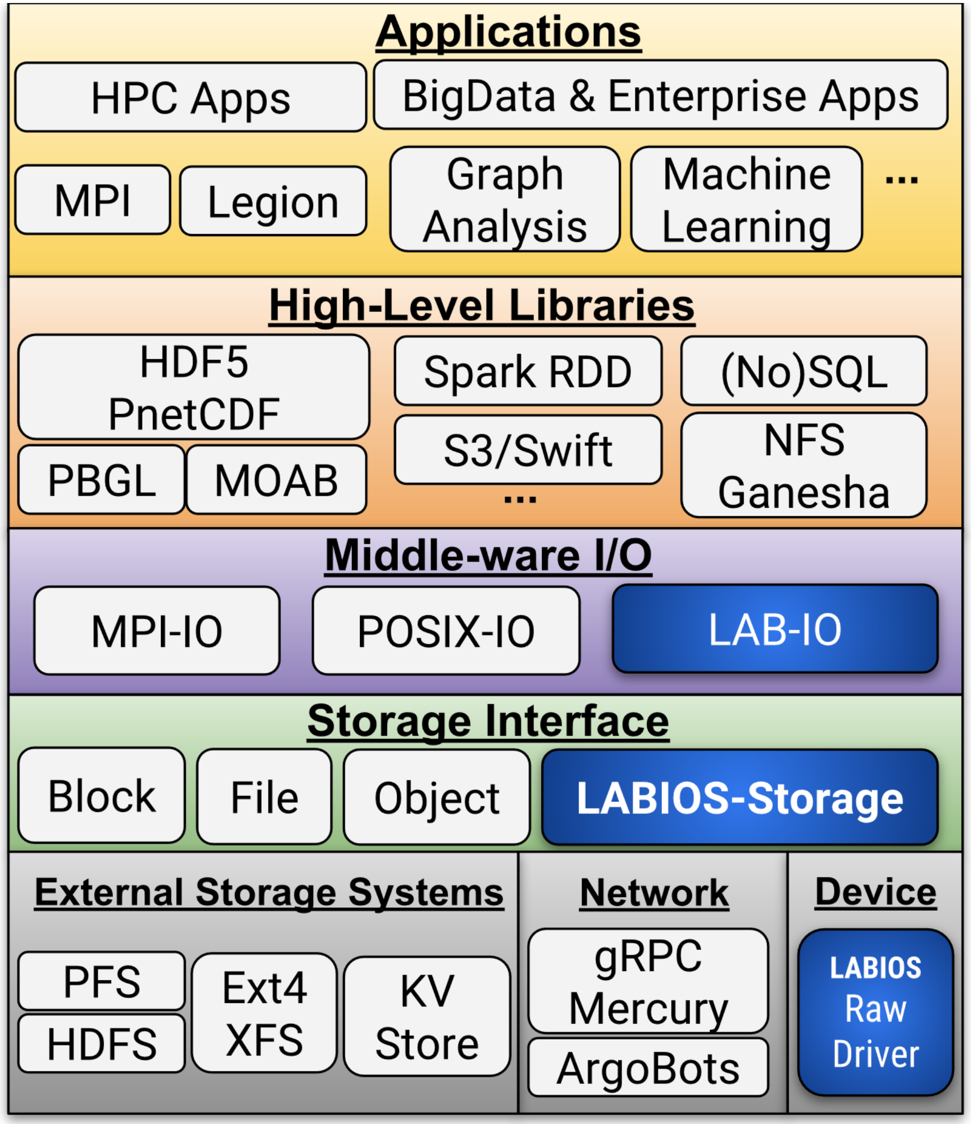
LABIOS: Label-Based I/O System

- Distributed, scalable, and adaptive storage solution
- Fully decoupled architecture
- Software defined storage (SDS)
- Energy-aware enabling power-capped I/O
- Reactive storage with tunable I/O performance
- Flexible API
- Intersection of HPC and BigData



Software Stack

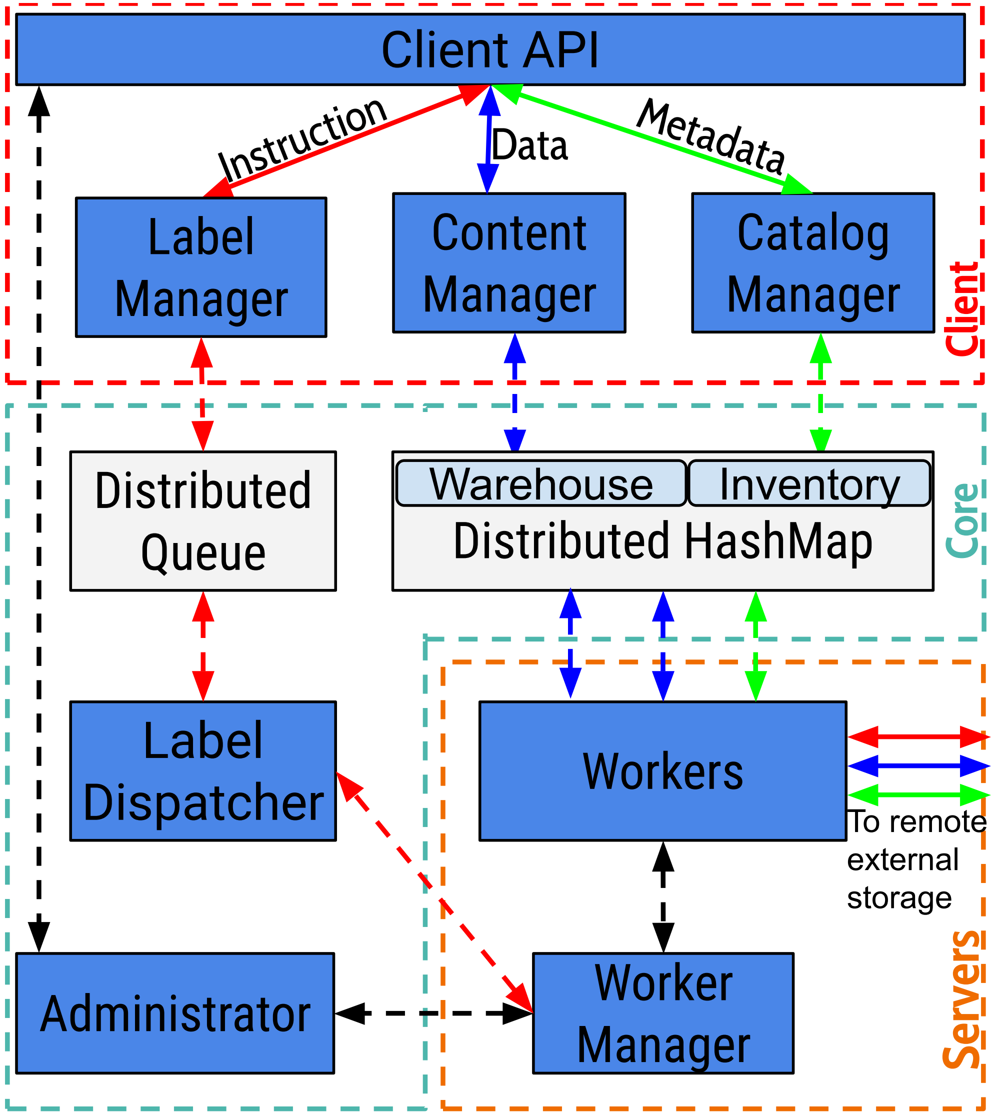
- Can be used as:
  - Middleware I/O library
    - via LABIOS API
  - Full-stack storage solution
    - via I/O call interception
- LABIOS can unify multiple namespaces by connecting to external storage systems. (storage bridging)



LABIOS

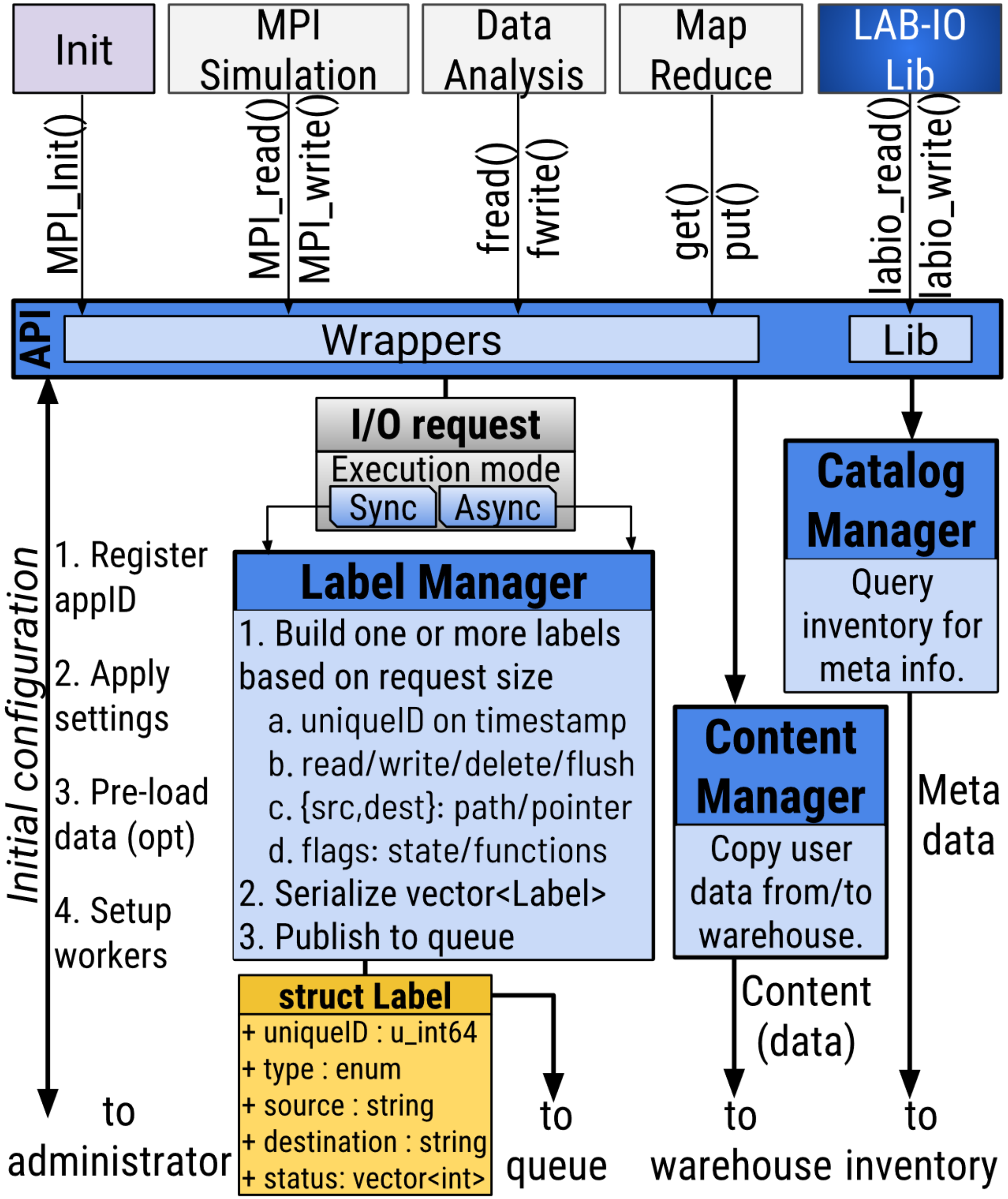
High-level Architecture

- Two main ideas:
  1. Split the data, metadata, and instruction paths.
  2. Decouple storage servers from the application.



LABIOS Client

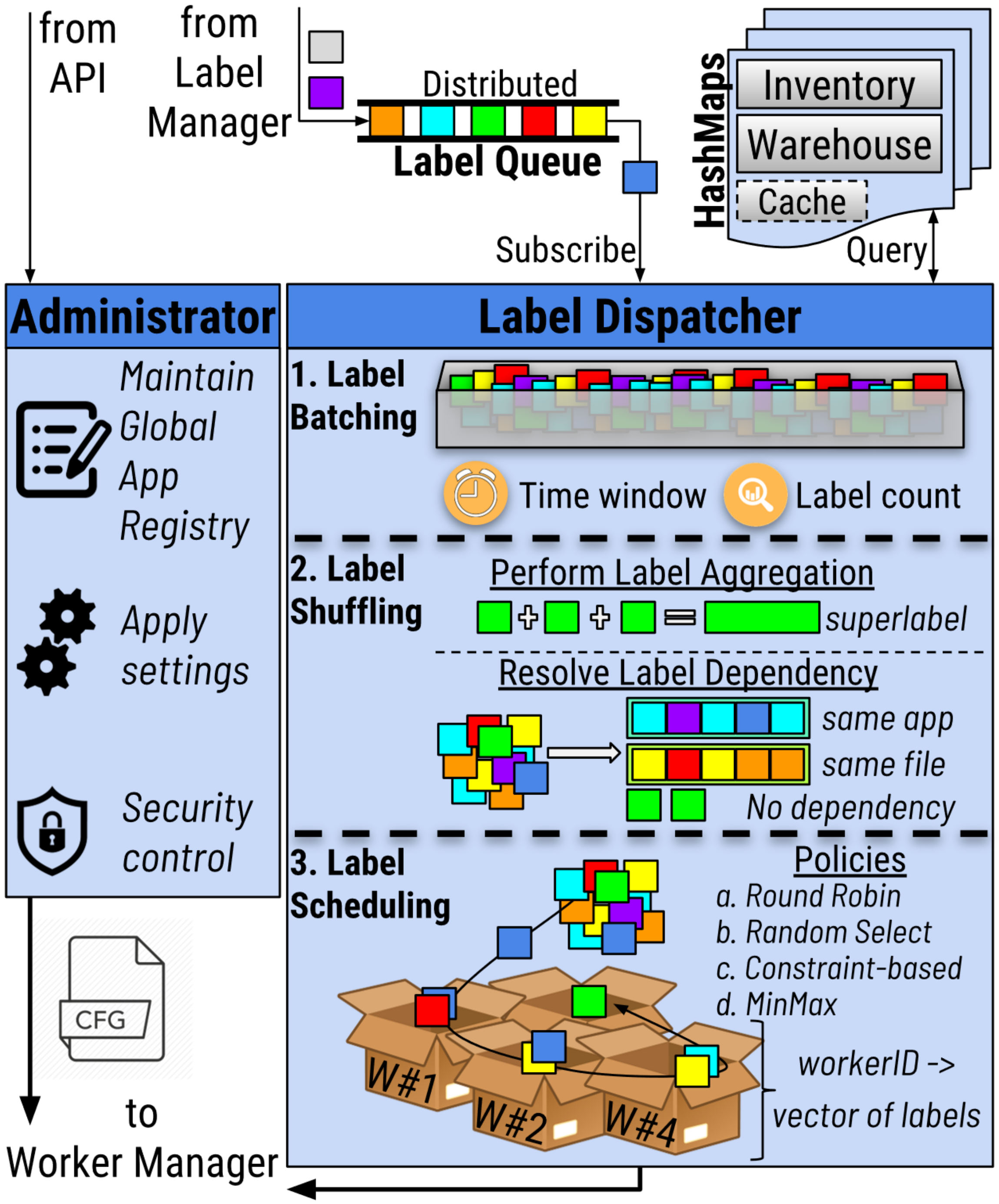
- Objectives:
  1. Performs system initialization per-application.
  2. Accepts application's I/O requests.
  3. Builds labels based on the incoming I/O.
- Modules:
  1. Label manager
  2. Content manager
  3. Catalog manager



LABIOS Core

- Manages the instruction, data, and metadata flow separately.
- Distributed data structures:
  - Label queue
  - Warehouse
- Modules:
  - Administrator
  - Label Dispatcher

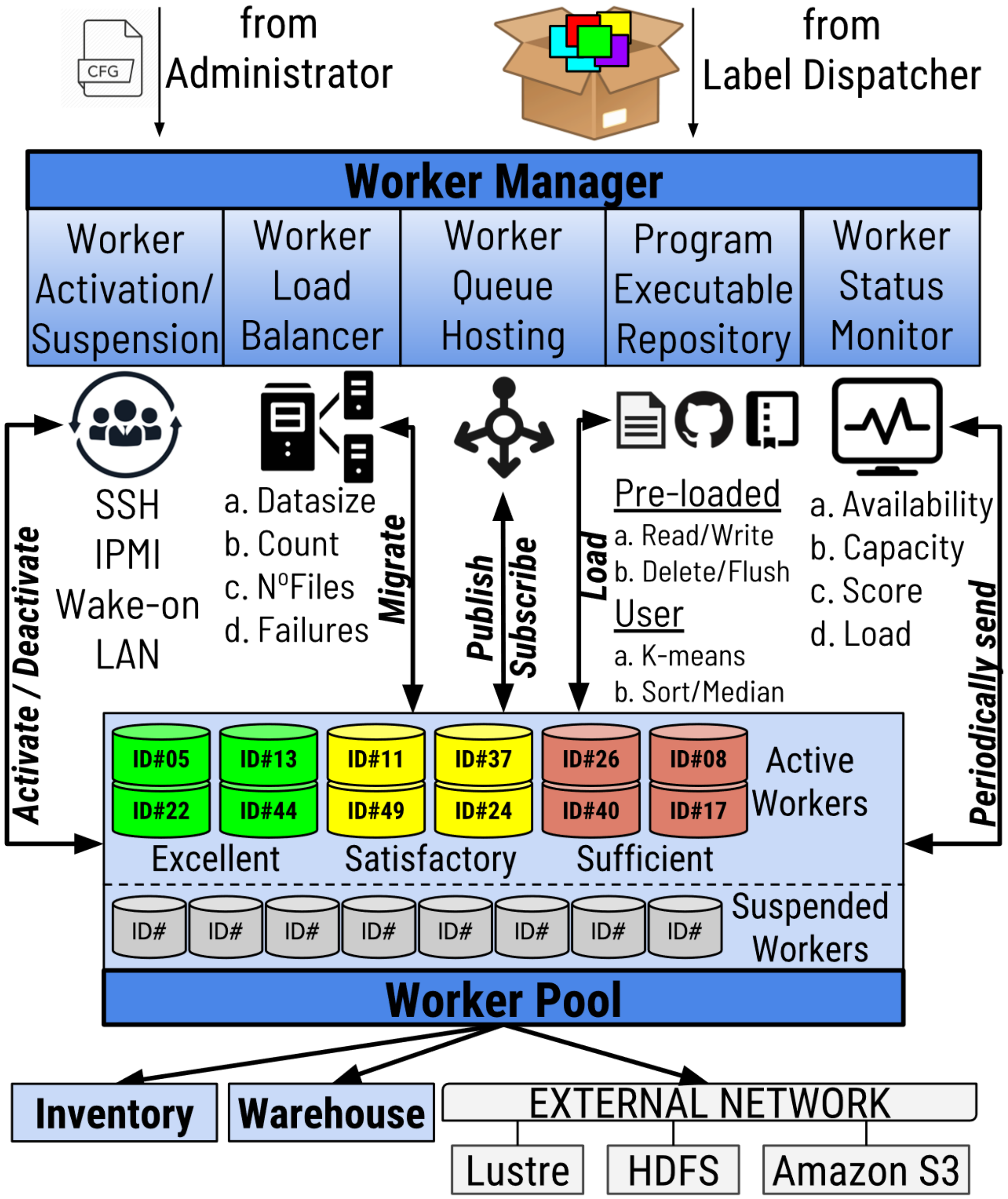
    Optimization and scheduling



LABIOS Server

- Manages workers (i.e., storage servers)
- Modules:
  - Worker

    Logical entity who carries the work
  - Worker manager



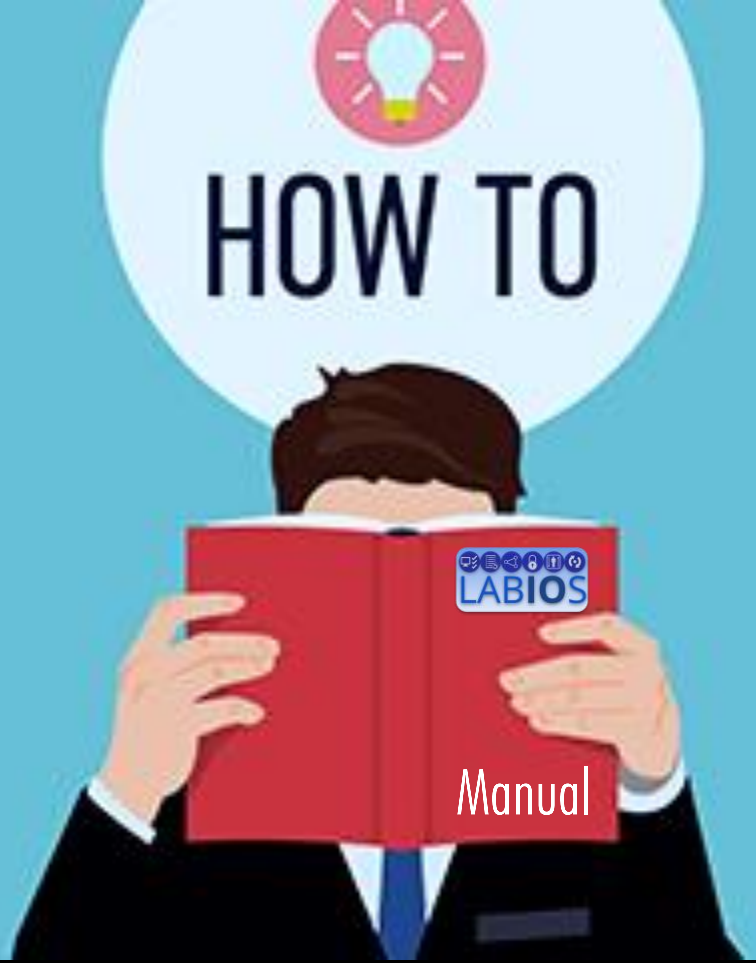
Worker

- The storage server in LABIOS
- Responsibilities:
  - service its own queue
  - execute labels
  - calculate its own worker score and send it to the worker manager periodically
  - auto-suspend itself if there are no labels in its queue for a given time window
  - connect to external storage sources
- Weighting system expresses the scheduling policy
- Final score is a double precision between 0 and 1
  - Higher score -> better worker

Variable	Value	Example
Availability	1-active, 0-suspended	1
Capacity	Double [0,1] (ratio remaining/total)	0.75
Load	Double [0,1] (ratio current/max queue size)	0.50
Speed	Integer [1,5] (grouping)	4
Energy	Integer [1,5] (grouping)	3

$$Score(workerID) = \sum_{n=1}^{5} Weight_j \times Variable_j$$

Priority	Availability	Capacity	Load	Speed	Energy
Low latency	0.5	0	0.35	0.15	0
Energy savings	0	0.15	0.2	0.15	0.5
High bandwidth	0	0.15	0.15	0.70	0

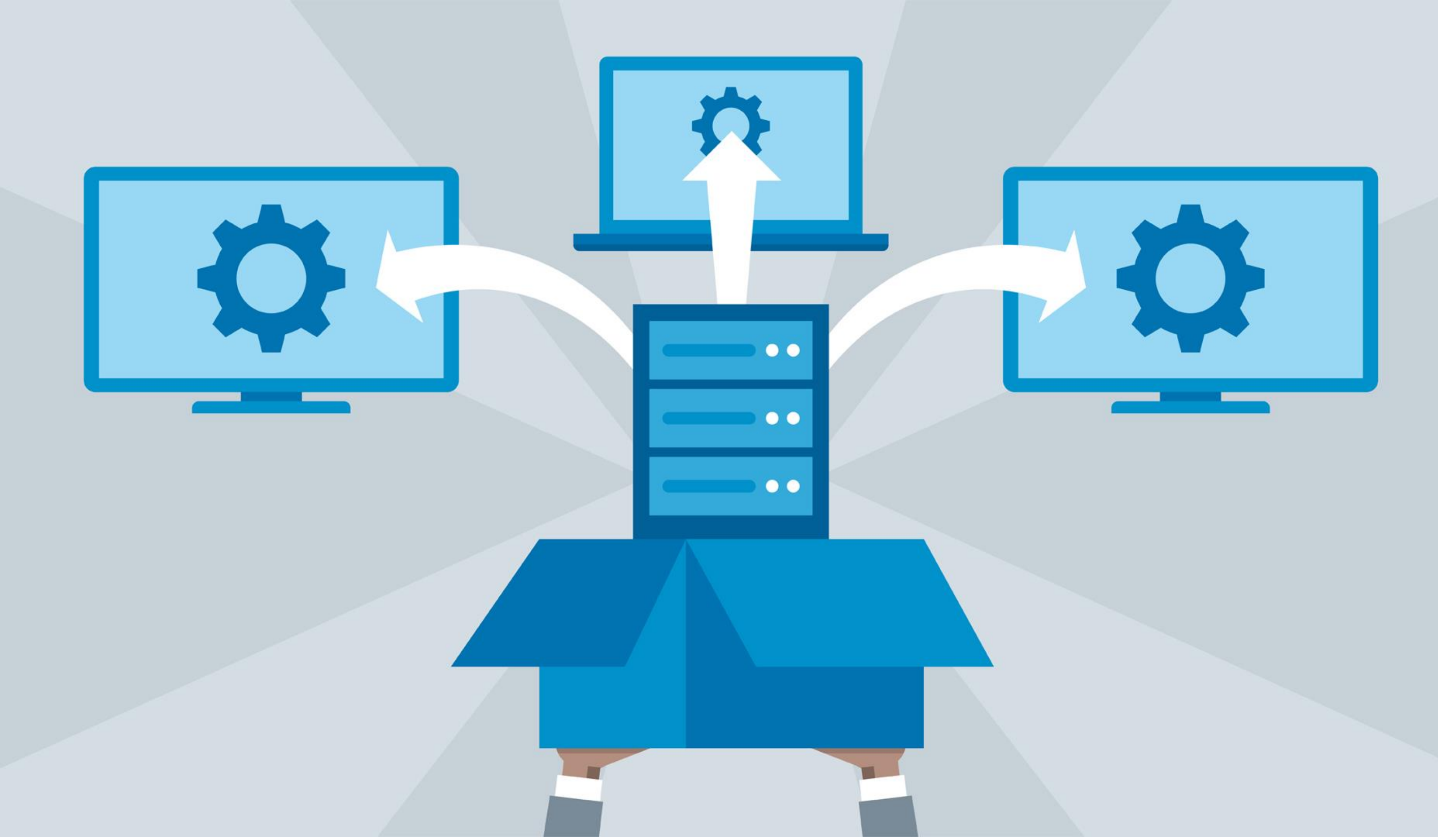


LABIOS in depth

- Label Scheduling
- Deployment Models
- LABIOS API example

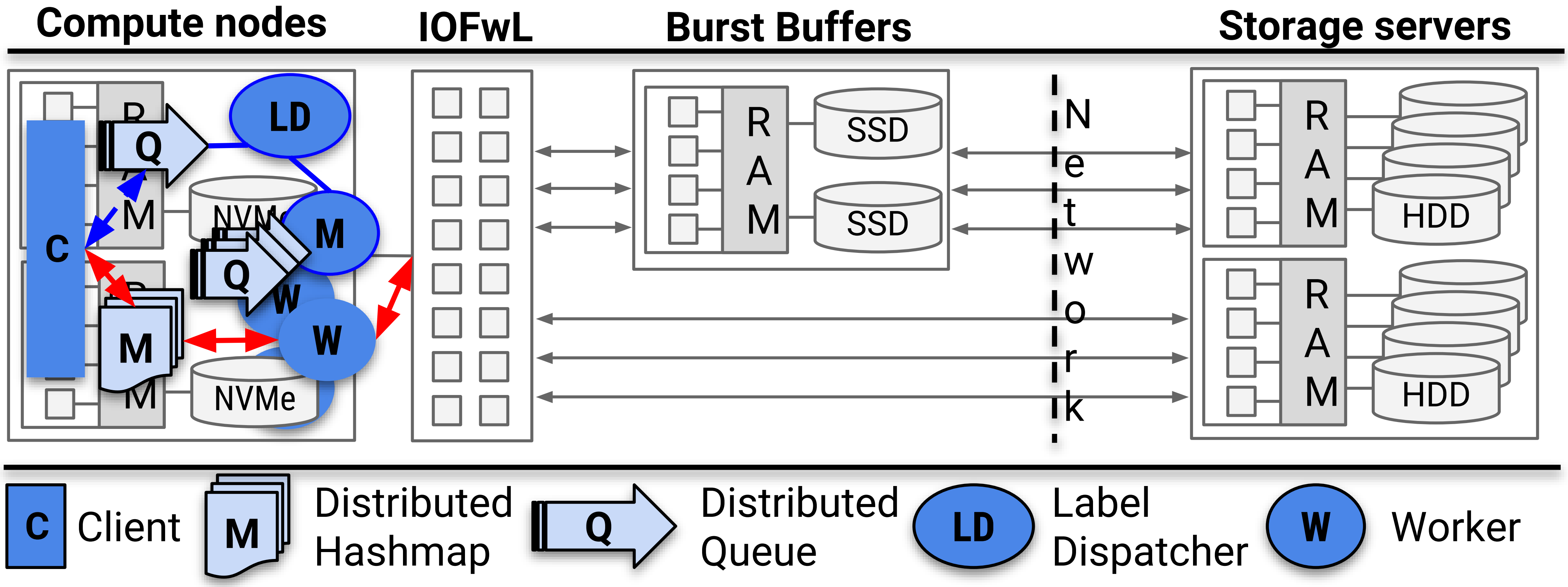
Label Scheduling

- Data distribution via scheduling policies:
  1. Round Robin
     - similar with PFS
  2. Random Select
     - randomly select workers
  3. Constraint-based (i.e., heuristically)
     - Priorities based on higher weight in the worker score
       - Availability, load, capacity, performance
  4. MinMax
     - Minimize energy consumption while maximizing performance
       - Subject to load and capacity
     - NP-hard combinatorial optimization
       - Multidimensional knapsack algorithm



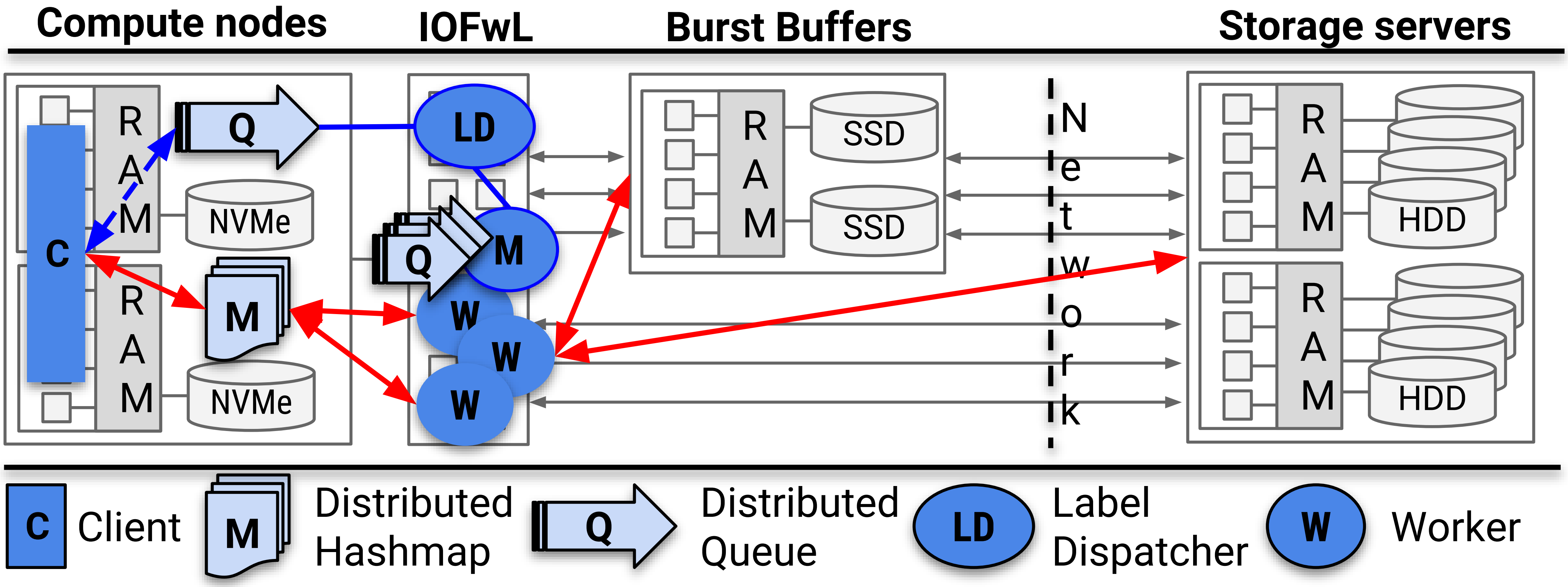
Deployment Model

- LABIOS can:
  1. replace existing distributed storage solutions
  2. be used as I/O accelerator to one or more underlying storage subsystems
- Machine model in use (motivated by the recent machines Summit in ORNL or Cori on LBNL):
  - Compute nodes equipped with a large amount of RAM
  - Local NVMe devices in each compute node
  - An I/O forwarding layer
  - A shared burst buffer installation based on SSD equipped nodes, and
  - A remote PFS installation based on HDDs



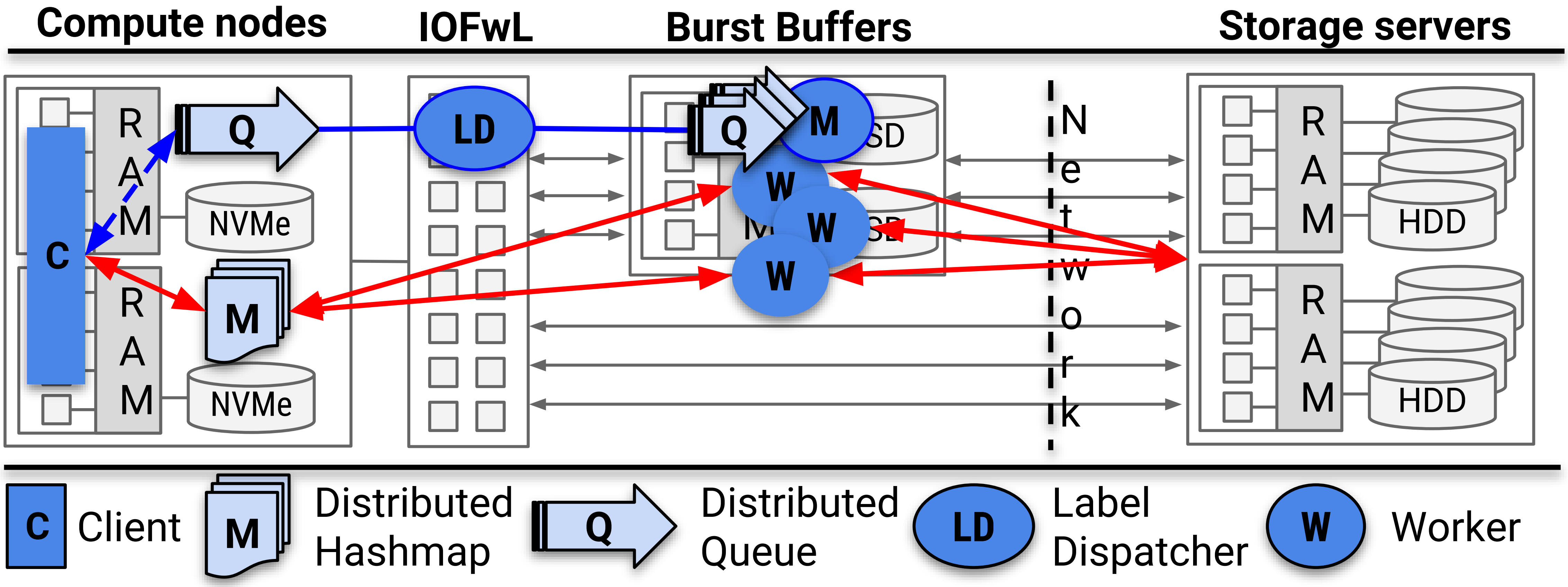
LABIOS as I/O accelerator (in compute nodes)

- Pros
  - Fast distributed cache
    - For temporary I/O
    - On top of external sources
  - Hadoop workloads with node local I/O
- Cons
  - Overheads by using compute cores to run its services
  - I/O traffic mixed with compute network



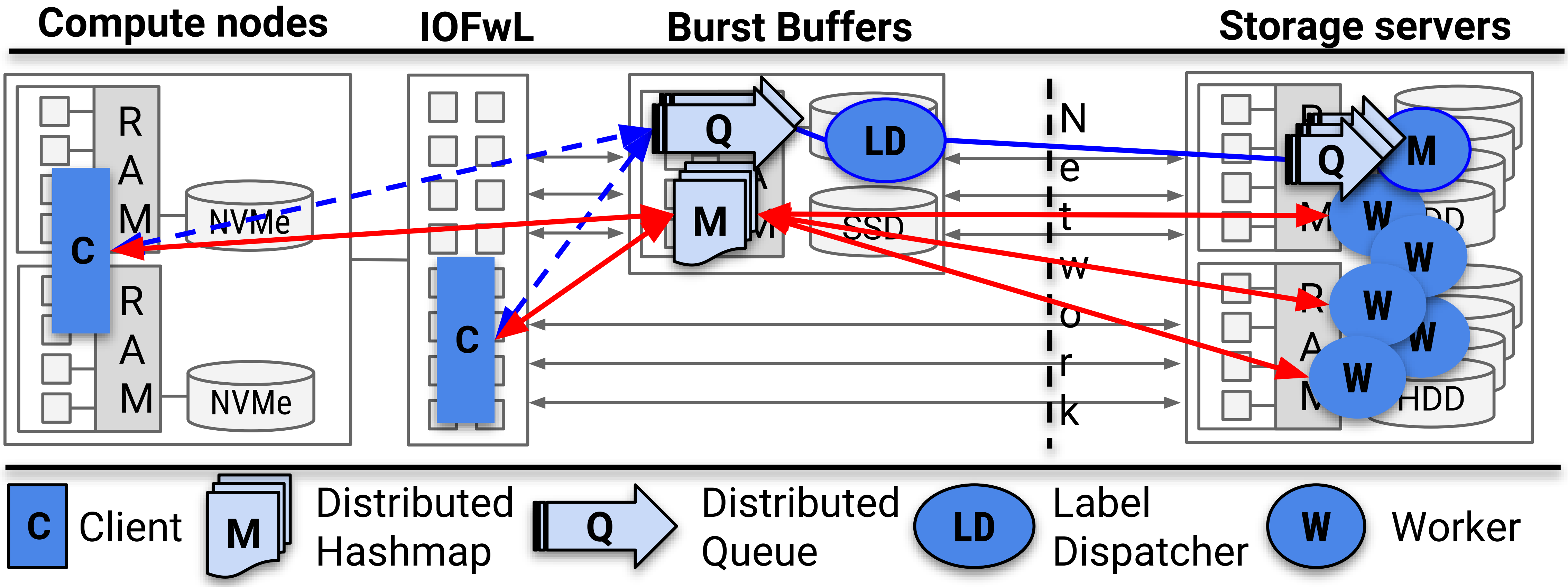
LABIOS as I/O forwarder (in ION)

- Pros
  - Asynchronous I/O
    - Non-blocking data movement
  - Connect to external storage
- Cons
  - Subject to I/O forwarding layer
  - Limited scalability



LABIOS as I/O buffering (in burst buffers)

- Pros
  - Fast scratch space
  - Data sharing between applications
  - In-situ visualization and analysis
- Cons
  - Requires additional resources (e.g., buffers)
    - Storage
    - Network



LABIOS as Remote Distributed Storage

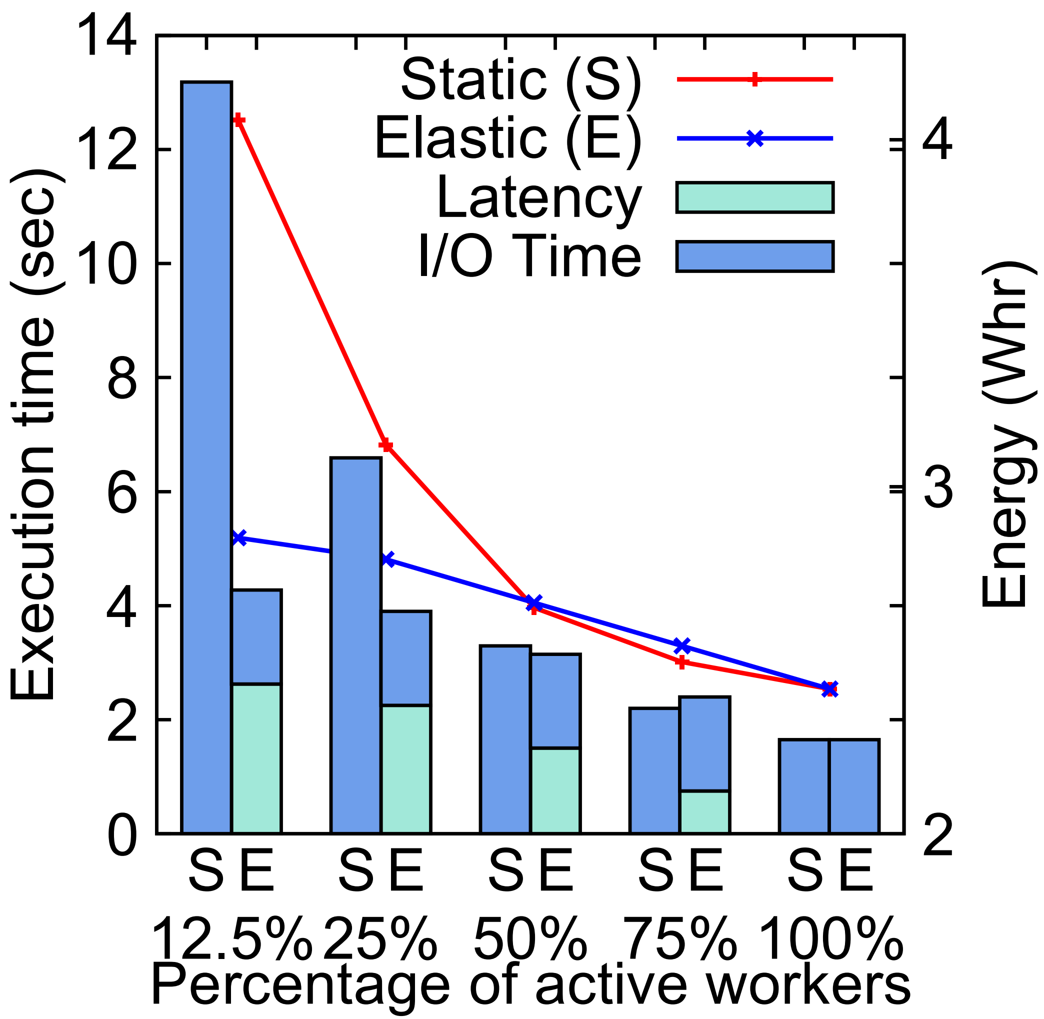
- Pros
  - Scalability
  - Better resource utilization
  - Higher flexibility
- Cons
  - Increased deployment complexity
  - Requires systems admins

Testbed

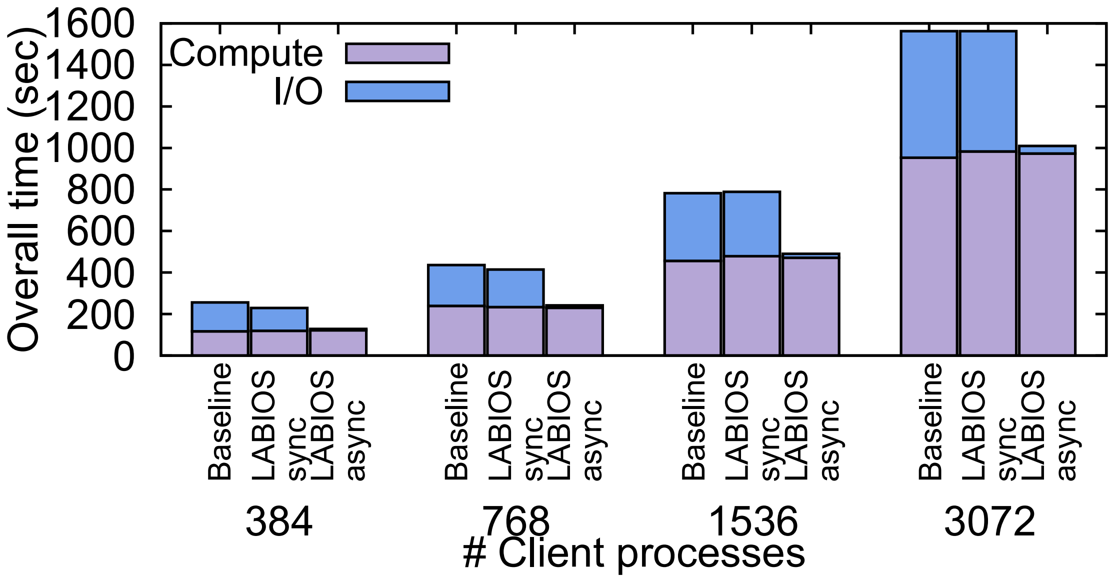
- All experiments on bare metal on Chameleon:
  - 64 client nodes
  - 8 burst buffer nodes
  - 32 storage servers
- Cluster OS: CentOS 7.1
- PFS: OrangeFS 2.9.6
- Workloads:
  - CM1 simulation
  - HACC simulation
  - Montage application
  - K-means clustering

Storage Malleability

- Metric: Total I/O time in sec
- 4096 labels of 1MB each
- Vary the ratio of active – suspended workers
- Worker activation in 3 sec on average
- Worker allocation techniques
  - Static: labels only on active workers
  - Elastic: labels to all workers (even on suspended paying the penalty of activation)
- When small % of workers are active, elastic boosts performance
- When enough workers are active, activation latency hurts performance

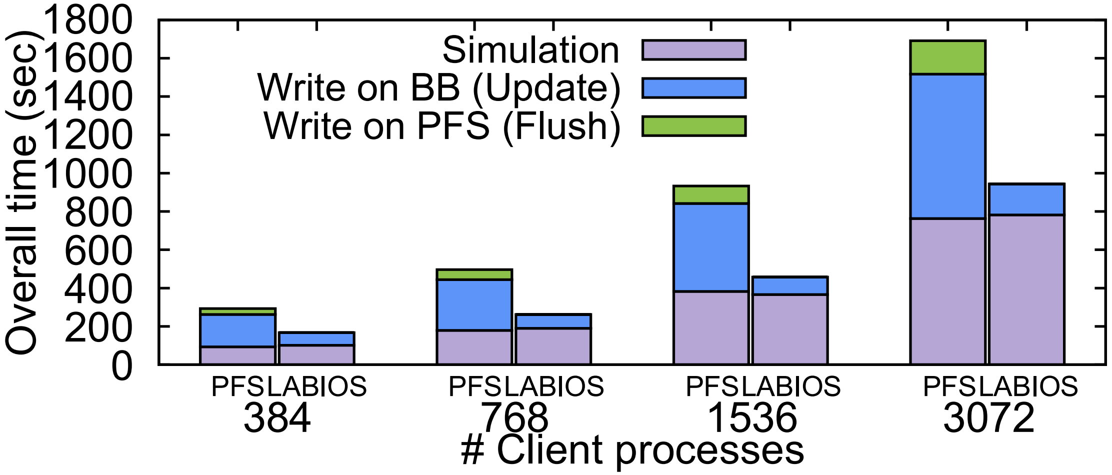


I/O Asynchronicity



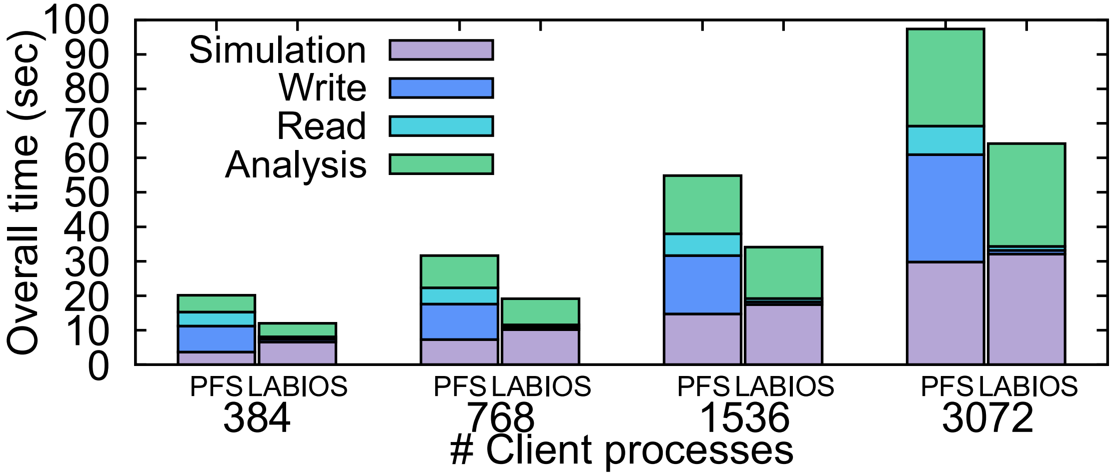
- Metric: Overall execution time in sec
- Support of both sync – async modes
- Label paradigm fits (naturally) in async
- CM1 simulation scaled up to 3072 processes with 16 time steps
- Each process writes 32MB of I/O
  - 100GB per step for the 3072 case
- Sync mode competitive with PFS baseline
- Async mode overlaps label execution with computations
  - **16x boost** in I/O performance
  - **40% reduction** in execution time

Resource Heterogeneity



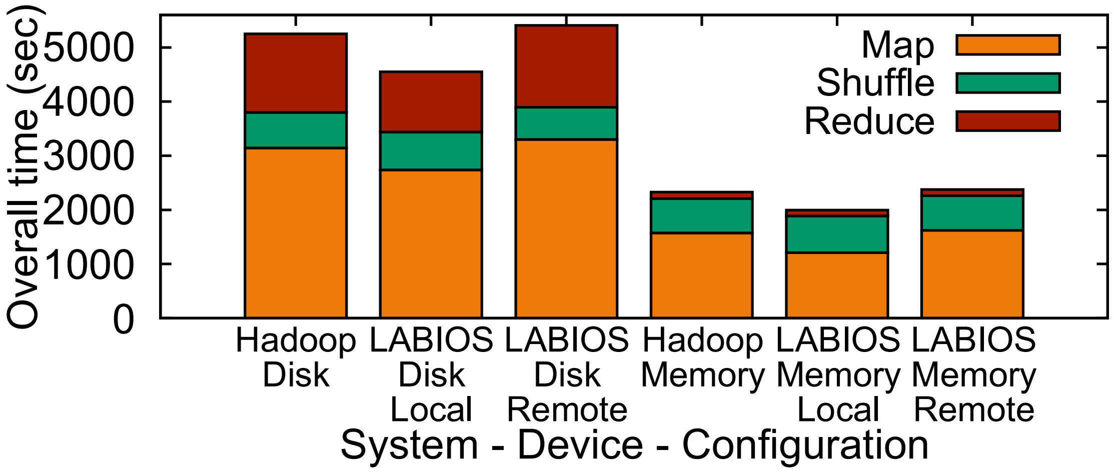
- Metric: Overall execution time in sec
- HACC simulation scaled up to 3072 processes with 16 time steps
- Update-heavy workload
  - Each process updates 32MB of I/O
  - Checkpoint in burst buffers
  - Final flush of last checkpoint data to PFS
- **6x improvement** in I/O performance
- Flushing in the background from workers

Data Provisioning



- Metric: Overall execution time in sec
- Montage application
  - Multiple executables that share data
- 50GB of intermediate results in temporary files in PFS
- LABIOS shares data via the warehouse (i.e., in-memory)
  - Label destination is analysis compute nodes
- Performance acceleration
  - No temporary files are created in remote storage
  - Simulation and analysis can be pipelined
- **17x boost** in I/O performance
- **65% reduction** in execution time

Storage Bridging



- Metric: Overall execution time in sec
- Two modes for LABIOS:
  - Node-local I/O (similar to HDFS)
  - Remote external I/O (similar to HPC)
- Map processes read 32MB each and then write them back to storage
- Reduce processes read 32MB each
- Shuffle sends 32MB through network
- Hadoop-memory optimized version
  - No disk I/O for intermediate results
- LABIOS employs collective I/O to perform data aggregations
- LABIOS successfully integrates MapReduce with HPC

Summary

LABIOS: A Successful Example of the Data Label Approach

- LABIOS provides storage flexibility, versatility, and agility due to a new data model, the data labels and its decoupled data-centric architecture; provide a new way to support:
  - Storage malleability
  - Asynchronous I/O
  - Resource Heterogeneity
  - Data Provisioning
  - Storage Bridging
- LABIOS can boost I/O performance on certain workloads by up to **17x** and reduce overall execution time by **40-60%**.
- Its potential is not fully explored

Take Home **Questions:**

- What is the next of LABIOS?
- What is the next of Data Label?

The Key Contribution

Data Label has separated the control flow with the data flow

Future Work

- Use LABIOS for data scheduling
  - HPC center
  - Data center
  - Cloud environment
- Establish a LABIOS compliant file system
- Extend LABIOS to a general software-defined IO system/storage
- Extend dLABEL to memory systems

SCALABLE COMPUTING
SOFTWARE LABORATORY

ILLINOIS INSTITUTE
OF TECHNOLOGY

Thank you
Any questions?

A. Kougkas, H. Devarajan, J. Lofstead, X.-H. Sun; "*LABIOS: A Distributed Label-Based I/O System*", *in* Proceedings of the 28th International Symposium on High-Performance Parallel and Distributed Computing (HPDC '19) (Best Paper Award)

Find more at:

www.cs.iit.edu/~scs

www.akougkas.com/research/labios

We would like to thank

A Kougka, H. Devarajan, K. Bateman, J. Cernuda, F. Ku, L. Logan, ...