TRITONSORT

A Balanced Large-Scale Sorting System

CSE 224 – Jan 20, 2022

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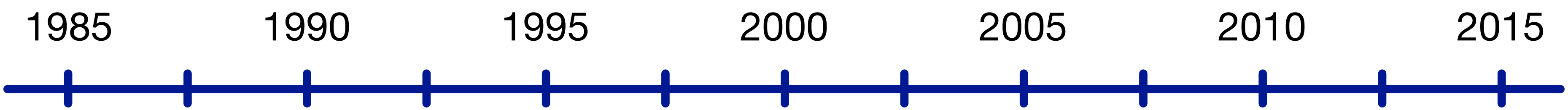
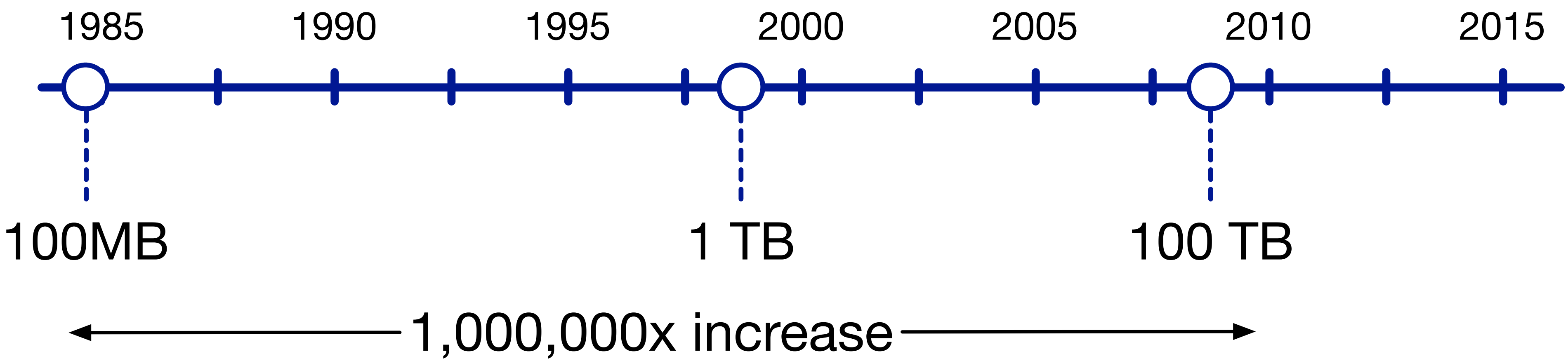
The Rise of Big Data Workloads

- Very high I/O and storage requirements
  - Large-scale web and social graph mining
  - Business analytics – “you may also like …”
  - Large-scale “data science”
- Recent new approaches to “data deluge”: data intensive scalable computing (DISC) systems
  - MapReduce, Hadoop, Dryad, …

Size of “data-intensive” has grown



Size of “data-intensive” has grown

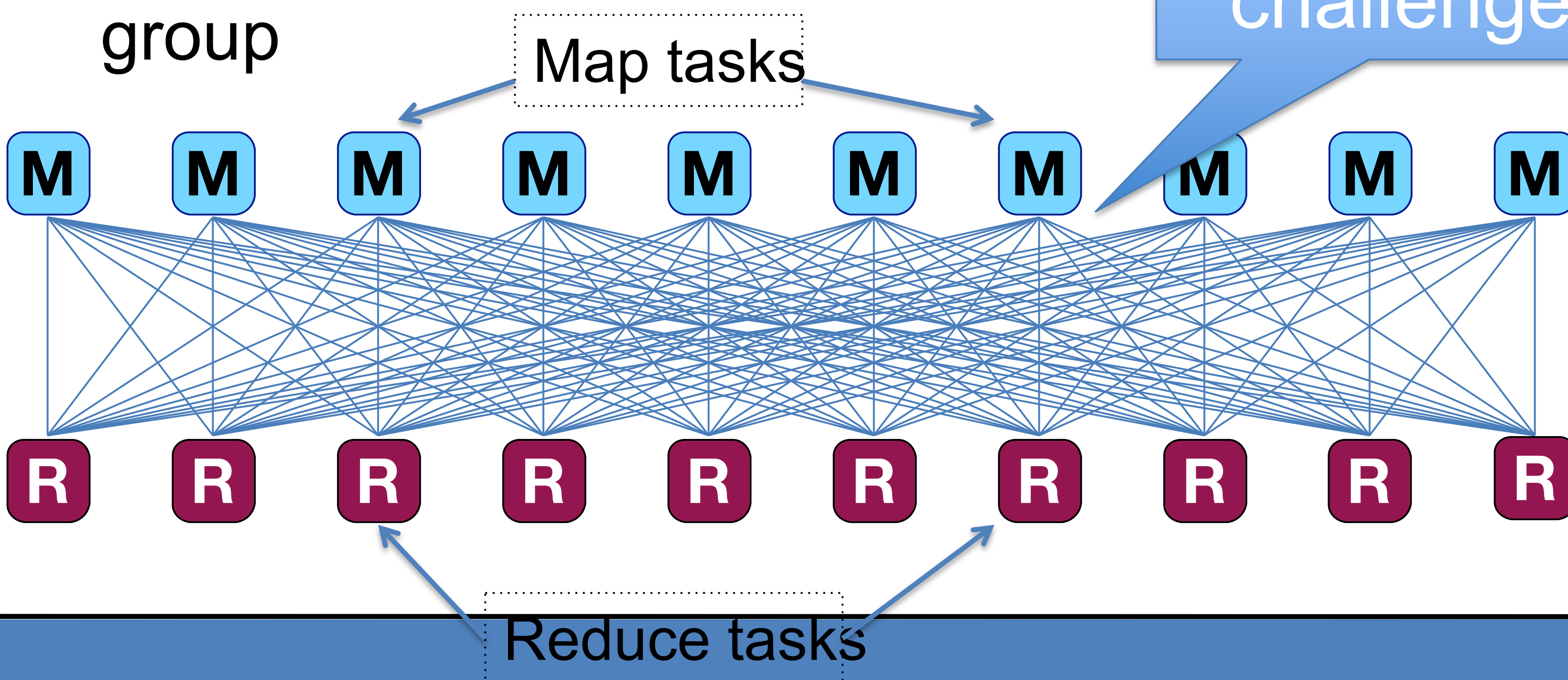


“Data-intensive” commonly means MapReduce

Input: Set<key-value pairs>

1. Apply *map()* to each pair
2. Group by key; sort each group
3. Apply *reduce()* to each sorted group

Sorting is the challenge!



Performance via scalability

- 10,000+ node MapReduce clusters deployed
  - With impressive performance
- Example: Yahoo! Hadoop Cluster Sort
  - 3,452 nodes sorting 100TB in less than 3 hours
- But…
  - Less Than 3 MB/sec per node
  - Single disk: ~100 MB/sec
- Not an isolated case
  - See “Efficiency Matters!”, SIGOPS 2010

Overcoming Inefficiency With Brute Force

- Just add more machines!
  - But expensive, power-hungry mega-datacenters!
- What if we could go from 3 MBps per node to 30?
  - 10x fewer machines accomplishing the same task
  - or 10x higher throughput

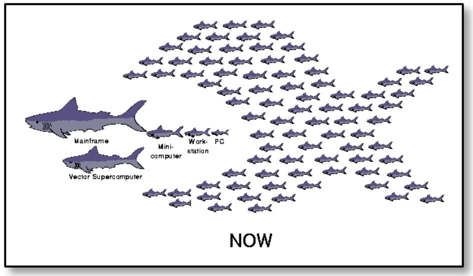

TDK
Bolt
NEW WR
SEIKO
9.58

GUINNESS WORLD RECORDS

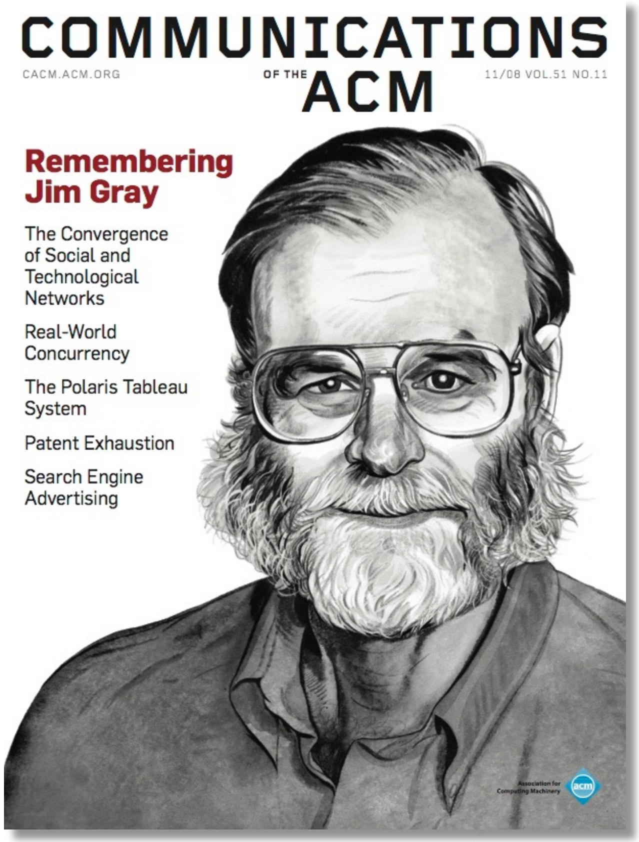
Sorting!

Evaluating IO efficiency: GraySort

- Sorting contest [Jim Gray et al.,1985]
  - Importance of the IO subsystem
  - 1985: Sort 100MB
  - 1999: Sort 1TB



  - 2009: Sort 100 TB



Anon et al, "A measure of transaction processing power," Datamation 31, 7 (April 1985), 112-118.

Sorting records

- GraySort:
  - Time to sort 100TB
- MinuteSort:
  - How much in 60s
- JouleSort:
  - How much in 1 Joule
- PennySort:
  - How much for 1¢
- CloudSort:
  - How much $$ to sort 100TB?

Top Results

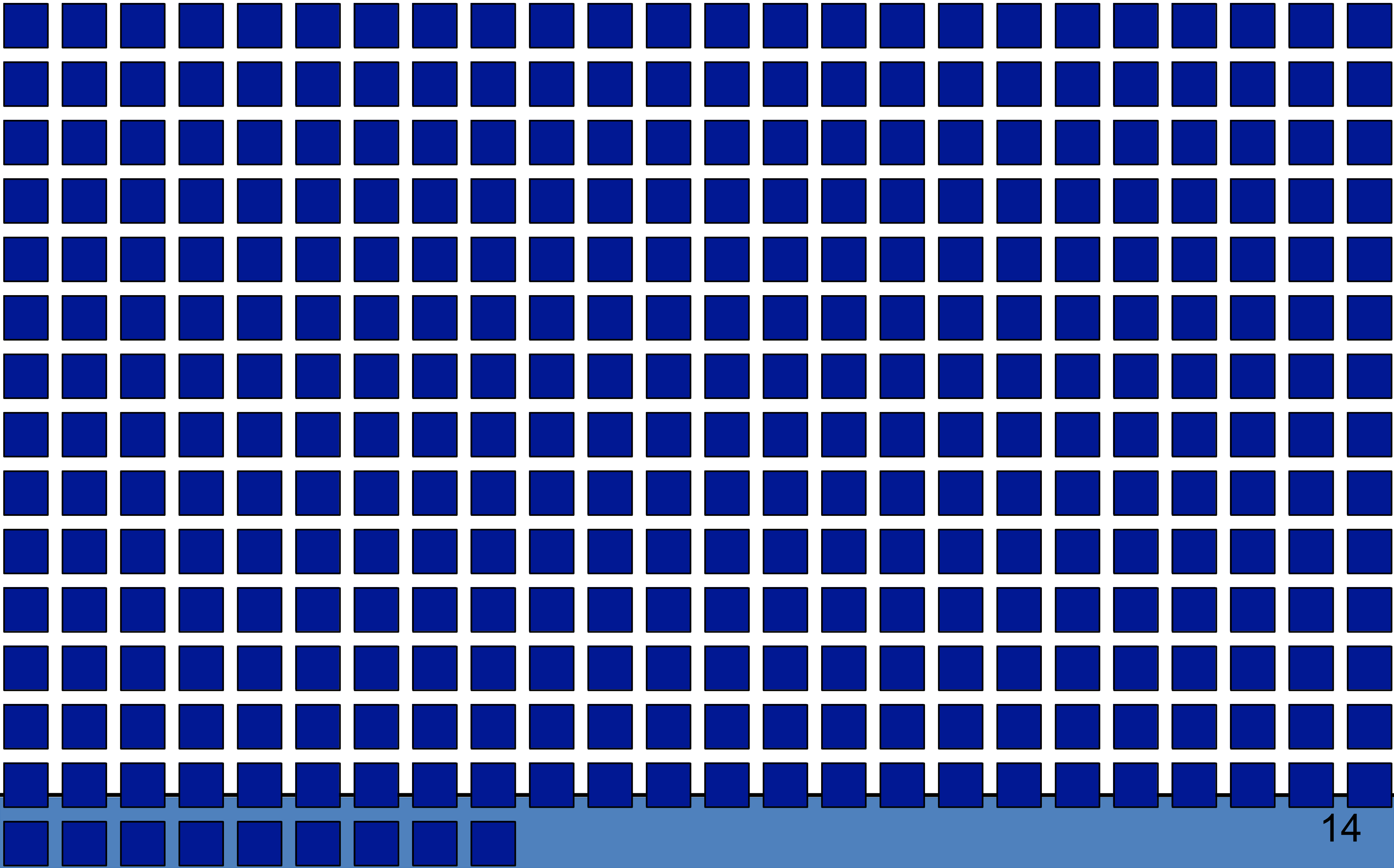
	Daytona	Indy
Gray	2011, 0.725 TB/min **TritonSort** 1,000,000,000,000 records in 8,274 seconds 52 nodes x (2 Quadcore processors, 24 GB memory, 16x500GB disks) Cisco Nexus 5096 switch Alex Rasmussen, Michael Conley, George Porter, Amin Vahdat, University of California, San Diego	2011, 0.938 TB/min **TritonSort** 1,000,000,000,000 records in 6,395 seconds 52 nodes x (2 Quadcore processors, 24 GB memory, 16x500GB disks) Cisco Nexus 5096 switch Alex Rasmussen, Michael Conley, George Porter, Amin Vahdat, University of California, San Diego
Penny	2011, 286 GB **psort** 2.7 Ghz AMD Sempron, 4 GB RAM, 5x320 GB 7200 RPM Samsung SpinPoint F4 HD332GJ, Linux Paolo Bertasi, Federica Bogo, Marco Bressan and Enoch Peserico Univ. Padova, Italy	2011, 334 GB **psort** 2.7 Ghz AMD Sempron, 4 GB RAM, 5x320 GB 7200 RPM Samsung SpinPoint F4 HD332GJ, Linux Paolo Bertasi, Federica Bogo, Marco Bressan and Enoch Peserico Univ. Padova, Italy
Minute	2009, 500 GB **Hadoop** 1406 nodes x (2 Quadcore Xeons, 8 GB memory, 4 SATA) Owen O'Malley and Arun Murthy Yahoo Inc.	2011, 1353GB **TritonSort** 52 nodes x (2 Quadcore processors, 24 GB memory, 16x500GB disks) Cisco Nexus 5096 switch Alex Rasmussen, Michael Conley, George Porter, Amin Vahdat, University of California, San Diego
Joule 10^8 recs	2011, 1,430 Joules **FAWNSort** 69,900 records sorted / joule Intel Core i5-2400S 2.5 GHz, 16GB RAM, Nsort, 7 x 120 GB Intel Series 510 series SSDs Padmanabhan Pillai, Michael Kaminsky, Michael A. Kozuch, Intel Labs Pittsburgh Vijay Vasudevan, Lawrence Tan, David Andersen Carnegie Mellon University	2011, 1,430 Joules **FAWNSort** 69,900 records sorted / joule Intel Core i5-2400S 2.5 GHz, 16GB RAM, Nsort, 7 x 120 GB Intel Series 510 series SSDs Padmanabhan Pillai, Michael Kaminsky, Michael A. Kozuch, Intel Labs Pittsburgh Vijay Vasudevan, Lawrence Tan, David Andersen Carnegie Mellon University
Joule 10^9 recs	2010, 27.9 kJoules **Nsort** 35,800 records sorted / joule Intel Atom 330 1.6GHz, 4GB RAM, 4 x Super Talent UltraDrive GX MLC 256GB Andreas Beckmann, Ulrich Meyer Goethe University Frankfurt am Main, Germany Peter Sanders, Johannes Singler Karlsruhe Institute of Technology, Germany	2010, 25.1 kJoules **EcoSort** 39,900 records sorted / joule Intel Atom 330 1.6GHz, 4GB RAM, 4 x Super Talent UltraDrive GX MLC 256GB Andreas Beckmann, Ulrich Meyer Goethe University Frankfurt am Main, Germany Peter Sanders, Johannes Singler Karlsruhe Institute of Technology, Germany
Joule 10^{10} recs	2011, 1,900 kJoules **Nsort** 5,273 records sorted / joule 2 x Intel Xeon X5550 2.67 GHz, 48 GB RAM 8 x 1TB Seagate 7200RPM SATA HDD Andreas Beckmann, Ulrich Meyer Goethe University Frankfurt am Main, Germany Peter Sanders, Johannes Singler Karlsruhe Institute of Technology, Germany	2010, 572 kJoules **DEMSort** 17,500 records sorted / joule Intel Atom 330 1.6GHz, 4GB RAM, 4 x Super Talent UltraDrive GX MLC 256GB Andreas Beckmann, Ulrich Meyer Goethe University Frankfurt am Main, Germany Peter Sanders, Johannes Singler Karlsruhe Institute of Technology, Germany
Joule 10^{12} recs	2011, 132 MJoules **TritonSort** 7,595 records sorted / joule 52 nodes x (2 Quadcore processors, 24 GB memory, 16x500GB disks) Cisco Nexus 5096 switch Alex Rasmussen, Michael Conley, George Porter, Amin Vahdat, University of California, San Diego	2011, 103 MJoules **TritonSort** 9,700 records sorted / joule 52 nodes x (2 Quadcore processors, 24 GB memory, 16x500GB disks) Cisco Nexus 5096 switch Alex Rasmussen, Michael Conley, George Porter, Amin Vahdat, University of California, San Diego

Inefficiency of deployed scale-out systems

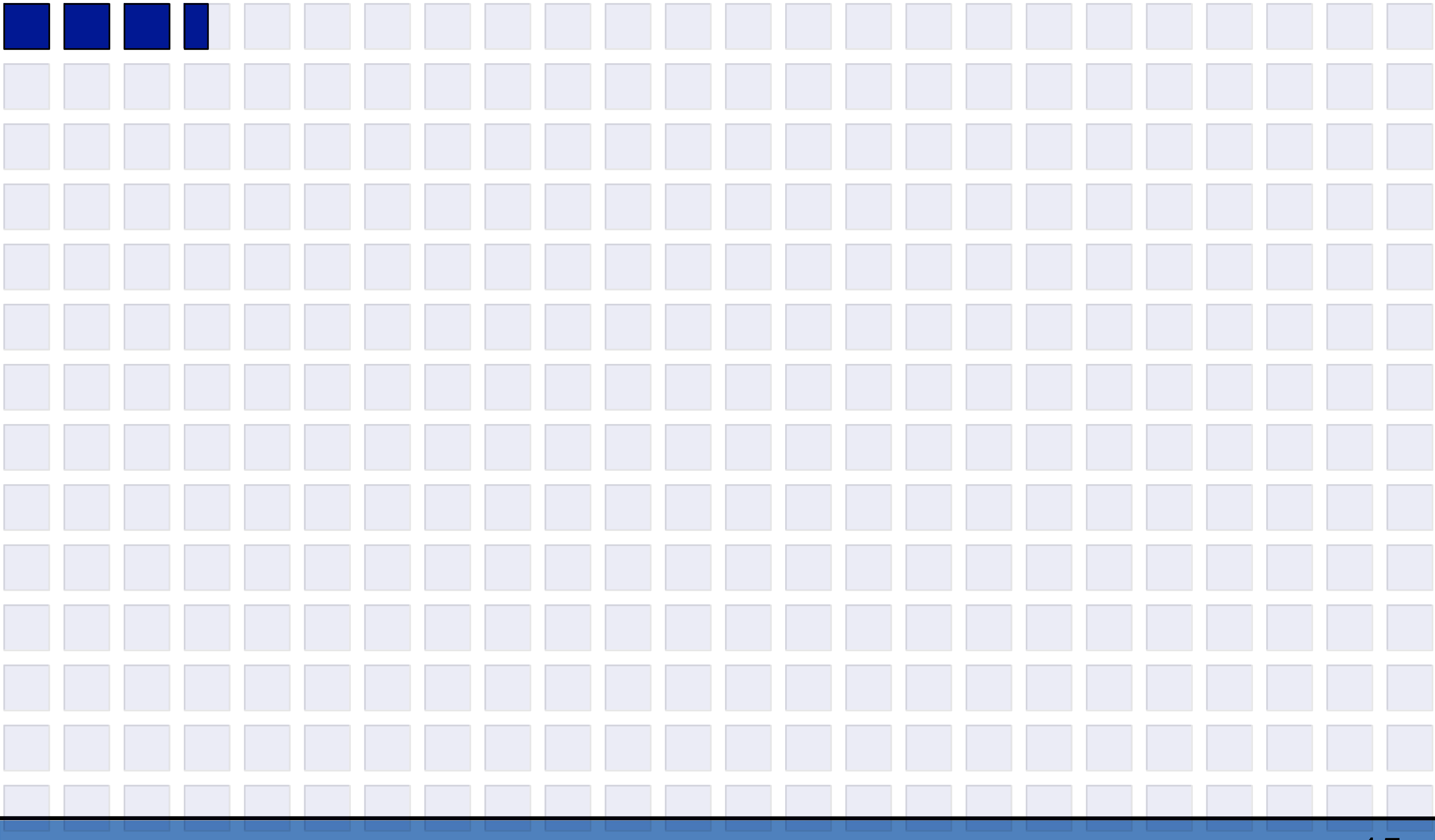
- Analysis of GraySort contest results*
  - On average: 94% disk IO idle; 33% of CPU idle
- Case study: 2009 Yahoo! Hadoop Cluster
  - Sorted 100TB with 3,452 nodes in ≈3 hours
  - 1% disk efficiency

* *Anderson and Tucek, "Efficiency matters!" SIGOPS OSR 44, 1 (March 2010)*

3452 nodes at 1% efficiency



35 nodes at 100% efficiency



TritonSort Goals

- Build a highly efficient DISC system that improves per-node efficiency by an order of magnitude vs. existing systems
  – Through balanced hardware and software
- Secondary goals:
  – Completely “off-the-shelf” components
  – Focus on I/O-driven workloads (“Big Data”)
  – Problems that don’t come close to fitting in RAM
  – Initially sorting, but have since generalized

Outline

- Define hardware and software balance
- TritonSort design
  - Highlighting tradeoffs to achieve balance
- Evaluation with sorting as a case study

Building a "Balanced" System

- *Balanced hardware* drives all resources as close to 100% as possible
  - Removing any resource slows us down
  - Limited by commodity configuration choices
- *Balanced software* fully exploits hardware resources

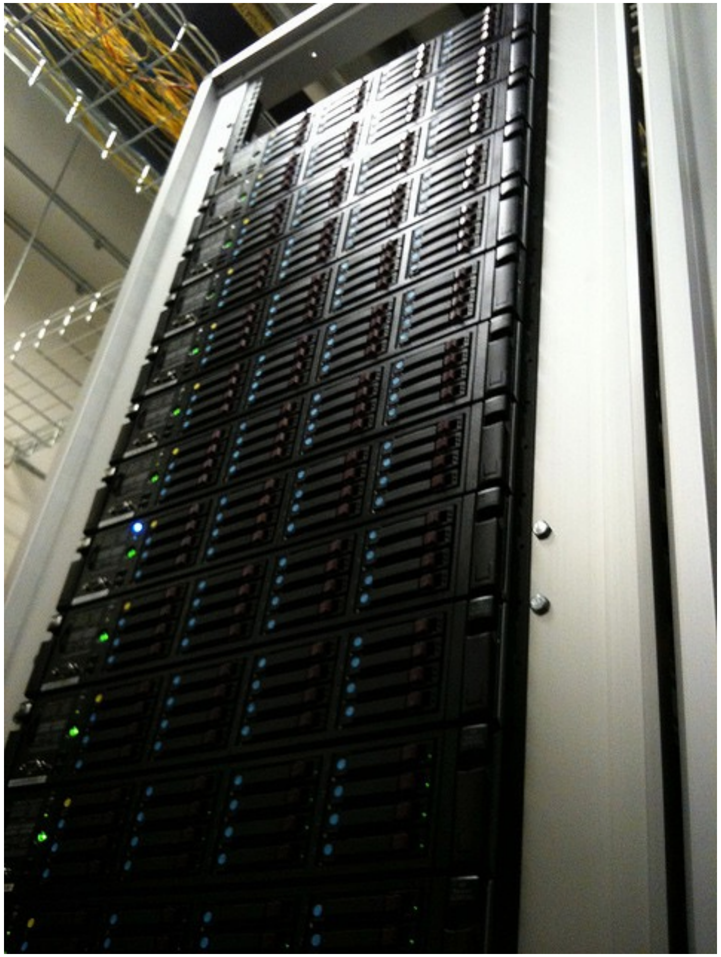
Hardware Selection (in 2010)

- Designed for I/O-heavy workloads
  - Not just sorting
- Static selection of resources:
  - Network/disk balance
    - 10 Gbps / 80 MBps ≈ 16 disks
  - CPU/disk balance
    - 2 disks / core = 8 cores
  - CPU/memory
    - Originally ~1.5GB/core… later 3 GB/core

Resulting Hardware Platform

52 Nodes:

- Xeon E5520, 8 cores
  (16 with hyperthreading)
- 24 GB RAM
- 16 7200 RPM hard drives
- 10 Gbps NIC
- Cisco Nexus 5020
  10 Gbps switch



Software Architecture

- Staged, pipeline-oriented dataflow system
- Program expressed as digraph of stages
  - Data stored in buffers that move along edges
  - Stage's work performed by *worker* threads
- Platform for experimentation
  - Easily vary:
    - Stage implementation
    - Size and quantity of buffers
    - Worker threads per stage
    - CPU and memory allocation to each stage

Why Sorting?

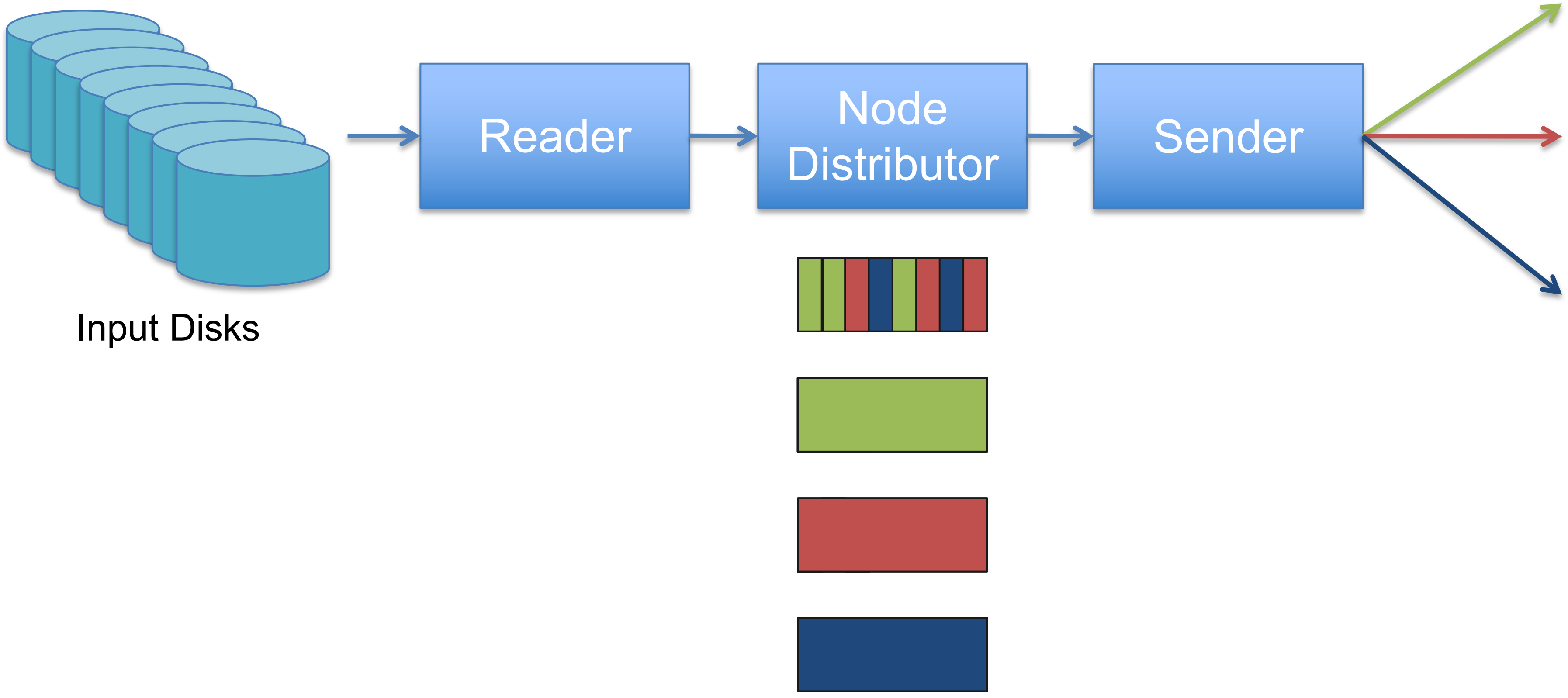
- Easy to describe
- Industrially applicable
- Uses all cluster resources

Current TritonSort Architecture

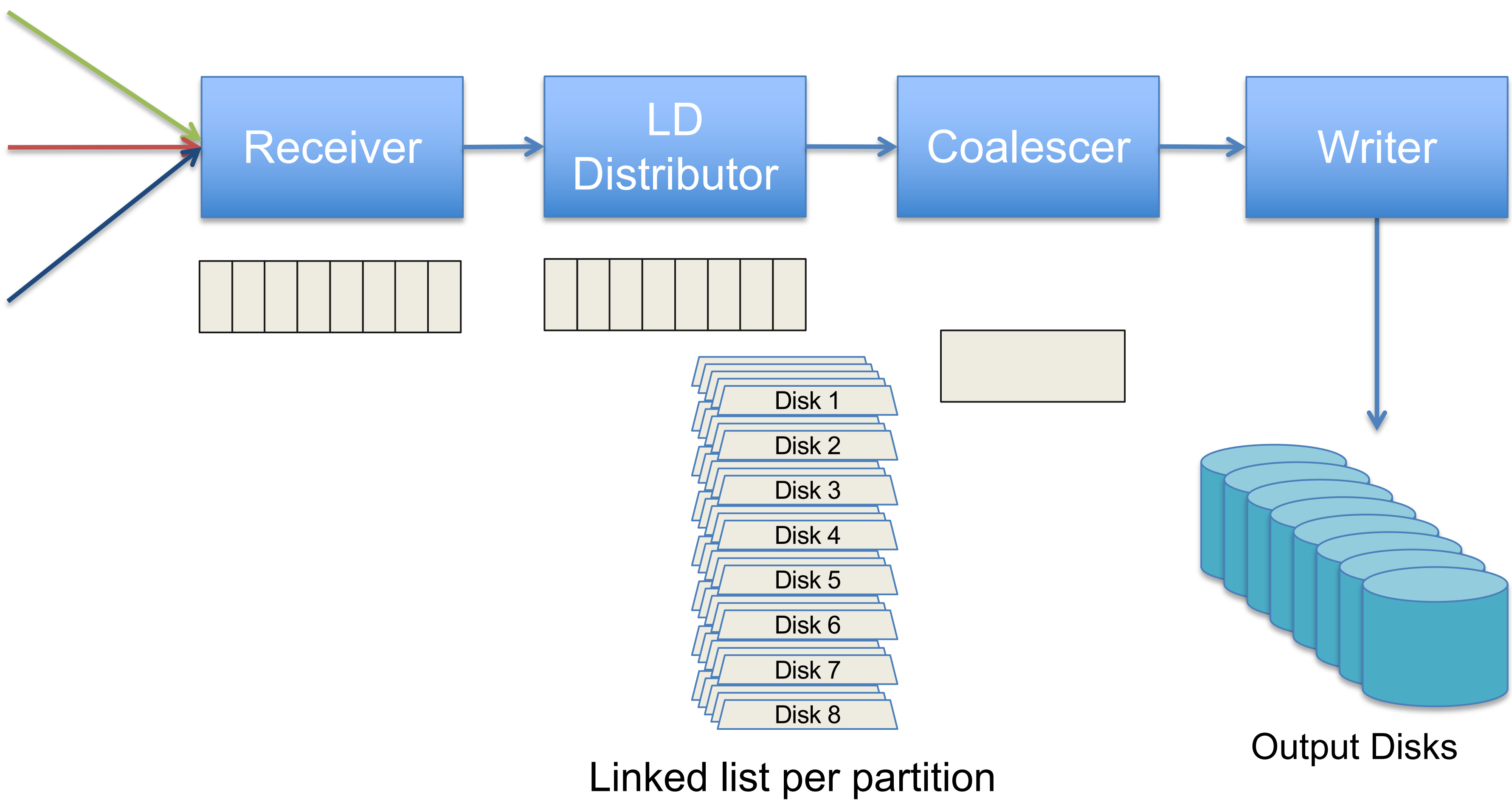
- External sort – two reads, two writes*
  - Don't read and write to disk at same time
    - Partition disks into input and output
- Two phases
  - **Phase one**: route tuples to appropriate on-disk partition (called a "logical disk") on appropriate node
  - **Phase two**: sort all logical disks in parallel

* A. Aggarwal and J. S. Vitter. The input/output complexity of sorting and related problems. CACM, 1988.

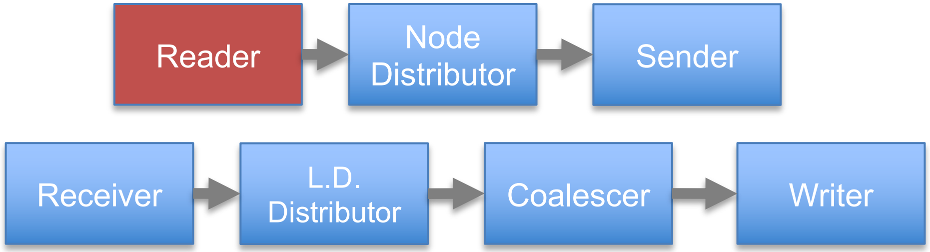
Architecture Phase One



Architecture Phase One

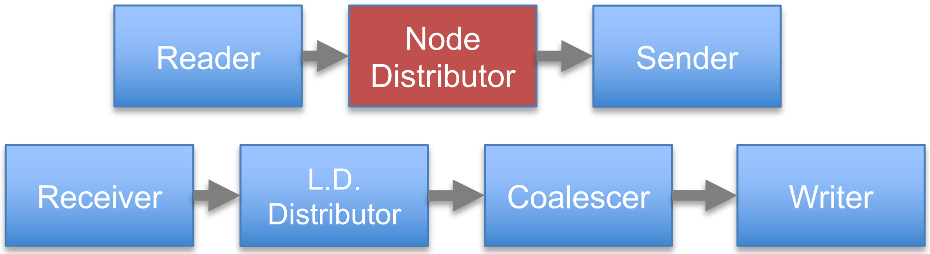


Reader



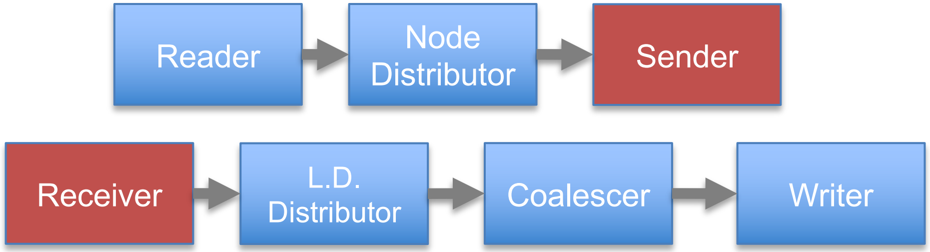
- 100 MBps/disk * 8 disks = 800 MBps
- No computation, entirely I/O and memory operations
  - Expect most time spent in iowait
  - 8 reader workers, one per input disk
    - ✓ All reader workers co-scheduled on a single core

NodeDistributor



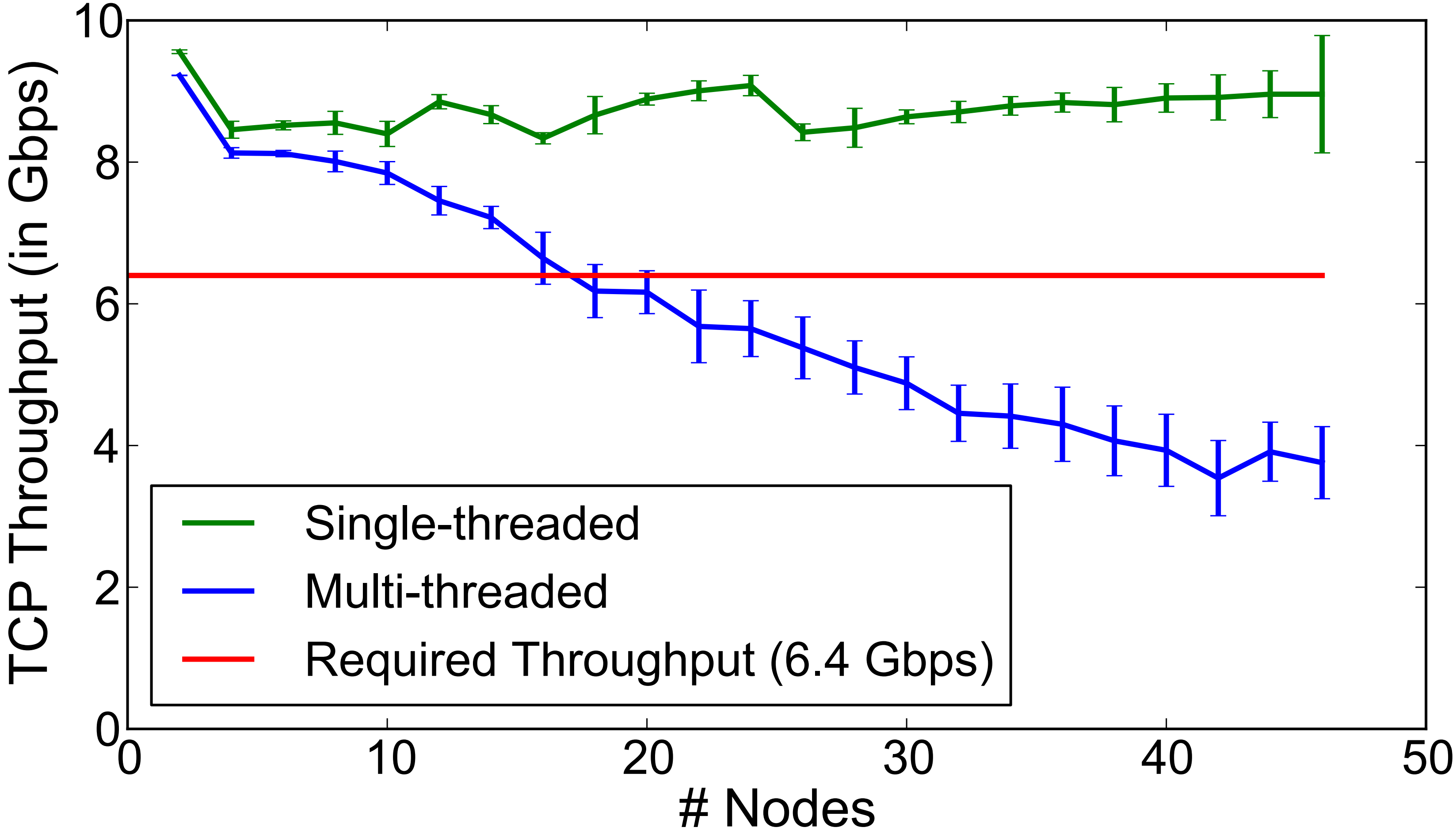
- Appends tuples onto a buffer per destination node
- Memory scan + hash per tuple
- 300 MBps per worker
  - Need three workers to keep up with readers

Sender & Receiver

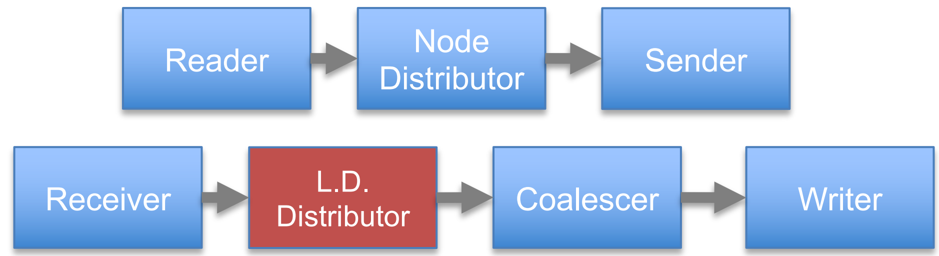


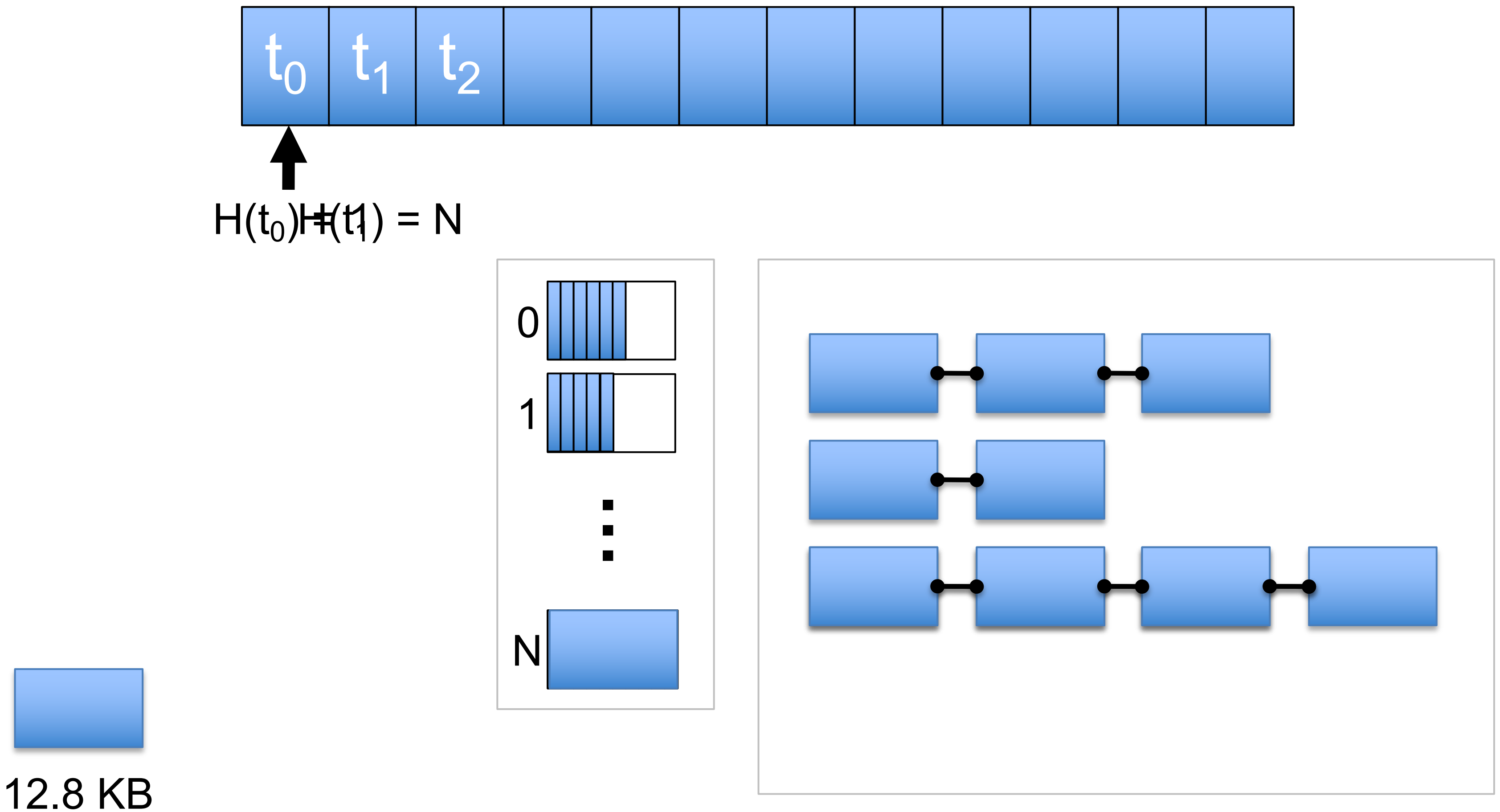
- 800 MBps (from Reader) is 6.4 Gbps
  – All-to-all traffic
- Must keep downstream disks busy
  – Don’t let receive buffer get empty
  – Implies strict socket send time bound
- Multiplex all senders on one core (single-threaded tight loop)
  – Visit every socket every 20 μs
  – Didn’t need epoll()/select()

Balancing at Scale

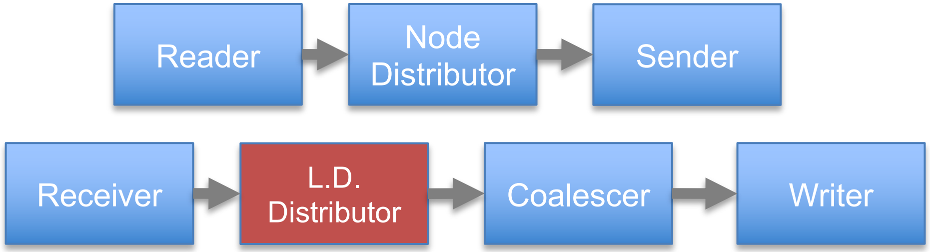


Logical Disk Distributor



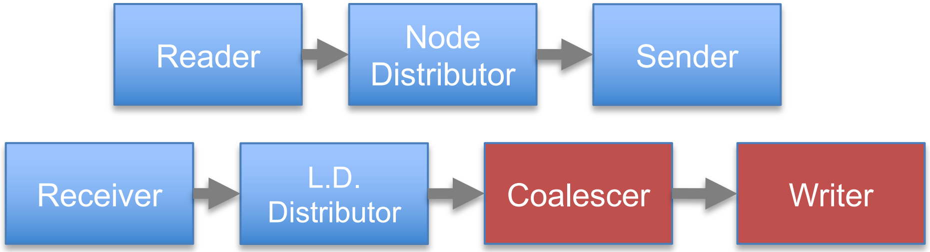


Logical Disk Distributor



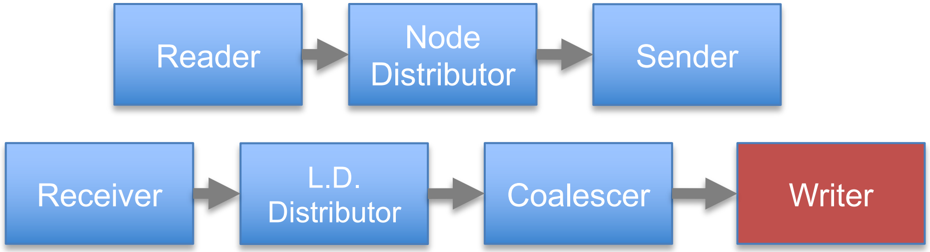
- Data non-uniform and bursty at short timescales
  - Big buffers + burstiness = head-of-line blocking
  - Need to use *all* your memory *all* the time
- **Solution**: Read incoming data into smallest buffer possible, and form chains

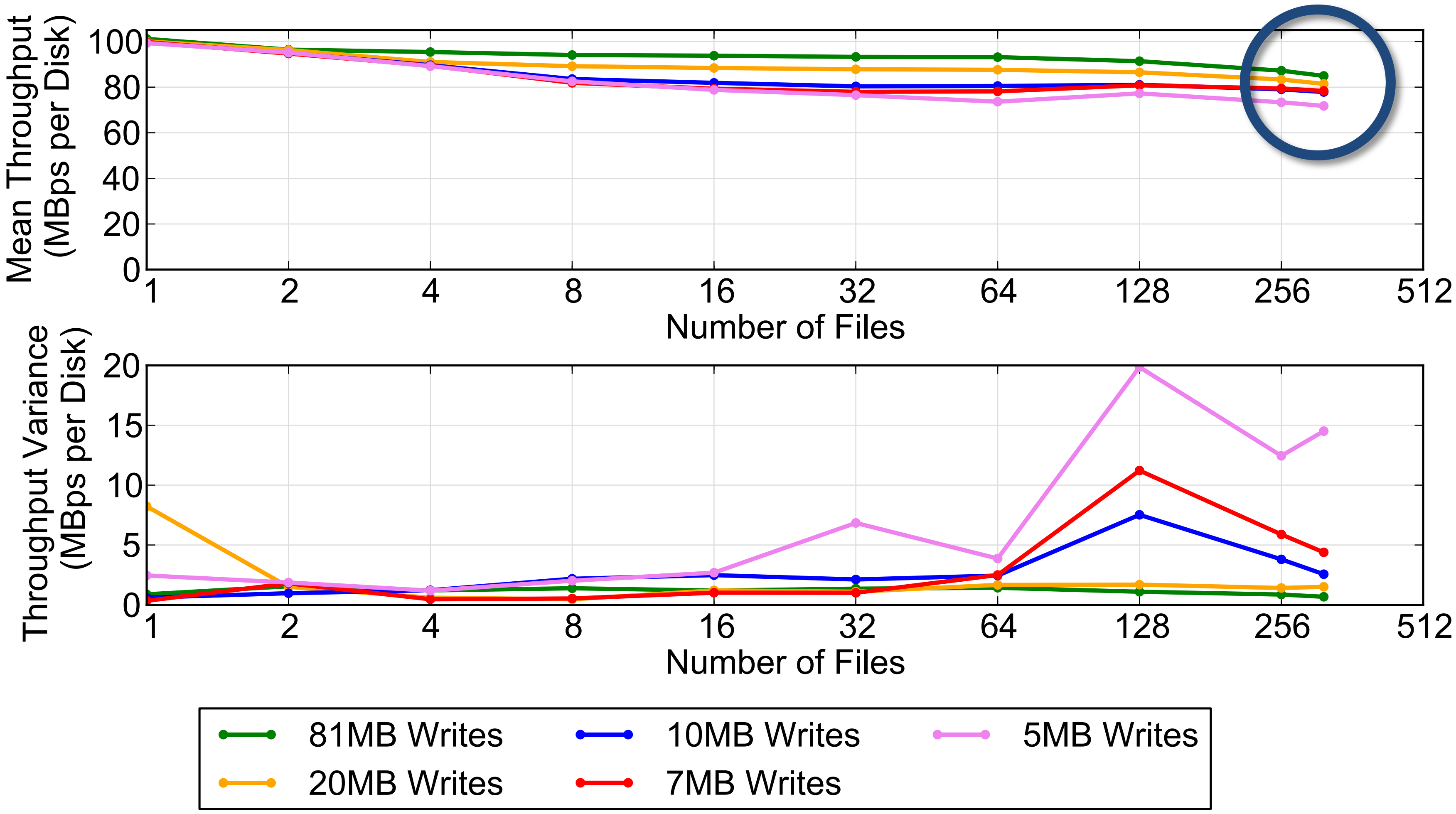
Coalescer & Writer



- Copies tuples from LDBuffer chains into a single, sequential block of memory
- Longer chains = larger write before seeking = faster writes
  - Also, more memory needed for LDBuffers
- Buffer size limits maximum chain length
  - How big should this buffer be?

Writer

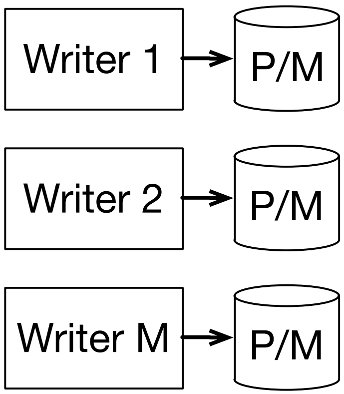

Reader
Node Distributor
Sender
Receiver
L.D. Distributor
Coalescer
Writer


Mean Throughput (MBps per Disk)
100
80
60
40
20
0
1
2
4
8
16
32
64
128
256
512
Number of Files
Throughput Variance (MBps per Disk)
20
15
10
5
0
1
2
4
8
16
32
64
128
256
512
Number of Files
81MB Writes
10MB Writes
5MB Writes
20MB Writes
7MB Writes

Appending records to partitions

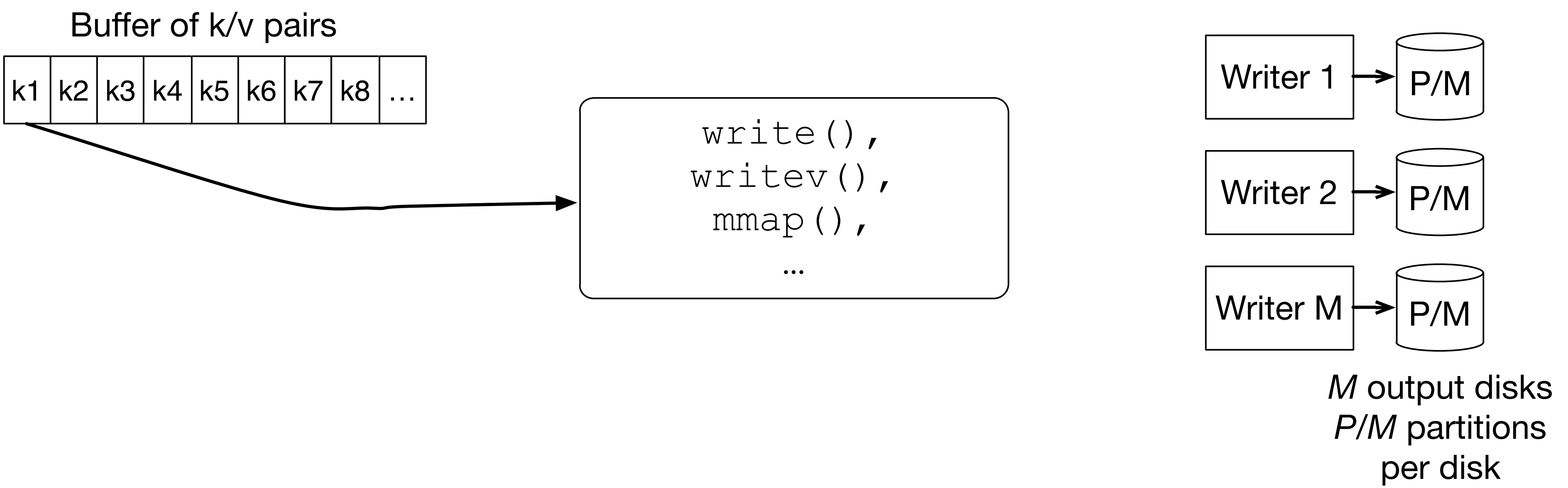
Buffer of k/v pairs

k1	k2	k3	k4	k5	k6	k7	k8	…



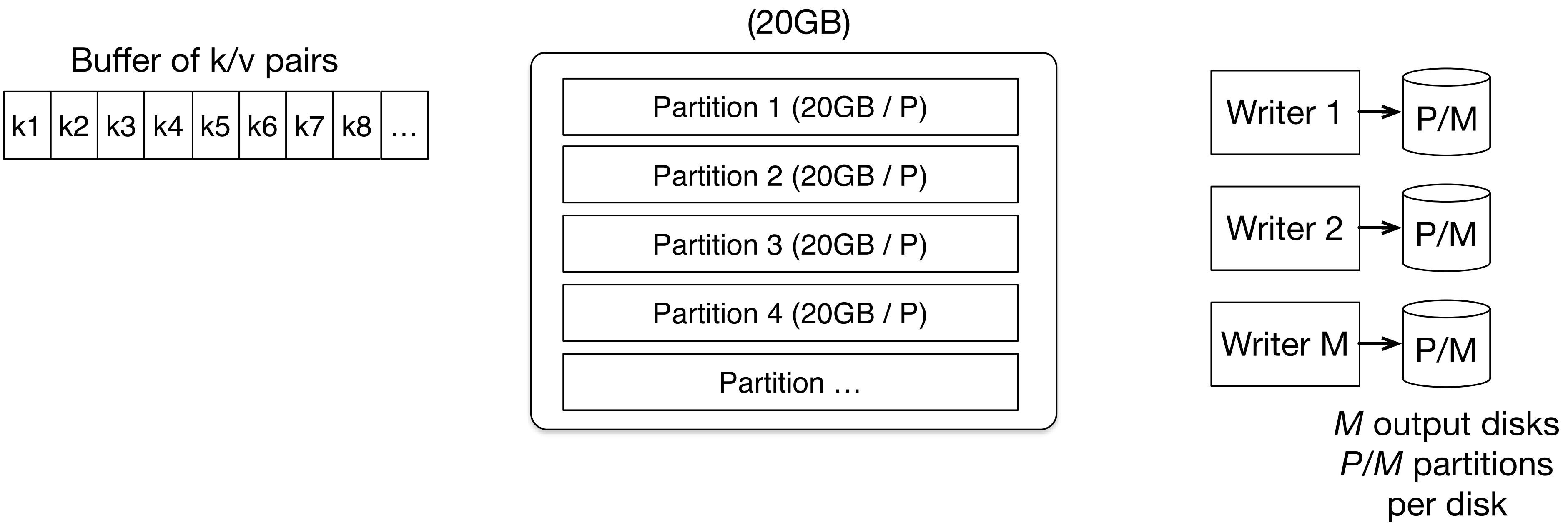
M output disks
P/M partitions
per disk

Approach #1: Delegate to OS

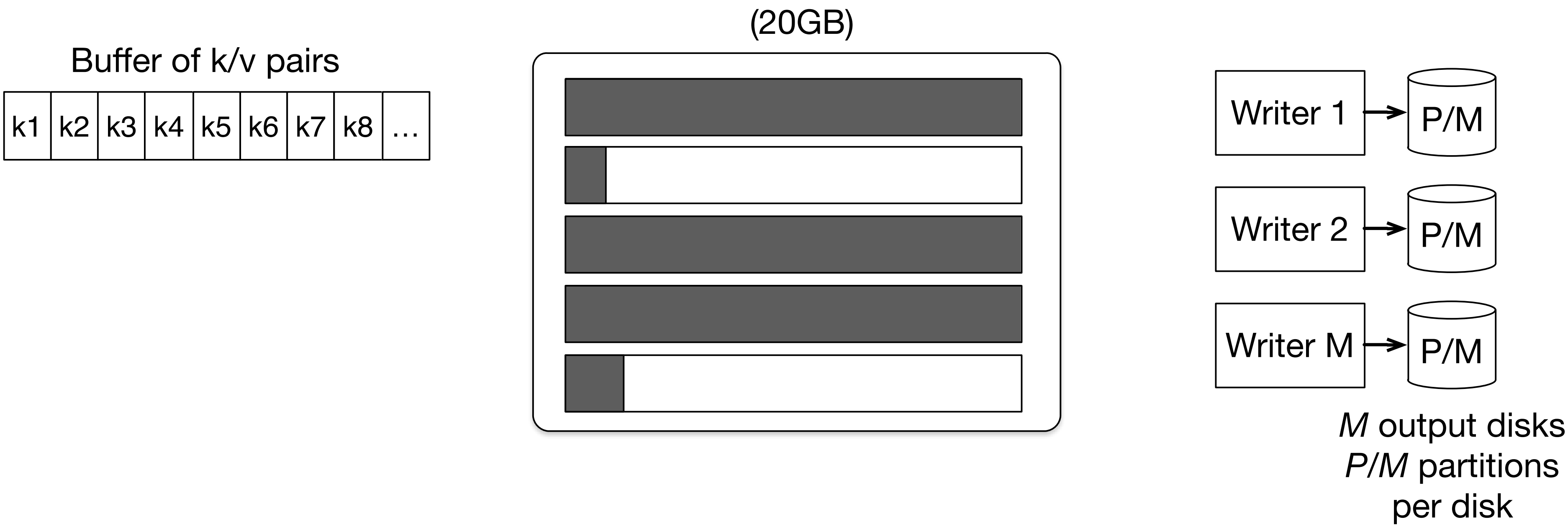


– Low performance due to insufficient batching

Approach #2: Per-partition buffers

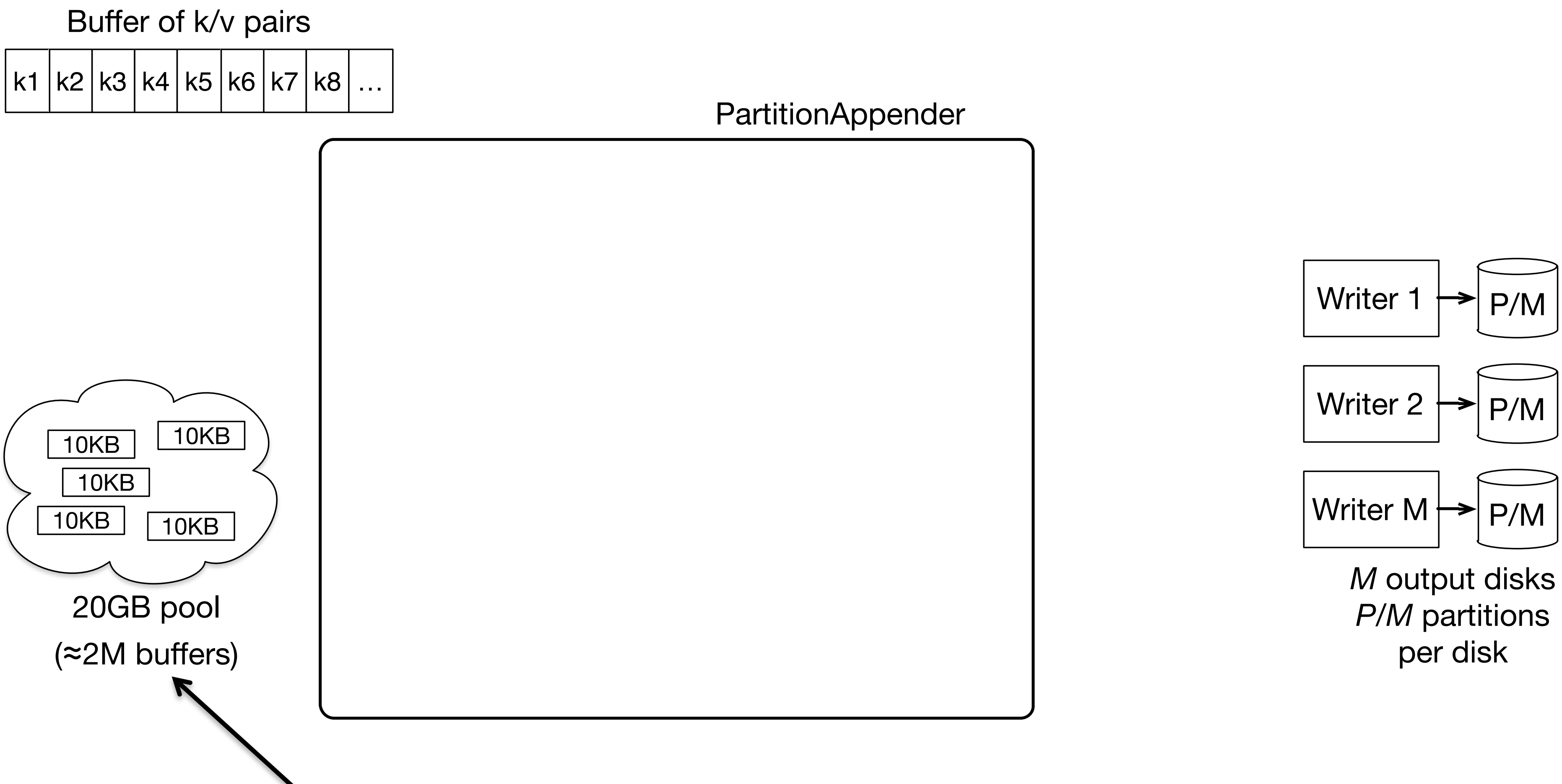


Approach #2: Per-partition buffers



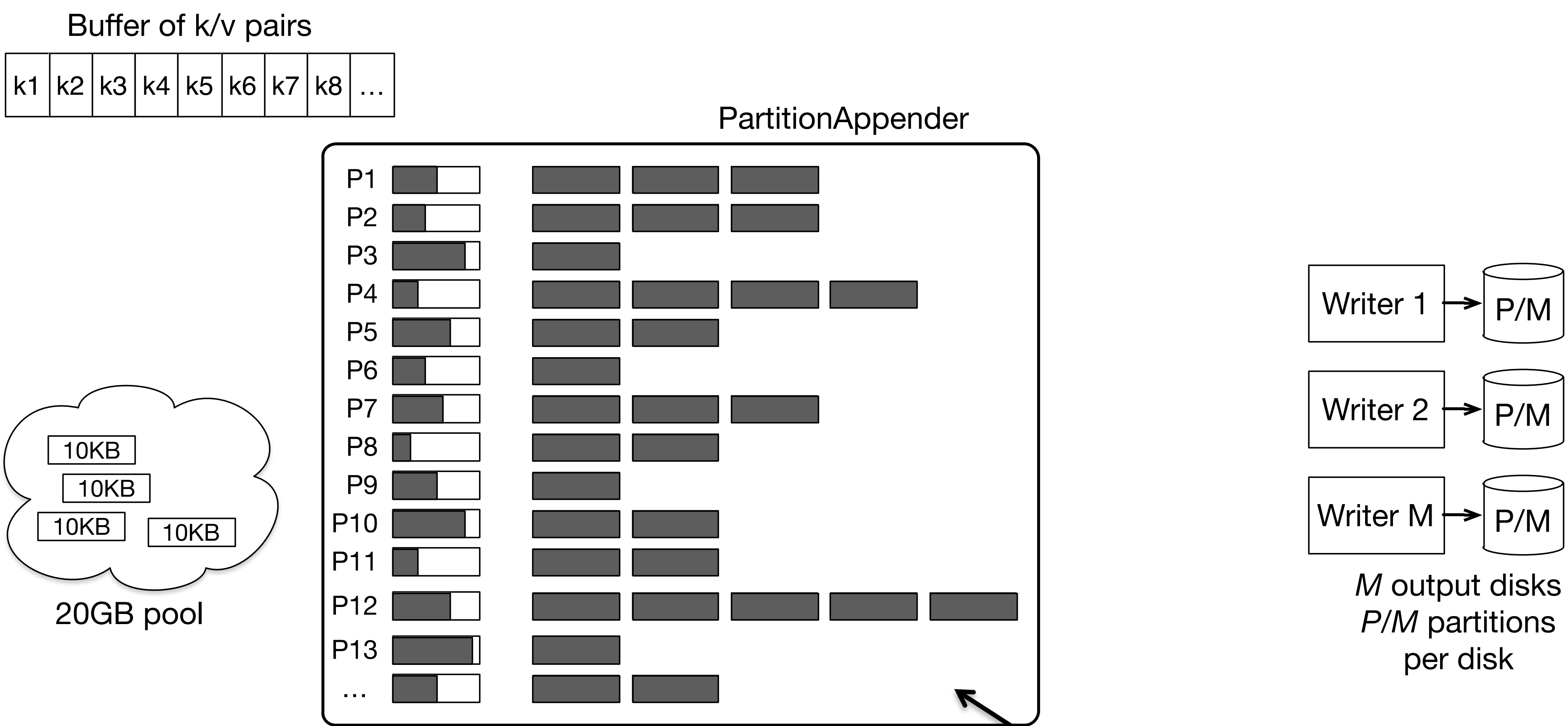
– Non-uniform arrivals result in “hot” buffers

TritonSort: Load-balancing across partitions



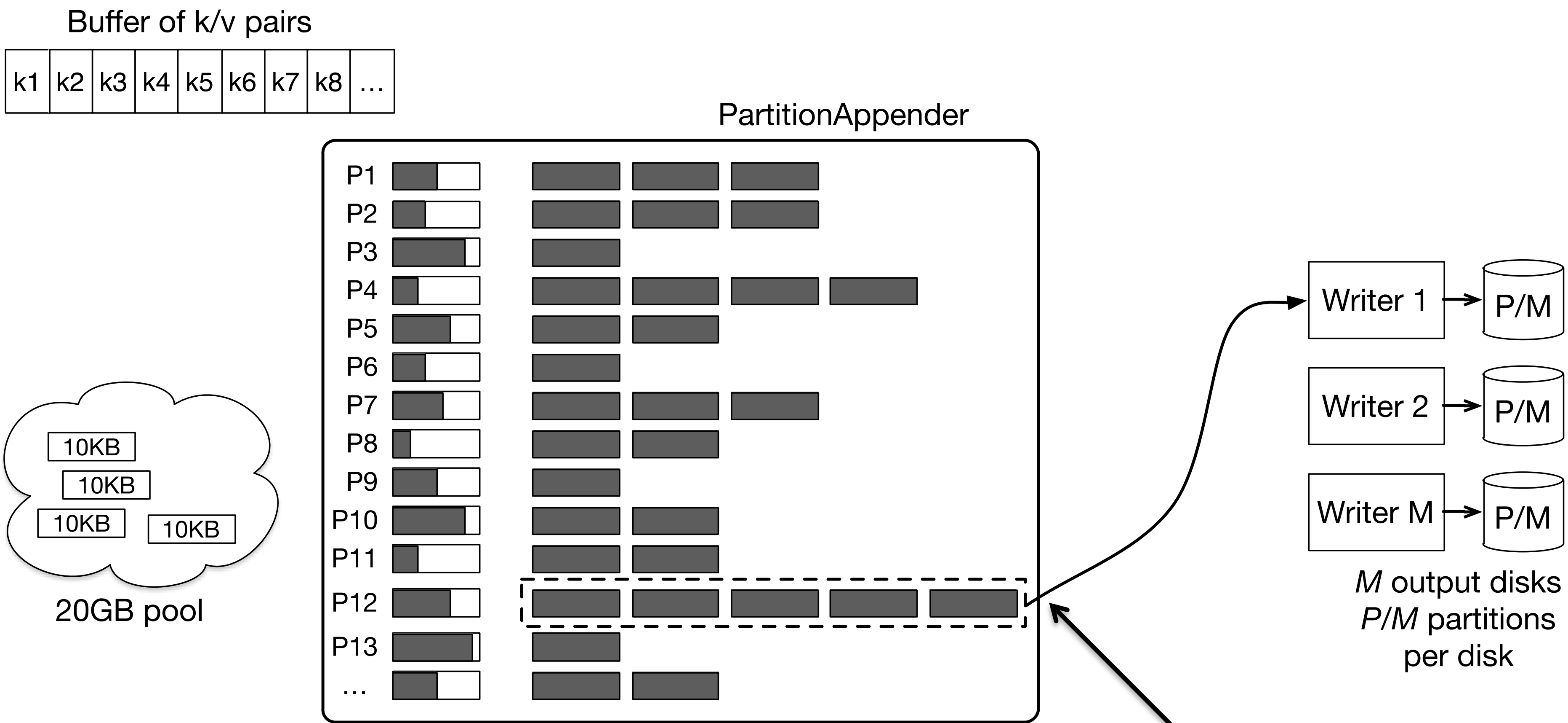
Fine-grained allocation of small buffers to partitions

TritonSort: Load-balancing across partitions



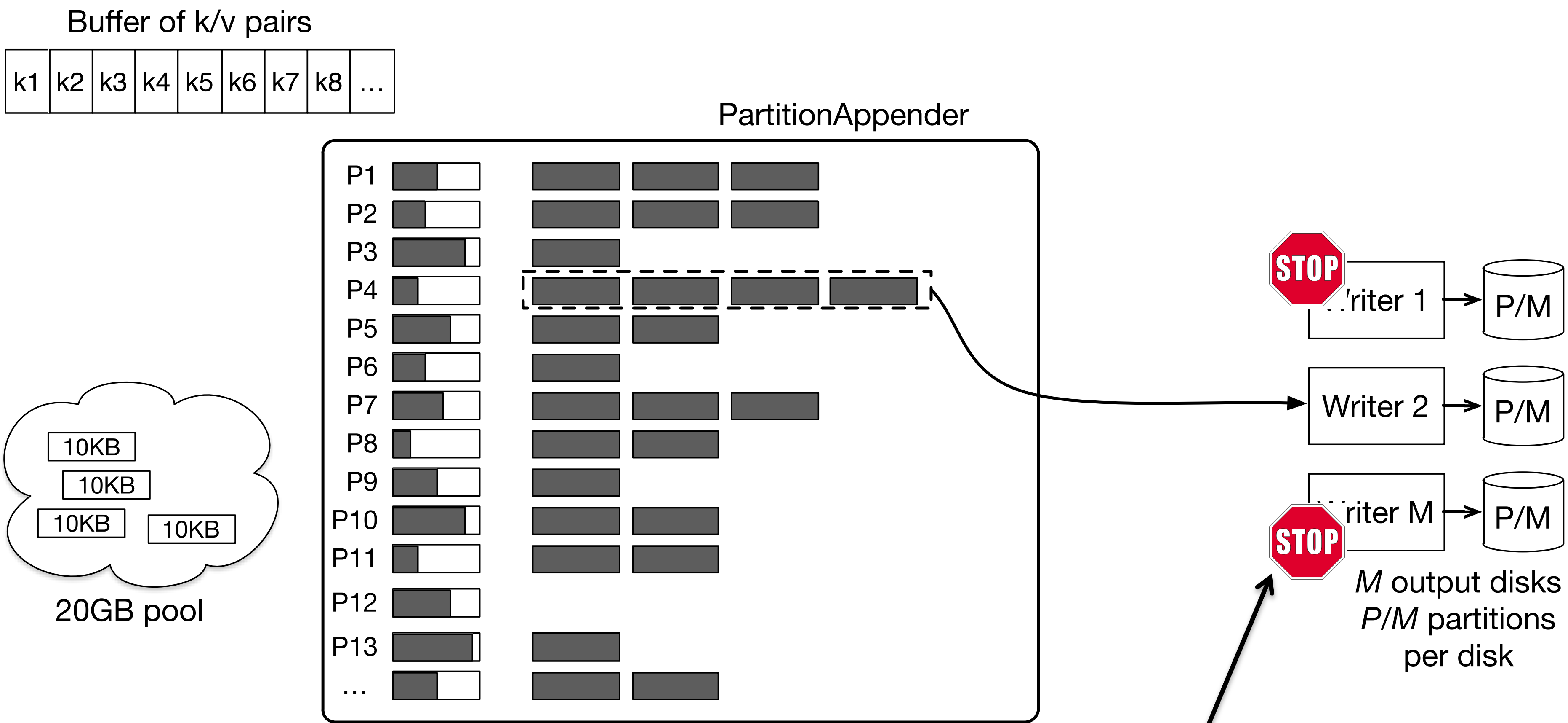
One "chain" of buffers per partition

Handling "hot" partitions



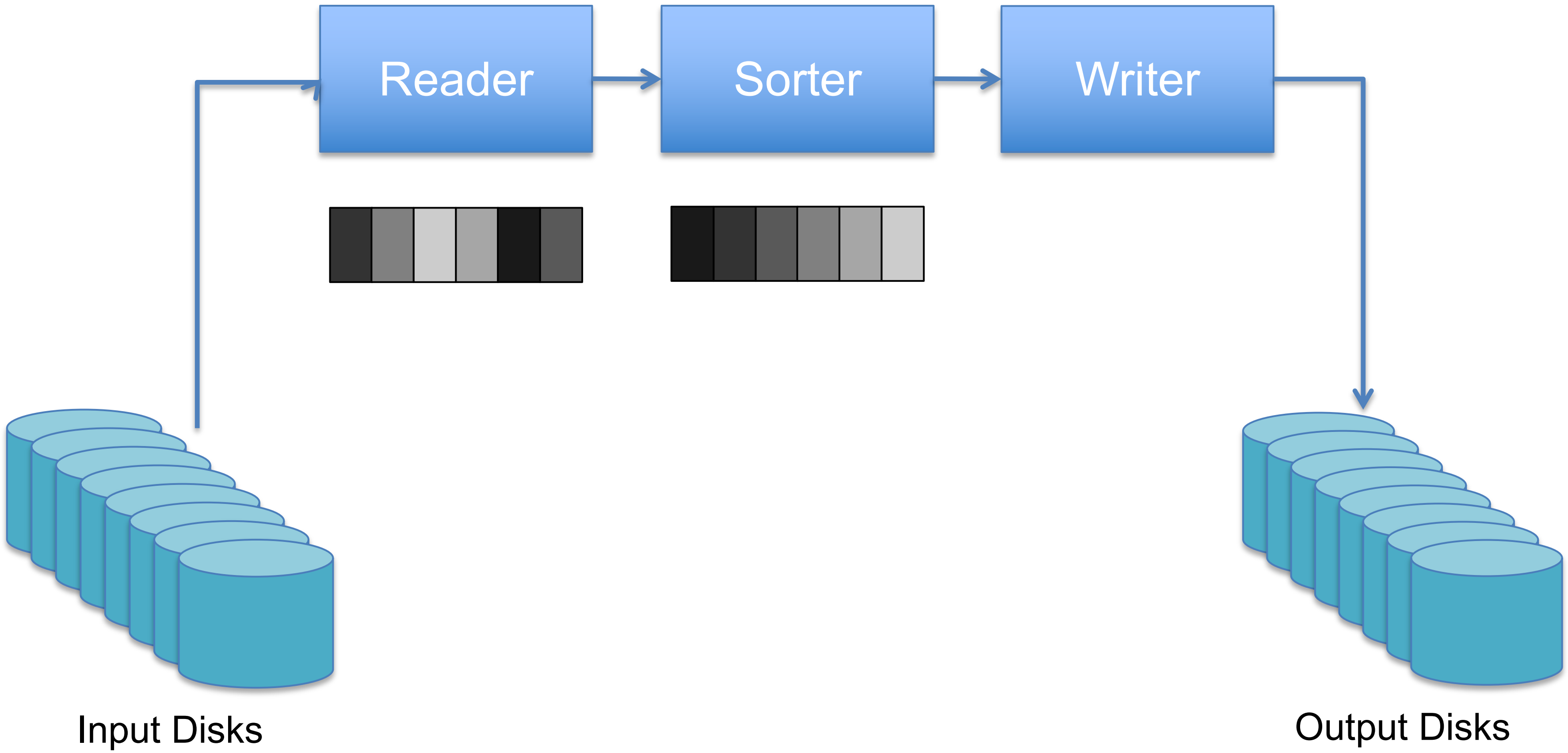
Largest chain = Largest possible write

Handling slow disks



Slow disks accept writes less often, leading to larger writes

Architecture Phase Two



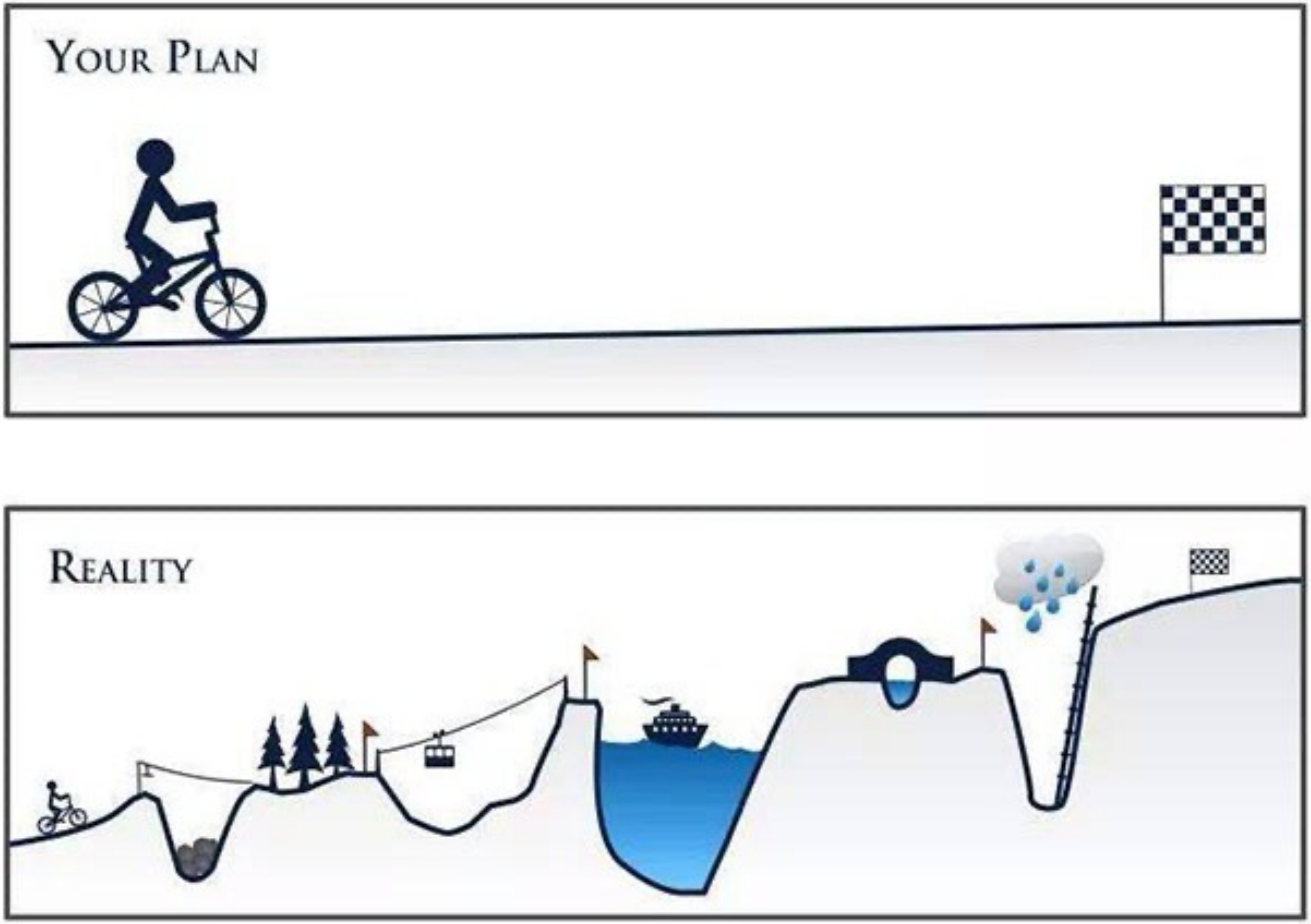
Evaluation

	100TB GraySort		100TB JouleSort
2009	Hadoop MapReduce	0.578 TB/min 3,452 nodes (2.8 MB/sec/node)	
2010	TritonSort	0.725 TB/min 52 nodes (232.4 MB/sec/node)	Created in 2010
2011	TritonSort		TritonSort
2012	TritonSort		TritonSort
2013	Hadoop MapReduce	1.42 TB/min 2,200 nodes (11.3 MB/sec/node)	TritonSort

Going after CloudSort

- Our team, with lead student Mike Conley, ported Themis to Amazon's Cloud Infrastructure
- Goal:
  - Learn how to migrate a system designed for **dedicated** resources to an **on-demand service**
  - Break the record using cloud computing

The project in a nutshell...

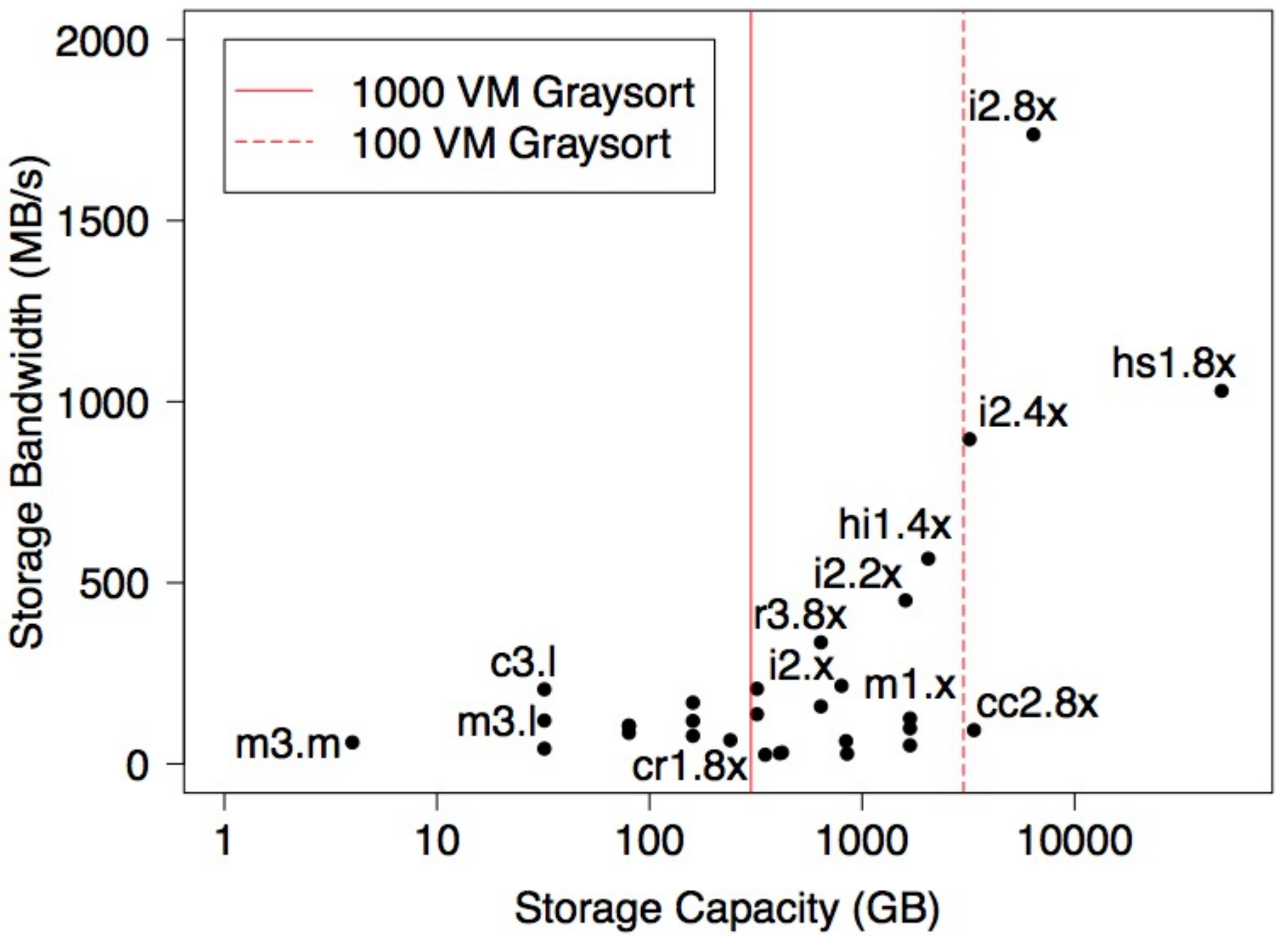


Key challenges

- "The cloud" often doesn't have any rain
  - We frequently couldn't get enough nodes ☹
- Performance(N-node cluster) !=

  N * Performance(1 node)
- Network bandwidth is not good

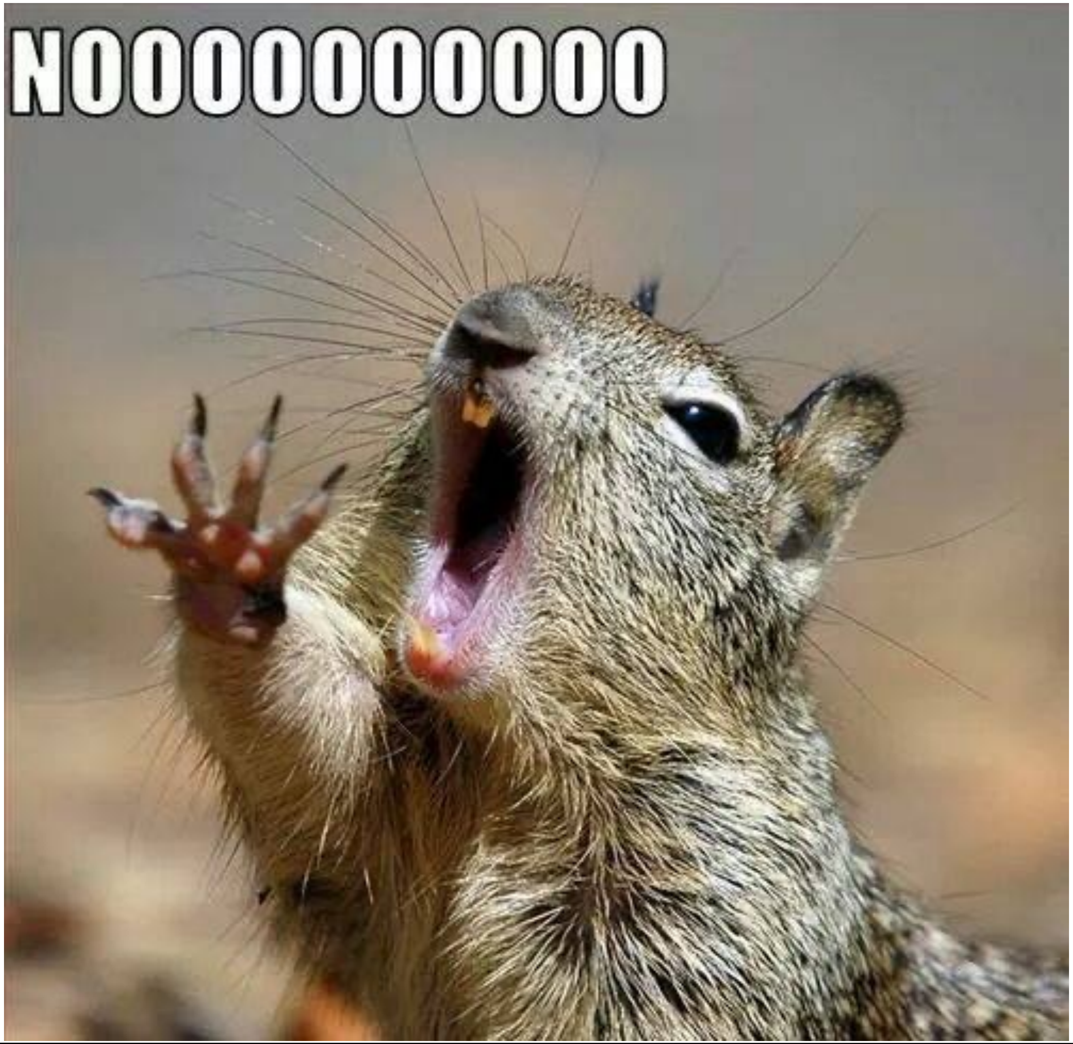
Characterizing each type of node



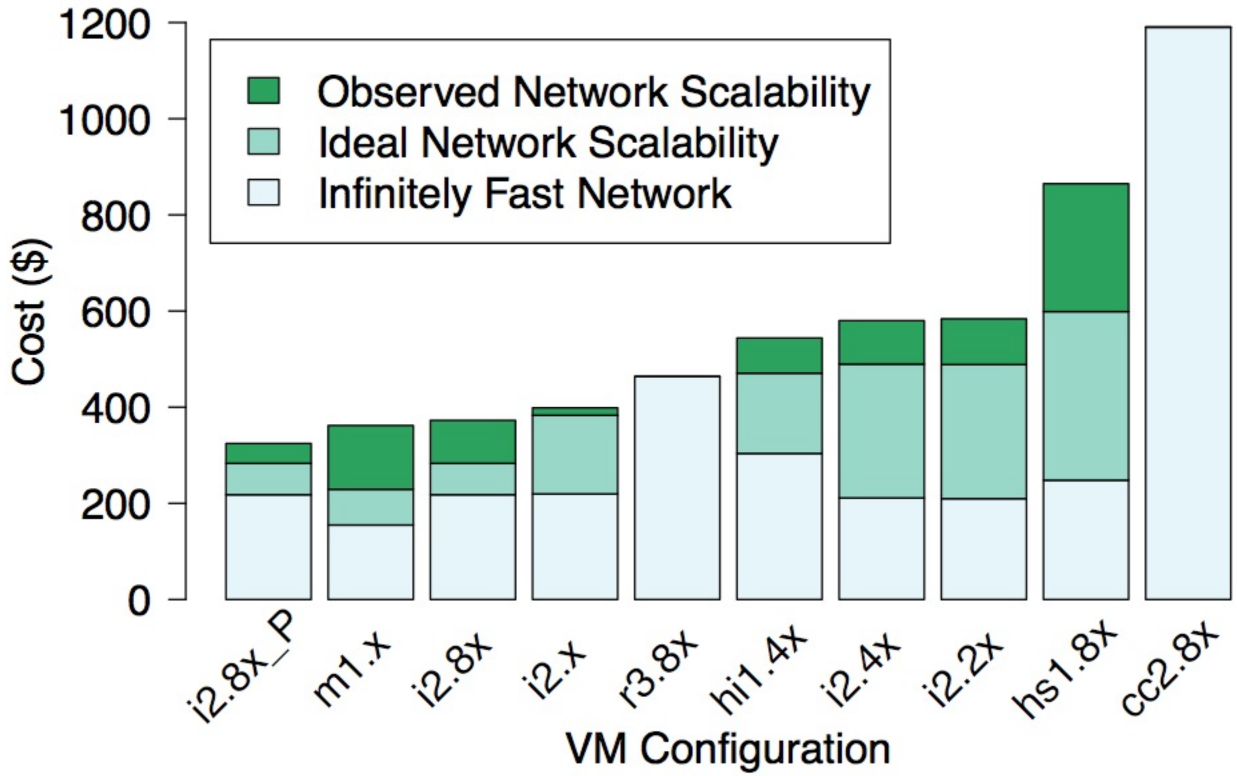
What a 100TB sort *should* cost

Instance type	Num nodes to sort 100 TB	Sort cost ($)
c3.large	9,375	28
m3.large	9,375	65
m3.medium	75,000	66
m1.xlarge	179	155
i2.4xlarge	94	211
i2.8xlarge	47	218
hs1.8xlarge	7	248
cr1.8xlarge	1,250	2,966

But then... the network...



Factoring in the network



Results

Category	Previous record	UCSD 2014 Result
Indy GraySort	1.42 TB/min (2,100 nodes)	6.76 TB/min (178 nodes)
Daytona GraySort	1.42 TB/min (2,100 nodes)	4.35 TB/min (186 nodes)
Indy MinuteSort	1401 GB (256 nodes)	4094 GB (178 nodes)
Indy CloudSort	N/A	$449.53 (330 nodes)
Daytona CloudSort	N/A	$449.53 (330 nodes)

For more information

- TritonSort: A Balanced Large-Scale Sorting System, Alexander Rasmussen, George Porter, Michael Conley, Harsha V. Madhyastha, Radhika Niranjan Mysore, Alexander Pucher, and Amin Vahdat, Proceedings of the 8th ACM/USENIX Symposium on Networked Systems Design and Implementation (NSDI), Boston, MA, March 2011.

- Themis: An I/O-Efficient MapReduce, Alexander Rasmussen, Michael Conley, Rishi Kapoor, Vinh The Lam, George Porter, and Amin Vahdat, Proceedings of the ACM Symposium on Cloud Computing (SOCC), San Jose, CA, October 2012.