A "Hitchhiker's" Guide to Fast and Efficient Data Reconstruction in Erasure-coded Data Centers

K. V. Rashmi, Nihar Shah, D. Gu,
H. Kuang, D. Borthakur, K. Ramchandran

Berkeley University of California

facebook

Need for Redundant Storage in Data Centers

- Frequent unavailability events in data centers
  - unreliable components
  - software glitches, maintenance shutdowns, power failures, etc.

- Redundancy necessary for reliability and availability

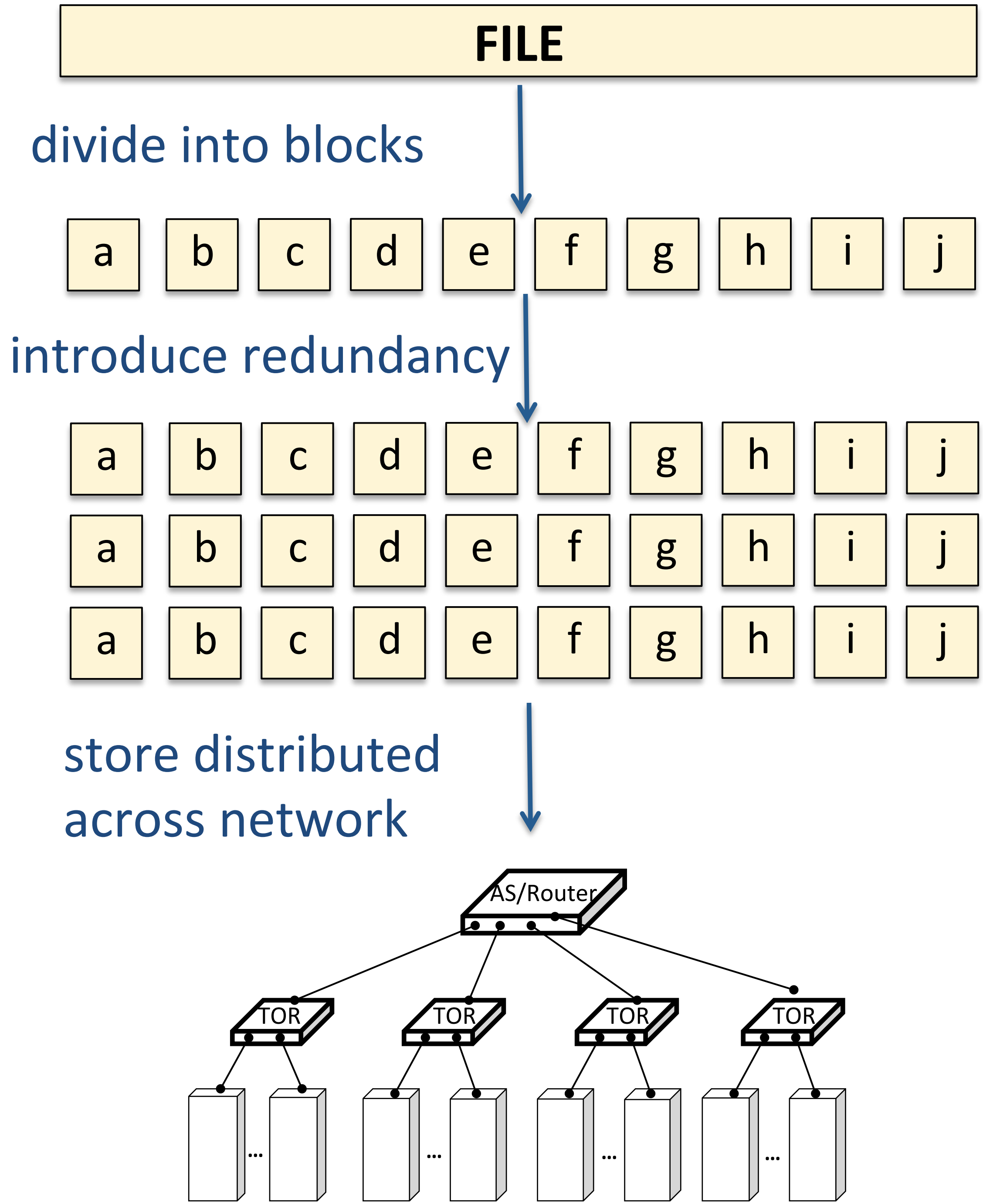
Popular Approach for Redundant Storage: Replication

- Distributed file systems used in data centers store multiple copies of data on different machines

- Machines typically chosen on different racks
  - to tolerate rack failures

E.g., Hadoop Distributed File System (HDFS) stores 3 replicas by default

HDFS


FILE
divide into blocks
a b c d e f g h i j
introduce redundancy
a b c d e f g h i j
a b c d e f g h i j
a b c d e f g h i j
store distributed
across network
AS/Router
TOR
TOR
TOR
TOR
...
...
...
...

Massive Data Sizes: Need Alternative to Replication

- Small to moderately sized data: disk storage is inexpensive
  - replication viable
- No longer true for massive scales of operation
  - e.g., Facebook data warehouse cluster stores multiple tens of Petabytes (PBs)

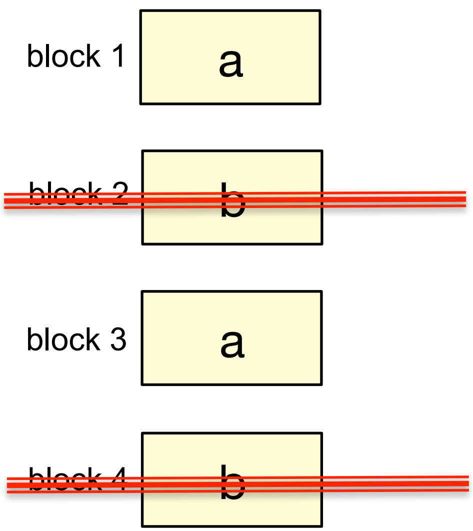
"Erasure codes" are an alternative

Erasure Codes in Data Centers

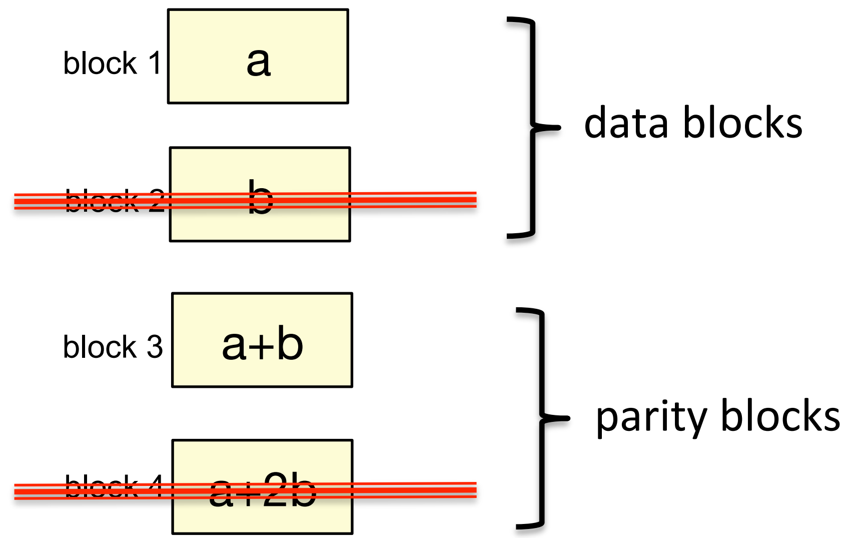
- Facebook data warehouse cluster
  - uses Reed-Solomon (RS) codes instead of 3-replication on a portion of the data
  - ***savings of multiple Petabytes of storage space***

Erasure Codes

Replication



Reed-Solomon (RS) code



	Replication	Reed-Solomon (RS) code
Overhead	2x	2x
Fault tolerance:	tolerates any one failure	tolerates any two failures

In general, erasure codes provide orders of magnitude higher reliability at much smaller storage overheads

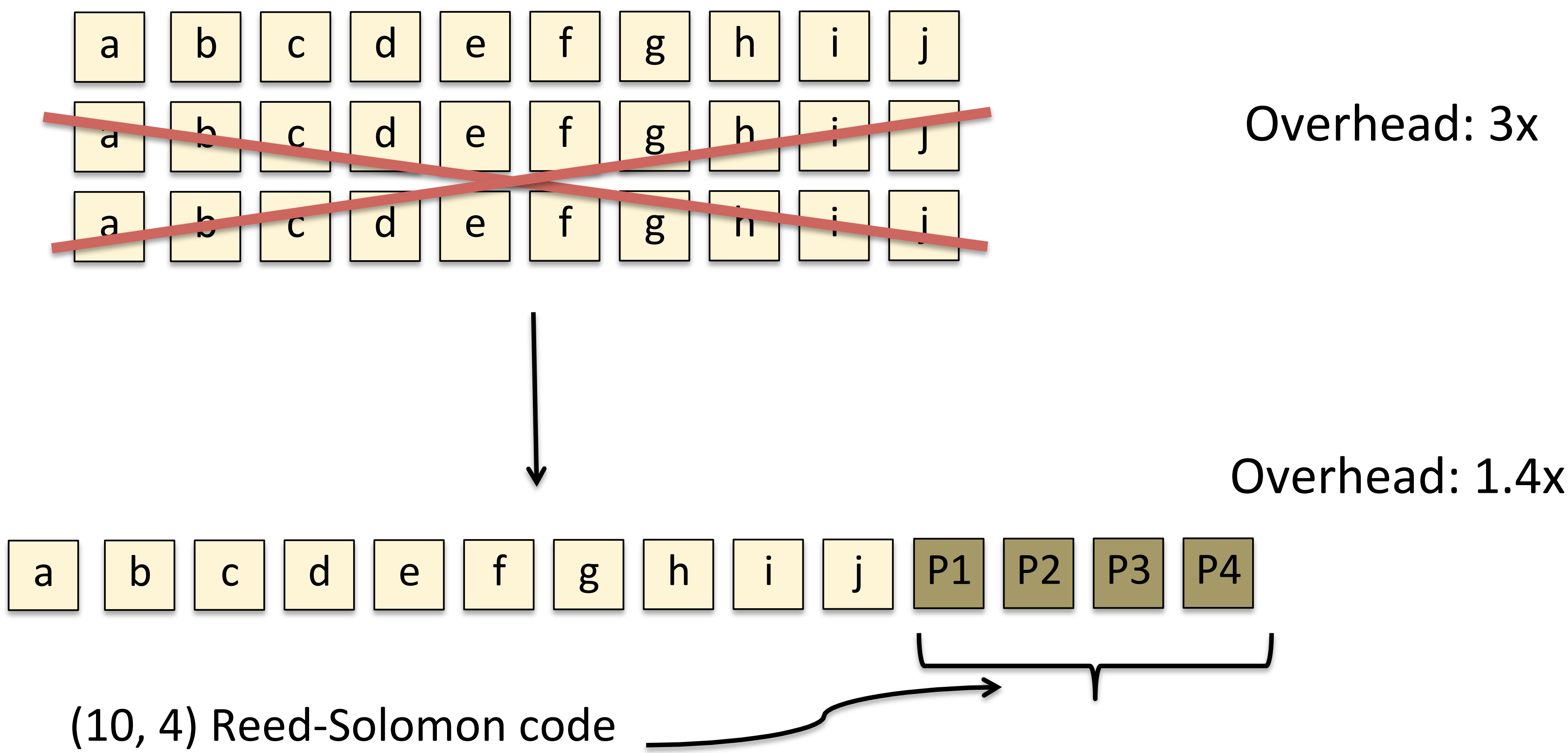
Outline

- Erasure Codes in Data Centers
  – HDFS
- Impact on the data center network
  – Problem description
- Our system: “Hitchhiker”
- Implementation and evaluation
  – Facebook data warehouse cluster
- Literature

Outline

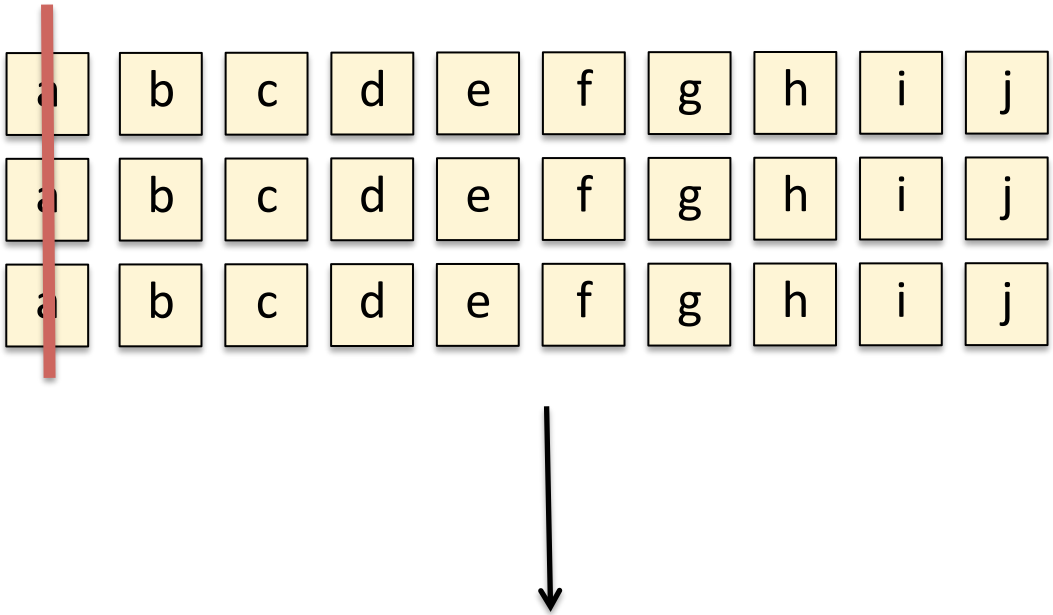
- Erasure Codes in Data Centers
  - HDFS
- Impact on the data center network
  - Problem description
- Our solution: "Hitchhiker"
- Implementation and evaluation
  - Facebook data warehouse cluster
- Literature

Erasure codes in Data Centers: HDFS-RAID



Borthakur, "HDFS and Erasure Codes (HDFS-RAID)"
Fan, Tantisiriroj, Xiao and Gibson, "DiskReduce: RAID for Data-Intensive Scalable Computing", PDSW 09

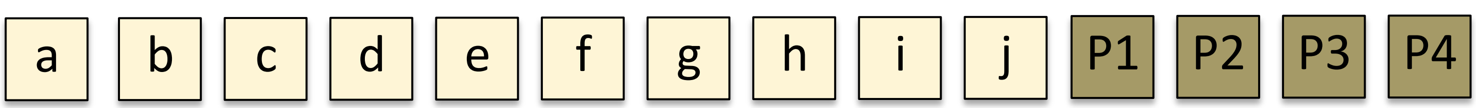
Erasure codes in Data Centers: HDFS-RAID



Overhead: 3x

Cannot tolerate many 3-failures

Overhead: 1.4x



(10, 4) Reed-Solomon code

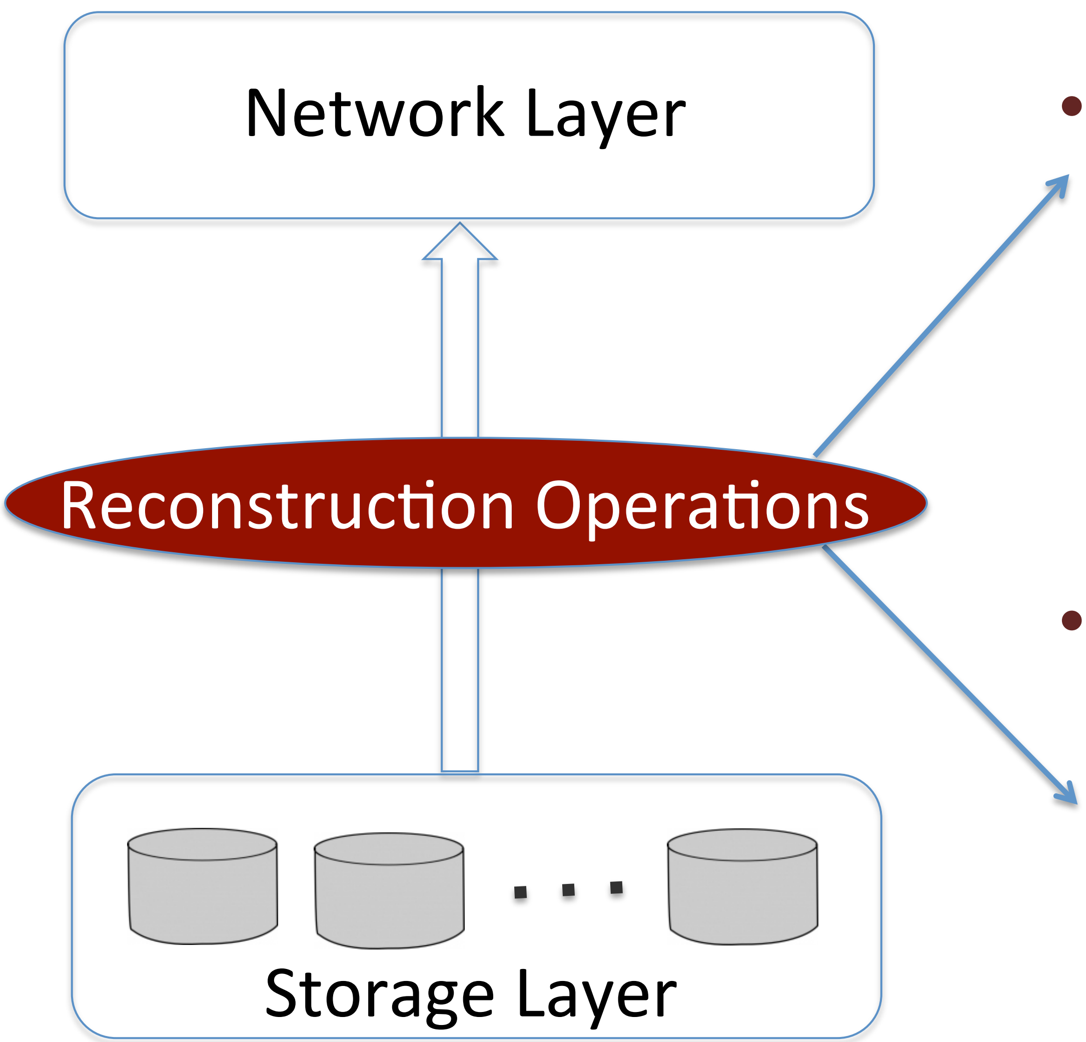
- Any 10 blocks sufficient
- Can tolerate any 4-failures

Borthakur, "HDFS and Erasure Codes (HDFS-RAID)"
Fan, Tantisiriroj, Xiao and Gibson, "DiskReduce: RAID for Data-Intensive Scalable Computing", PDSW 09

Outline

- Erasure Codes in Data Centers
  - HDFS
- Impact on the data center network
  - Problem description
- Our system: “Hitchhiker”
- Implementation and evaluation
  - Facebook data warehouse cluster
- Literature

Impact on Data Center Network

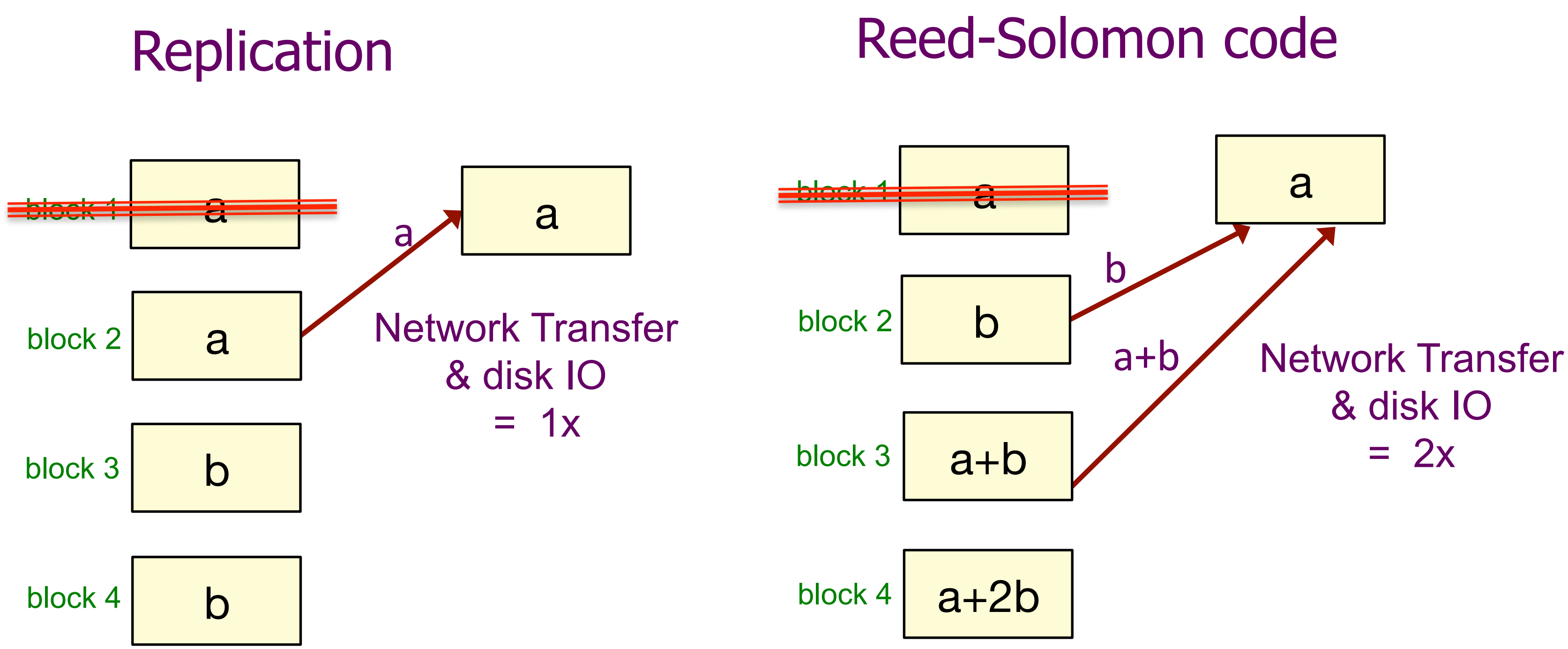


- Degraded Reads
  - requesting currently unavailable data
  - on-the-fly reconstruction
- Recovery
  - periodically replace unavailable blocks
  - to ensure desired level of reliability

Impact on Data Center Network

RS codes significantly increase network usage during reconstruction

Impact on Data Center Network

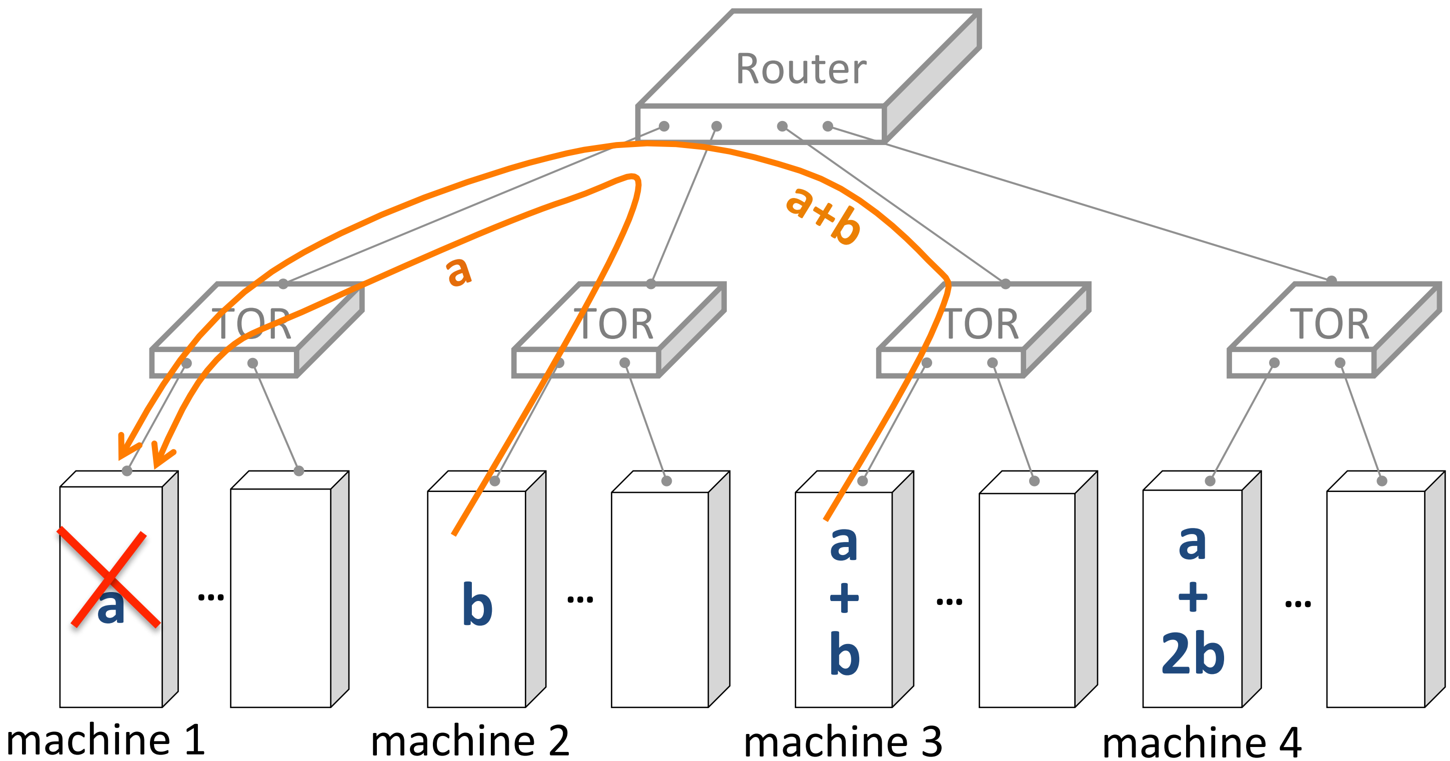


Network transfer & disk IO

= (#data-blocks) x (size of data to be reconstructed)

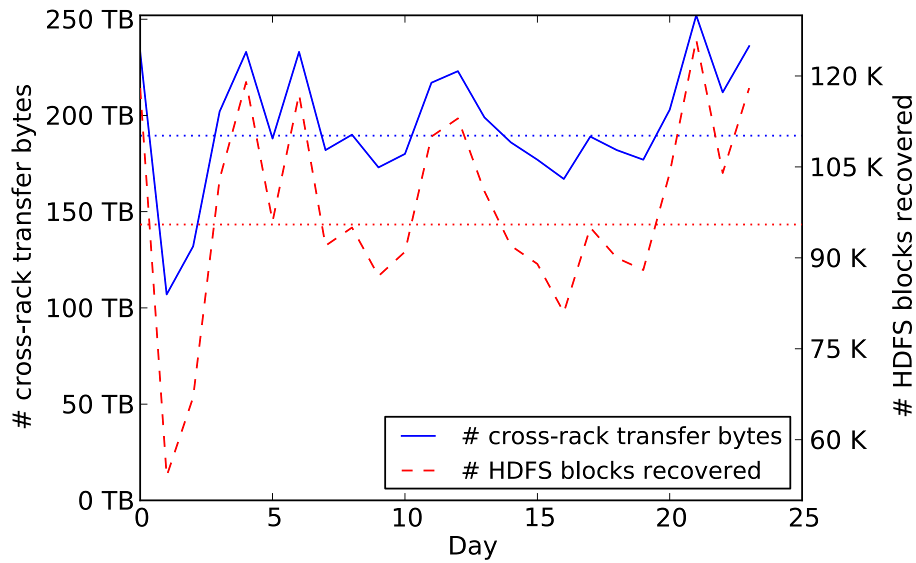
In (10, 4) RS, it is 10x

Impact on Data Center Network



Burdens the already oversubscribed Top-of-Rack and higher level switches

Impact on Data Center Network: Facebook Data Warehouse Cluster



- Multiple PB of Reed-Solomon encoded data
- Median of 180 TB transferred across racks per day for RS reconstruction ≈ 5 times that under 3-replication

Rashmi et al., "A Solution to the Network Challenges of Data Recovery in Erasure-coded Storage: A Study on the Facebook Warehouse Cluster", Usenix HotStorage Workhsop 2013

RS codes: The Good and The Bad

- Maximum possible fault-tolerance for given storage overhead
  - storage-capacity optimal
  - ("*maximum-distance-separable*" in coding theory parlance)
- Flexibility in choice of parameters
  - Supports any number of data and parity blocks

- Not designed to handle reconstruction operations efficiently
  - negative impact on the network

Goal

RS codes: The Good and The Bad

- Maximum possible fault-tolerance for given storage overhead
  - storage-capacity o
  - (“*maximum-dista* theory parlance)
- Flexibility in choice of parameters
  - Supports any number of data and parity blocks

Maintain

- Not designed to handle reconstruction operations effi
  - negative impact on the network

Improve

Goal

To build a system with:

Maintain

Same (optimal) storage requirement and fault tolerance

Same (complete) flexibility in choice of design parameters

Improve

Reduced data transfer across network and reduced IO from disk during reconstruction

Hitchhiker

Is a system with:

Maintain

Same (optimal) storage requirement and fault tolerance ☑

Same (complete) flexibility in choice of design parameters ☑

Improve

25 to 45% less network transfers and disk IO during reconstruction ☑

Outline

- Erasure Codes in Data Centers
  - HDFS
- Impact on the data center network
  - Problem description
- Our system: “Hitchhiker”
- Implementation and evaluation
  - Facebook data warehouse cluster
- Literature

At an Abstract Level

HITCHHIKER

Hitchhiker's Erasure Code

Reed-Solomon Code

+

Hop-and-couple (disk layout)

Hitchhiker's Erasure Code: Toy Example

Start with the RS code

block 1	a_1	a_2
block 2	b_1	b_2
block 3	a_1+b_1	a_2+b_2
block 4	a_1+2b_1	a_2+2b_2
	1 byte	1 byte

Intermediate Code

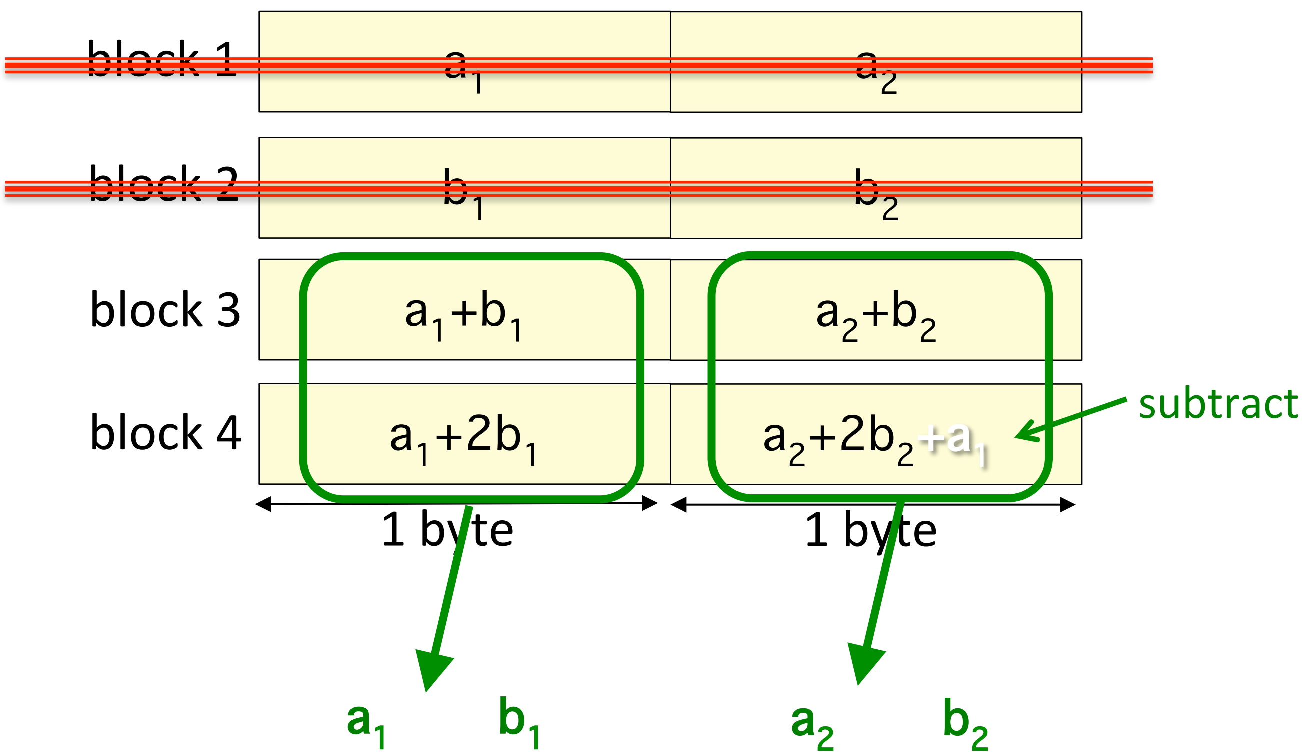
Add information from first group on to parities of the second group

	1 byte	1 byte
block 1	a_1	a_2
block 2	b_1	b_2
block 3	a_1+b_1	a_2+b_2
block 4	a_1+2b_1	$a_2+2b_2+a_1$

No extra storage

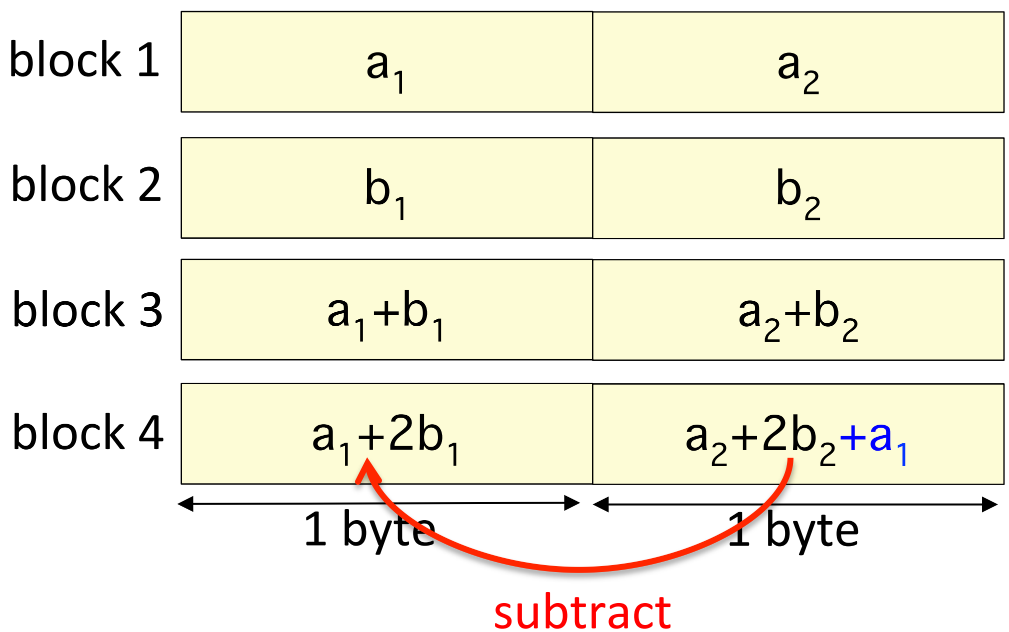
Storage-optimality of Intermediate Code

Retains failure tolerance of RS codes:
can tolerate failure of any 2 nodes



Final Code

Invertible operation *within* a block



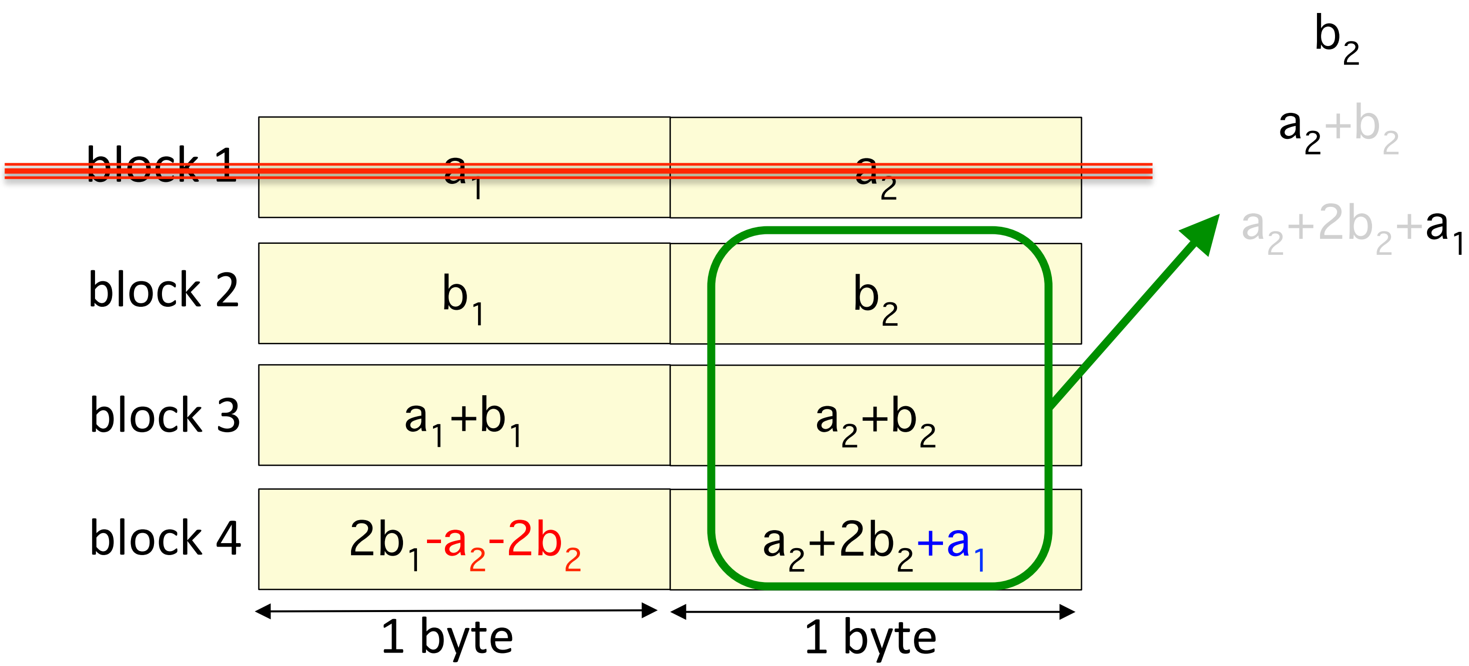
Final Code

Invertible operations *within* blocks do not change storage or fault tolerance

block 1	a_1	a_2
block 2	b_1	b_2
block 3	a_1+b_1	a_2+b_2
block 4	$2b_1-a_2-2b_2$	$a_2+2b_2+a_1$
	1 byte	1 byte

Efficient Reconstruction

Data transferred: only 3 bytes
(instead of 4 bytes as in RS)



Efficient Reconstruction

Data transferred: only 3 bytes
(instead of 4 bytes as in RS)

block 1	a_1	$\boxed{a_2}$
~~block 2~~	$\cancel{b_1}$	$\cancel{b_2}$
block 3	a_1+b_1	$\boxed{a_2+b_2}$
block 4	$\boxed{2b_1-a_2-2b_2}$	$a_2+2b_2+a_1$
	1 byte	1 byte

Hitchhiker's Erasure Code

- Builds on top of RS codes
- Uses our theoretical framework of "Piggybacking"*
- Three versions
  - XOR
  - XOR+
  - non-XOR

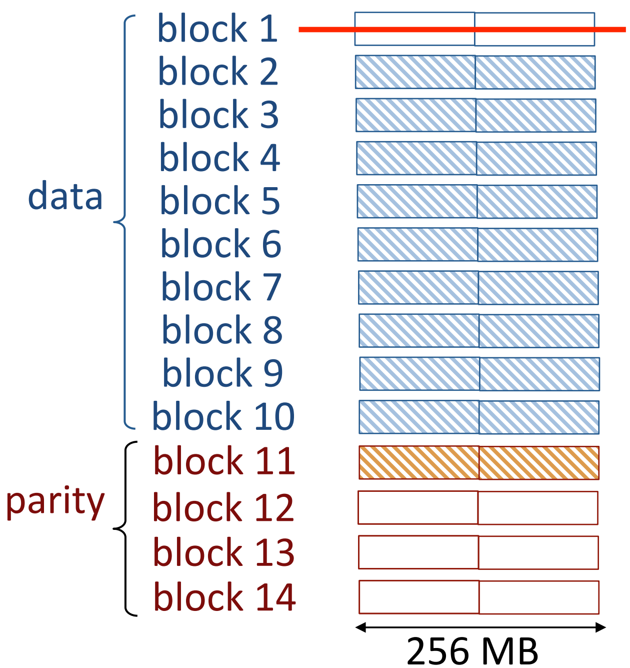
* K.V. Rashmi, Nihar Shah, K. Ramchandran, "*A Piggybacking Design Framework for Read-and Download-efficient Distributed Storage Codes*", in IEEE International Symposium on Information Theory, 2013.

Hop-and-couple (disk layout)

- Way of choosing which bytes to mix
  - couples bytes farther apart in block
  - to minimize fragmentation of reads during reconstruction
- Translate savings in network-transfer to savings in disk-IO as well
  - By making reads contiguous

RS vs Hitchhiker from the Network's Perspective…

Data Transfer during Reconstruction in RS-based System

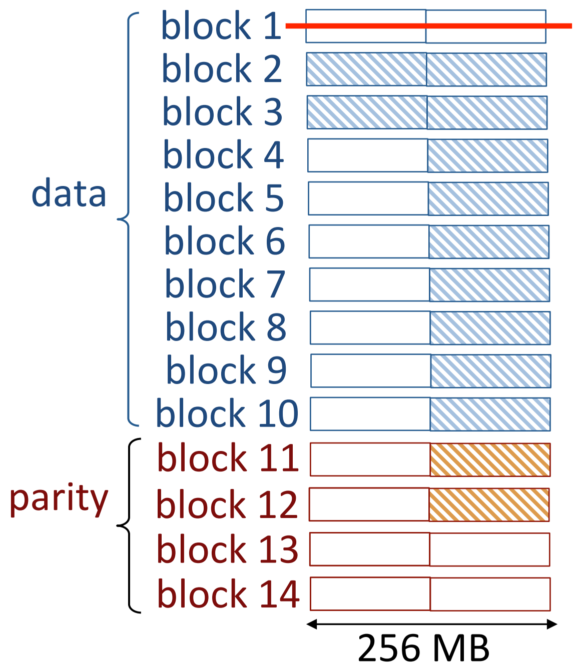


Transfer: 10 full blocks

Connect to 10 machines

Data Transfer during Reconstruction in Hitchhiker

Reconstruction of data blocks 1-9:

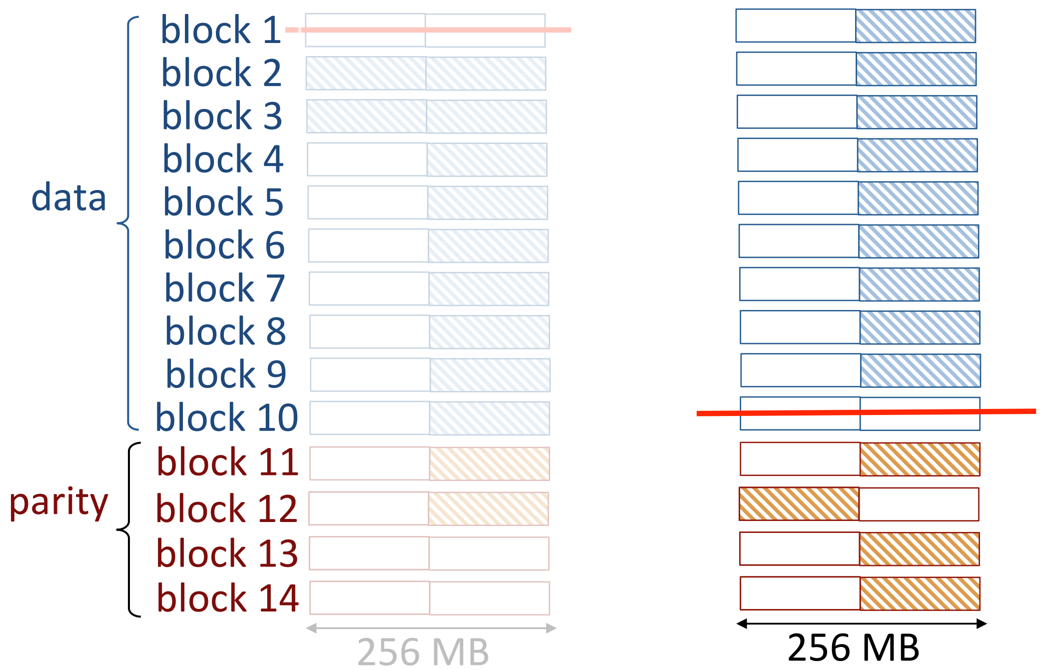


Transfer: 2 full blocks + 9 half blocks (= 6.5 blocks total)

Connect to 11 machines

Data Transfer during Reconstruction in Hitchhiker

Reconstruction of block 10:



Transfer: 13 half blocks (= 6.5 blocks total)

Connect to 13 machines

Outline

- Erasure Codes in Data Centers
  - HDFS
- Impact on the data center network
  - Problem description
- Our system: “Hitchhiker”
- Implementation and evaluation
  - Facebook data warehouse cluster
- Literature

Implementation & Evaluation Setup (1)

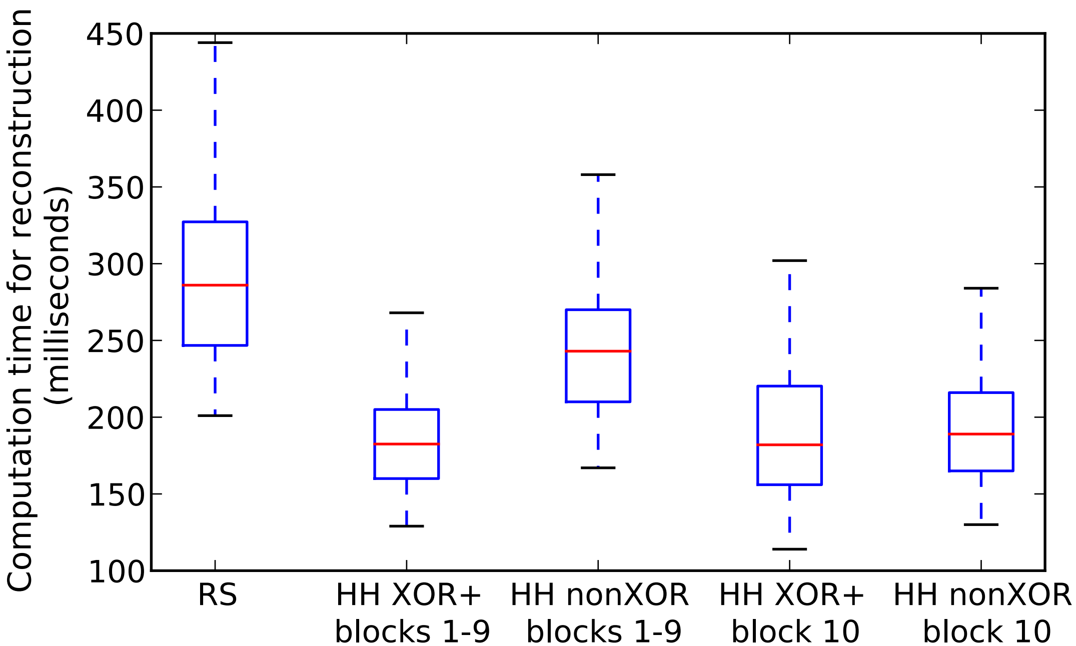
- Implemented on top of HDFS-RAID
  - erasure coding module in HDFS based on RS
  - used in the Facebook data warehouse cluster

- Deployed and tested on a 60 machine test cluster at Facebook
  - verified 35% reduction in the network transfers during reconstruction

Implementation & Evaluation Setup (2)

- Evaluation of timing metrics on the Facebook data warehouse cluster in production
  - under real-time production traffic and workloads
  - using Map-Reduce to run encoding and reconstruction jobs, just as HDFS-RAID

Decoding Time



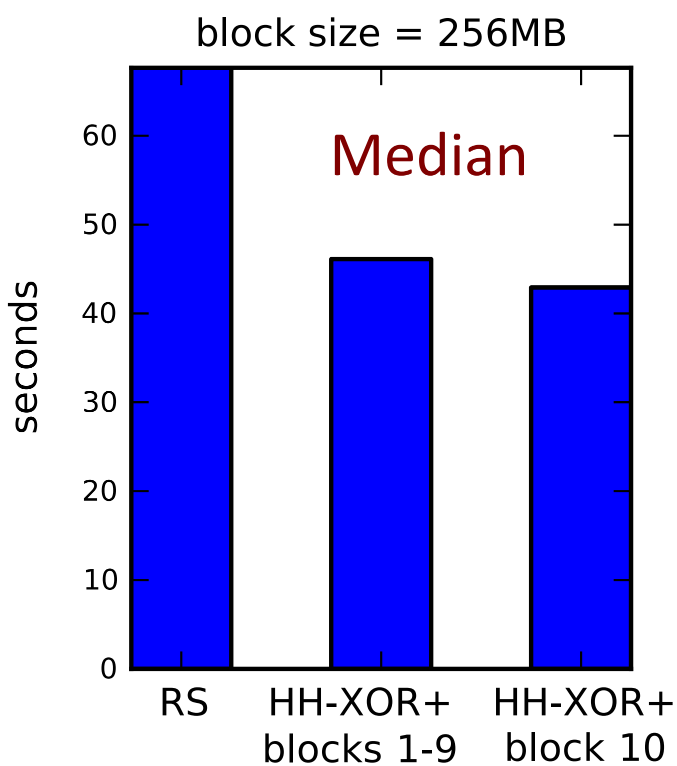
36% reduction

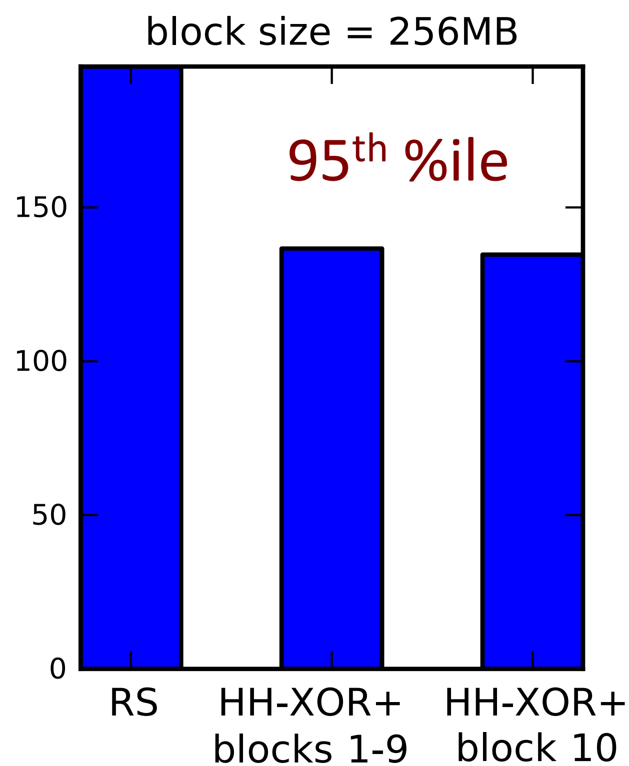
- RS decoding on only half portion of the blocks
- Faster computation for degraded reads and recovery

- XOR versions: 25% lesser than non-XOR

Read & Transfer Time

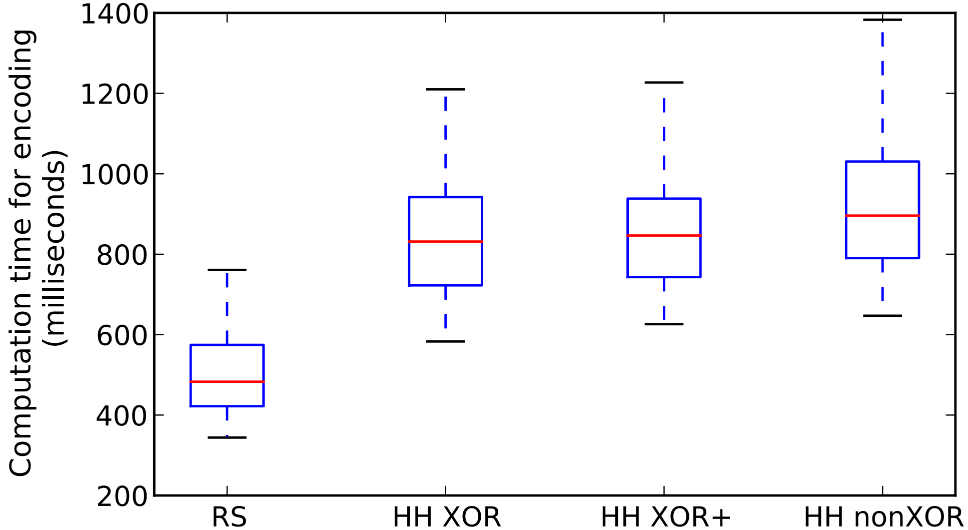
System	Data transfer	Connectivity (#machines)
RS	2.56 GB	10
HH blocks 1-9	1.67 GB	11
HH block 10	1.67 GB	13





- Read & transfer time 30% lower in Hitchhiker (HH)
- Similar reduction for other block sizes as well

Encoding Time



72% higher

Benefits outweigh higher encoding cost in many systems (e.g., HDFS):

- encoding is one time operation
- often run as a background job
- does not fall along any critical path

Outline

- Impact on the data center network
  - Problem description
- Our system: “Hitchhiker”
- Implementation and evaluation
  - Facebook data warehouse cluster
- Literature

Existing Systems

- Need additional storage
  - Huang et al. (Windows Azure) 2012, Sathiamoorthy et al. (Xorbas) 2013, Esmaili et al. (CORE) 2013
    - Add additional parities to reduce download
  - Hu et al. (NCFS 2011)

- Highly restricted parameters
  - Khan et al. (Rotated-RS) 2012: #parity ≤ 3
  - Xiang et al., Wang et al. 2010, Hu (NCCloud) et al. 2012: #parity ≤ 2
  - Hitchhiker performs as good or better for these restricted settings as well

Hitchhiker: Summary

Code metrics:

Storage requirement	Same (optimal)
Supported parameters	All
Fault tolerance	Same (optimal)

Reconstruction:

Network transfers	35% less
Disk IO	35% less
Data read and transfer time (median)	31.8% less
Data read and transfer time (95th %ile)	30.2% less
Computation time (median)	36.1% less

Encoding:

Encoding time (median)	72.1% more

Thanks!

Backup Slides

Hop-and-Couple

- Technique to pair bytes under Hitchhiker's erasure code
- Makes disk reads during reconstruction contiguous