Using Similarity in Content and Access Patterns to Improve Space Efficiency and Performance in Storage Systems

Xing Lin

PhD Defense
July 22, 2015

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- Total number of photos stored by 2010

  260 billion
  (20 petabytes)

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Amazon S3

Amazon S3 – Two Trillion Objects

by Jeff Barr | on 18 APR 2013 | in Amazon S3 | Permalink | Comments

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(Assume) average object size is 100 KB, total data size is 200 PB

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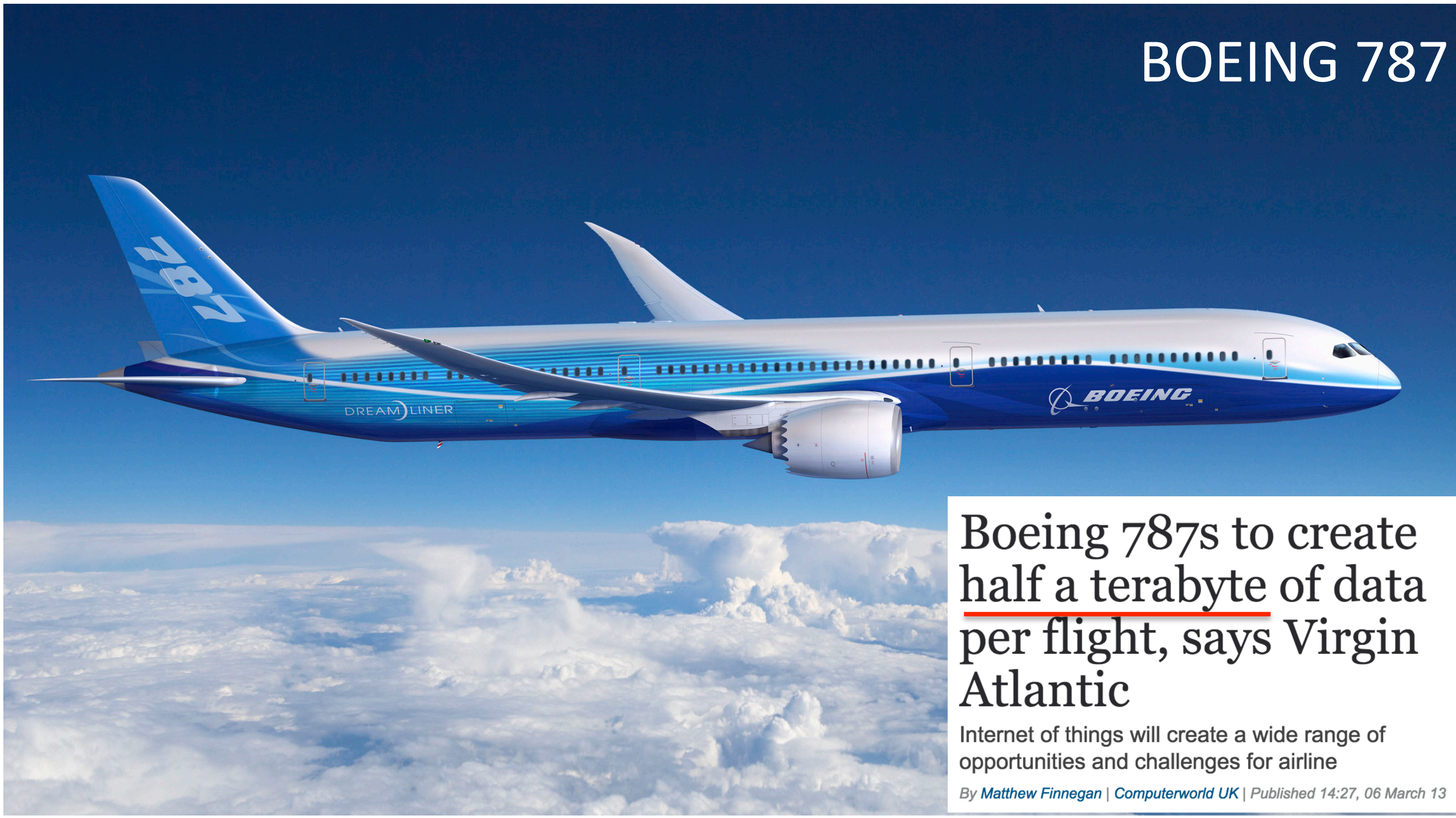
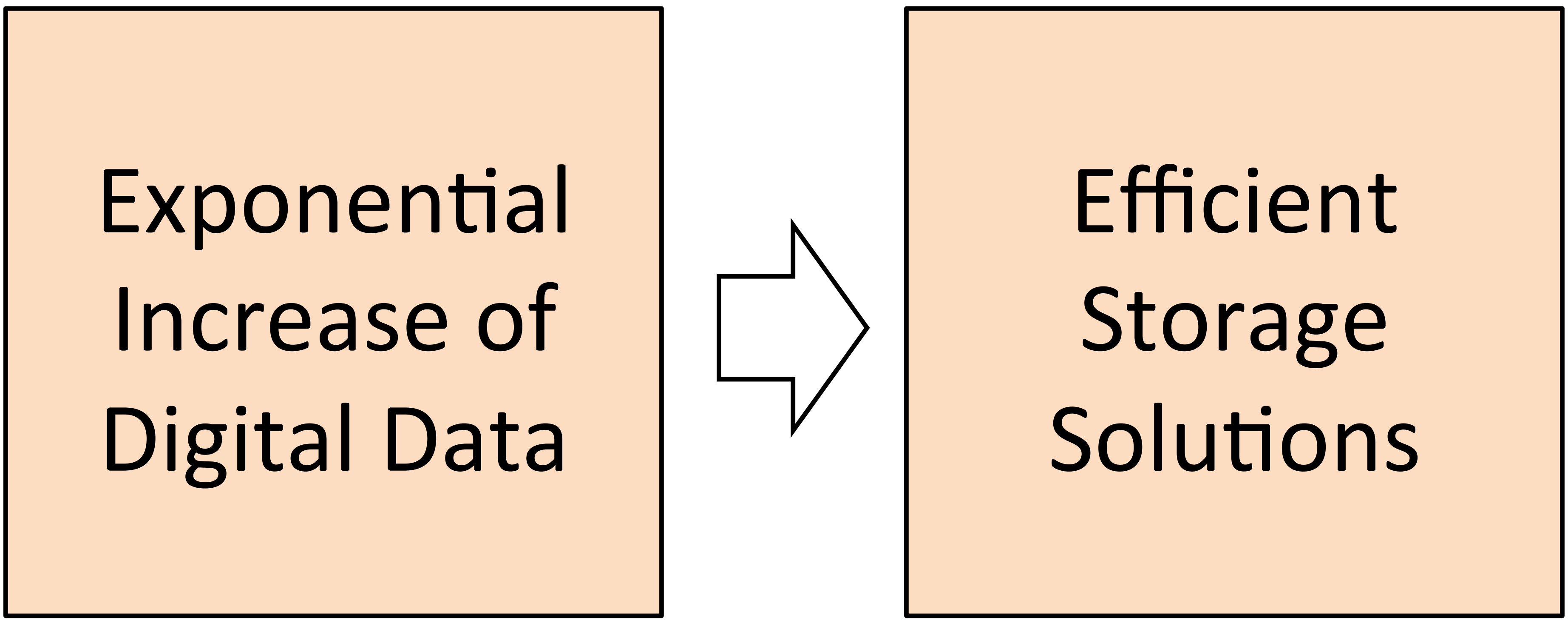


Exponential Increase of Digital Data


Exponential Increase of Digital Data
Efficient Storage Solutions

Data Reduction Techniques

- **Compression**: find redundant strings and replace with compact encodings
  - 2x reduction
  - LZ ([Ziv and Lempel 1997]), lz4, gzip, bzip2, 7z, xz, …

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- **Compression**: find redundant strings and replace with compact encodings
  - 2x reduction
  - LZ ([Ziv and Lempel 1997]), lz4, gzip, bzip2, 7z, xz, …
- **Deduplication**: find duplicate chunks and store unique ones
  - 10x reduction for backups
  - Venti ([Quinlan FAST02]), DataDomain FileSystem ([Zhu FAST08]), iDedup ([Srinivasan FAST12]), …

Limitations

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- **Deduplication**: interleave metadata with data
  - Frequent metadata changes introduce many unnecessary unique chunks

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- **Deduplication**:
  - Separate metadata from data, to store ***same*** type of data together (Chap3, HotStorage15)
  - Use deduplication for efficient disk image storage (Chap4, TridentCom15)
- **Differential IO Scheduling**: schedule ***same*** type of IO requests for predictable and efficient performance (Chap5, HotCloud12)

Thesis Statement

Similarity in content and access patterns can be utilized to improve **space efficiency**,
by storing **similar** data together
and **performance predictability and efficiency**,
by scheduling **similar** IO requests to the same hard drive.

Outline

- ✓ Introduction
    - ✓ ***Migratory Compression***
    - ✓ Improve deduplication by separating metadata from data
    - ✓ Using deduplication for efficient disk image deployment
    - ✓ Performance predictability and efficiency for Cloud Storage Systems
- ✓ Conclusion

Background on Compression

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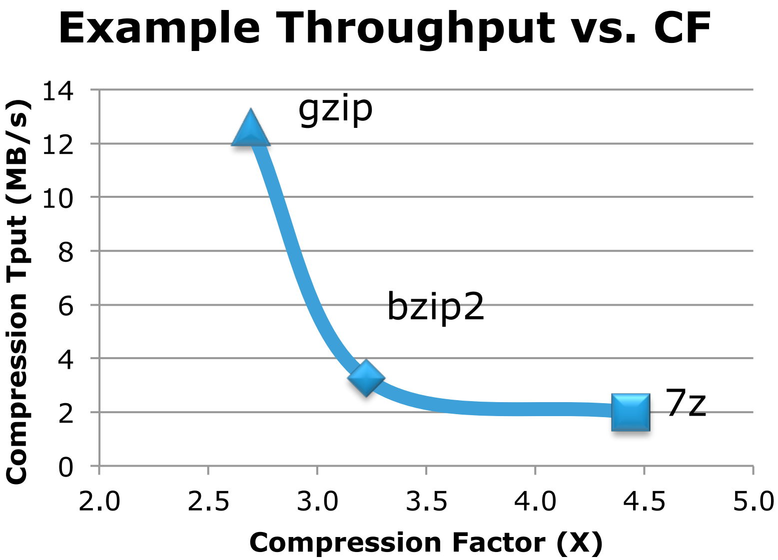

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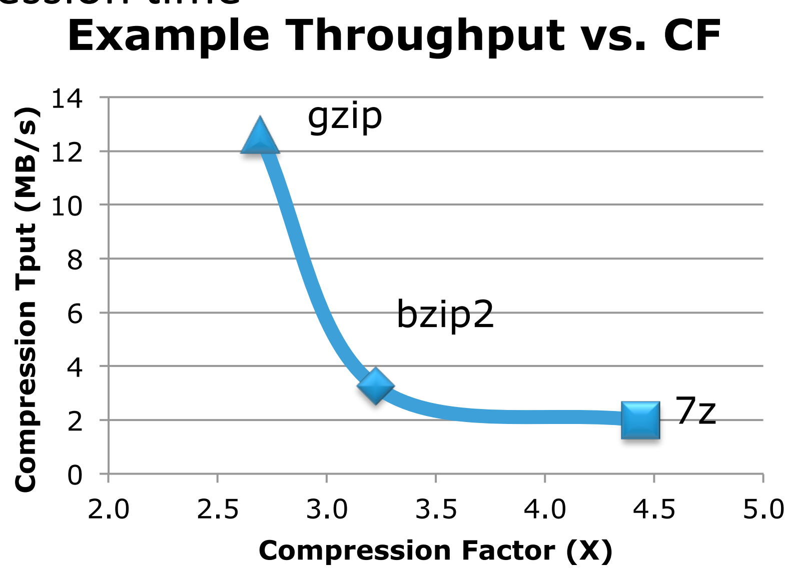

The larger the window, the **better** the compression but **slower**.
Fundamental reason: finding redundancy in ***string level*** does **not** scale to ***large windows***

Migratory Compression

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- **Key idea**: group by similarity in ***block level***, enabling standard compressors to find repeated strings with ***small windows***

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- **Key idea**: group by similarity in ***block level***, enabling standard compressors to find repeated strings with ***small windows***
- ***Migratory compression (MC)***: coarse-grained reorganization to group ***similar*** blocks to improve compressibility
  - A generic pre-processing stage for standard compressors
  - In many cases, improve **both** compressibility and throughput
  - Effective for improving compression for archival storage

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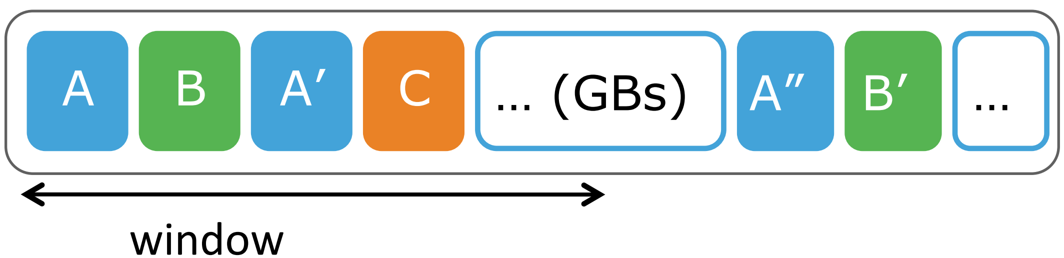

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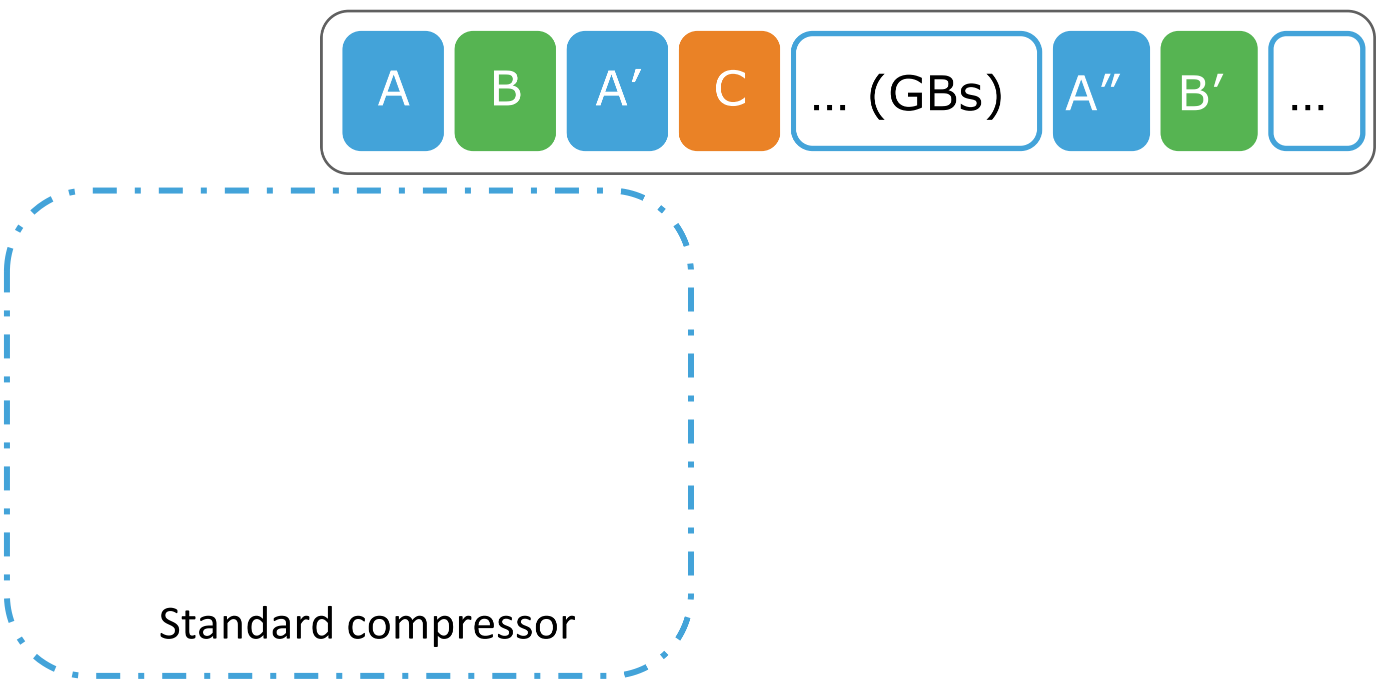

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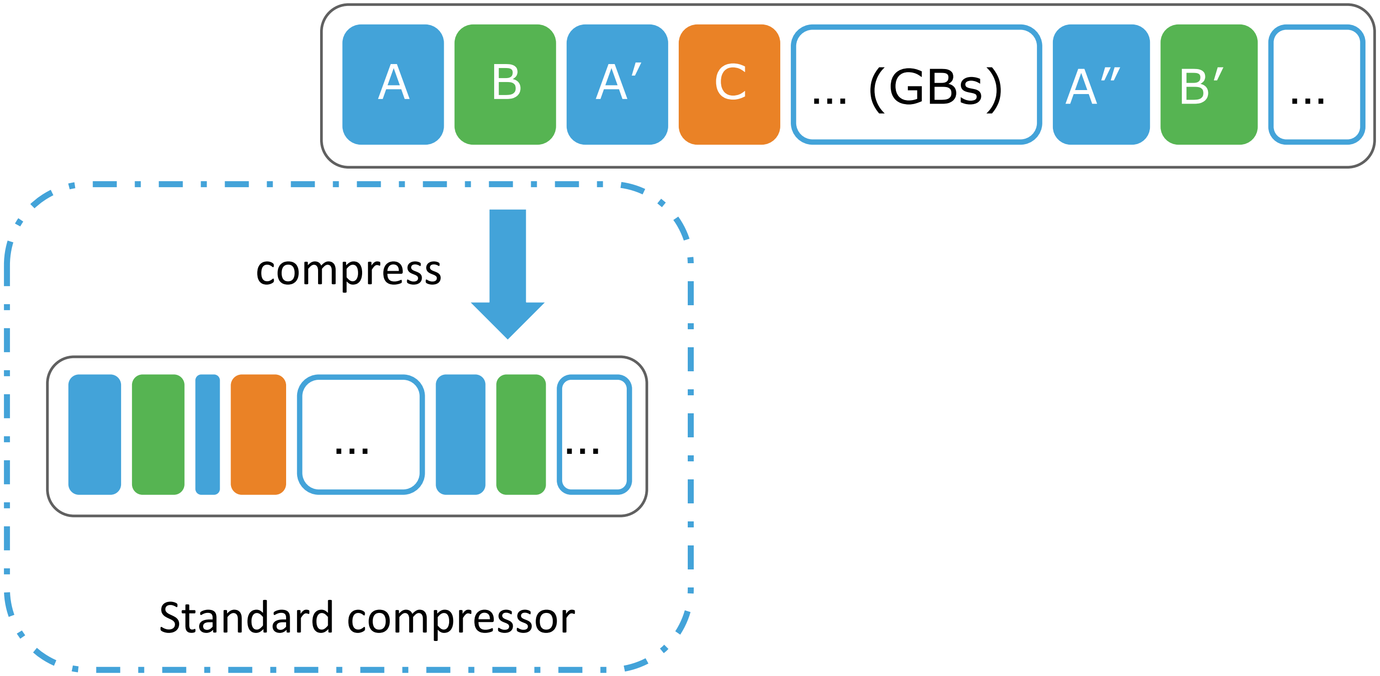

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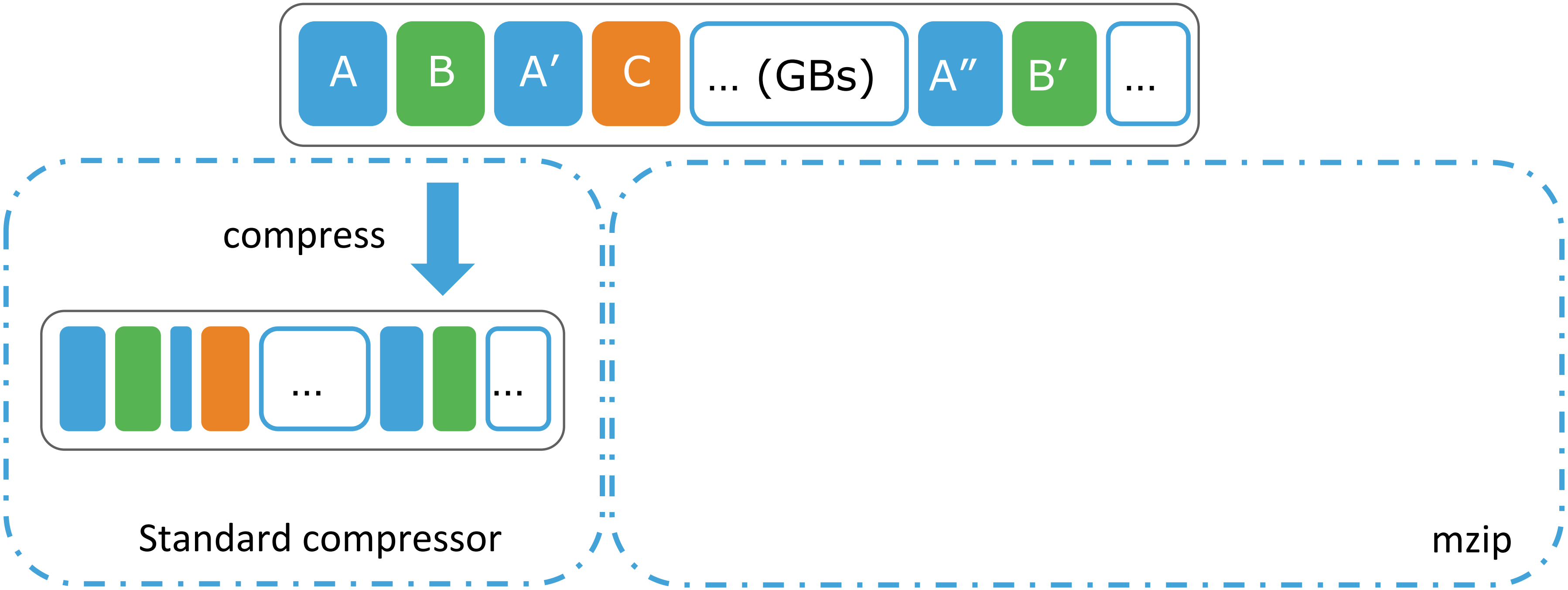

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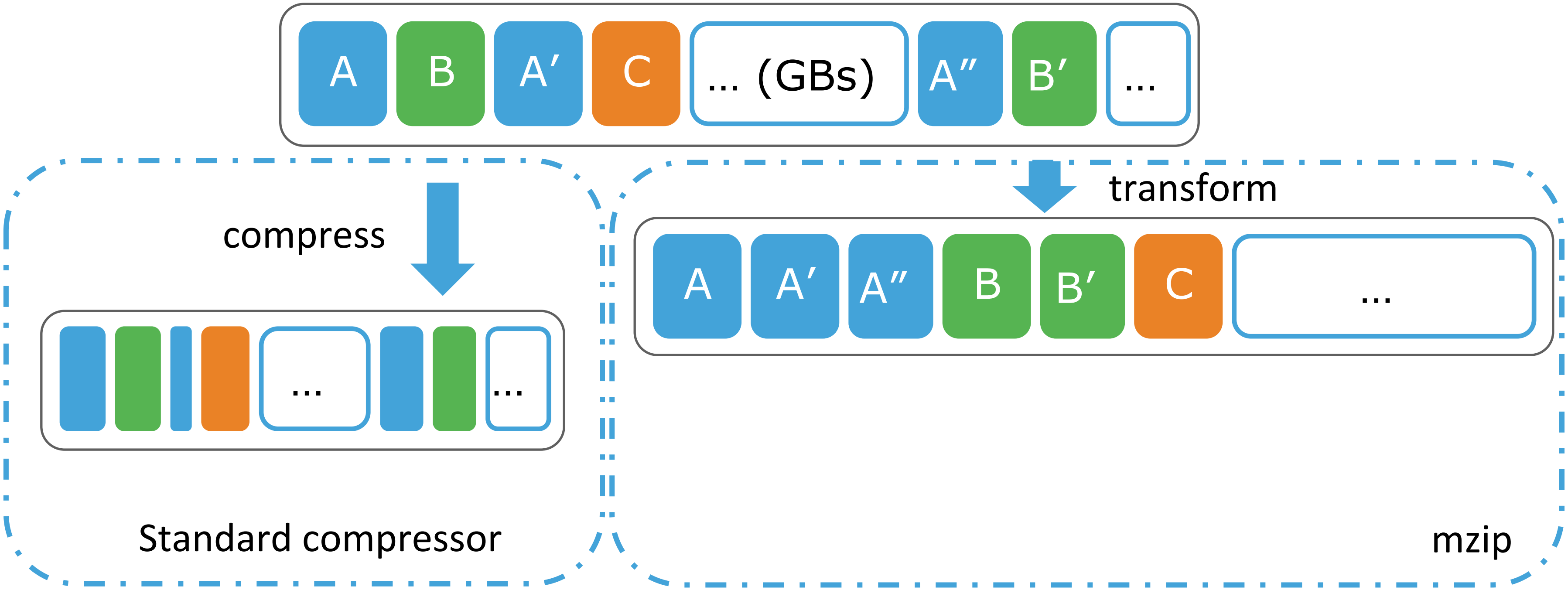

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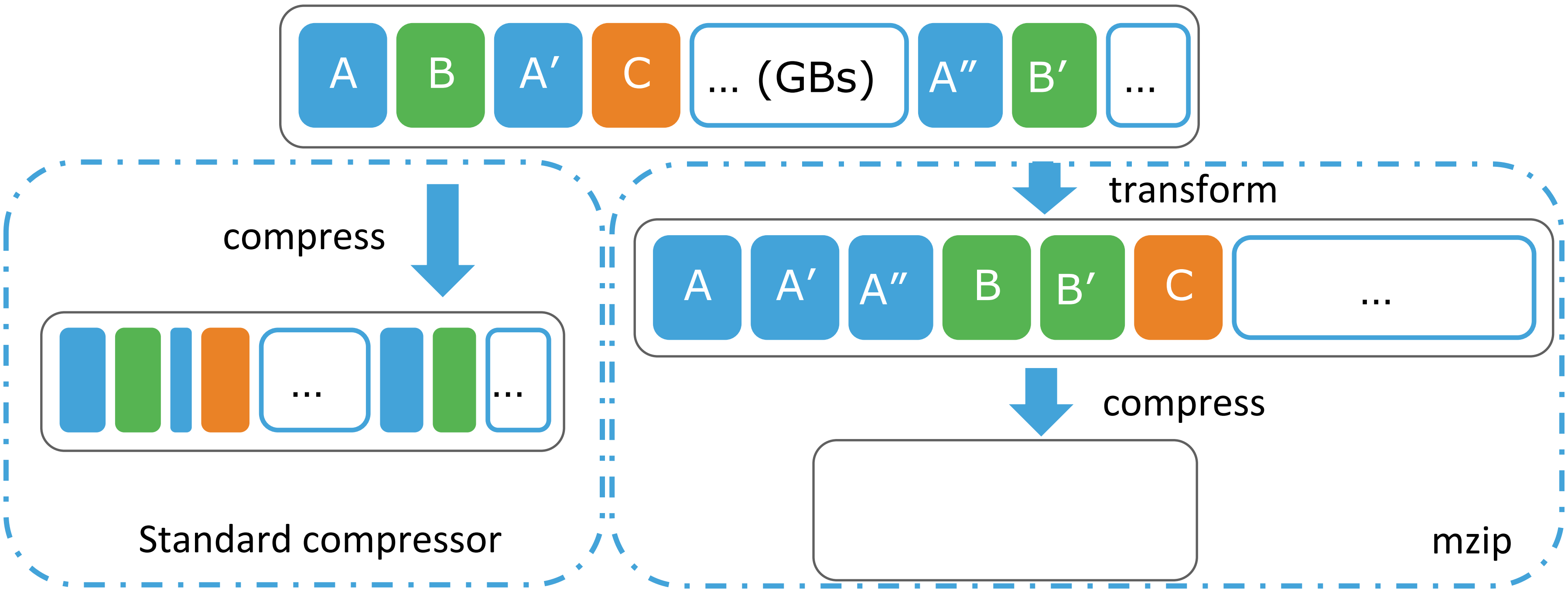

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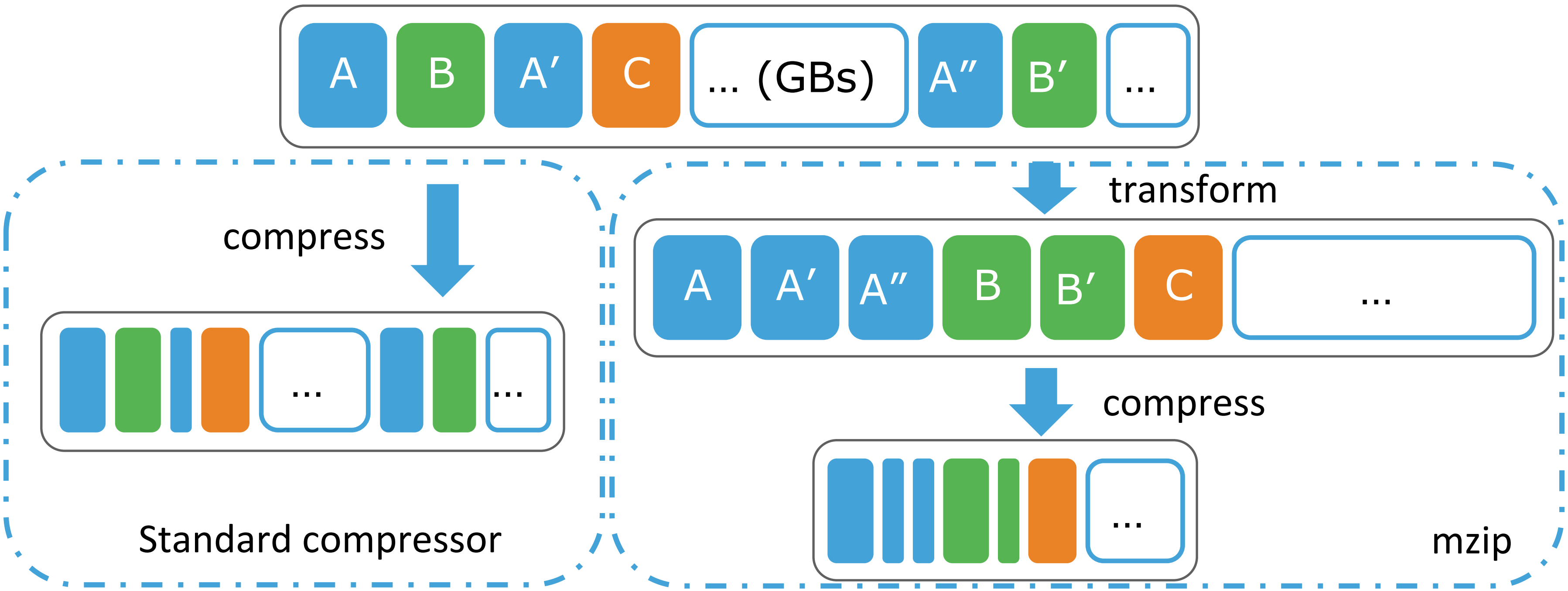

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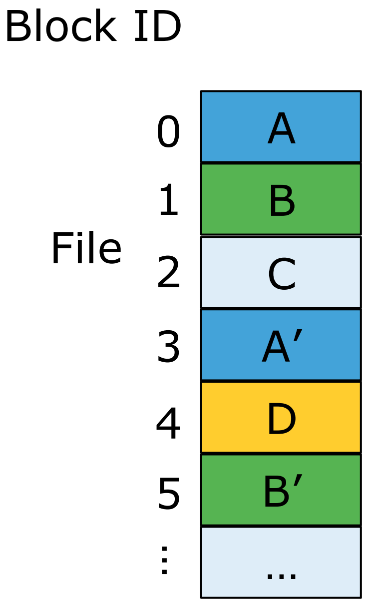

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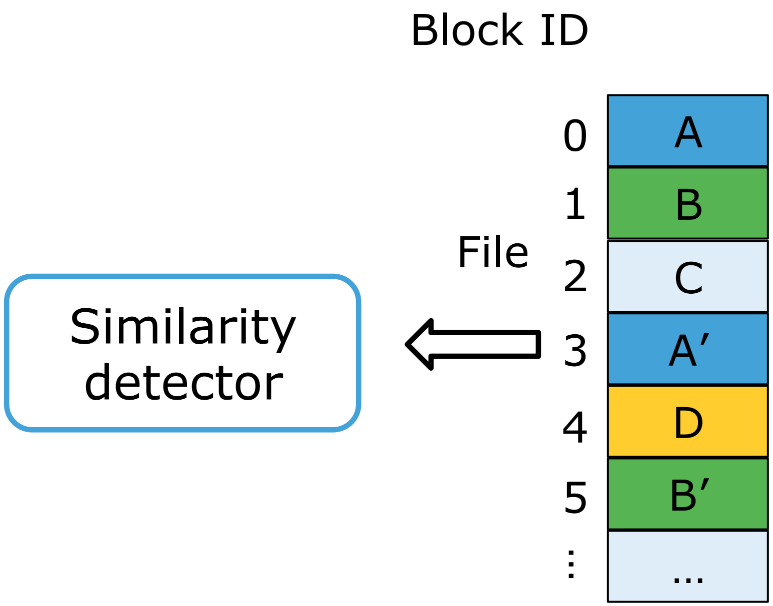

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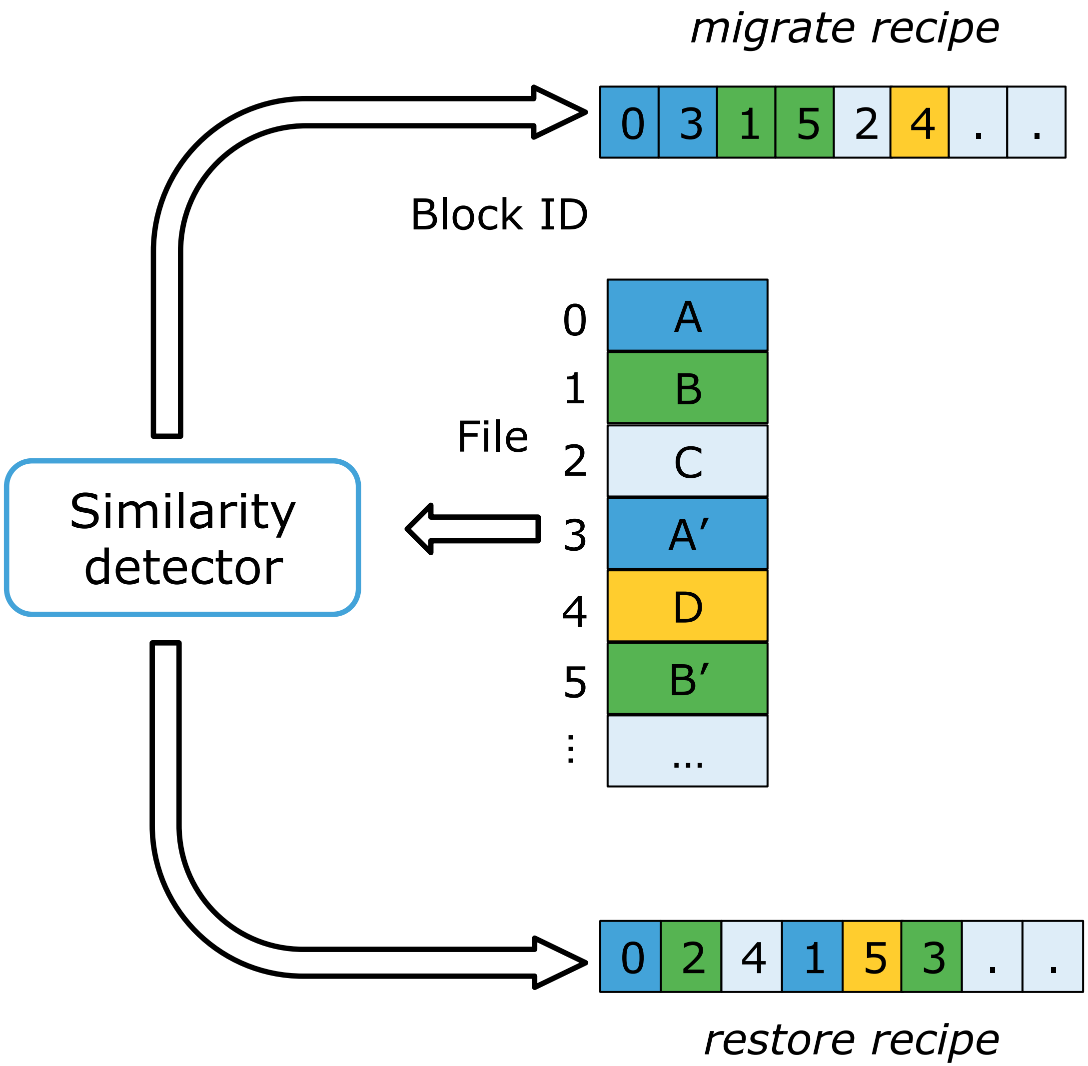

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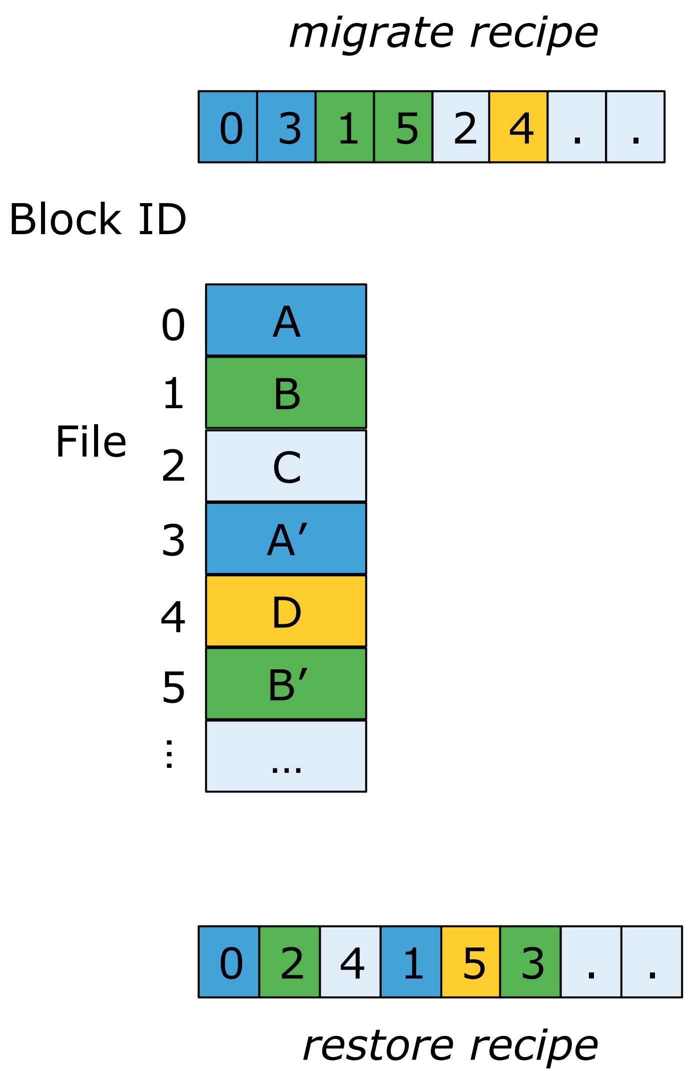

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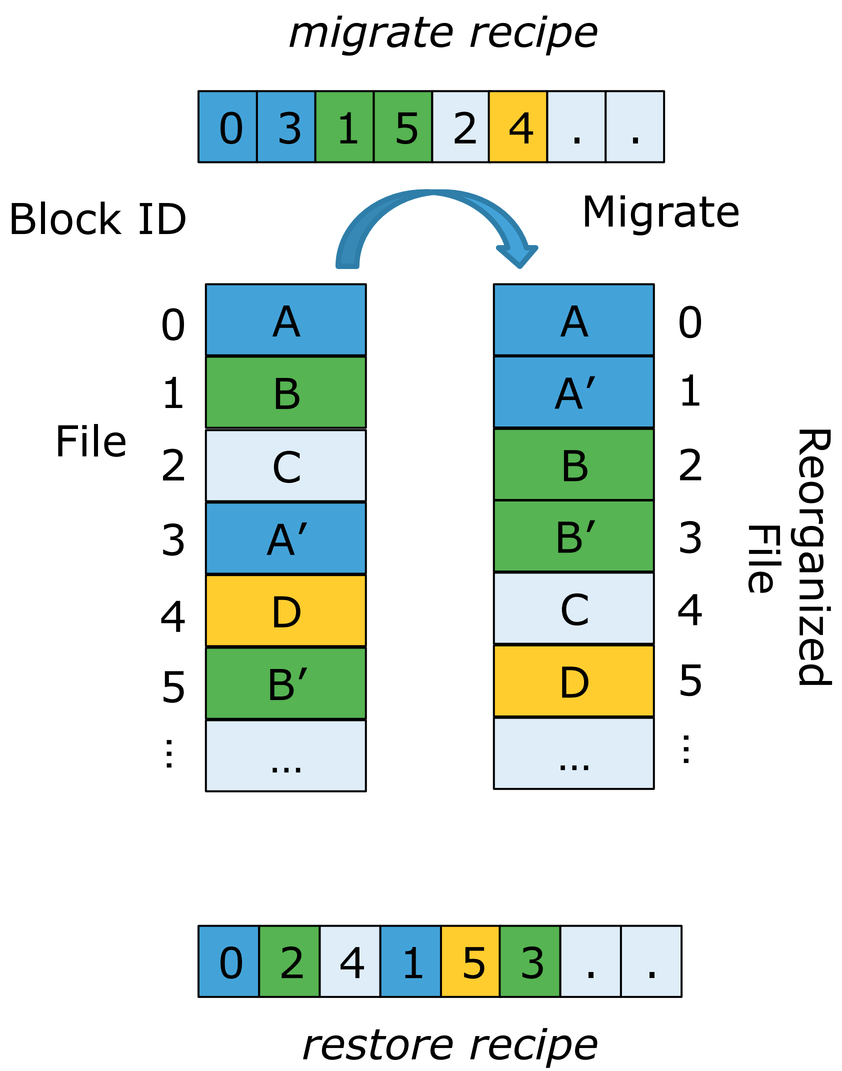

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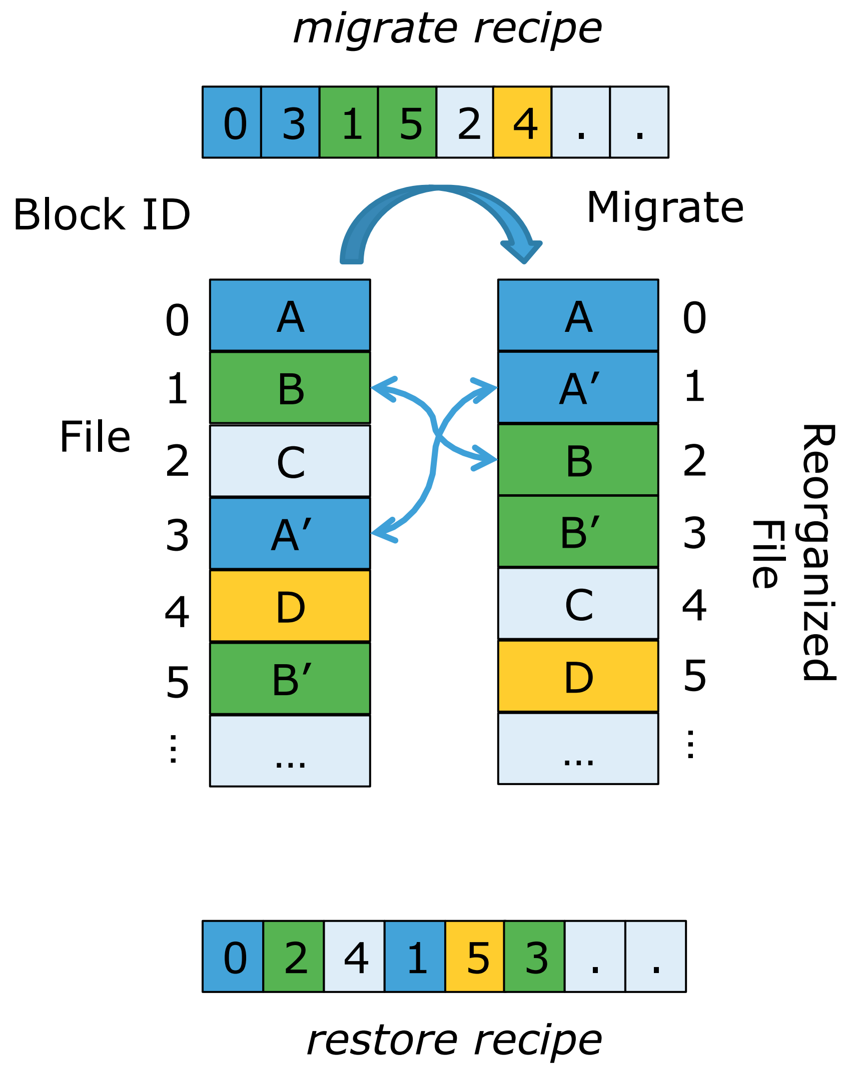

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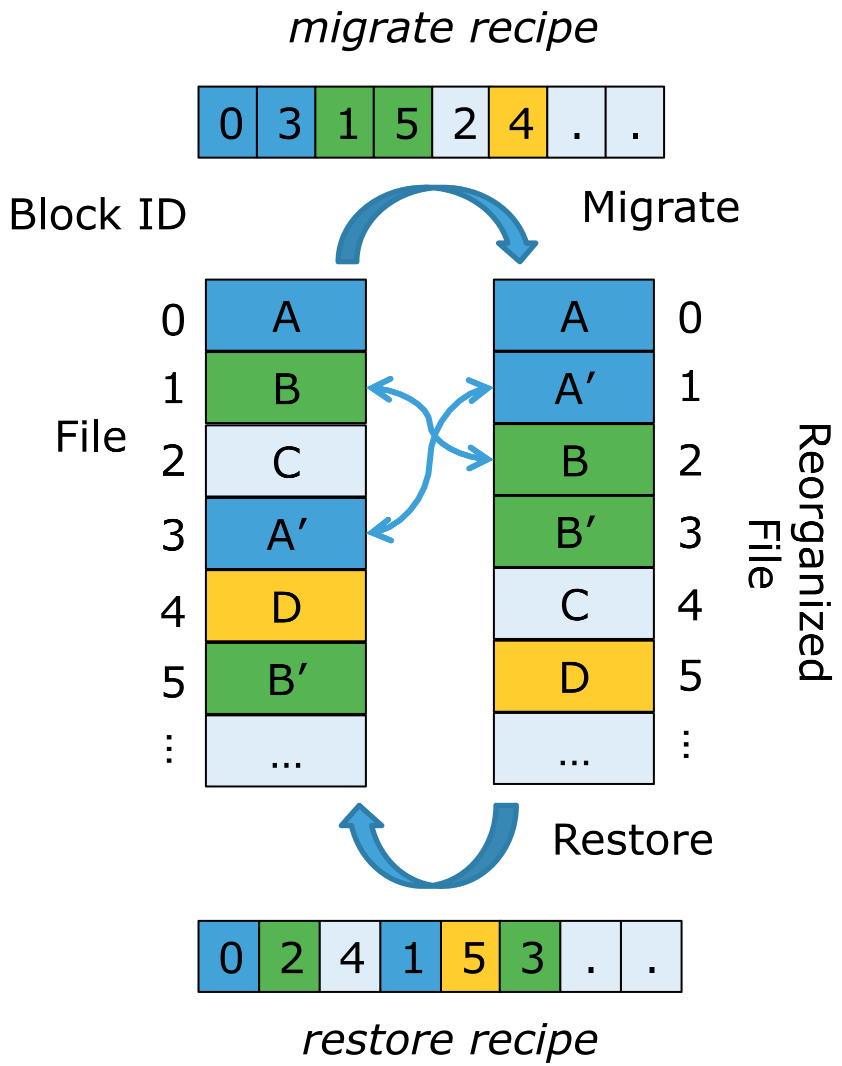

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Similarity feature: hash ([Broder 1997])

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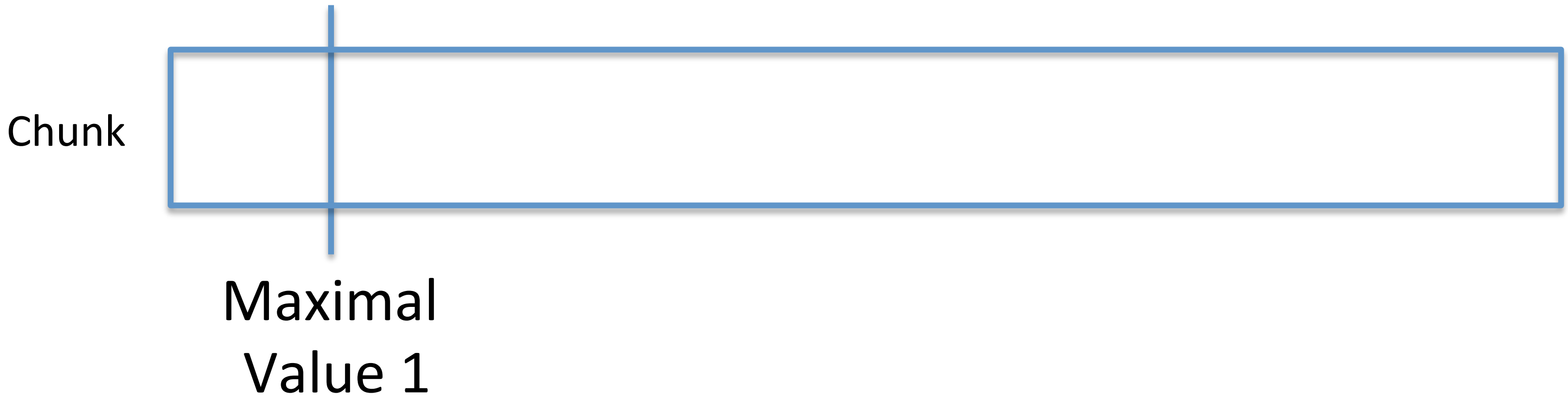

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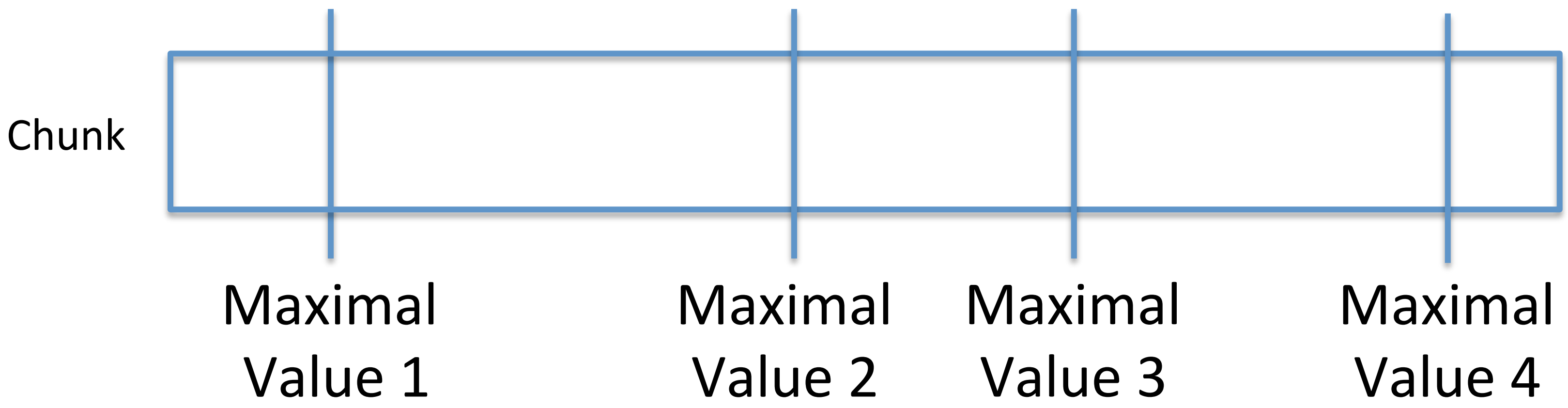

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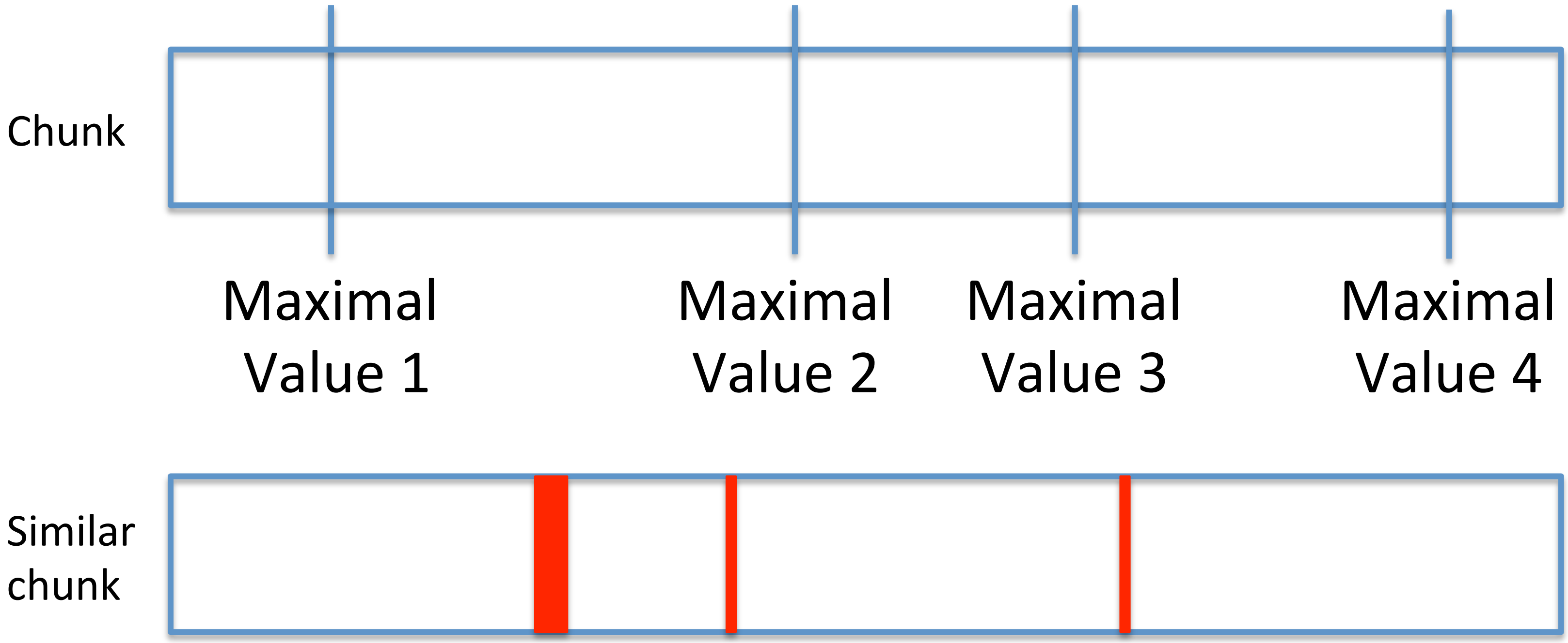

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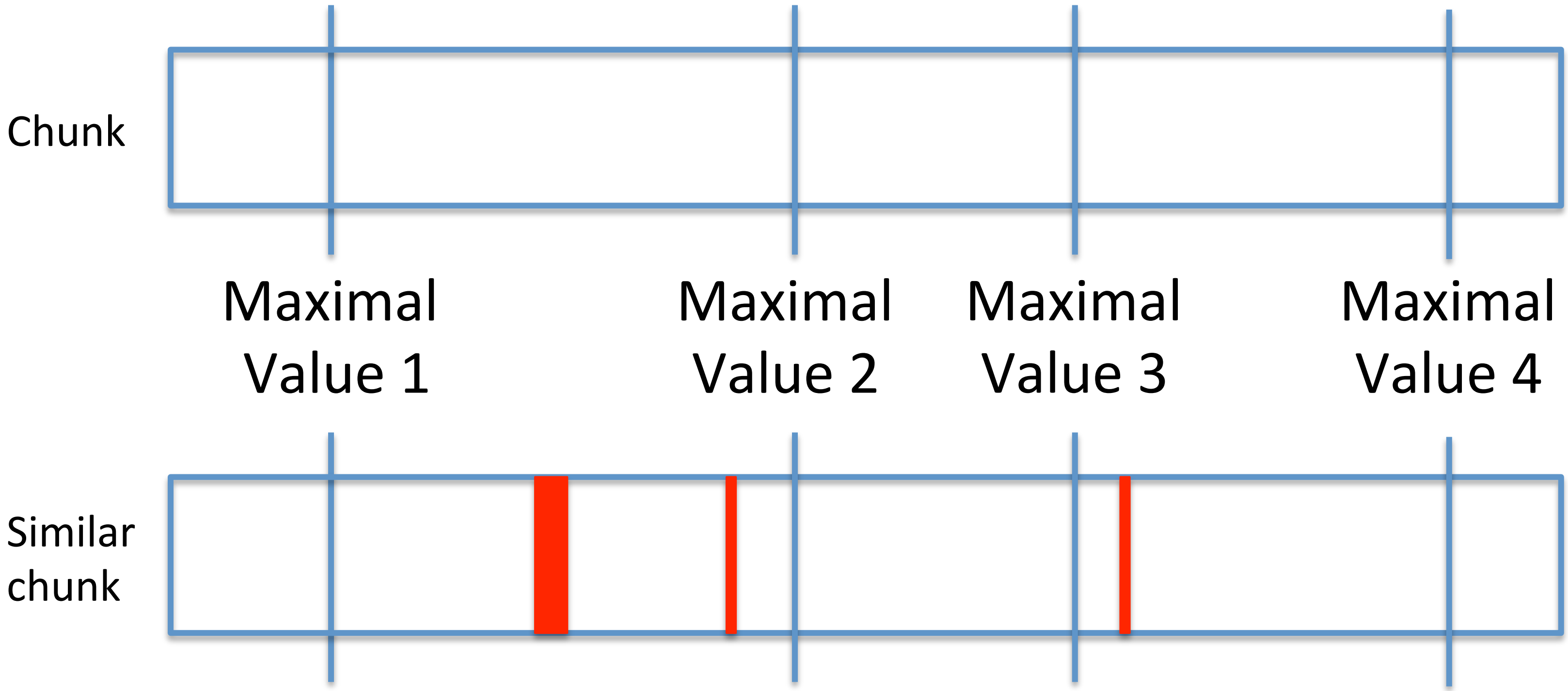

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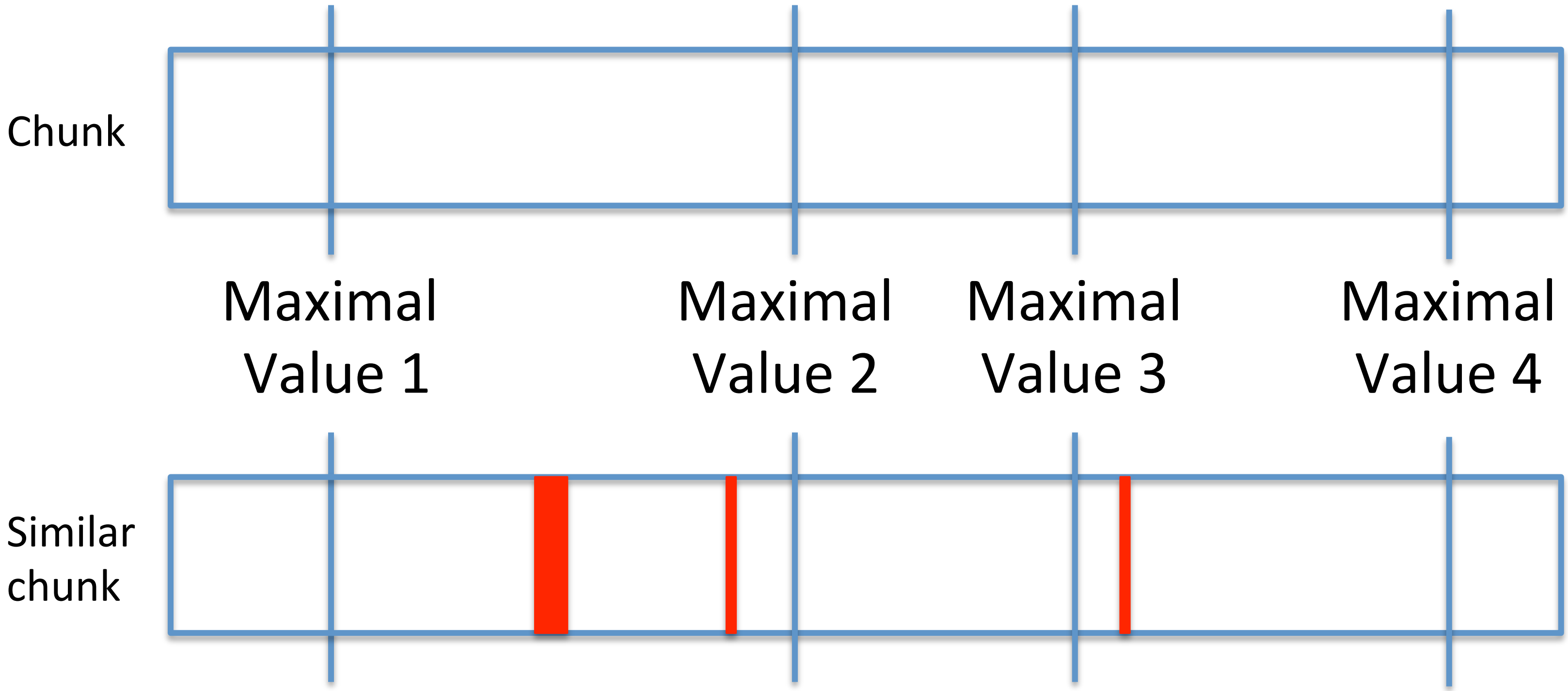

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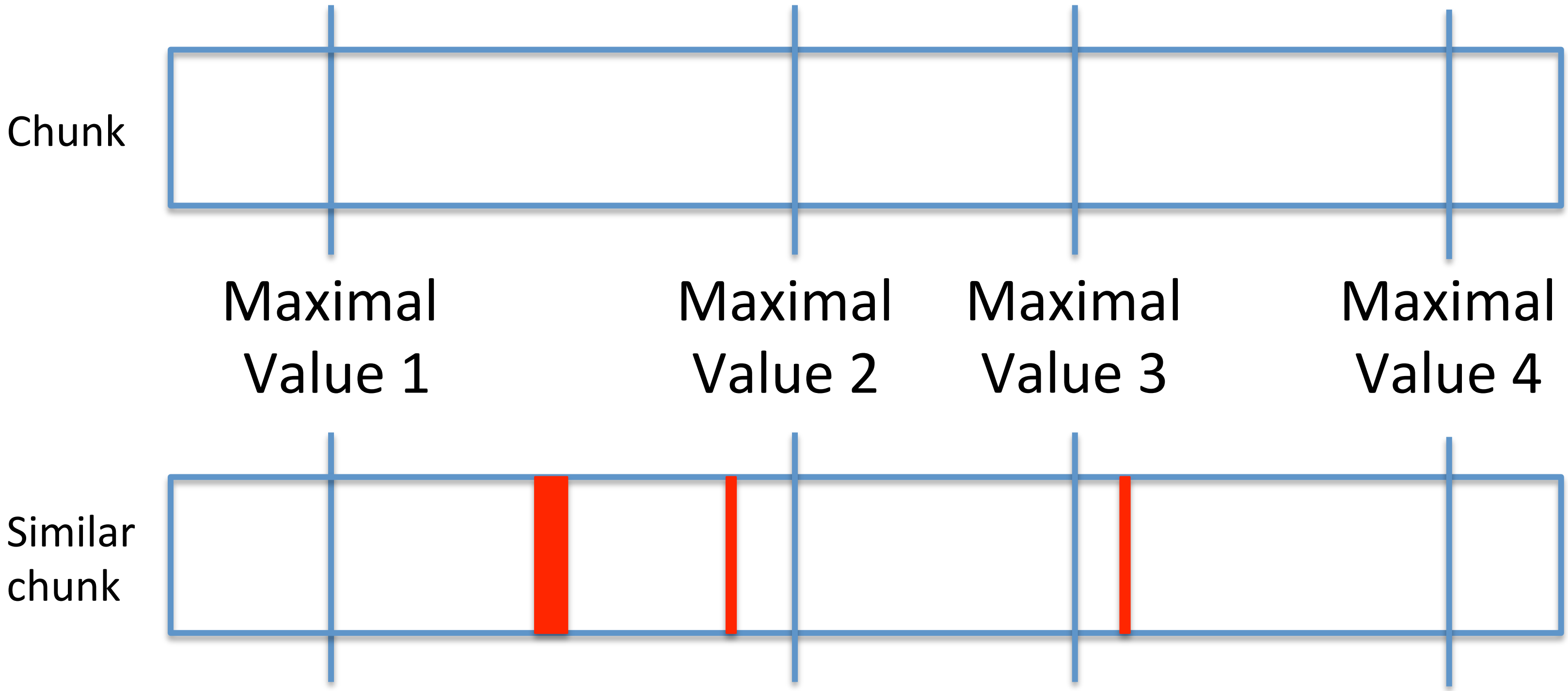

Super-feature ([Shilane FAST12])

A match on any super-feature is good enough

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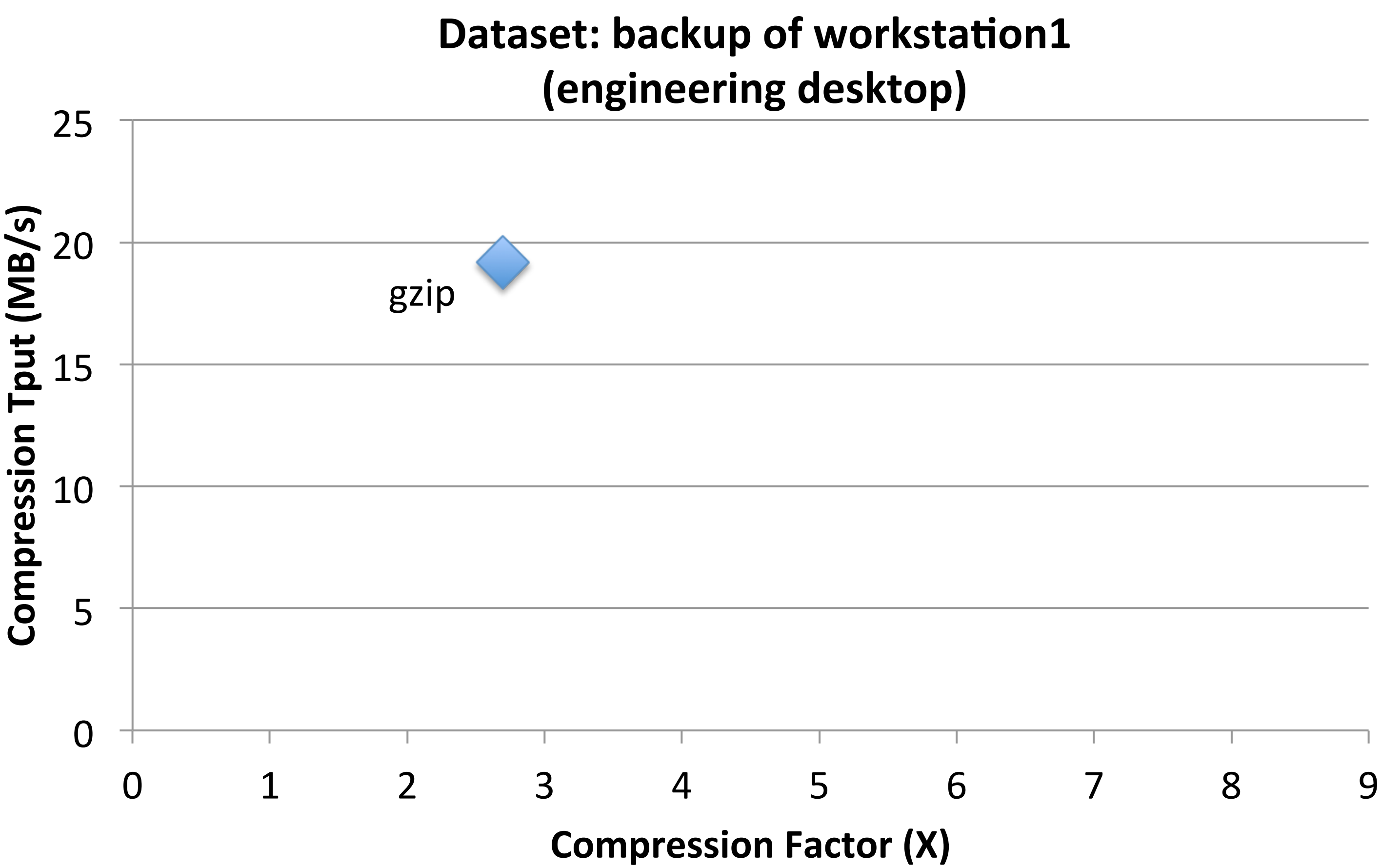
- Hard drives: does not perform well
- SSD: provides good random IO performance
- Multi-pass: helps considerably for hard drives
  - convert random IOs into multiple scans of input files

Evaluation

- How much can compression be improved?
  - Compression Factor (CF): original size / compressed size
- What is the complexity (runtime overhead)?
  - Compression throughput: original size / runtime
- More in the paper
  - How does SSD or HDD affect data reorganization performance? For HDD, does multi-pass help?
  - How does MC perform, compared with delta compression?
  - What are the configuration options for MC?

Migratory Compression - Evaluation



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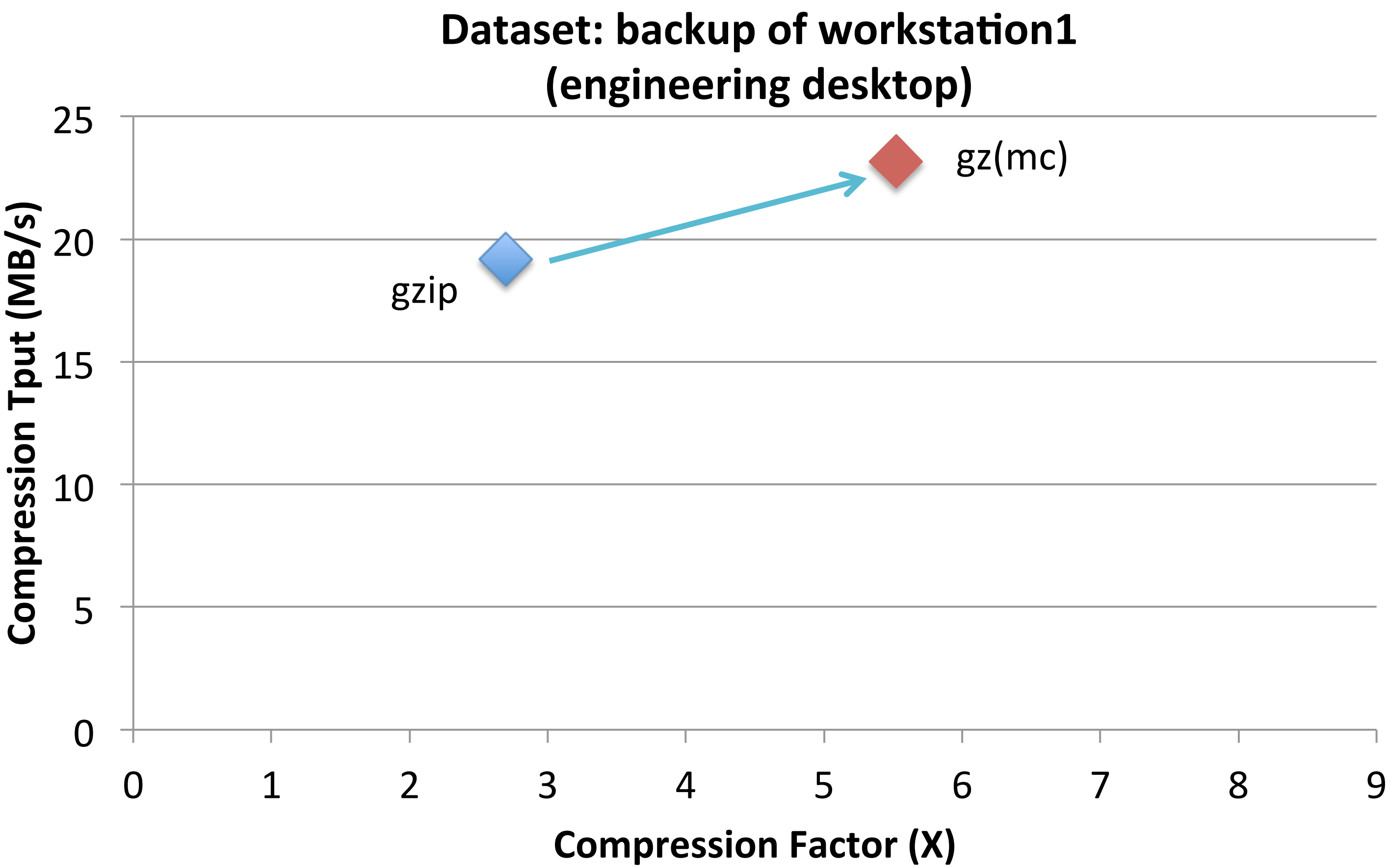

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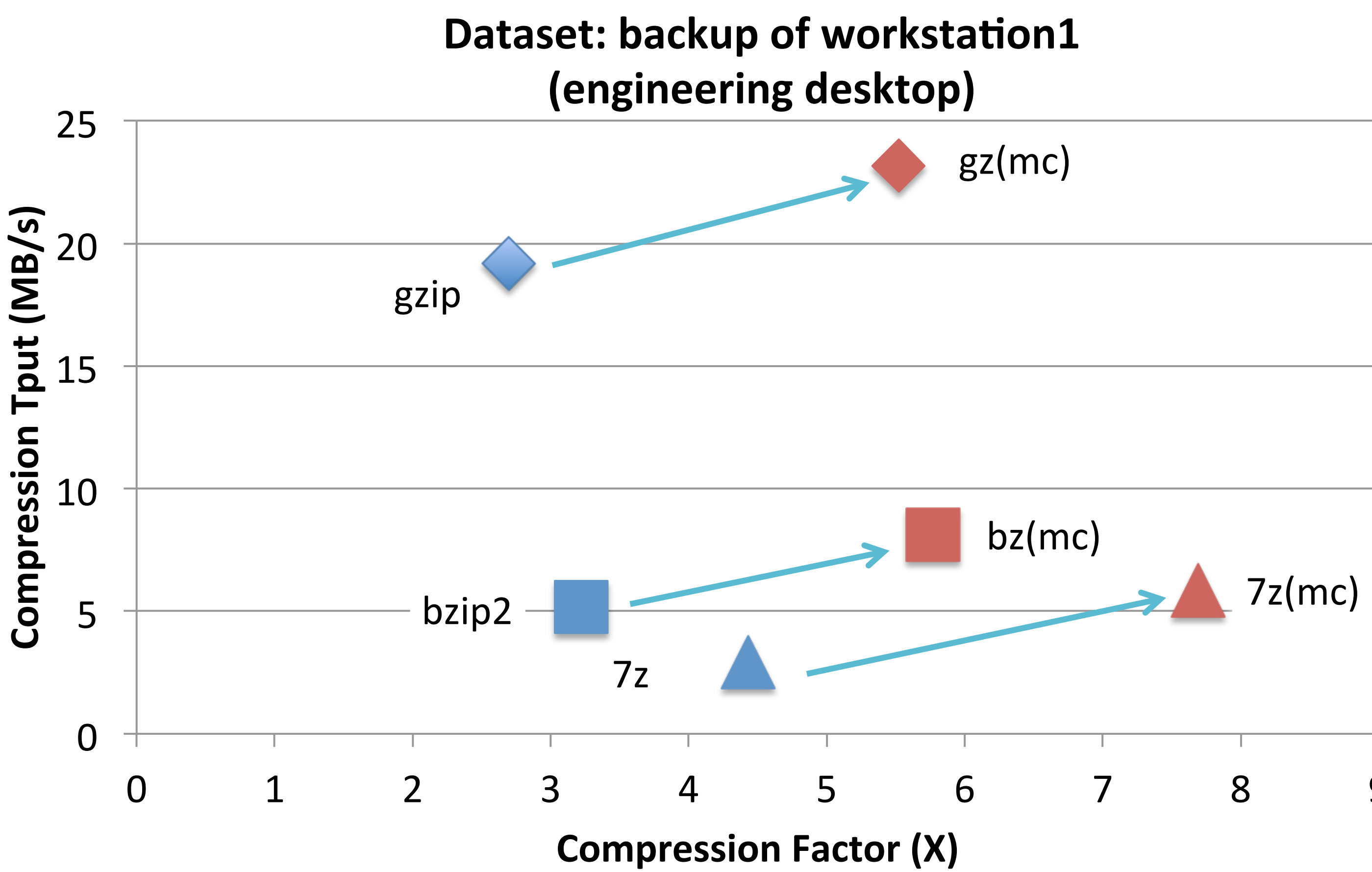

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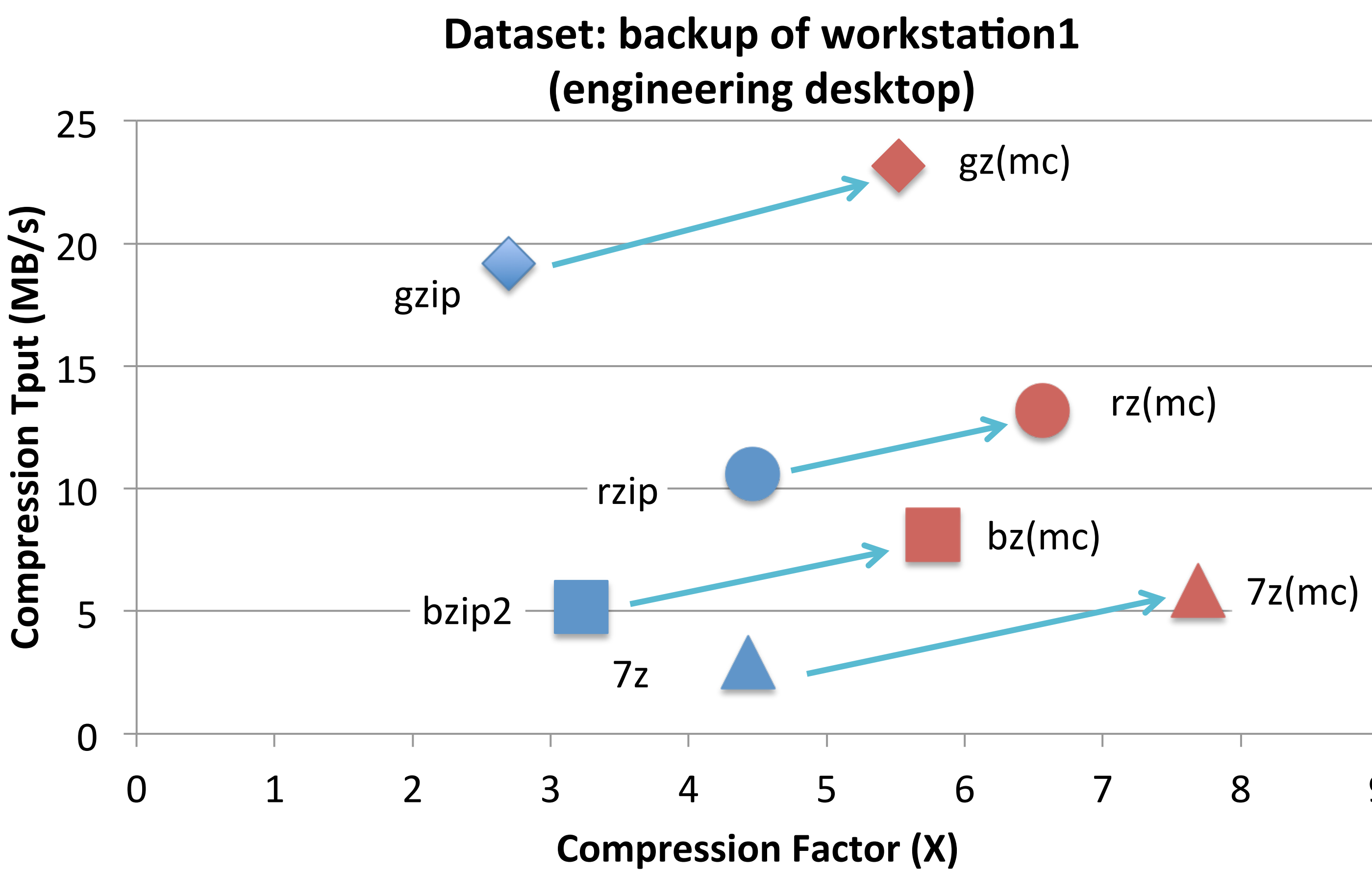

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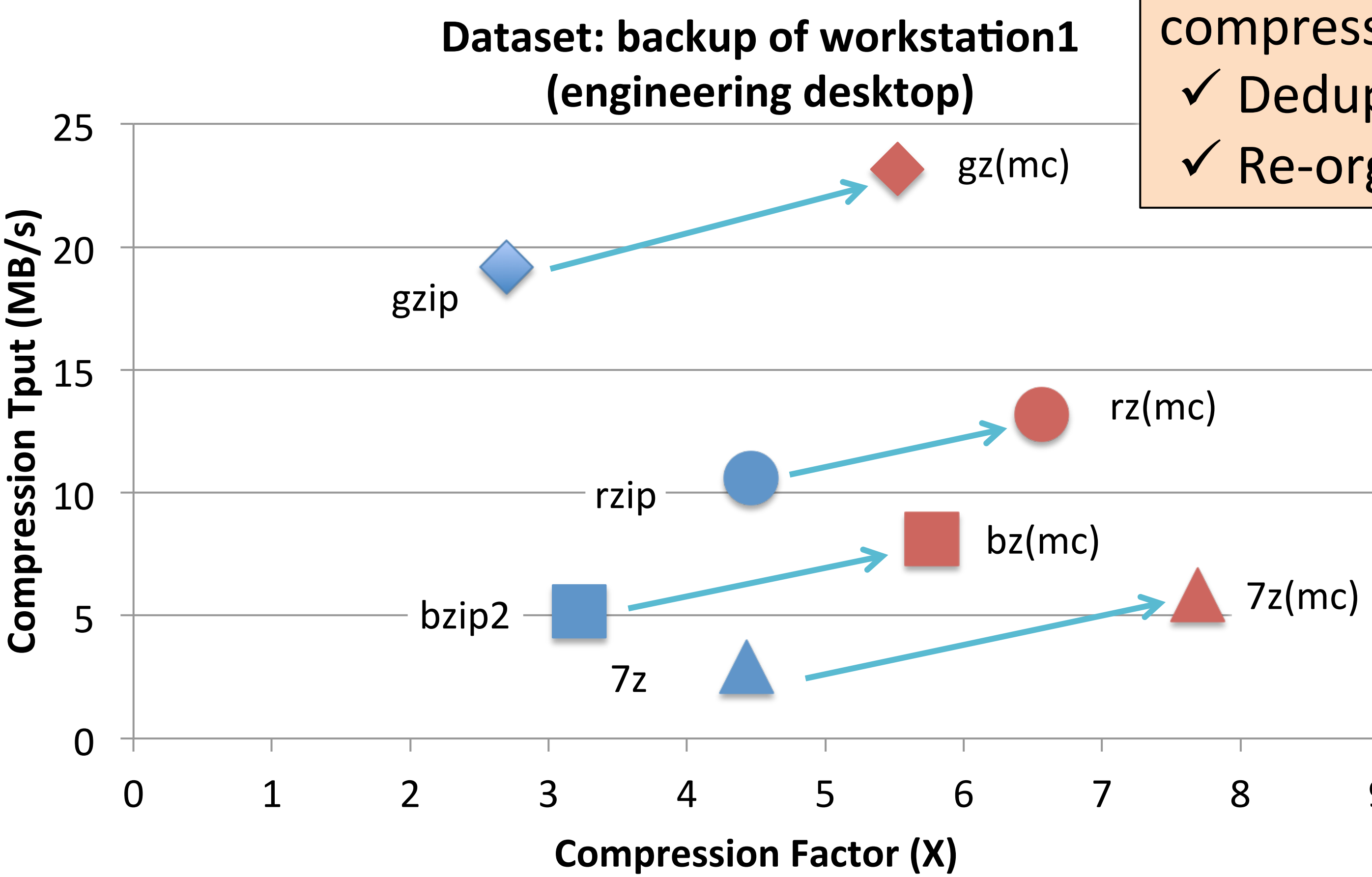
- intra-file dedupe
- bzip2 remainder

Migratory Compression - Evaluation

MC improves both CF and compression throughput
- ✓ Deduplication
- ✓ Re-organization



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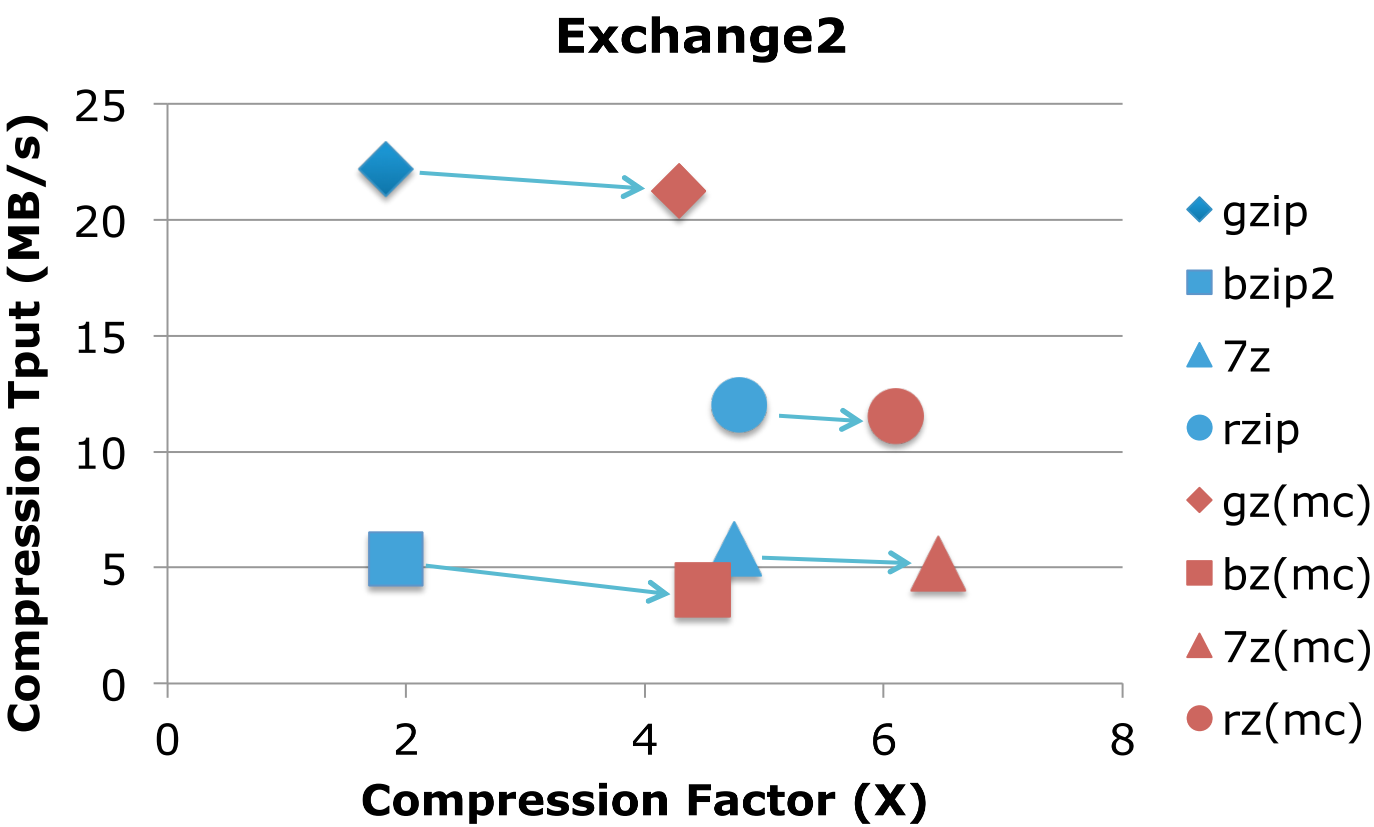
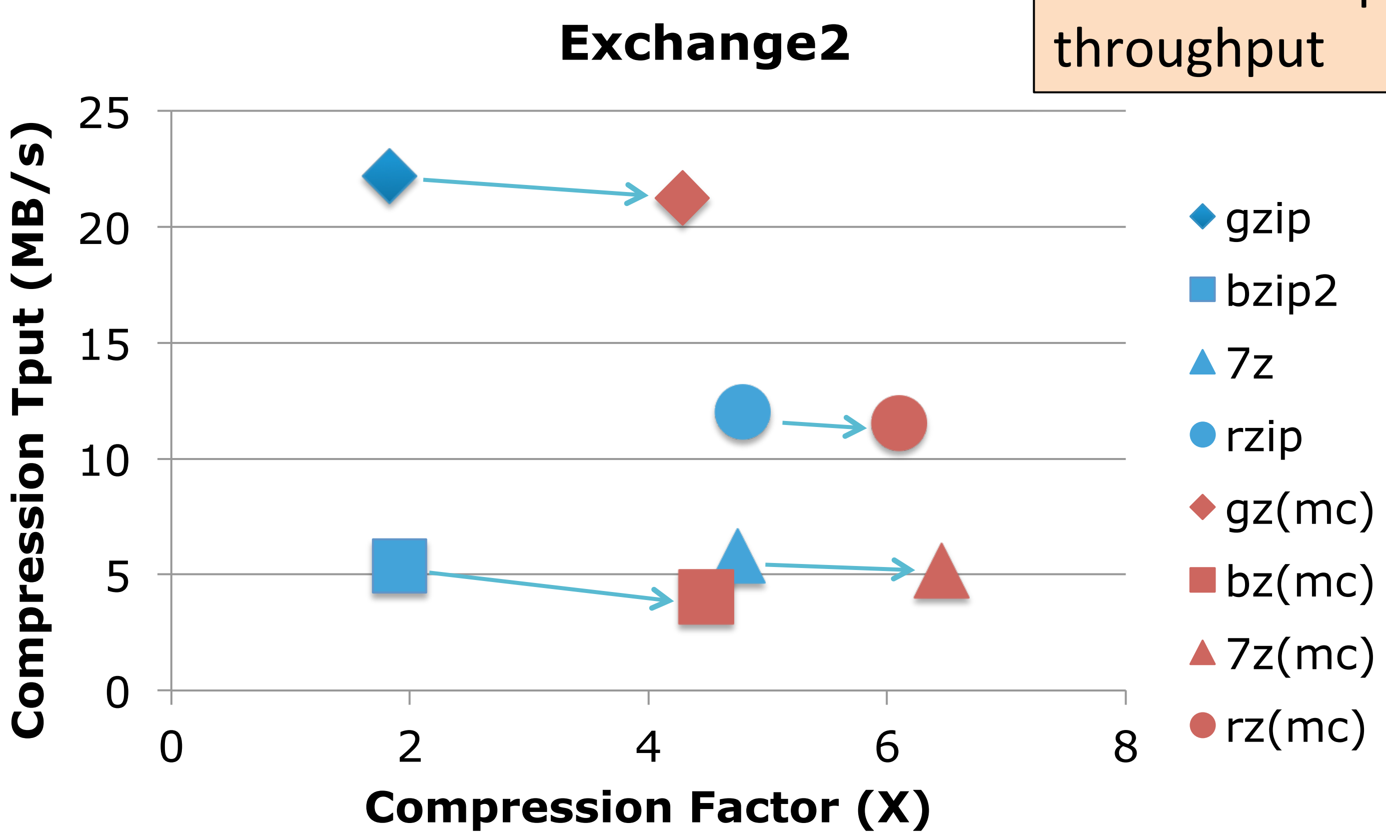


Compression Factor vs. Compression Throughput

MC improves CF but slightly reduces compression throughput



Migratory Compression - Summary

- More results in the paper
  - Decompression performance
  - Default vs. maximal compression
  - Memory vs. SSD vs. hard drives
  - Application of MC for archival storage

Migratory Compression: Coarse-grained Data Reordering to Improve Compressibility
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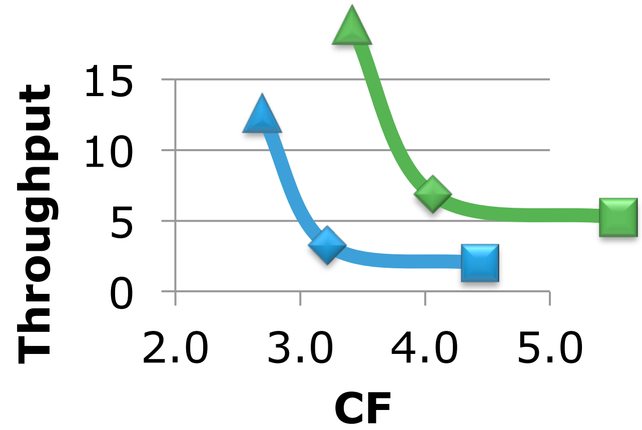

- Migratory Compression
  - Improves existing compressors, in both **compressibility** and frequently **runtime**
  - ***Redraw the performance-compression curve!***

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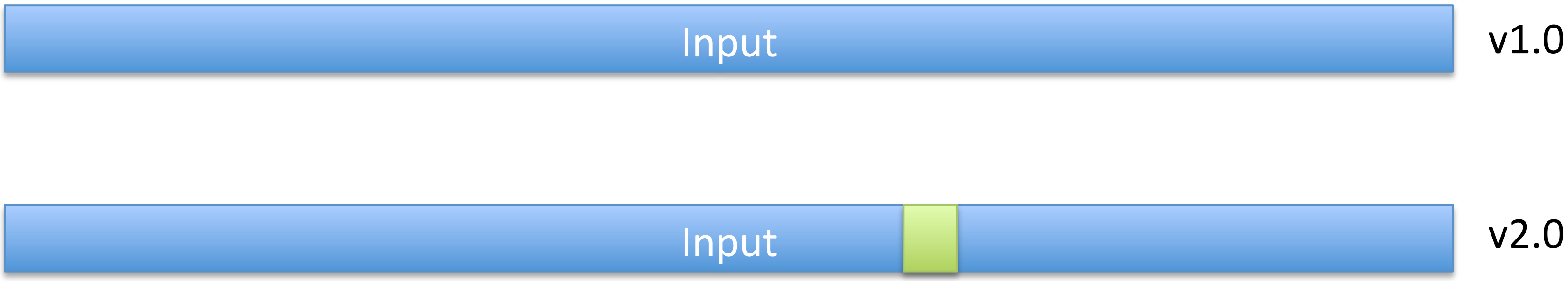

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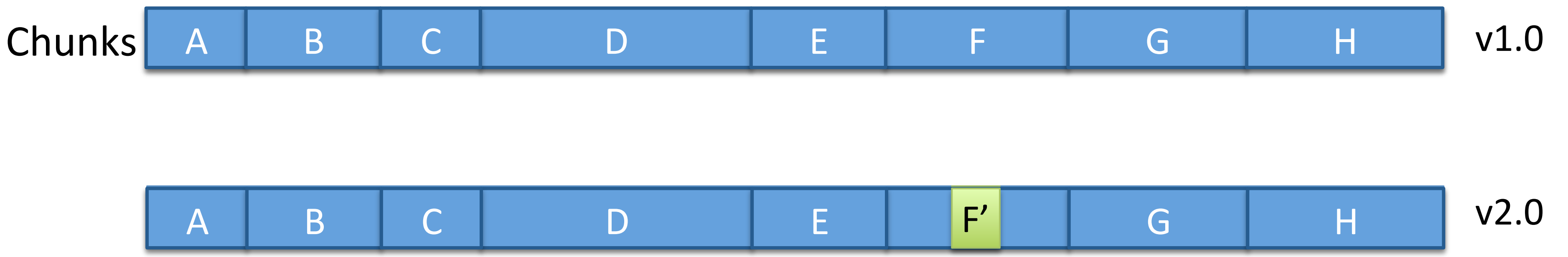

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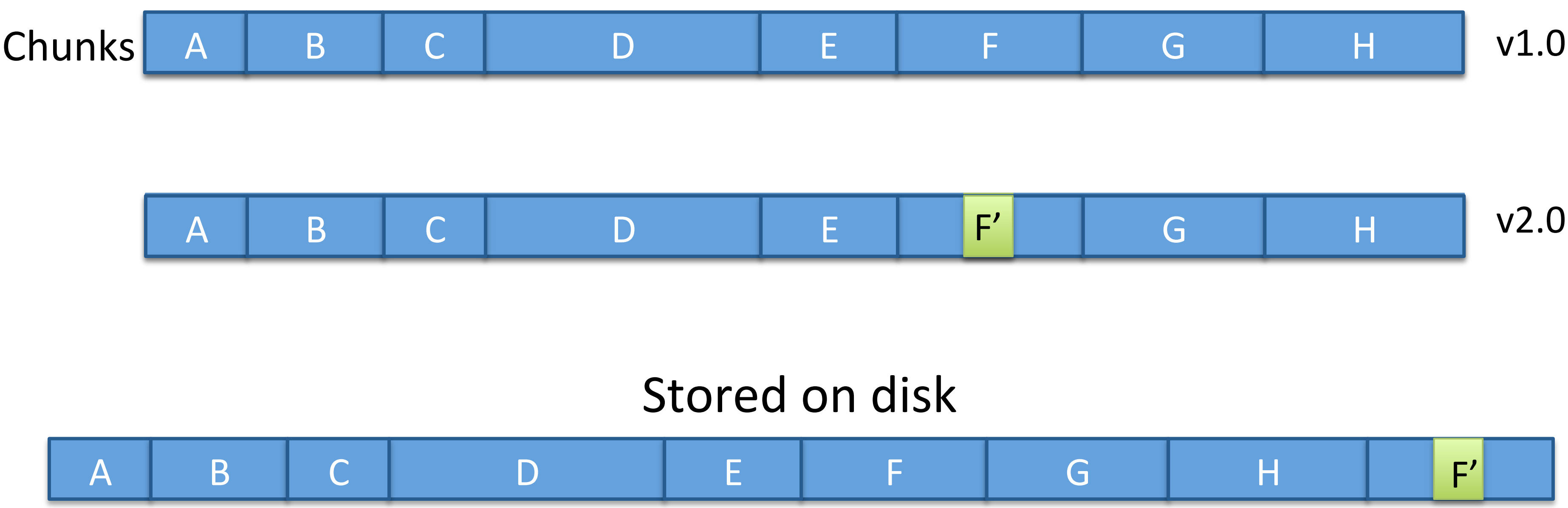

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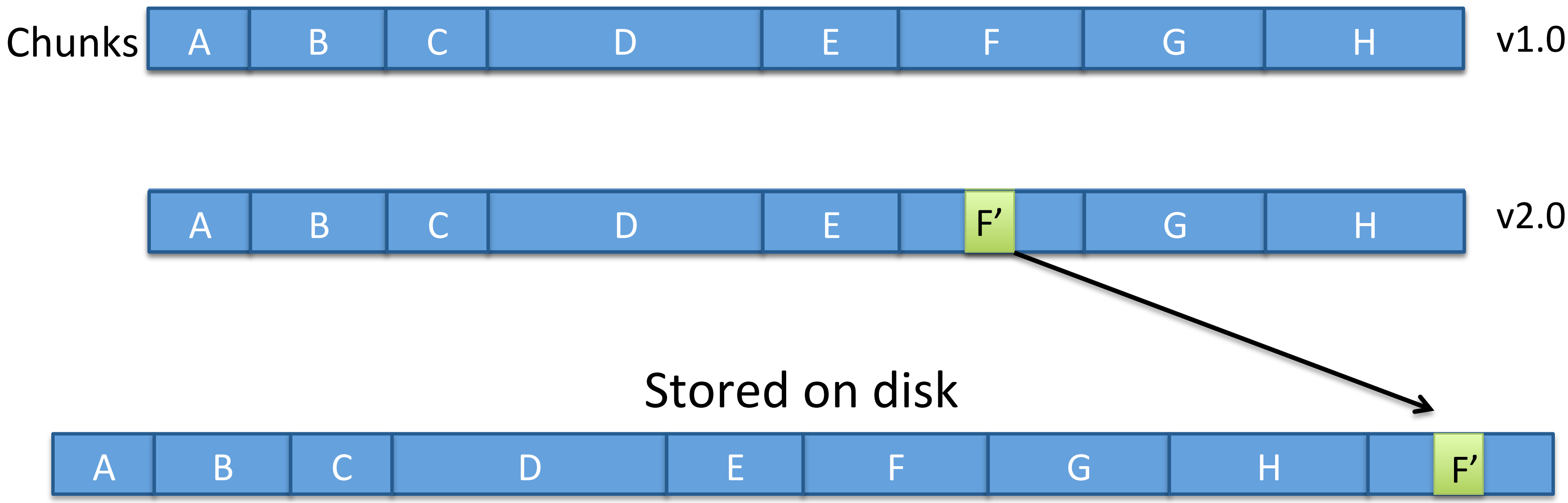

Eliminate nearly all of v2.0 on disk

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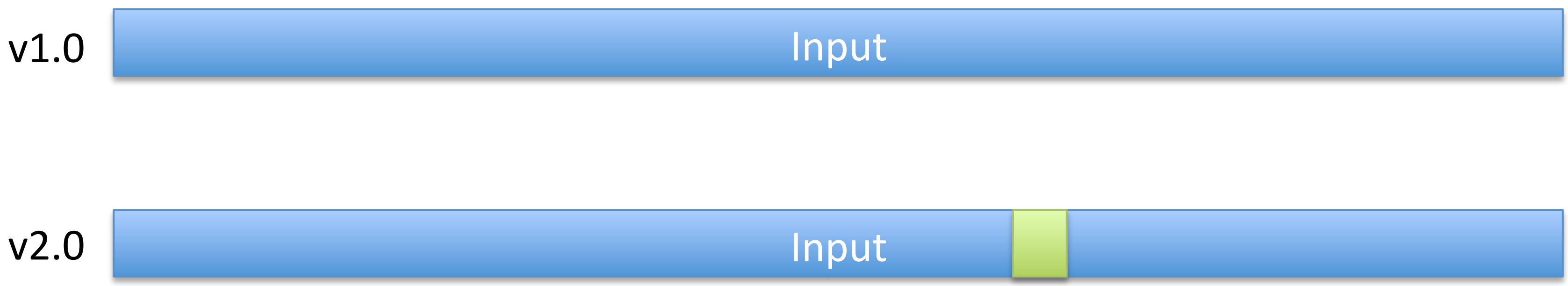

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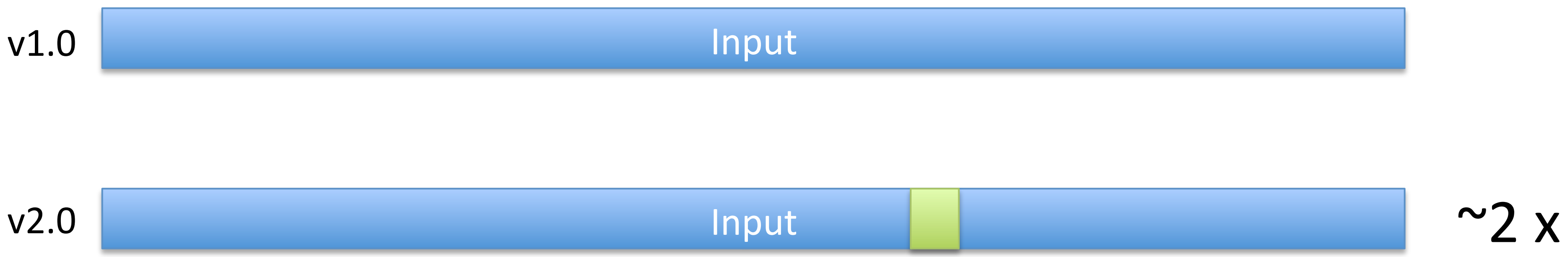

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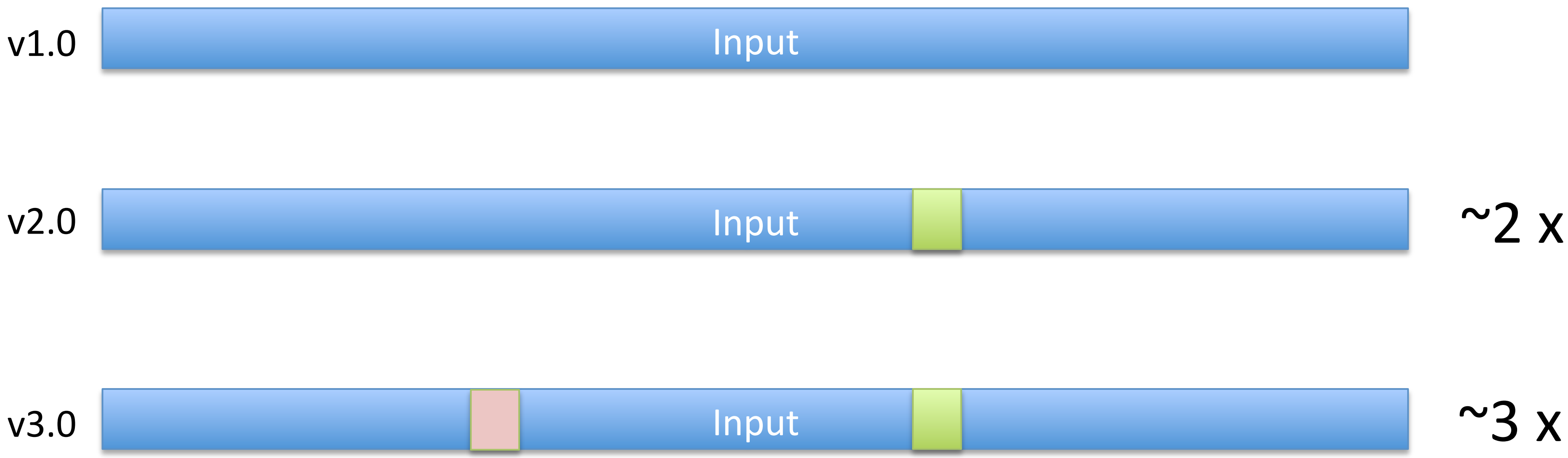

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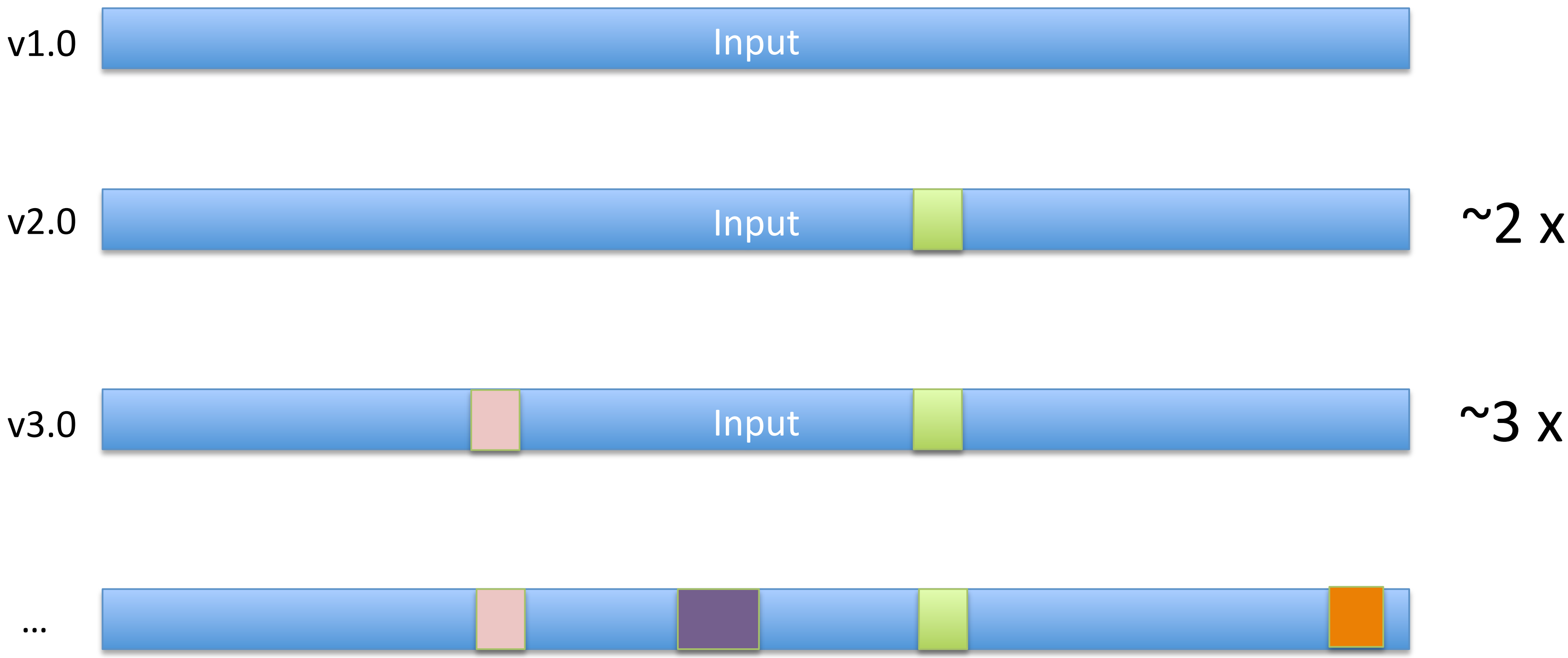

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- ***In Reality***
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  - Other examples of awful deduplication
- ***Contributions***
  - Identify and categorize barriers to deduplication
  - Solutions
    - EMC Data Domain (industrial experience)
    - GNU tar (academic research)

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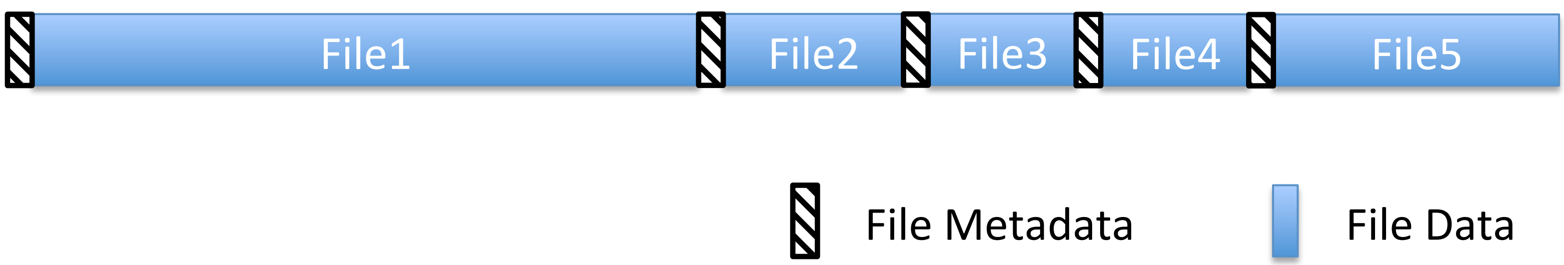

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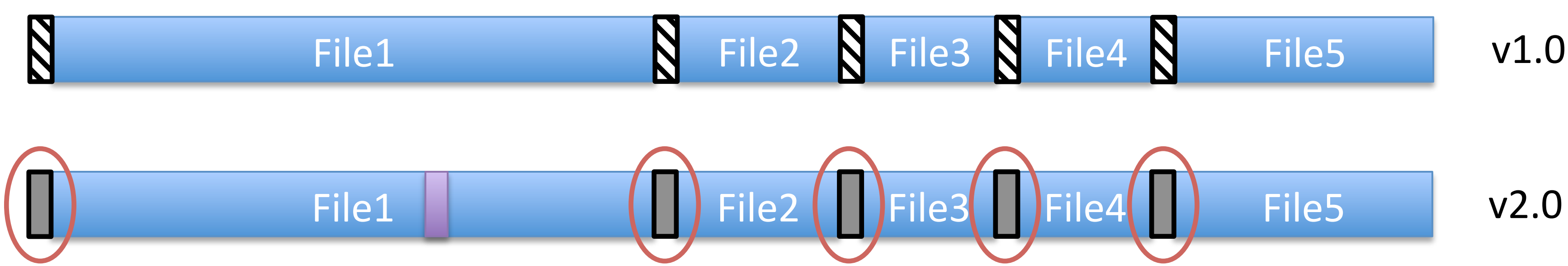

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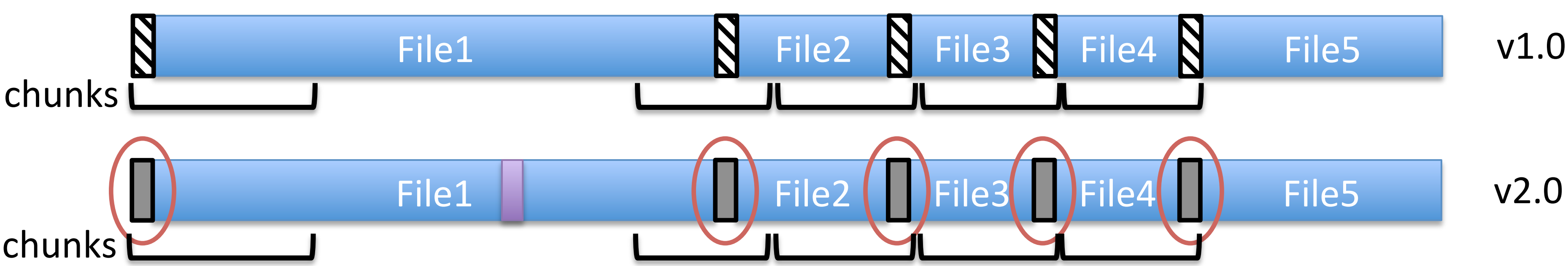

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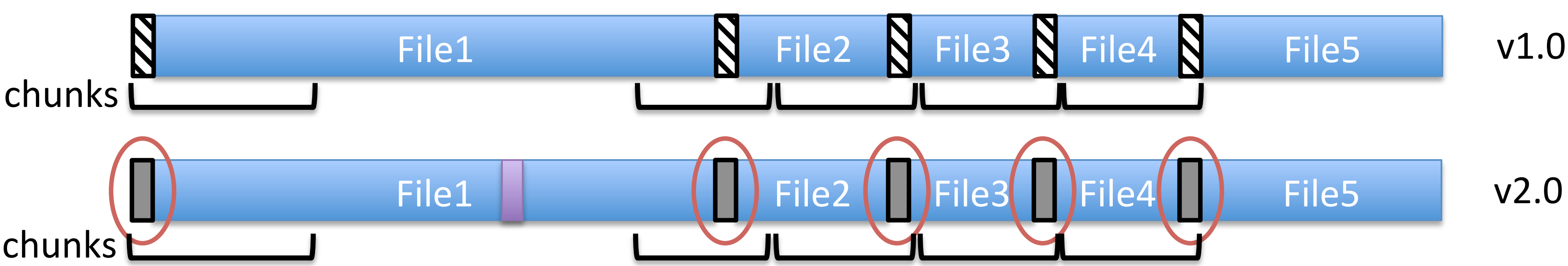

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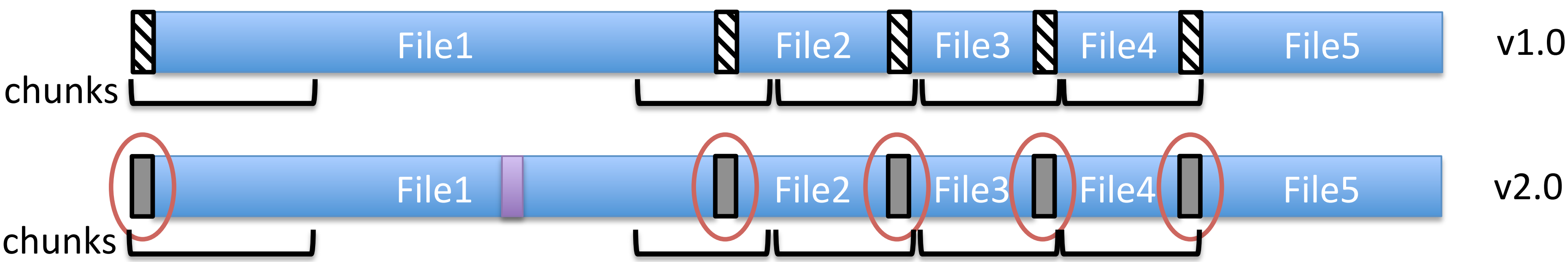

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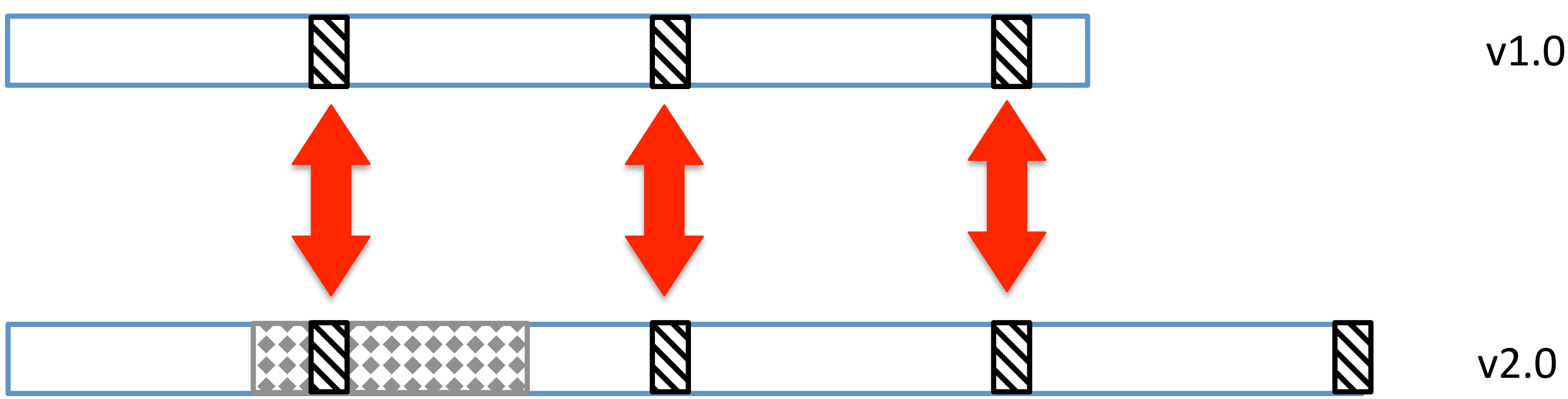

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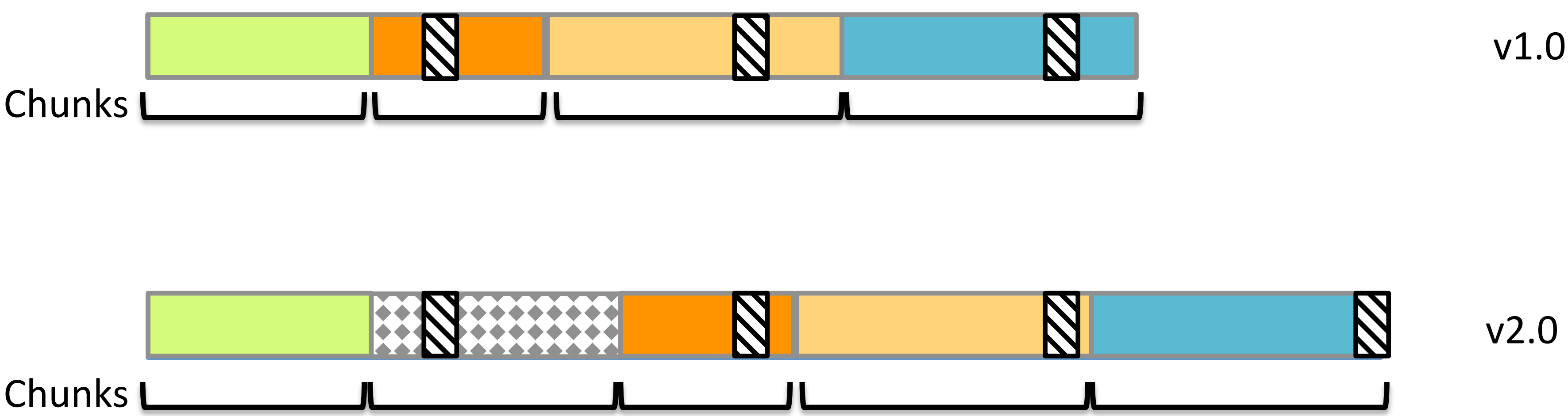

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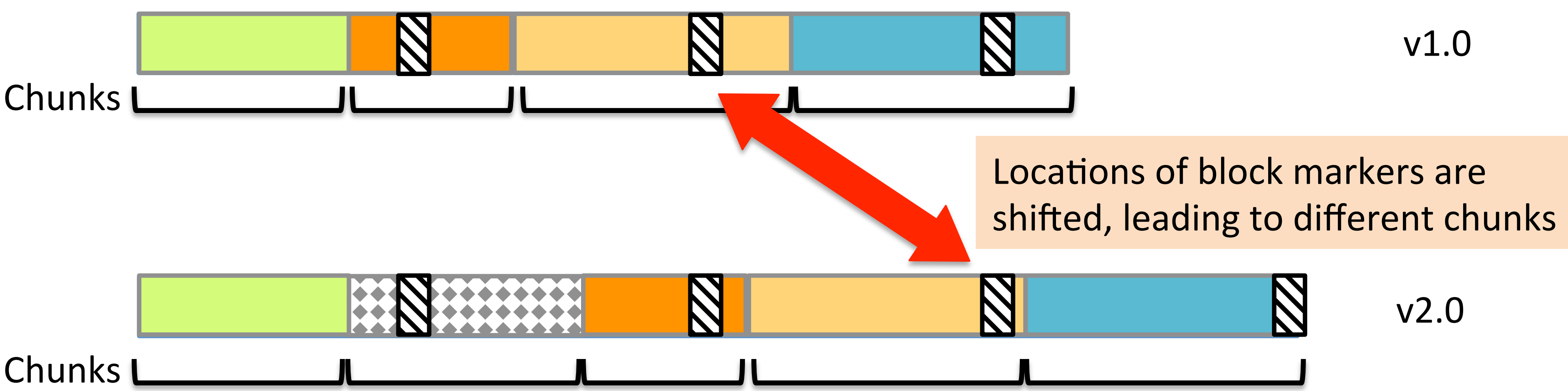

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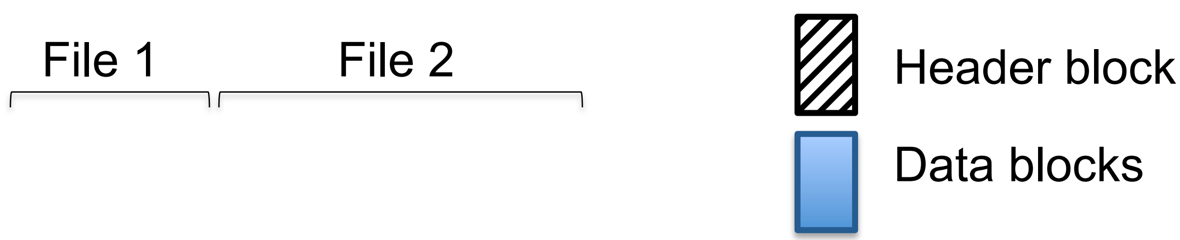

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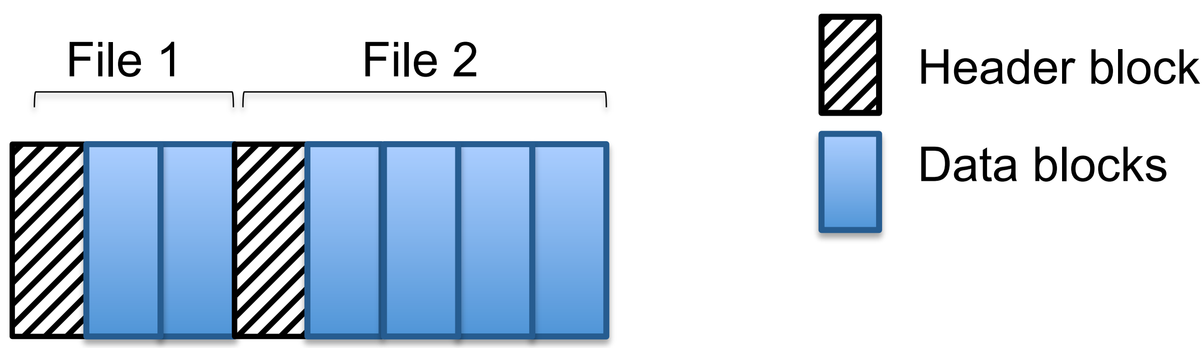

Metadata Changes with GNU tar

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SHA1s	linux-2.6.39.3/README	a735c31cef6d19d56de6824131527fdce04ead47
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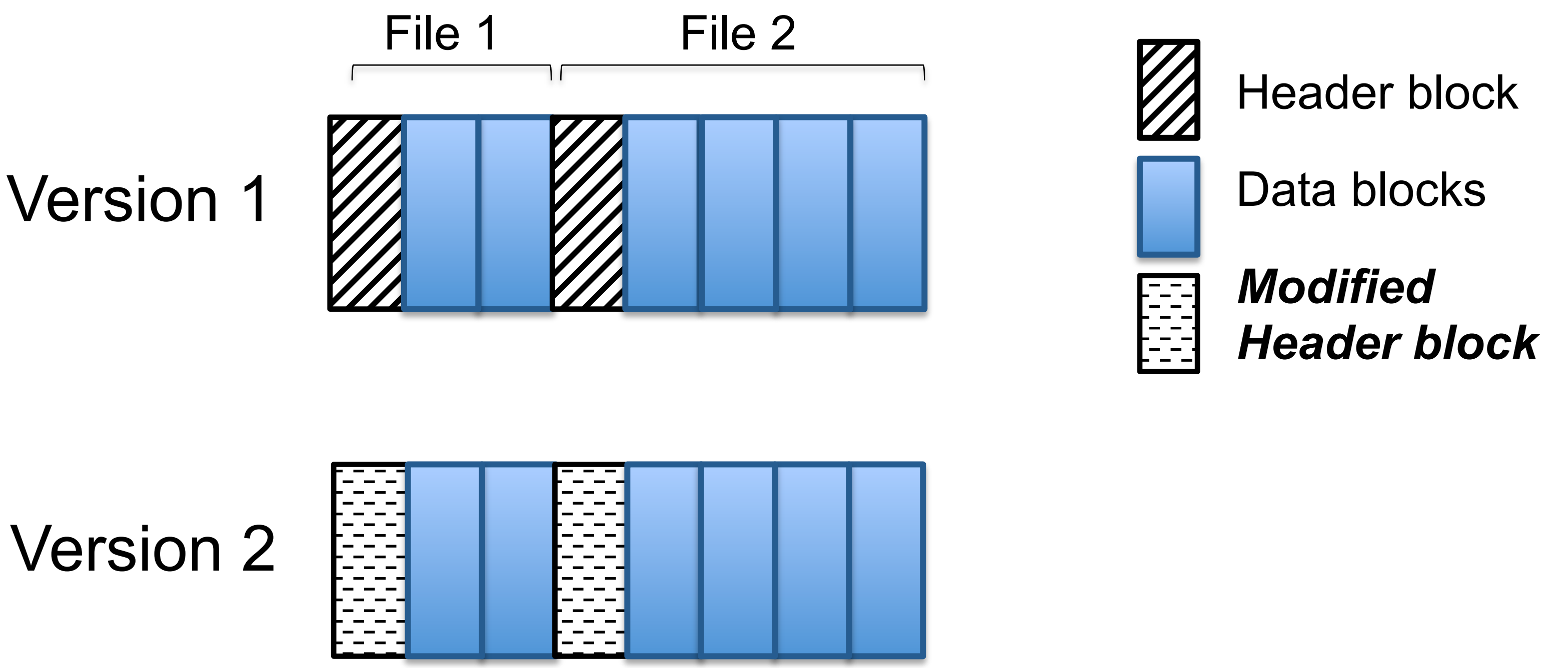

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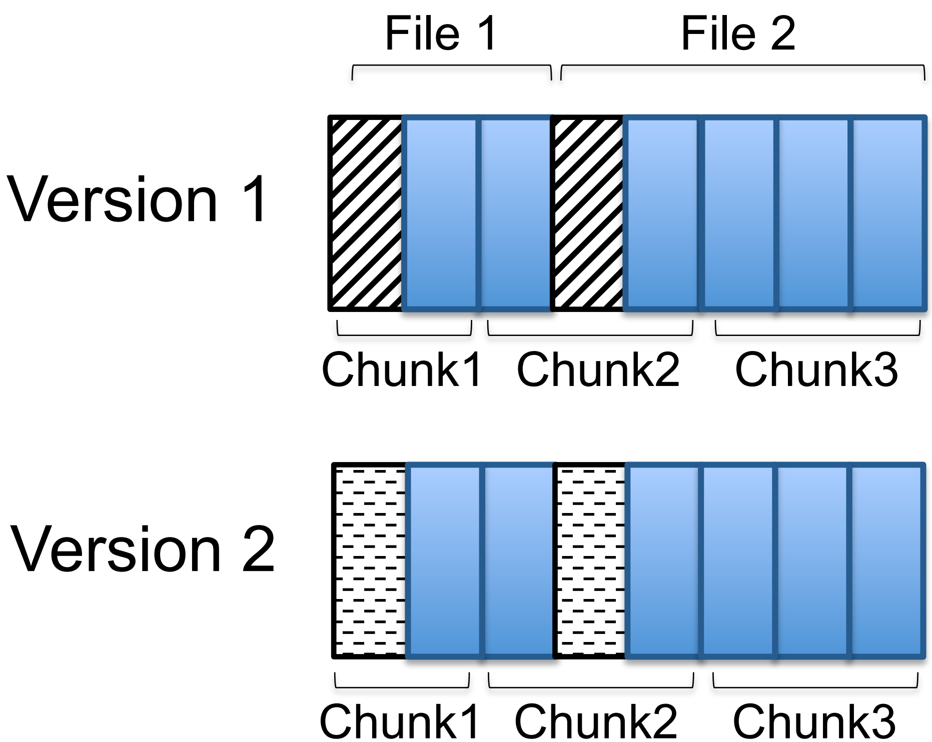

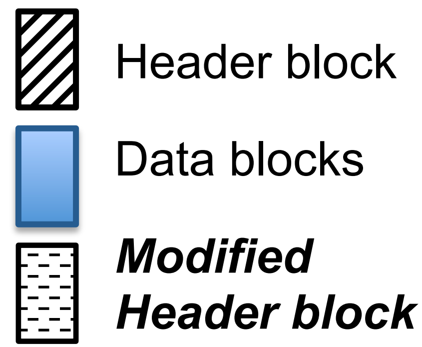

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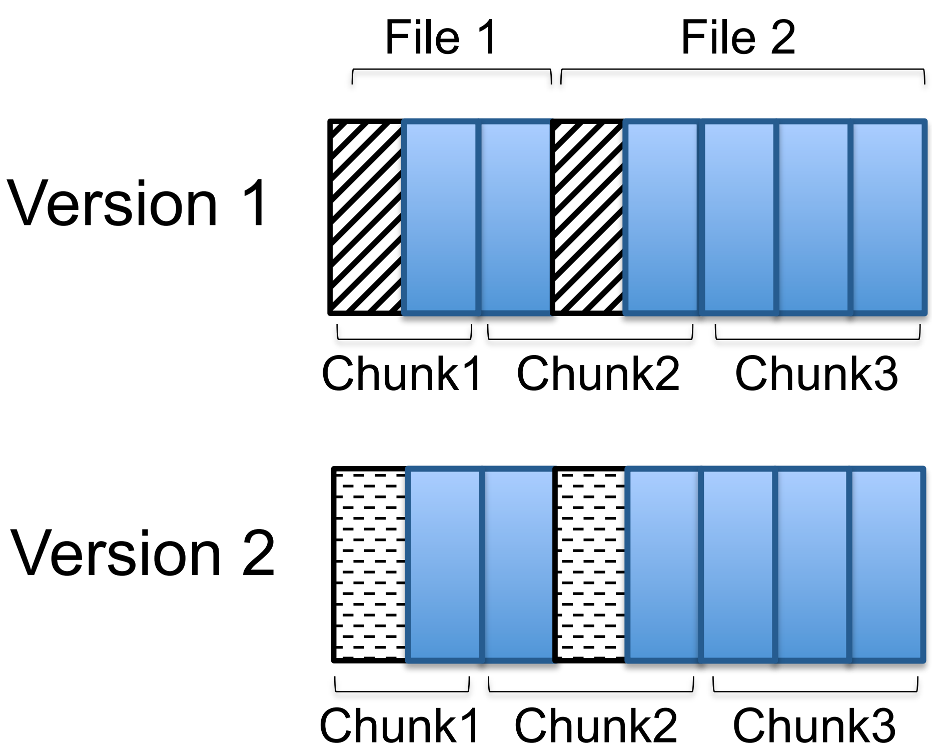

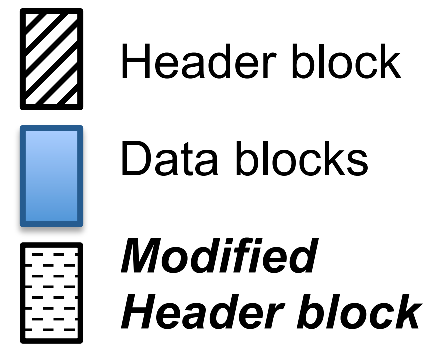

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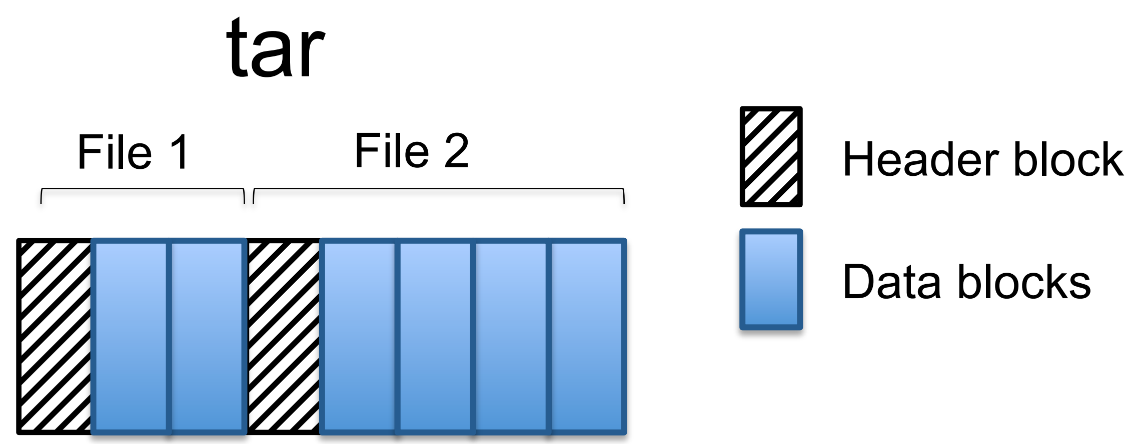
2 x for 308 versions of Linux

Migratory tar (mtar)



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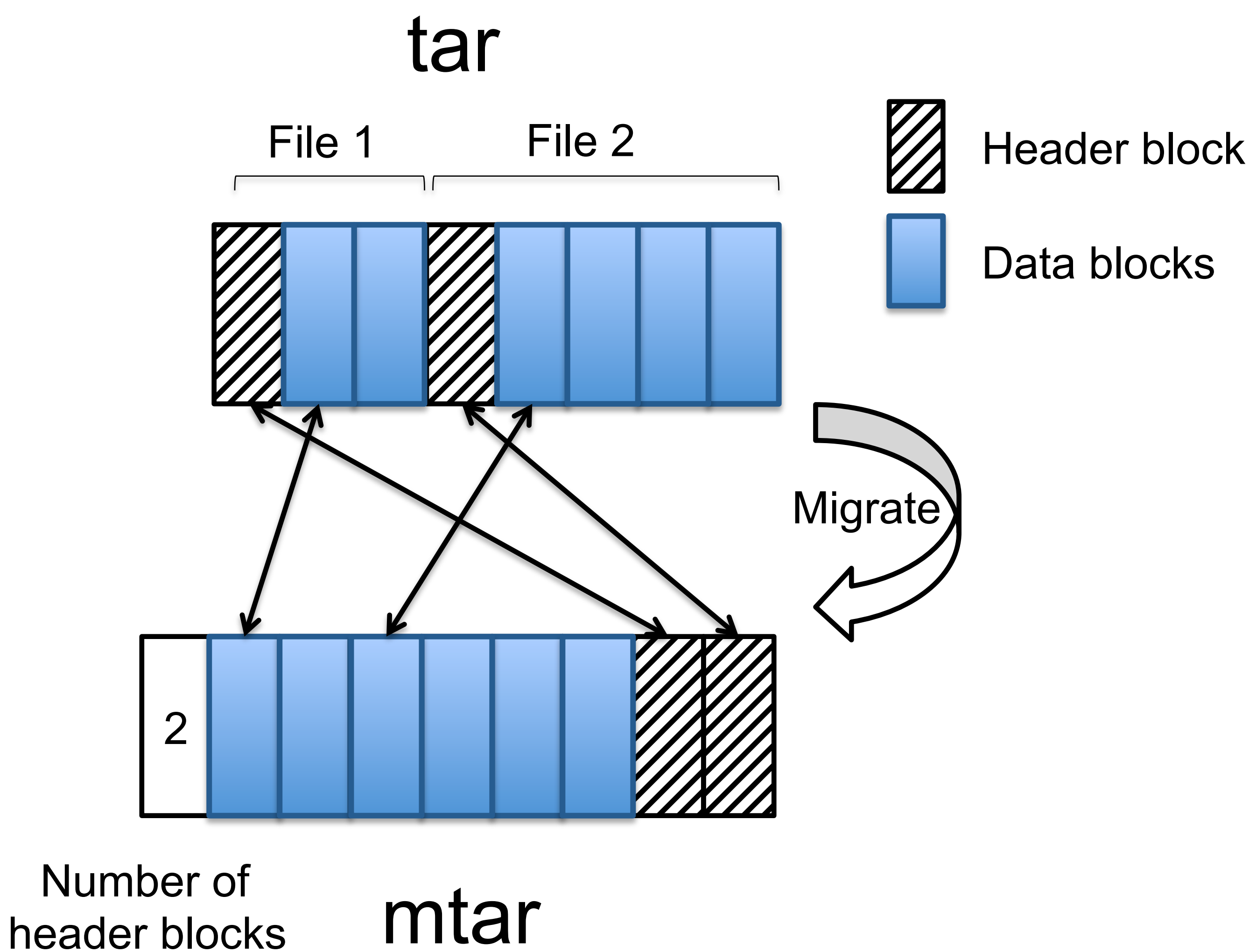

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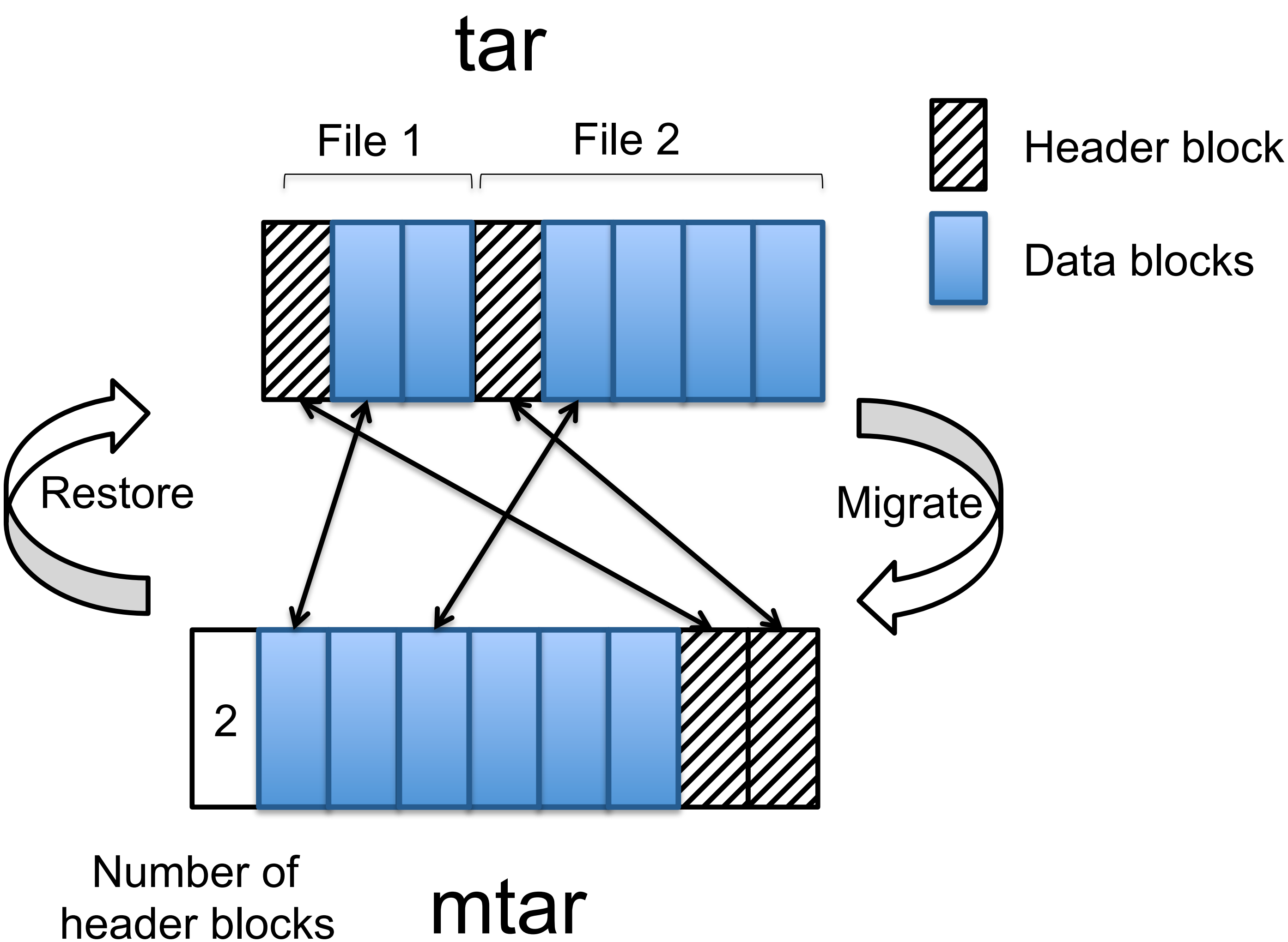

mtar - Evaluation

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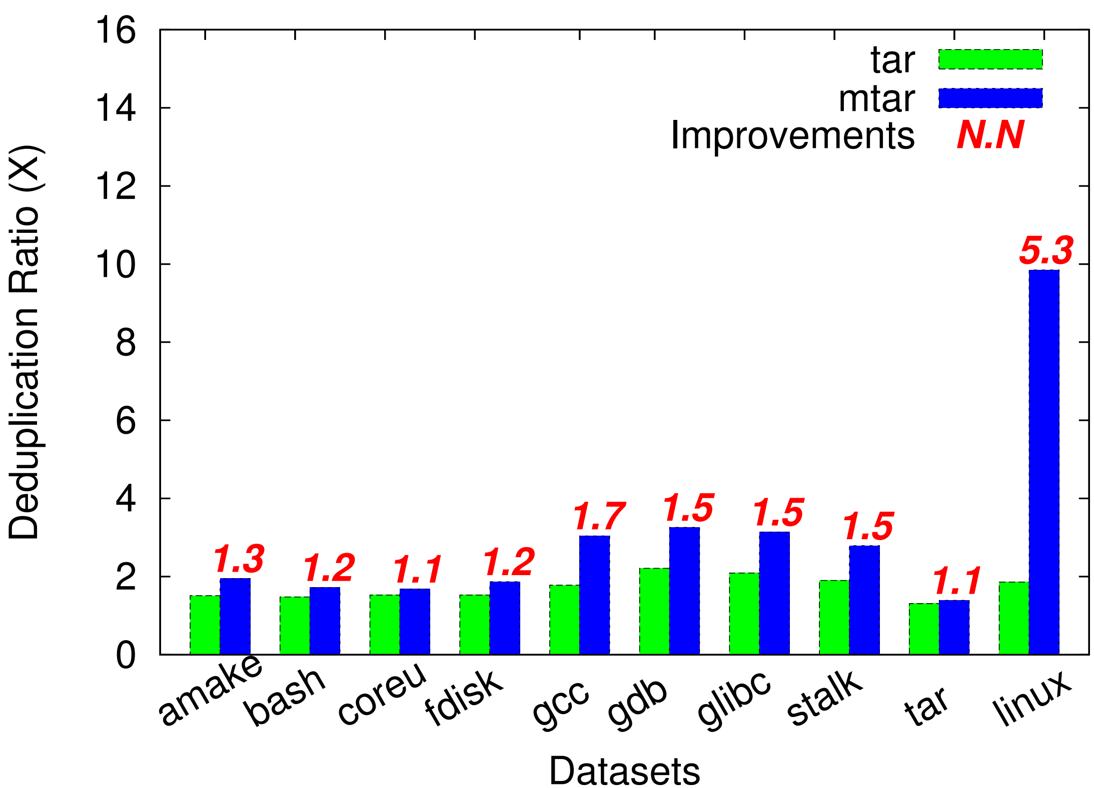

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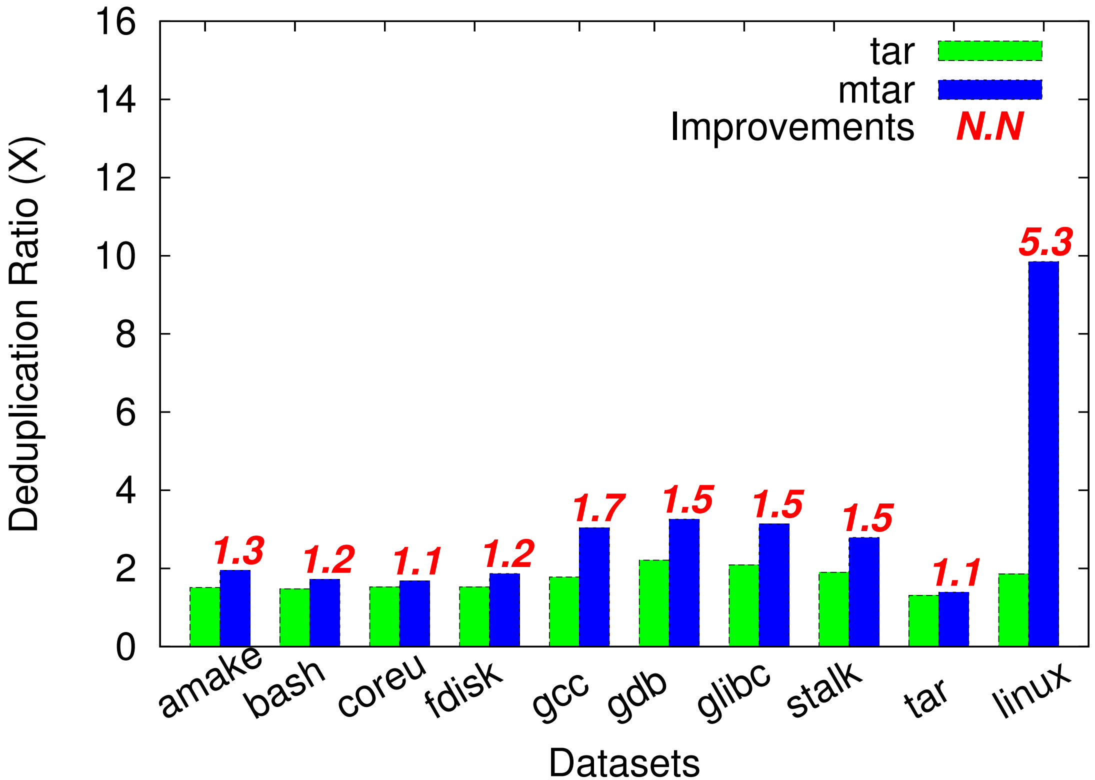

Improvements:
1. Across all datasets
2. Huge: 1.5-5.3×

More in the Paper

- ***Design deduplication-friendly formats***
  - ***Case study: EMC NetWorker***
- Application-level post-processing
  - Case study: GNU tar
- ***Format-aware Deduplication***
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Summary

- Metadata impacts deduplication
  - Metadata changes more frequently, introducing many *unnecessary* unique chunks
- Solution: separate metadata from data
  - Up to 5× improvements in deduplication

Metadata Considered Harmful … to Deduplication
Xing Lin, Fred Douglis, Jim Li, Xudong Li, Robert Ricci, Stephen Smaldone and Grant Wallance
HotStorage '15: 7th USENIX Workshop on Hot Topics in Storage and File Systems

Outline

- ✓ Introduction
  - ✓ Migratory Compression
  - ✓ Improve deduplication by separating metadata from data
  - ✓ ***Using deduplication for efficient disk image deployment***
  - ✓ Performance predictability and efficiency for Cloud Storage Systems
- ✓ Conclusion

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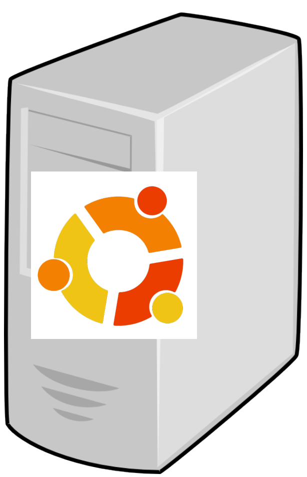
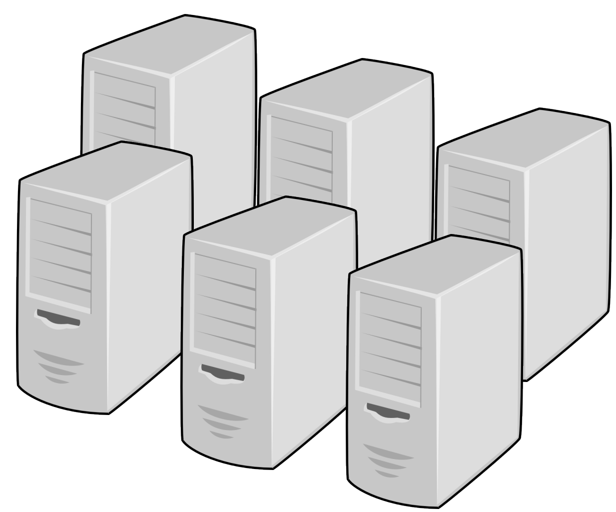


Image server



Compute Nodes

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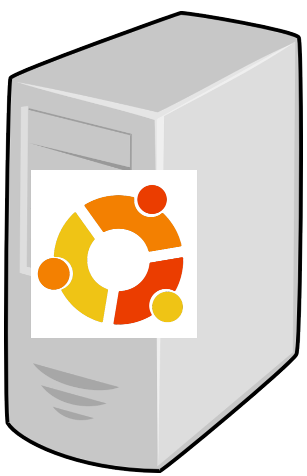

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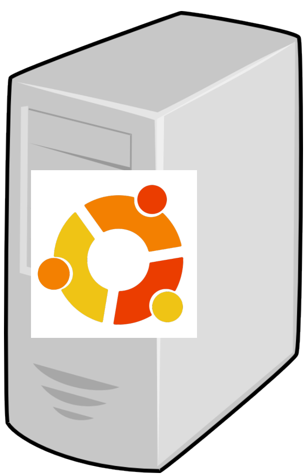
Requirements: efficient image transmission and installation



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Compute Nodes

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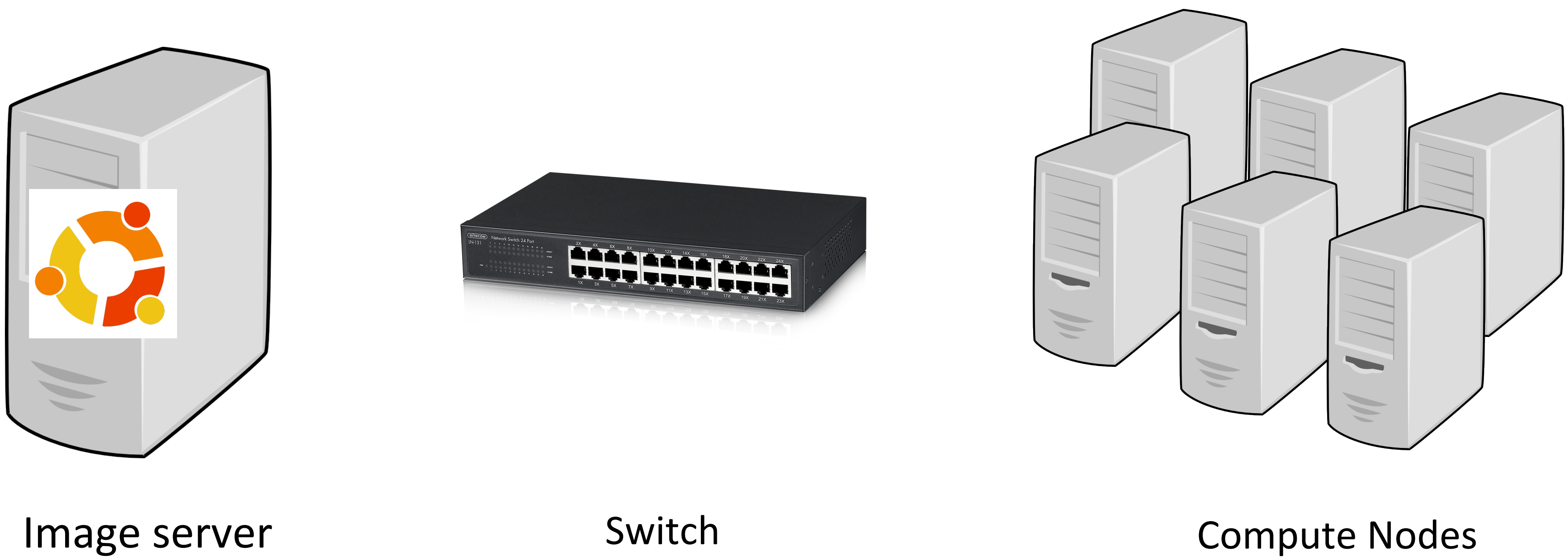

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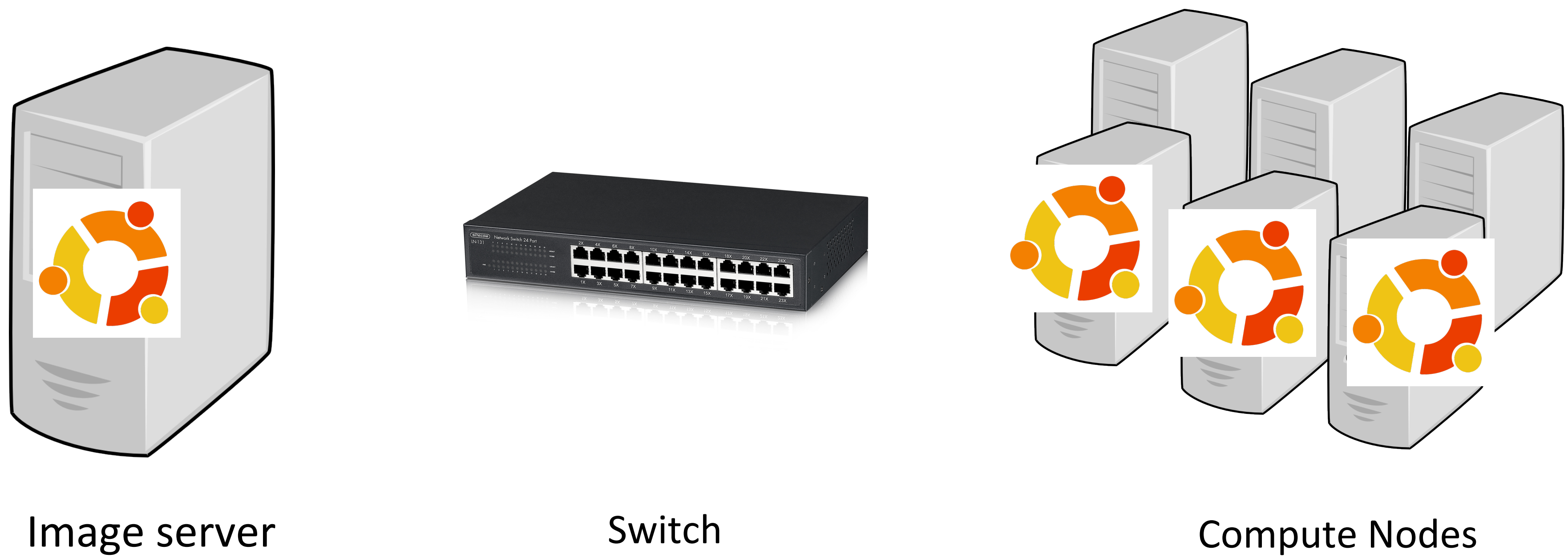

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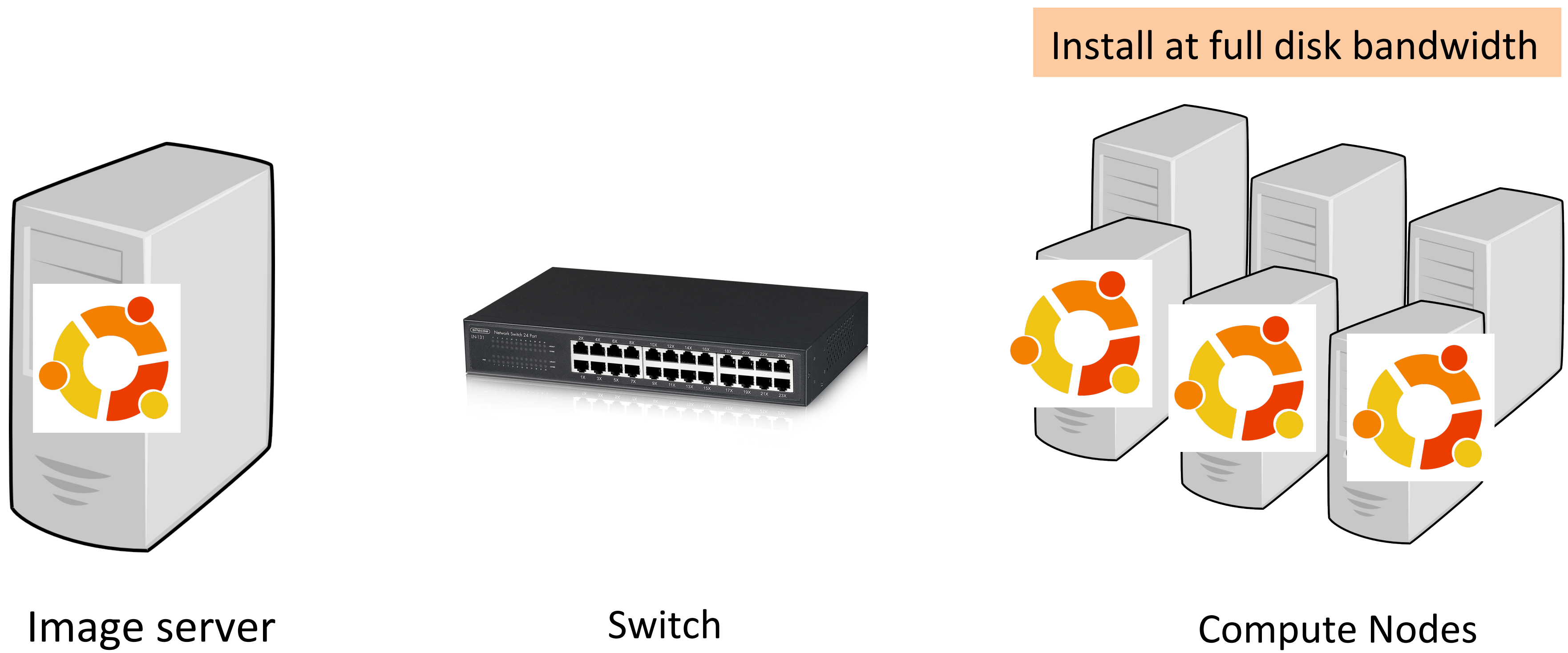

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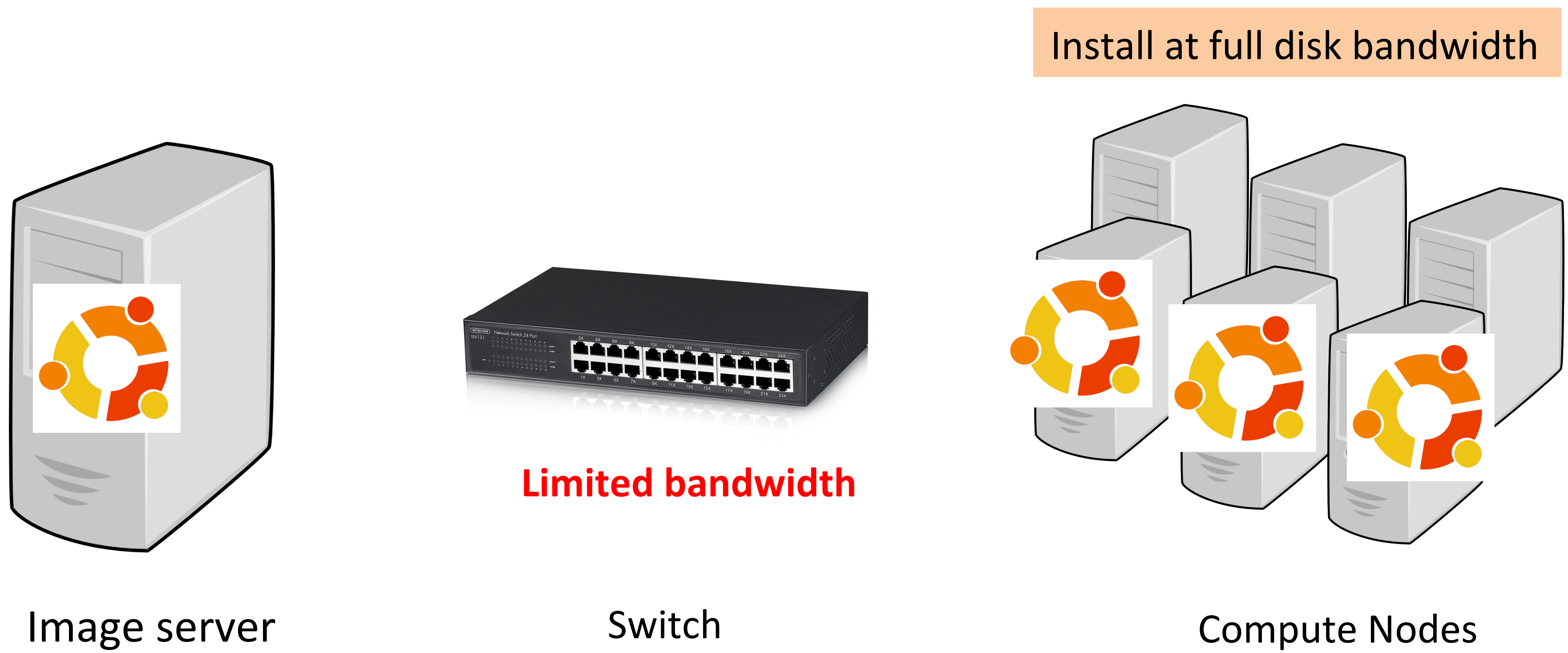

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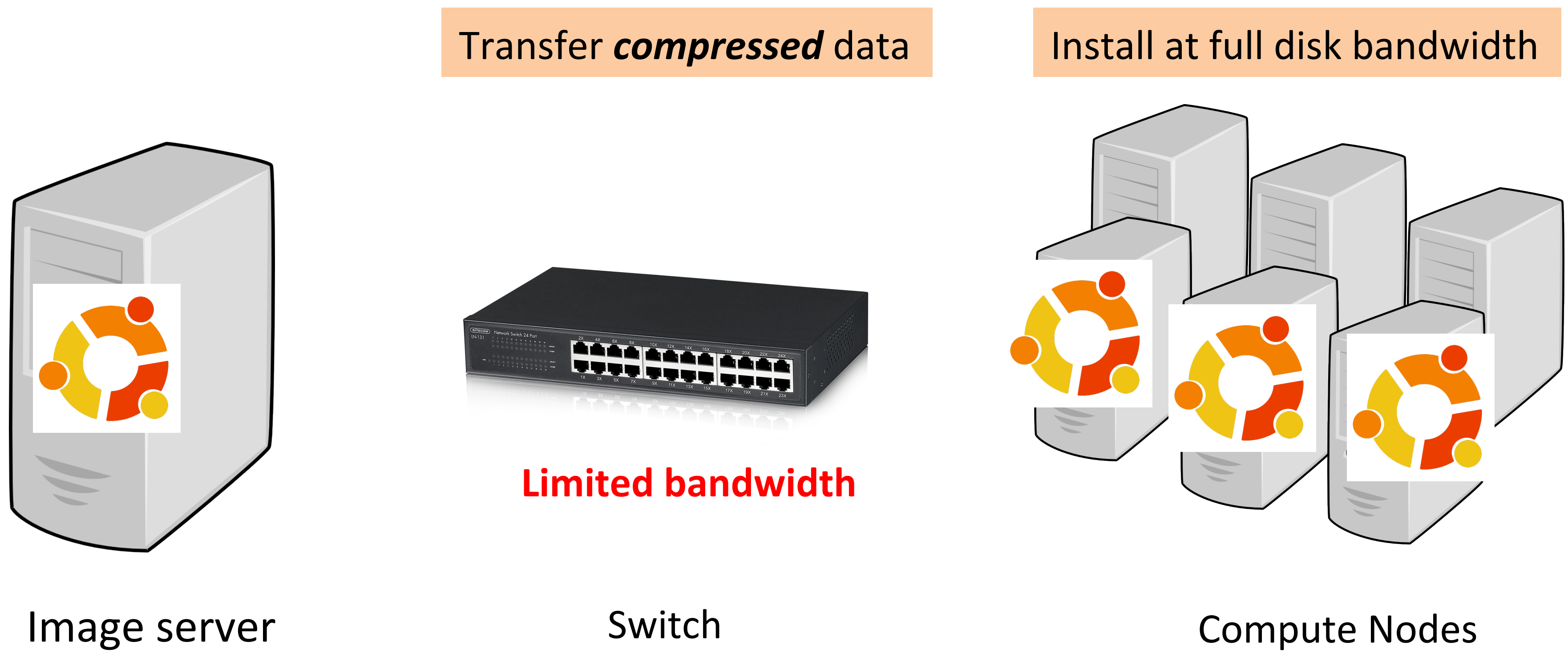

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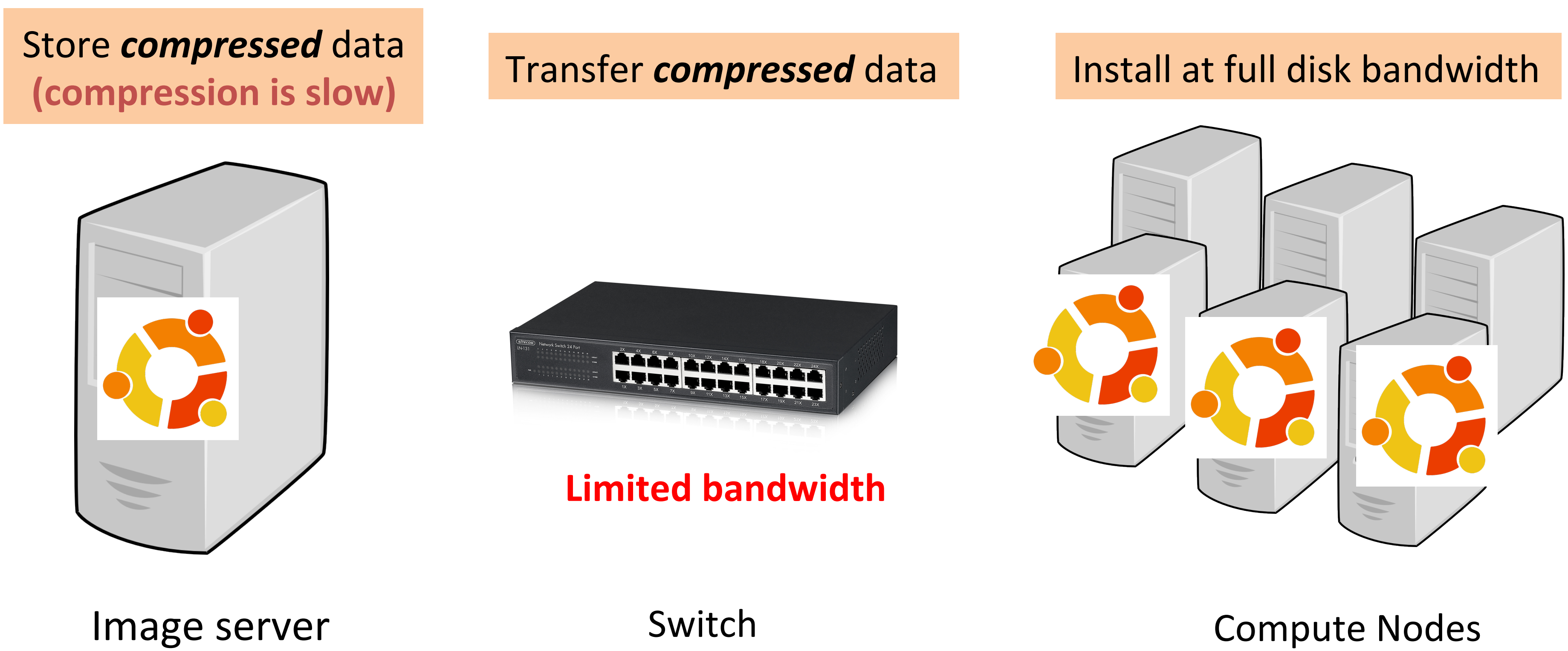
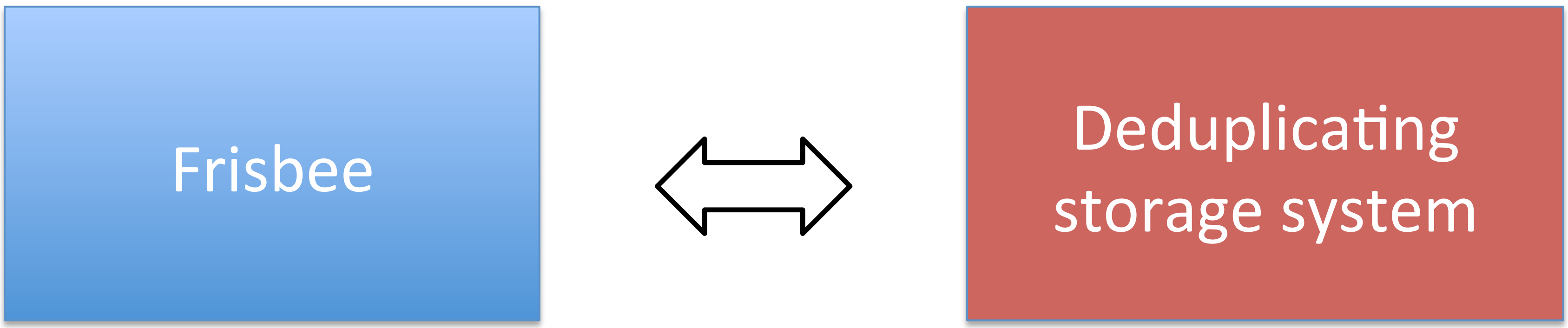


Integrate Frisbee with Deduplicating Storage



Efficient Image Deployment

Efficient Image Storage

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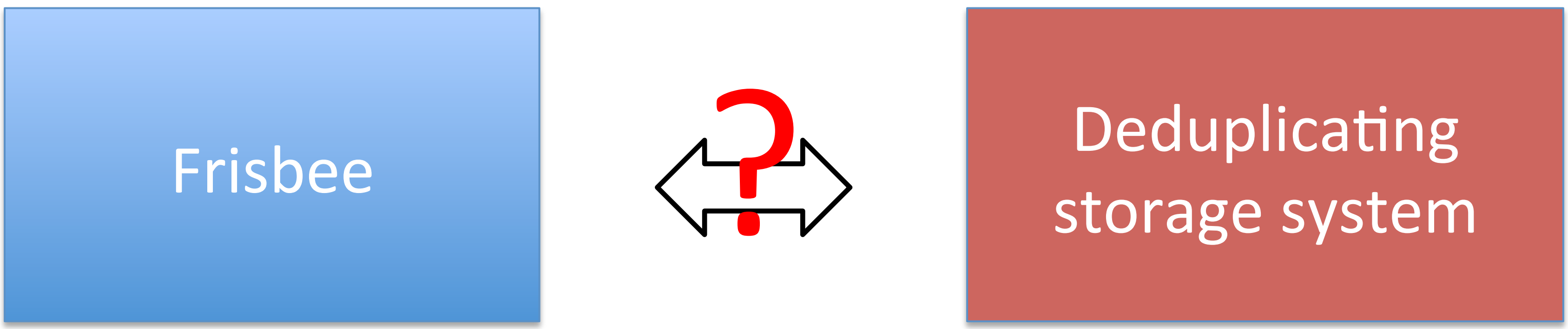

Efficient Image Deployment

Efficient Image Storage

How to achieve efficient image deployment and storage ***simultaneously***, by integrating these two systems?

Requirements for the Integration

Use compression

Use filesystem to skip unallocated data

Image installation at full disk bandwidth

Independent installable Frisbee chunks

Requirements

Solutions

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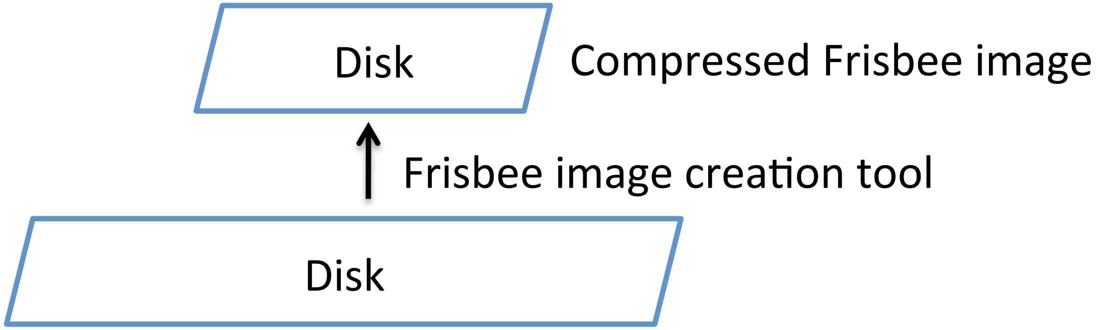

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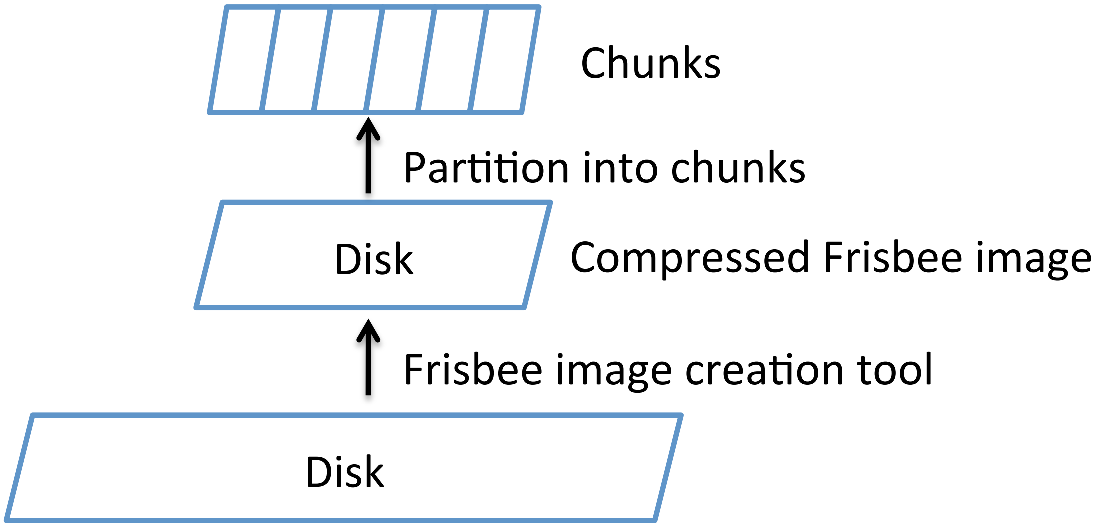

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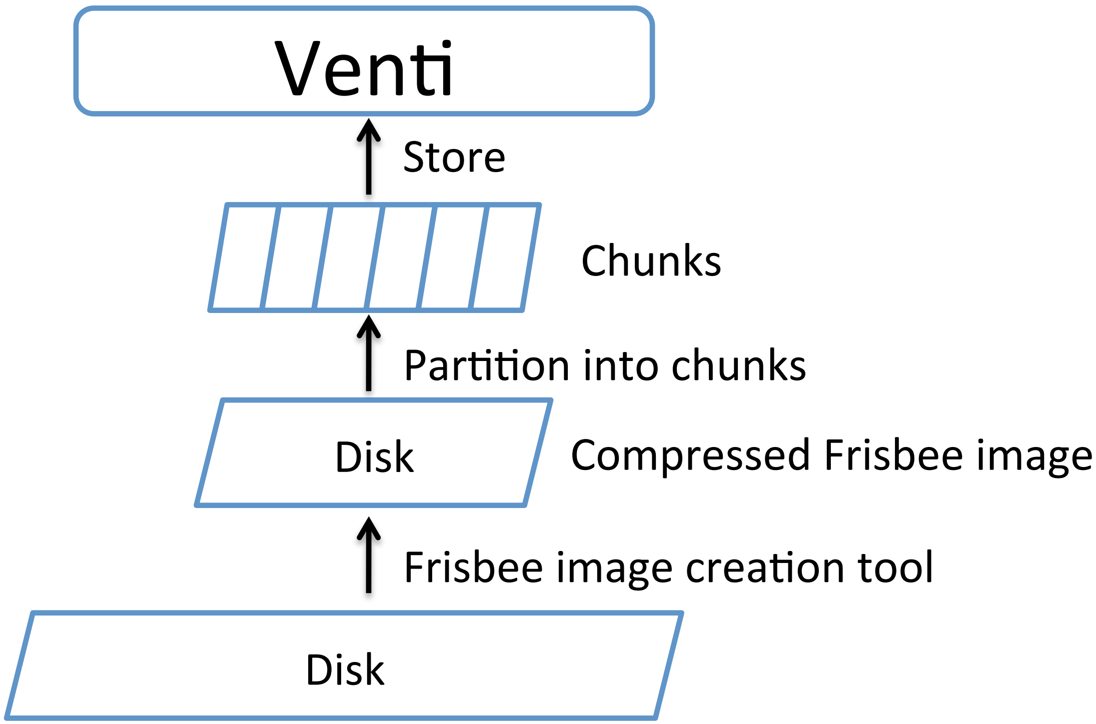

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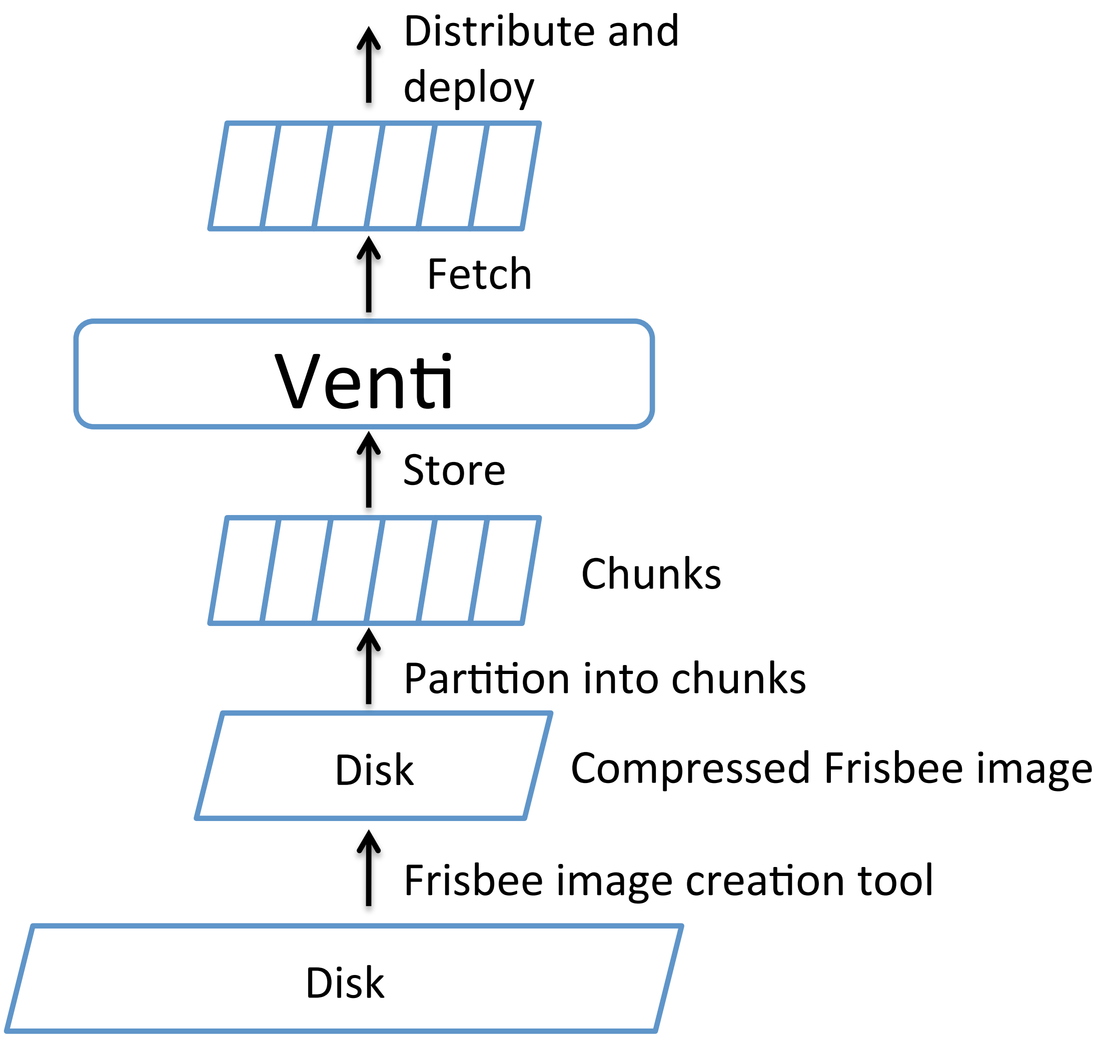

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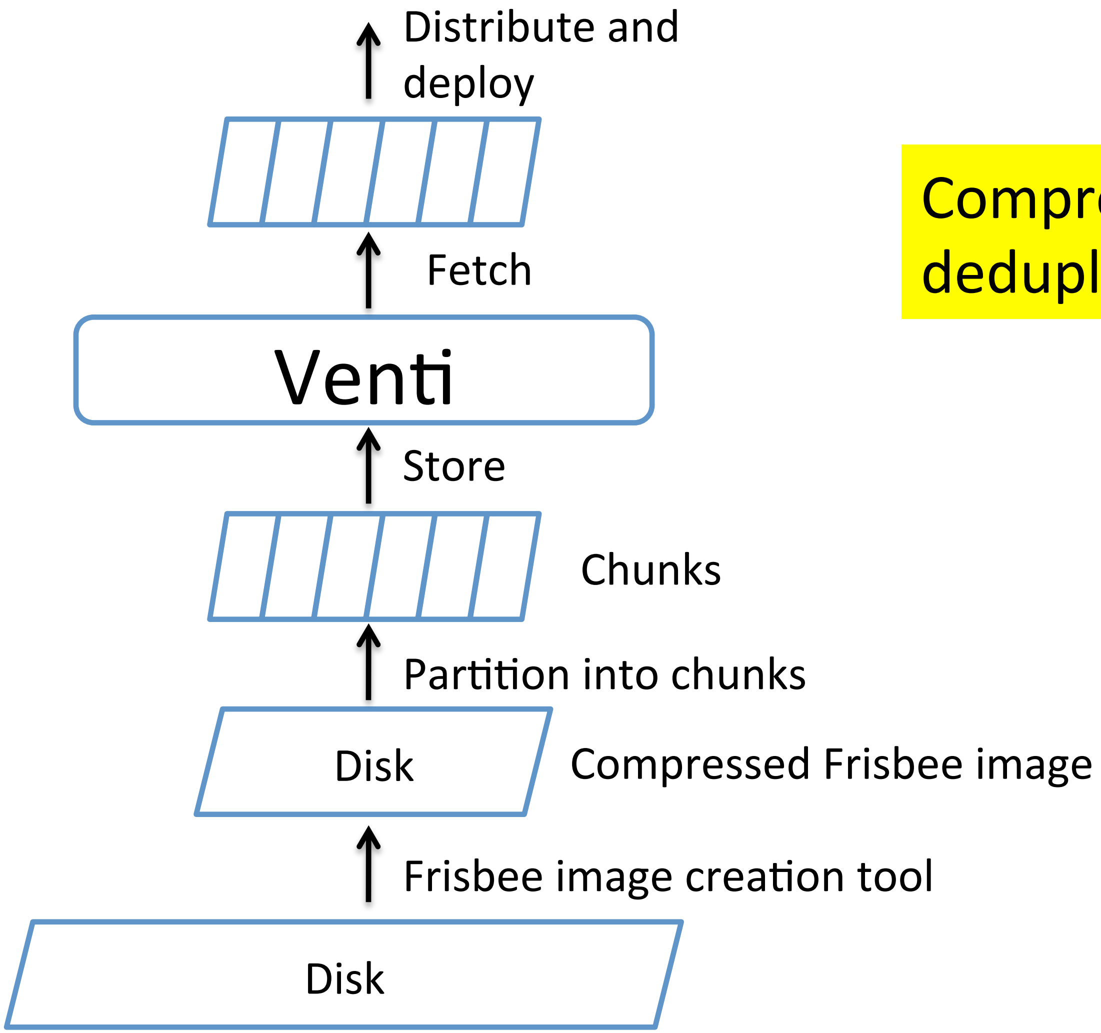

Compressed data does not deduplicate well

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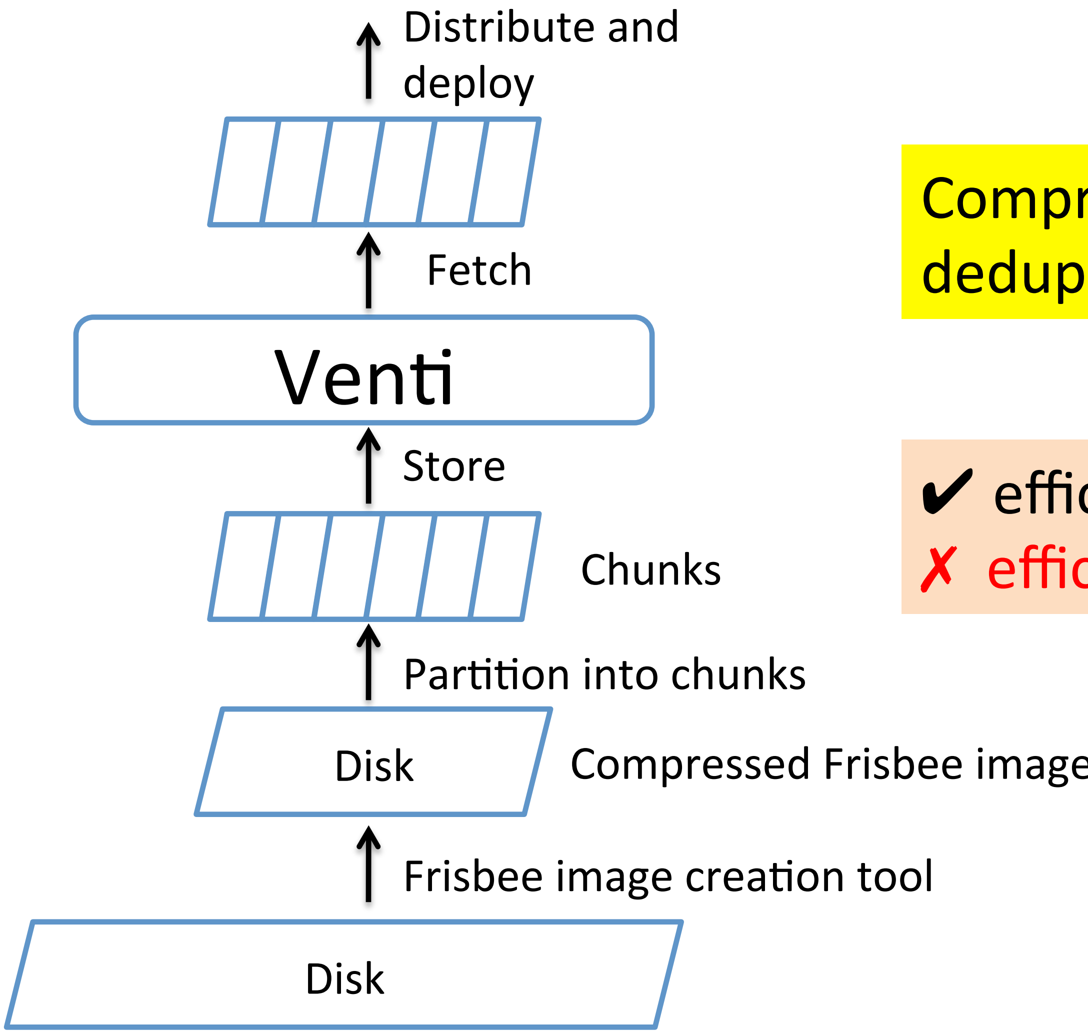

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✔ efficient image deployment
✗ efficient image storage

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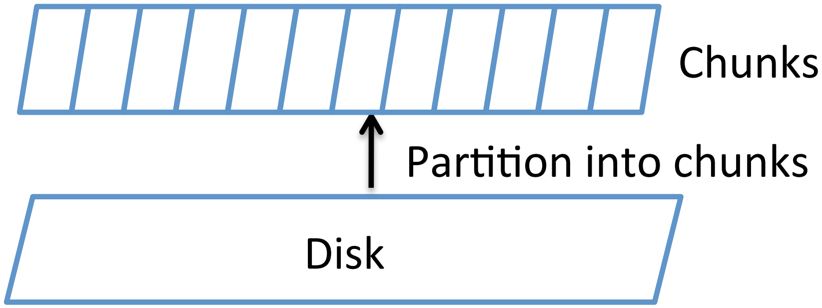

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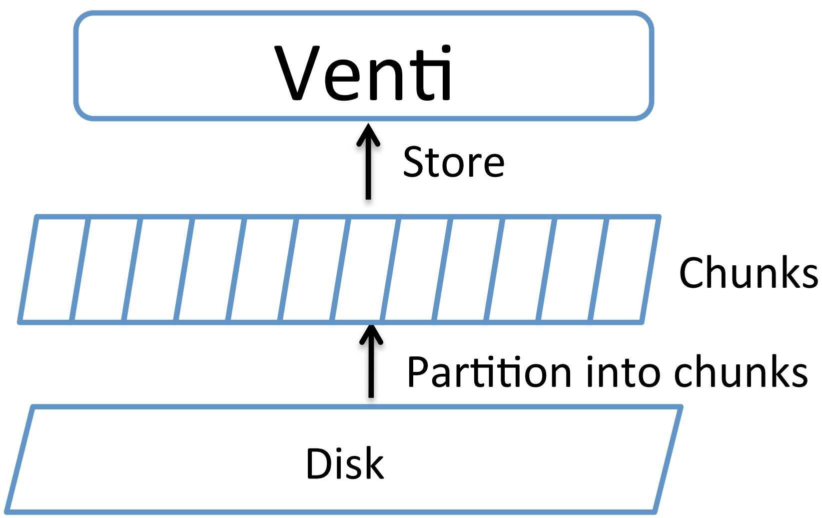

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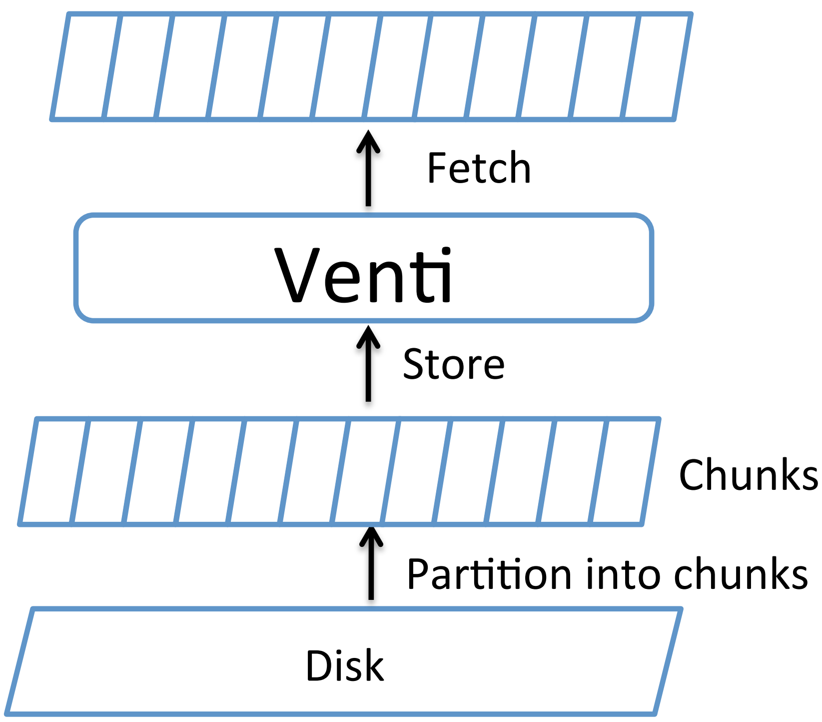

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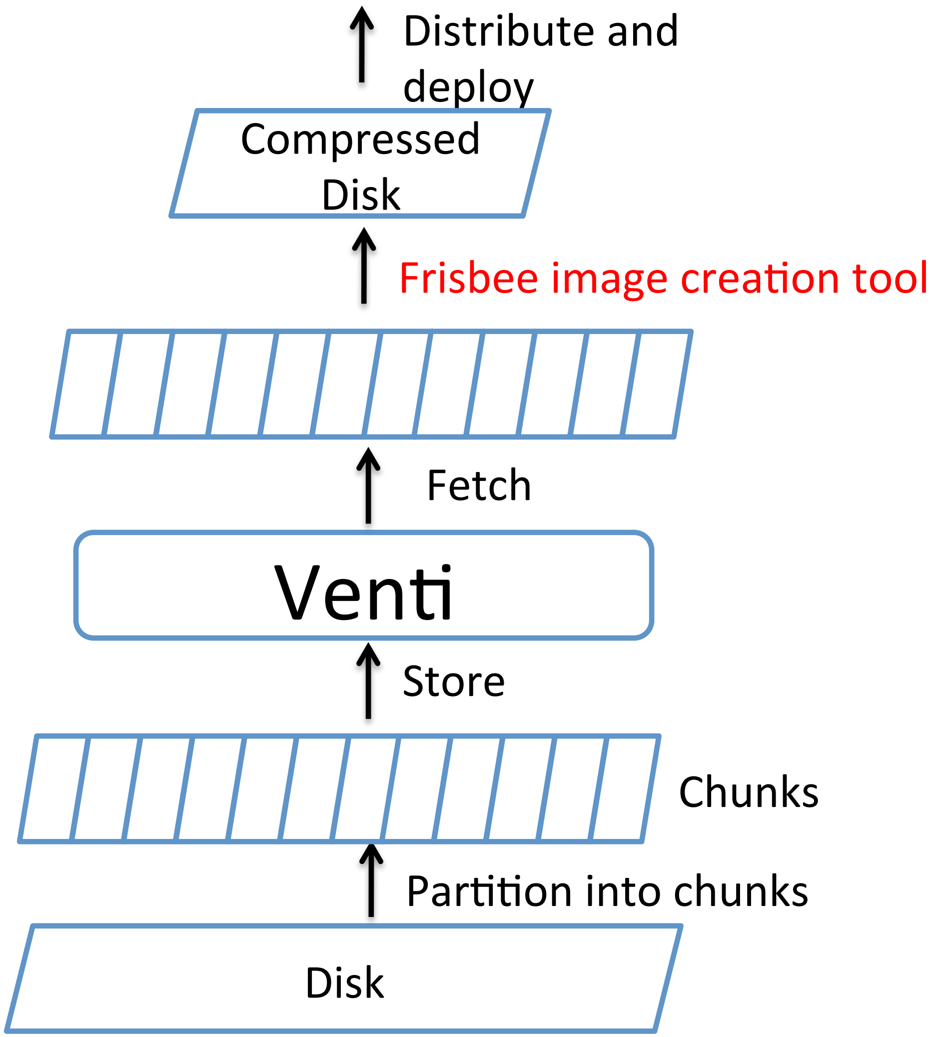

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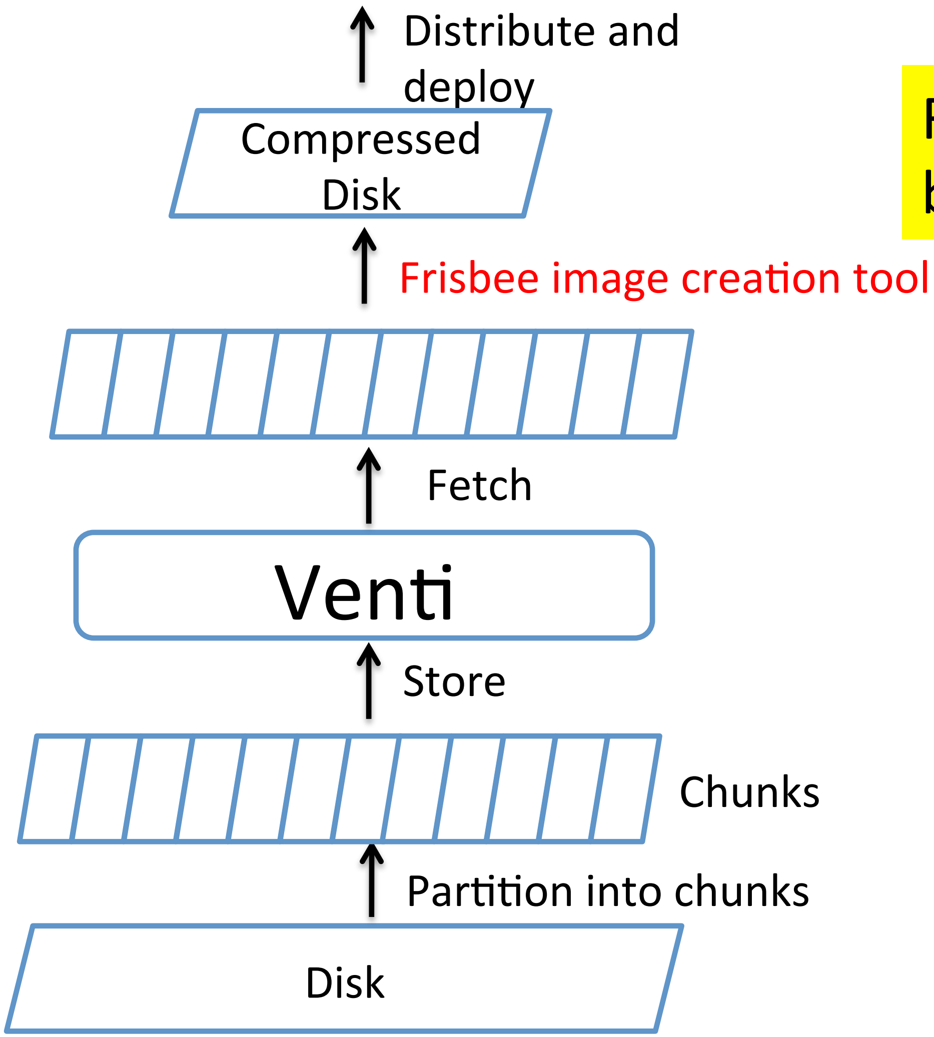

Frisbee compression will become the bottleneck

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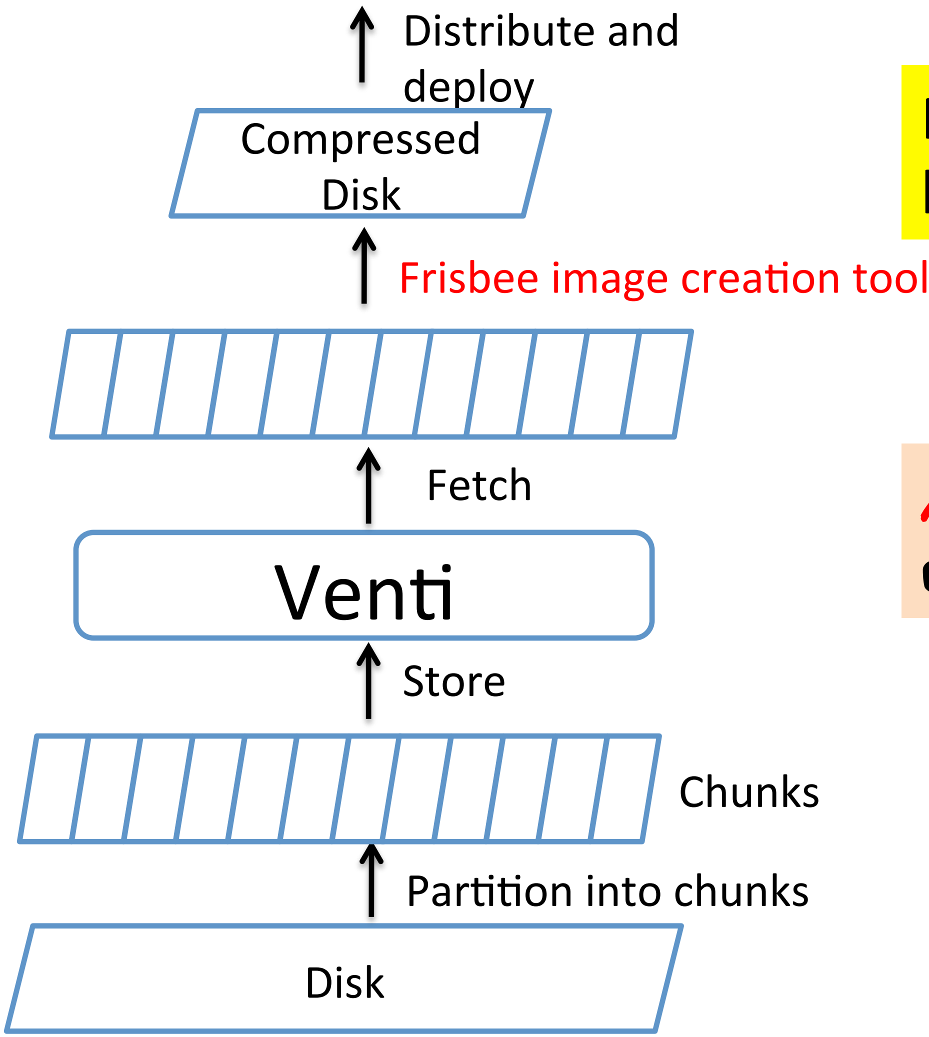

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✗ efficient image deployment
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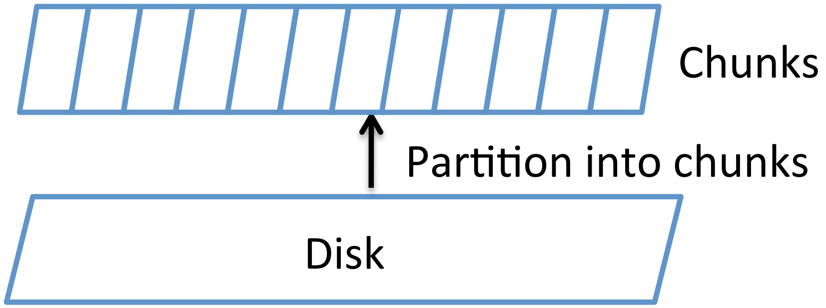

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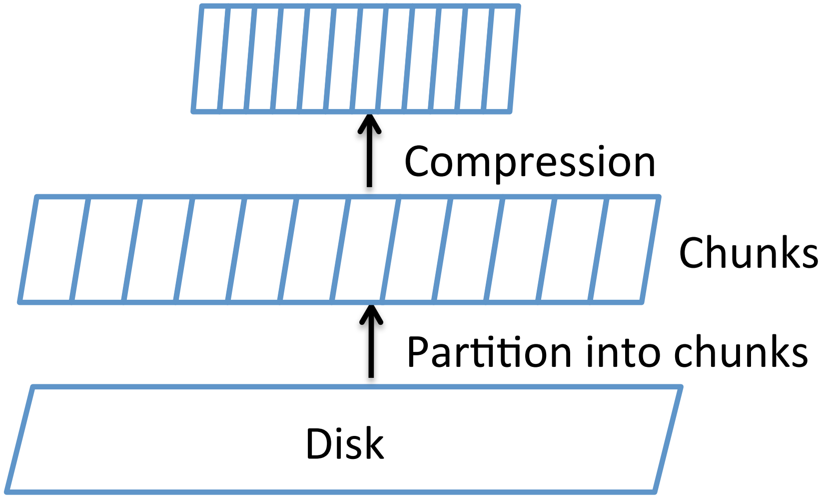

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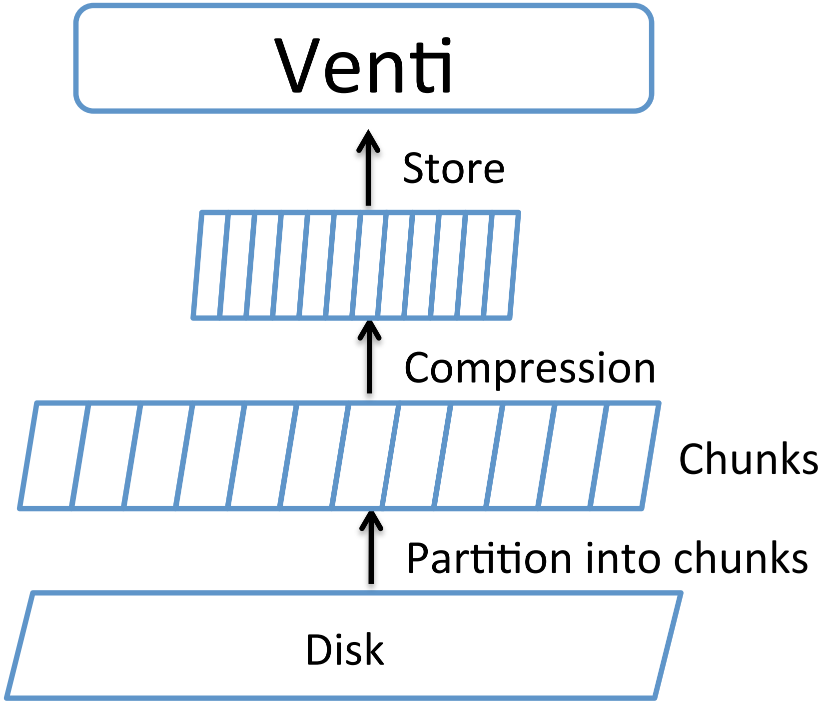

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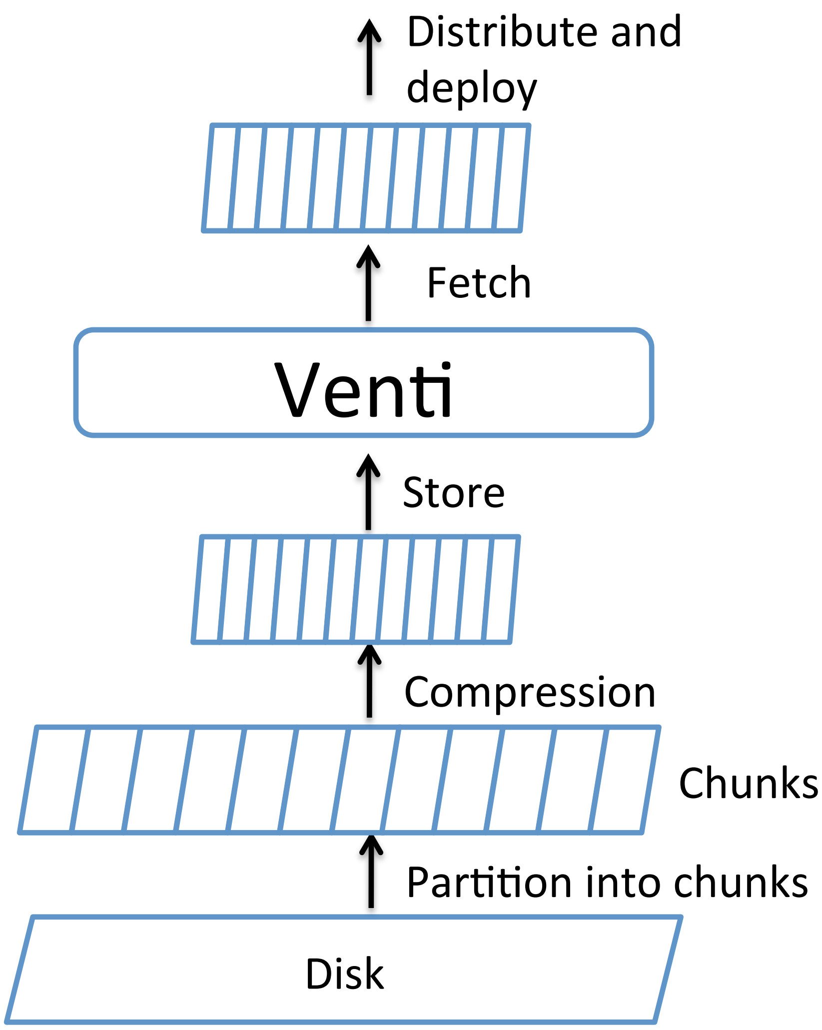

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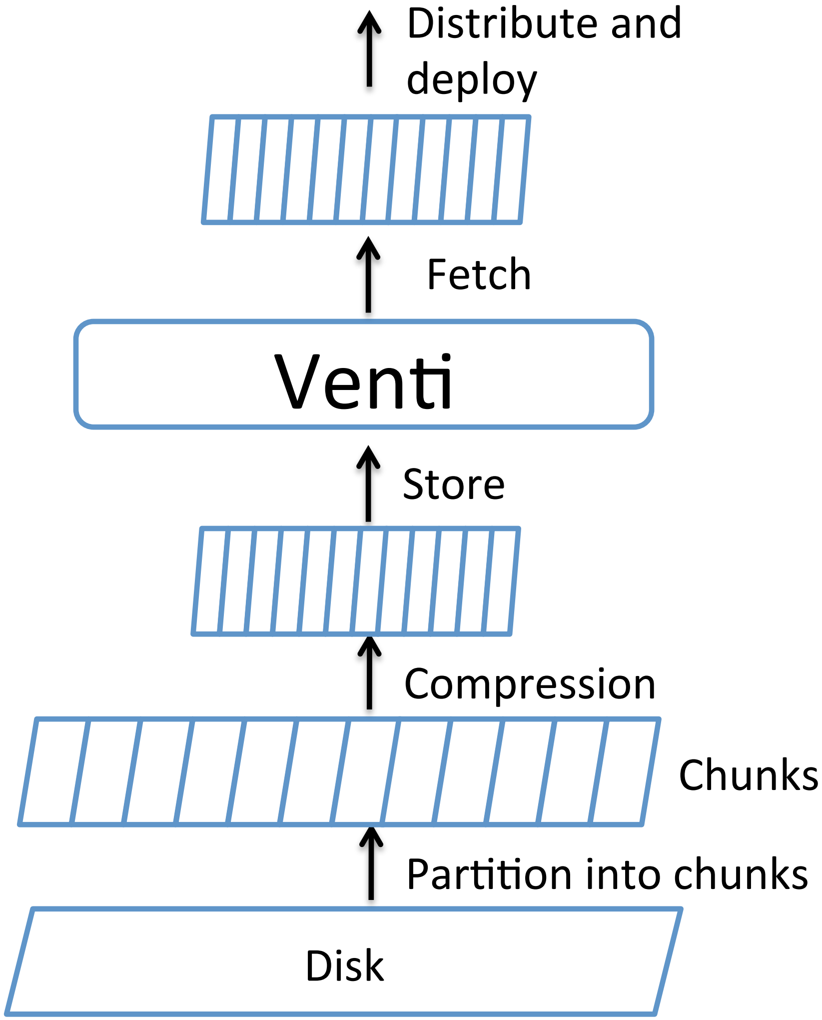

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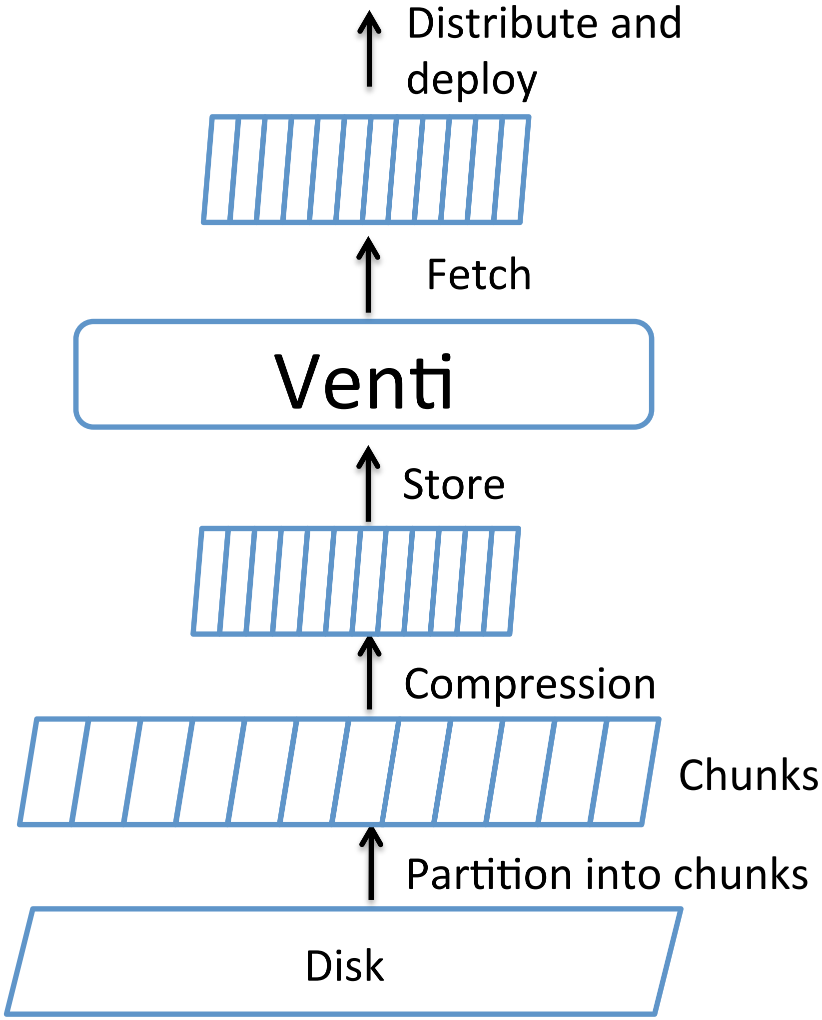

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✔ efficient image deployment
✔ efficient image storage

Efficient Image Storage

- Dataset: 430 Linux images
  - Filesystem size: 21 TB (allocated 2 TB)

Format	Size (GB)
Frisbee Images	233
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3× reduction

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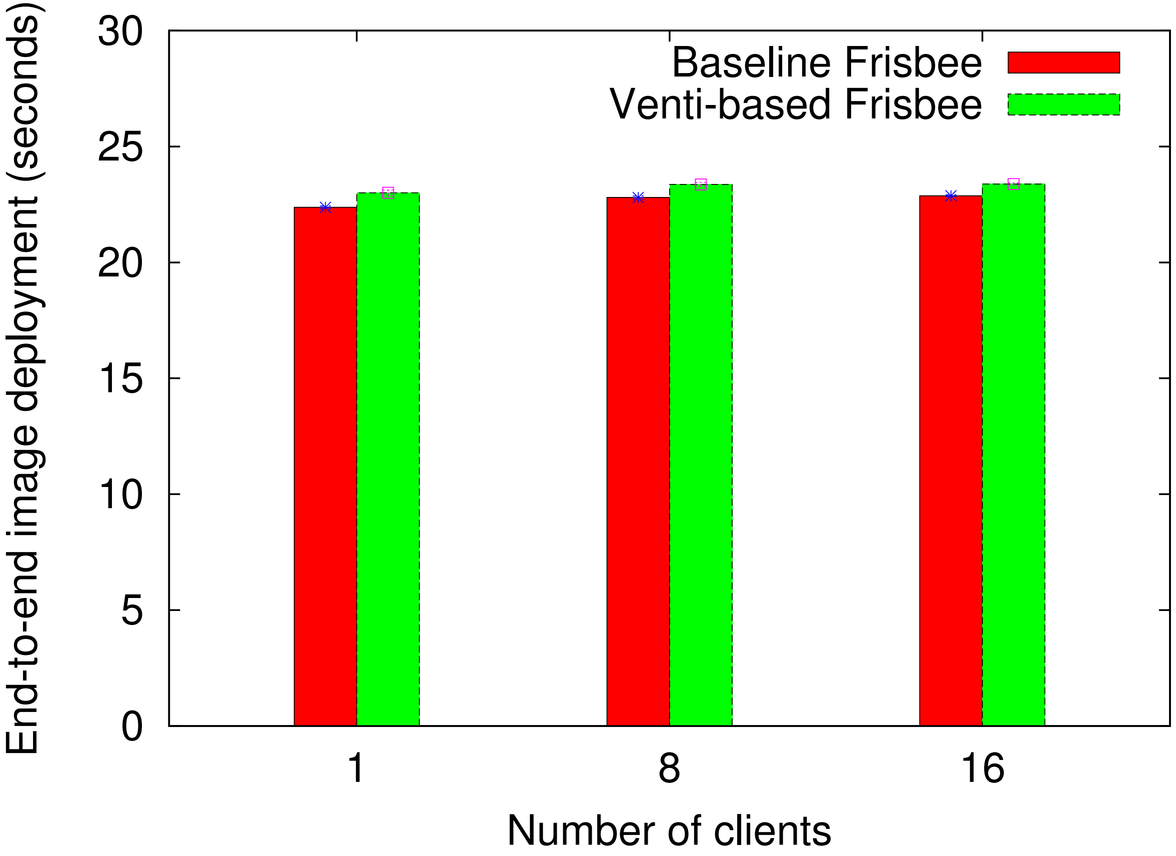
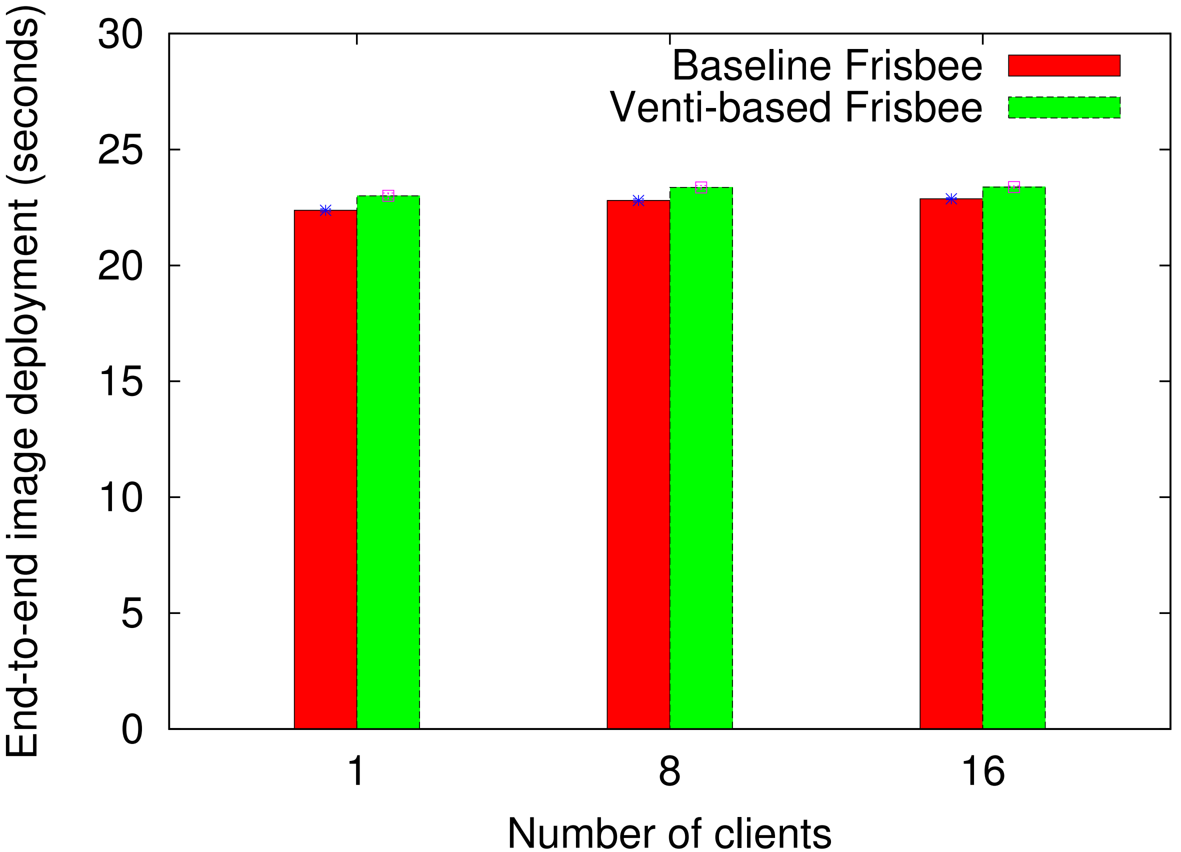


End-to-End Image Deployment Performance

Efficient Image Deployment



Similar performance
In image deployment

End-to-End Image Deployment Performance

More in the Paper

- Aligned Fixed-size Chunking (AFC)
- Image retrieve time based on chunk sizes
  - Smaller chunk size: better deduplication
  - Larger chunk size: better image deployment performance
- Image deployment performance with staging nodes

Summary

- Compress each chunk
- Aligned Fixed-size Chunking
- Careful selection of chunk size
- Pre-computation of Frisbee chunk headers

→

✔ efficient image deployment
✔ efficient image storage

Using Deduplicating Storage for Efficient Disk Image Deployment
Xing Lin, Mike Hibler, Eric Eide, and Robert Ricci
TridentCom '15: 10th international conference on testbeds and research infrastructures for the development of networks & communities

Outline

- ✓ Introduction
  - ✓ Migratory Compression
  - ✓ Improve deduplication by separating metadata from data
  - ✓ Using deduplication for efficient disk image deployment
  - ✓ ***Performance predictability and efficiency for Cloud Storage Systems***
- ✓ Conclusion

Introduction

- Cloud Computing is becoming popular
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  - Random and sequential workloads [Gulati VPACT '09]
  - Read and write workloads [Ahmad WWC '03]
- Targeting environments: a ***large*** number of ***mixed*** workloads

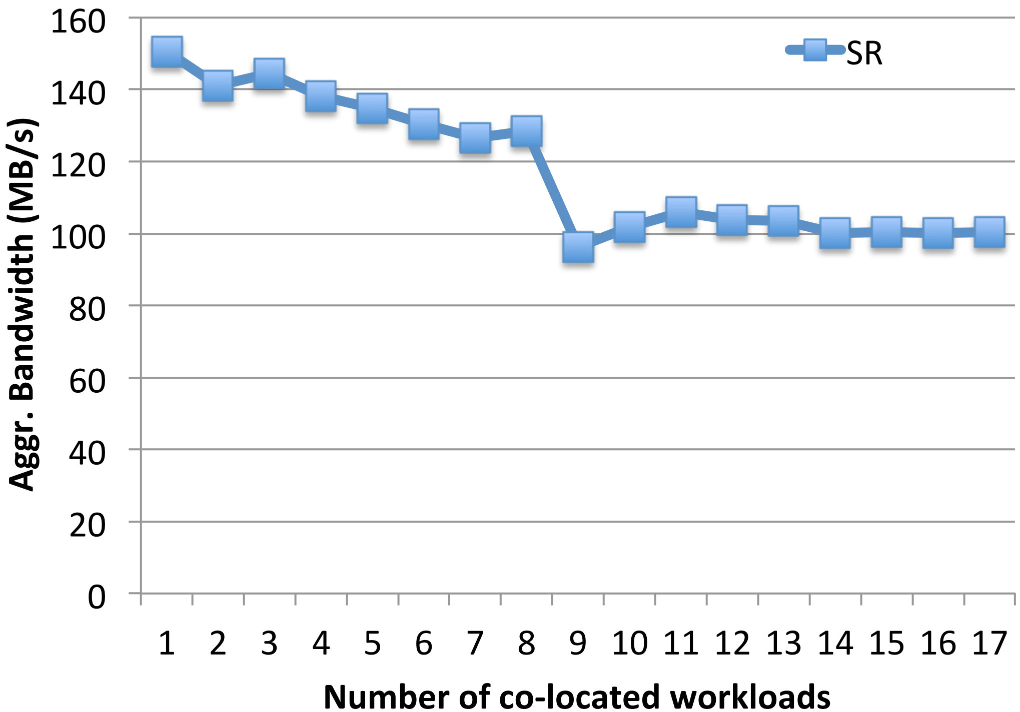
Random Workloads' Impact on Disk Bandwidth

Workloads:

- All sequential
- 1 sequential, adding more random ones

High disk bandwidth = high disk utilization

Random Workloads' Impact on Disk Bandwidth



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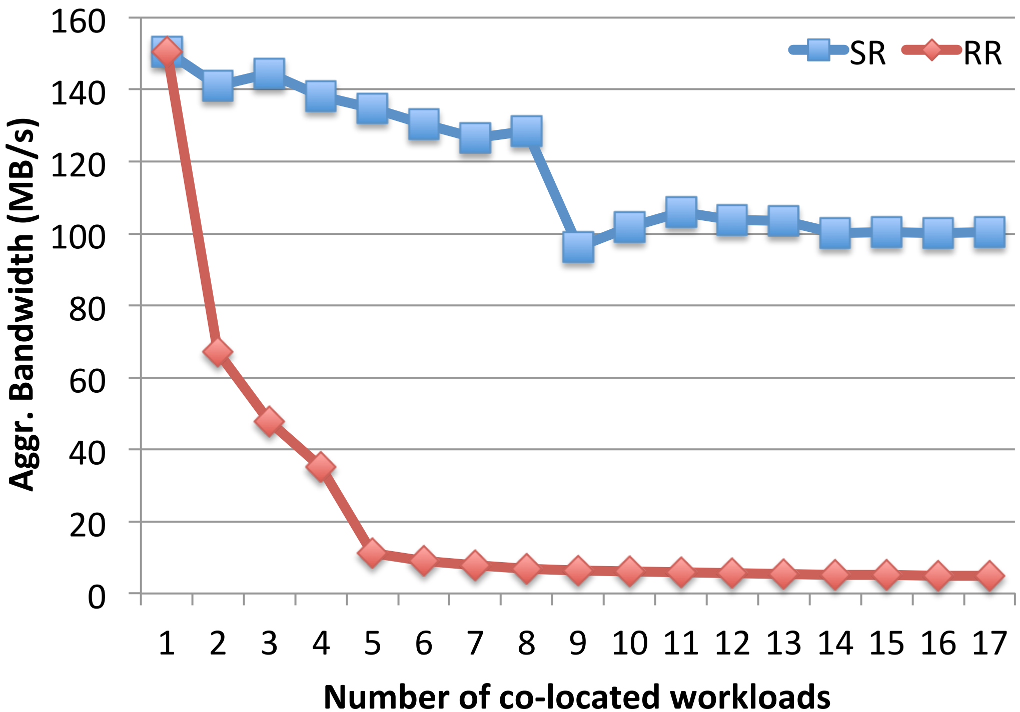

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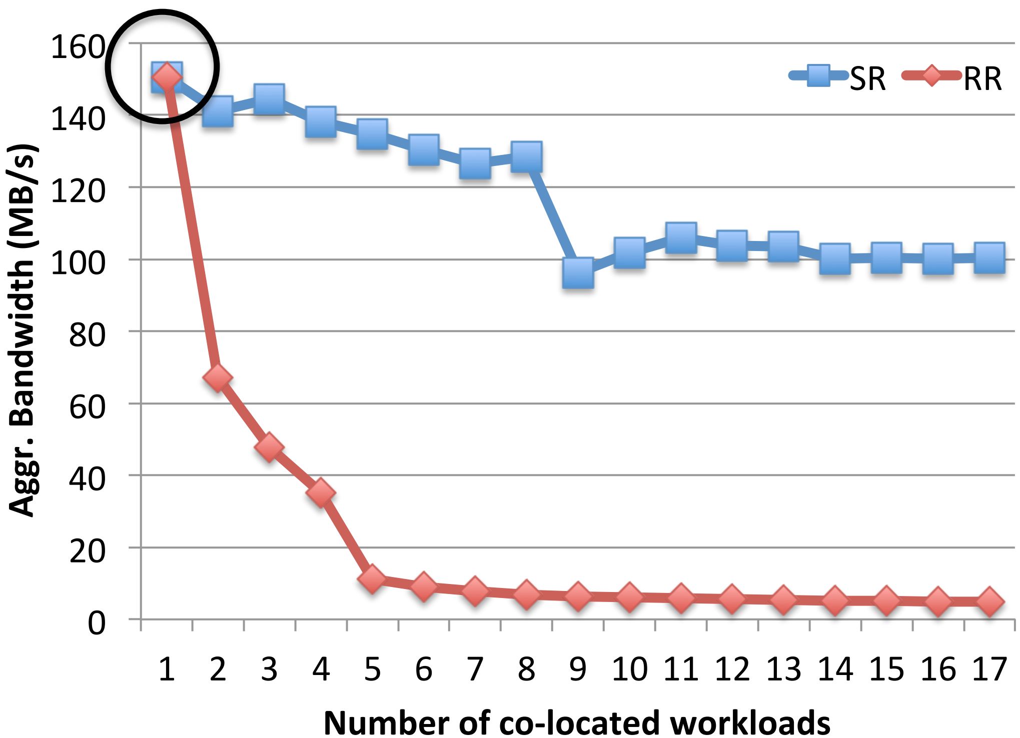

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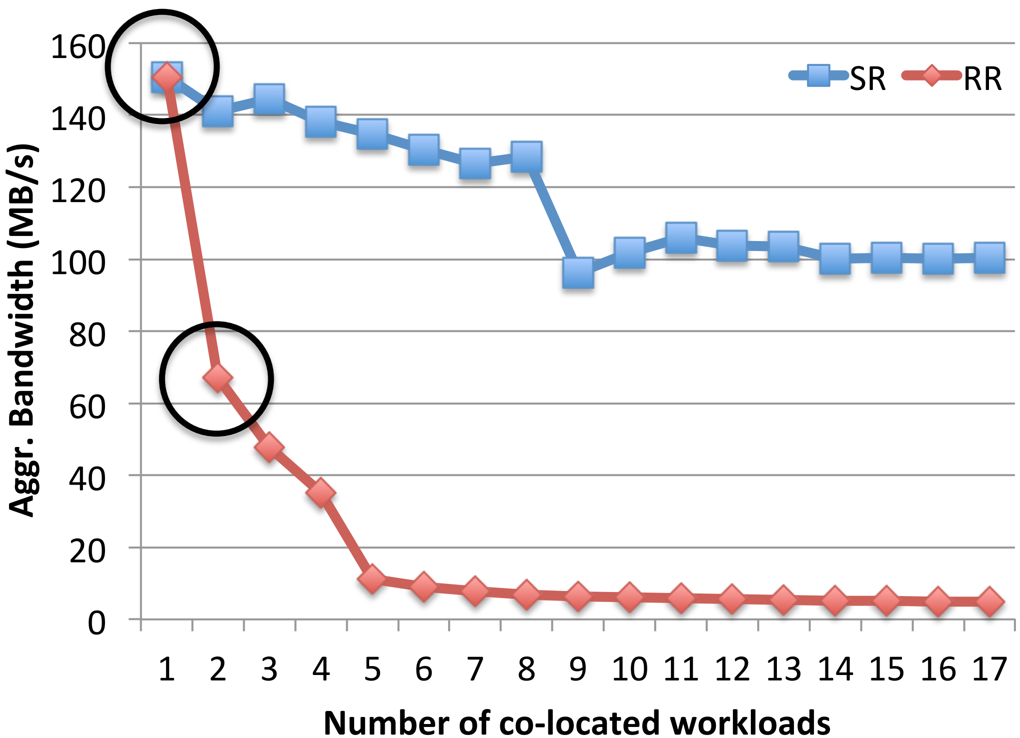

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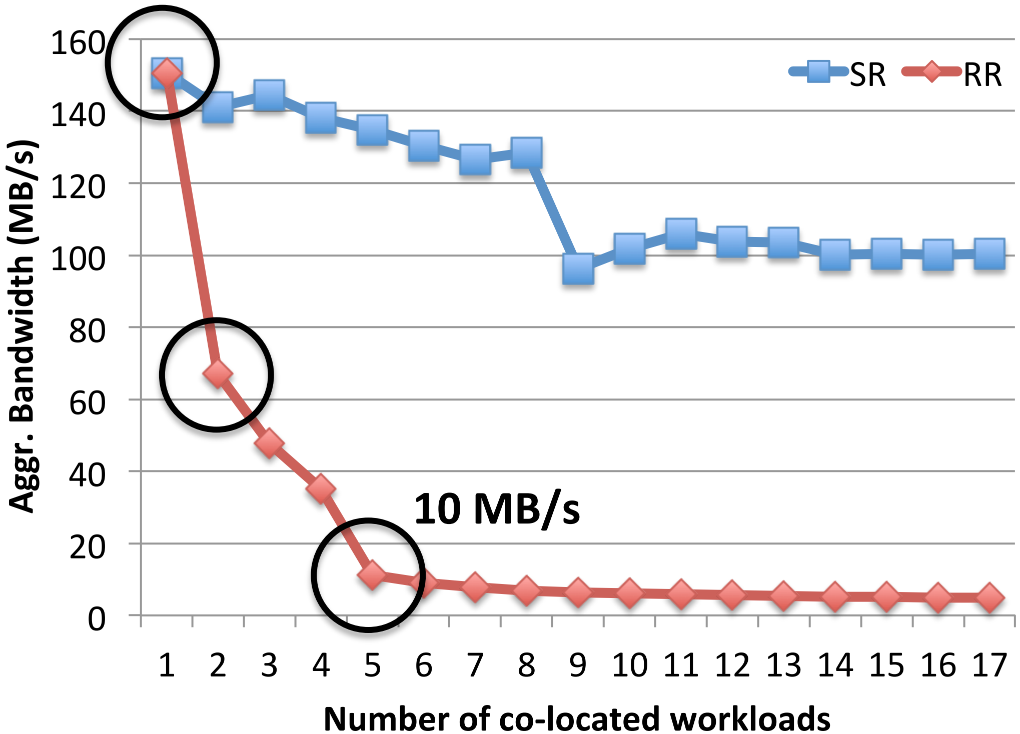

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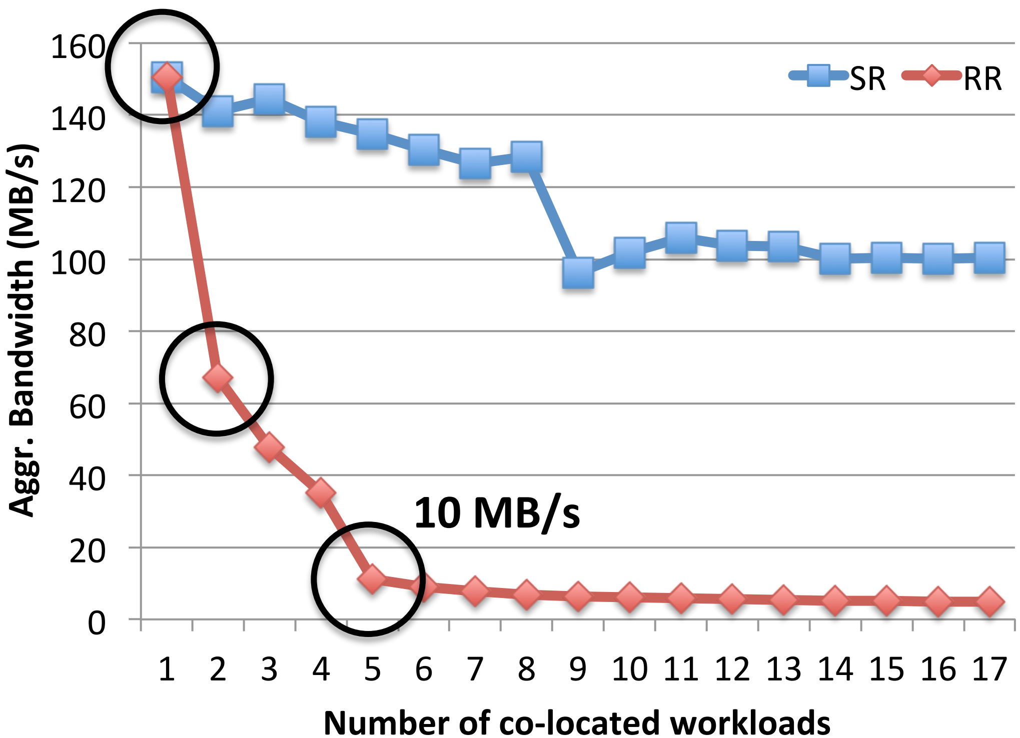

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Random workloads are harmful for disk bandwidth

High disk bandwidth = high disk utilization

Differential I/O Scheduling (DIOS)

- **Opportunity**: replication is commonly used in cloud storage systems
  - Google Filesystem, Ceph, sheepdog, etc.
- **Idea**: dedicate each disk to serve one type of requests

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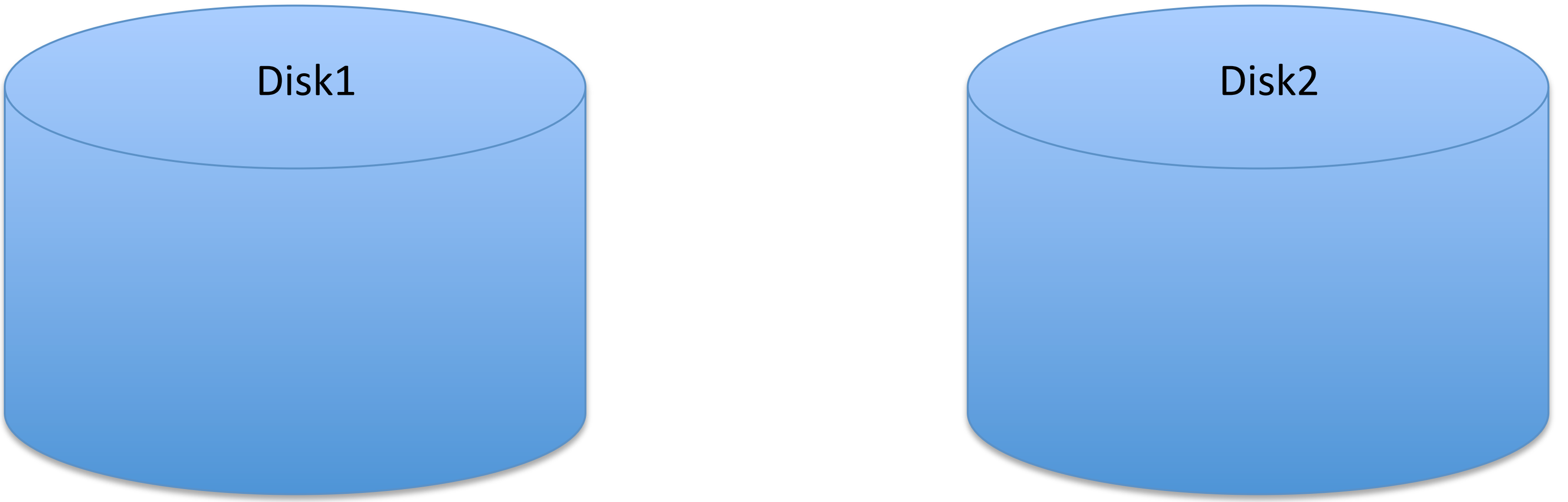
- **Opportunity**: replication is commonly used in cloud storage systems
  - Google Filesystem, Ceph, sheepdog, etc.
- **Idea**: dedicate each disk to serve one type of requests
- **System implications (tradeoff)**
  - High bandwidth for disks serving sequential requests
  - Lower performance for random workloads

Architecture



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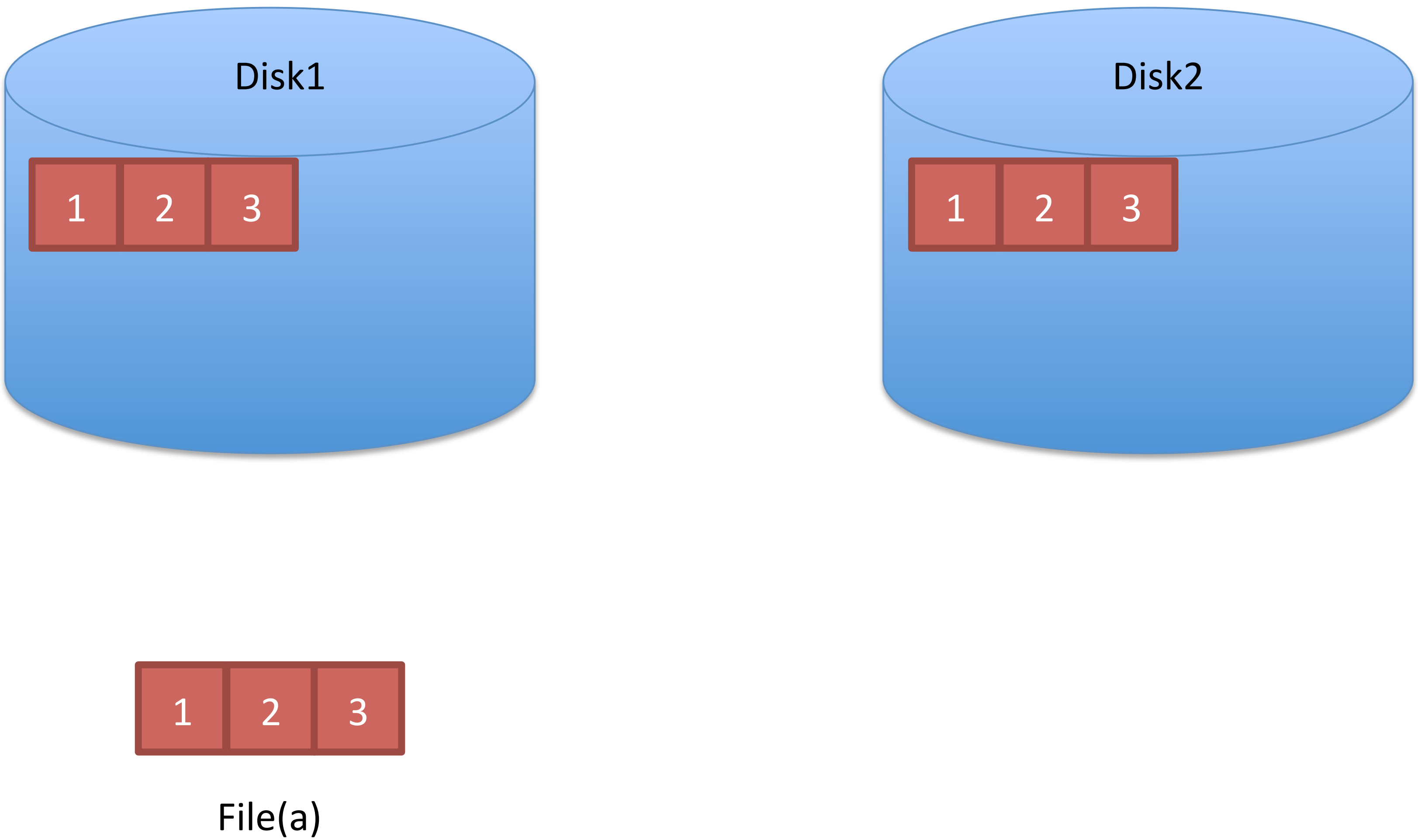

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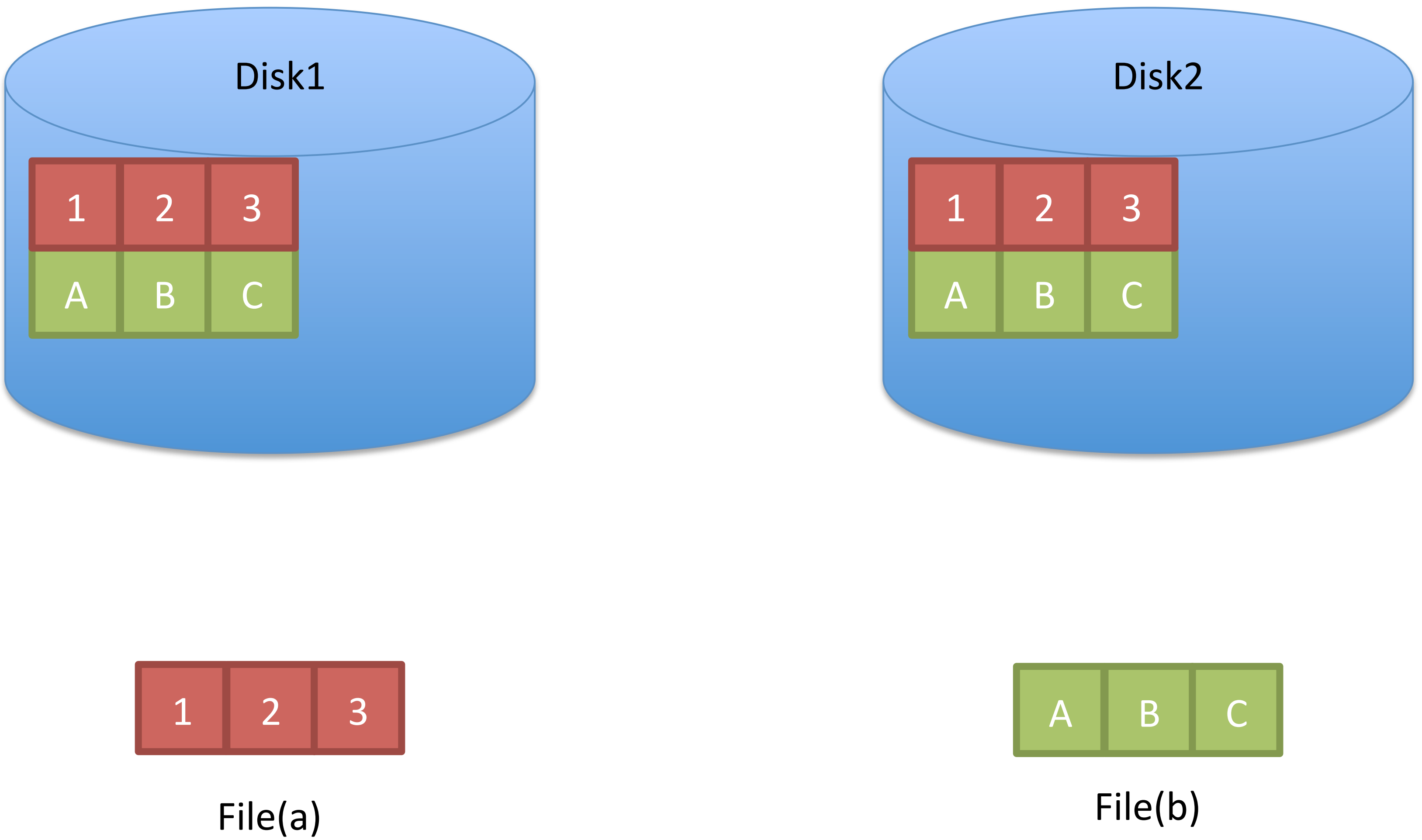

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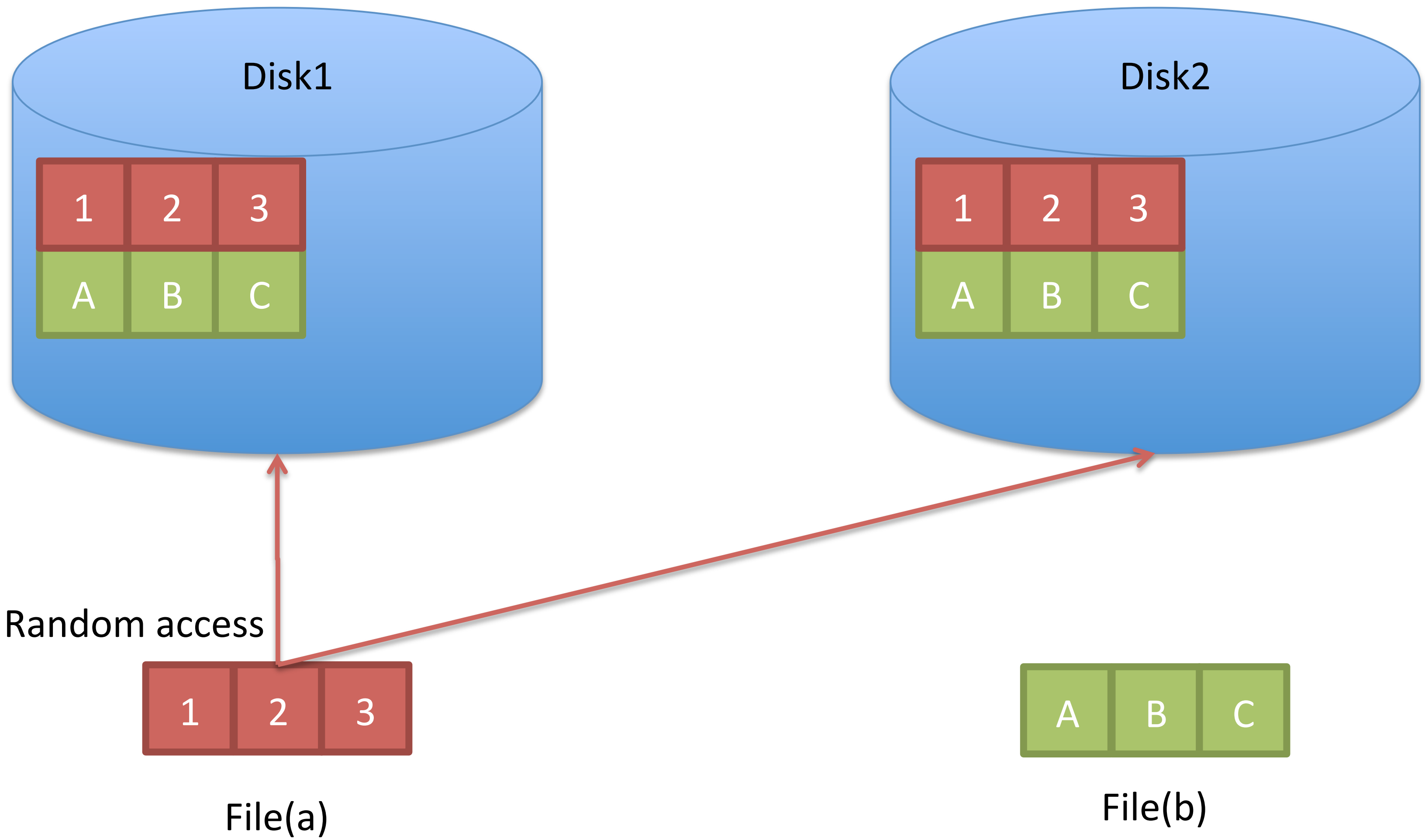

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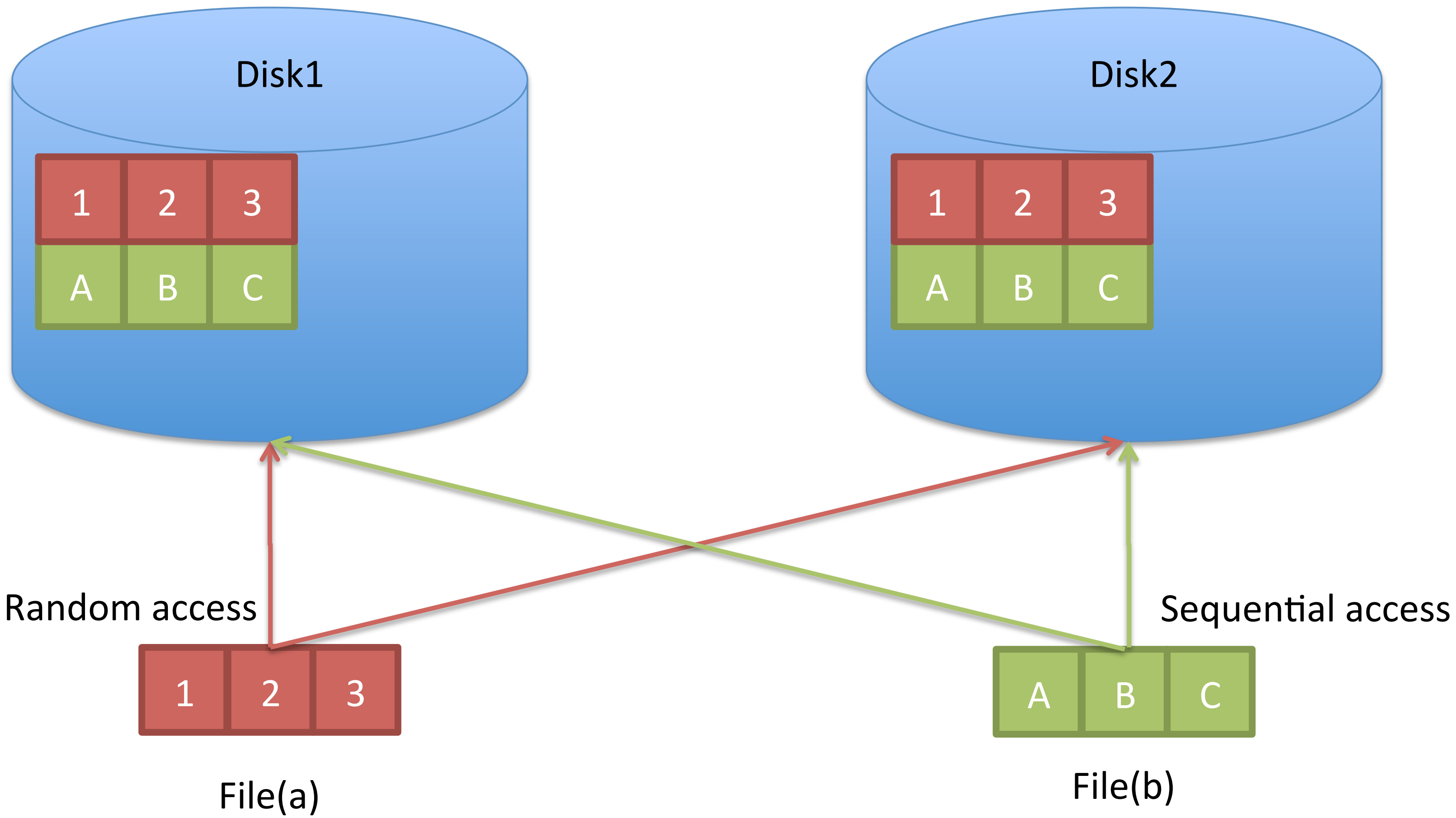

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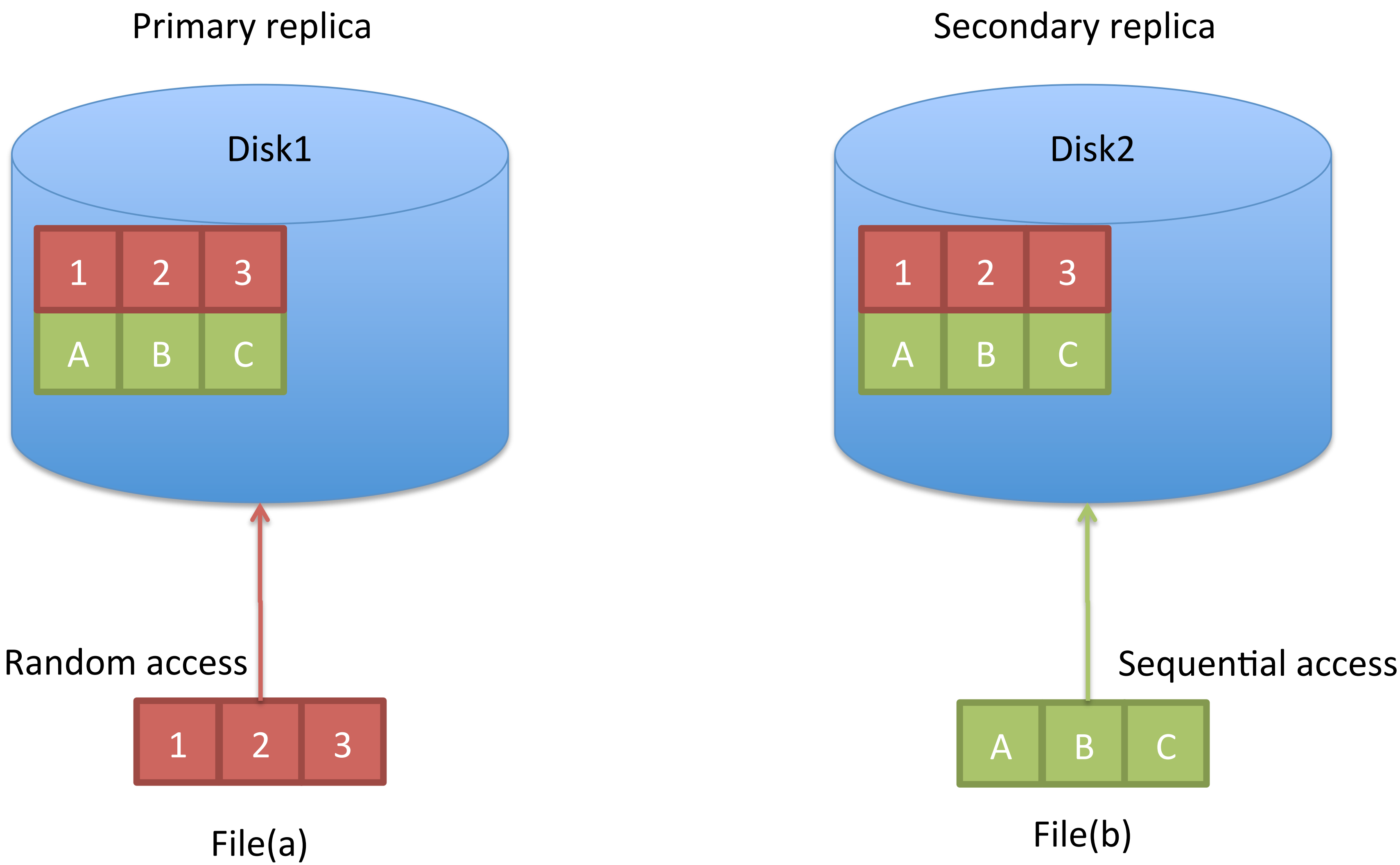

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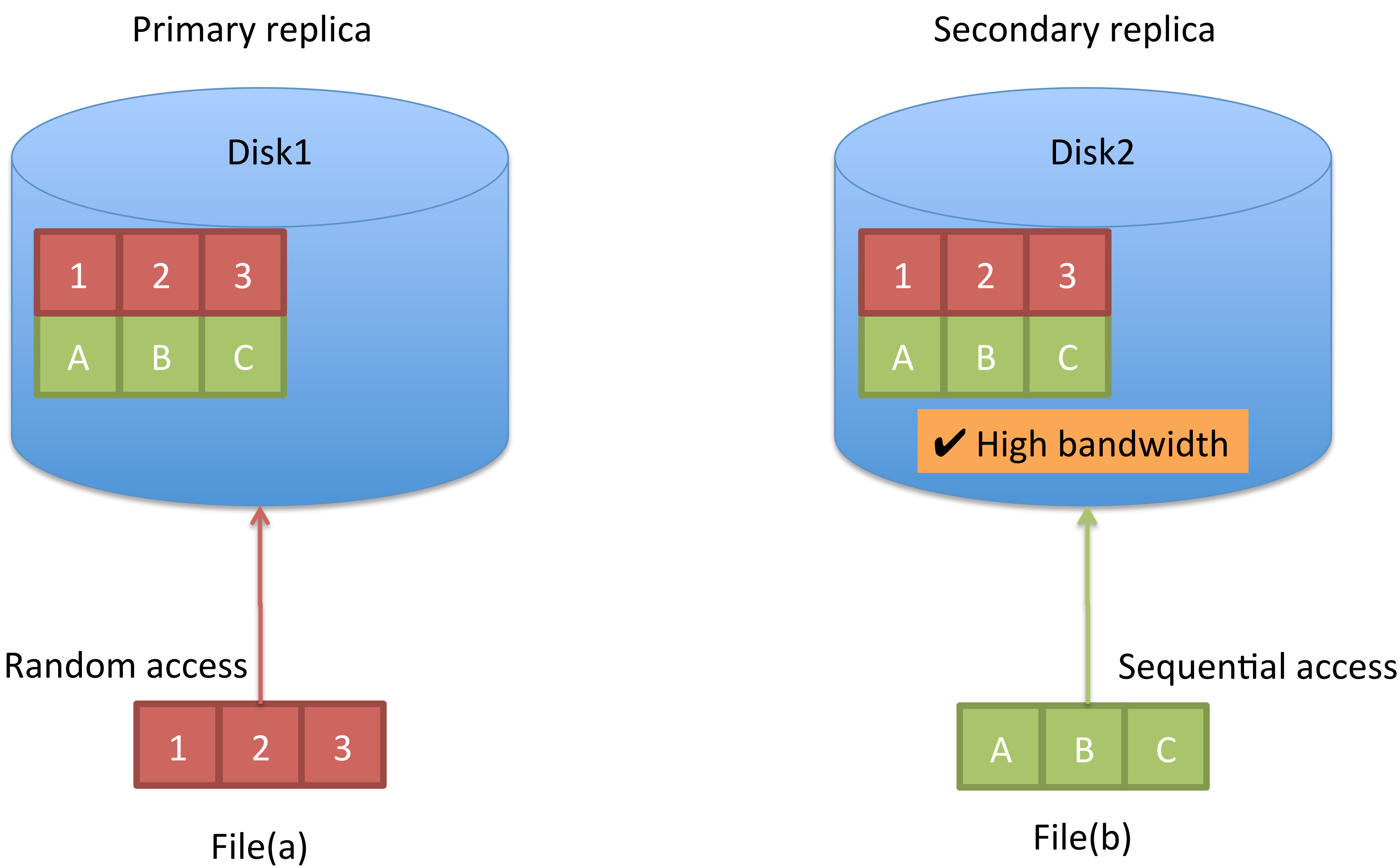


Implementation

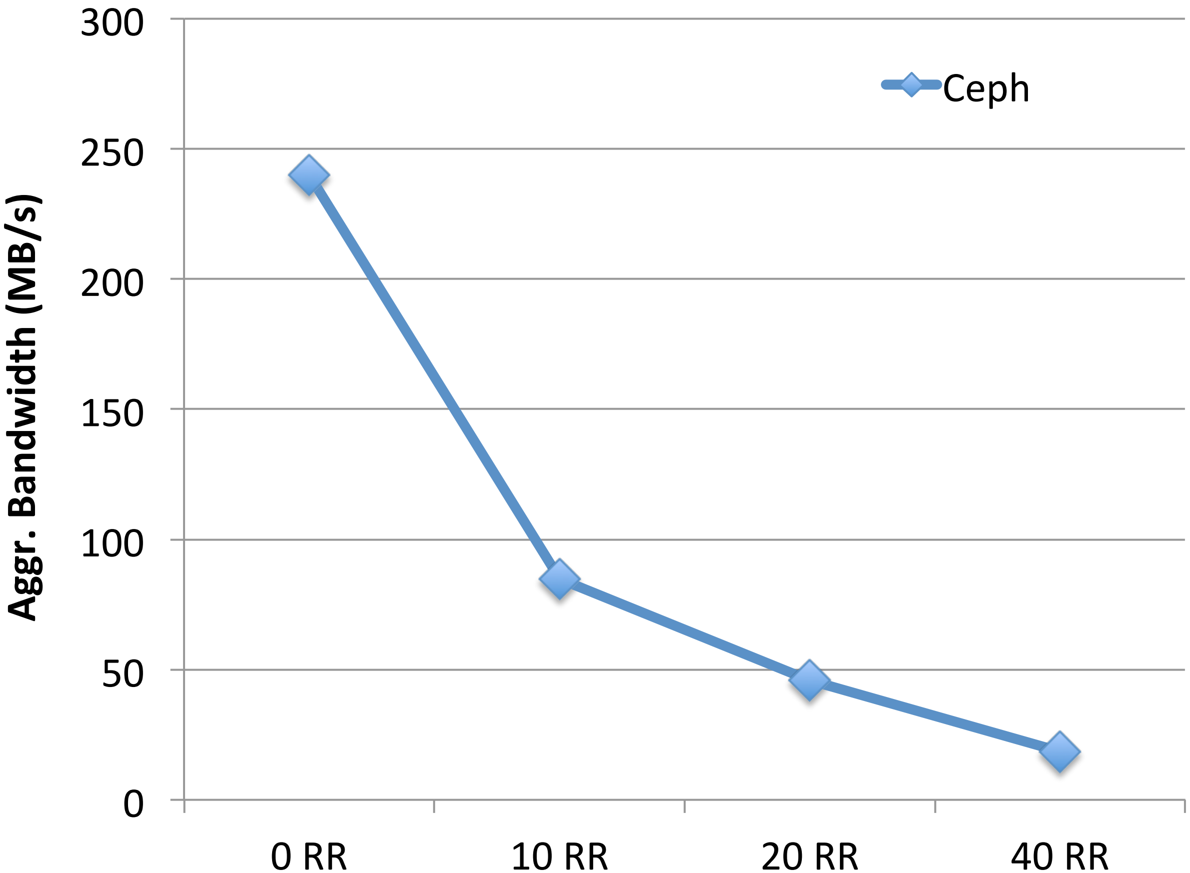
- Ceph: distributed storage system that implements replication
  - Use randomness in selecting replicas
- DIOS: modified Ceph with deterministic replica selections and request type-aware scheduling

Evaluation – Sequential Workloads

Workload:
20 sequential, mixing with different numbers of random workloads.

Total data disks: 6

Evaluation – Sequential Workloads



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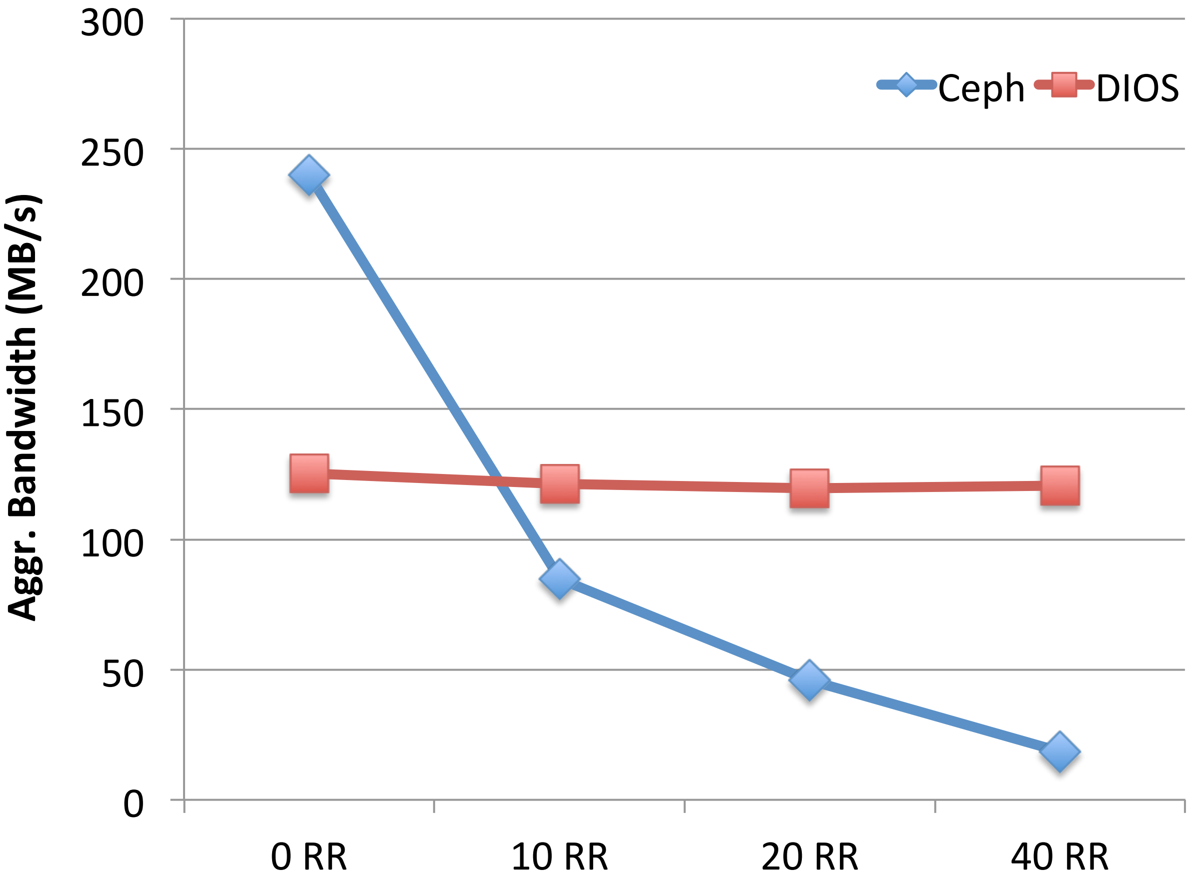

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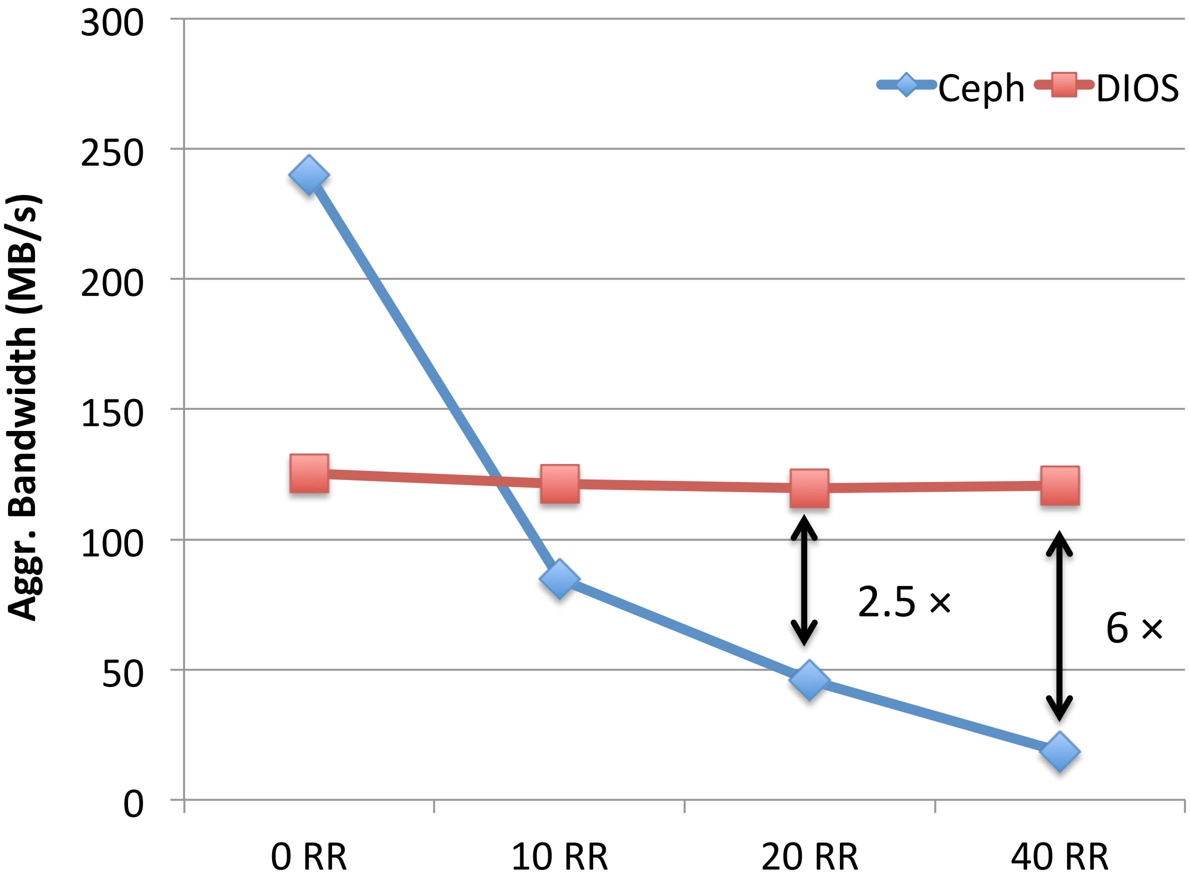

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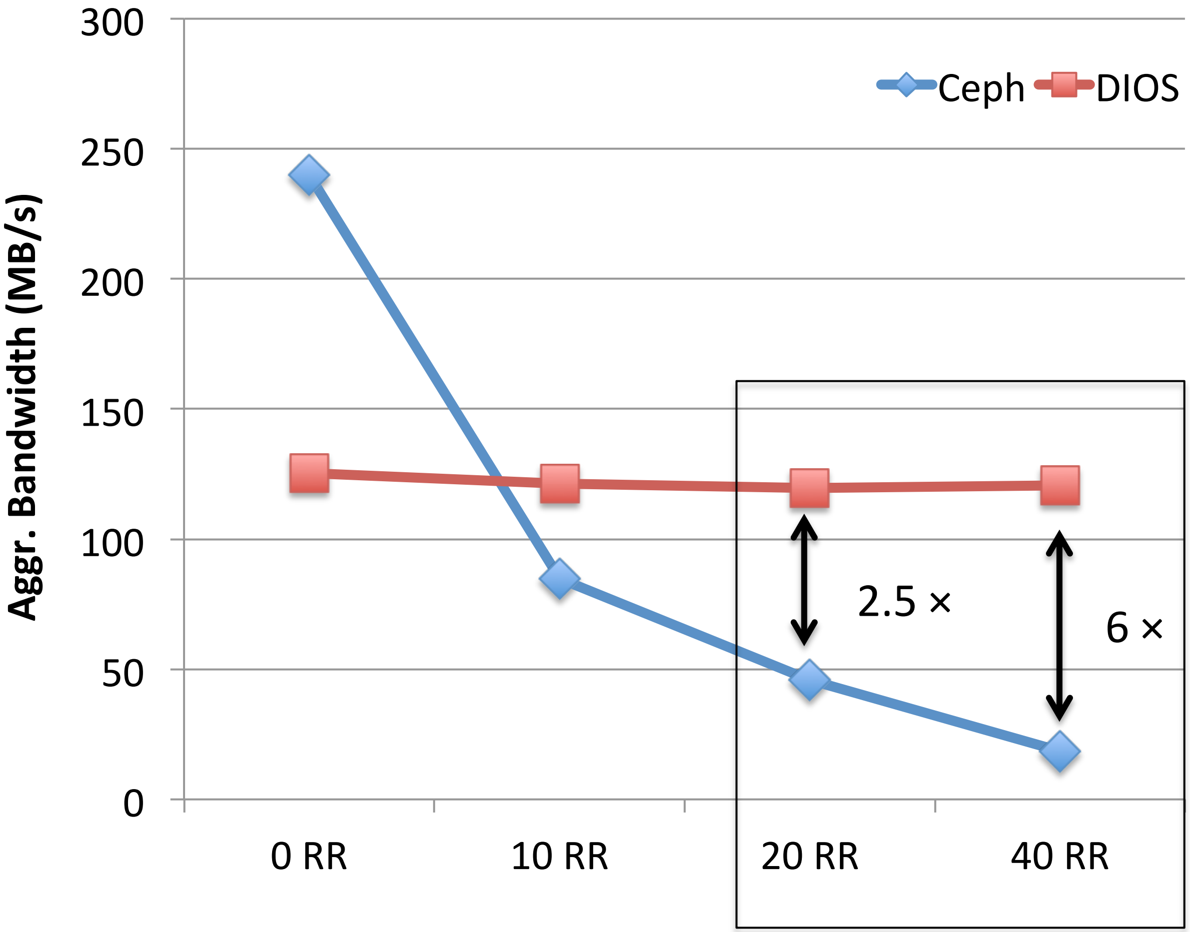

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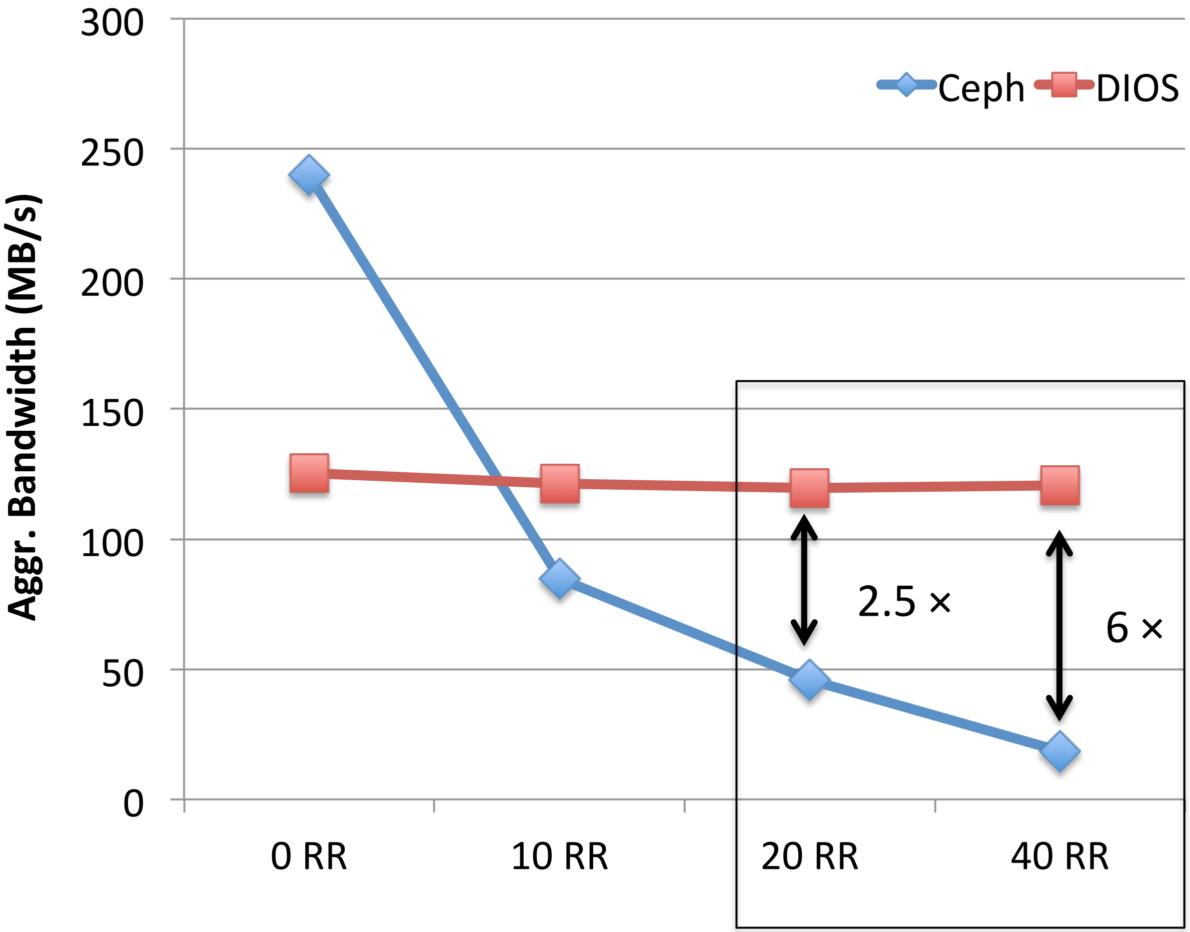

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DIOS:
- Consistent performance
- Higher bandwidth (disk util)

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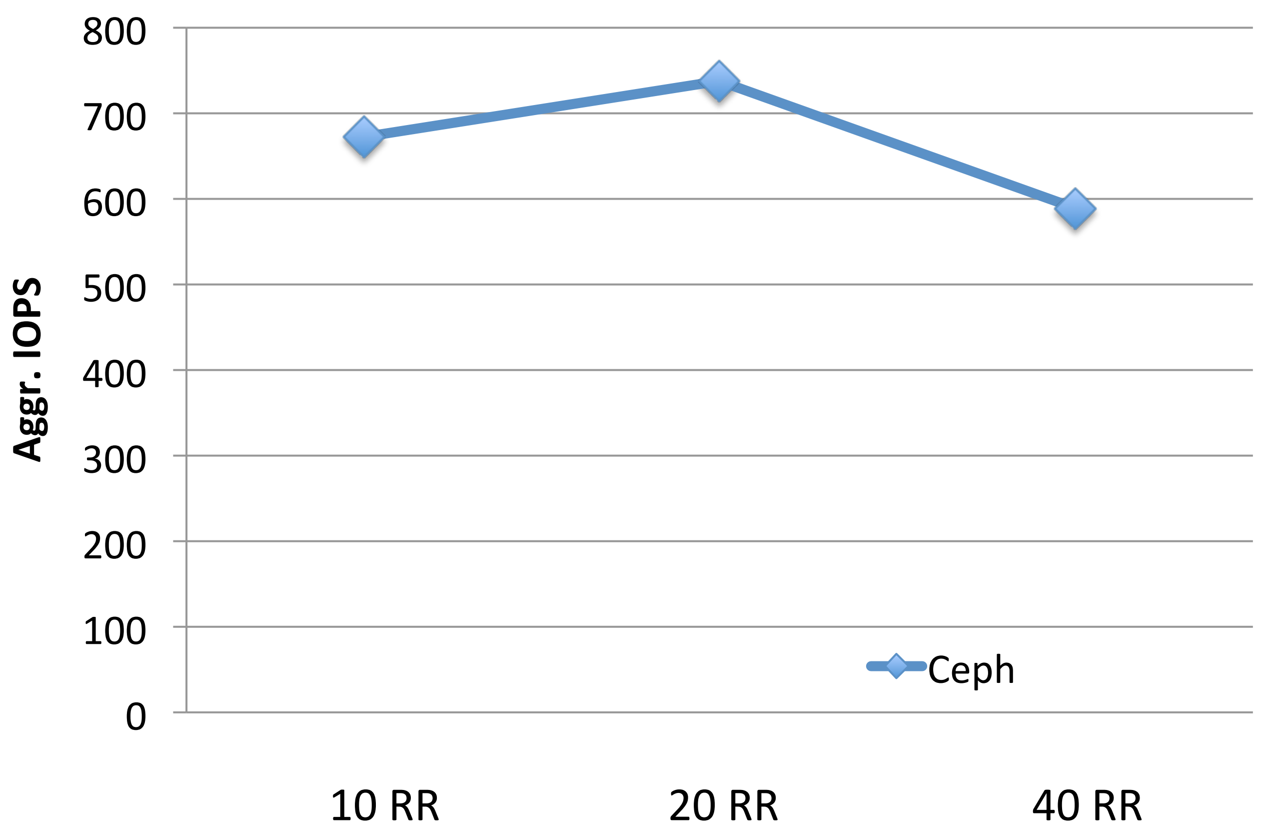

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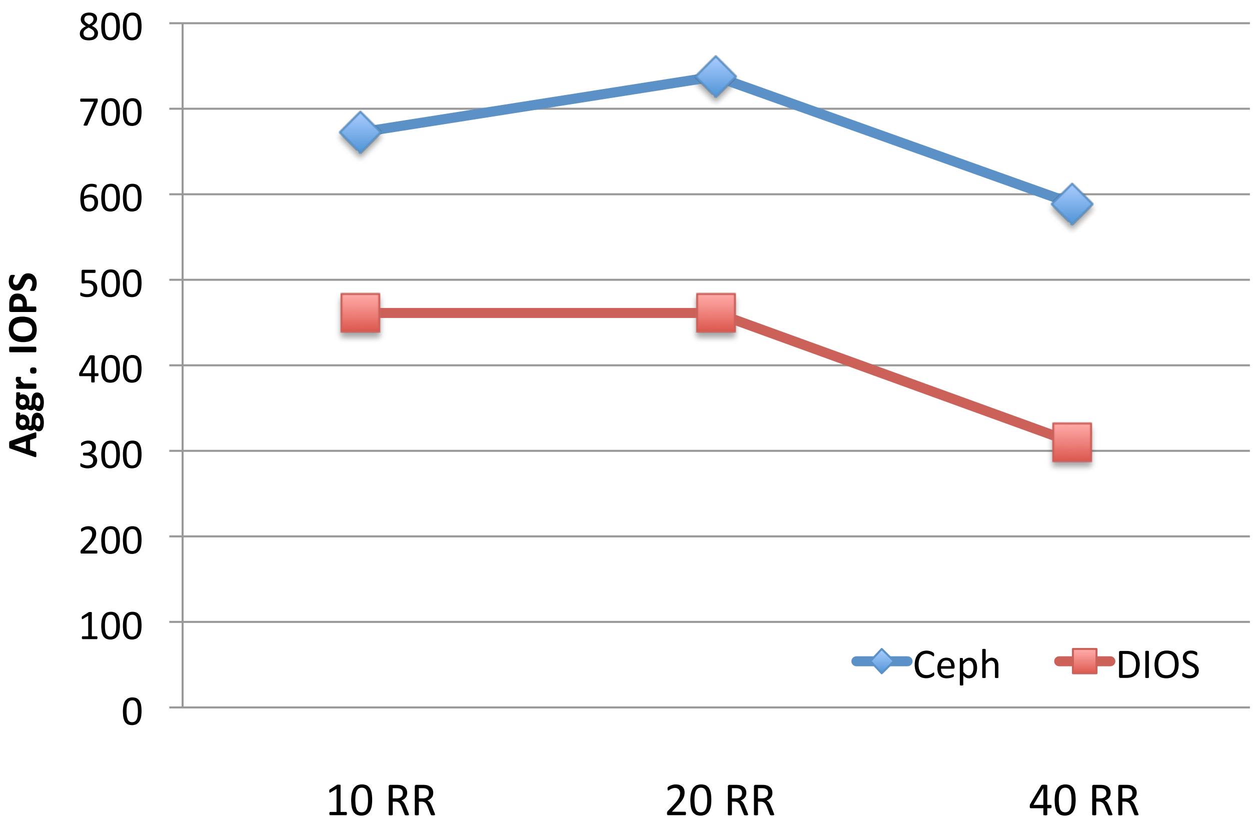

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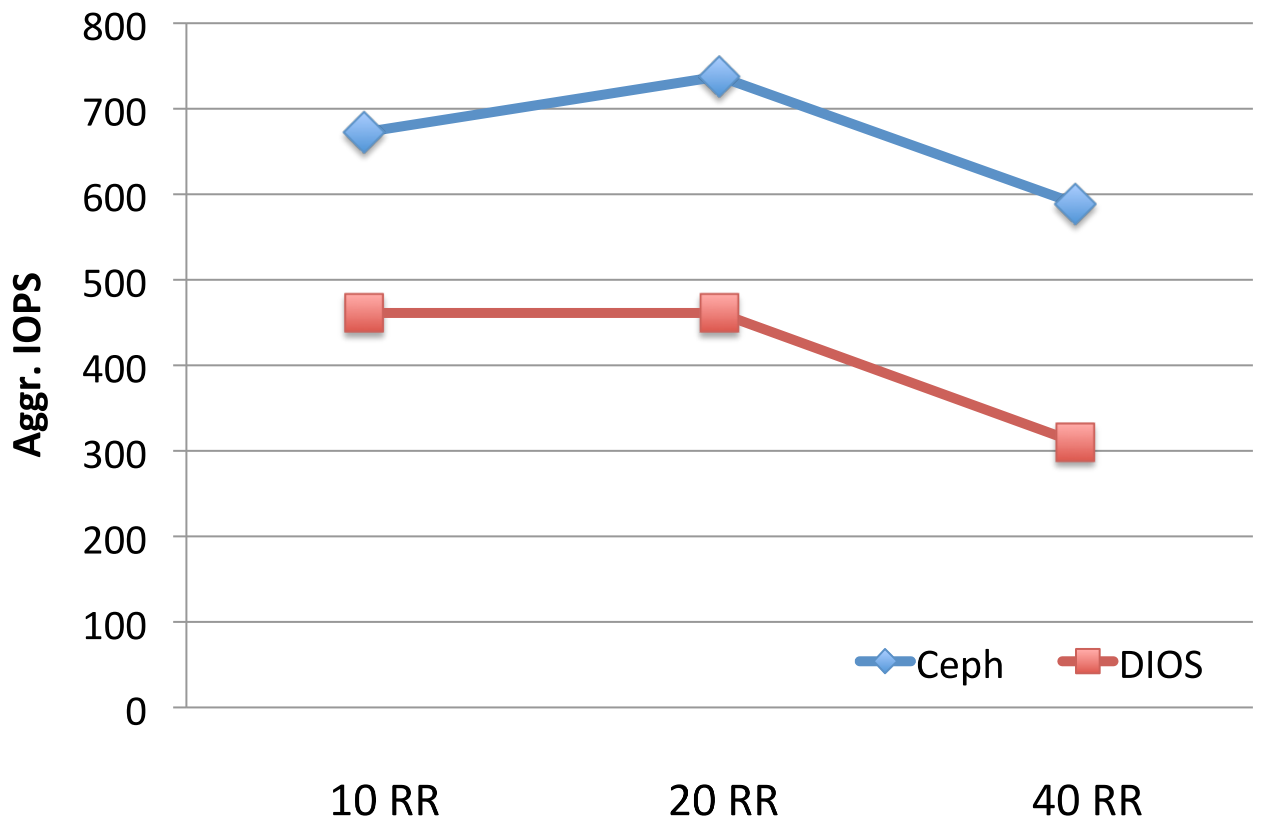

Half of disks are serving random workloads

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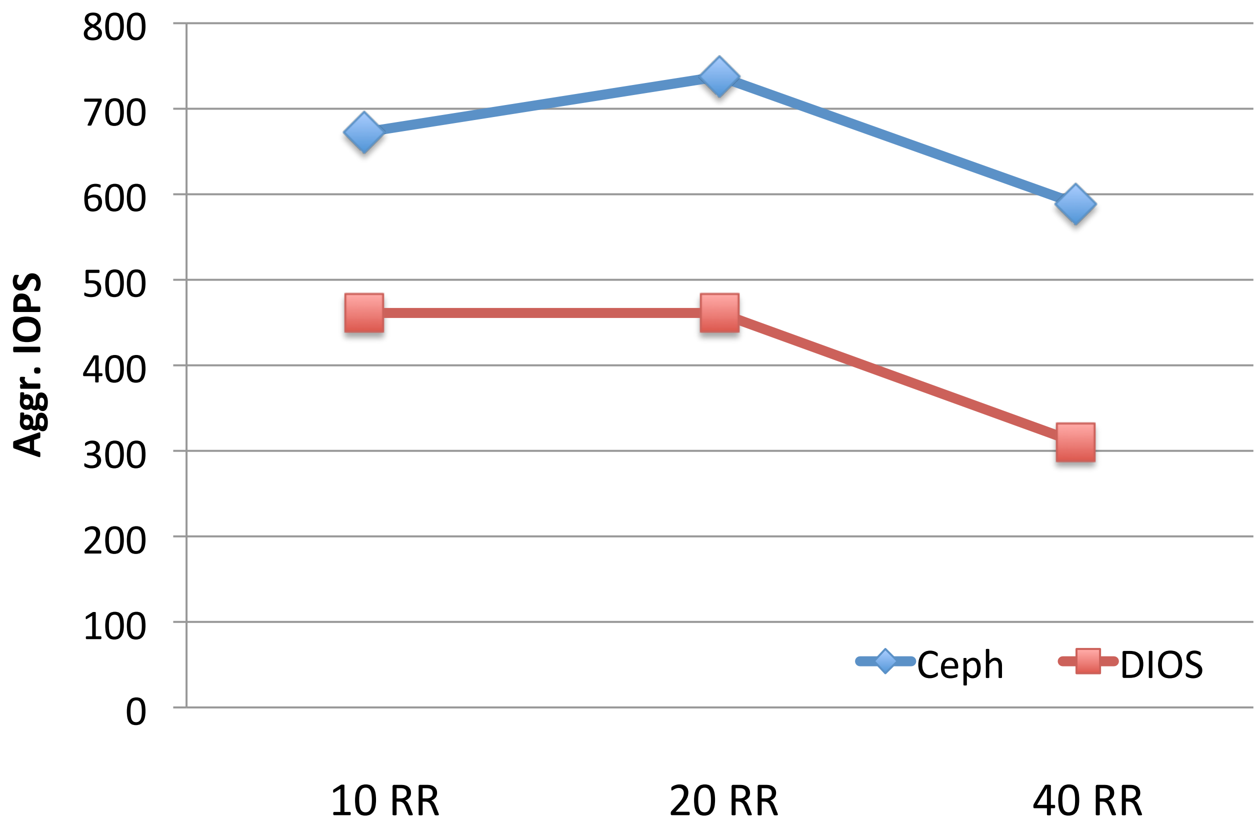

Half of disks are serving random workloads

High disk utilization for the other half of disks

Summary

- It is more ***efficient*** and leads to ***more predictable*** performance, by dedicating a disk to serve a single type of read requests.
- Future directions
  - Write workloads
  - Extension to 3-way replication (load balance)

Towards Fair Sharing of Block Storage in a Multi-tenant Cloud
Xing Lin, Yun Mao, Feifei Li, Robert Ricci
HotCloud '12: 4th USENIX Workshop on Hot Topics in Cloud Computing, June 2012

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- ✓ ***Conclusion***

Conclusion

- Problems:
  - Limitations in traditional compression and deduplication
  - Performance interference for cloud storage
- Use **similarity** in content and access patterns
  - Migratory compression: find **similarity** in block level and do re-organization
  - Deduplication: store **same** type of data blocks together
  - Differential IO scheduling: schedule **same** type of requests to same disk

Thesis Statement

Similarity in content and access patterns can be utilized to improve **space efficiency**,
by storing **similar** data together
and **performance predictability and efficiency**,
by scheduling **similar** IO requests to the same hard drive.

Acknowledgements

- **Advisor**, for ***always*** supporting my work
  - Robert Ricci
- **Committee members**, for providing feedback
  - Rajeev Balasubramonian
  - Fred Douglis
  - Feifei Li
  - Jacobus Van der Merwe
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Thank You !

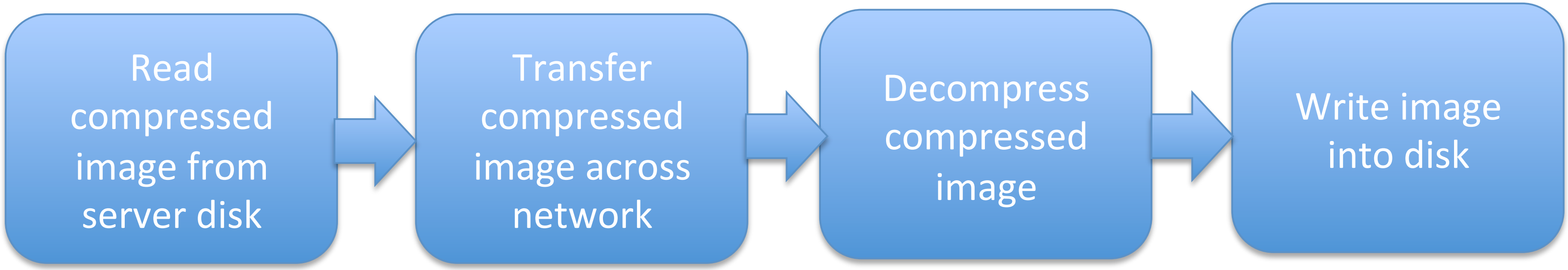
Backup Slides

VF - Related Work

- Deduplication analysis for virtual machine images [Jin SYSTOR '09]
  - **Benefit**: 70~80% of blocks are duplicates
  - Only analysis
- LiveDFS: deduplicating filesystem for storing disk images for OpenStack [Ng middleware '11]
  - Focus on spatial locality and metadata prefetching
  - Scales linearly and only 4 VMs; no compression
- Emustore: an early attempt for this project [Pullakandam Master Thesis 2011]
  - Compression during image deployment
  - Used regular fixed-size chunking

Disk Image Deployment Pipeline

- Compression factor is 3.18X for this image
- Available network bandwidth: 500 Mb/s (60 MB/s)



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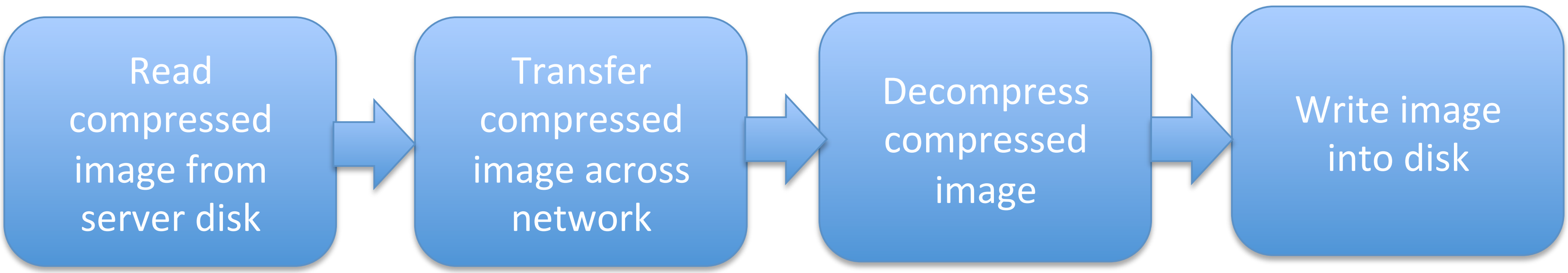

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Effective throughput (uncompressed data) (MB/s)

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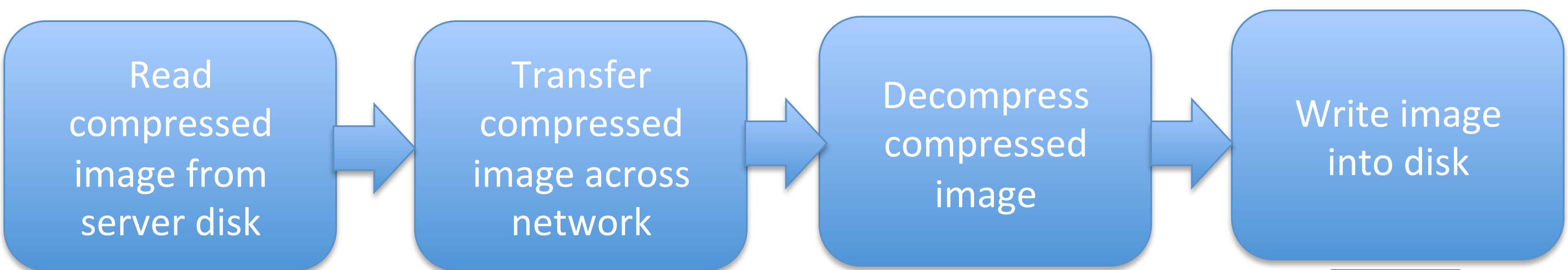

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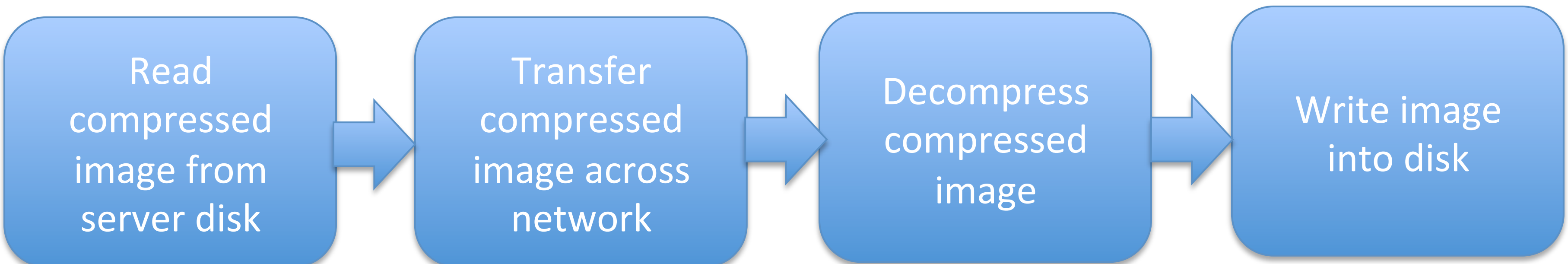

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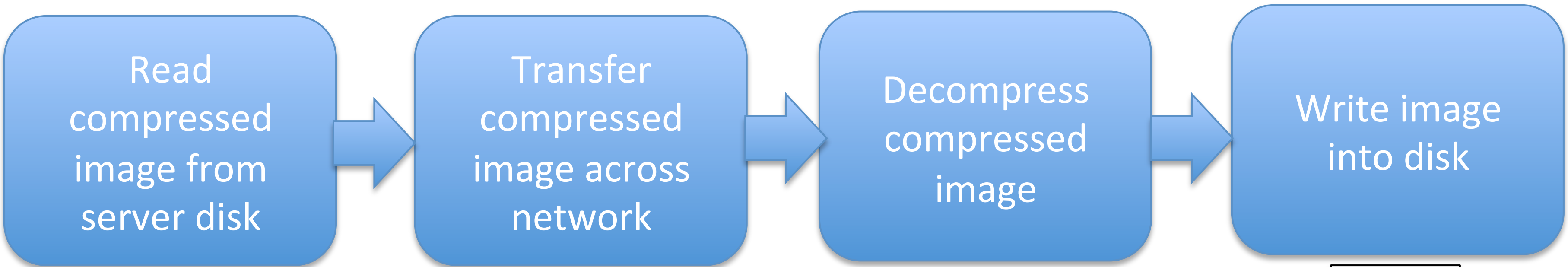

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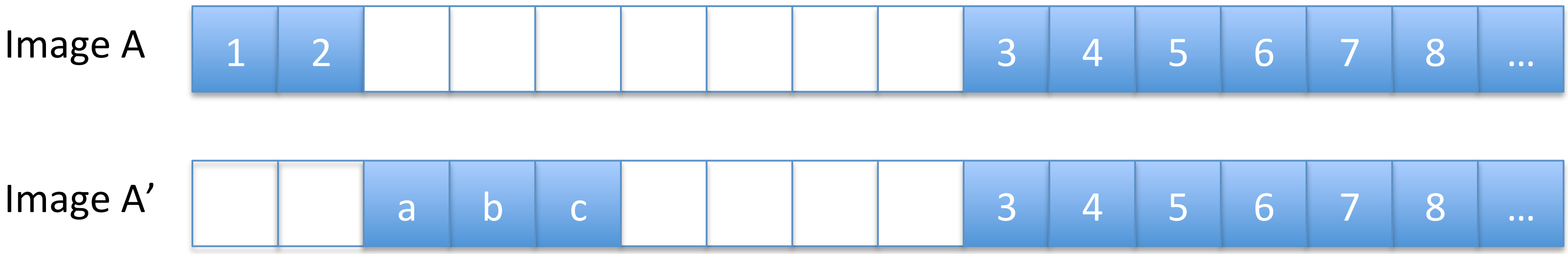

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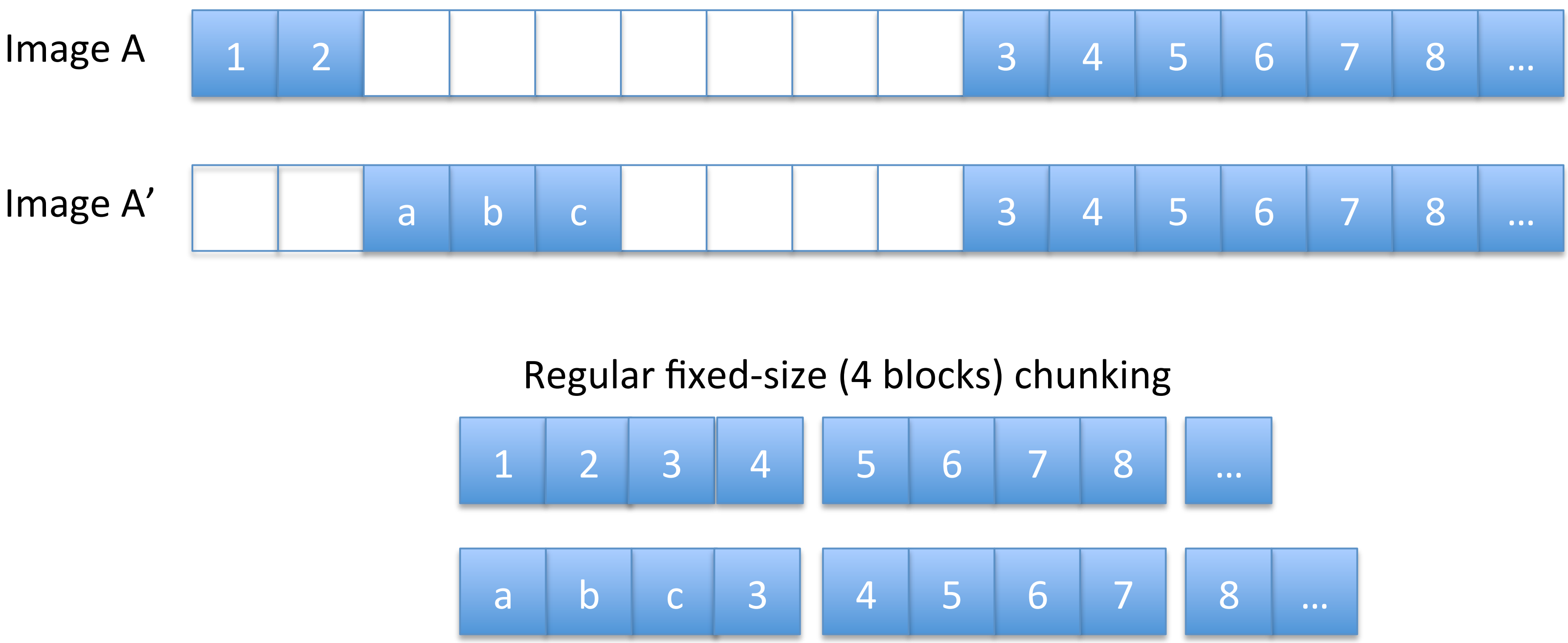

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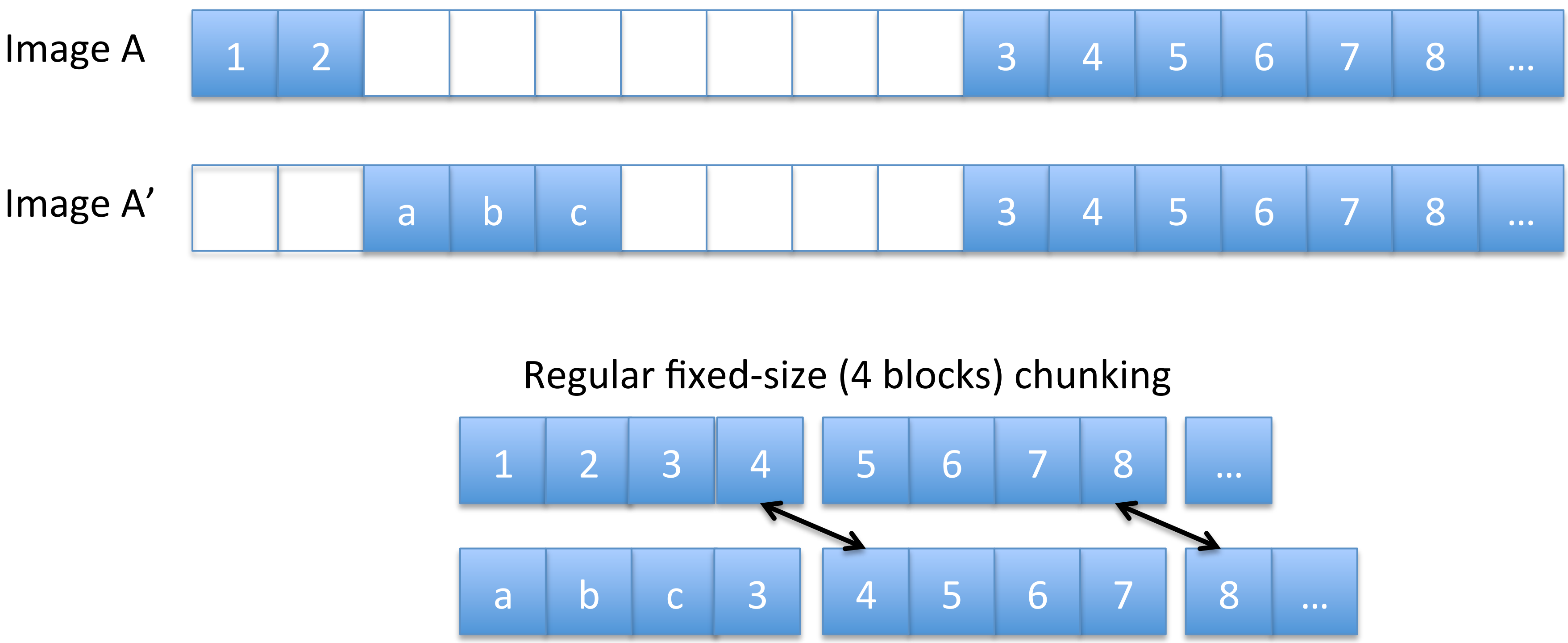

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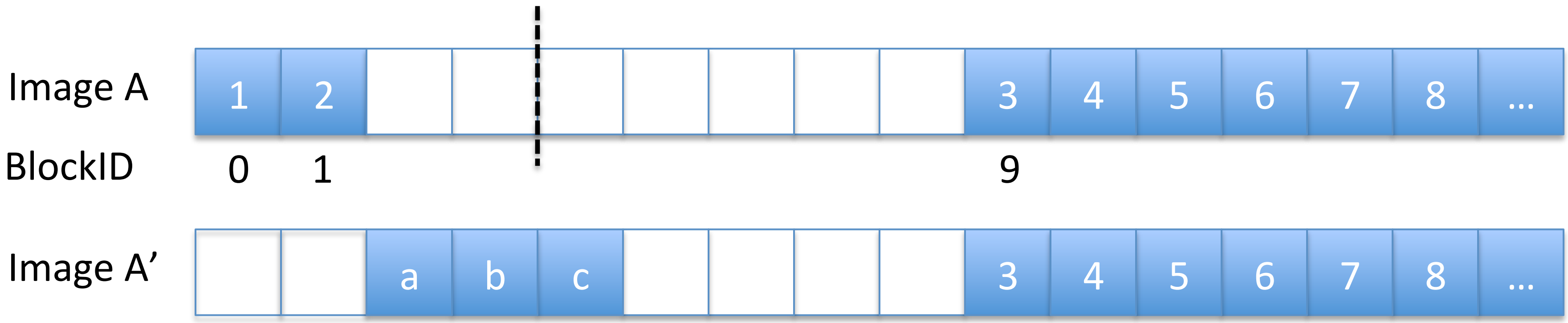

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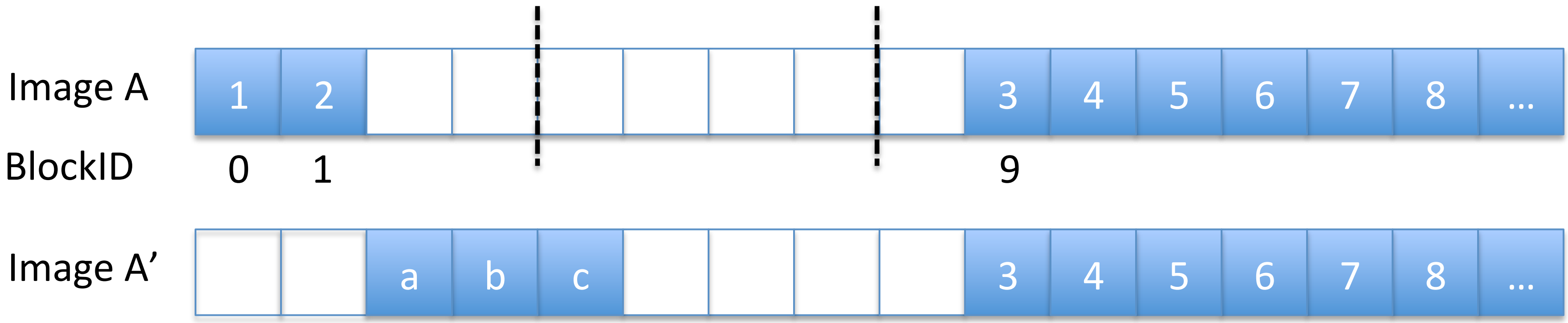

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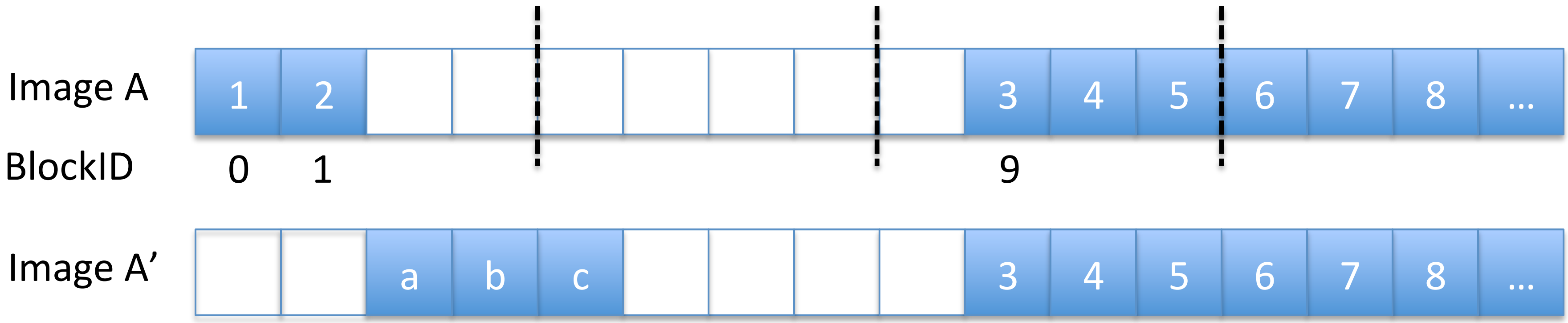

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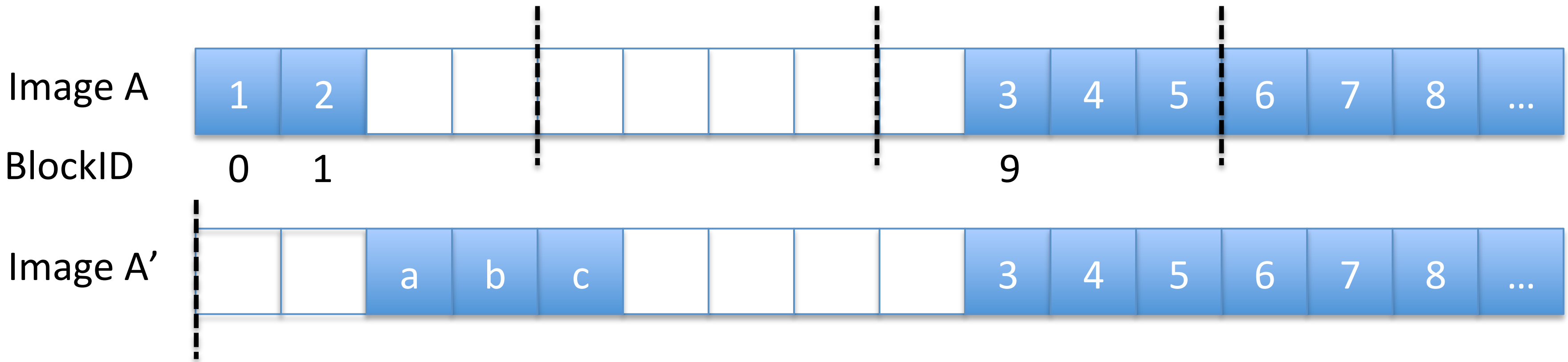

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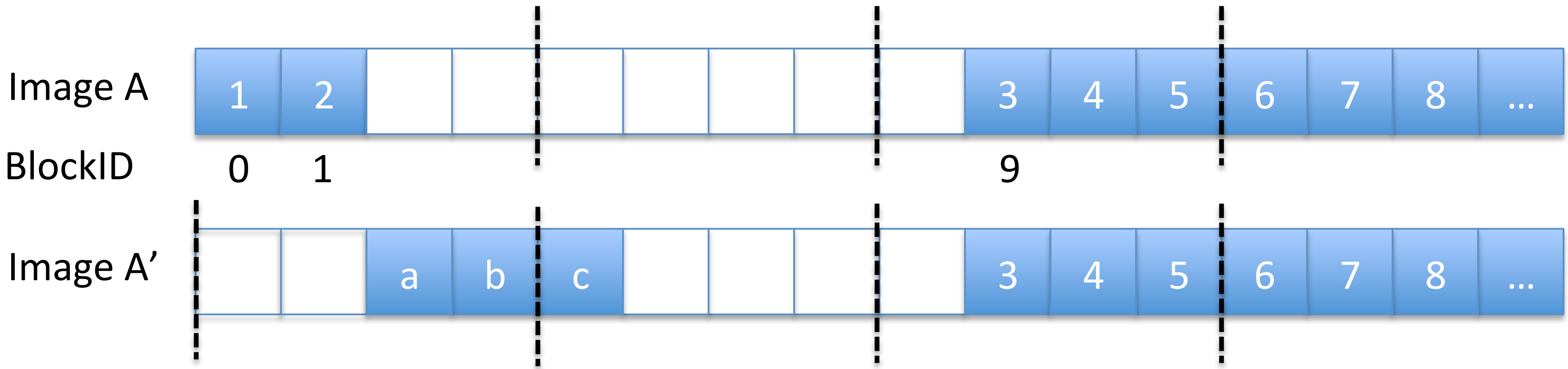

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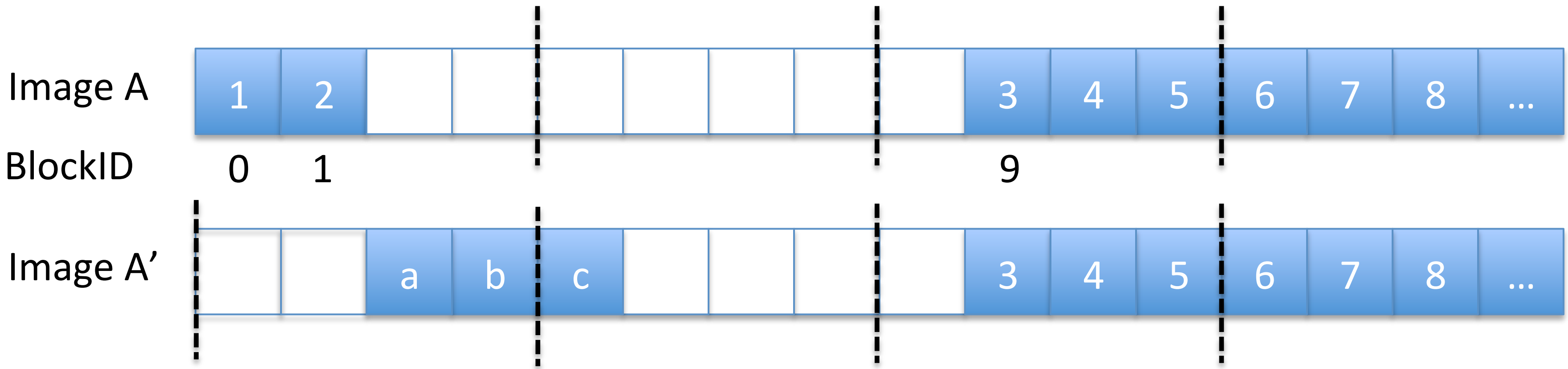

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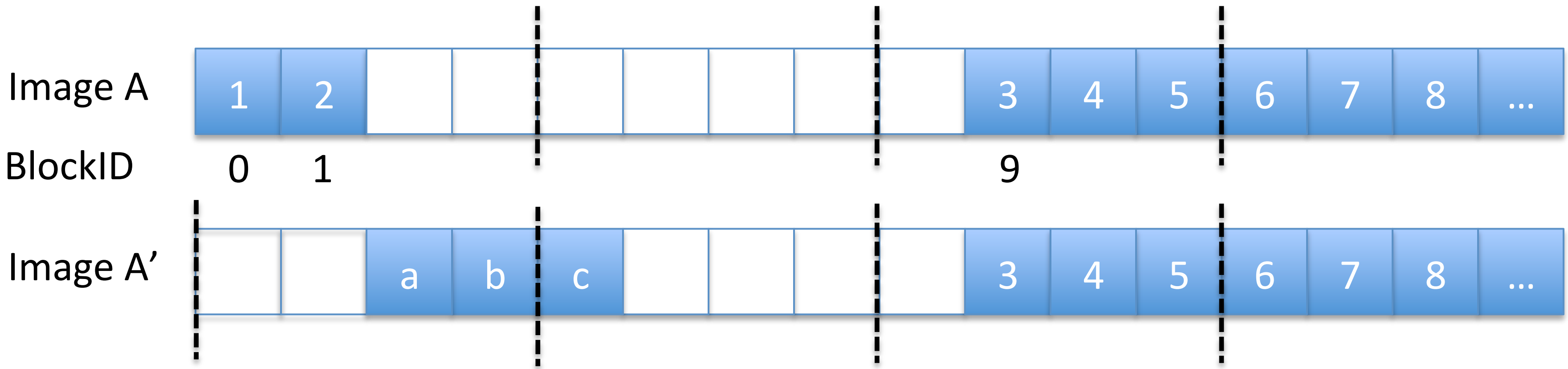

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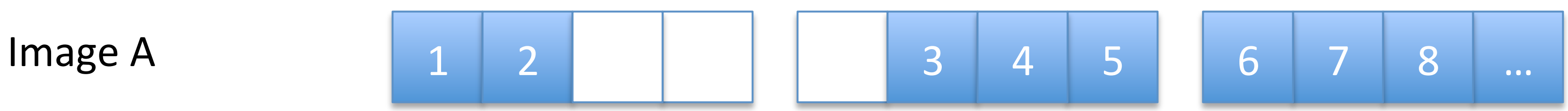

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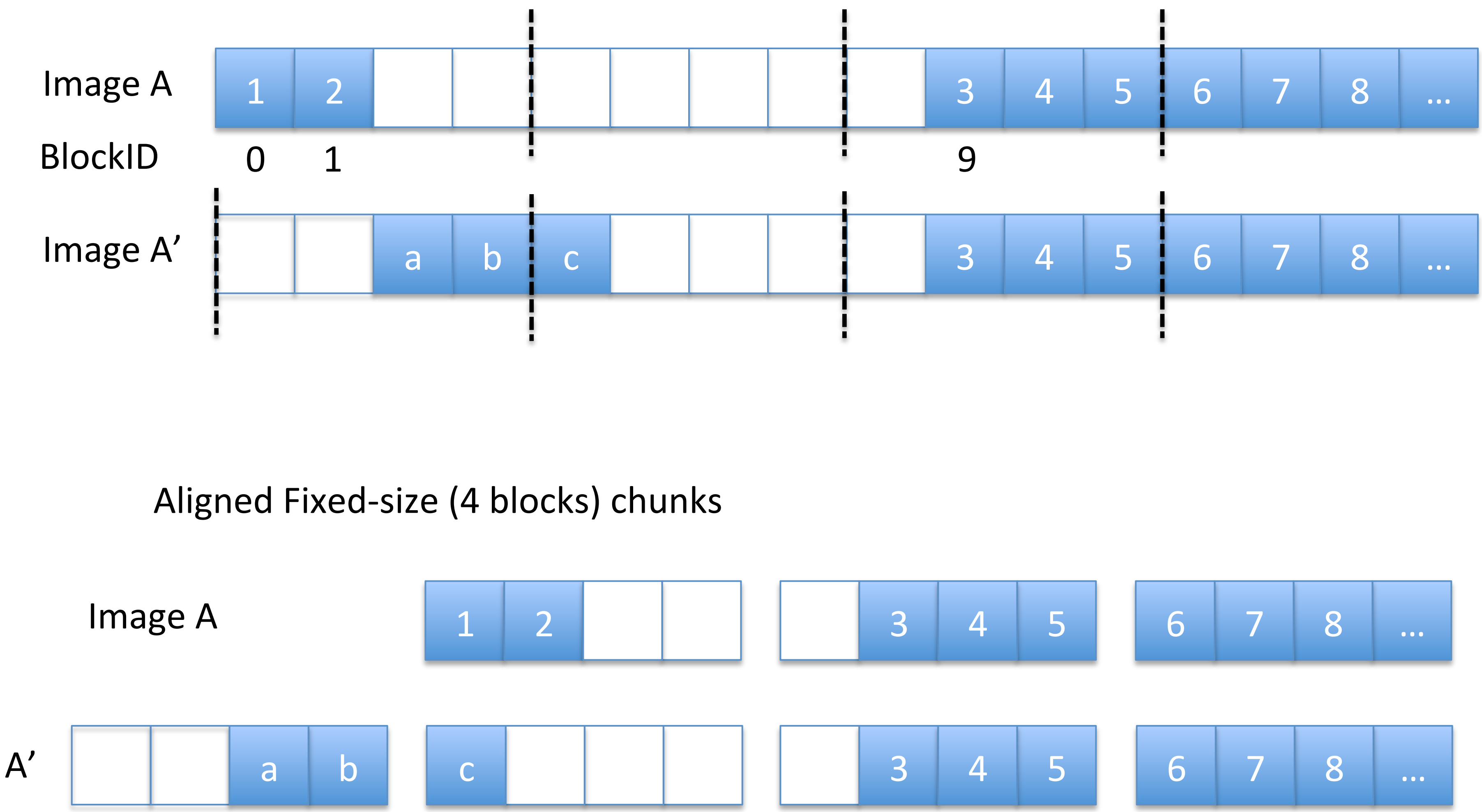

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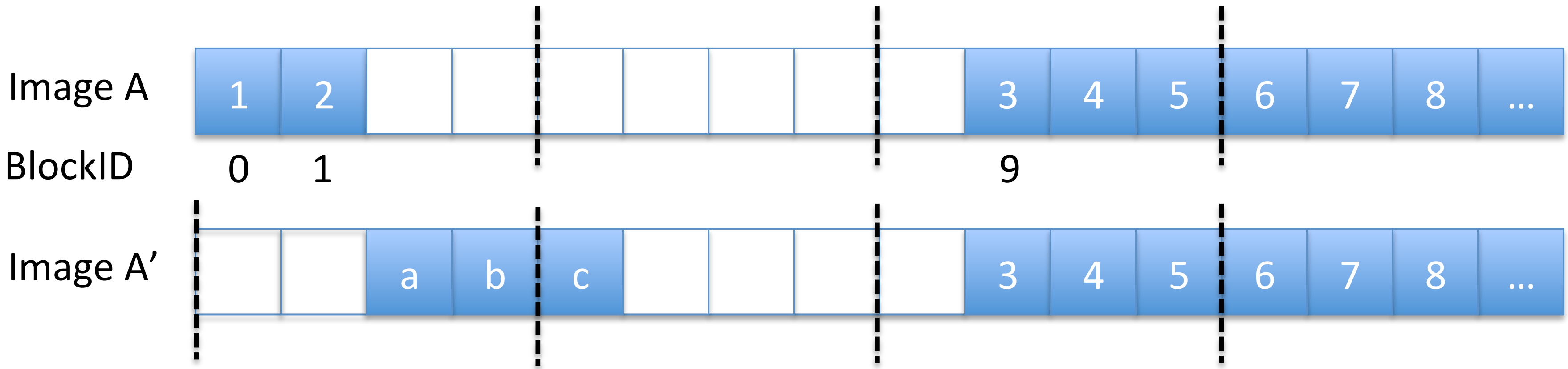

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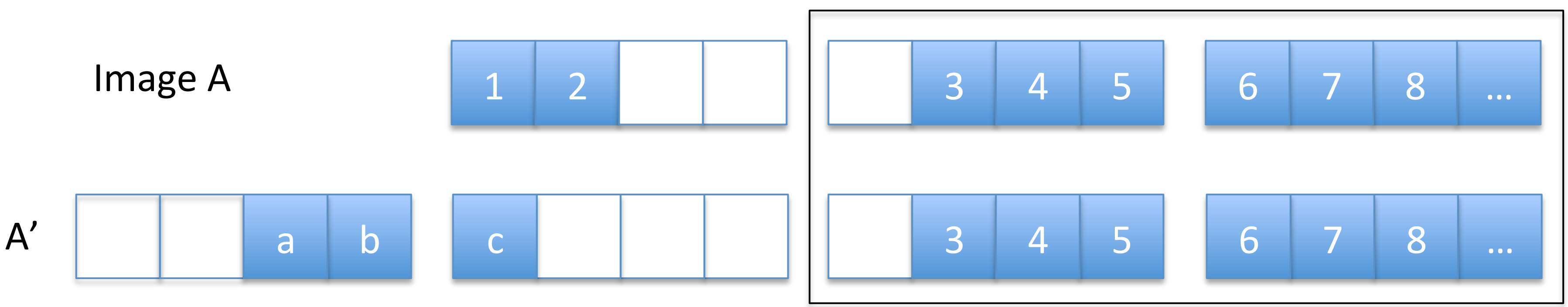

AFC - Evaluation