Deduplication: Overview & Case Studies

CSCI 333
Williams College

Lecture Outline

- Background
  - Content Addressable Storage (CAS)
  - Deduplication
    - Chunking
    - The Index
  - Other CAS applications

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Content Addressable Storage (CAS)

Deduplication systems often rely on Content Addressable Storage (CAS)

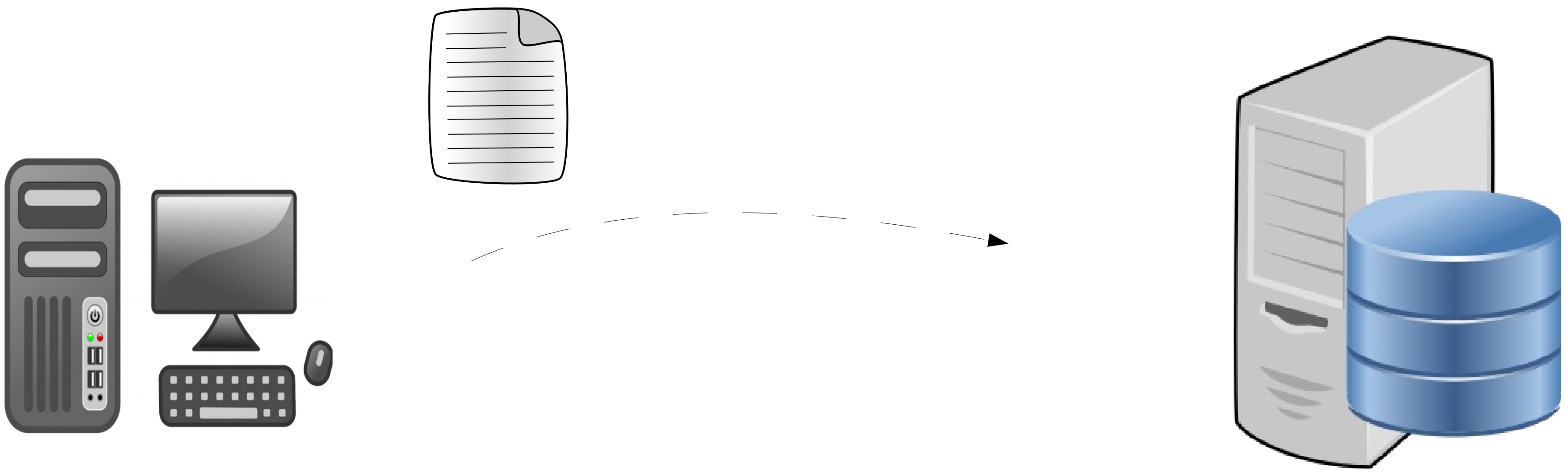
Data is indexed by some **content identifier**

The **content identifier** is determined by some function over the data itself
- often a cryptographically strong hash function

CAS

Example:

I send a document to be stored remotely
on some content addressable storage



CAS

Example:

The server receives the document, and calculates a unique identifier called the data's **fingerprint**

CAS

The **fingerprint** should be:

unique to the data
- *NO* collisions

one-way
- hard to invert

CAS

The **fingerprint** should be:

unique to the data
- *NO* collisions

one-way
- hard to invert

10^{24} objects before it is more likely than not that a collision has occurred

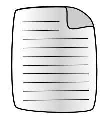
SHA-1:

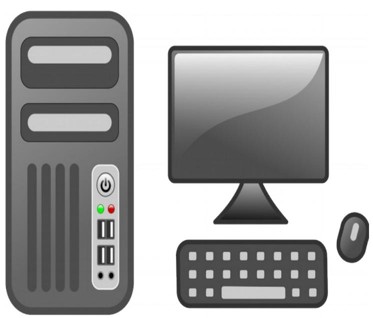
20 bytes (160 bits)

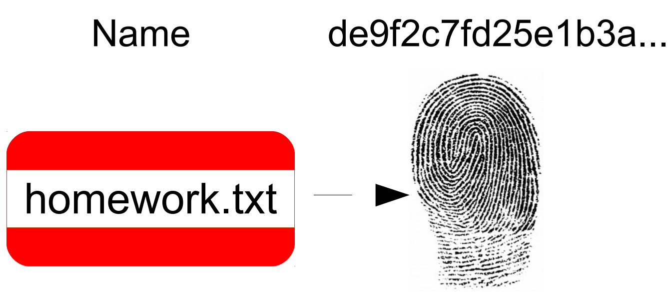
$P(\text{collision}(a,b)) = (½)^{160}$
$\text{coll}(N, 2^{160}) = ({}_N C_2)(½)^{160}$

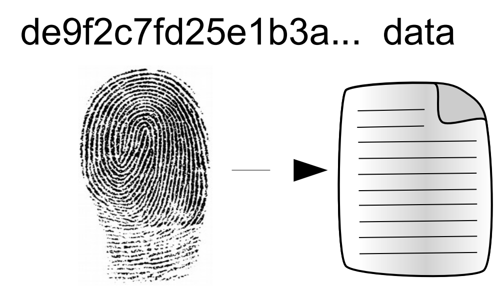
CAS

Example:

SHA-1() = de9f2c7fd25e1b3a...



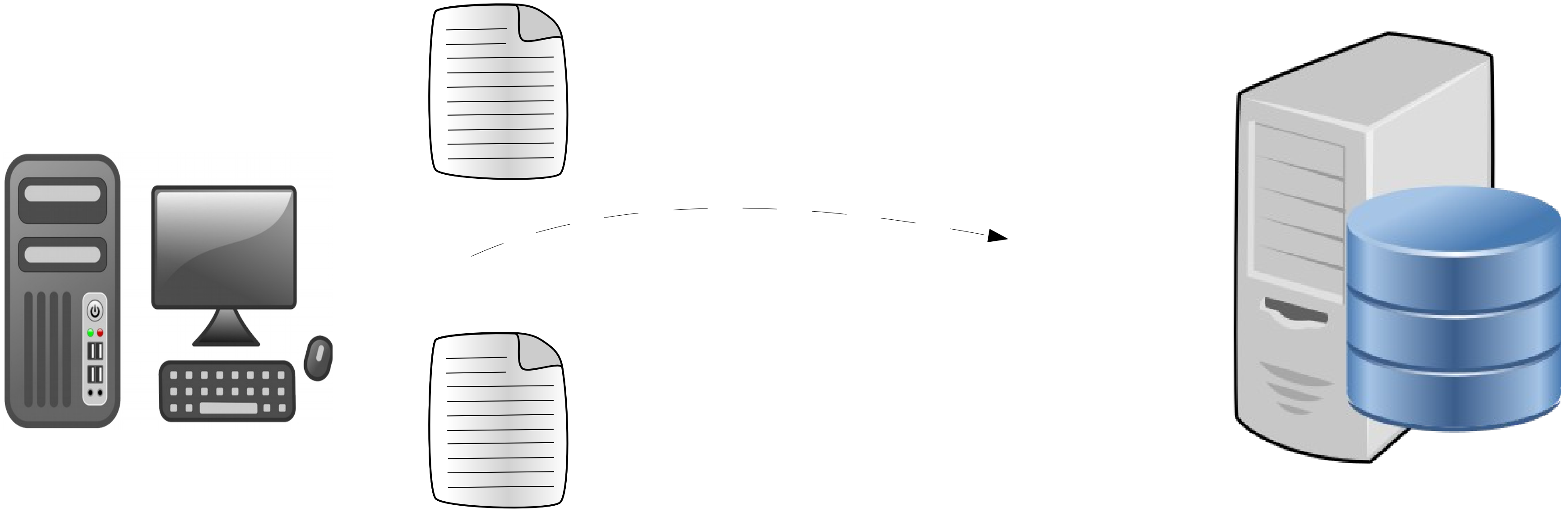




CAS

Example:

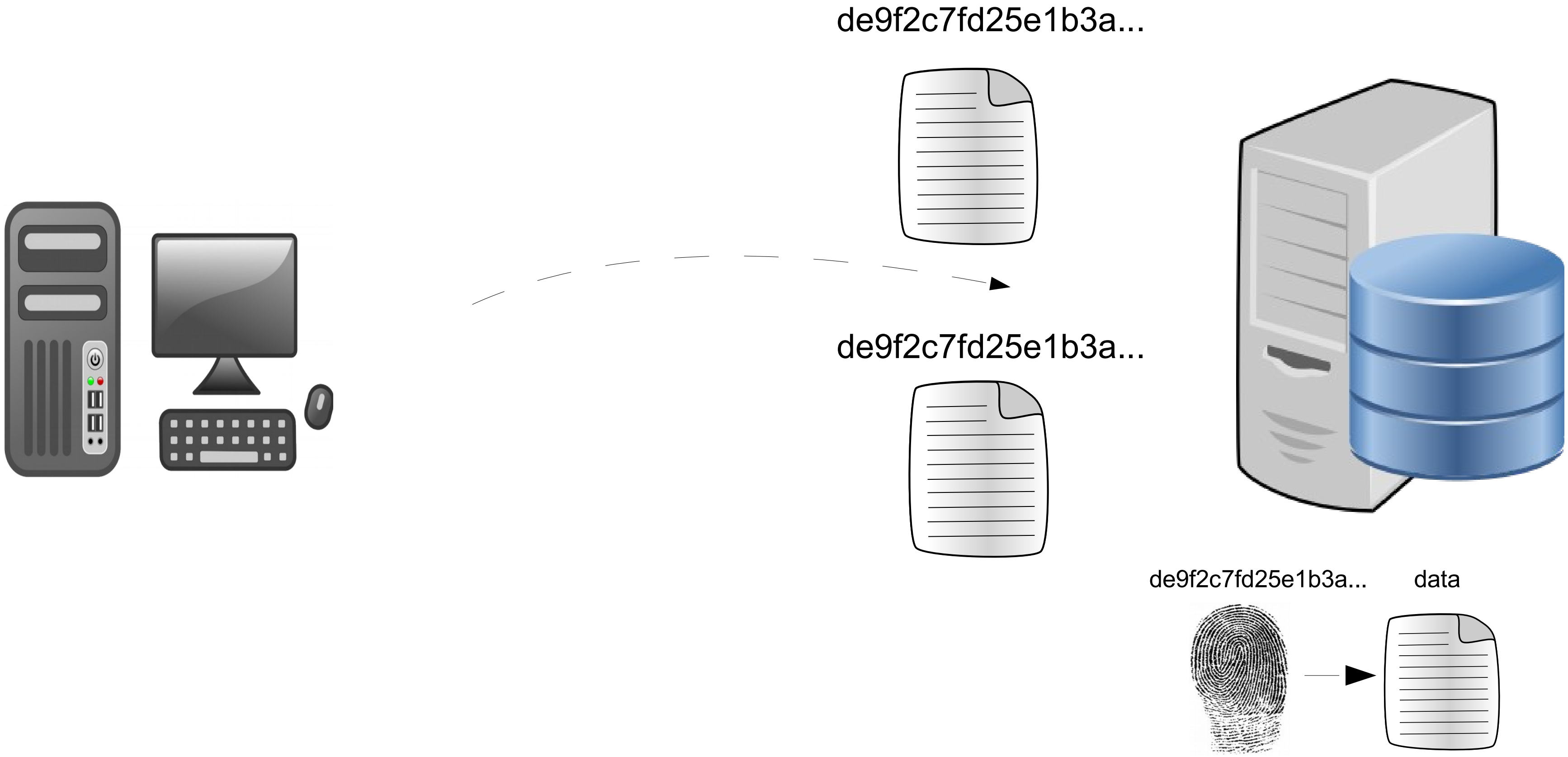
I submit my homework, and my “buddy”
Harold also submits my homework...



CAS

Example:

Same contents, same fingerprint.

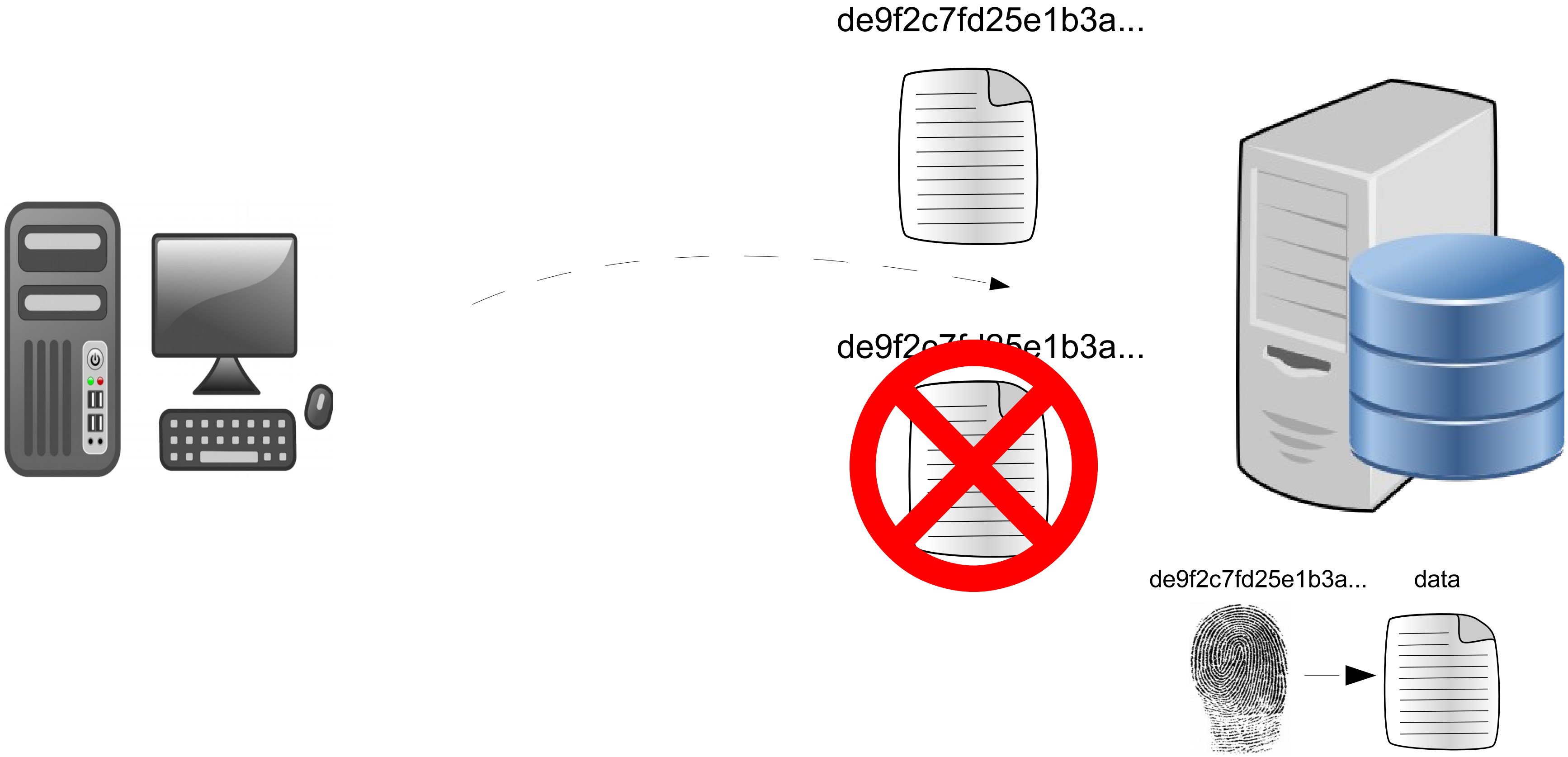


CAS

Example:

Same contents, same fingerprint.

The data is only stored once!



Background

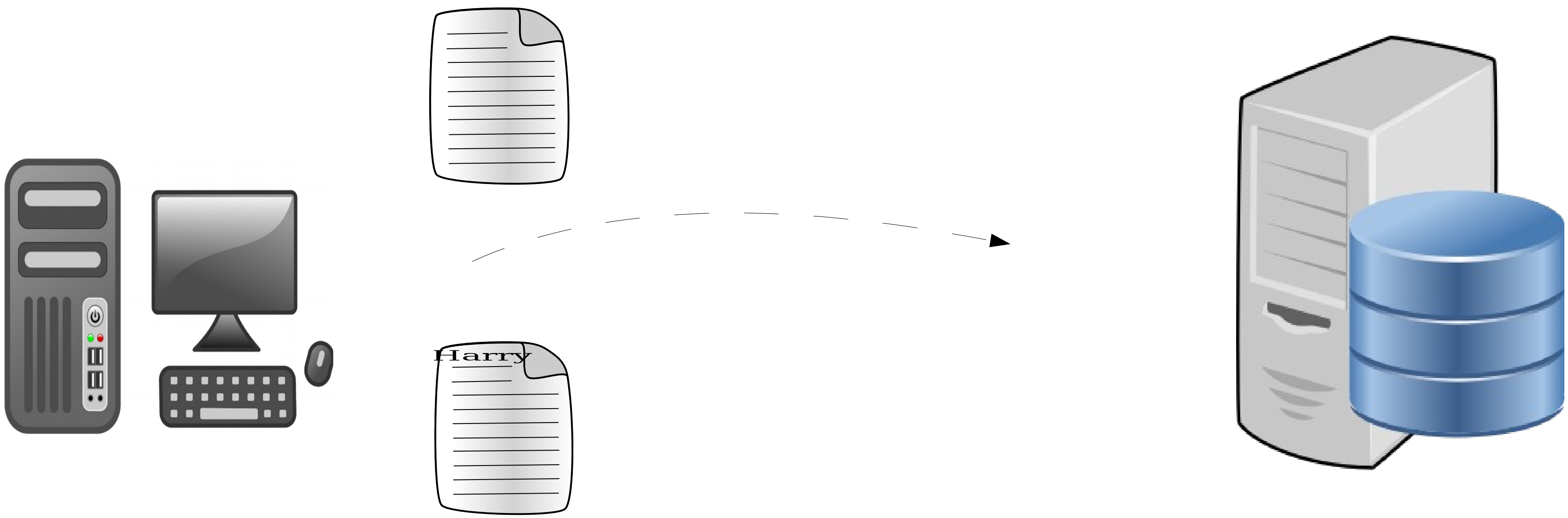
Background

- Content Addressable Storage (CAS)
- **Deduplication**
  - Chunking
  - The Index
- Other applications

CAS

Example:

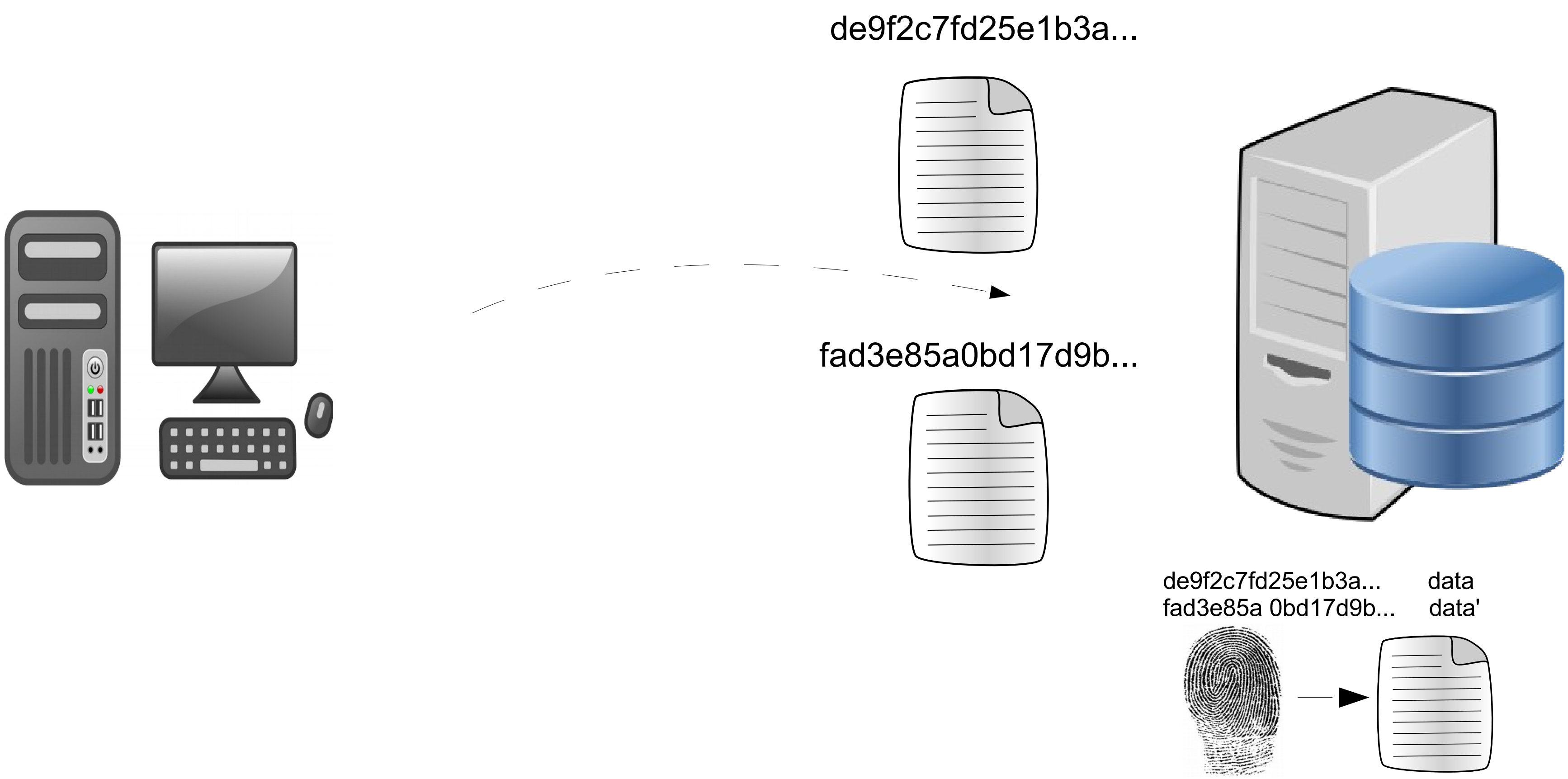
Now suppose Harry writes his name at the top of my document.



CAS

Example:

The fingerprints are completely different, despite the (mostly) identical contents.



CAS

Problem Statement:

What is the appropriate granularity to address our data?

What are the tradeoffs associated with this choice?

Background

Background

- Content Addressable Storage (CAS)
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Deduplication

Chunking breaks a data stream into segments

SHA1(DATA) becomes

SHA1(CK1) + SHA1(CK2) + SHA1(CK3)

How do we divide a data stream?

How do we reassemble a data stream?

Deduplication

Division.

Option 1: fixed-size blocks

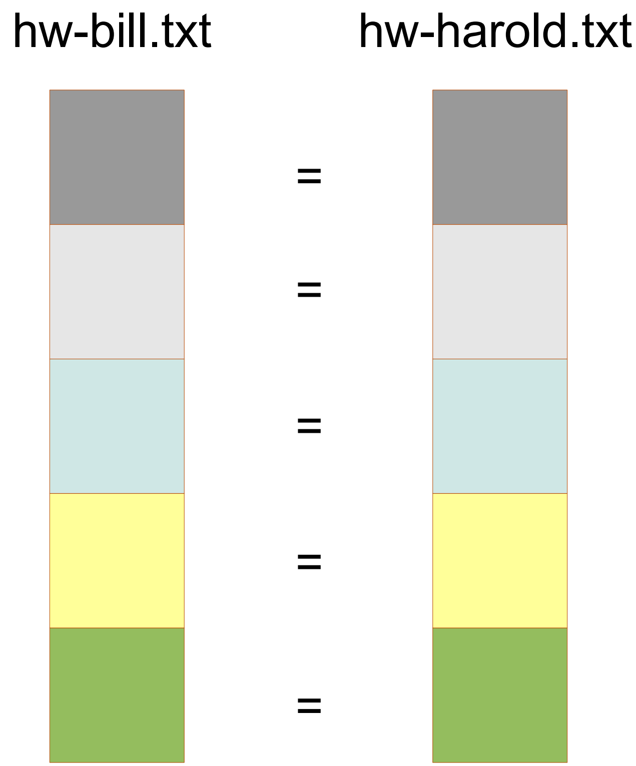
- Every (?)KB, start a new chunk

Option 2: variable-size chunks

- Chunk boundaries dependent on chunk contents

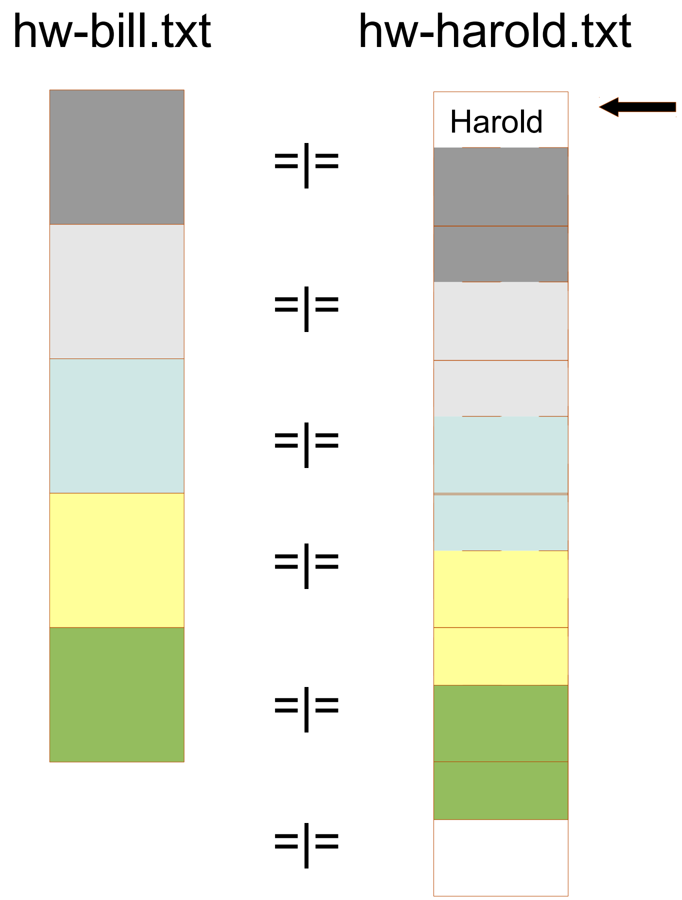
Deduplication

Division: fixed-size blocks



Deduplication

Division: fixed-size blocks



Suppose Harold adds his name to the top of my homework

This is called the **boundary shifting problem**.

Deduplication

Division.

Option 1: fixed-size blocks

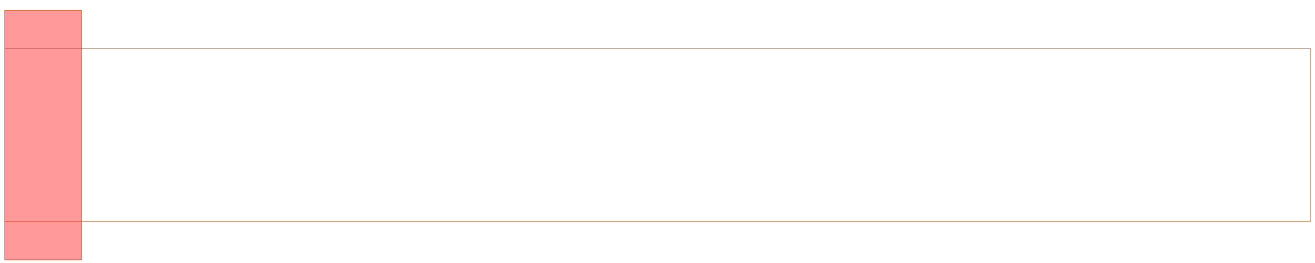
- Every 4KB, start a new chunk

Option 2: variable-size chunks

- Chunk boundaries dependent on chunk contents

Deduplication

Division: variable-size chunks



<u>parameters:</u>

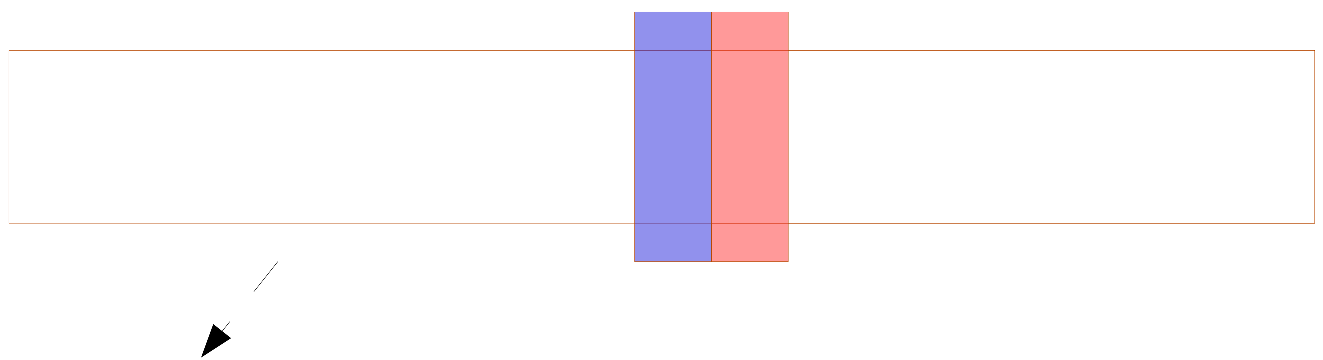
Window of width *w*
Target pattern *t*

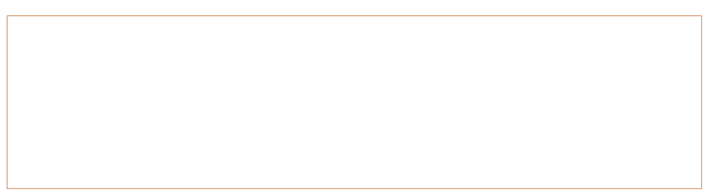
- Slide the window byte by byte across the data, and compute a window fingerprint at each position.

- If the fingerprint matches the target, *t*, then we have a **fingerprint match** at that position

Deduplication

Division: variable-size chunks





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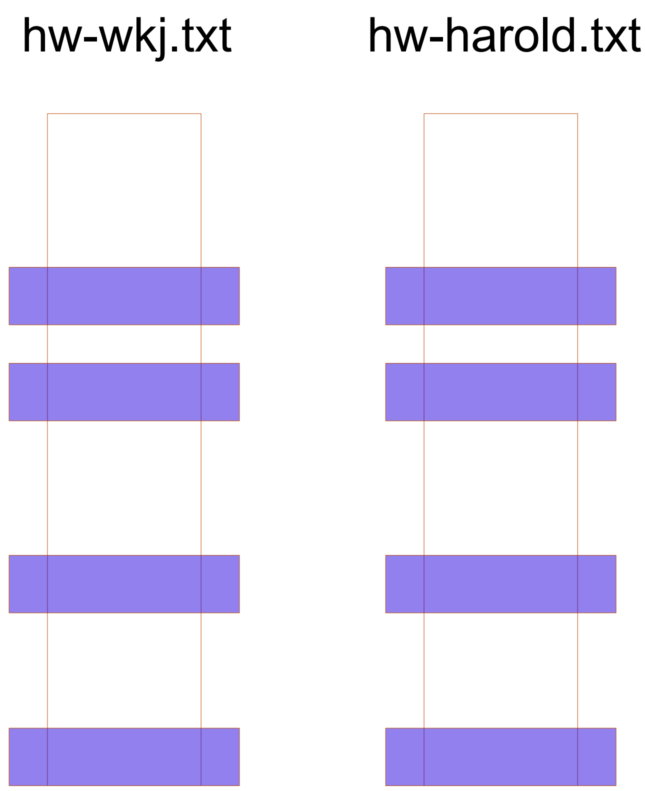
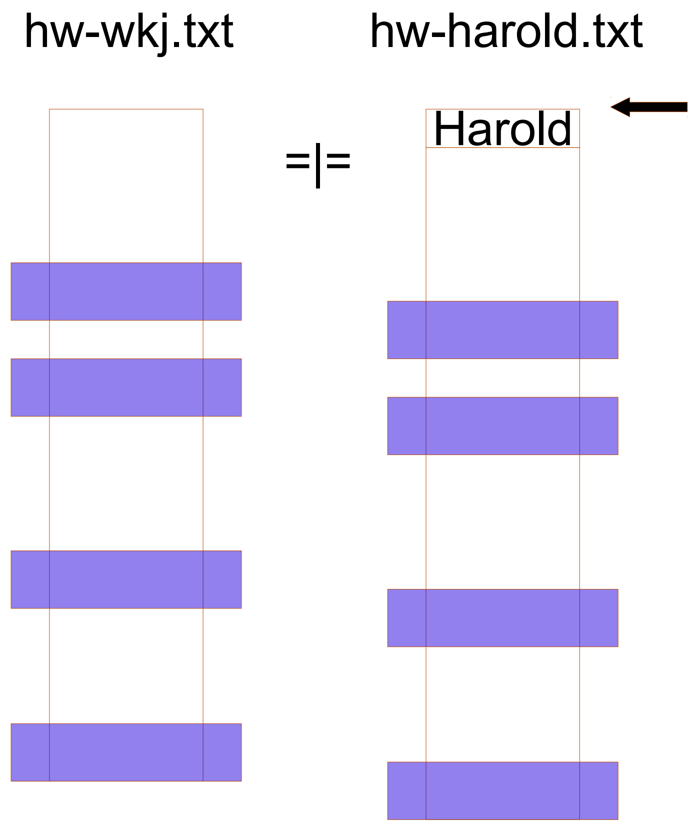
Deduplication

Division: variable-size chunks



Deduplication

Division: variable-size chunks



Suppose Harold adds his name to the top of my homework

Only introduce one new chunk to storage.

Deduplication

Division: variable-size chunks

Sliding window properties:

- collisions are OK, but
    - average chunk size should be configurable
- reuse overlapping window calculations

→ Rabin fingerprints

Deduplication

Division: variable-size chunks

Rabin fingerprint: preselect divisor *D*, and an irreducible polynomial

$$\mathbf{R}(b_1,b_2,\ldots,b_w) = (b_1p^{w-1} + b_2p^{w-2} + \ldots + b_w) \ \mathbf{mod}\ D$$

$$\mathbf{R}(\underbrace{b_i,\ldots,b_{i+w-1}}_{\substack{\text{Arbitrary}\\ \text{window}\\ \text{of width } w}}) = ((\underbrace{\mathbf{R}(b_{i-1}, \ldots, b_{i+w-2})}_{\substack{\text{previous}\\ \text{window}\\ \text{calculation}}} - \underbrace{b_{i-1}p^{w-1}}_{\substack{\text{previous}\\ \text{first}\\ \text{term}}})p + b_{i+w-1}) \ \mathbf{mod}\ D$$

Deduplication

Recap:

Chunking breaks a data stream into smaller segments

→ What do we gain from chunking?

→ What are the tradeoffs?

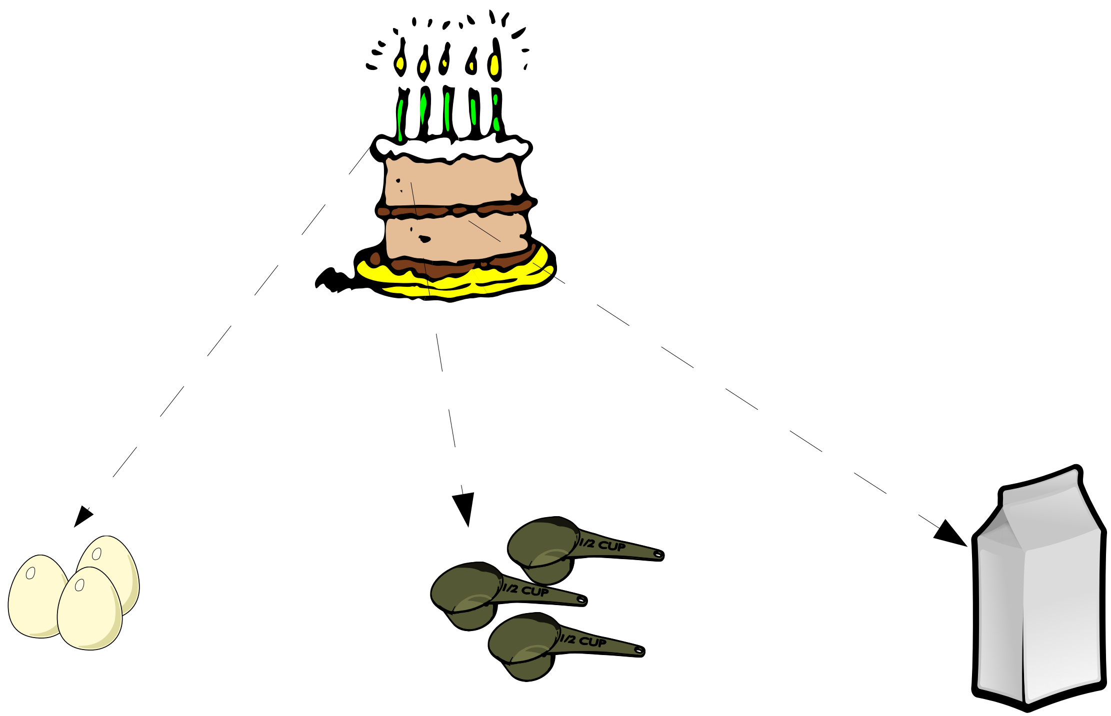
+ Finer granularity of sharing
+ Finer granularity of addressing

- Fingerprinting is an expensive operation
- Not suitable for all data patterns
- Index overhead

Deduplication

Reassembling chunks:

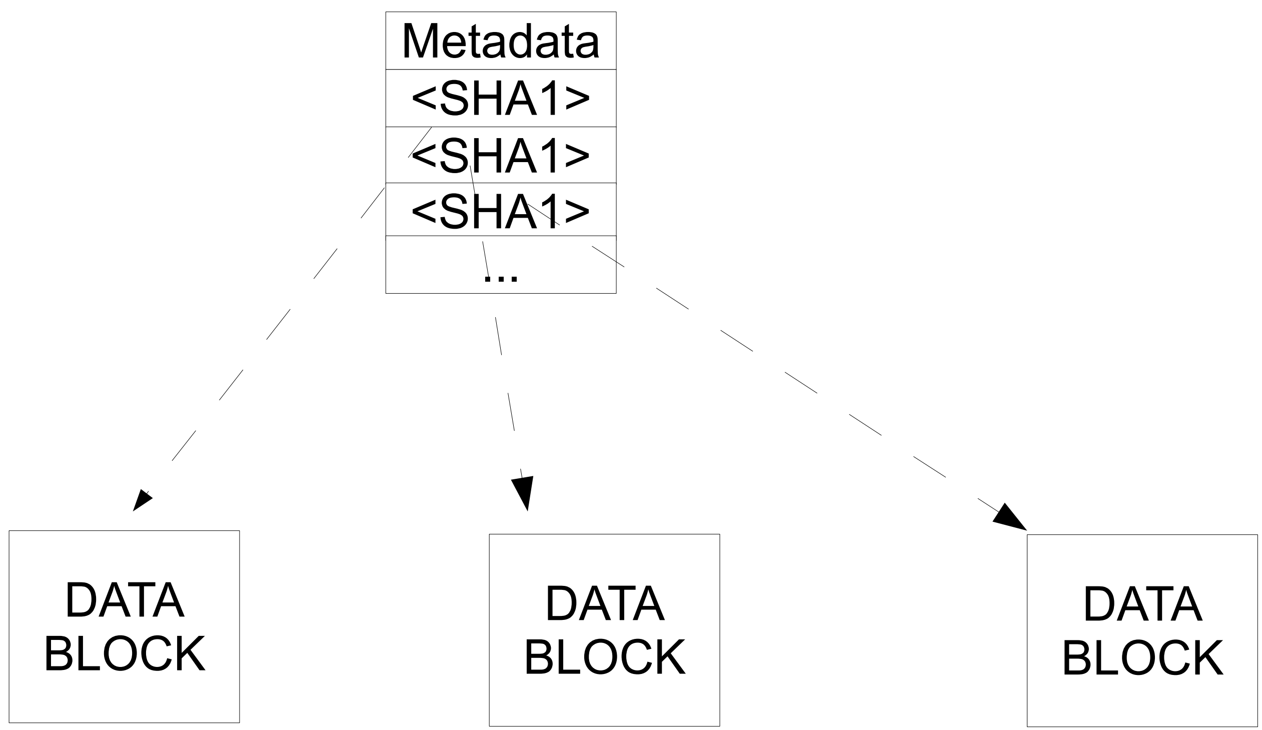
Recipes provide directions for reconstructing files from chunks



Deduplication

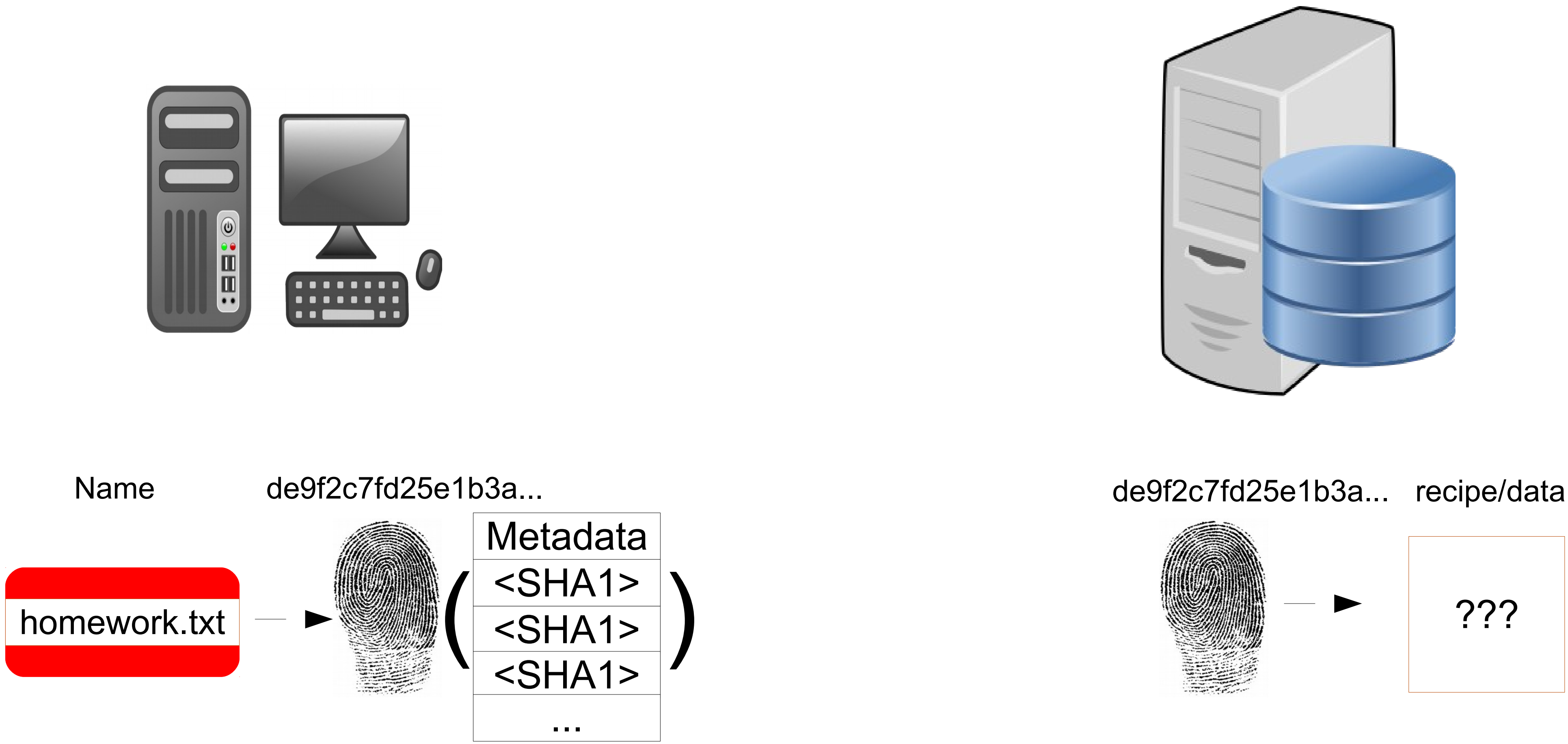
Reassembling chunks:

Recipes provide directions for reconstructing files from chunks



CAS

Example:



Name
de9f2c7fd25e1b3a...
homework.txt
Metadata
<SHA1>
<SHA1>
<SHA1>
...
de9f2c7fd25e1b3a...
recipe/data
???

Deduplication

Background

- Content Addressable Storage (CAS)
- Deduplication
  - Chunking
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- Other applications

Deduplication

The Index:

SHA-1 fingerprint uniquely identifies data, but the index translates fingerprints to chunks.

$$
\begin{array}{ccc}
\langle \text{sha-1}_1 \rangle & \longrightarrow & \langle \text{chunk}_1 \rangle \\
\langle \text{sha-1}_2 \rangle & \longrightarrow & \langle \text{chunk}_2 \rangle \\
\langle \text{sha-1}_3 \rangle & \longrightarrow & \langle \text{chunk}_3 \rangle \\
\dots & & \dots \\
\langle \text{sha-1}_n \rangle & \longrightarrow & \langle \text{chunk}_n \rangle
\end{array}
$$

$\langle \text{chunk}_i \rangle$ = {location, size?, refcount?, compressed?, ...}

Deduplication

The Index:

For small chunk stores:
- database, hash table, tree

For a large index, legacy data structures won't fit in main memory
- each index query requires a disk seek

- why?
    - SHA-1 fingerprints independent and randomly distributed
        - no locality

Known as the **index disk bottleneck**

Deduplication

The Index:

Back of the envelope:

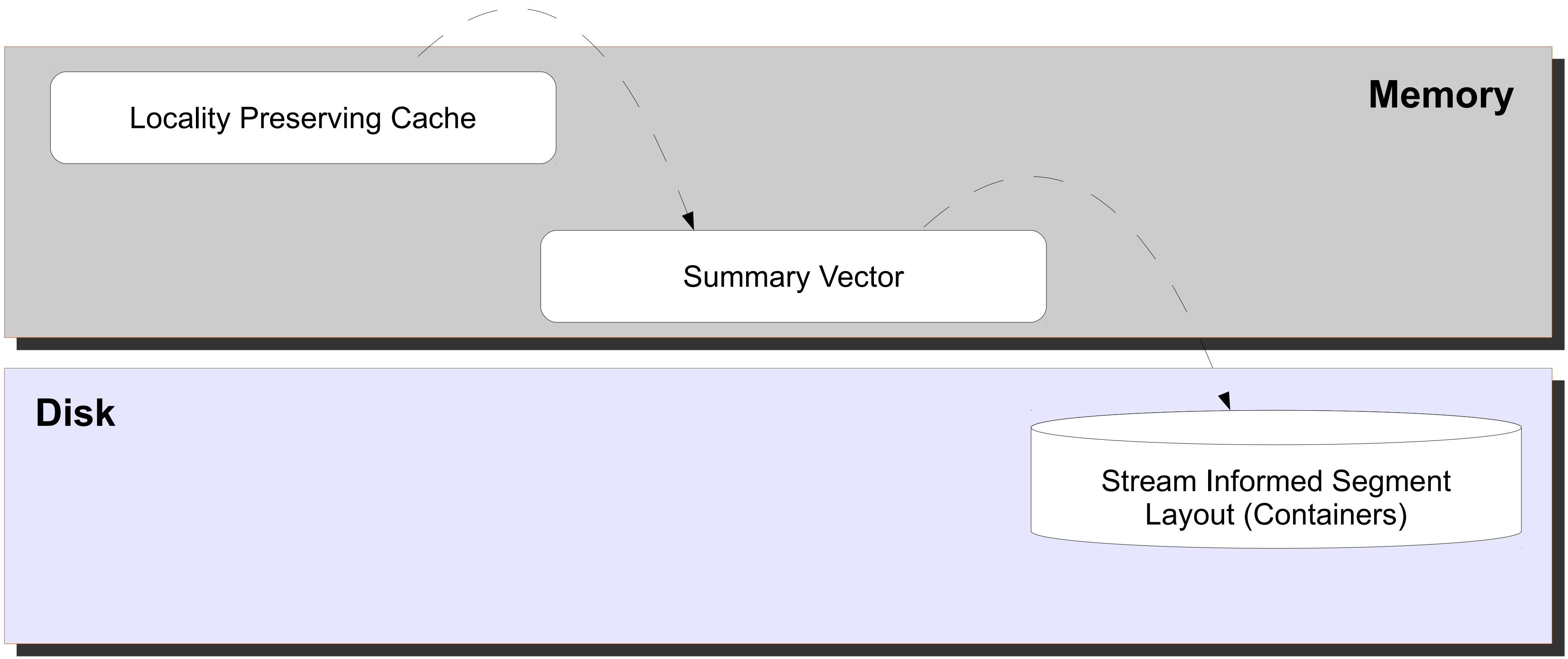
Average chunk size: 4KB
Fingerprint: 20B

20TB unique data = 100GB SHA-1 fingerprints

Deduplication

Disk bottleneck:

Data Domain strategy:
- filter unnecessary lookups
- piggyback useful work onto the disk lookups that *are* necessary

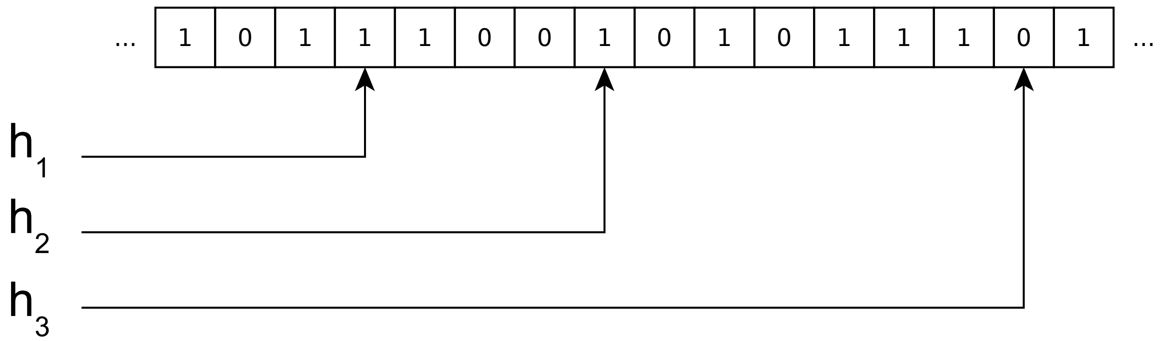


Deduplication

Disk bottleneck:

Summary vector

- Bloom filter (any AMQ data structure works)



Filter properties:

- No false negatives
  - if an FP is in the index, it is in summary vector
- Tuneable false positive rate
  - We can trade memory for accuracy

Note: on a false positive, we are no worse off
- We just do the disk seek we would have done anyway

Deduplication

Disk bottleneck:

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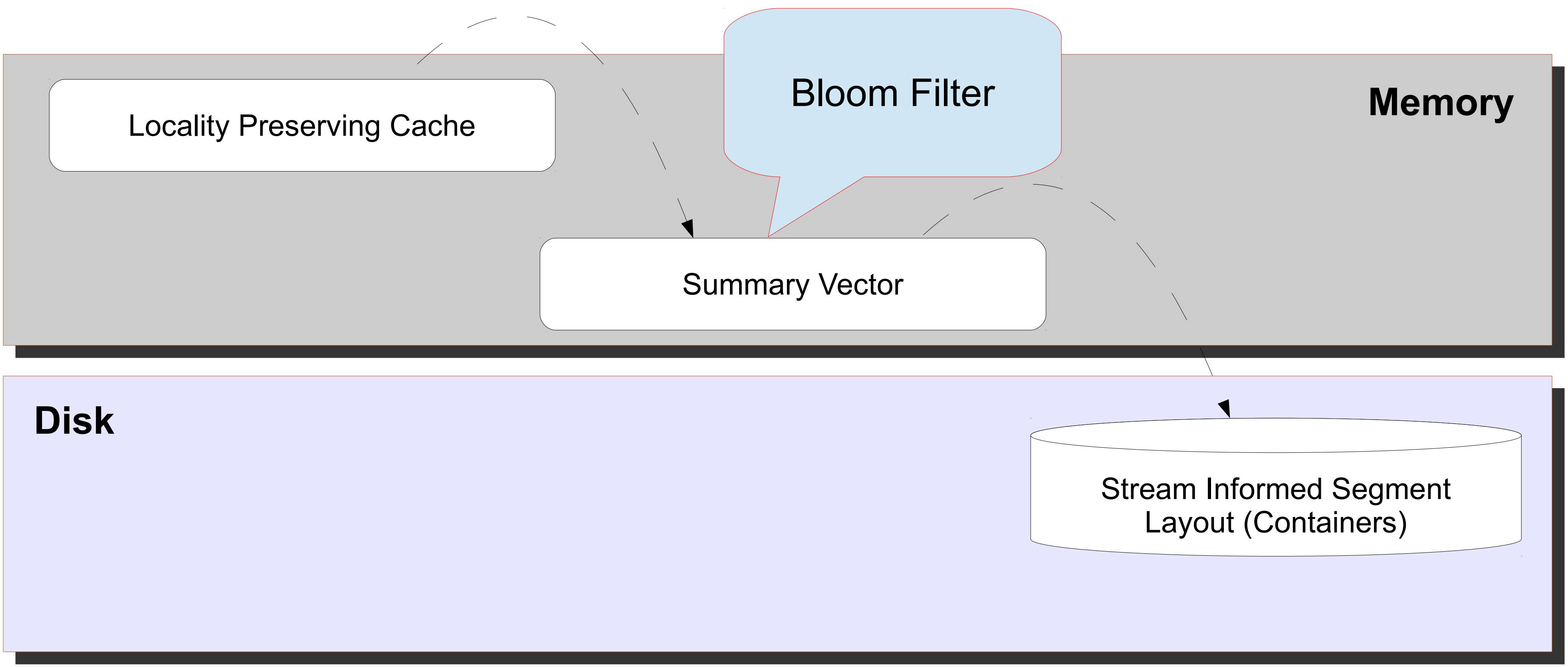


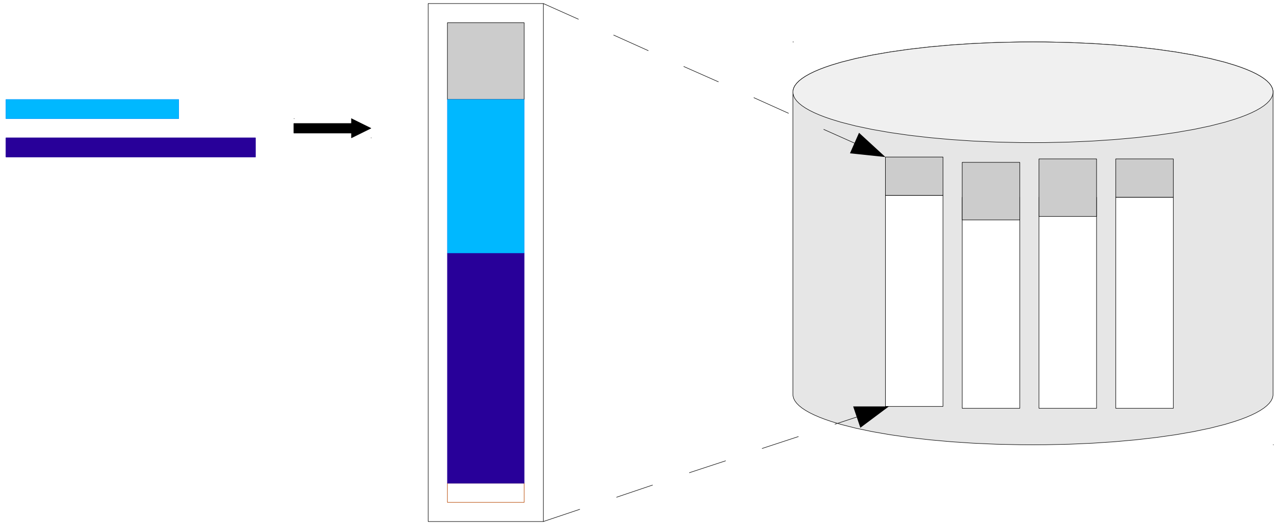
Deduplication

Disk bottleneck:

Stream informed segment layout (SISL)

- variable sized chunks written to fixed size containers
- chunk descriptors are stored in a list at the head

  →“temporal locality” for hashes within a container



Principle:

- backup workloads exhibit **chunk locality**

Deduplication

Disk bottleneck:

Data Domain strategy:
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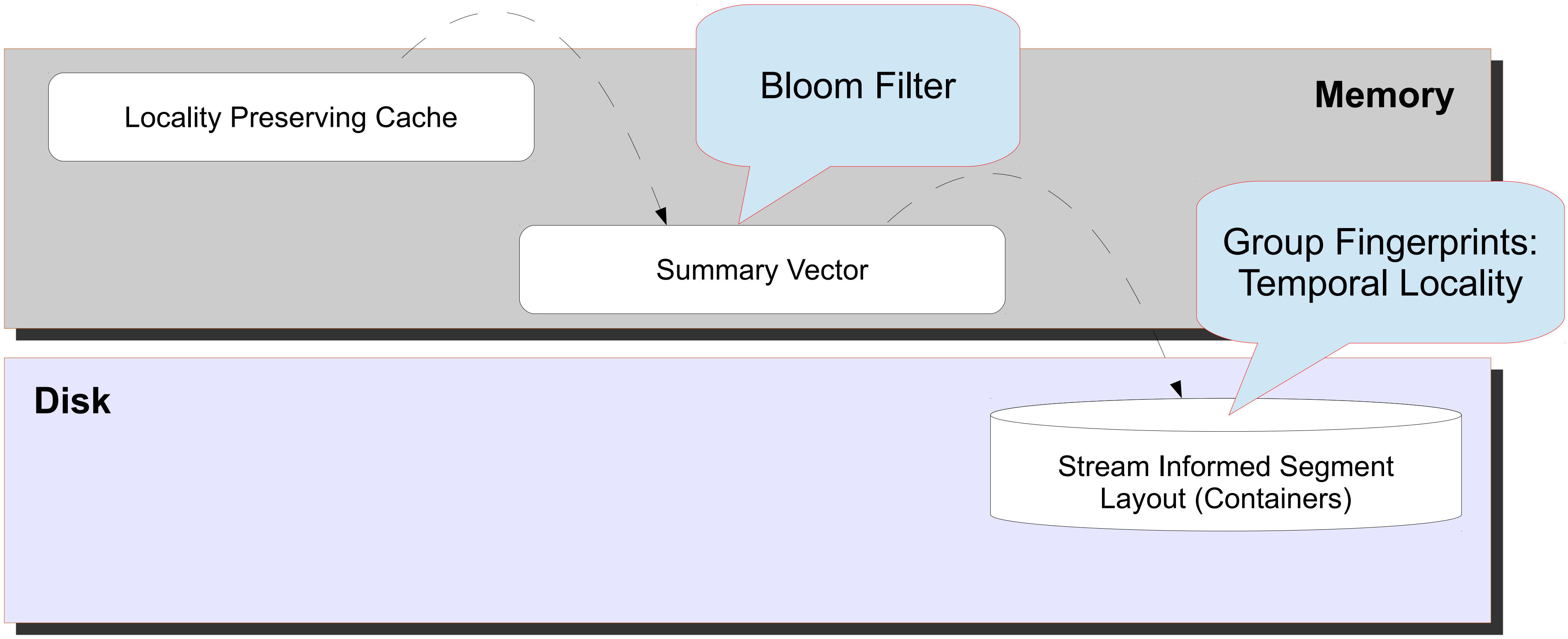
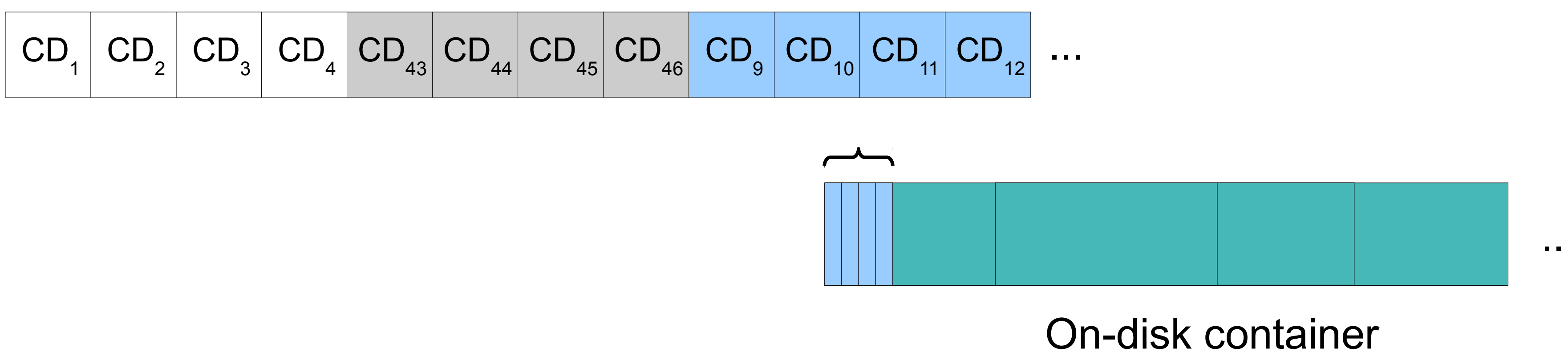


Deduplication

Disk bottleneck:

Locality Preserving Cache (LPC)

- LRU cache of candidate fingerprint groups

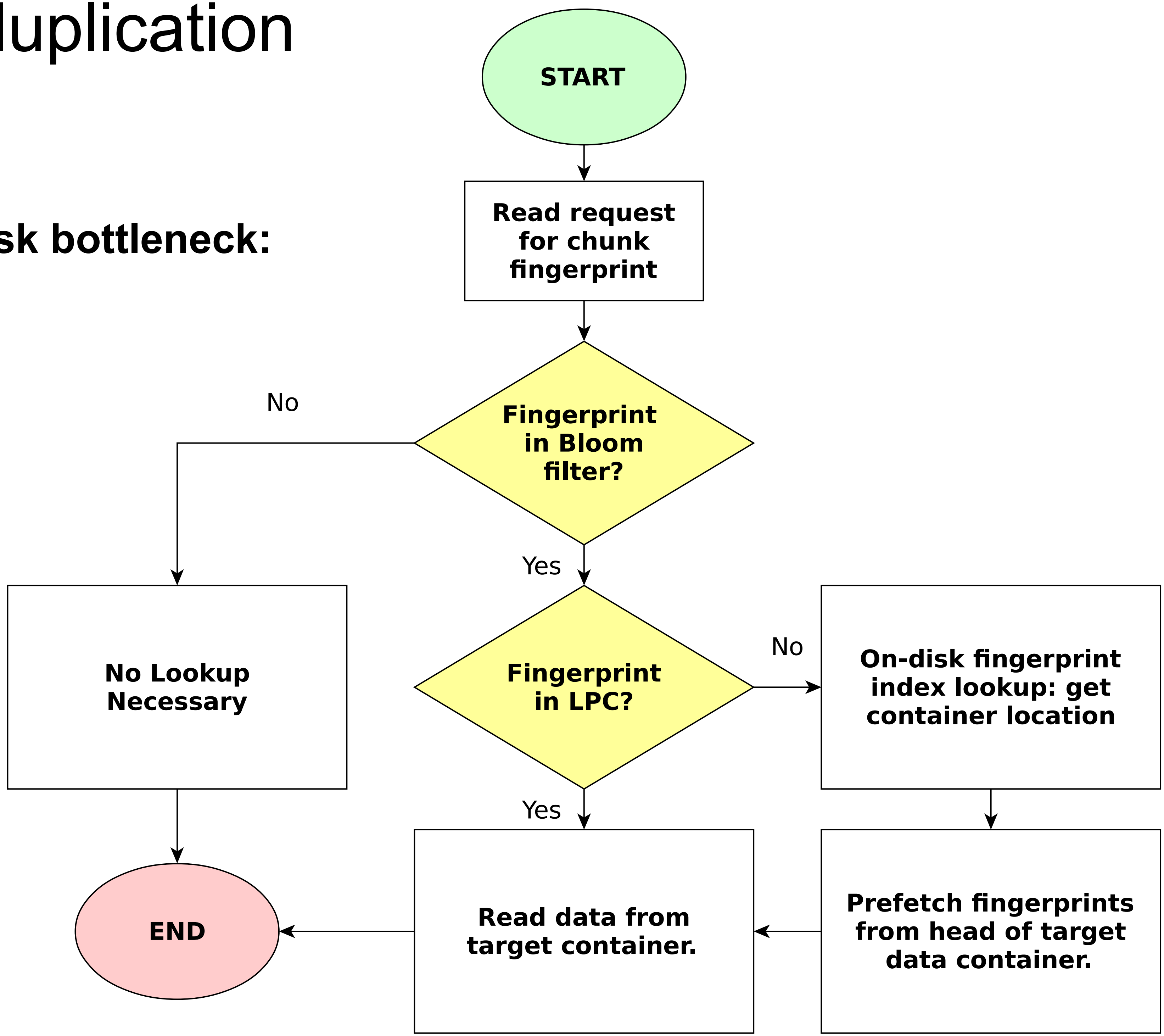


Principle:

- if you must go to disk, make it worth your while

Deduplication

Disk bottleneck:



Deduplication

Summary: Dedup and the 4 W's

Dedup Goal: eliminate repeat instances of identical data

What (granularity) to dedup?

Where to dedup?

When to dedup?

Why dedup?

Deduplication

Summary: Dedup and the 4 W's

Hybrid?
Context-aware.

What (granularity) to dedup?

	Whole-file	Fixed-size	Content-defined
Chunking overheads	N/A	offsets	Sliding window fingerprinting
Dedup Ratio	All-or-nothing	Boundary shifting problem	Best
Other notes	Low index overhead, compressed/ encrypted/ media	(Whole-file)**+** Ease of implementation, selective caching, synchronization	Latency, CPU intensive

Deduplication

Summary: Dedup and the 4 W's

Where to dedup?

source

Dedup before sending
data over the network
+ save bandwidth
- client complexity
- trust clients?

destination

Dedup at storage server
+ server more powerful
- centralized data structures

hybrid

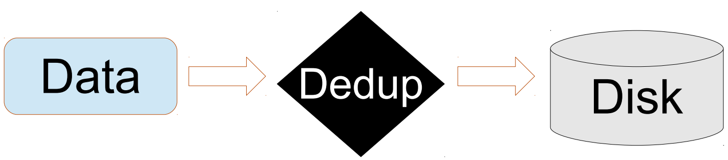
Client index checks membership,
Server index stores location

Deduplication

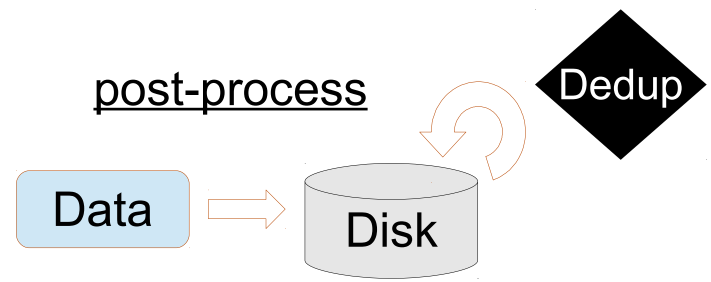
Summary: Dedup and the 4 W's

When to dedup?

inline



post-process



\+ never store duplicate data
\- slower → index lookup per chunk
\+ faster → save I/O for duplicate data

\- temporarily wasted storage
\+ faster → stream long writes, reclaim in the background
\- may create (even more) fragmentation

hybrid

→ post-processing faster for initial commits
→ switch to inline to take advantage of I/O savings

Deduplication

Why dedup?

Perhaps you have a loooooot of data...
- enterprise backups

Or data that is particularly amenable to deduplication...
- small or incremental changes
- data that is not encrypted or compressed

Or that changes infrequently.
- blocks are immutable → no such thing as a “block modify”
- rate of change determines container chunk locality

Ideal use case: “Cold Storage”

Background

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- Content Addressable Storage (CAS)
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Other CAS Applications

Data verification

CAS can be used to build tamper evident storage. Suppose that:

- you can't fix a compromised server,
- but you never want be fooled by one

Insight: Fingerprints uniquely identify data

- hash before storing data, and save the fp locally
- rehash data and compare fps upon receipt