# Deduplication: Overview & Case Studies

CSCI 333 – Spring 2020

Williams College

# Lecture Outline

## Background

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

# Lecture Outline

## Background

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

# Content Addressable Storage (CAS)

Deduplication systems often rely on Content Addressable Storage (CAS)

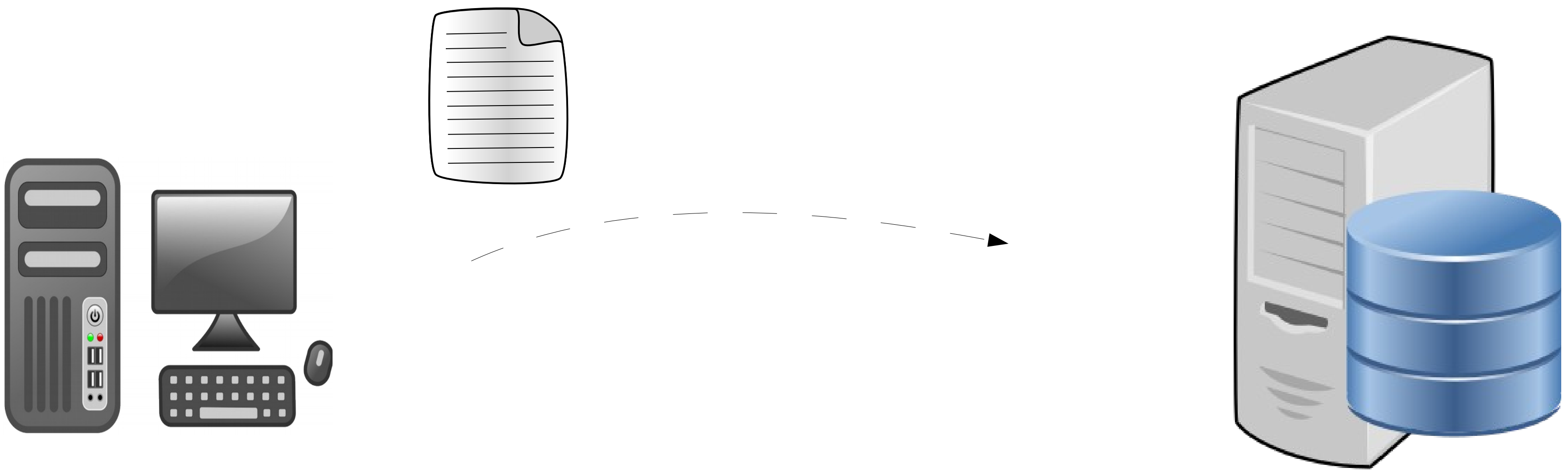
Data is indexed by some **content identifier**

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

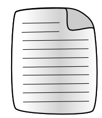
SHA-1:

20 bytes (160 bits)

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

# CAS

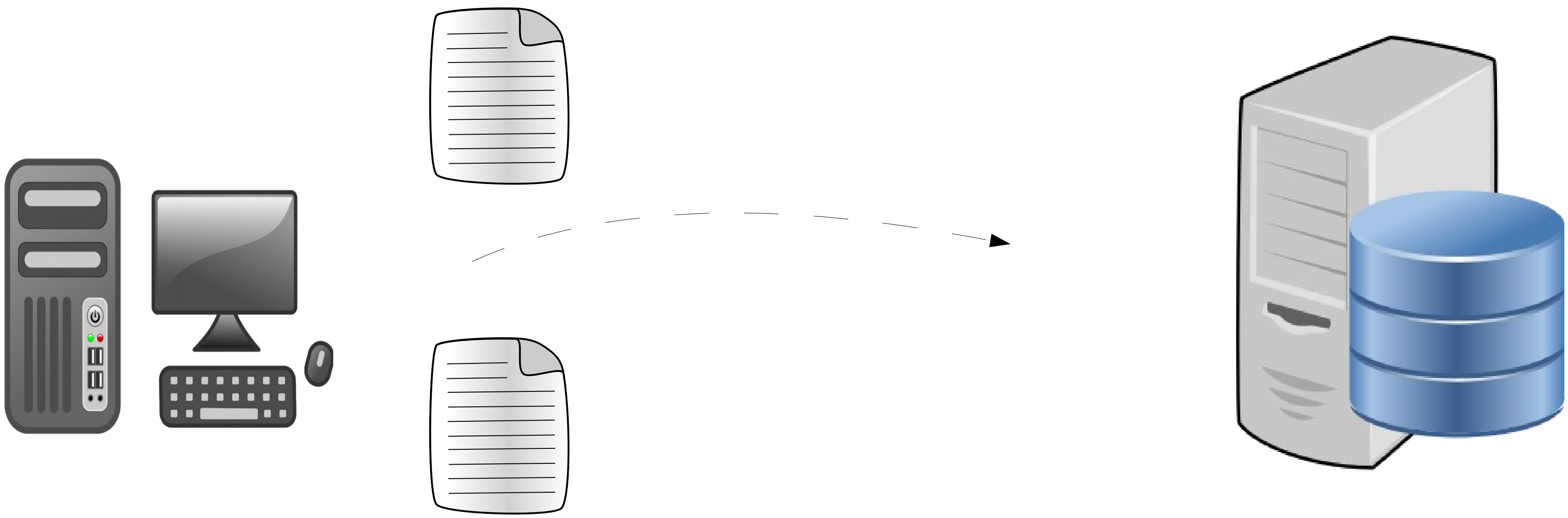
Example:

SHA-1(  ) = de9f2c7fd25e1b3a...

# CAS

Example:

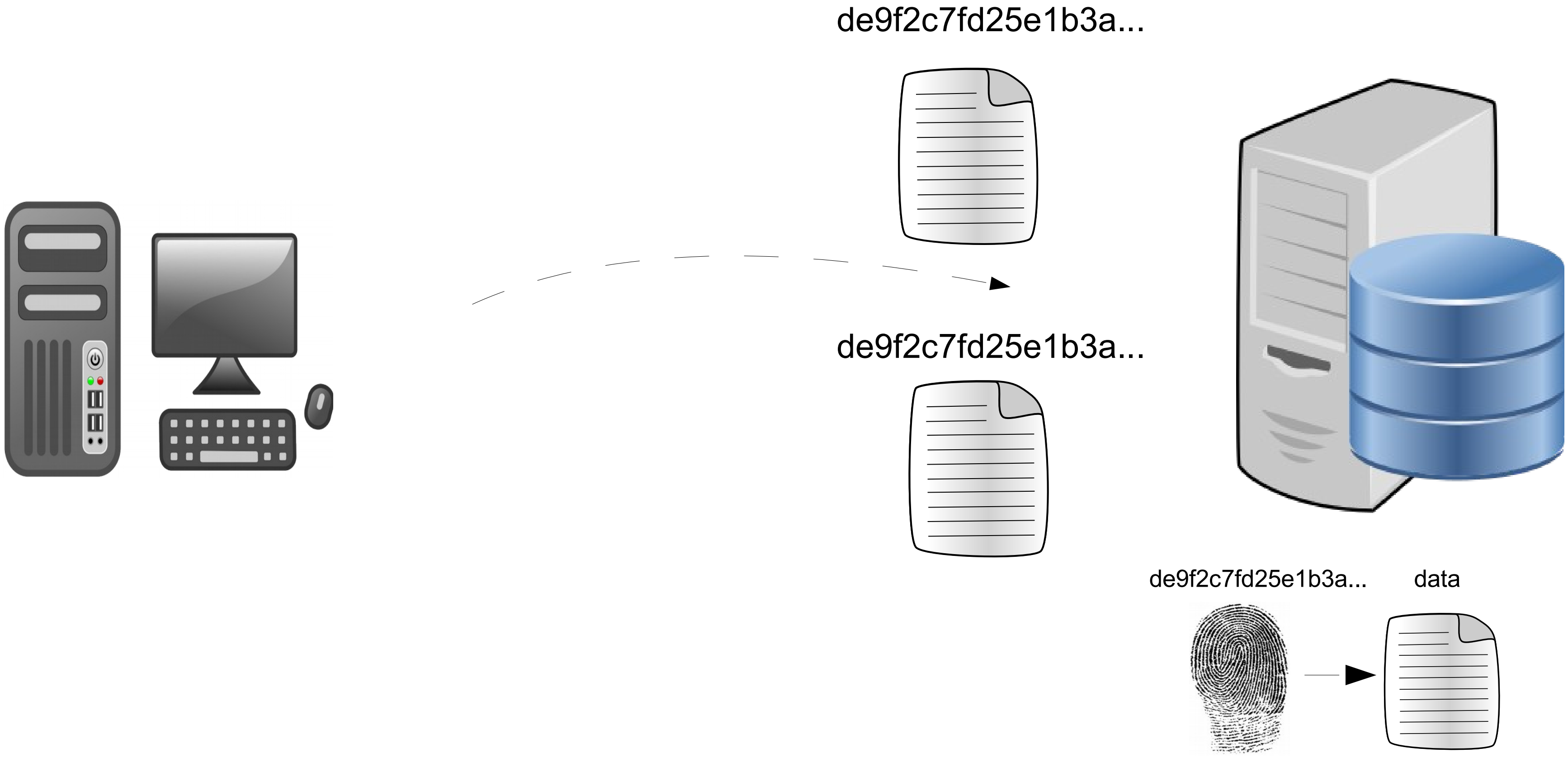
I submit my homework, and my “buddy” Harold also submits my homework...



# CAS

Example:

Same contents, same fingerprint.

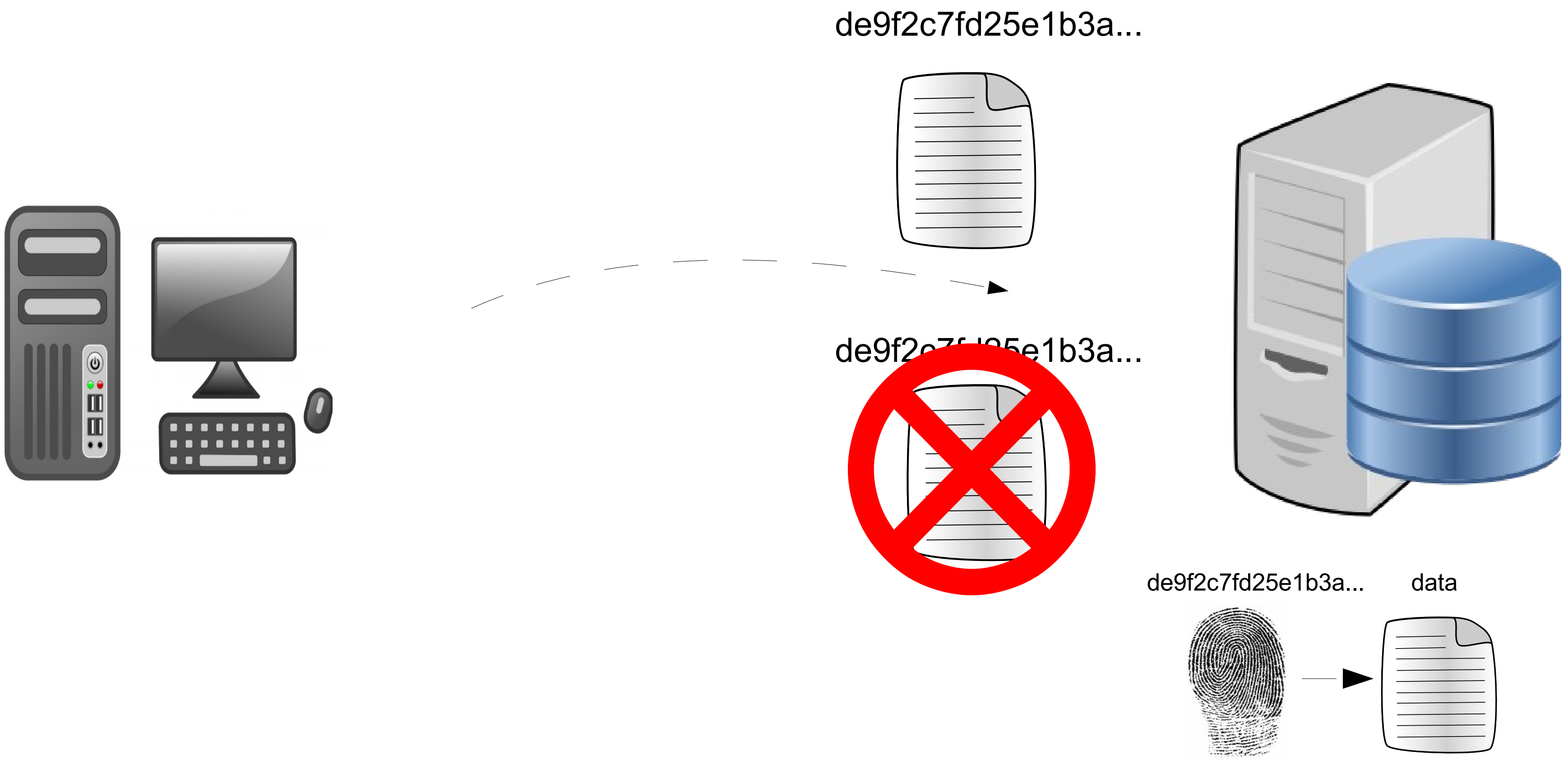


# CAS

Example:

Same contents, same fingerprint.

The data is only stored once!



# Background

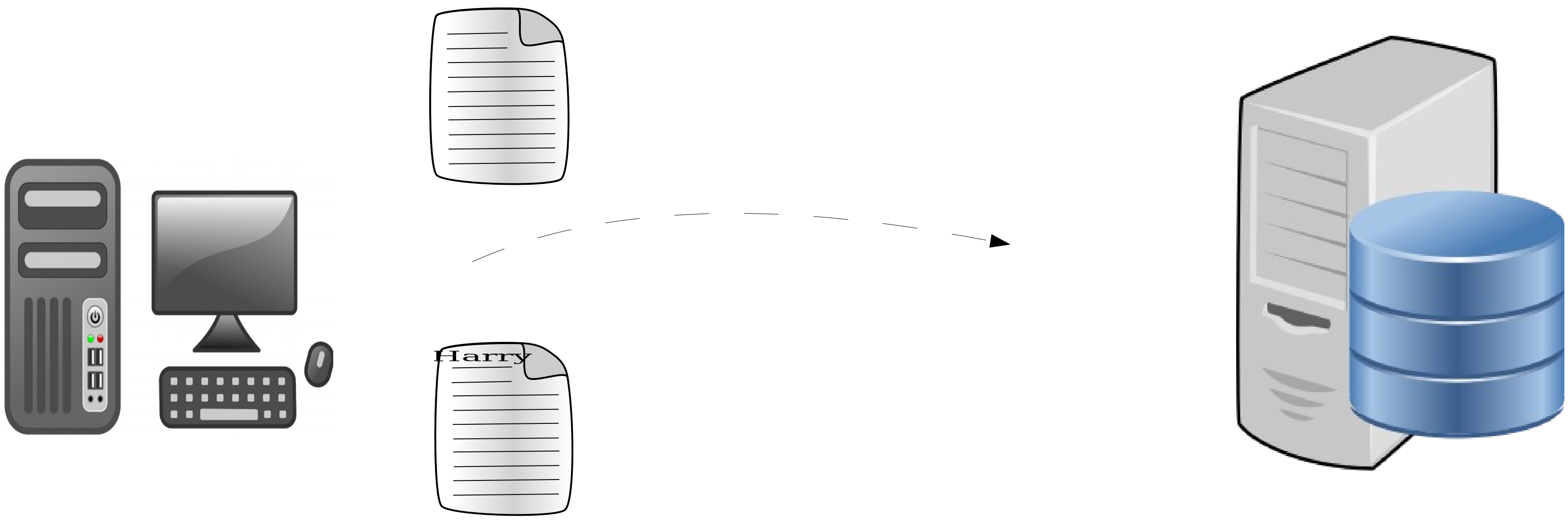
## Background

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

# CAS

Example:

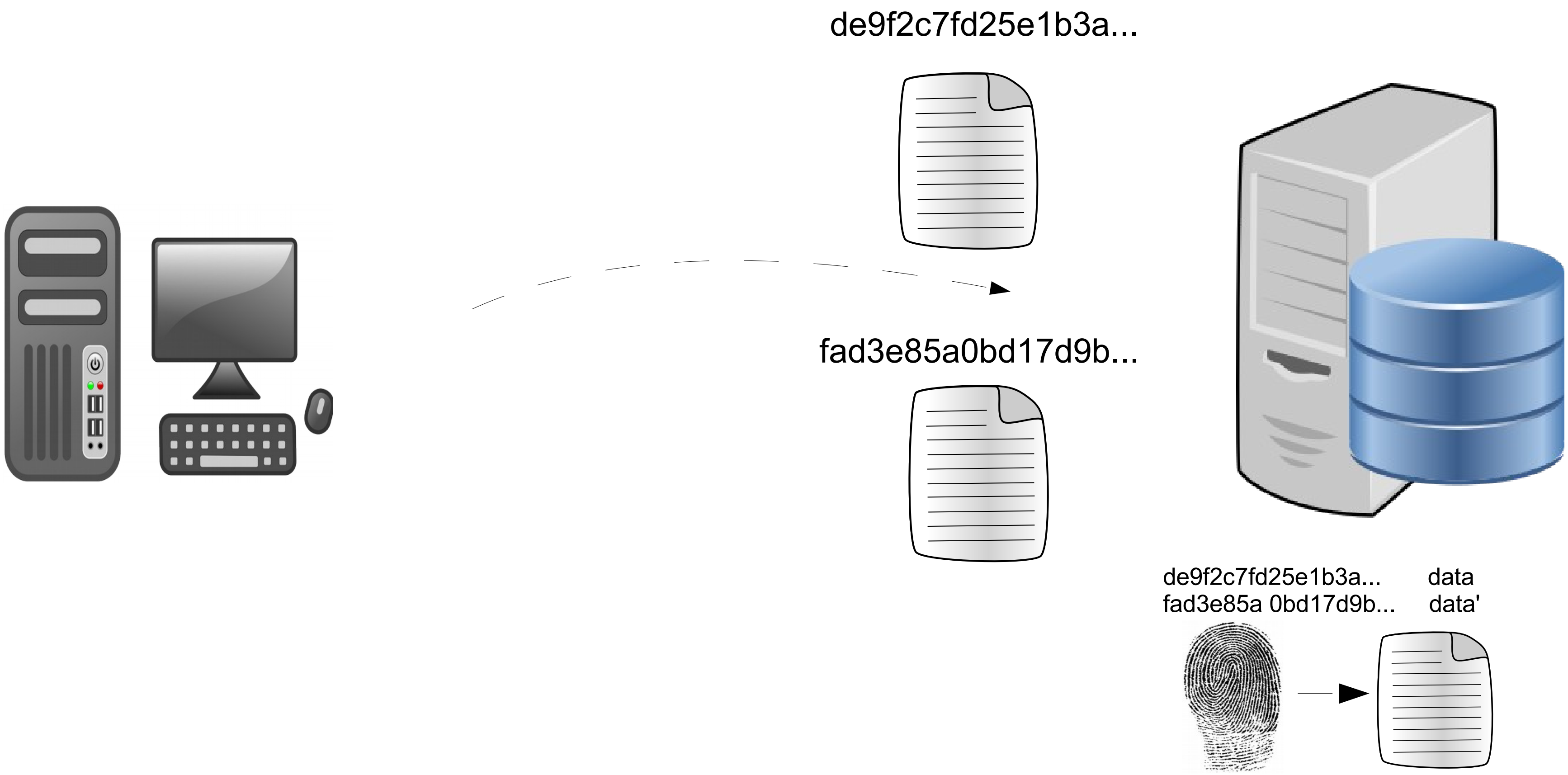
Now suppose Harry writes his name at the top of my document.



# 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)
- Deduplication
  - Chunking
  - The Index
- Other applications

# 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

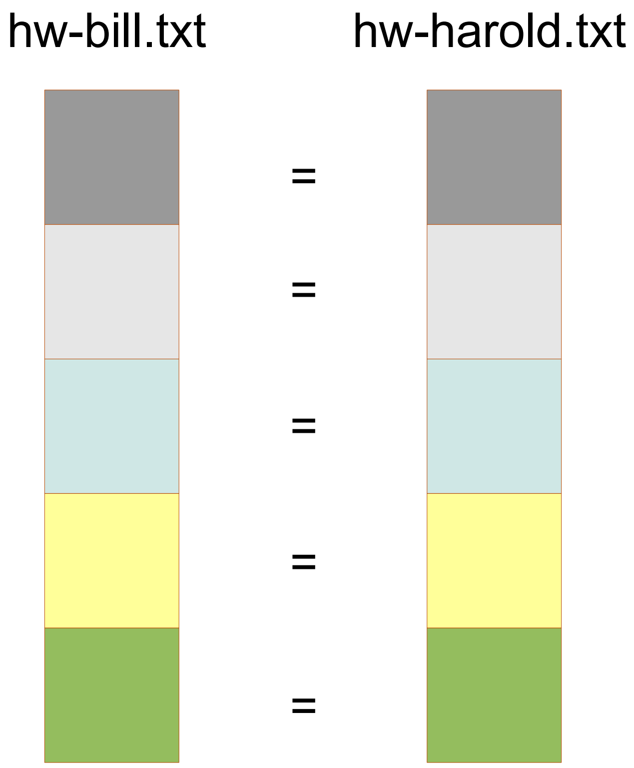
- Every (?)KB, start a new chunk

Option 2: variable-size chunks

- Chunk boundaries dependent on chunk contents

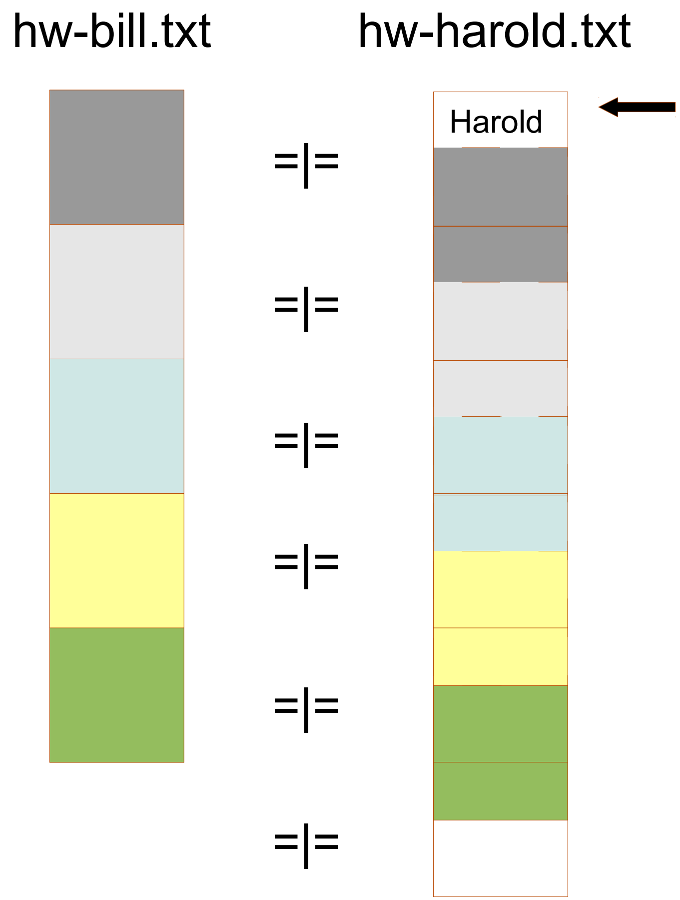
# Deduplication

**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

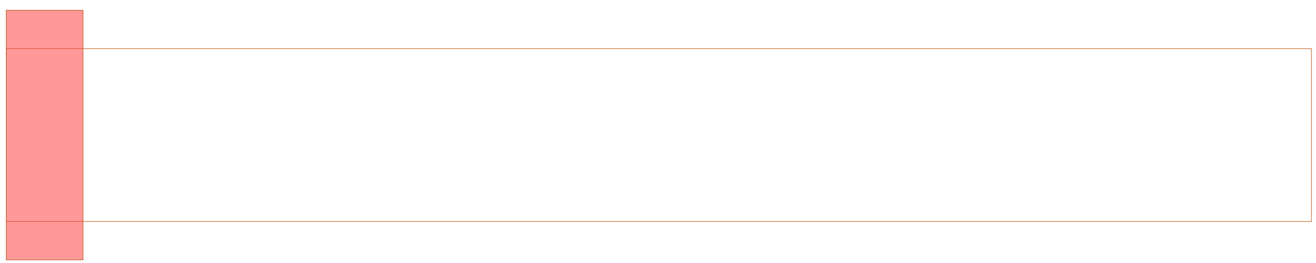
- Every 4KB, start a new chunk

Option 2: variable-size chunks

- Chunk boundaries dependent on chunk contents

# Deduplication

**Division:** variable-size chunks



<u>parameters:</u>

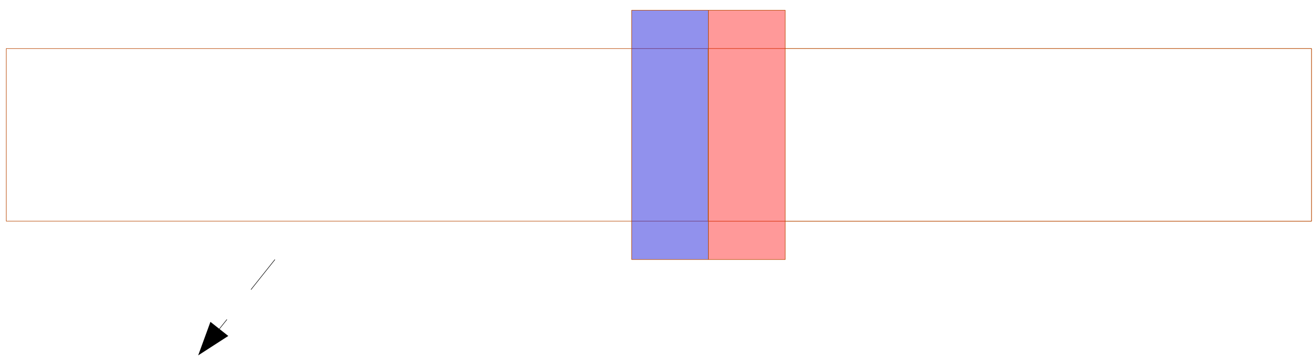
Window of width *w*
Target pattern *t*

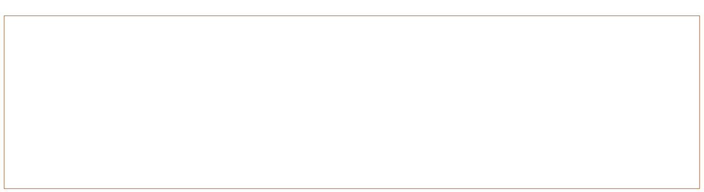
- Slide the window byte by byte across the data, and compute a window fingerprint at each position.

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

# Deduplication

**Division:** variable-size chunks



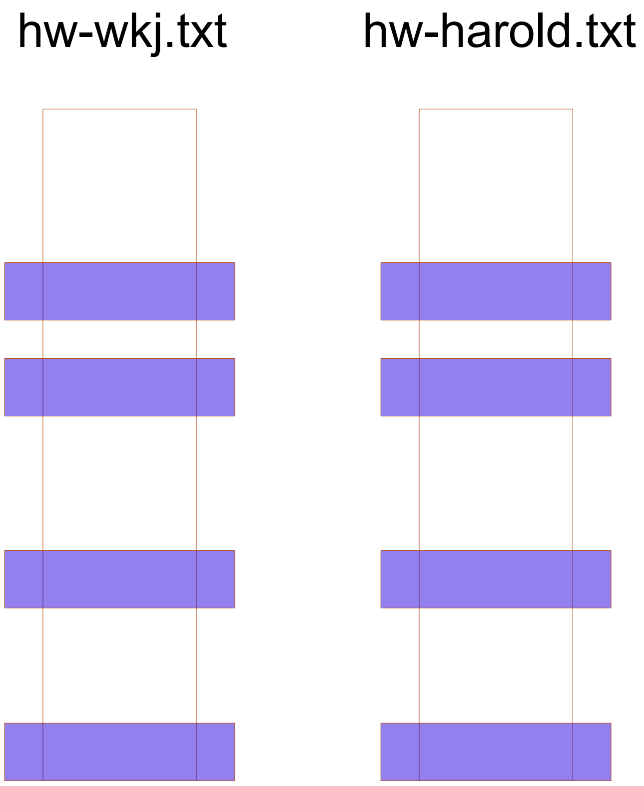


- Slide the window byte by byte across the data, and compute a window fingerprint at each position.

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

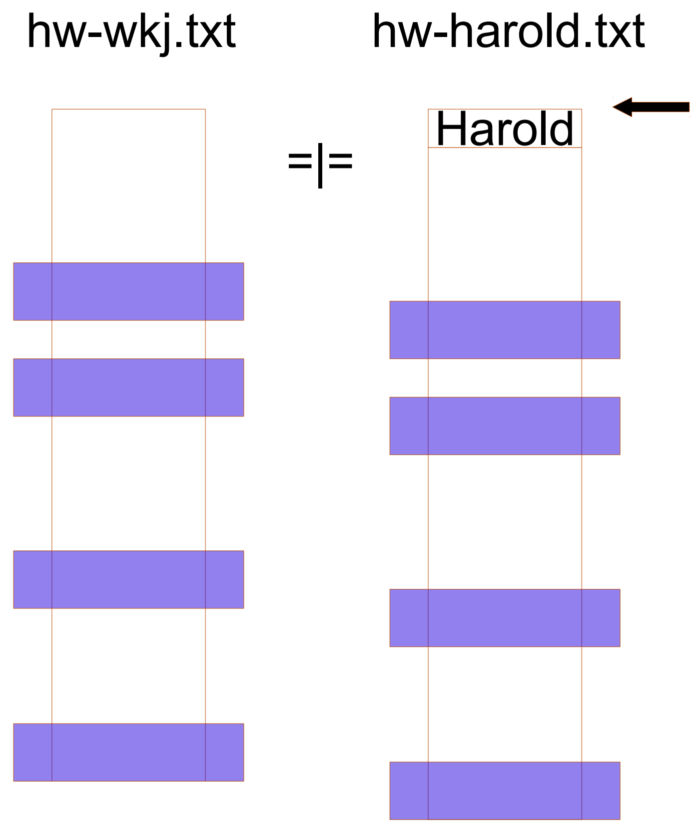
# Deduplication

**Division:** variable-size chunks



# 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

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

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

# Deduplication

**Recap:**

Chunking breaks a data stream into smaller segments

→ What do we gain from chunking?

→ What are the tradeoffs?

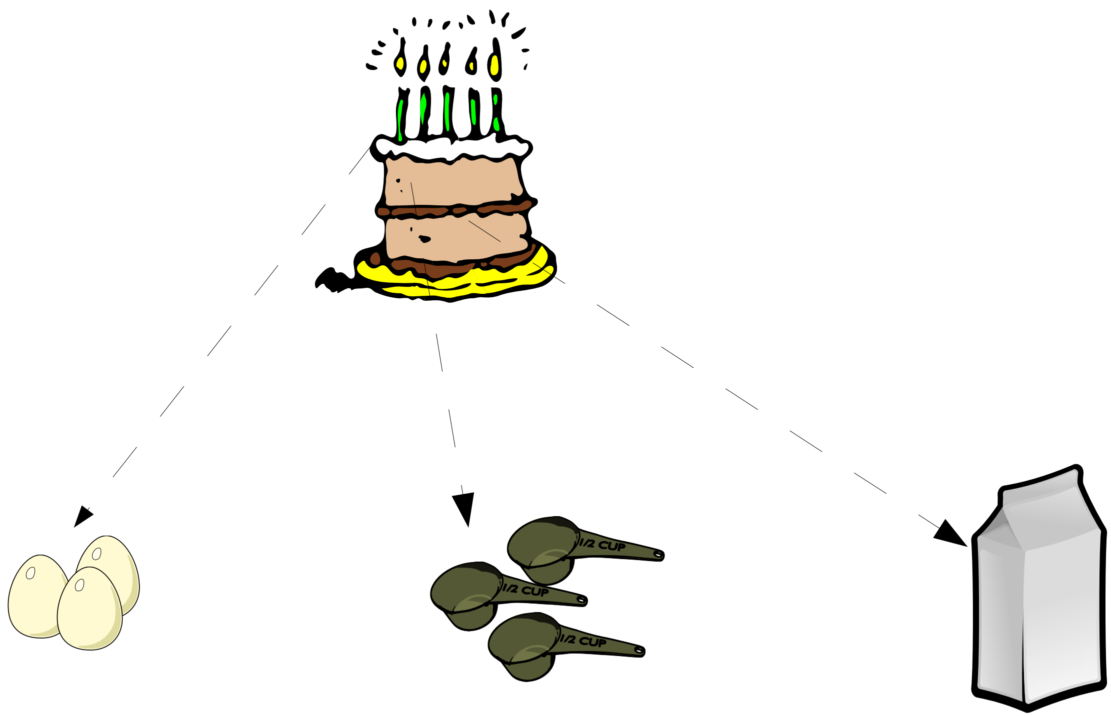
+ Finer granularity of sharing
+ Finer granularity of addressing

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

# Deduplication

**Reassembling chunks:**

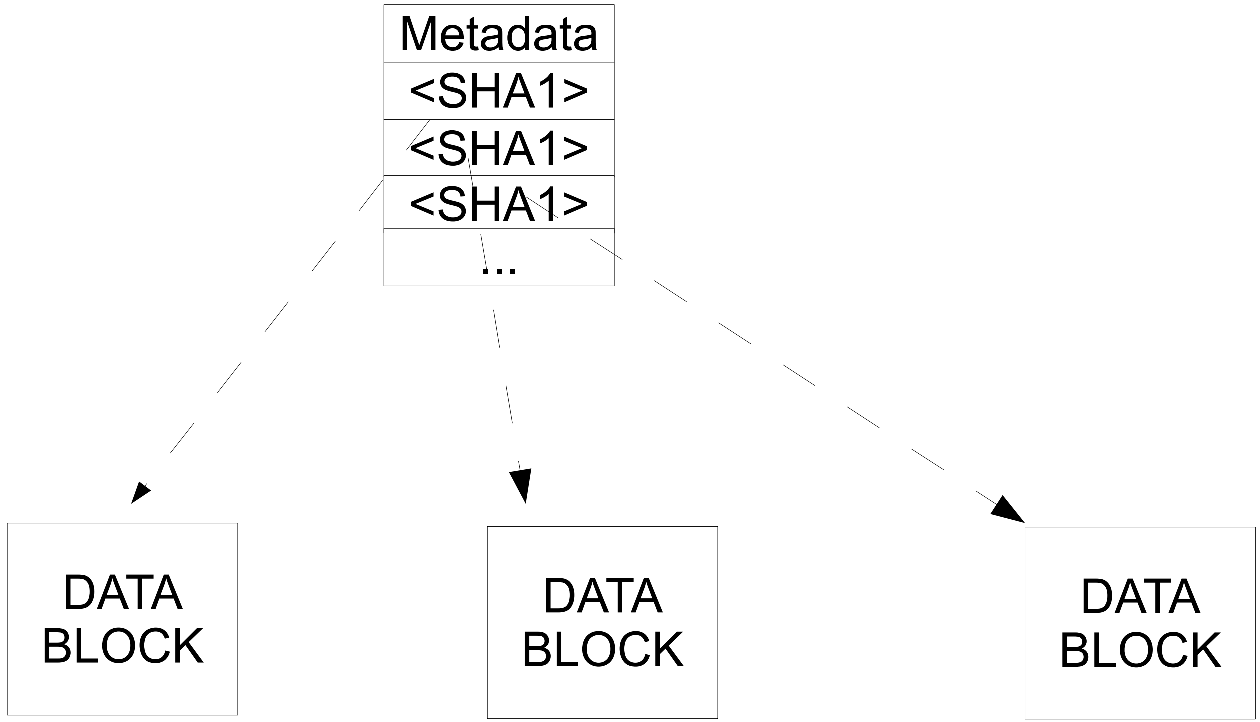
Recipes provide directions for reconstructing files from chunks



# Deduplication

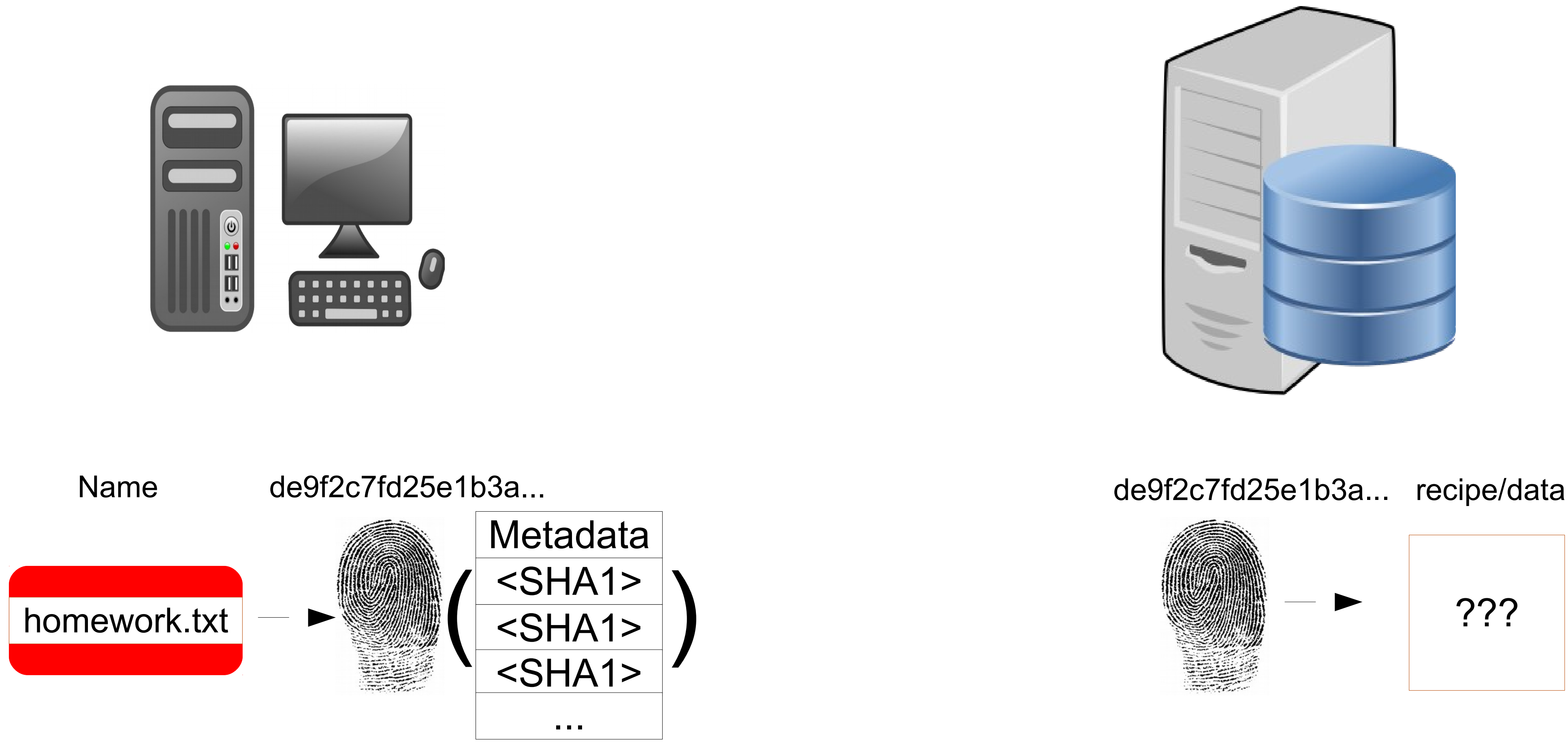
**Reassembling chunks:**

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
  - The Index
- Other applications

# Deduplication

**The Index:**

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

$$<\text{sha-1}_1> \rightarrow <\text{chunk}_1>$$
$$<\text{sha-1}_2> \rightarrow <\text{chunk}_2>$$
$$<\text{sha-1}_3> \rightarrow <\text{chunk}_3>$$
$$\ldots \qquad \ldots$$
$$<\text{sha-1}_n> \rightarrow <\text{chunk}_n>$$

$<\text{chunk}_i>$ = {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:

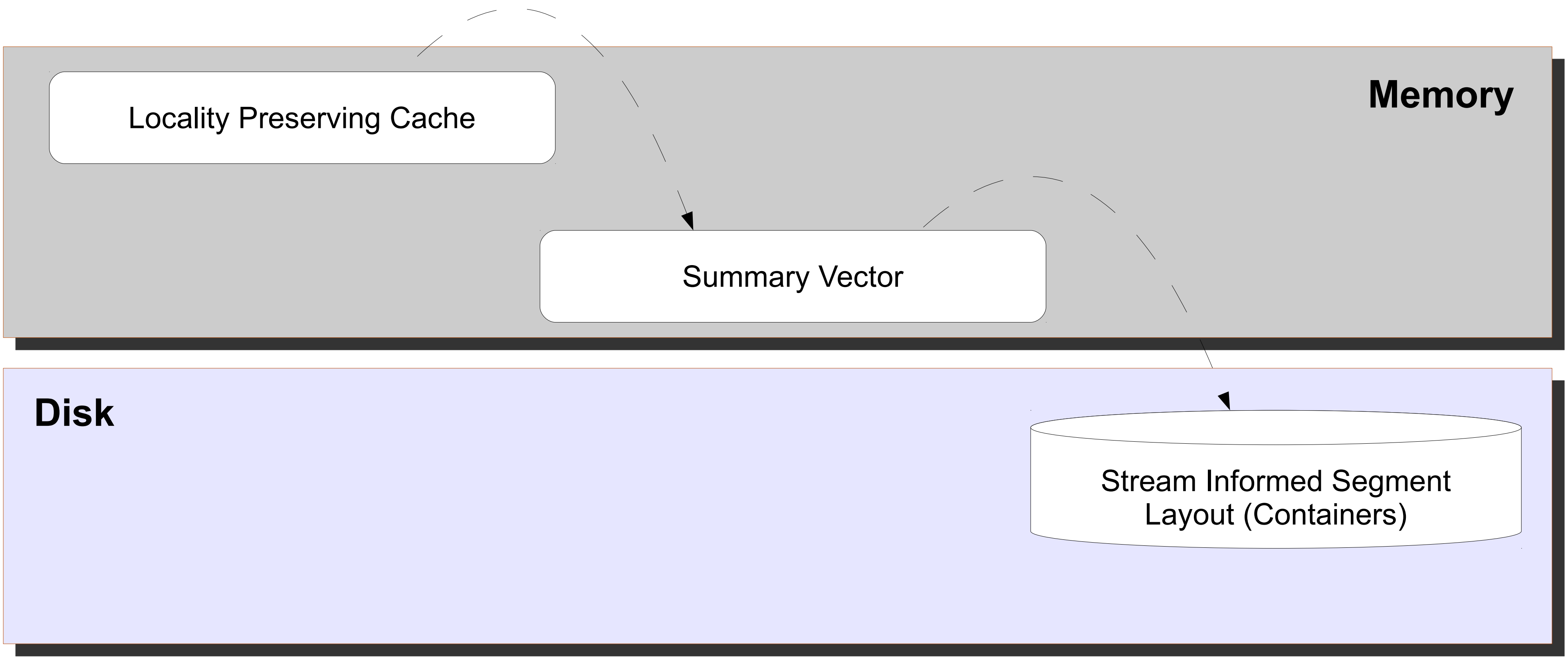
Average chunk size: 4KB
Fingerprint: 20B

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

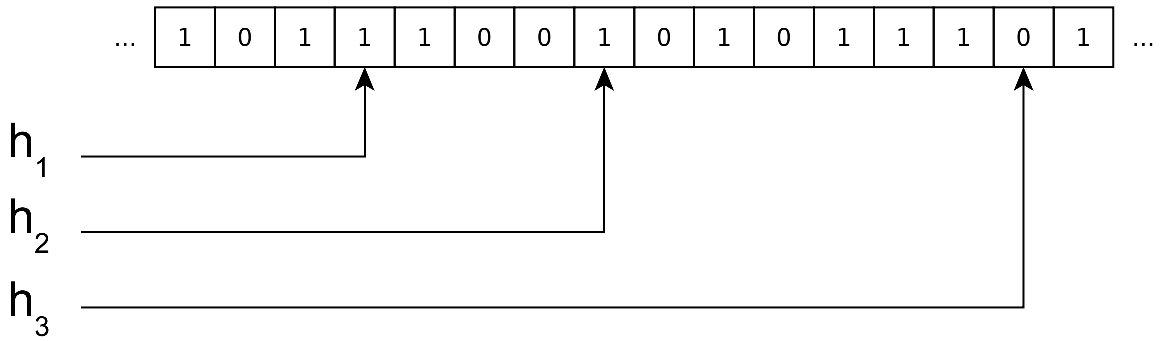


# Deduplication

**Disk bottleneck:**

Summary vector

- Bloom filter (any AMQ data structure works)




**Filter properties:**

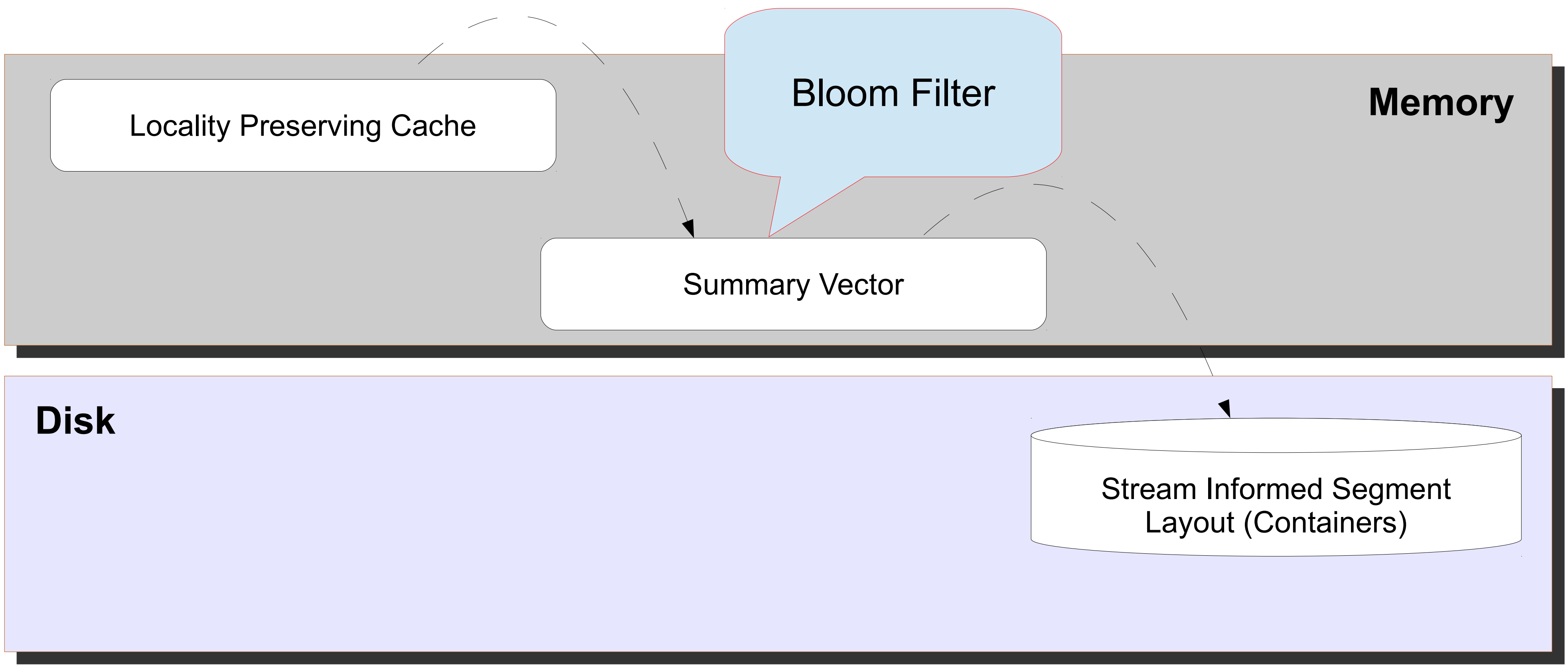
- No false negatives
  - if an FP is in the index, it is in summary vector
- Tuneable false positive rate
  - We can trade memory for accuracy

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

# Deduplication

## Disk bottleneck:

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



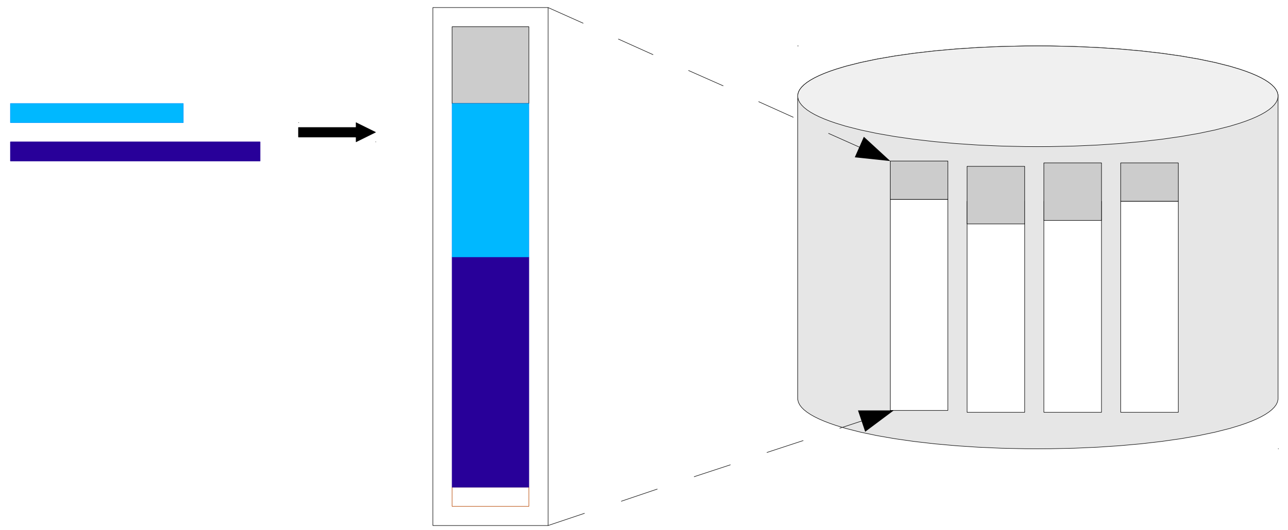
# Deduplication

**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



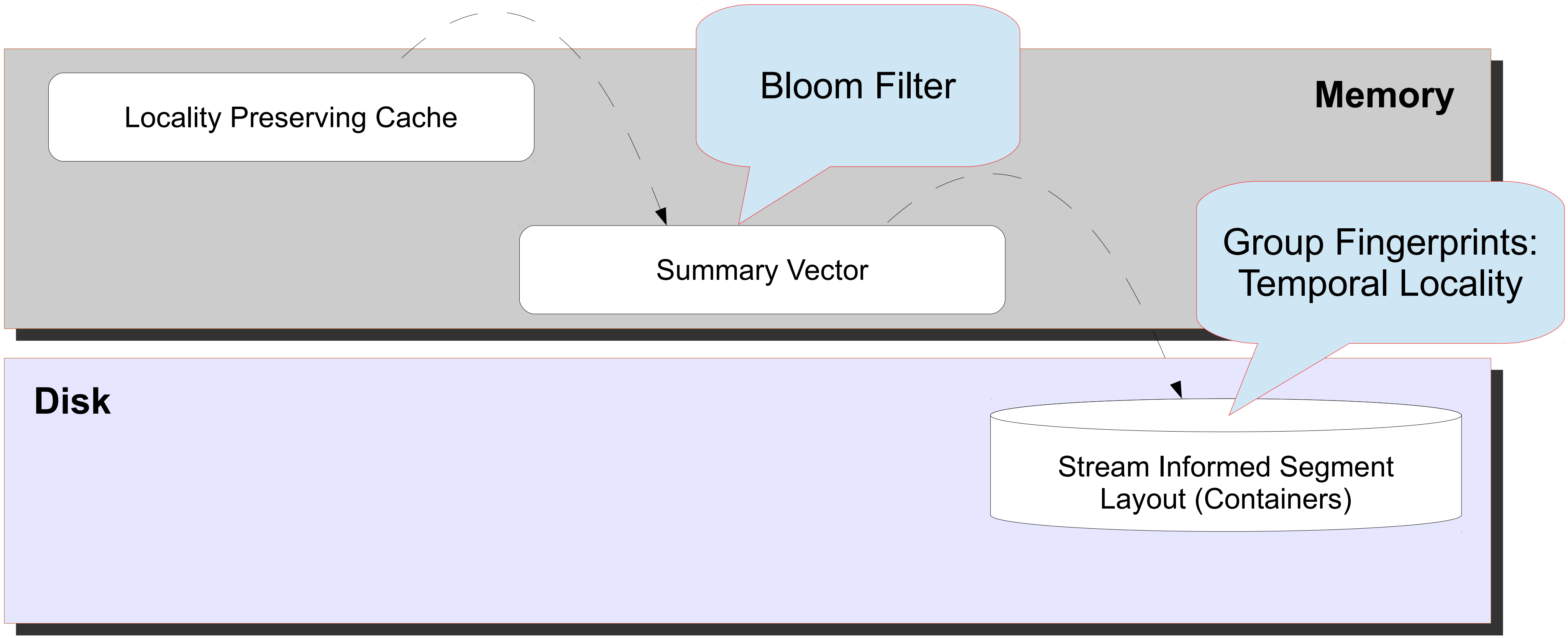
Principle:

- backup workloads exhibit **chunk locality**

# Deduplication

## Disk bottleneck:

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

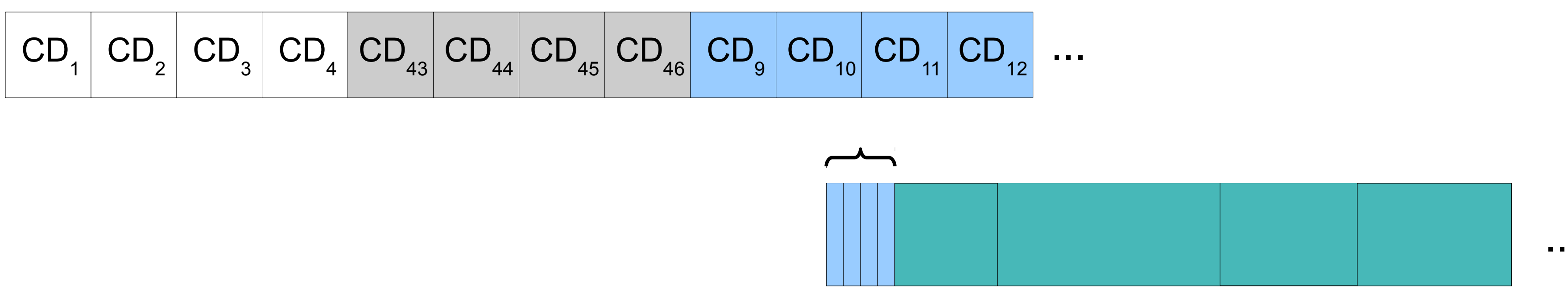


# Deduplication

**Disk bottleneck:**

Locality Preserving Cache (LPC)

- LRU cache of candidate fingerprint groups



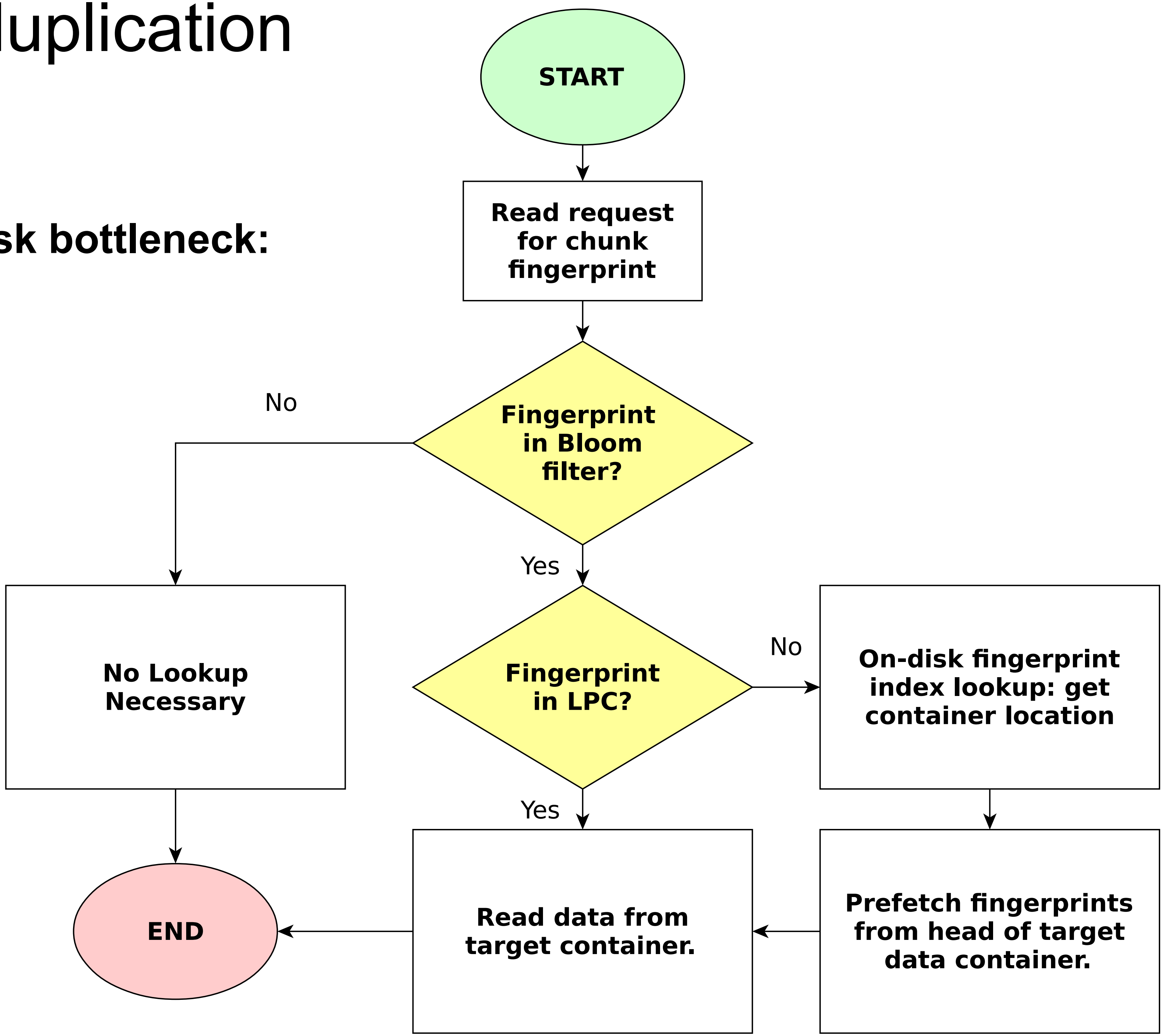

On-disk container

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**

***What*** (granularity) to dedup?

Hybrid?
Context-aware.

| | 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

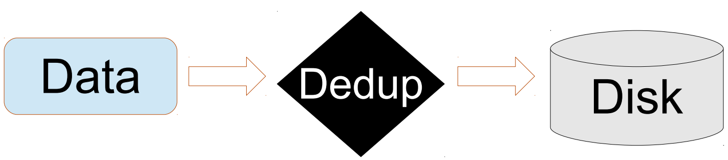
Client index checks membership,
Server index stores location

# Deduplication

## Summary: Dedup and the 4 W's

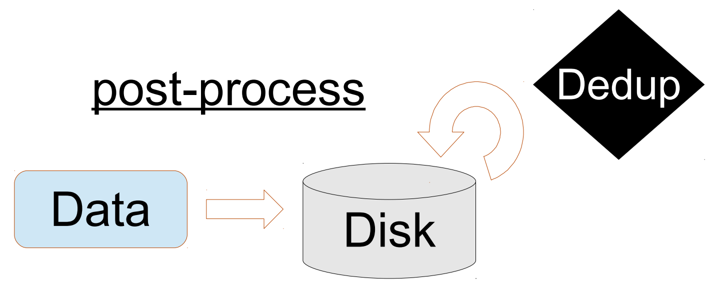
***When*** to dedup?

inline




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

post-process




- 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

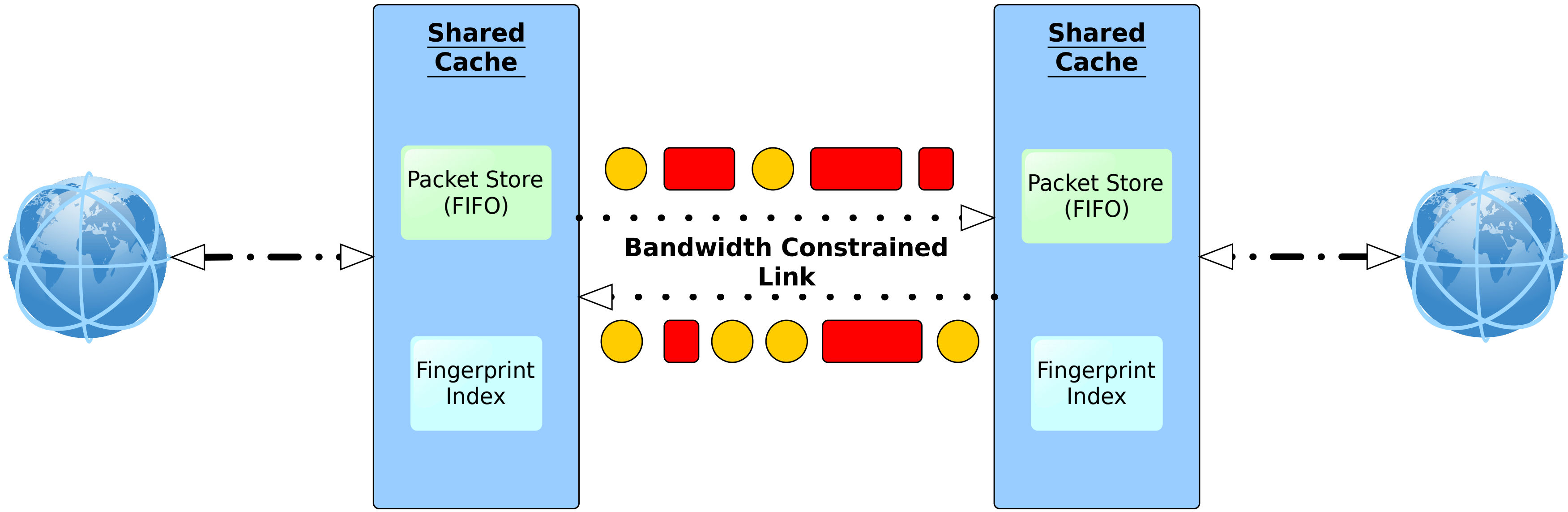
**Ideal use case: “Cold Storage”**

# Deduplication

**Why dedup?**

Perhaps your bottleneck isn't the CPU

- Use dedup if you can favorably trade other resources




**Example:** Protocol Independent Technique for Eliminating Redundant Network Traffic

# Background

## Background

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

# 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