DeepSketch:
A New Machine Learning-Based Reference Search Technique for Post-Deduplication Delta Compression

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USENIX FAST 2022

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Executive Summary

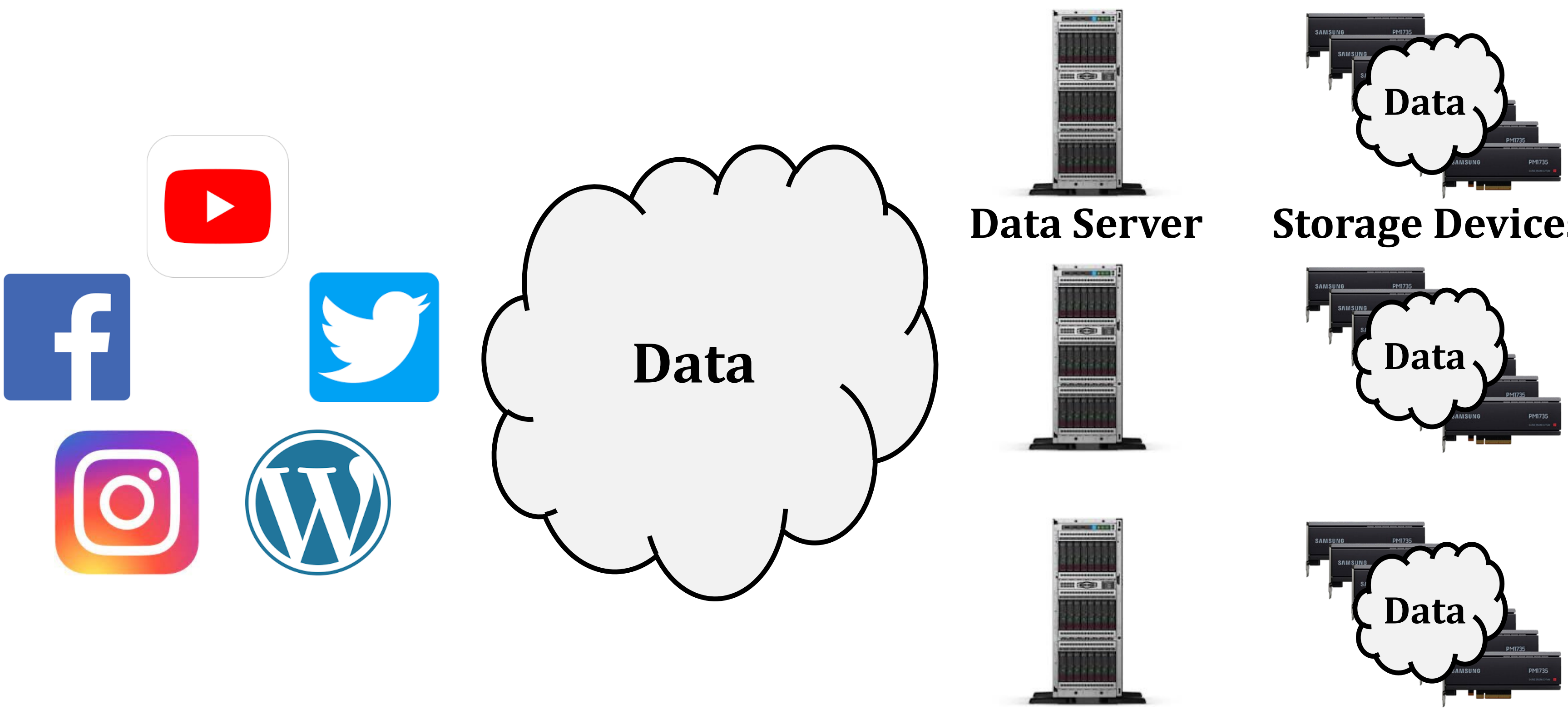
- **Motivation**
  - Data reduction: Effective at reducing the management cost of a data center by reducing the amount of data physically written to storage devices
  - Post-deduplication delta compression: Maximizes the data-reduction ratio by applying delta compression along with deduplication and lossless compression
- **Problem:** Existing post-deduplication delta-compression techniques provide significantly low data-reduction ratios compared to the optimal.
  - Due to the limited accuracy of reference search for delta compression
  - Cannot identify a good reference block for many incoming data blocks
- **Key Idea:** DeepSketch, a new machine learning-based reference search technique that uses the learning-to-hash method
  - Generates a given data block's signature (sketch) using a deep neural network
  - The higher the delta-compression benefit of two data blocks, the more similar the signatures of the two blocks to each other
- **Evaluation Results:** DeepSketch reduces the amount of physically-written data
  - Up to 33% (21% on average) compared to a state-of-the-art baseline

Talk Outline

- Data Reduction in Storage Systems
- DeepSketch: A New Machine Learning-based Reference Search Technique
- Evaluation Results

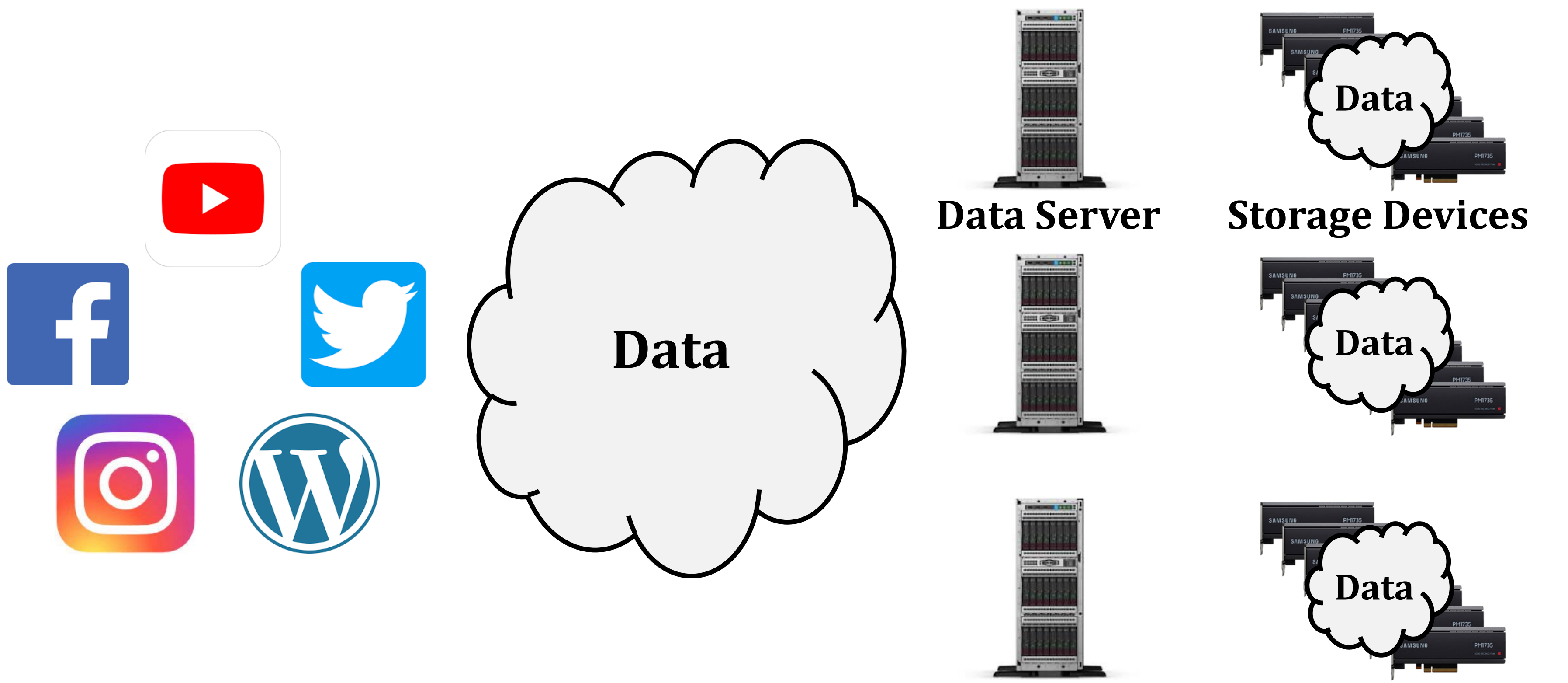
Big Data Era

- Unprecedented amounts of data processed in modern computing systems
  - e.g., Facebook generates 4 petabytes of new data every day



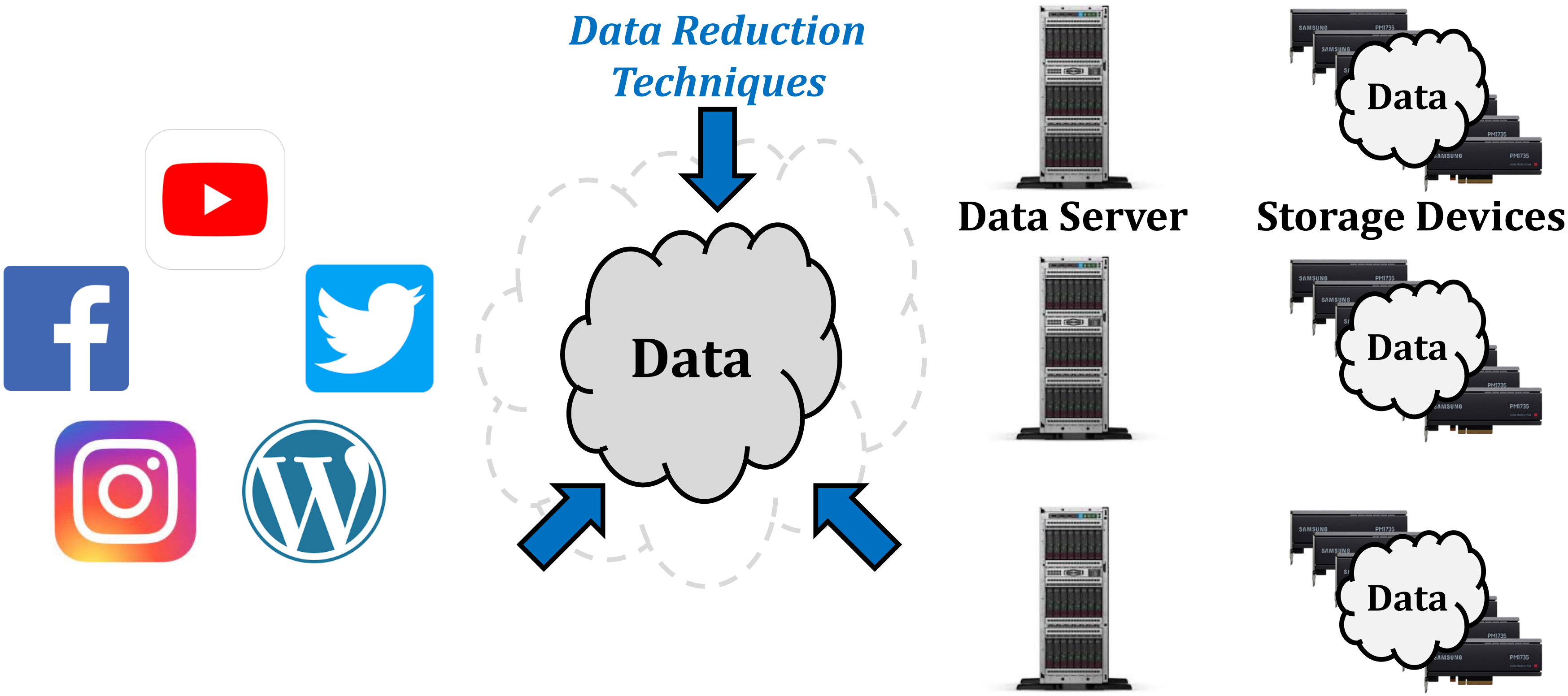
Data Reduction in Storage Systems

- Effective at reducing the management cost of a data center



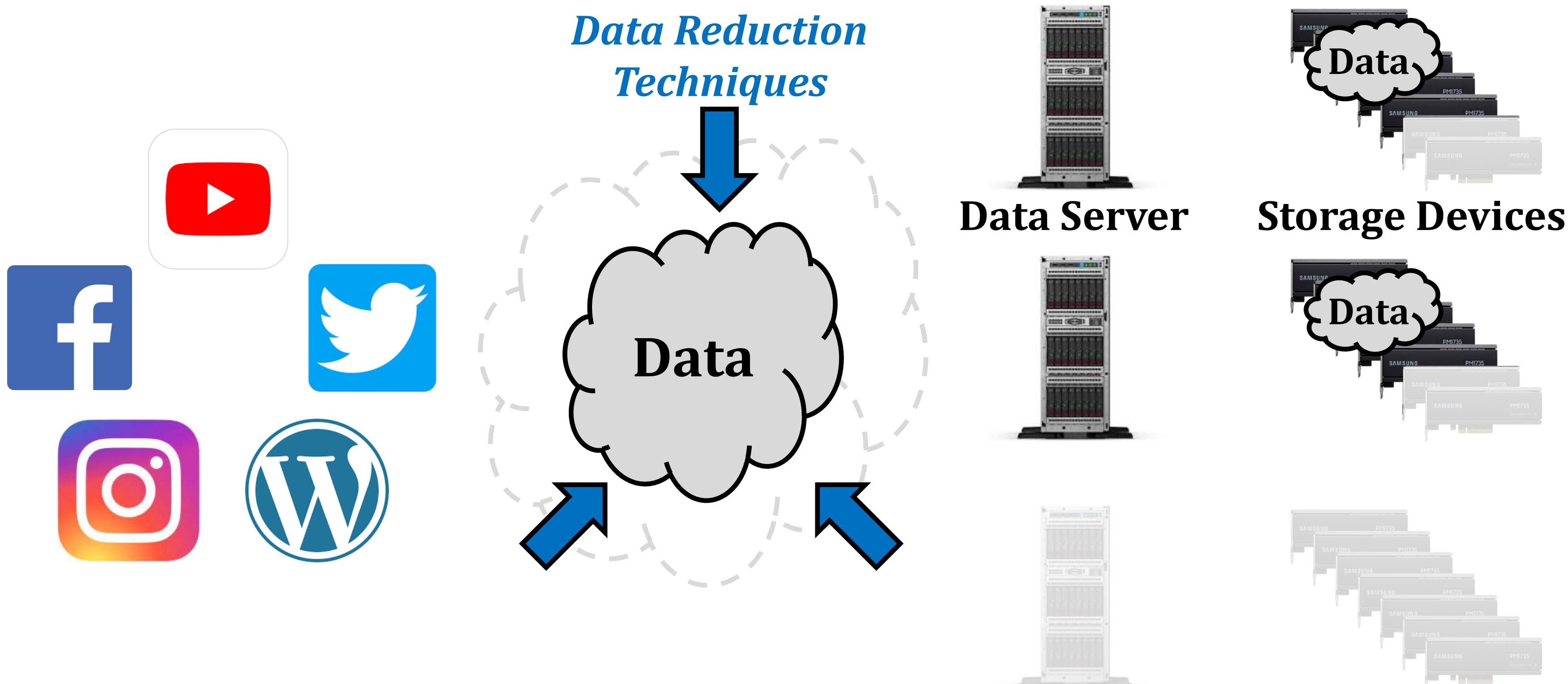
Data Reduction in Storage Systems

- Effective at reducing the management cost of a data center
  - By reducing the amount of written data to storage devices



Data Reduction in Storage Systems

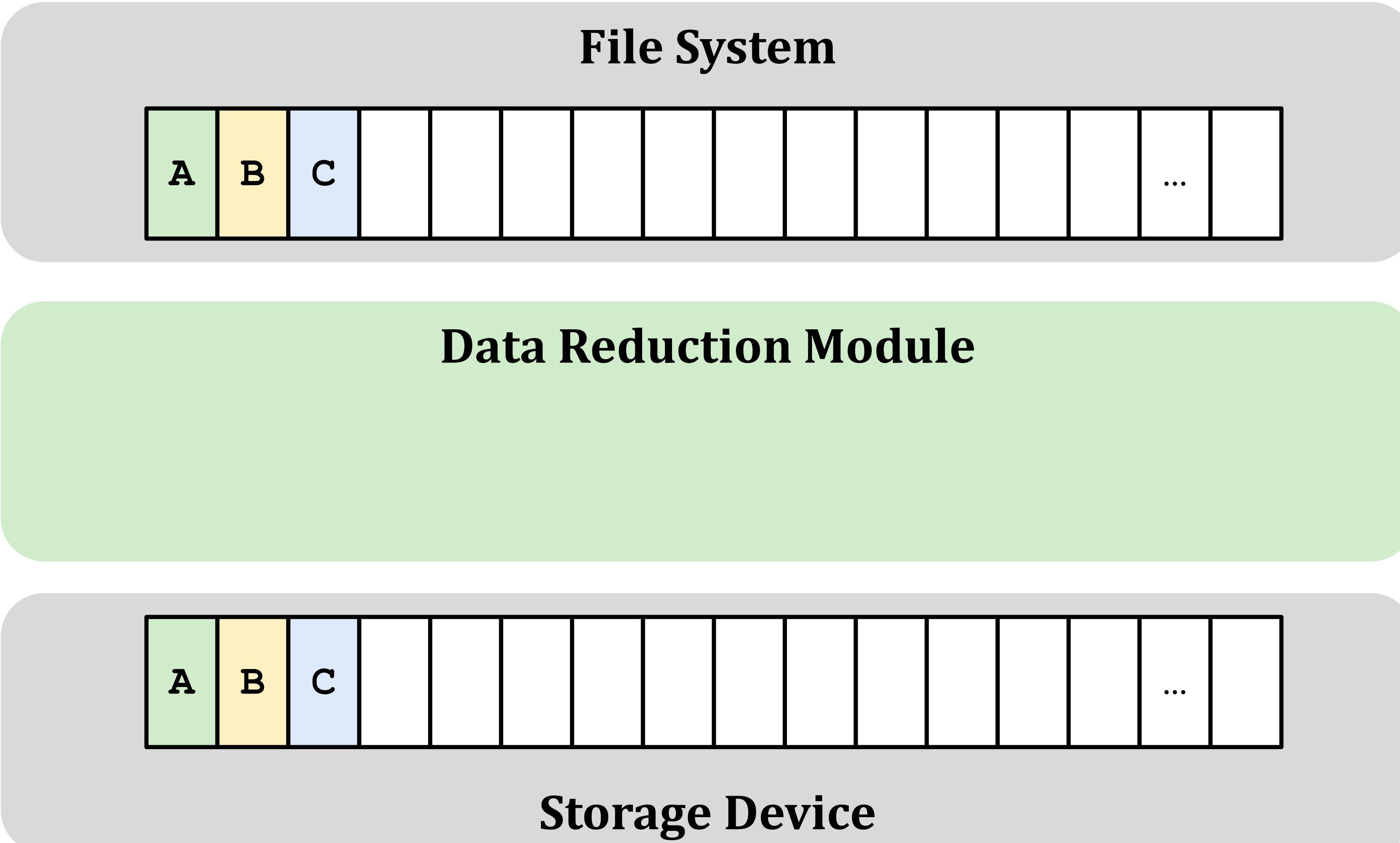
- Effective at reducing the management cost of a data center
  - By reducing the amount of written data to storage devices
  - Enabling the system to deal with the same amount of data with fewer and/or smaller storage devices



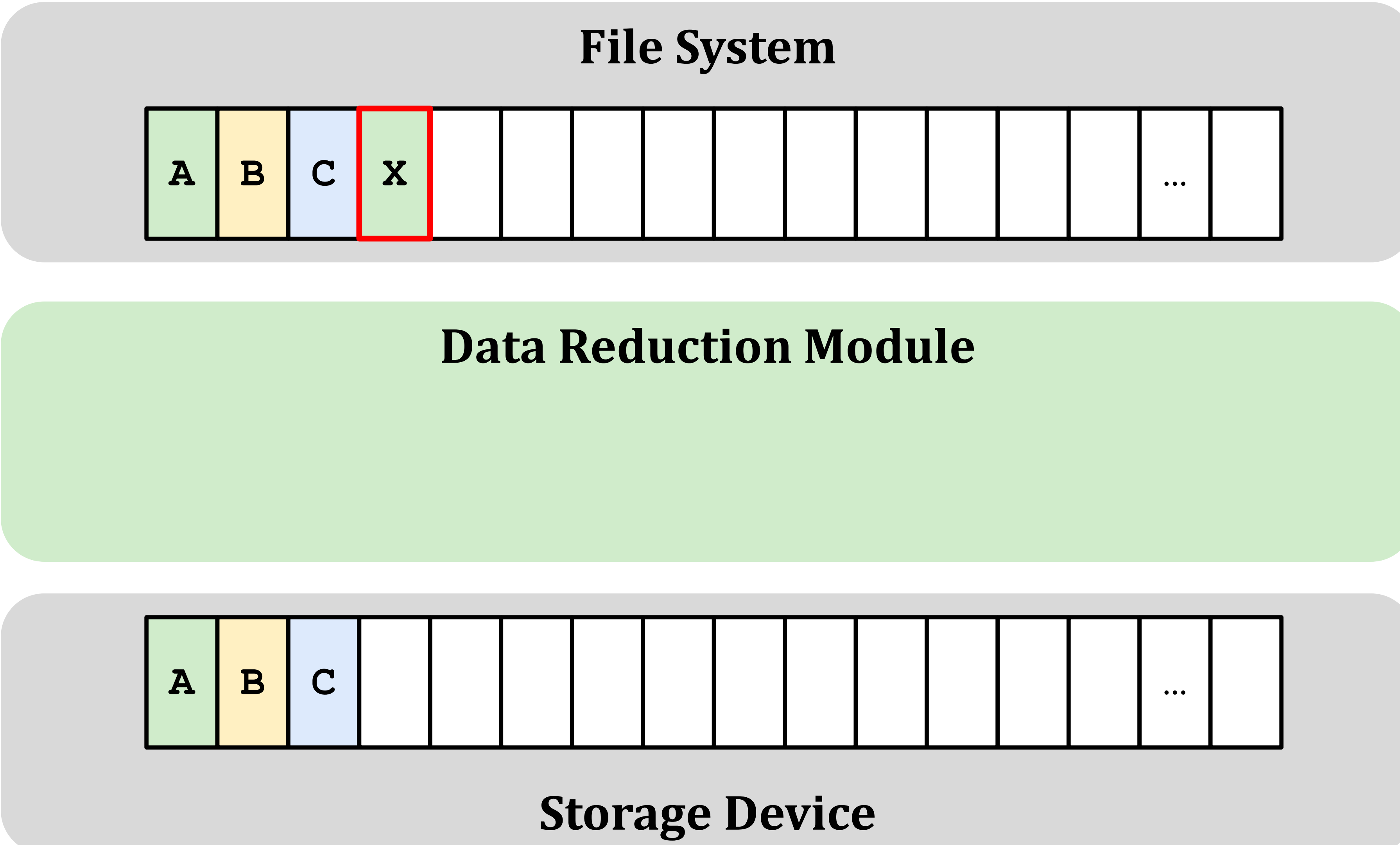
Post-deduplication Delta Compression

- Combines three different data-reduction approaches
  - To maximize the data-reduction ratio $\left(= \frac{Original\ Data\ Size}{Reduced\ Data\ Size}\right)$
  - Deduplication → Delta compression → Lossless compression
  - Can achieve more than 2x data reduction over a simple combination of deduplication and lossless compression

Overview of Post-Deduplication Delta Compression



Step 1: Deduplication



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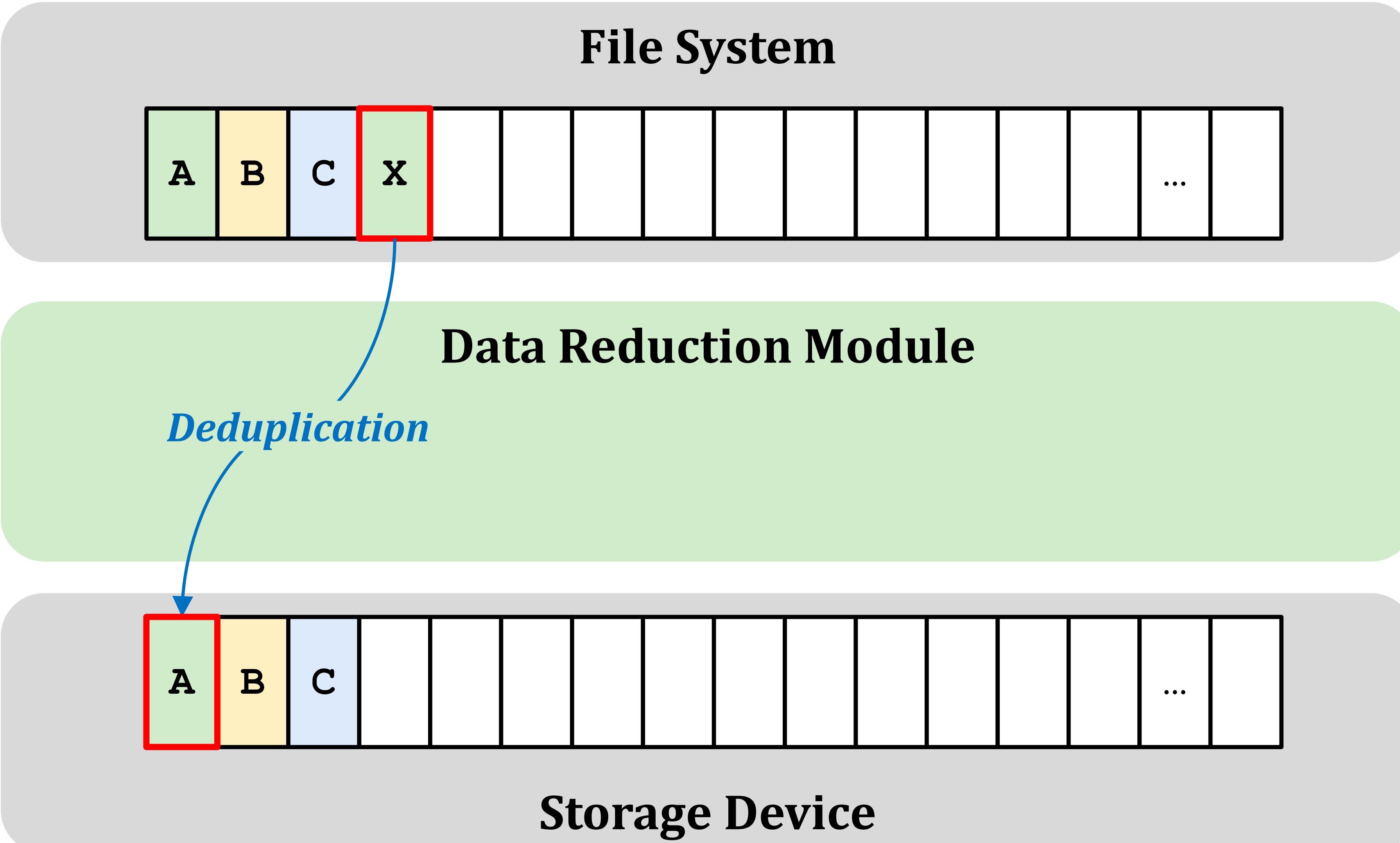
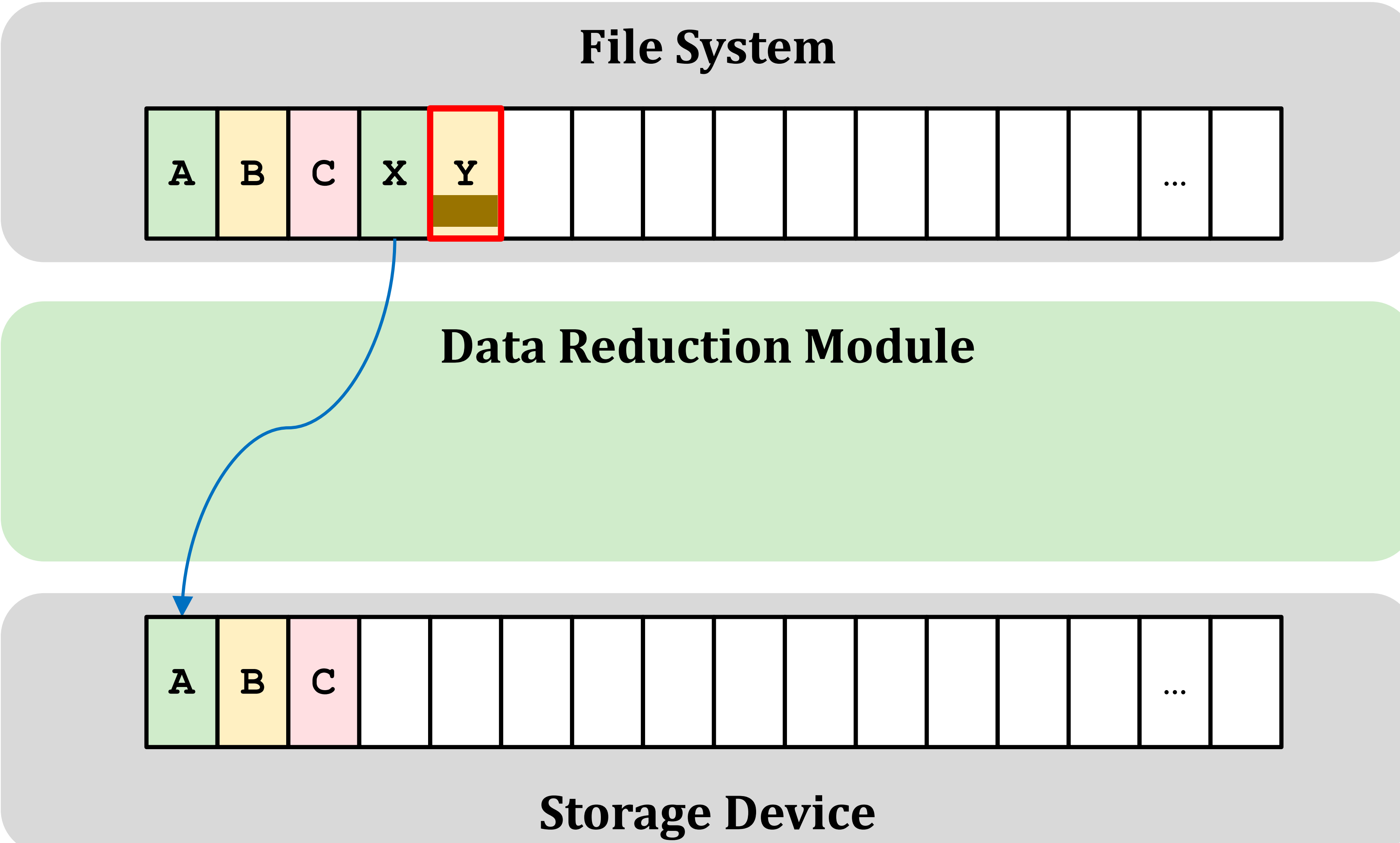


Step 2: Delta Compression



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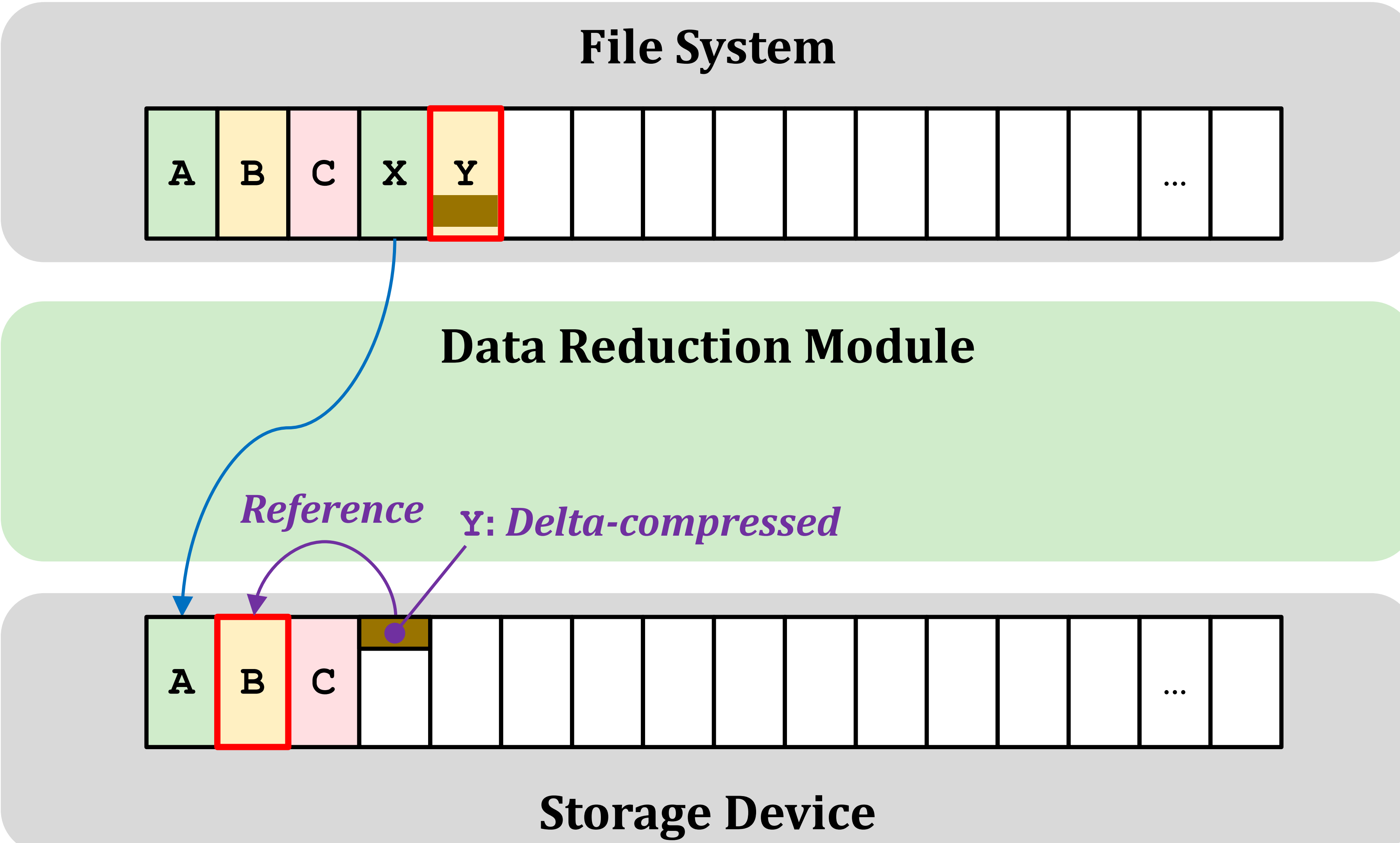
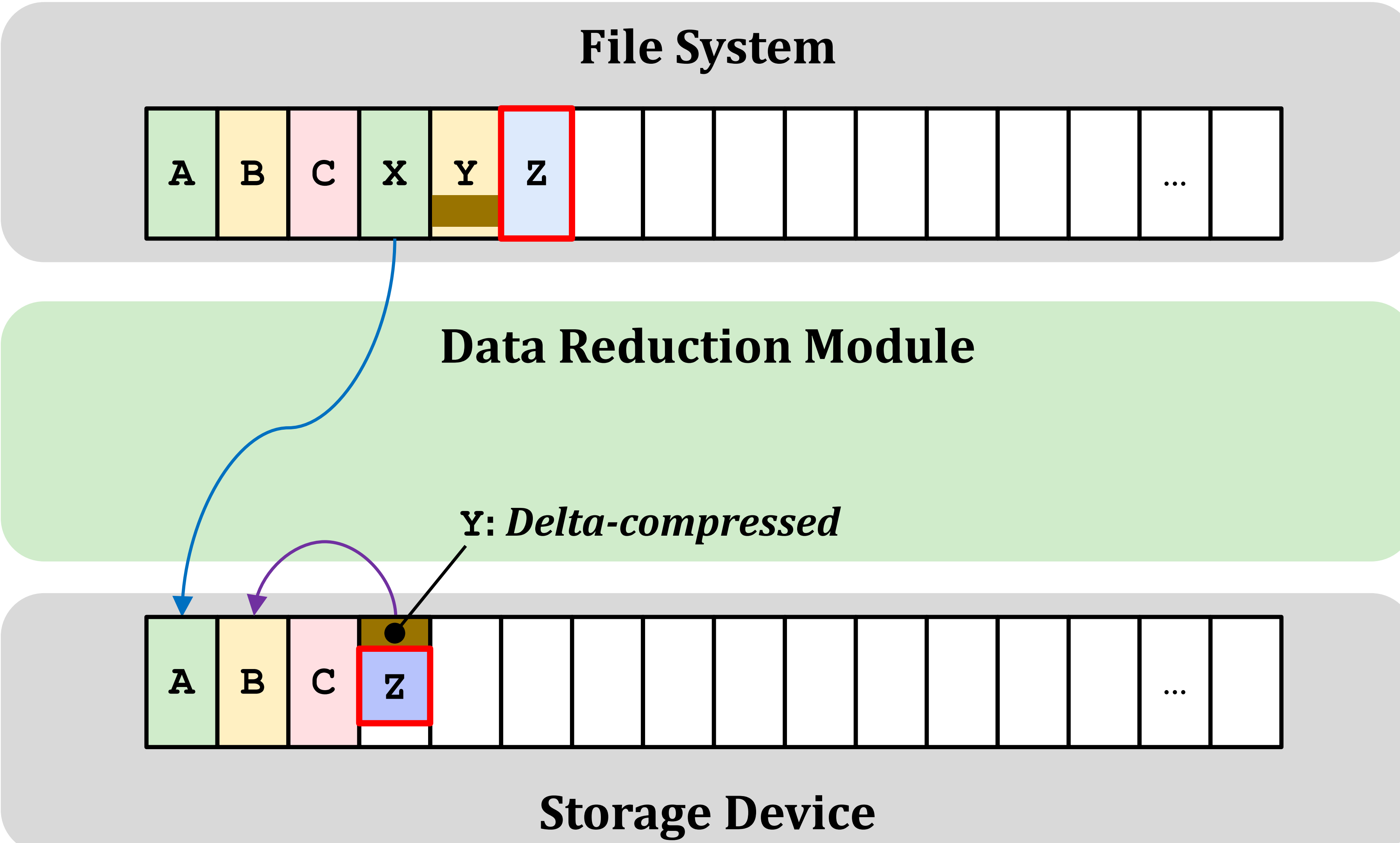


Step 3: Lossless Compression



Key Challenge: Reference Search

- How to find a good reference block for an incoming data block across a wide range of stored data at low cost

- Scanning all stored data blocks: Prohibitive performance overhead

- Reference search in deduplication
  - Uses a strong hash function (e.g., SHA1 or MD5) to generate a data block's fingerprint
  - Enables quick reference search by comparing only fingerprints

- Reference search in delta compression
  - Difficult to use a strong hash function that generates significantly different hash values for non-identical yet similar data blocks

State-of-the-Art: Data Sketching

- Generates a data signature (called sketch) of each data block
  - Sketch: More approximate signature than fingerprint
  - Goal: two similar data blocks have similar sketches

Block 1	U	S	E	N	I	X	F	A	S	T	2	0	2	2
Block 2	U	S	E	N	I	X	F	A	S	T	2	0	2	0

$Feature_1 = H_1(\texttt{SENI}) = \texttt{0x73}$

$Feature_2 = H_2(\texttt{FAST}) = \texttt{0x32}$

$Feature_3 = H_3(\texttt{USEN}) = \texttt{0xF1}$

$Feature_4 = H_4(\texttt{S202}) = \texttt{0xCC}$

$Feature_1 = H_1(\texttt{SENI}) > H_1(\texttt{2020})$

$Feature_2 = H_2(\texttt{FAST}) > H_2(\texttt{2020})$

$Feature_3 = H_3(\texttt{USEN}) > H_3(\texttt{2020})$

$Feature_4 = H_4(\texttt{S202}) > H_4(\texttt{2020})$

Super Feature

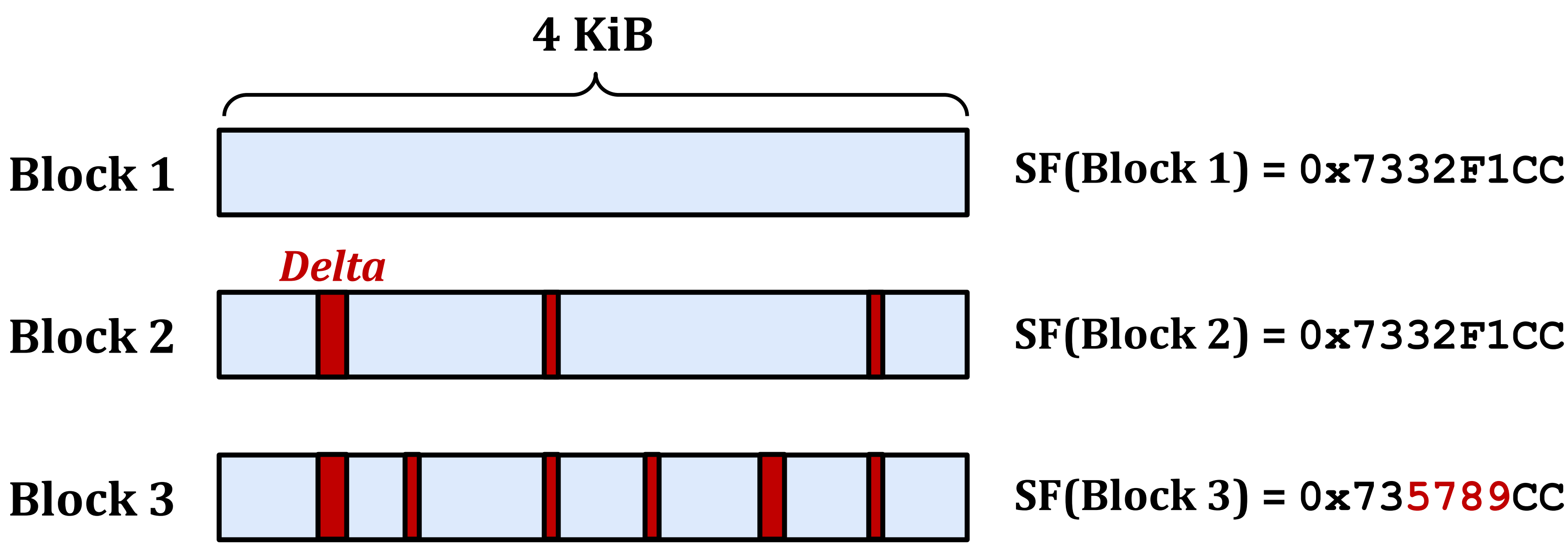
$SF(\text{Block 1}) = \texttt{0x7332F1CC}$

$SF(\text{Block 2}) = \texttt{0x7332F1CC}$

Limitations of Existing Techniques

- Provide significantly lower data-reduction ratios than the optimal
  - Due to limited accuracy in reference search for delta compression

- In a general-PC-usage workload, an SF-based approach
  - Provides only 60% of the data-reduction ratio of brute-force search
  - High false-negative ratio: Fails to find any reference data block for 36% of the incoming data blocks that can benefit from delta compression



Talk Outline

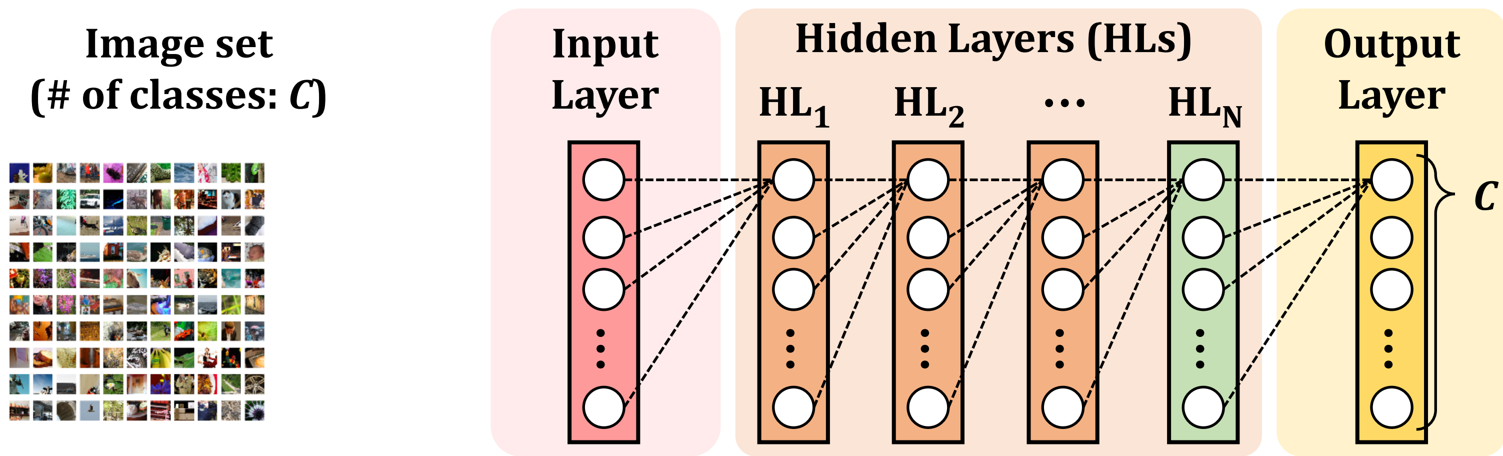
- Data Reduction in Storage Systems

- DeepSketch: A New Machine Learning-based Reference Search Technique

- Evaluation Results

DeepSketch: Key Idea

- Use the learning-to-hash method for sketch generation
  - A promising machine learning (ML)-based approach for the nearest-neighbor search problem



<Learning-to-hash for content-based image retrieval>

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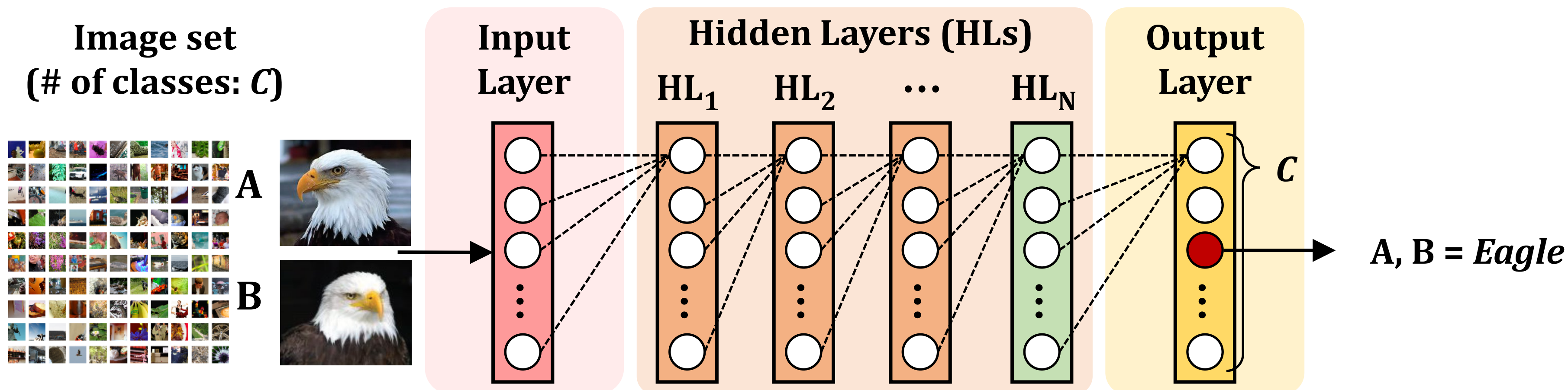

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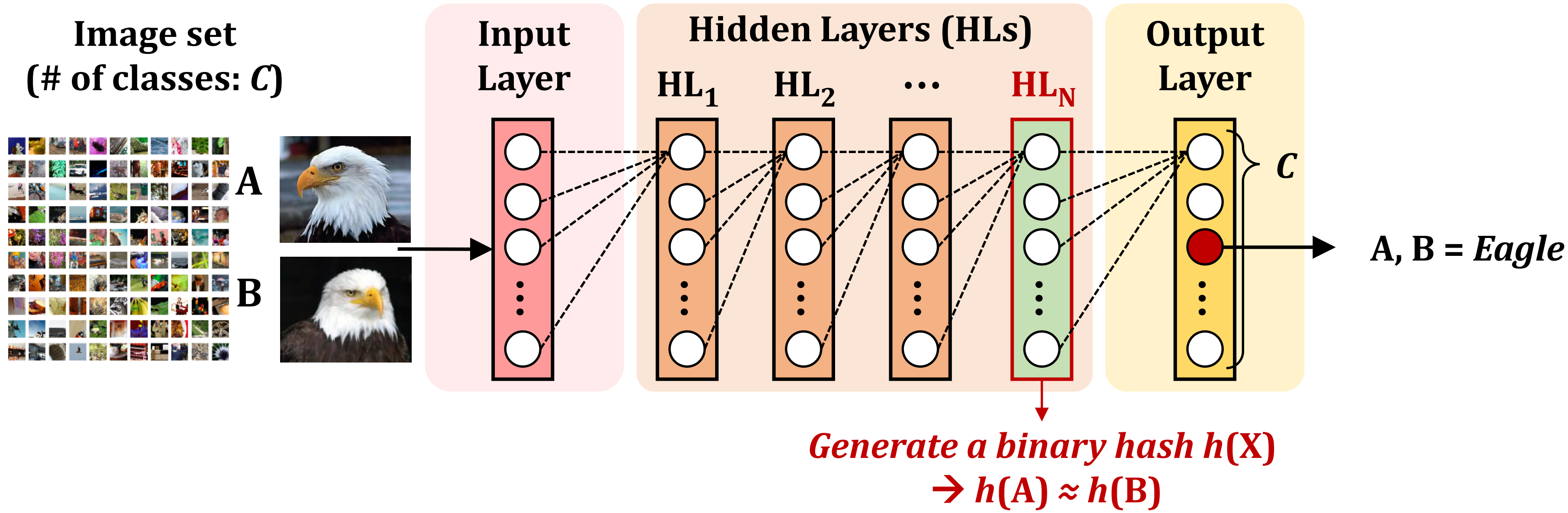
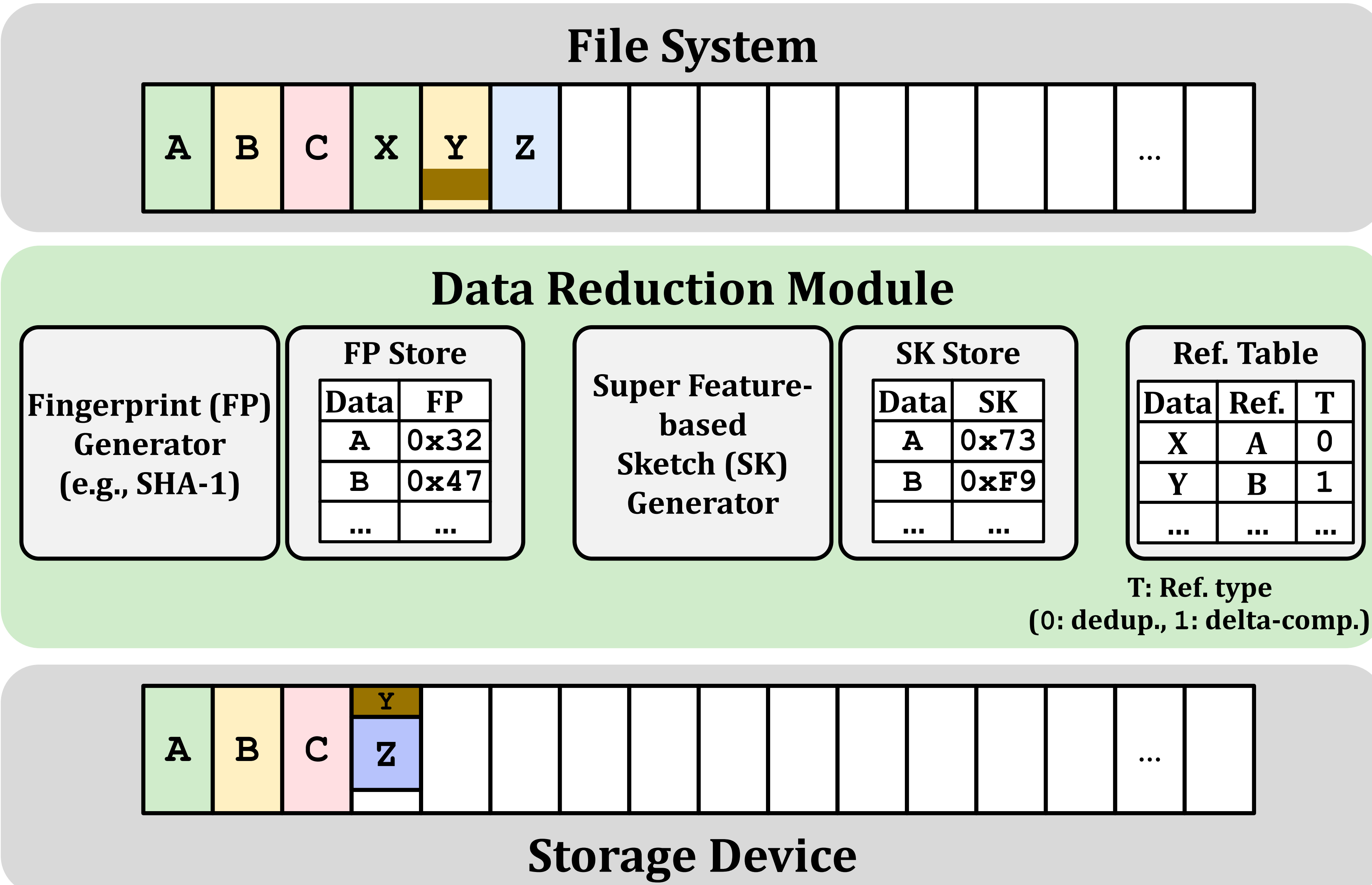
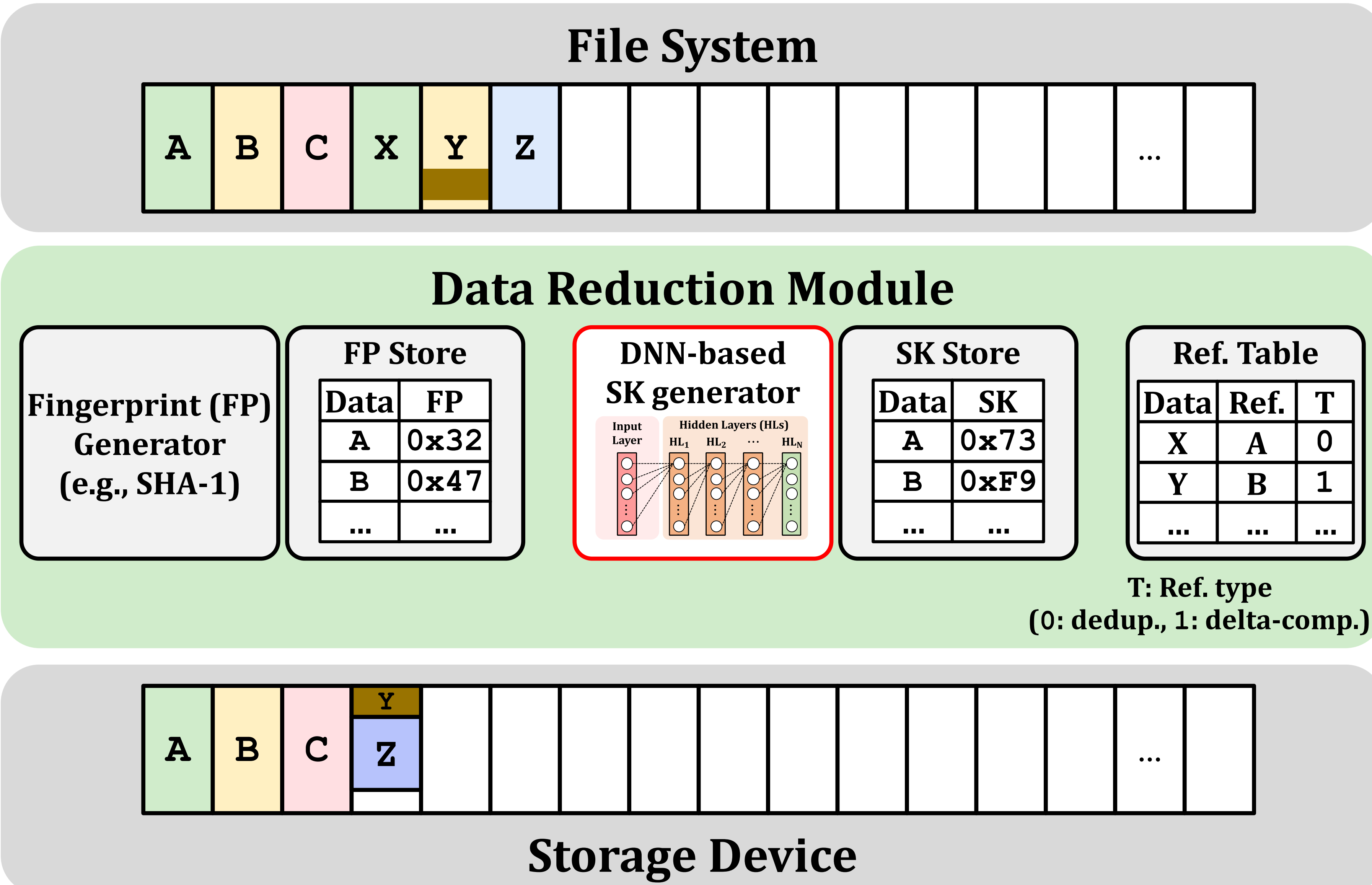


<Learning-to-hash for content-based image retrieval>

DeepSketch: Overview



DeepSketch: Overview



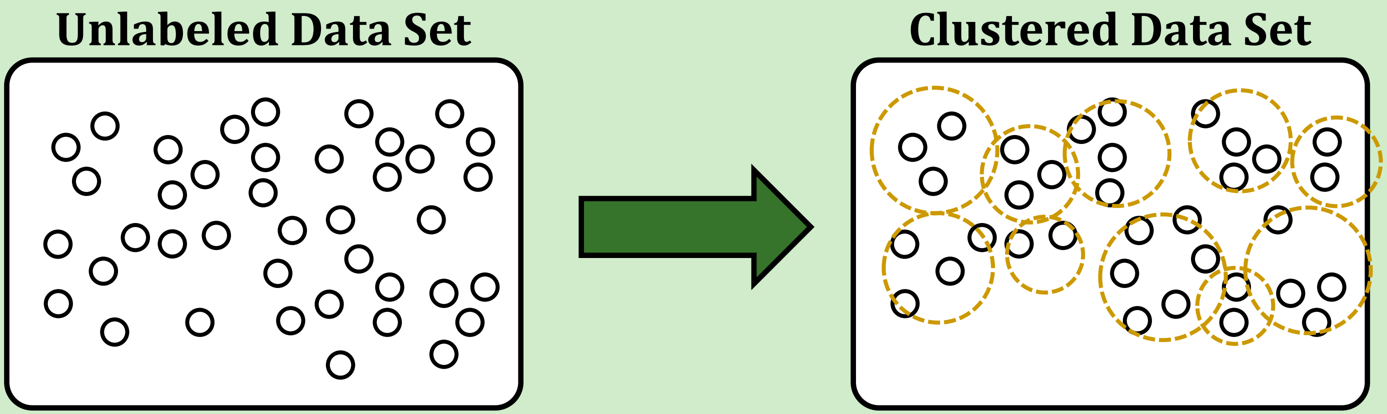
DeepSketch: Challenges

- Lack of semantic information
  - Most prior learning-to-hash approaches deal with specific data types (e.g., image sets with well-defined classes)
  - DeepSketch needs to process general binary data

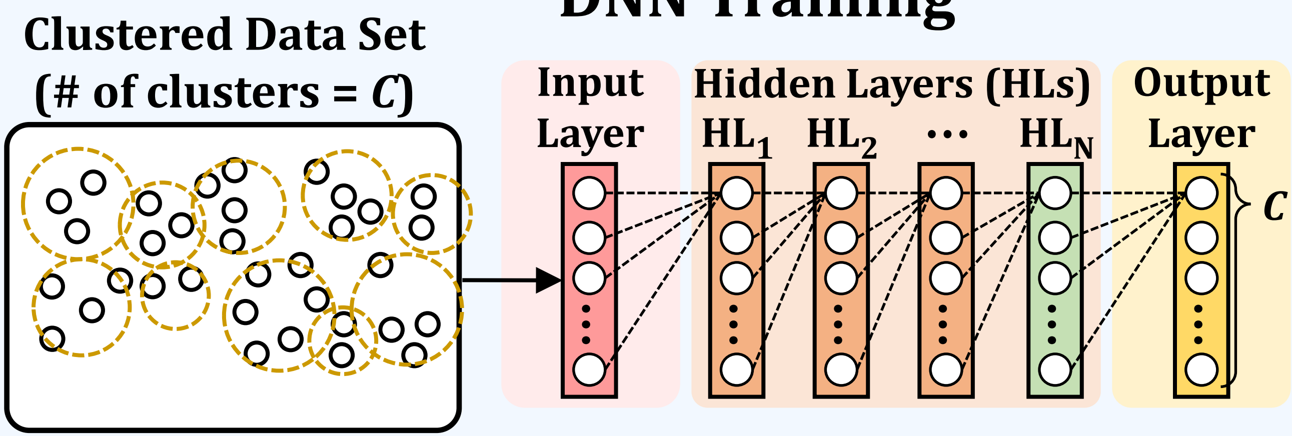
- Extremely high dimensional space
  - Possible bit patterns: $2^{4,096 \times 8}$ for a data block size of 4 KiB
  - Difficult to collect large enough data to train the DNN with high inference accuracy

Training the DNN of DeepSketch

Clustering



DNN Training



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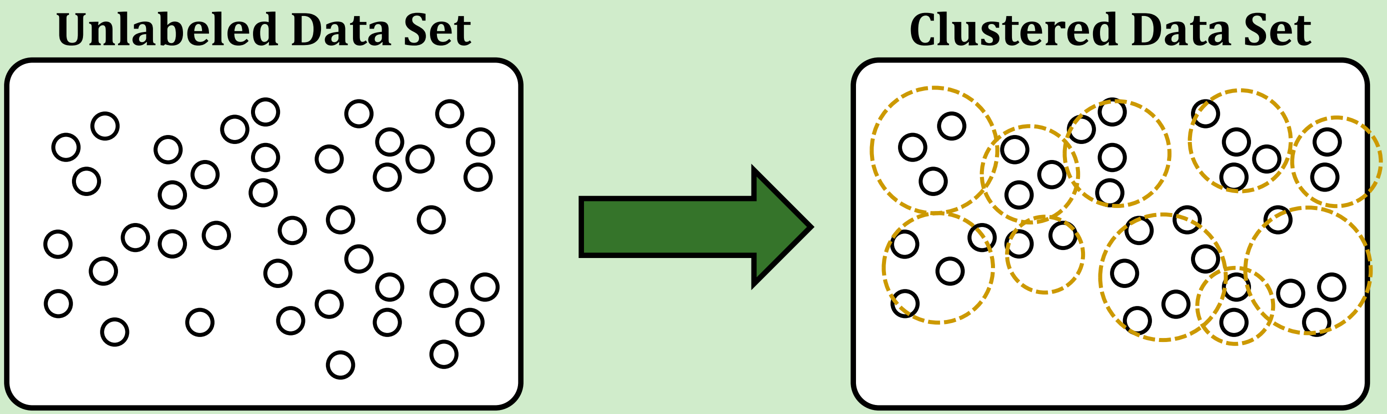

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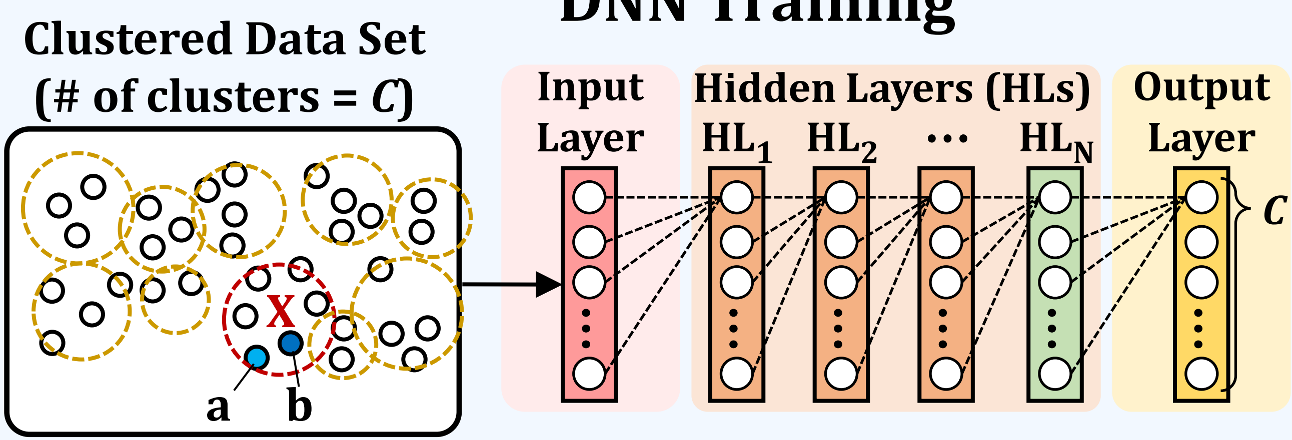

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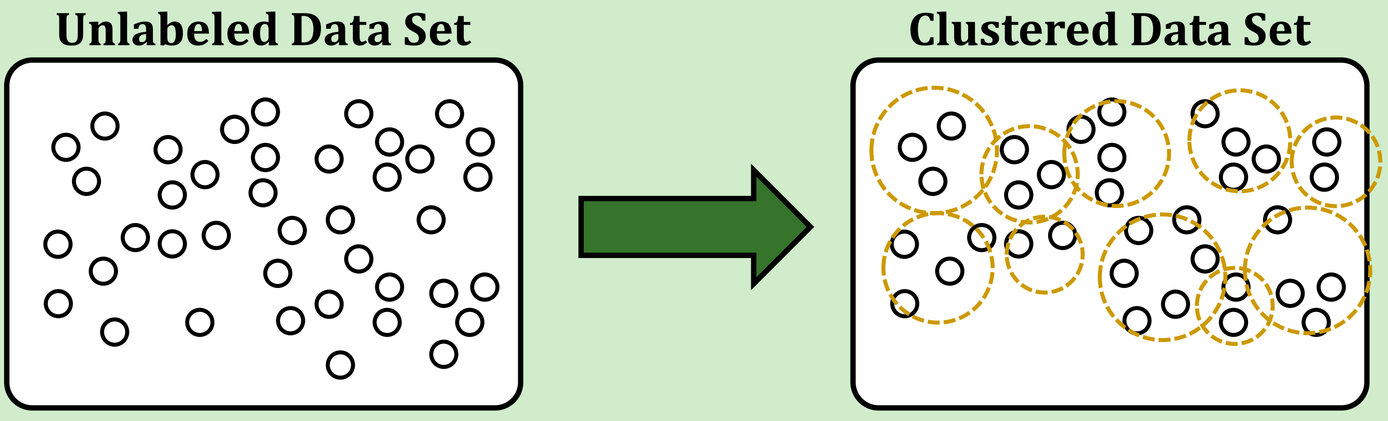

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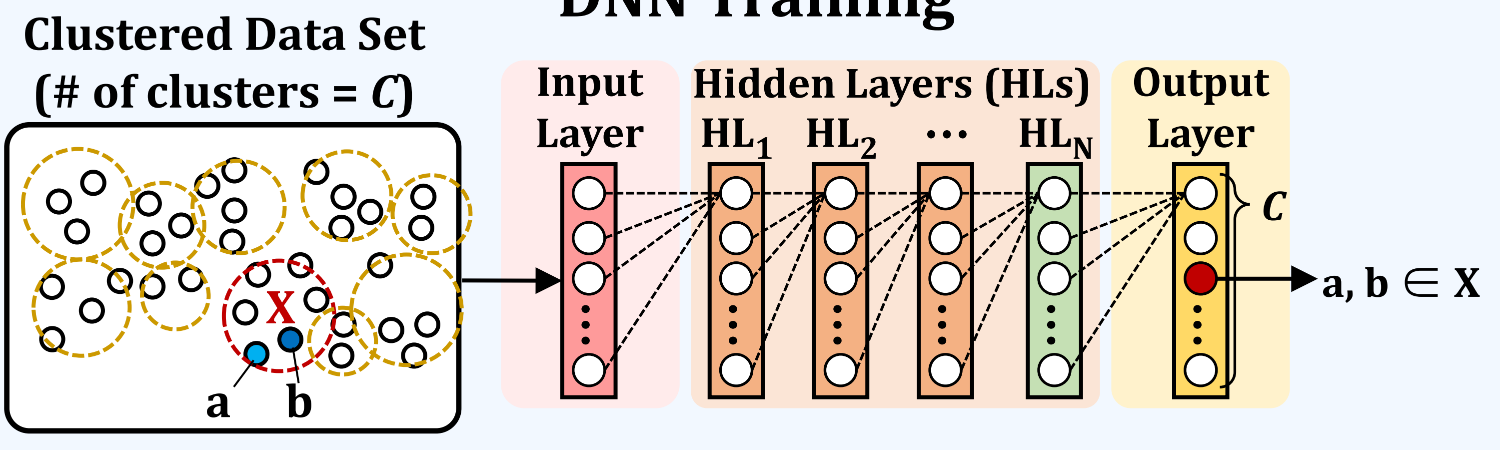

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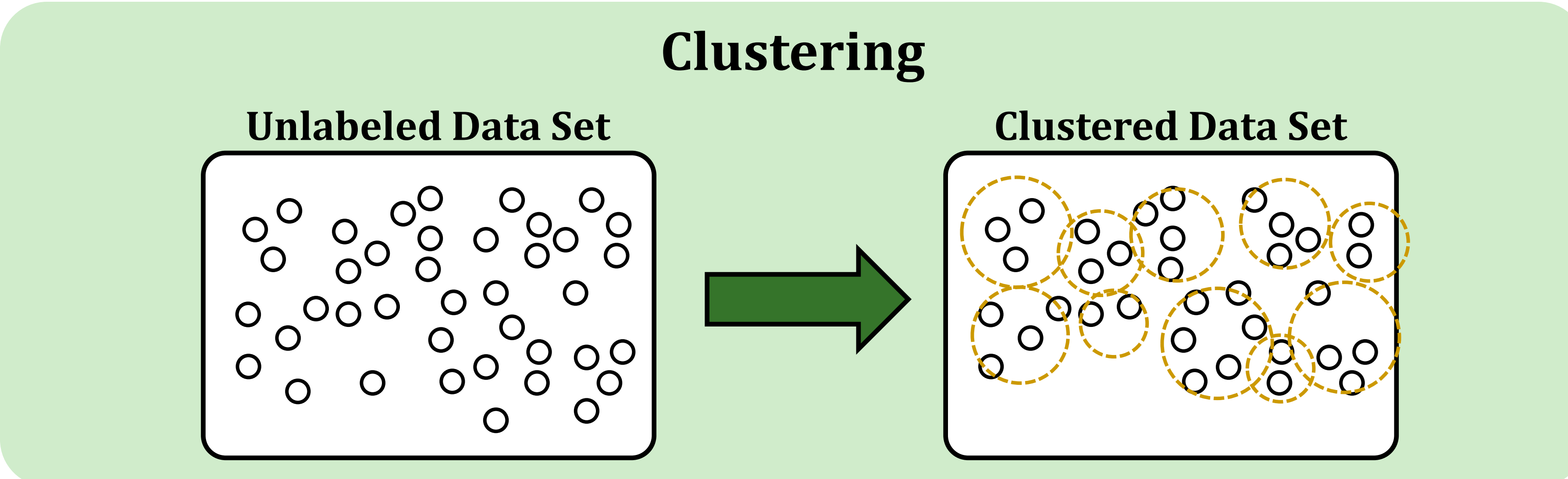
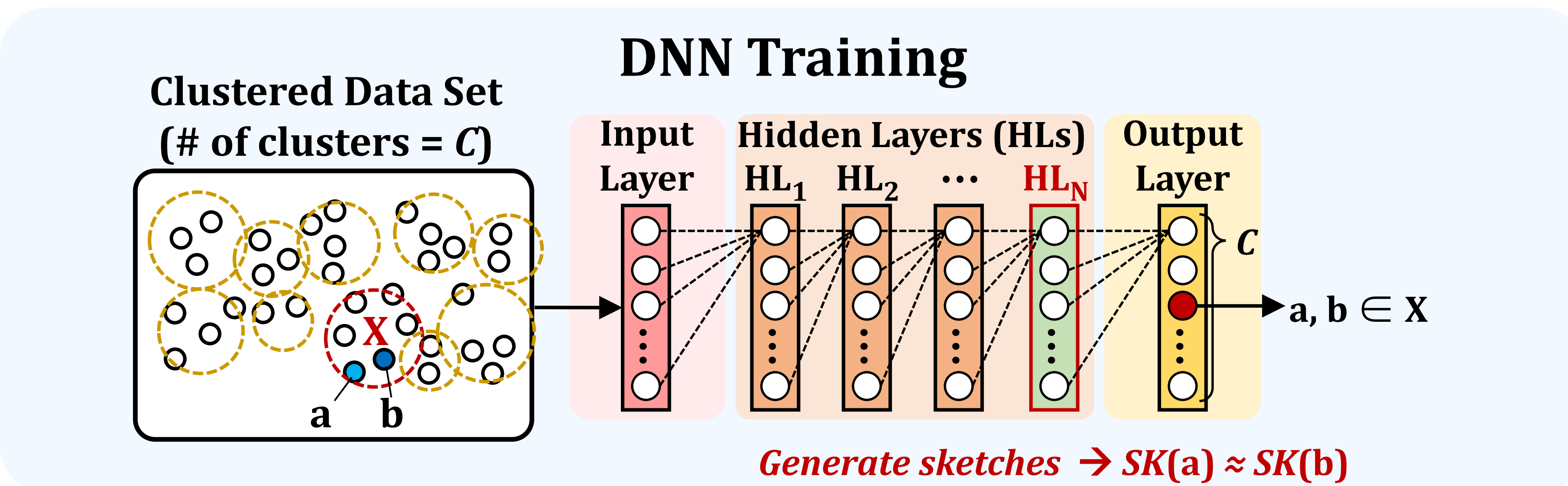




Data Clustering for DeepSketch

- Existing clustering algorithms are unsuitable for DeepSketch
  - K-means clustering: No information of appropriate initial parameter values (e.g., # of cluster *k*) in DeepSketch
  - Hierarchical clustering: Huge computation and memory overheads for large data sets

- Dynamic k-means clustering (DK-Clustering)
  - A version of k-means clustering that dynamically refines the value for *k* while clustering a data set
  - Key idea: Two-step clustering that iterates
    - Step 1: Coarse-grained clustering to roughly group data blocks at low cost and remove low-impact data blocks
    - Step 2: Fine-grained clustering to find the best mean block and outliers of each group

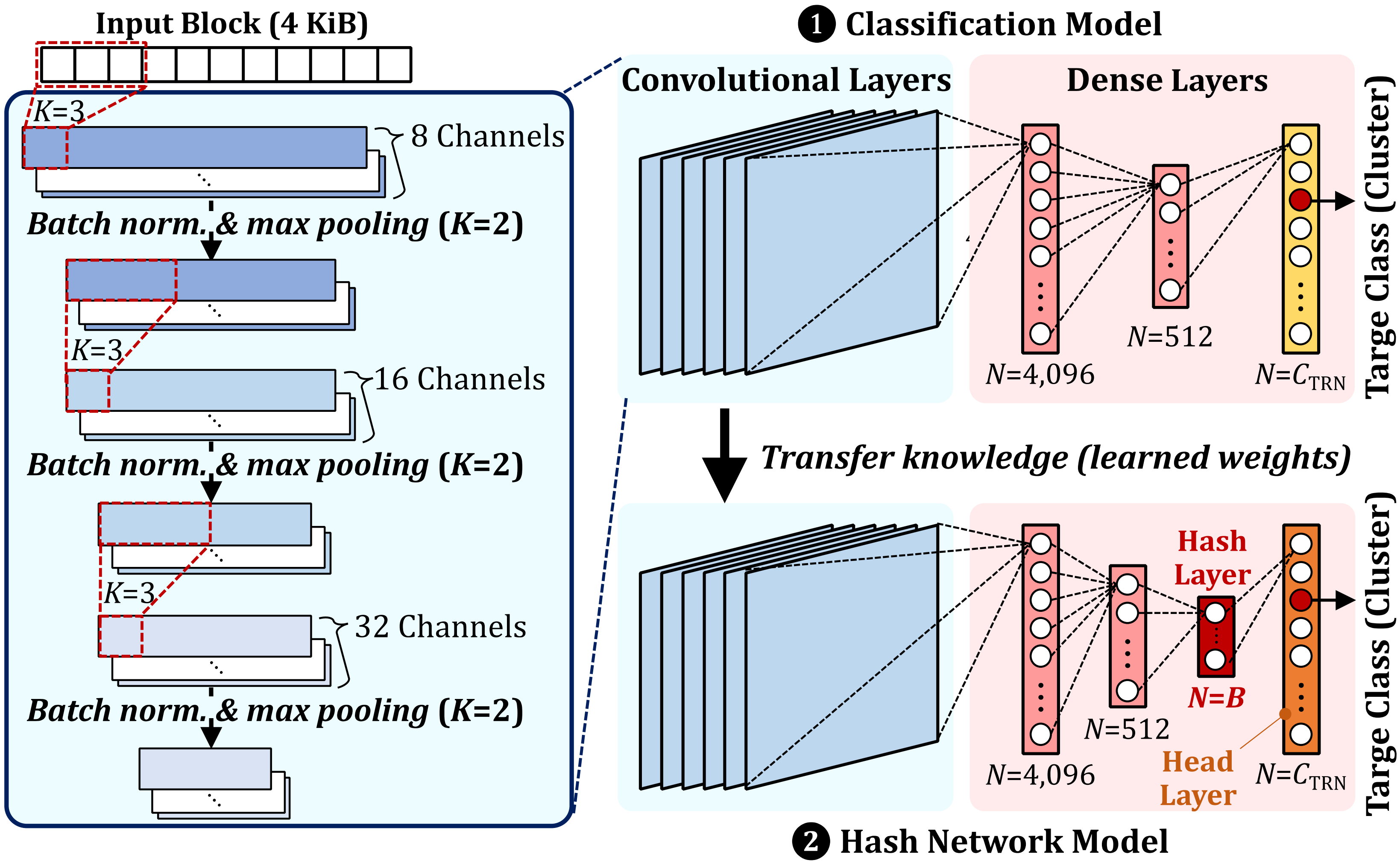
Post-Processing for Training Data Set

- Non-uniform distribution of data blocks across the clusters
  - e.g., the largest 10% clusters contain 47.93% of the total data blocks.
  - Can make DNN training significantly biased towards specific data patterns

- Resize every cluster to have the same number of data blocks
  - If # of data blocks > T → Randomly select T data blocks
  - If # of data blocks < T → Add randomly-modified data blocks (shifting random part of data blocks)

DNN Training

- Two-step transfer learning from GreedyHash [Su+, NeurIPS'18]



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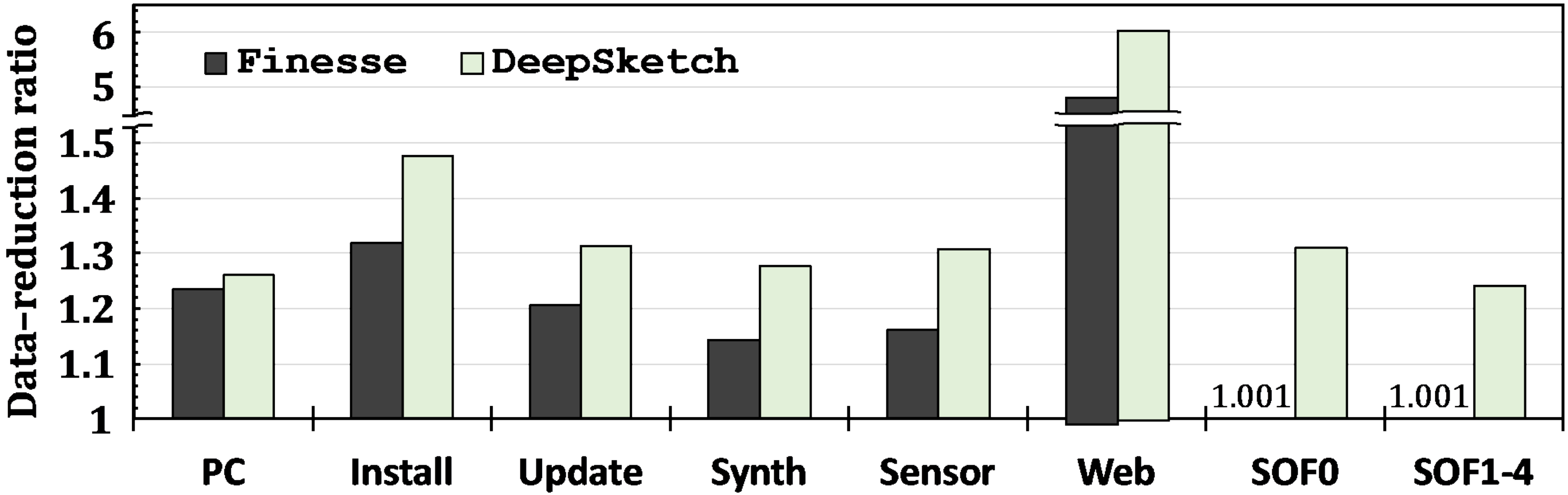
Evaluation Methodology

- Compared data-reduction techniques
  - Dedup+Comp: Deduplication → Lossless compression (LZ4)
  - Finesse [Zhang+, FAST'19]
    - High-performance super-feature-based reference search
    - Deduplication → Delta compression (XDelta) → LZ4
- Workloads
  - Six workloads collected from real systems w/ written data
    - PC, Install, Update, Synth, Sensor, Web
    - 10% of each trace: Training data set
    - Remaining 90%: Data-reduction & performance evaluation
  - Five workloads collected while storing Stack Overflow databases (SOF)
    - Not used for training
    - To see the generality of DeepSketch

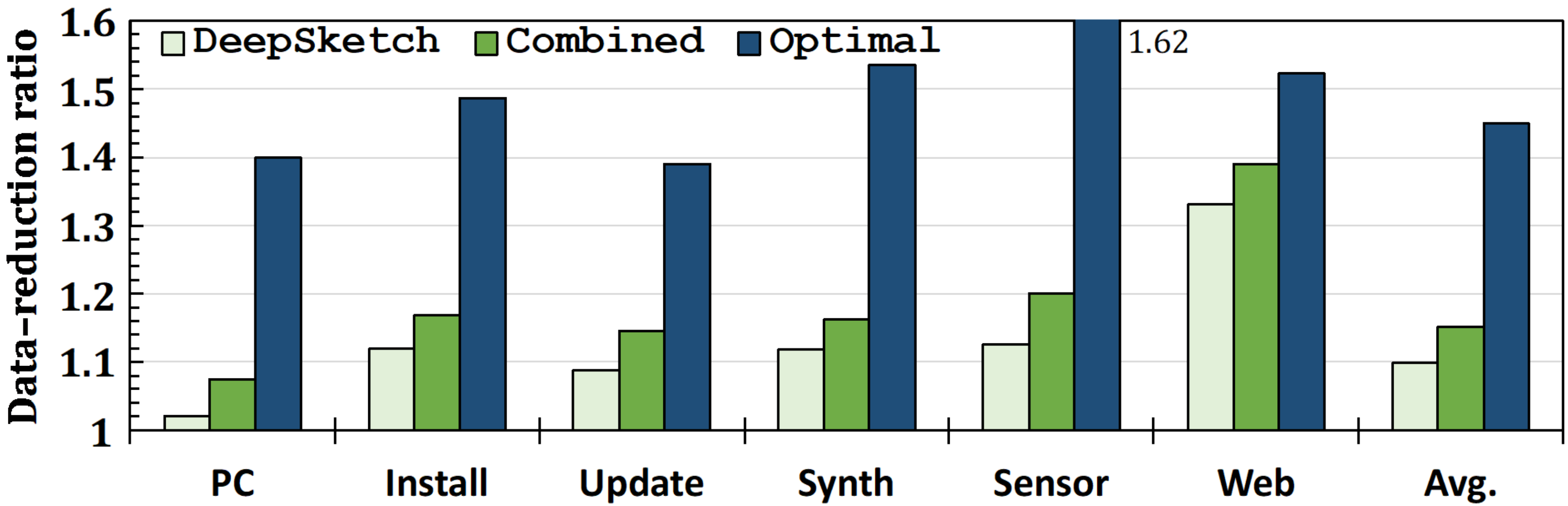
Overall Data-Reduction Benefits



Large data-reduction improvement:
Up to 33% (21% on average)

Effective for unseen workloads (SOFs)
that cannot benefit from the state-of-the-art

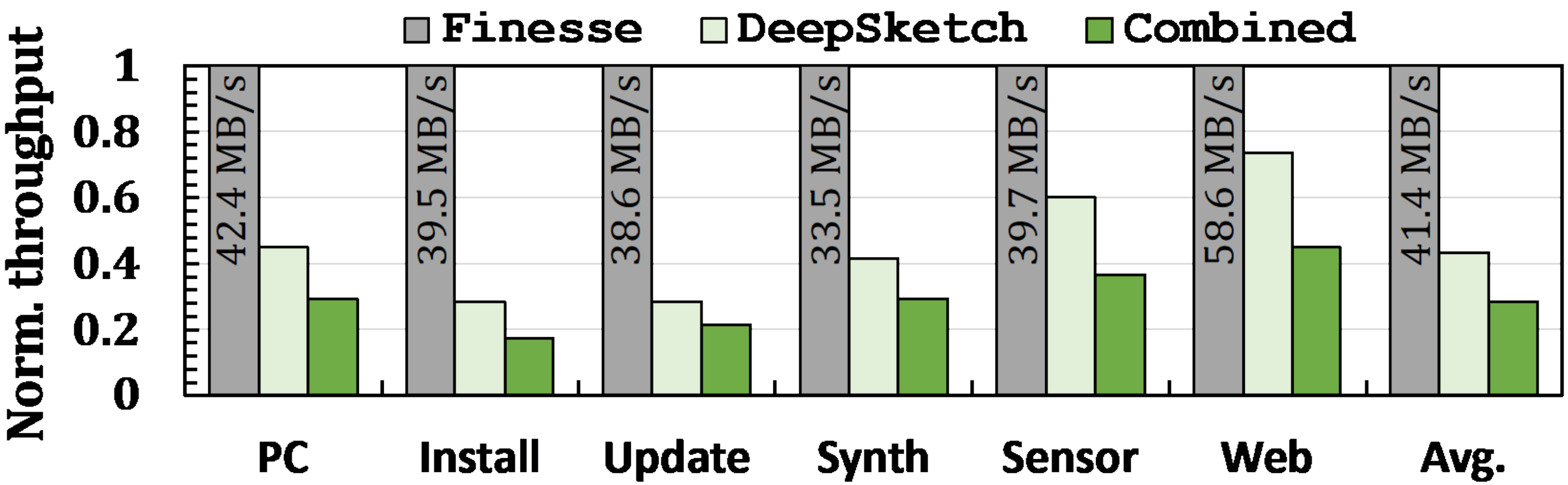
Combined w/ Existing SF-Based Technique



Higher benefits over stand-alone techniques:
DeepSketch and Finesse can complement each other

Call for future work: Significant room for improvement

Performance Overhead



Call for future work: Non-trivial performance overheads due to approximate nearest-neighbor search (details in the full paper)

Other Analyses in the Paper

- Empirical Study on Super Feature-Based Reference Search
- Hyper-Parameter Exploration for DeepSketch's DNN
- Performance and Space Overheads
- Reference Search Patterns of DeepSketch and Finesse
- Impact of Training Data Set

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- **Key Idea:** DeepSketch, a new machine learning-based reference search technique that uses the learning-to-hash method
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We hope that our key ideas inspire many valuable studies going forward

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DeepSketch: Application Scenarios