10. Capacity Optimization

Special Topics in Computer Systems:
Modern Storage Systems
(IC820-01)

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Capacity Optimization

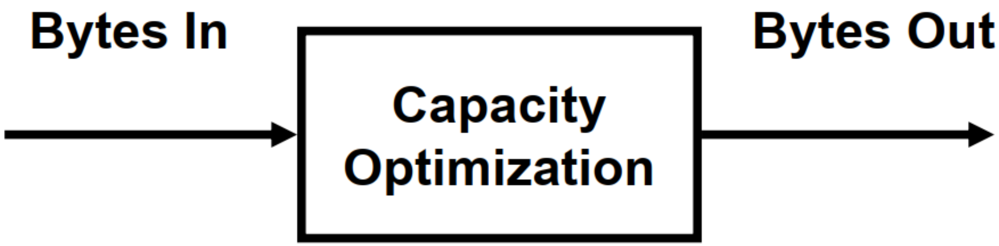
storage capacity를 향상시키기 위한 방법에는 다음의 두 가지가 유명하다.
1. Data Deduplication
2. Data Compression

- **There are two popular methods to improve storage capacity**
  - **Method 1: *Data Deduplication***
    - The replacement of multiple copies of data with references to a shared copy in order to save storage space
  - **Method 2: *Data Compression***
    - The encoding of data to reduce its storage requirements

- **Widely used in modern storage systems and devices**
  - Not only improve *storage capacity*, but *I/O performance* and *energy efficiency*

단순히 capacity를 늘리는 효과뿐만 아니라,
I/O performance와 energy efficiency를 증대시키는 효과까지 있다.

Space Reduction Ratio & Percent



$$\text{Ratio} = \frac{\text{Bytes In}}{\text{Bytes Out}} \qquad \% = \frac{\text{Bytes In} - \text{Bytes Out}}{\text{Bytes In}}$$

들어온 양보다
얼마나 줄였는지에 대한 비율.

$$\text{Ratio} = \left(\frac{1}{1 - \%}\right) \qquad \% = 1 - \left(\frac{1}{\text{Ratio}}\right)$$

Space Reduction Ratio & Percent (Cont.)

Space Reduction Ratio	Space Reduction Percent
2:1	1/2 = 50%
5:1	4/5 = 80%
10:1	9/10 = 90%
20:1	19/20 = 95%
100:1	99/100 = 99%
500:1	499/500 = 99.8%

- Ratios can meaningfully be compared only under the same set of assumptions
- Relatively low space reduction ratios provide significant space savings

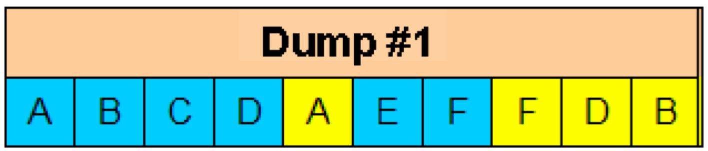
500 byte 들어왔는데 나가는 게 1 byte 뿐이다
-> 499/500 = 99.8% Space Reduction Percent

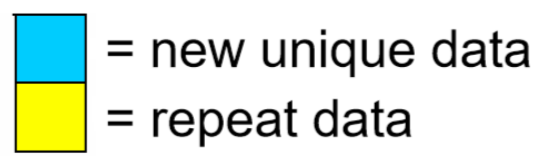
이런 term들은 기억해두는 게 좋다.

Outline

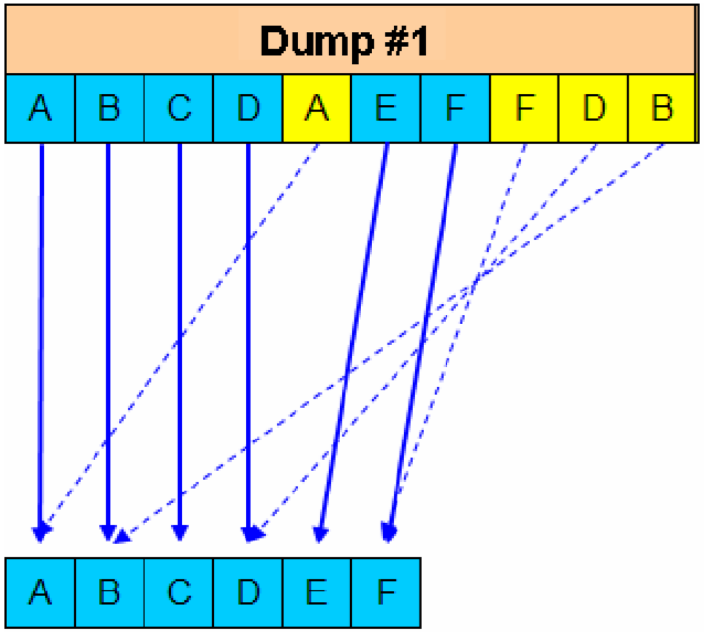
- Data Deduplication
- Data Compression
- Case Studies

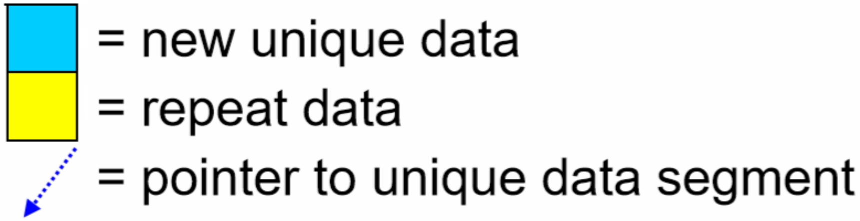
Data Deduplication Simplified



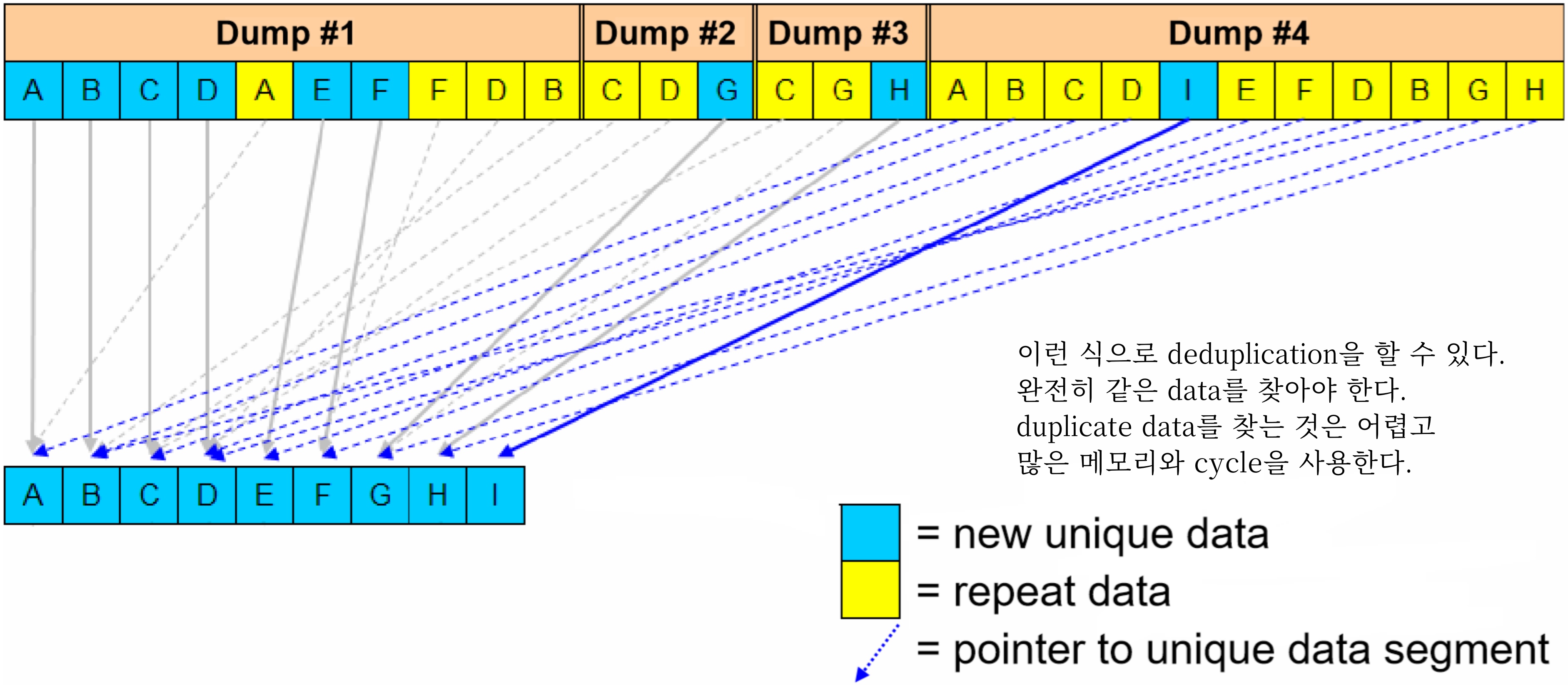


Data Deduplication Simplified (Cont.)



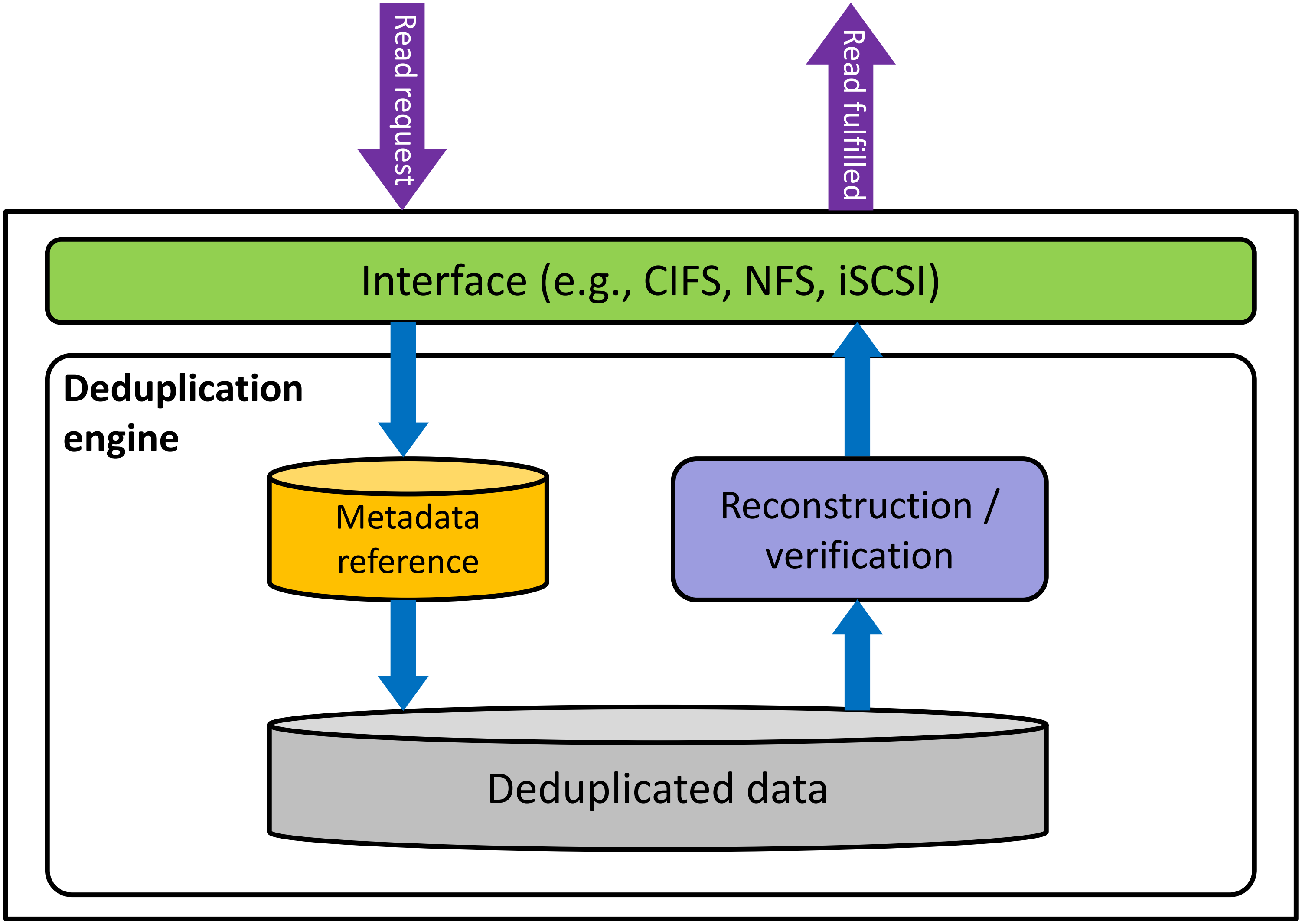


Data Deduplication Simplified (Cont.)

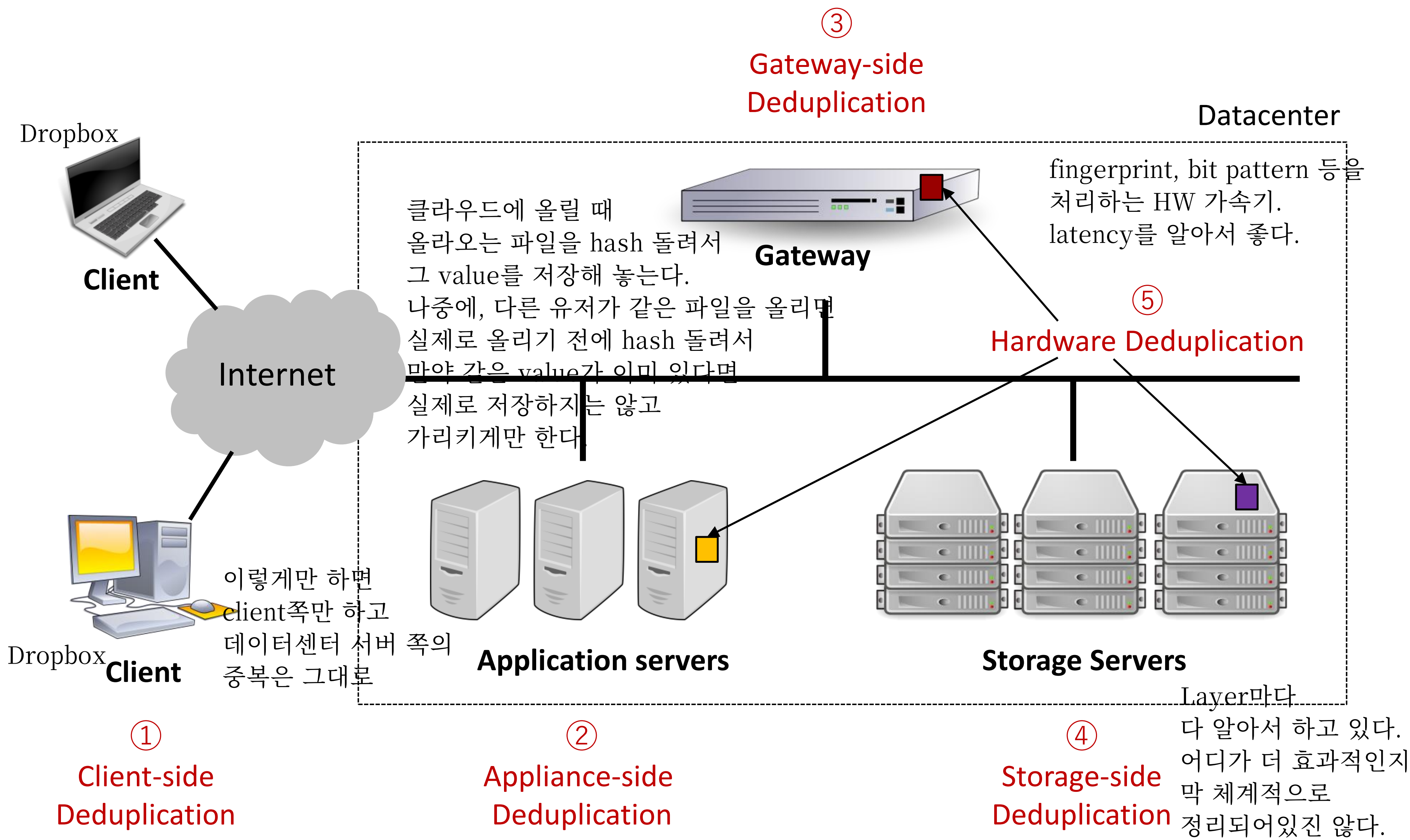


이런 식으로 deduplication을 할 수 있다.
완전히 같은 data를 찾아야 한다.
duplicate data를 찾는 것은 어렵고
많은 메모리와 cycle을 사용한다.

Reading Duplicated Data



Where is Dededupliation Deployed?



Source and Target

Dedup을 Source에서 하냐, Target에서 하냐.

- ***Source Deduplication***

  애초에 Source인 client에서 dedup해서 unique한 data만 server에게 보낸다.

  - Identifies duplicate data at the client
  - Transfers unique segments to a central repository
  - Separate client and server components

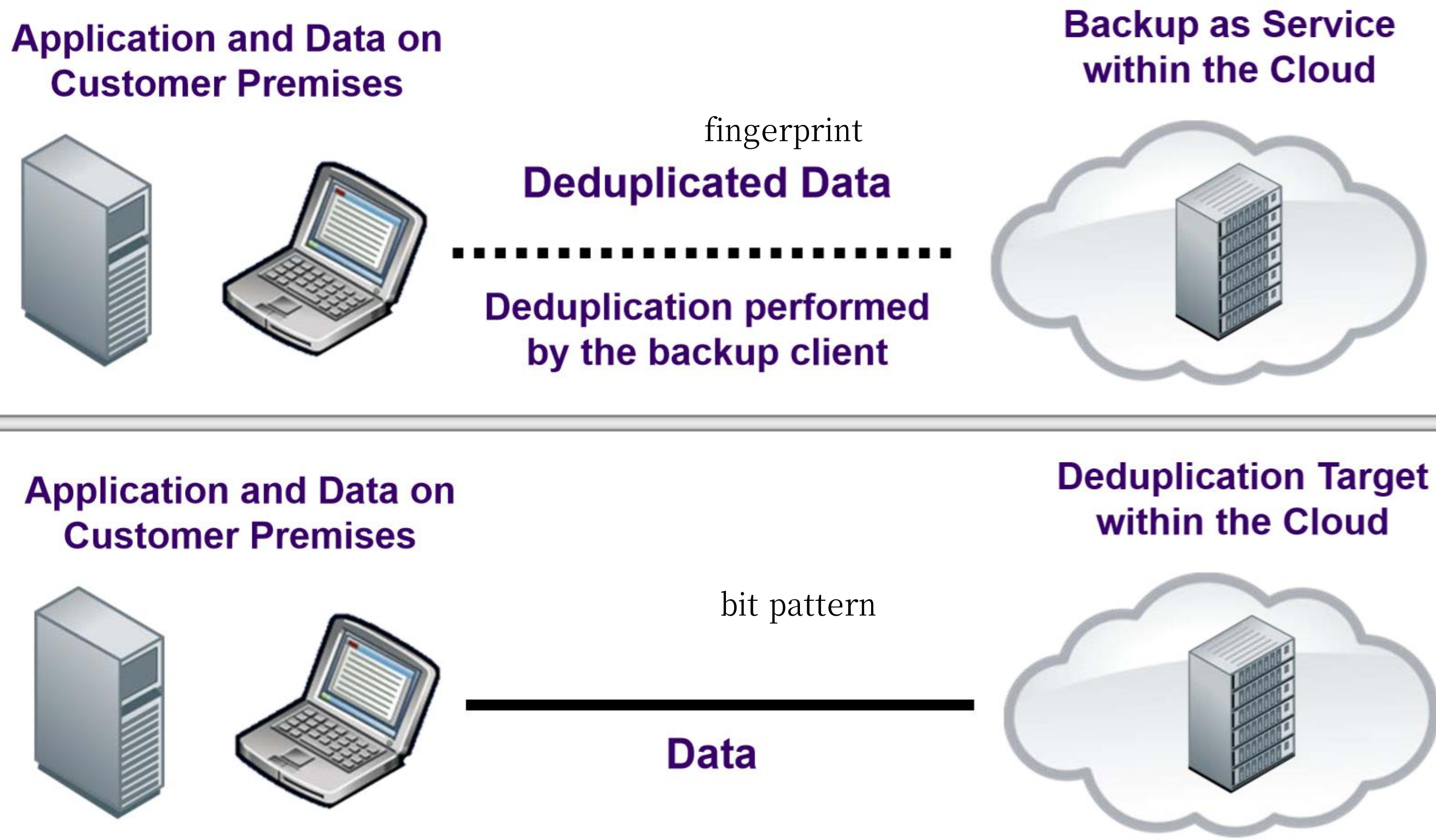
- ***Target Deduplication***

  Target인 server에서 host에게 데이터를 받아서 dedup한 뒤 저장한다.

  - Identifies duplicate data where the data is being stored
  - Stores unique segments
  - Standalone systems

- **Consideration**
  - Neither approach enables a greater or lesser space savings
  - Scope of data deduplication may vary by implementation

Source and Target (Cont.)



Inline or Post-Process

Inline과 Post - Process

Inline Deduplication

- Data deduplication performed *before* writing the duplicate data
- May improve I/O performance
- Low deduplication ratio

들어올 때 line에서
가속기가 제거

Post-process Deduplication

- Data deduplication performed *after* the data to be deduplicated has been initially stored
- May degrade I/O performance
- High deduplication ratio

저장된 후에 조사해서 dedup하니까
느리지만 효과는 좋다.

Fixed or Variable Size Segment

Dedup을 Fixed - length segment 기준으로 하느냐,
Variable - length segment 기준으로 하느냐.

■ *Subfile Data Deduplication*

- ***Fixed-length Segment Deduplication***
  - Evaluation of data includes a fixed reference window used to look at segments of data during deduplication process
  - Provide fixed granularity (e.g., 4 KB, 8 KB, or 128 KB)

4KB 중 조금만 다르면 안된다.
그래서 그런 애들만
1KB로 잘라서 dedup하면 잘 될 것.
그런데 어떻게 판단? 어렵다.

- ***Variable-length Segment Deduplication***
  - Evaluation of data uses a variable length window to find duplicate data in stream or volume of data processed
  - Provide variable granularity

variable length window로 duplicate data를 찾아서
dedup하기.

■ *Single Instance Deduplication*

- Operate at a granularity of an entire file or data object

Outline

- Data Deduplication
- Data Compression
- Case Studies

Data Compression

data loss를 허용하나 않느냐

- **Lossless versus lossy compression**
  - Lossless compression means that no information is lost when a file is compressed and then uncompressed
  - Lossy compression usually results in better compression ratio, but some information is lost

- **For data storage, lossless compression is mainly used**

LZ1 algorithm이 sliding window history buffer에서 매칭되는 data를 찾는다.

  - LZ1-Based algorithm combined with Huffman encoding
    - LZ1 algorithm to identify matches in a sliding window history buffer
    - A post encoder to Huffman encode the matches and literals
  - Hardware and software implementations

LZ1 Architecture

- A ***String-Matcher*** searches a History-Buffer to find repeating strings of bytes

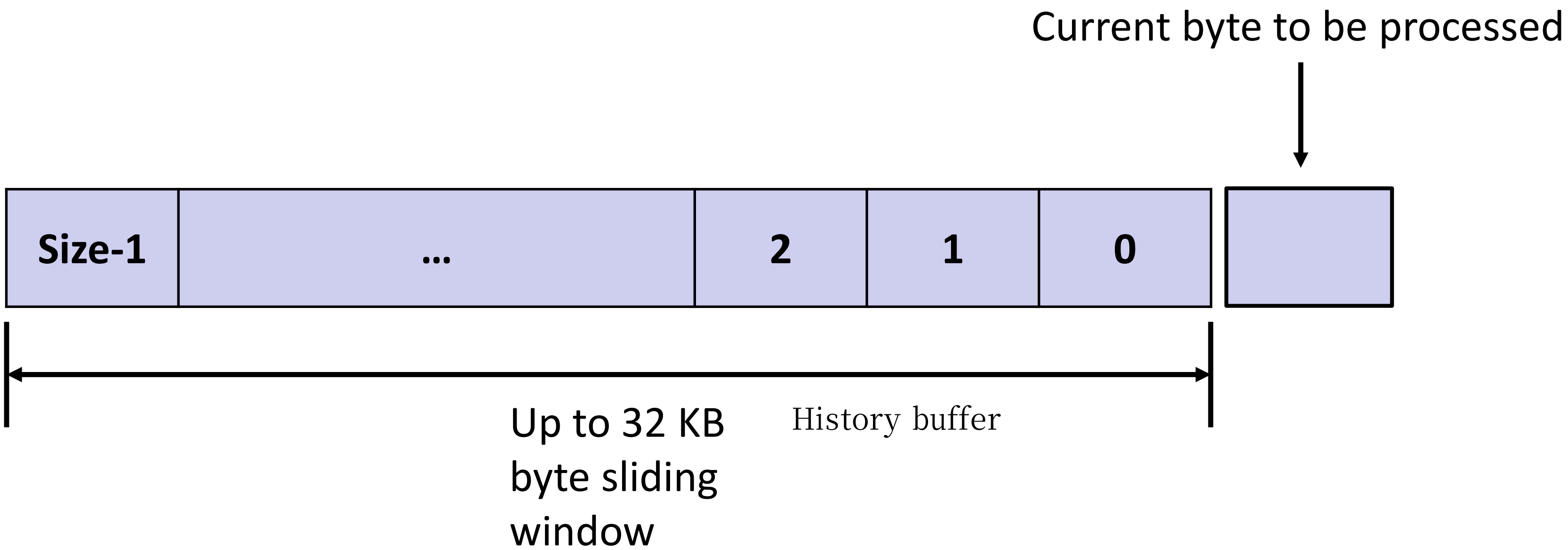
String Matcher가 History - Buffer를뒤져서
반복되는 byte string을 찾는다.

- A sliding-window ***History-Buffer*** adds one new byte and drops off one byte from the back end of the buffer

sliding - window history - buffer가 sliding하며
one new byte를 뒤에 추가하고 하나를 drop한다.

- A ***Post-Encoder*** is a prefix encoder
  - Use statistics to encode the most common string matches with a smaller number of bits

LZ1 Algorithm and History Buffer



LZ1 String Matching

Input String: ABCDABCFCDAB…..

Kept in the history buffer

Input	Output
A	A
B	B
C	C
D	D
ABC	Distance=4, Length=3
F	F
CDAB	Distance=6, Length=4

4개 전부터 3개를 보면 된다는 뜻

Encoded string

Huffman Encoding

Input String: A B B C B A D B

Probability of Occurrence

Input character	Probability
A	0.25
B	0.5
C	0.125
D	0.125

Huffman Encoding (Cont.)

```
      /\
    0   1
   /       \
  B      /  \
        0      1
       /          \
      A         /  \
              0      1
             /          \
            C            D
```

metadata를
저장해야 하지만
압축률은 좋다.

Symbol	Code	Pr
A	10	0.25
B	0	0.5
C	110	0.125
D	111	0.125

- Reduction =

  ½[0.25(2) + 0.5(1) + 0.125(3) + .125(3)]
  = 0.875

- Reduction in data size due to Huffman encoding.

Data Dependent

- Random data provides poor compression ratio performance
- Data with repeating byte strings, 2-byte or longer provides grater compression ratio performance
- Compression ratio greater than 100:1 are possible
- May expand if attempting to compress previously compressed data, but a system could detect this and send original data without compression

Algorithm Dependent

- Size of sliding window
- Static or dynamic Huffman encoding
- Number of matches tracked
- Length of matches the algorithm will search for

Hardware Implementation

software compression은 I/O throughput과 latency를 하향해서 안 좋다.

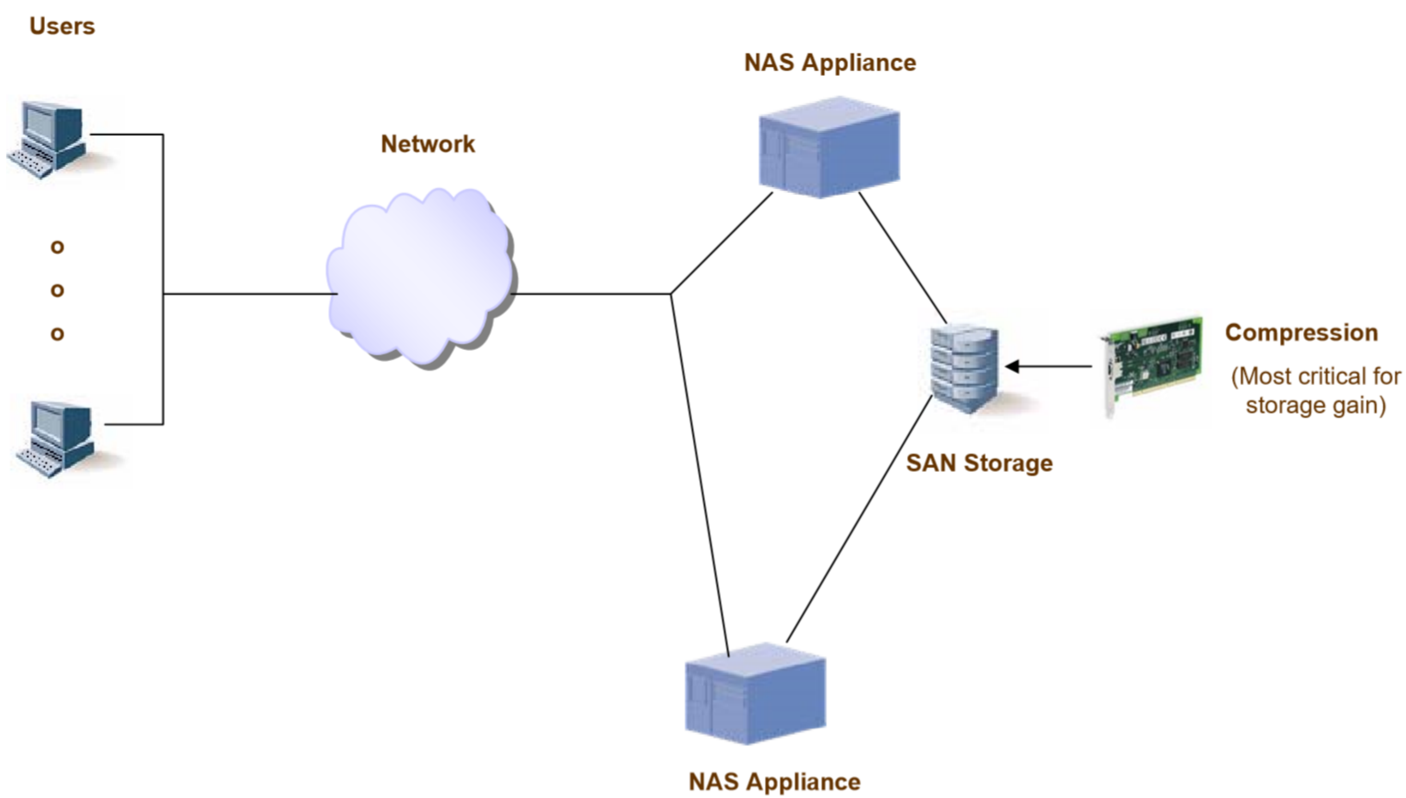
- **Software compression may result in the degradation of I/O throughput and latency as well as energy consumption**

- **Hardware compression**
  - (+) Higher data rate throughput (10x)
  - (+) Free up valuable CPU bandwidth
  - (+) reduce power consumption
  - (+) Speed up a network link by sending shorter files
  - (–) Lower compression ratio

- **Several hardware-specific compression algorithms are available**
  - Hardware implementation of GZIP algorithms
  - X-Match PRO: Real-time compression / decompression popular paper

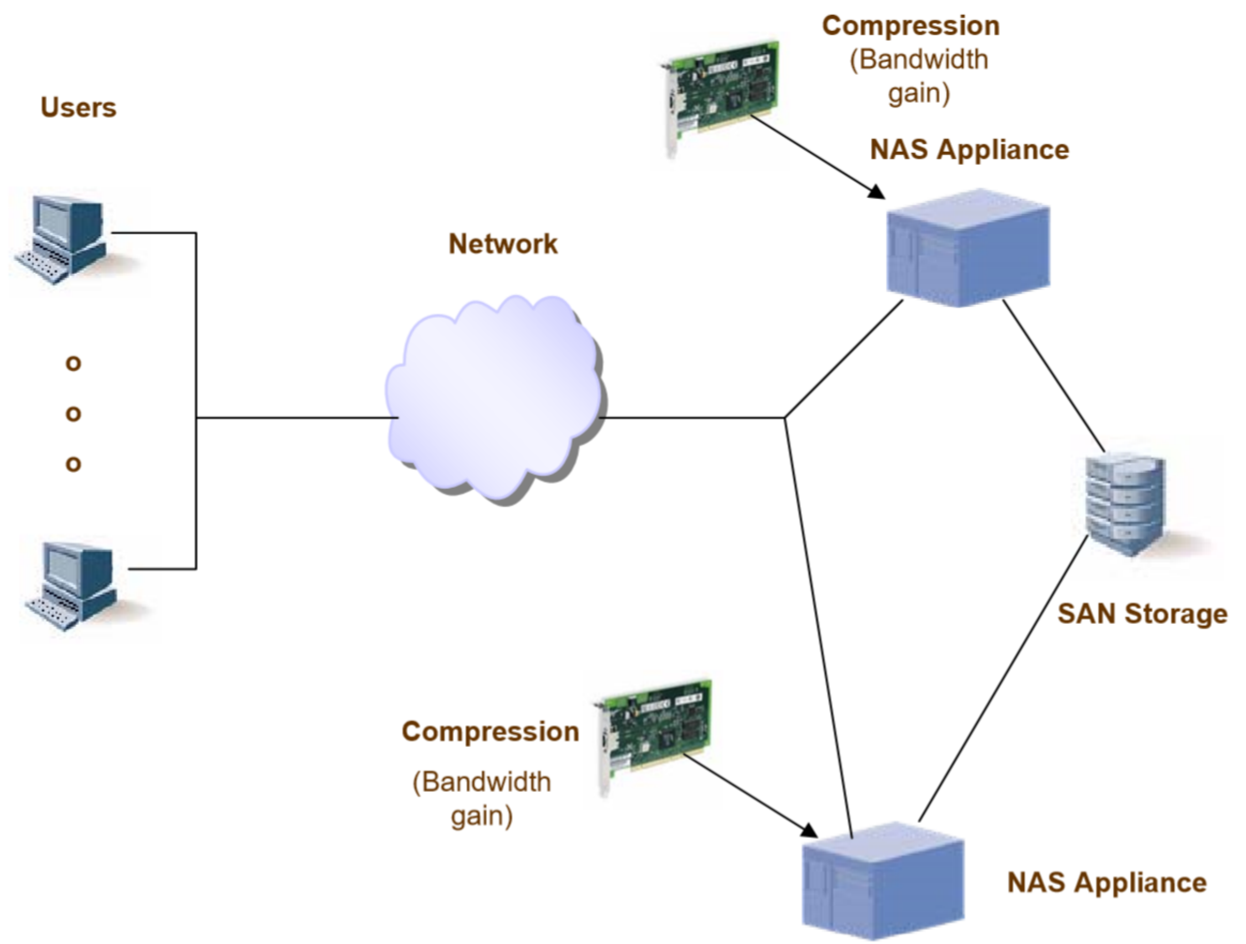
Deployment of Compression

- Similar to deduplication; combined with deduplication



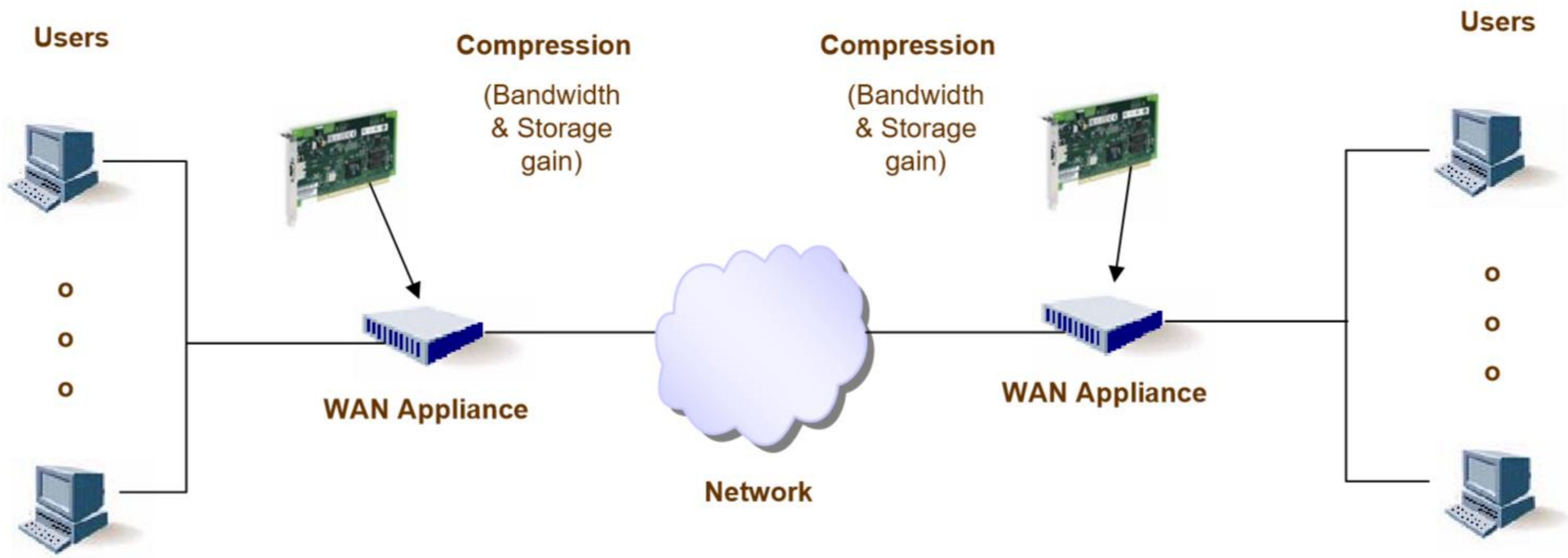
Deployment of Compression (Cont.)

- Similar to deduplication; combined with deduplication



Deployment of Compression

- Similar to deduplication; combined with deduplication



Data Deduplication vs Data Compression

먼저 dedup으로 큰 단위로 제거하고
약간 달라서 안되는 작은 애들을 compression. 일반적. 두 가지 다 쓴다.

- **Data deduplication**
  - (+) Large space saving is possible for exactly matched segments or files
  - (–) Even a single-bit difference makes deduplication ineffective
  - (–) Unable to get rid of repeated bit patterns of segments or files

- **Data compression**
  - (+) Effectively remove repeated bit patterns from input data streams
  - (–) Do not provide a high compression ratio all the times

input data를 받을 때 deduplication을 하고
그렇게 받은 data를 storage에 저장할 때 lossless compression을 해서 저장한다.

- **Common design practice**
  - Use deduplication for input data streams
  - Use lossless compression for storage of duplicate data and remaining meta data

Outline

- Data Deduplication
- Data Compression
- **Case Studies**
  - **CA-SSD: Content-aware Solid-state Drives**
  - BlueZIP: Hardware-accelerated Compression
  - DAC: Dedup-assisted Compression

Value Locality

- **To improve the reliability and performance of SSD, many FTL schemes exploit temporal/spatial locality**
  - Temporal locality: buffering writes to eliminate duplicate writes
  - Spatial locality: coalescing multiple sub page writes into fewer page writes

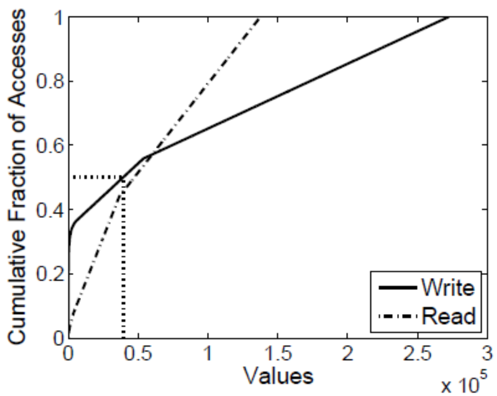
- **However, another form of locality, *Value Locality*, has not been completely unexplored**
  - Value locality: certain content is accessed preferentially

FTL이 temporal locality, spatial locality는 처리해도
value locality는 아직 할 수 없다.

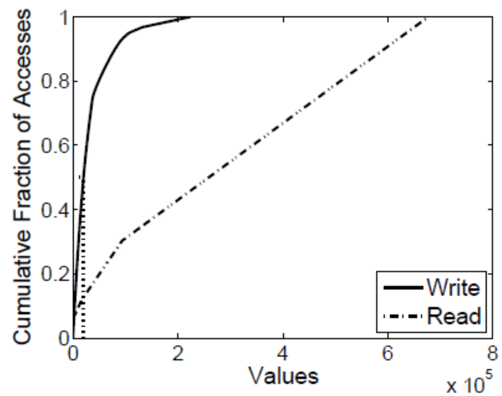
Value Popularity (VP)

Value popularity: 각 unique value의 등장횟수

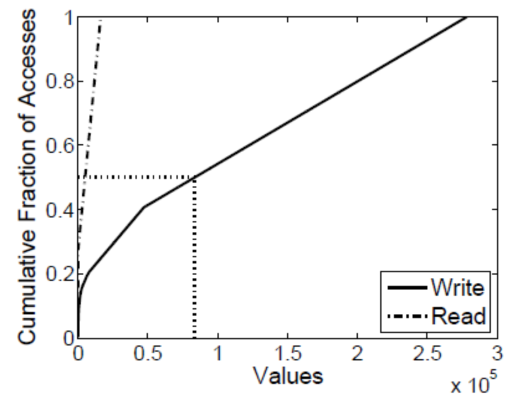
- Value popularity: the number of occurrences of each unique value
- Value popularity in real-word workloads



(a) web



(b) mail



(c) homes

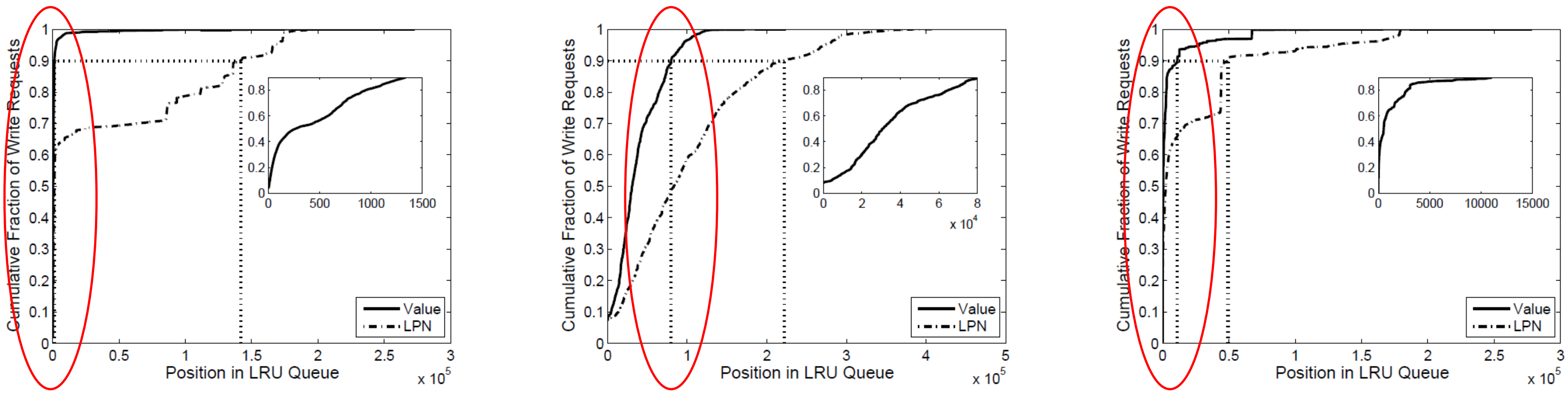
- Workload statistics

Workload	Size (GB)	% Writes	Req. (mill.)	Unique Request (%) Write	Unique Request (%) Read	Seq. %
web	1.95	77.01	3.8	42.35	32.05	83.8
mail	4.22	77.32	3.6	7.83	80.85	94.7
homes	3.02	96.76	4.4	66.37	80.75	70.8

Temporal Value Locality (TVL)

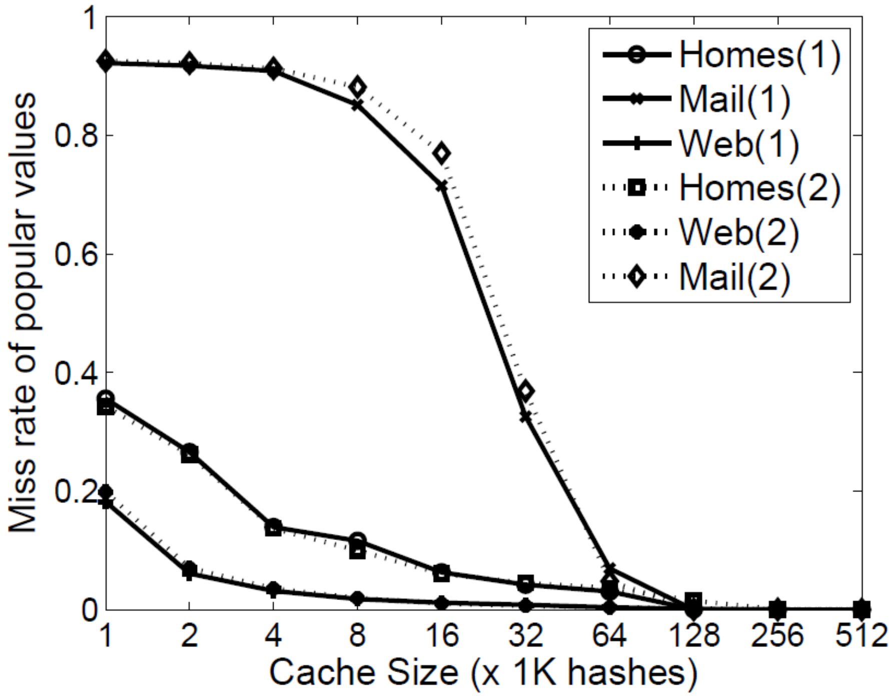
- **Temporal Value Locality**: If a certain value is accessed now, it is likely to be accessed again in the near future

- **Temporal value locality in real-world workloads**
  - The metadata cache is managed as a queue with an LRU eviction policy
  - CDFs of number of writes of the value at the (i+1)st location in the LRU queue



(a) web (b) mail (c) homes

Cache Miss Rate for Popular Values



- Popular values represent the minimum number of values which account for 50% of accesses
- All the three traces achieve about 90% hit rate with 1.75 MB metadata cache (64 K hashes X 28 B = 1.75 MB)

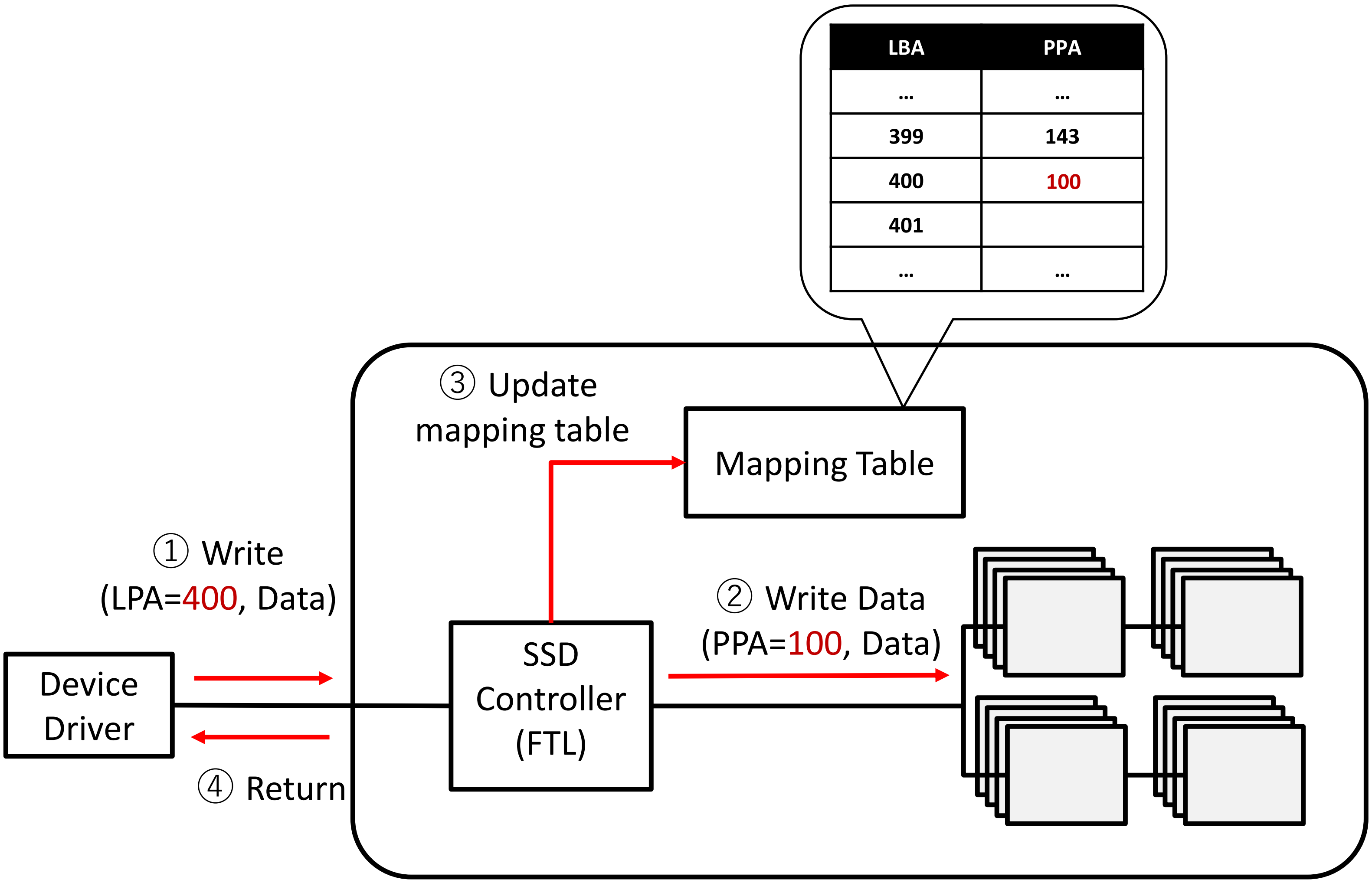
Content-Aware SSD

- **The presence of value locality in a workload means that it preferentially accesses certain content over others**

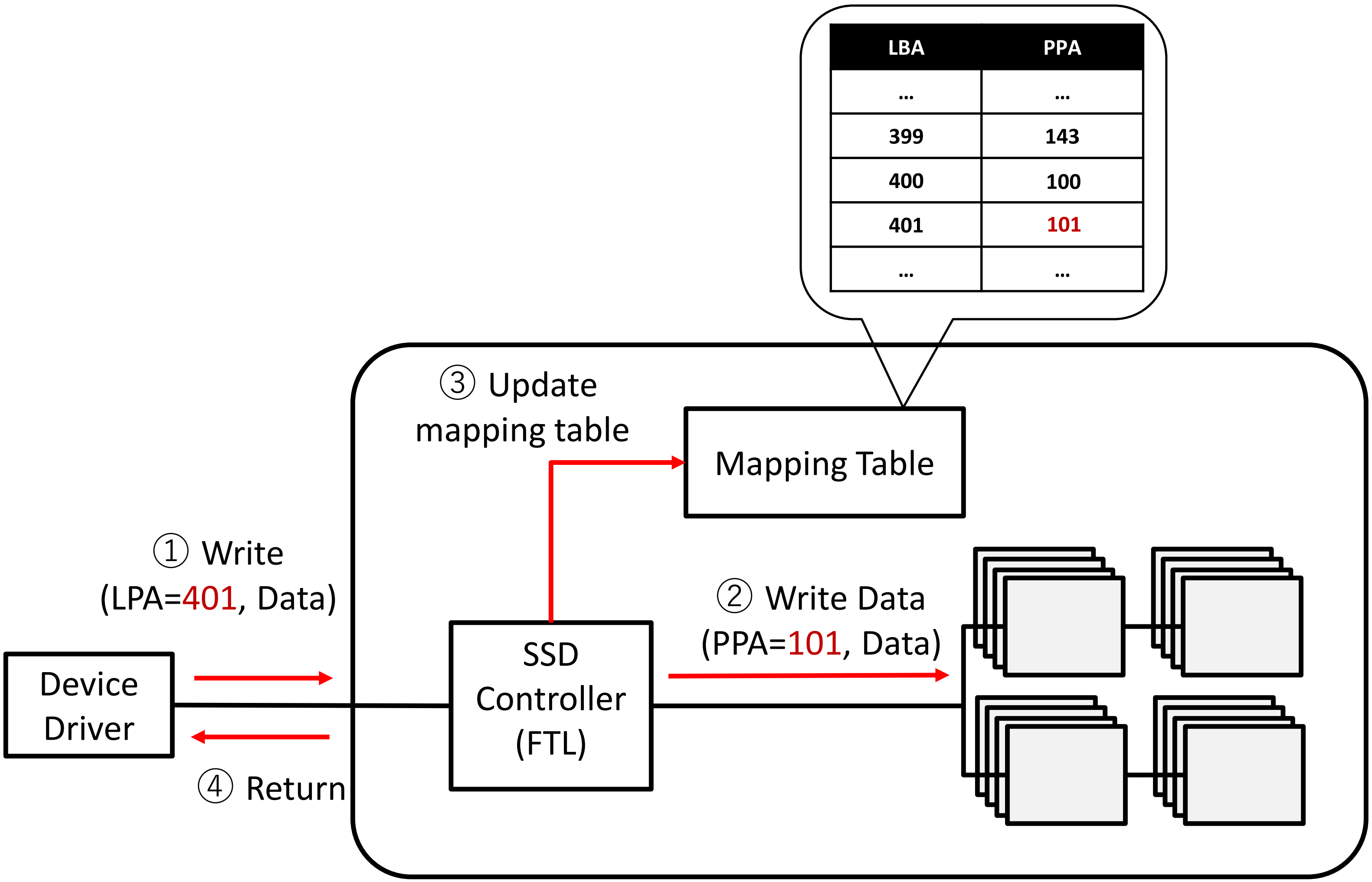
  value locality가 꽤 있다는 것을 볼 수 있다.
  즉, SSD 내부에서 dedup할 하는 게 의미가 있다는 것.

- **This property facilitates data de-duplication inside an SSD**
  - Store only a non-intersecting chunk having *a unique hash value*
  - Other data blocks with the same content point to the unique block

How a Conventional SSD Works?

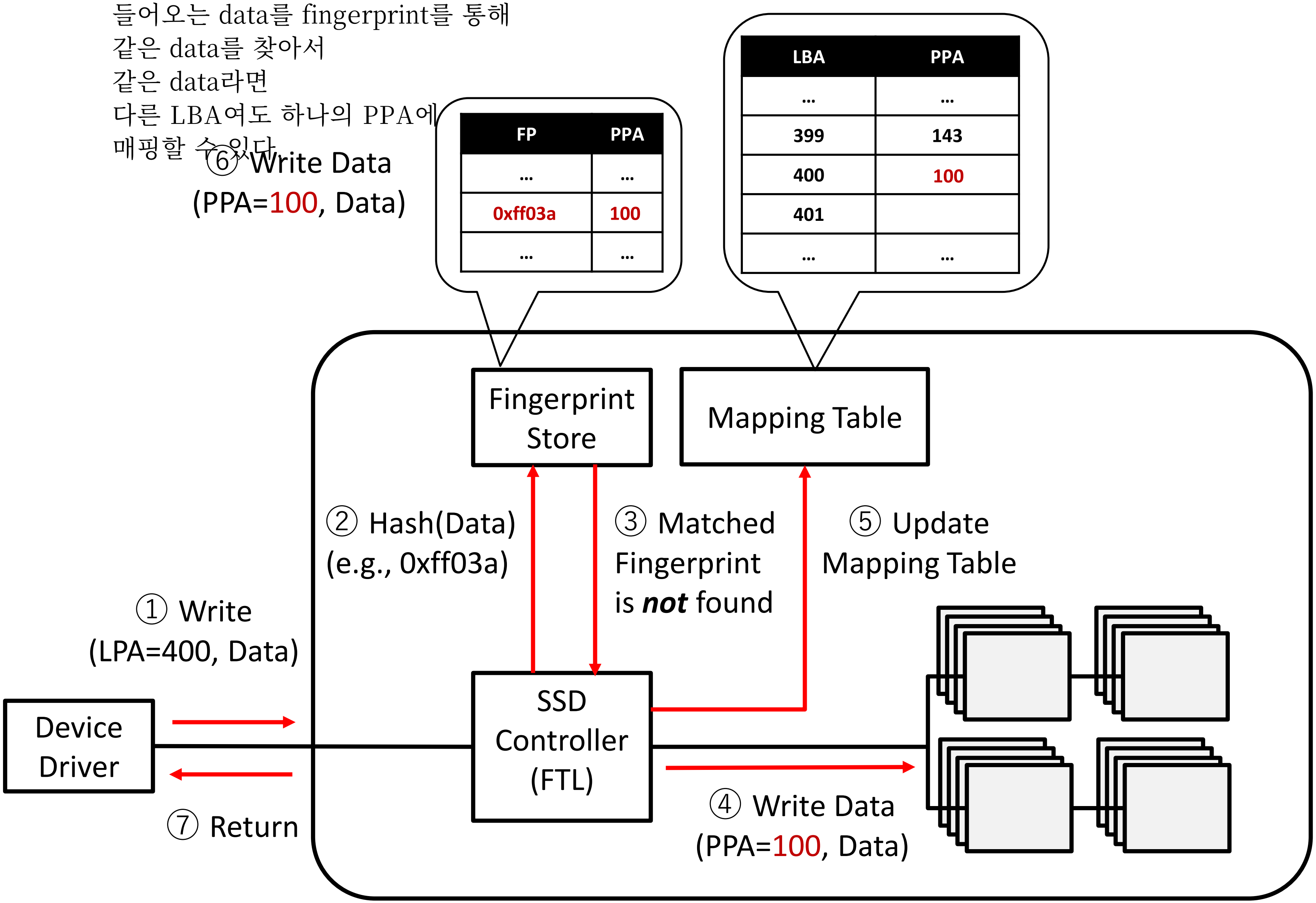


How a Conventional SSD Works?

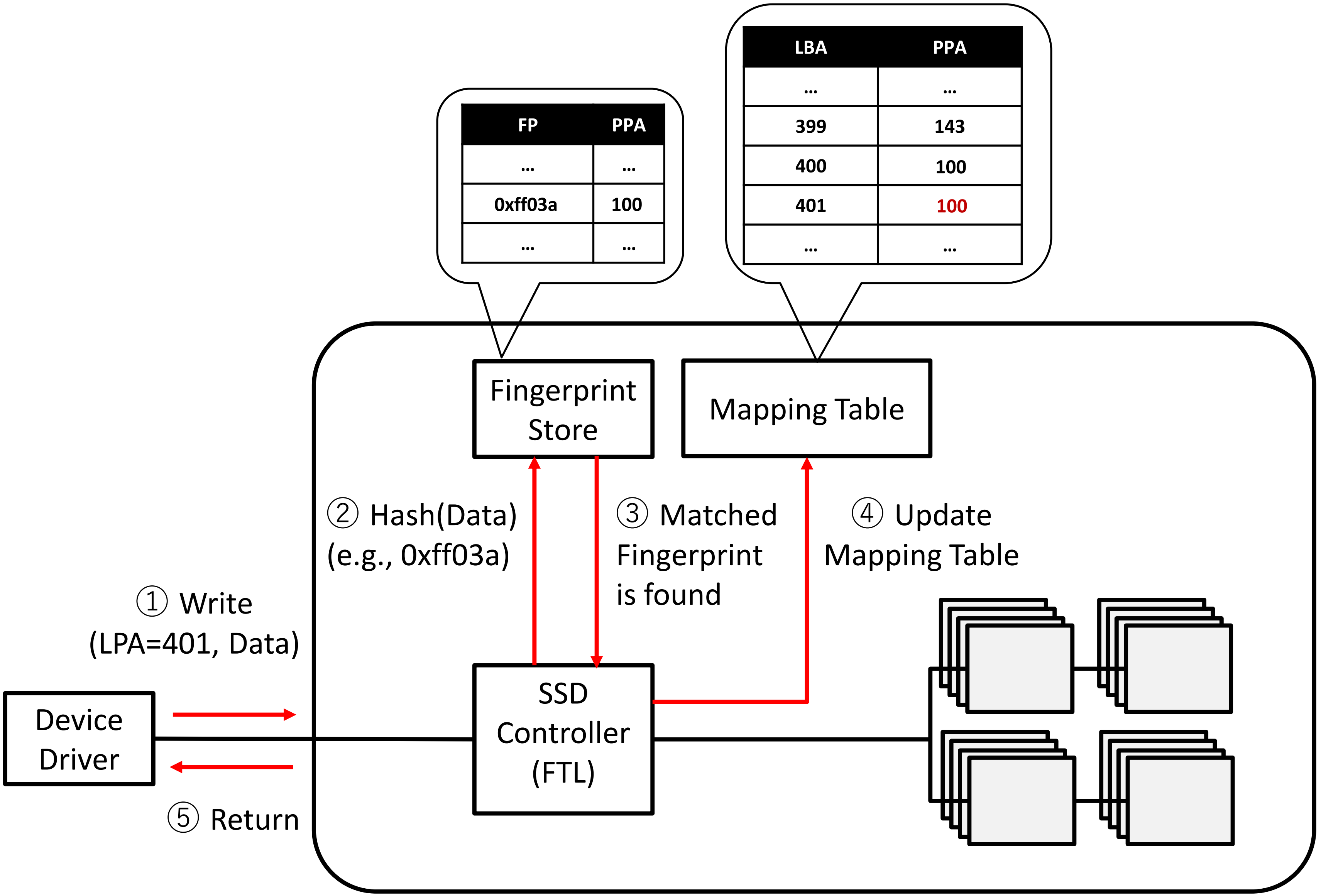


How CA-SSD Work? (Simplified)

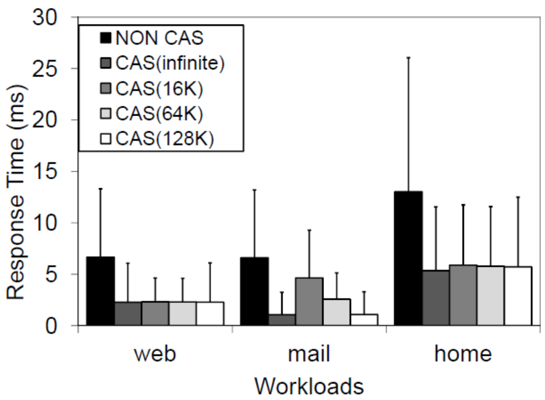
들어오는 data를 fingerprint를 통해
같은 data를 찾아서
같은 data라면
다른 LBA여도 하나의 PPA에
매핑할 수 있다



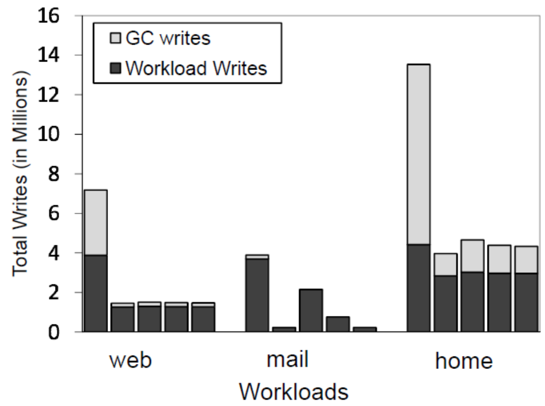
How CA-SSD Work? (Simplified) (Cont.)



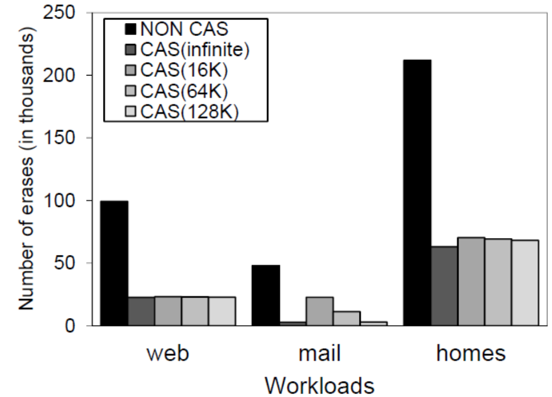
Experimental Results



(a) Response Time



(b) Total Writes



(c) Block Erases

- The reduction in write traffic: 77%, 93%, and 70% for web, mail, and home
- The write reduction benefits directly translate into the reduced response time and the reduced block erases
- CAS(128K) provides the performance close to the CA(infinite)
  - mail shows lower TVL and requires a larger metadata cache

Outline

- Data Deduplication
- Data Compression
- **Case Studies**
  - CA-SSD: Content-aware Solid-state Drives
  - **BlueZIP: Hardware-accelerated Compression**
  - DAC: Dedup-assisted Compression

2년동안 연구했는데
hotstorage 등 워크샵에도 다 떨어져서
약한 저널에 냈음.

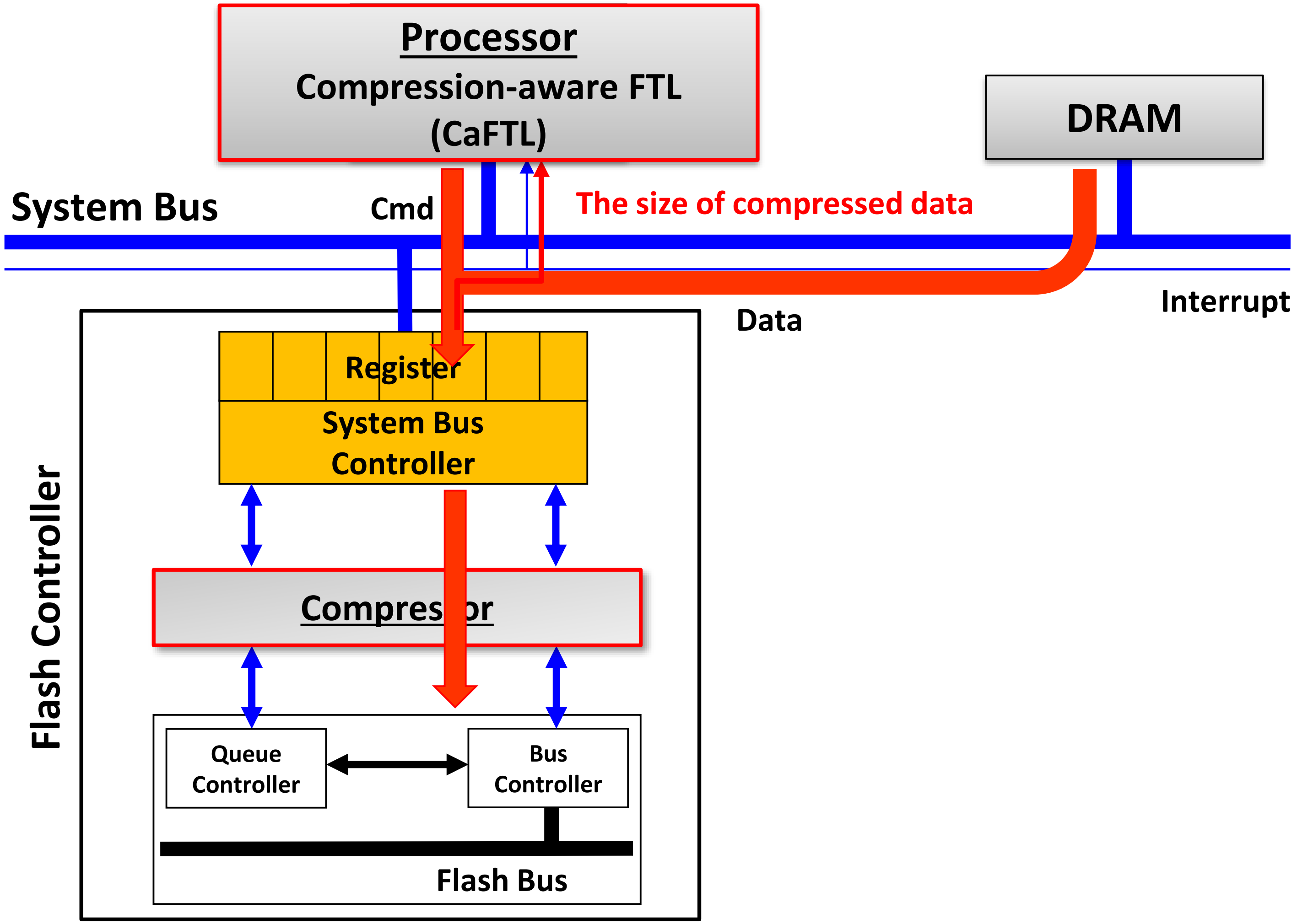
BlueZIP: Hardware-accelerated Compression

- **Requested data contain lots of repeated bit patterns**
  - Lossless compression helps to eliminate such repeated bit patterns.

- **BlueZIP: A hardware-accelerated compression technique,**
  - Compress requested data at runtime 하드웨어 가속기를 통해 runtime에 data를 compress한다.
    - Use a hardware-accelerated compression module
    - Provide software support for maximizing the benefits of hardware-accelerated compression 하드웨어 가속기 압축을 제대로 쓰기 위해 소프트웨어 지원 제공
  - Improve the lifetime and performance of storage devices
    - Reduce the amount of data written to flash memory
    - Reduce the time taken to transfer data between a host system and flash memory 실제로 플래시 메모리에 쓰여지는 데이터 양과 호스트 시스템에서 플래시 메모리로 전달될 때의 transfer time을 줄일 수 있다.

Overall Architecture of BlueZIP

- Implement the hardware compression module inside the flash controller to reduce system bus traffic

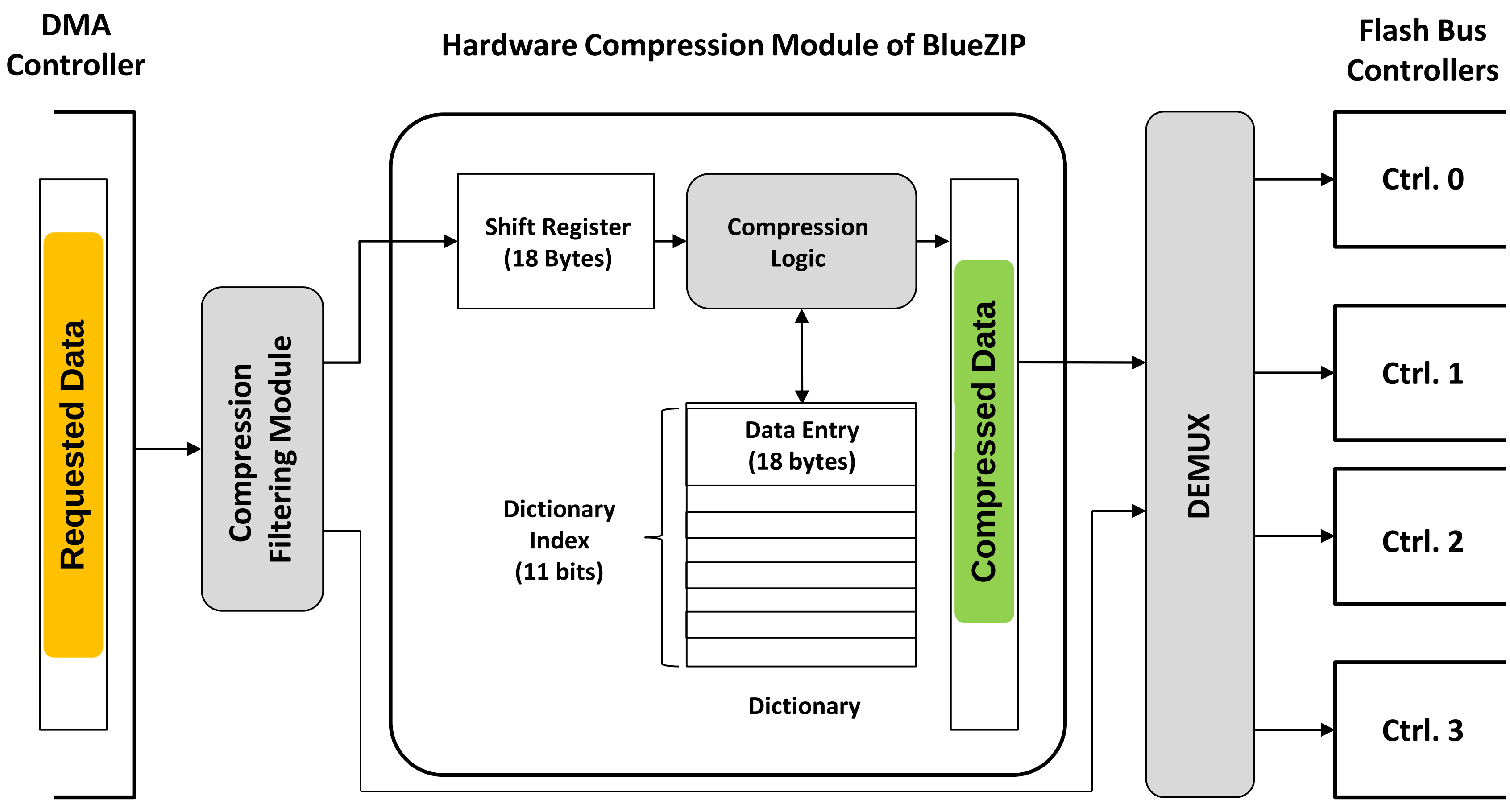


HW: Compression Algorithm

- **Use the LZRW3 compression algorithm**
  - Relatively high compression ratio
  - Easy hardware implementation

Compression Algorithm	Hardware Complexity	Performance (Cycles)	Compression Ratio	Description
X-Match	Low	1,024 cycles / 4 KB (20.48 us@ 50 MHz)	Low (e.g., 20%)	Hardware-Based Memory Compression
LZ77	High	4,096 cycles > / 4 KB	High (e.g., 50%)	File Compression
LZRW3	Middle	4,096 cycles / 4 KB (81.92 us@ 50 MHz)	High (e.g., 40%)	File Compression

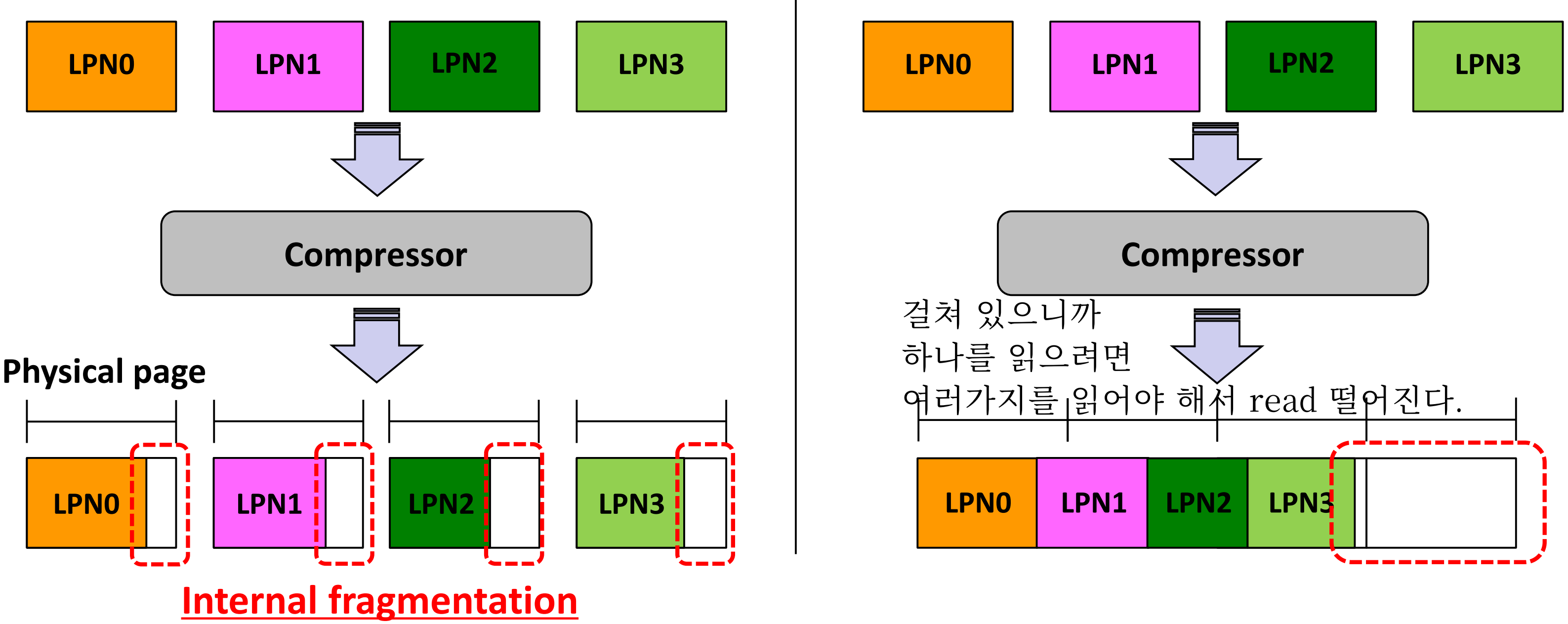
HW: Implementation



HW-SW: Compression Unit

- **Chunk-based I/O**
  여러 logical page들을 여러 physical page들로 압축한다.
  internal fragmentation을 줄이는 컨셉.
  - Compress several logical pages into several physical pages
  - Mitigate the internal fragmentation problem
- **Read performance penalty**
  read 성능이 떨어지니,
  read buffer를 둬서 압축되기 전의 페이지들을 유지해놓는다.
  - Use a read buffer that holds previously decompressed pages

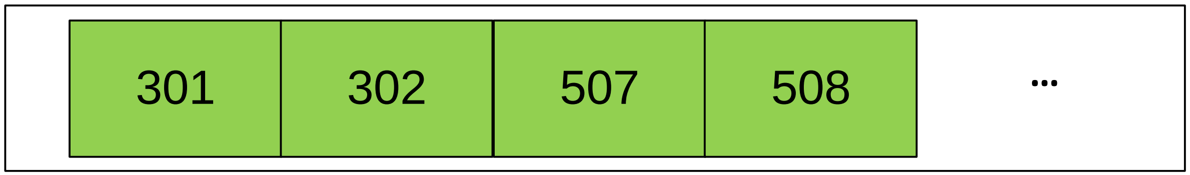
<Compressing Individual pages> | **<Chunk-based I/O>**



걸쳐 있으니까
하나를 읽으려면
여러가지를 읽어야 해서 read 떨어진다.

SW: Compression-Aware FTL

Write Buffer



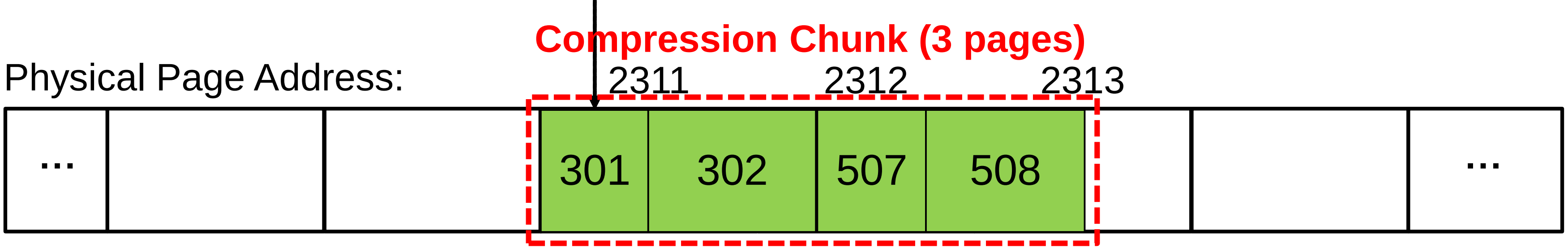
LPA -> PPA -> PPA들 안의 chunk들 중 어느부분이 원하는 data인지

Page Mapping Table

Logical Page Address	Physical Page Address
⋮	⋮
301	2311
302	2311
507	2311
508	2311

Data Chunk Table

Physical Page Address	Valid Page Counter	No. of Physical Pages	Compression Indicator
⋮	⋮	⋮	⋮
2311	4	3	1
2312	4	3	1
2313	4	3	1
	⋮	⋮	⋮



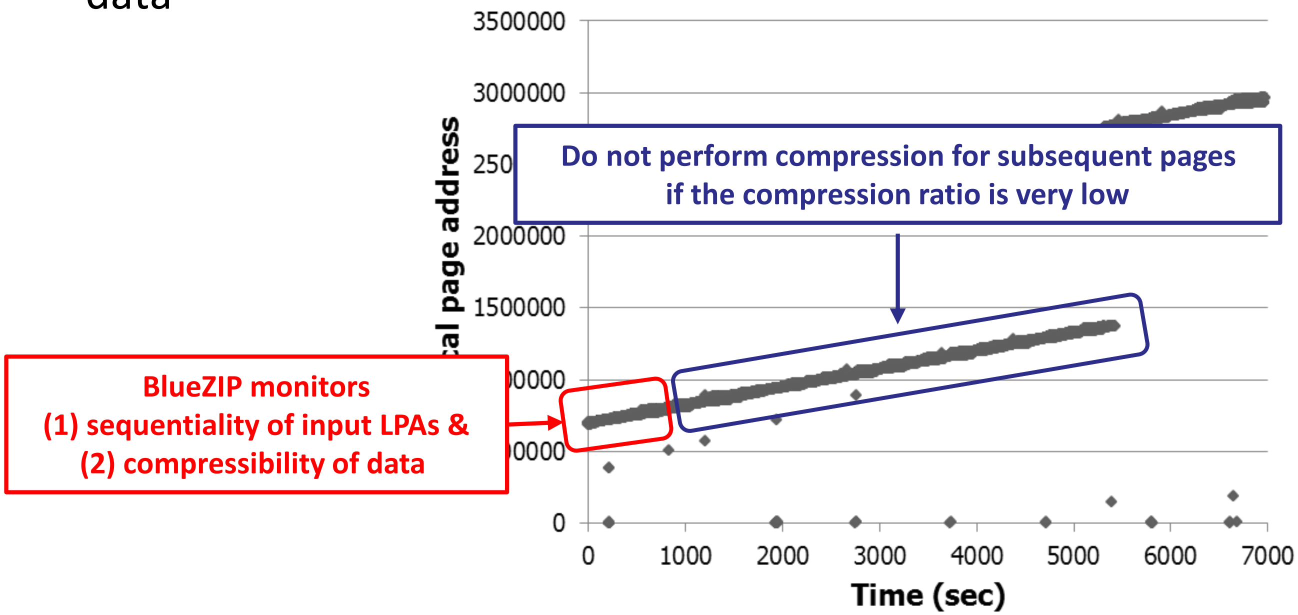
NAND Flash Memory

선택적 압축

SW: Selective Compression

압축한 데이터가 오히려 더 커지는 경우가 있어서
압축 잘 안되는 sequential write 같은 것들은 미리 감지해서
압축하지 않기로 하자.

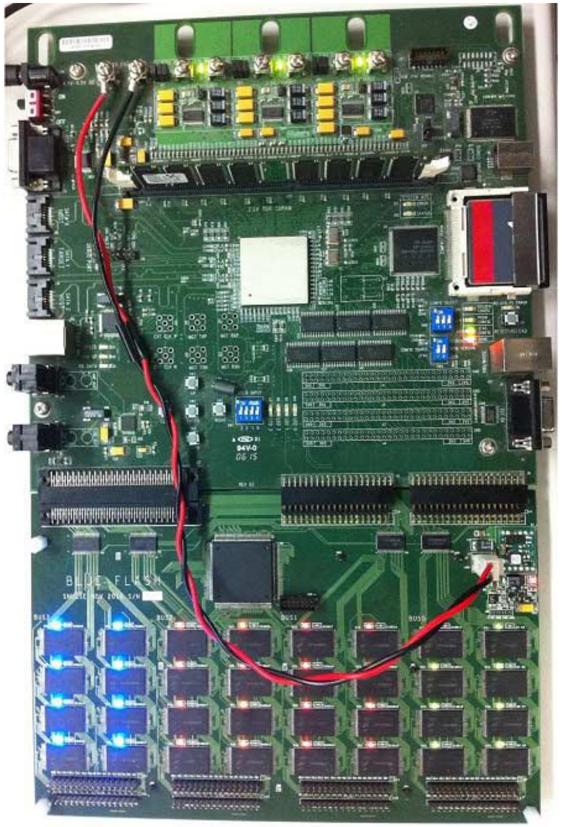
- **The data size expansion problem**
  - The size of compressed data > the size of original data
  - Degrade storage performance and lifetime
  - Usually observed in writing multimedia files
- **Selective compression**
  - Detect poorly compressed sequential writes in advance and do not compress those data



Experimental Settings

■ Benchmarks

Benchmark	Description	Compression Ratio
SENSOR	A set of sensor data files which were collected during a semiconductor fabrication process	Very high
LINUX	A subset of the Linux kernel 2.6.32 source files	high
DOCUMENT	A set of documents and image files	medium
MP3	A set of MP3 files already highly compressed	Very low

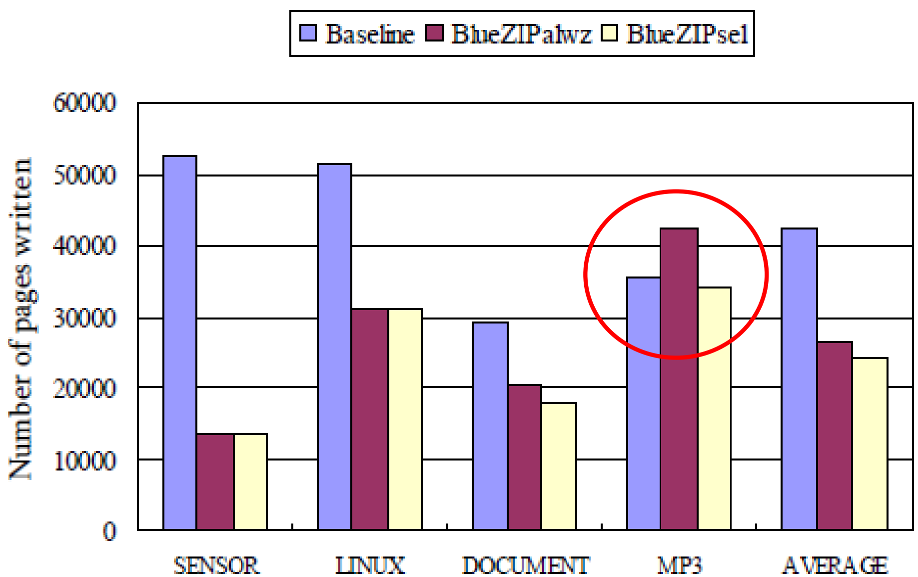


<BlueZIP prototype>

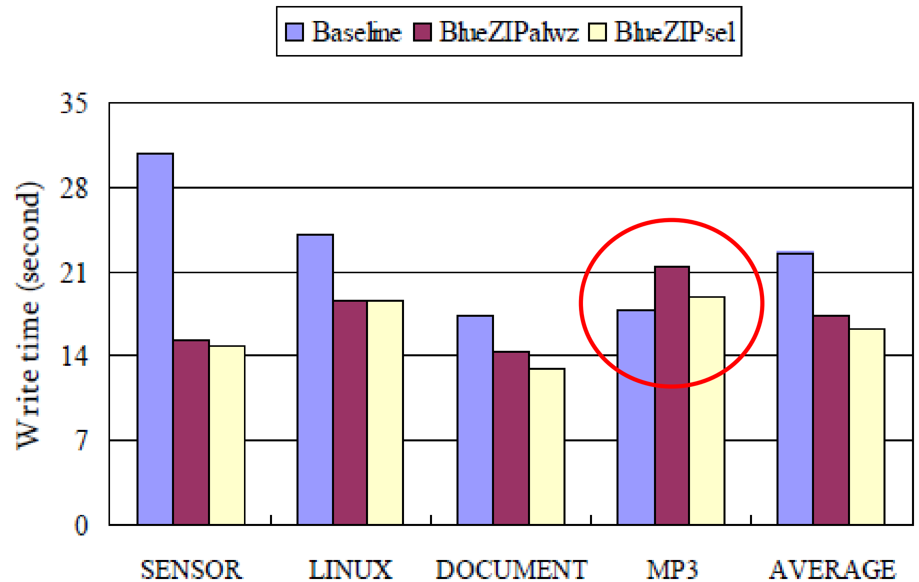
■ SSD Configurations

Configurations	Description
Baseline	Use no lossless compression
BlueZIPalwz	Use lossless compression all the time
BlueZIPsel	Use selective compression

Experimental Results



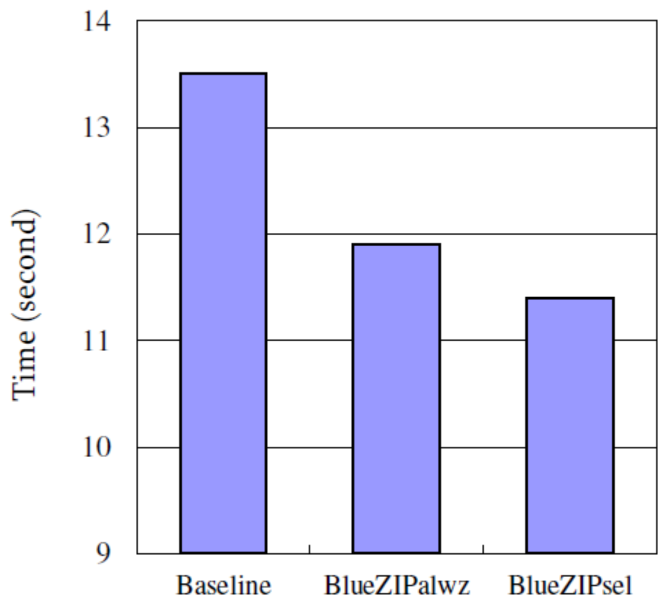
The number of pages written



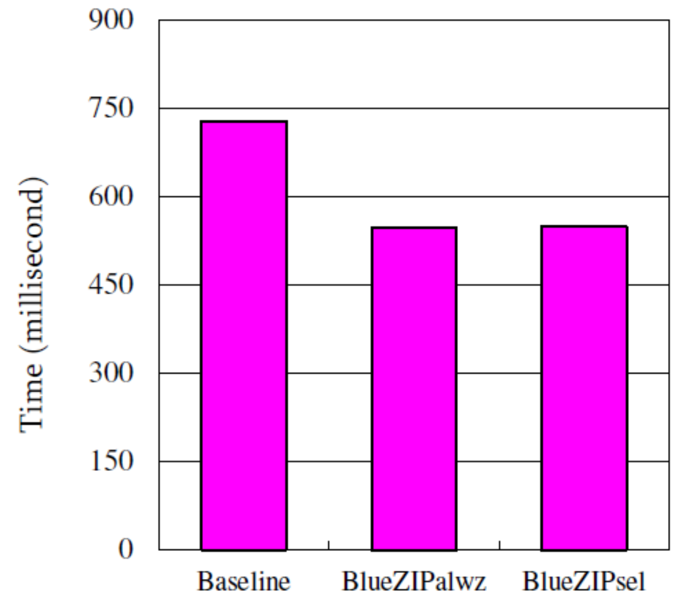
Time (second)

- **BlueZIPsel writes 38% less data over Baseline.**
  - The amount of written data is increased with BlueZIPalwz due to the data expansion problem of lossless compression.
- **BlueZIPsel achieves 17%-50% higher performance than Baseline**

Read Performance



Grep



Find

- BlueZIPsel improves the overall read performance by 20% on average.
- The reduction in the number of pages sufficiently offsets the decompression overhead.

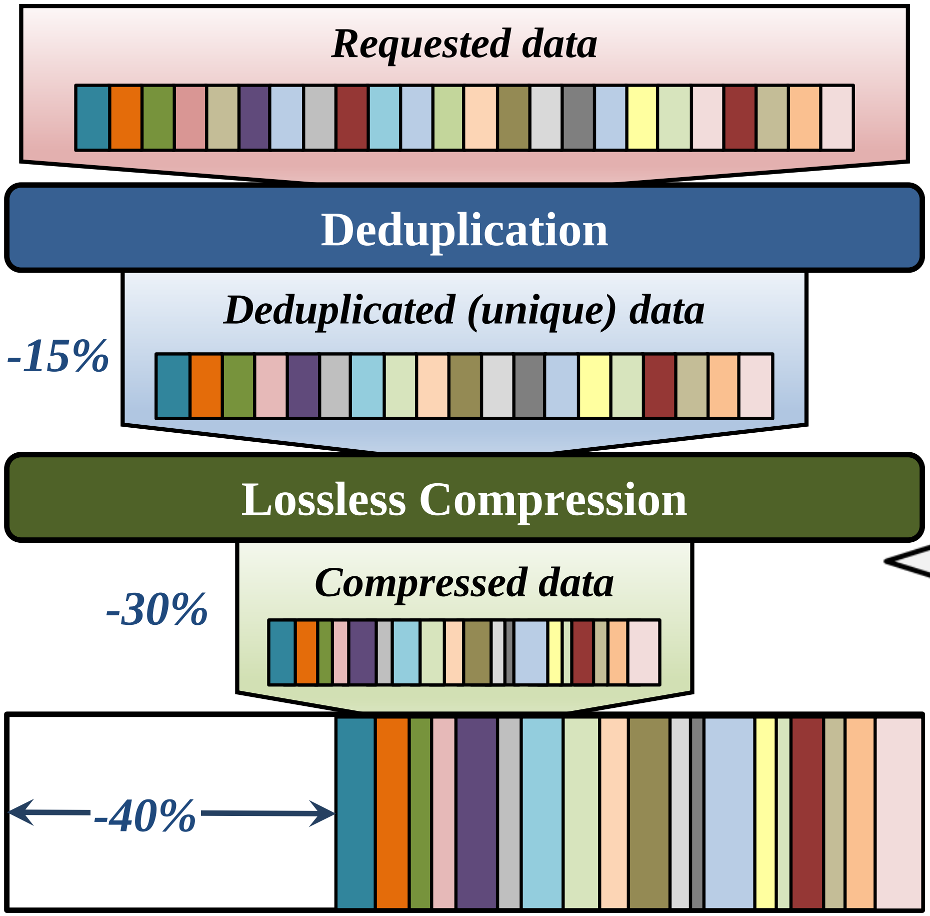
Outline

- Data Deduplication
- Data Compression
- **Case Studies**
  - CA-SSD: Content-aware Solid-state Drives
  - BlueZIP: Hardware-accelerated Compression
  - **DAC: Dedup-assisted Compression**

Dedup, Compression을 같이 쓴 연구

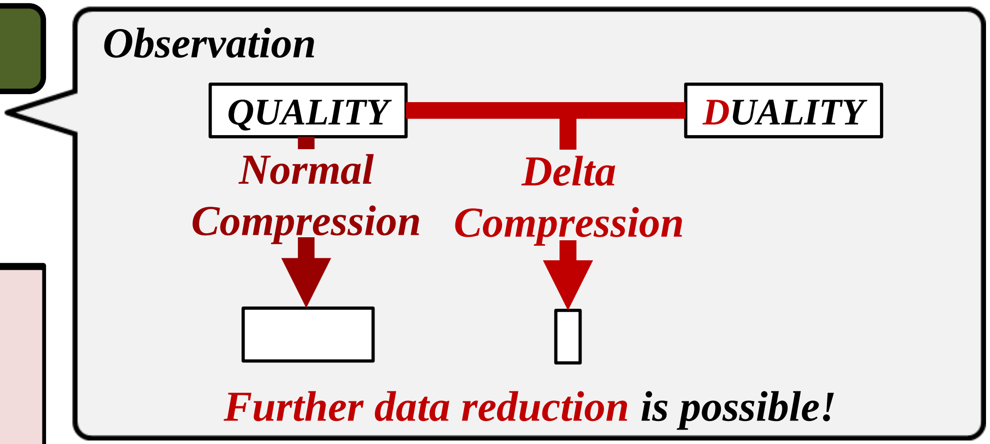
Integration of Capacity-optimization Techniques

- **Maximizing the data compression ratio**
  - Improvements can be accumulated



Q: Can we do better?

기존에는 이렇게
Dedup - > Comp로 둘다 따로따로 했다.



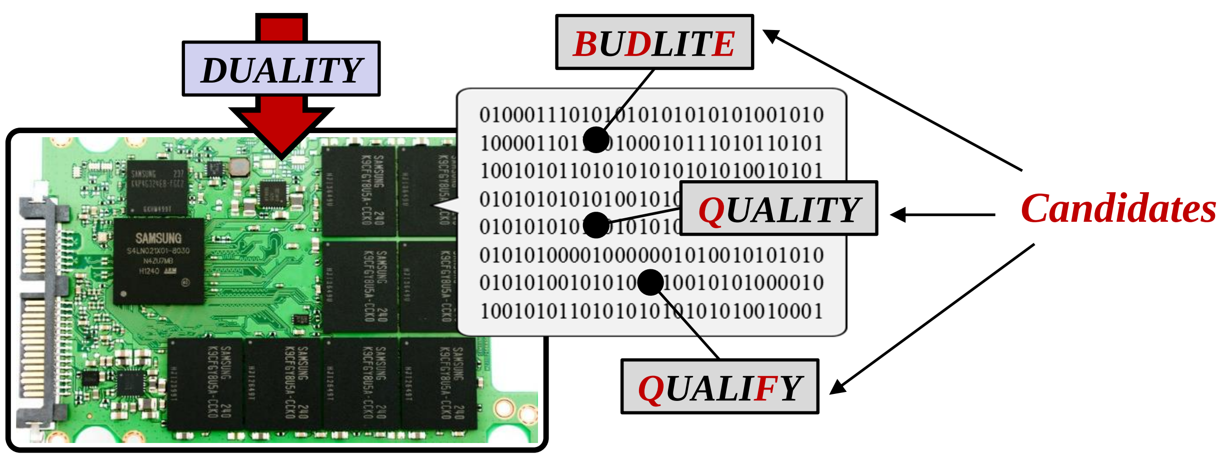
DAC: Dedup-Assisted Compression

한번에 할 수 있지 않을까? Dedup - Assisted Compression

- **A novel integrated data reduction technique**
  - Exploiting data similarity to further increase data reduction ratio

  data similarity를 이용해서 data reduction ratio를 더 늘리자.

- **Reference search is not easy**



DAC: Reference Data Search

- **Exploiting partial fingerprints (hashes) of data**
  - Generated by the strong hash module for deduplication (Dedup-Assisted)

Requested data

Strong hash → 0x242F56

Reference data

0x242F56

Fingerprint (FP) Store

Page FP	Page Addr
…	…
0x141250	0x022
0x242F56	0x0F1
0x44516F	0x011
0x6DFF25	0x1CB
…	…

Deduplication

Cannot reflect similarity

0x95FE3A

Difference

0x44 0x41 0x51 0x45

0x242F56

0x44 0x41 0x74 0x45

Sub-Page Fingerprint Store

	1st FP	2nd FP	3rd FP	4th FP	Page Addr
	…	…	…	…	…
50%	0x44	0x2F	0x51	0x7E	0x02F
75%	0x44	0x41	0x74	0x45	0x0F1
25%	0x44	0x5E	0x3C	0x7A	0x012
0%	0x45	0x0D	0x45	0x6D	0x13B
	…	…	…	…	…

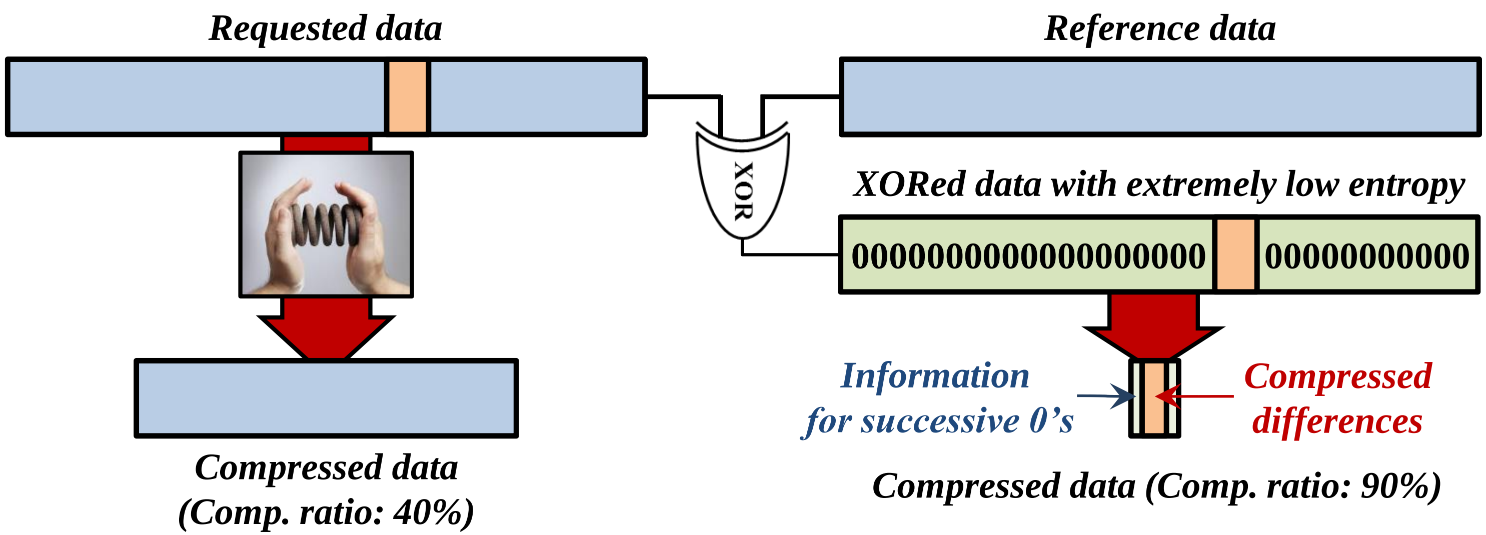
Dedup-Assisted Compression

Wide searching range, constant searching time, and quantified data similarity

DAC: Data Compression with a Reference

두가지를 xor hardware 하나로 처리.

- **Exploiting XOR logic to extremely reduce data entropy**

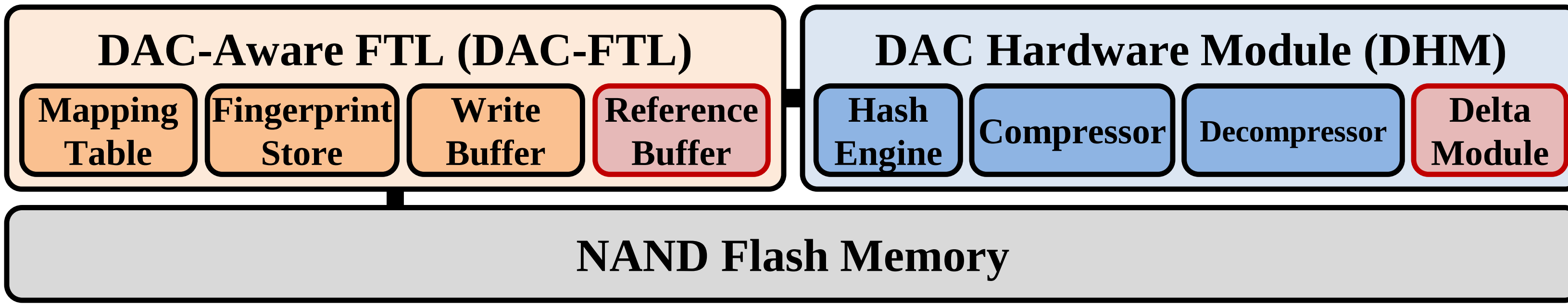


- **Lossless compression algorithm: XmatchPRO**
  - Employing both the run-length and dictionary-based data encoding
  - Easily implementable in H/W
  - High performance and comparable compression ratio

Higher compression efficiency w/o an additional delta-aware data encoding

Experimental Environment

- **Target SSD Architecture**
  - Recent high-end SSDs employing deduplication and compression



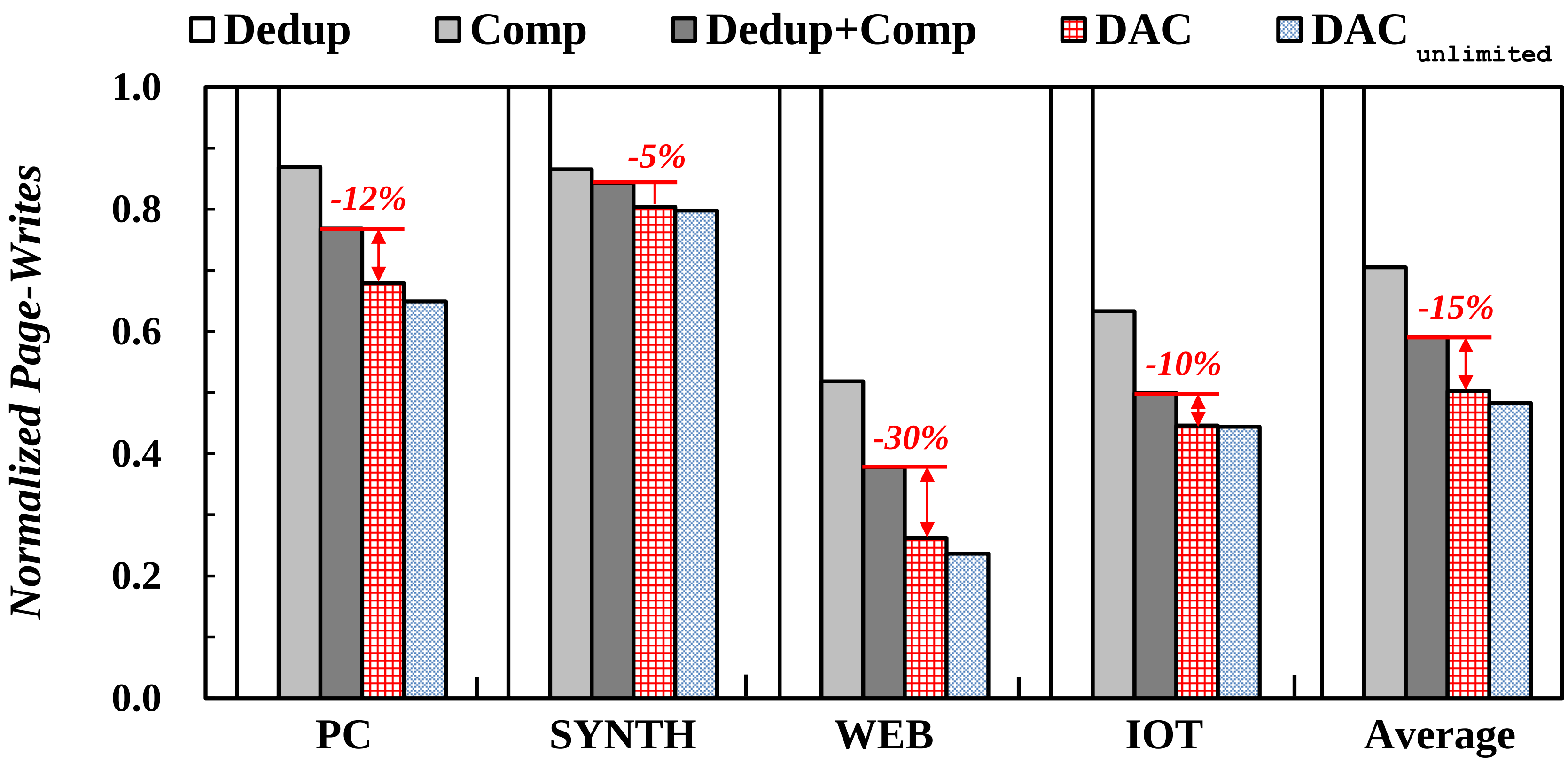
- **Evaluation on a storage emulation environment**
  - Hardware modules for a strong hash function (MD5) and lossless compression (XmatchPRO) were emulated by software.
- **Benchmarks: block I/O traces collected form a high-end PC**

Benchmark	PC	SYNTH	WEB	IOT
Data Redundancy	*Moderate*	*Low*	*Very High*	*High*
Data Compressibility	*Moderate*	*Low*	*Very High*	*High*

Evaluation Result

- Compared with a combination of deduplication and lossless compression, DAC reduces write traffic by up to 30% and 15% on average
- DAC can further increase data reduction whether data entropy is high or not

휴먼테크 수상



End of Chapter 10