Evanesco: Architectural Support for Efficient Data Sanitization in Modern Flash-Based Storage Systems

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**M. Kim and J. Park equally contributed.*

Executive Summary

- **Motivation:** Secure deletion is essential in storage systems as modern computing systems process a large amount of security-sensitive data.

- **Problem:** It is challenging to support data sanitization in NAND flash-based SSDs.
  - **Erase-before-write property** → no overwrite on stored data
  - **Physical data destruction** → high performance & reliability overheads

- **Evanesco:** A low-cost data-sanitization technique w/o reliability issues
  - Uses on-chip access-control mechanisms instead of physically destroying data
  - Manages access-permission (AP) flags inside a NAND flash chip
    - Data is not accessible once the flash controller sets the data's AP flag to *disabled*.
    - An AP flag cannot be reset before erasing the corresponding data.

- **Results**
  - Provides the same level of reliability as an unmodified SSD (w/o data-sanitization support)
    - Validated w/ 160 real state-of-the-art 3D NAND flash chips
  - Significantly improves performance and lifetime over existing data-sanitization techniques
    - Provides comparable (94.5%) performance with an unmodified SSD

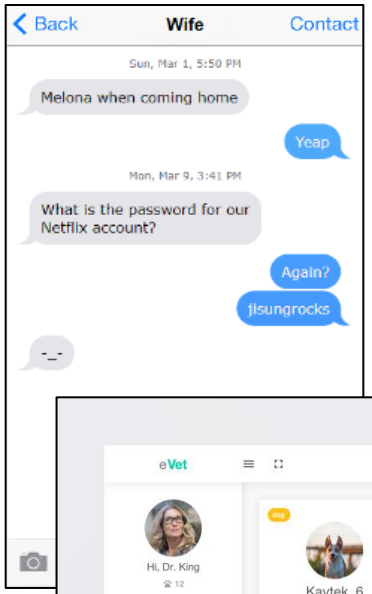
Outline

- **Secure Deletion in NAND Flash-Based SSDs**
- **Evanesco: Lock-Based Data Sanitization**
  - pageLock: Page-Level Data Sanitization
  - blockLock: Block-Level Data Sanitization
  - SecureSSD: An Evanesco-Enabled SSD
- **Evaluation**
- **Conclusion**

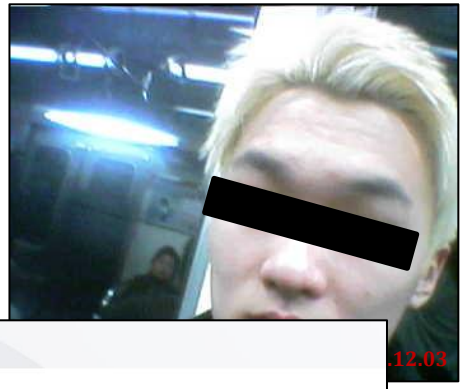
Secure Deletion in Storage Systems

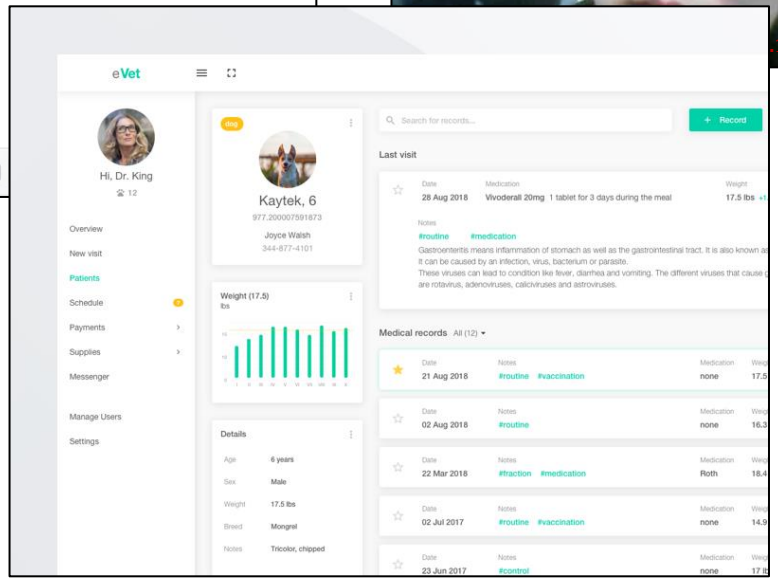
- Security-sensitive data is increasing in modern storage systems.

Private Message



Private Photo





Confidential Data (e.g., Medical Record)

Secure Deletion in Storage Systems

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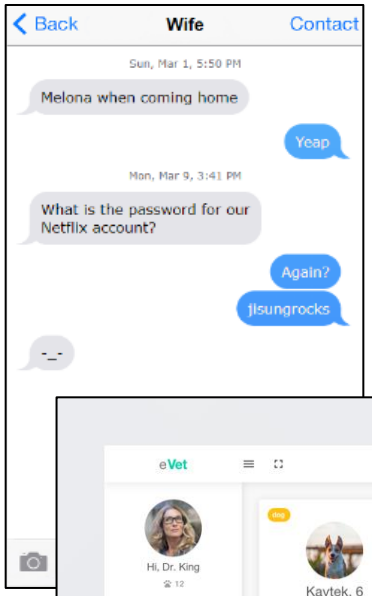

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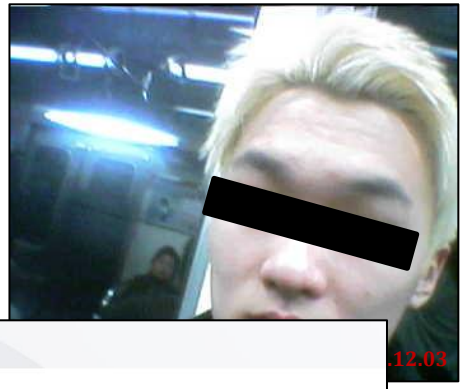
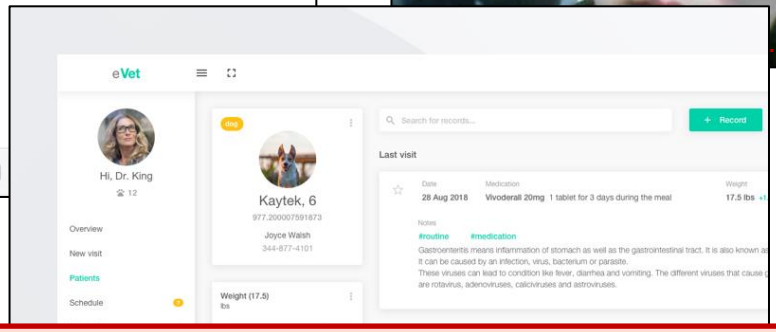


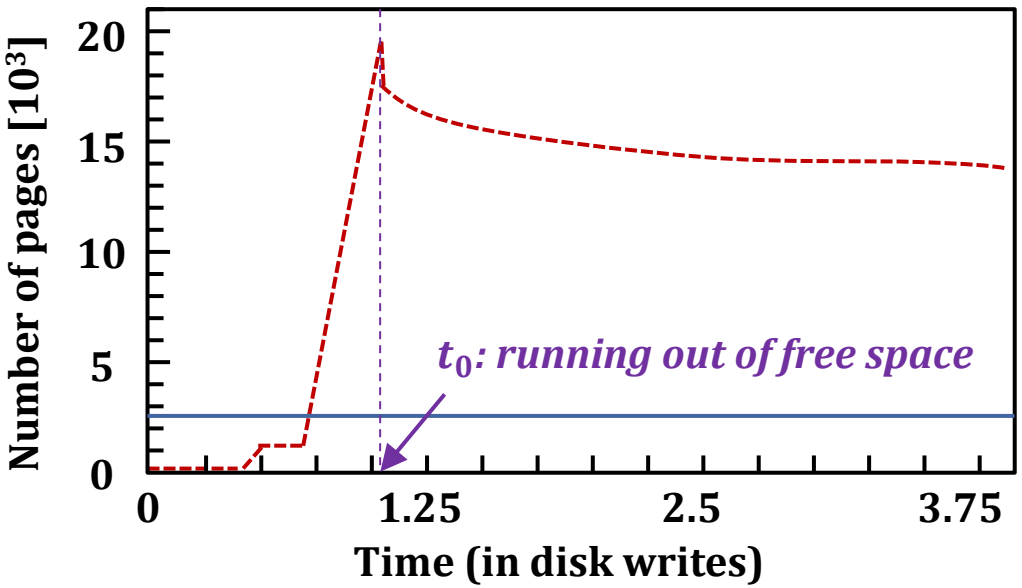


Once a user deletes security-sensitive data,
a storage system should guarantee its irrecoverability

Confidential Data (e.g., Medical Record)

Data Versioning Problem

- Obsolete data in NAND flash-based solid-state drives (SSDs)
  - Old versions of updated or deleted files can remain in the SSD for a long time.



f: a heavily-updated DB file

# of valid pages of file *f*

# of invalid pages of file *f*

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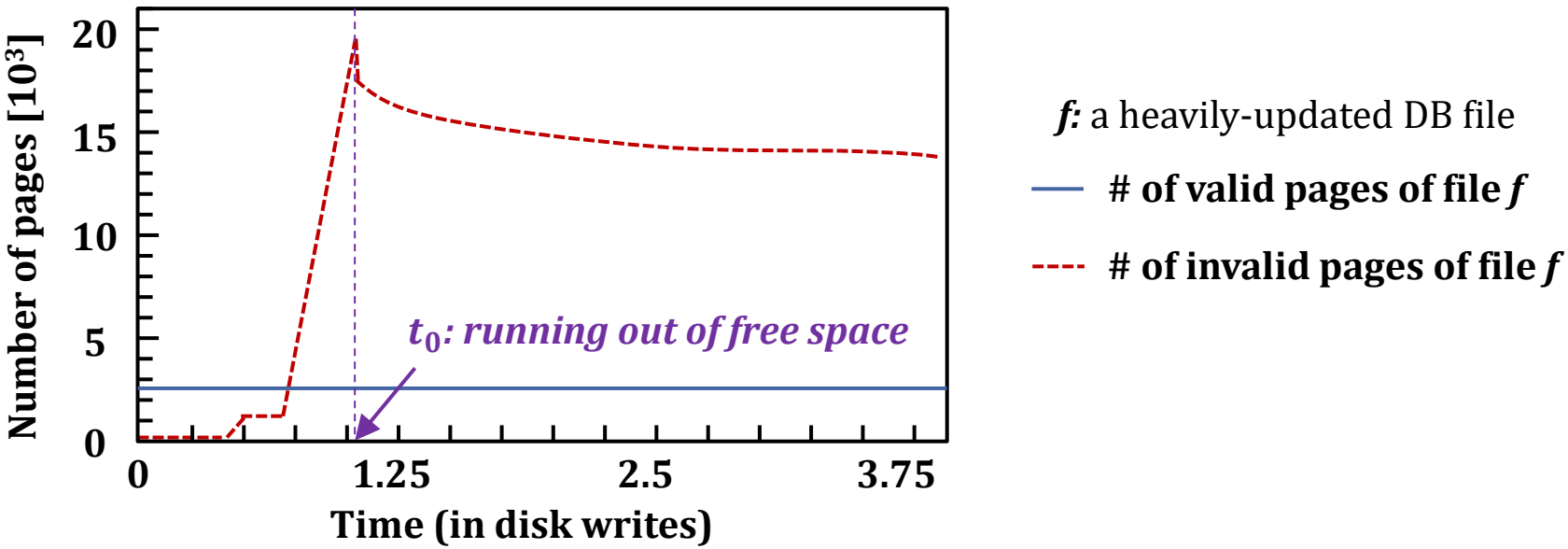
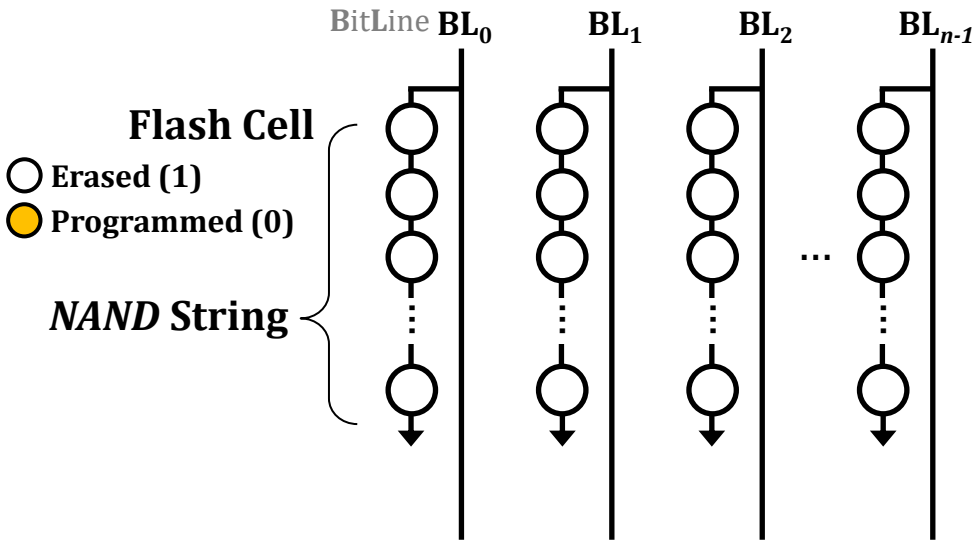


Updated or deleted data of a file can remain in SSDs due to unique features of NAND flash memory

NAND Flash Memory Organization & Operations



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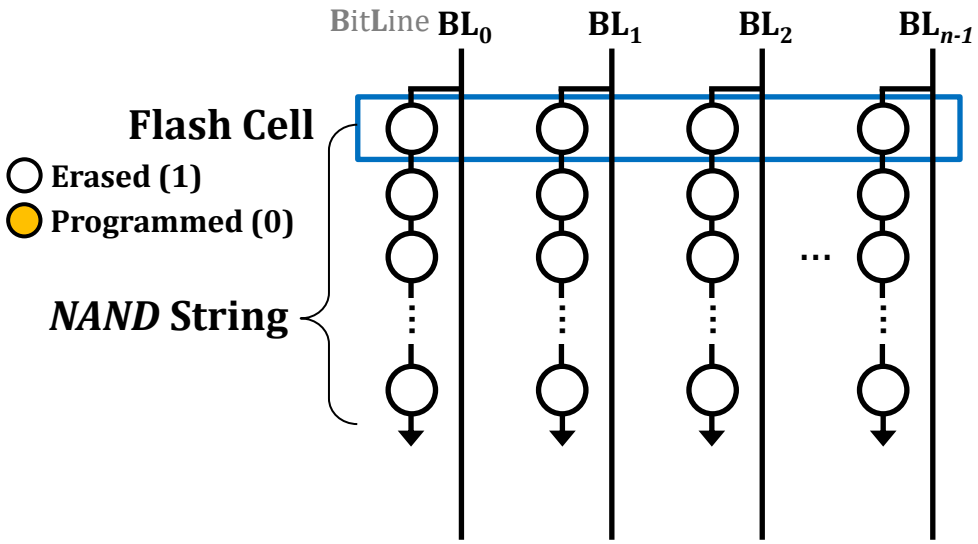

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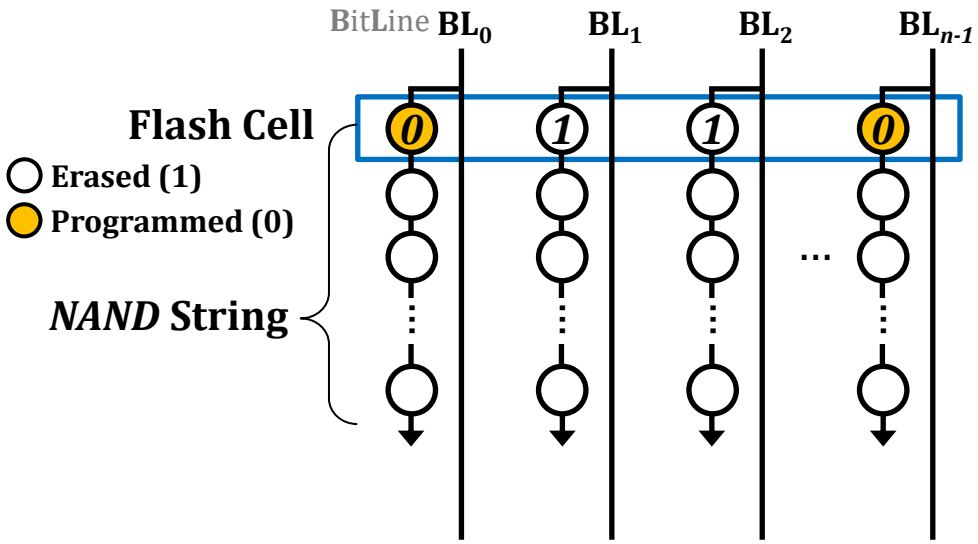

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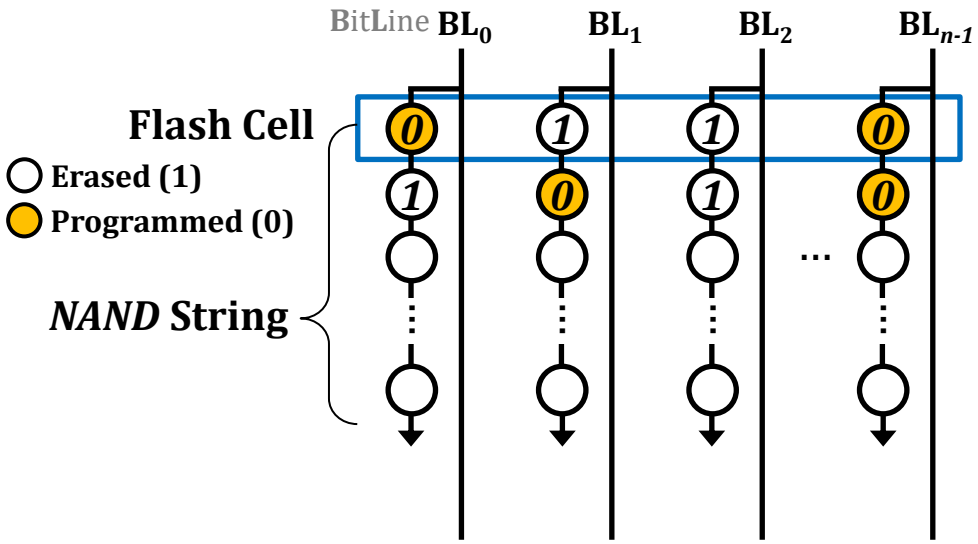

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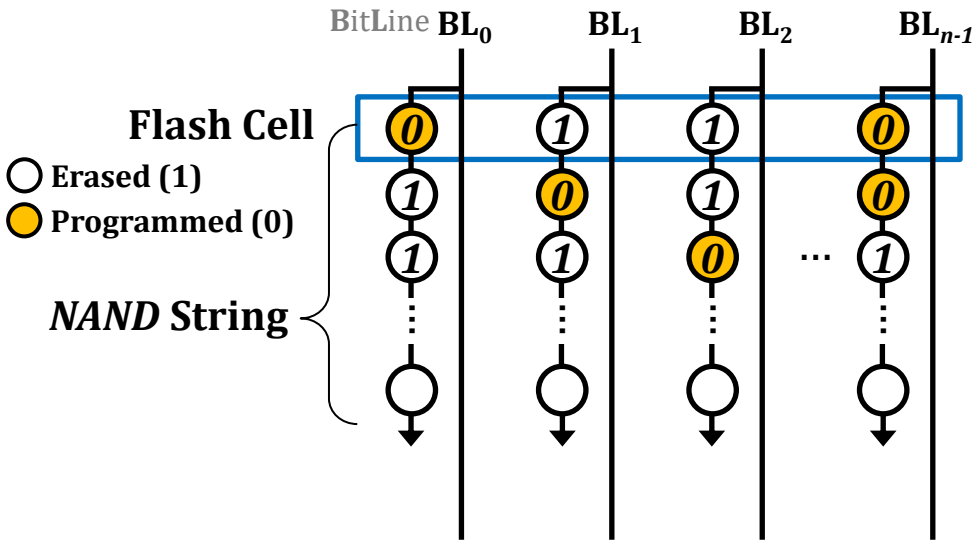

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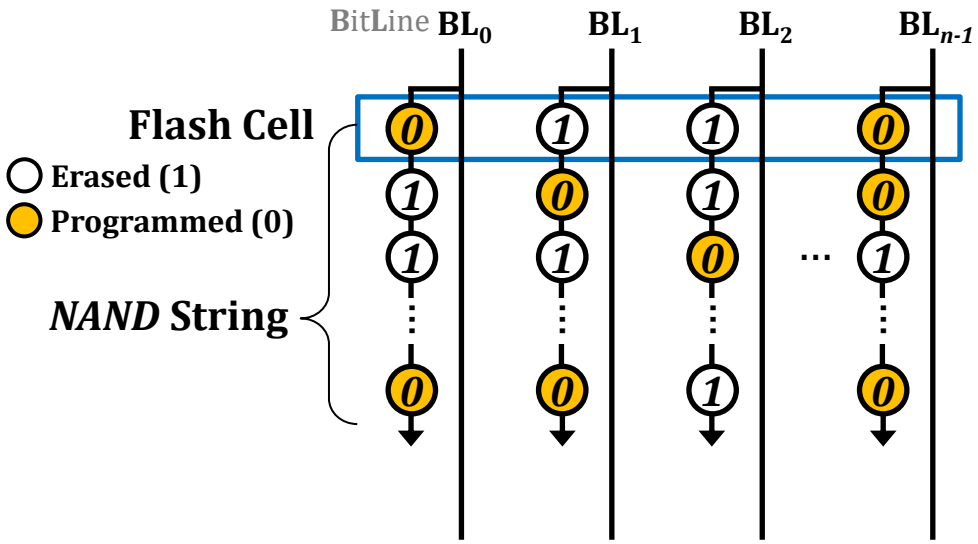

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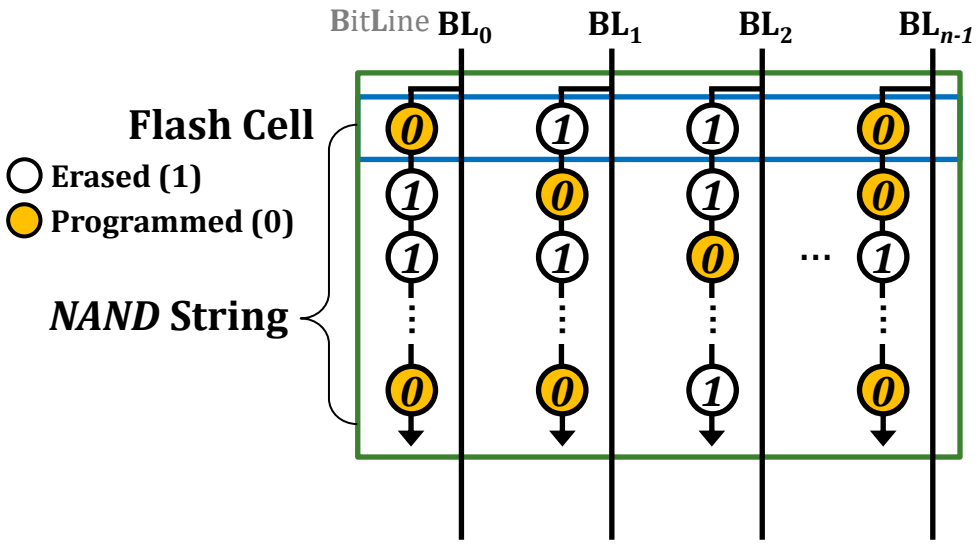

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Block: Erase unit
(e.g., 576 pages: 9-MiB block)

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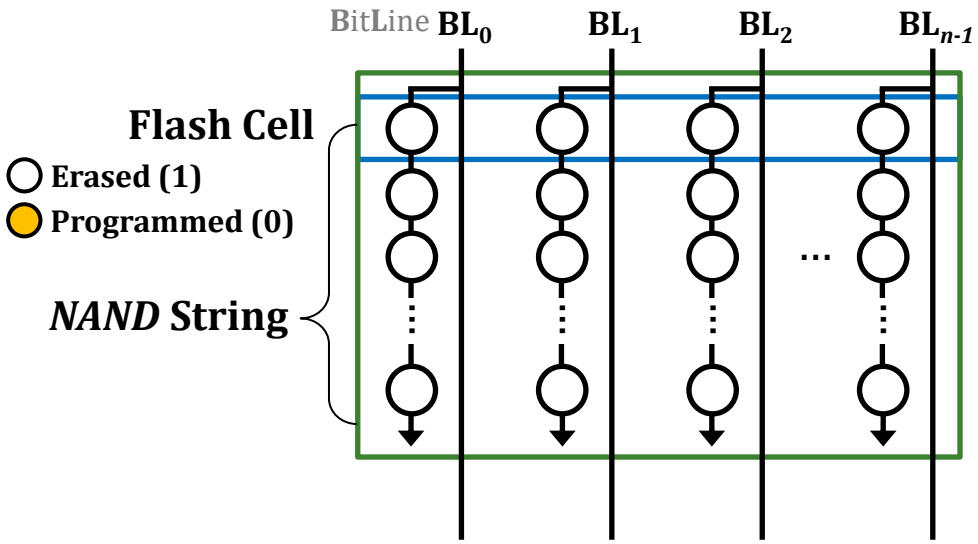

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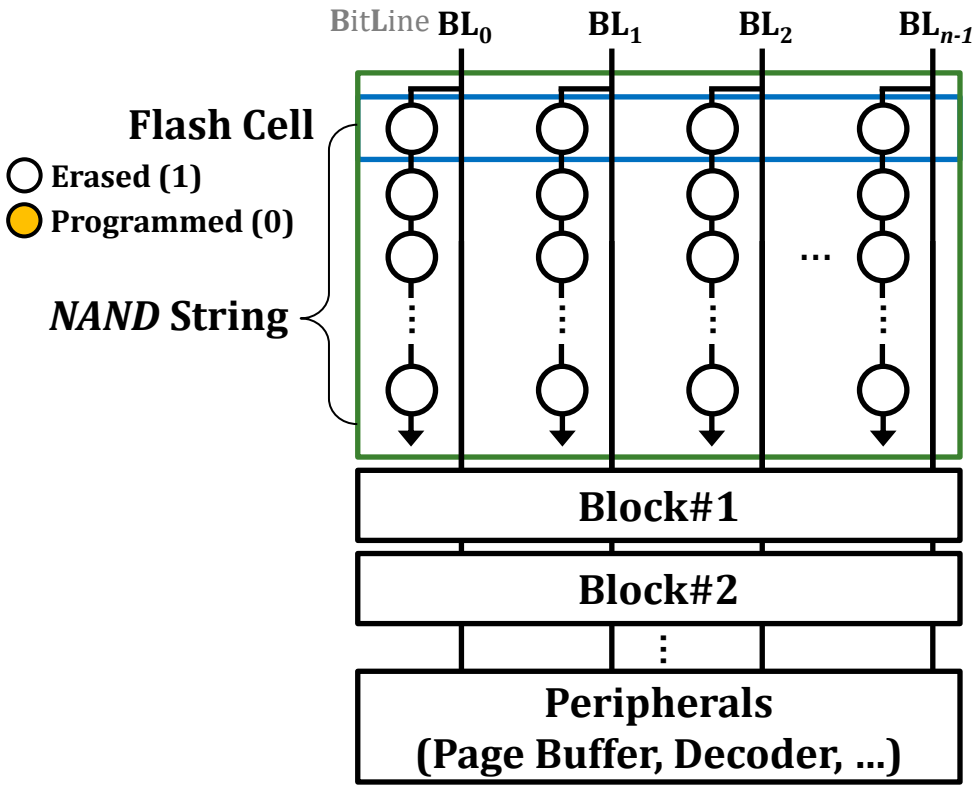

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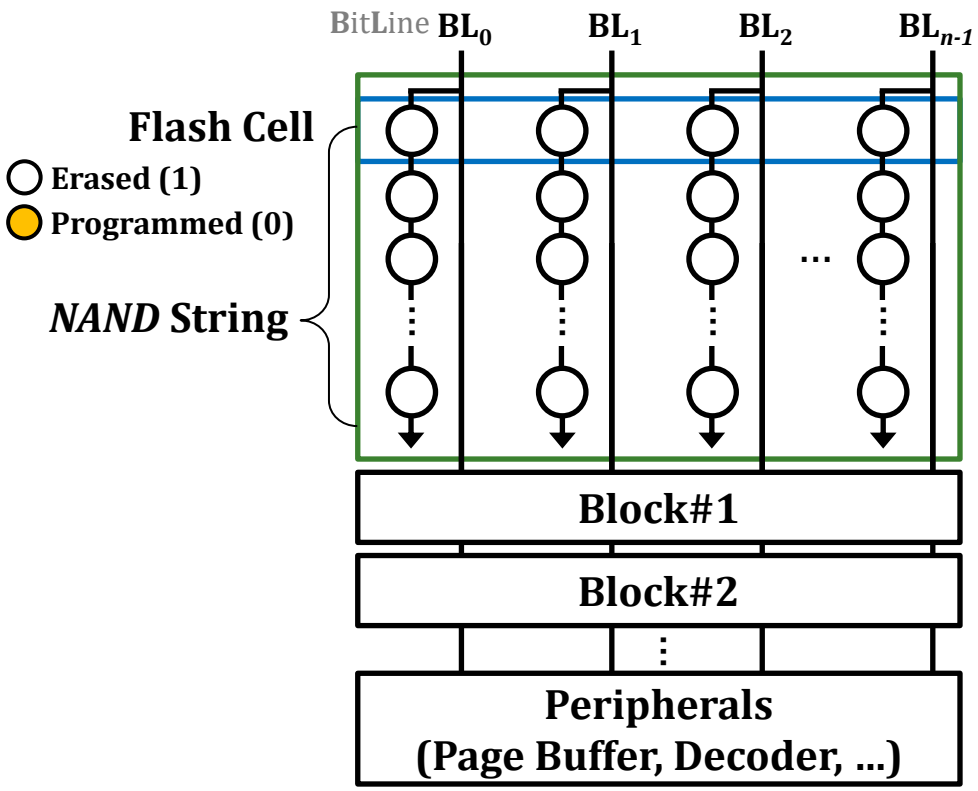

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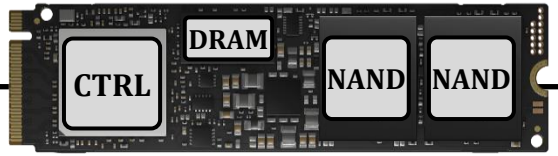
***Erase-before-write*: A block needs to be erased before programming a page (i.e., no overwrite on a page)**

NAND Flash-Based SSD

File System



Flash-Based SSD

Flash Controller

Chip#0

0
1
2
3
Block#0

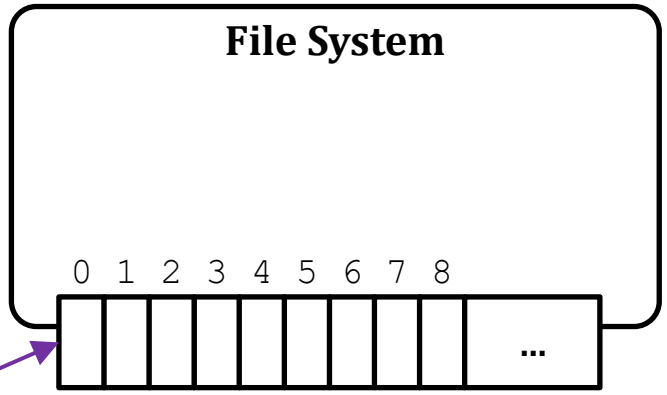
4
5
6
7 Page
Block#1

Chip#1

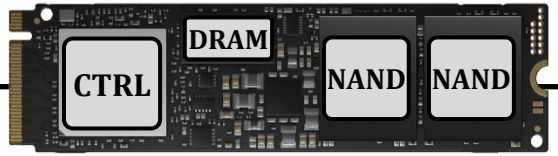
8
9
10
11
Block#2

12
13
14
15
Block#3

NAND Flash-Based SSD



Logical block-device view that supports overwrites



Flash-Based SSD

Flash Translation Layer (FTL)

Flash Controller

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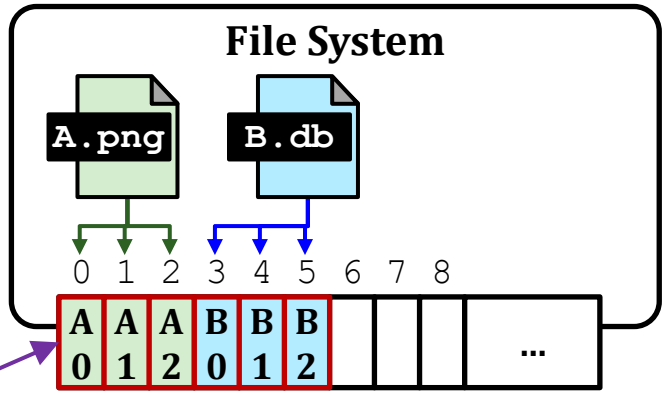

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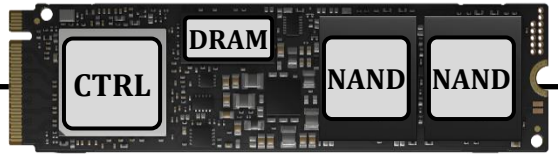

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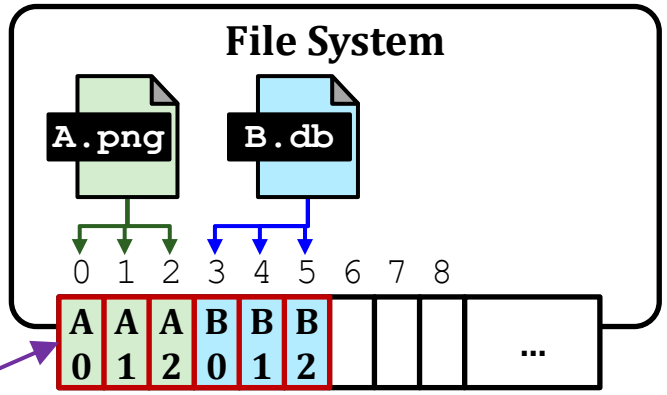

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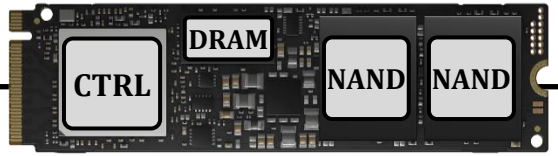
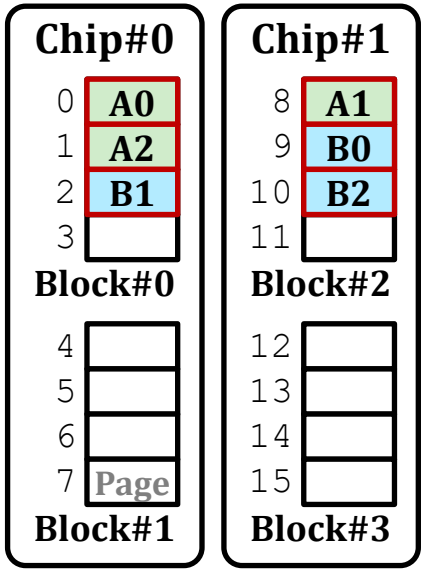


Flash-Based SSD

Flash Translation Layer (FTL)

- **Address translation**
  - Distributes host writes to fully exploit internal parallelism

Flash Controller



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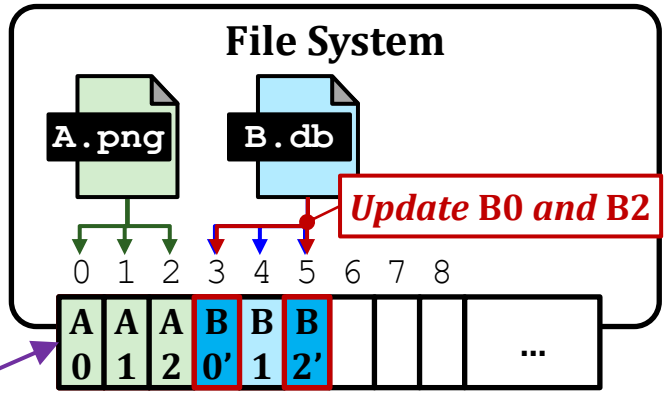

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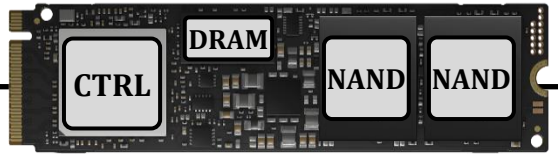

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Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	

Block#0

4	
5	
6	
7	Page

Block#1

Chip#1

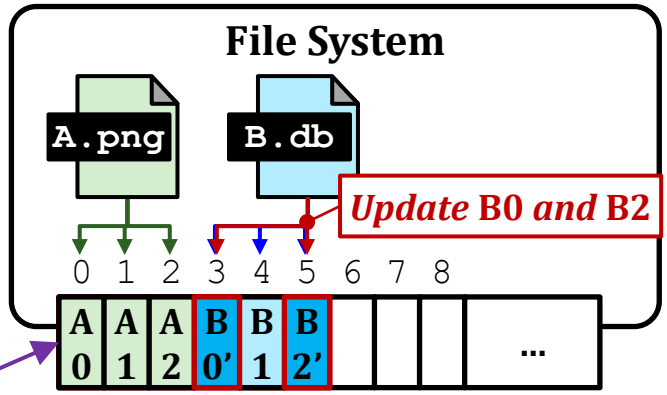
8	A1
9	B0
10	B2
11	

Block#2

12	
13	
14	
15	

Block#3

NAND Flash-Based SSD



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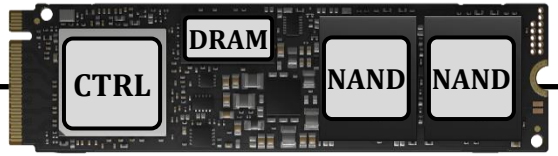

Flash-Based SSD

Flash Translation Layer (FTL)

- **Address translation**
  - Distributes host writes to fully exploit internal parallelism
  - Out-of-place updates

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	
5	
6	
7	Page

Block#1

Chip#1

8	A1
9	B0
10	B2
11	B2'

Block#2

12	
13	
14	
15	

Block#3

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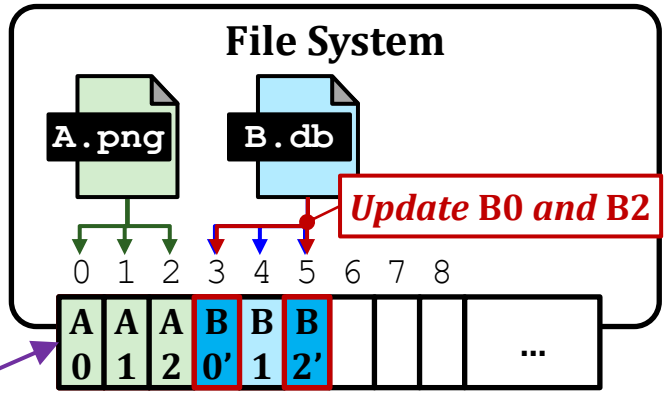

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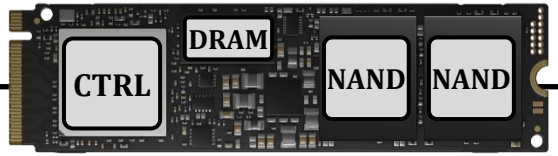

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- **Address translation**
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Logical Page Address

→ Logical-to-physical (L2P) mappings (e.g., LPA 1 → PPA 8)

Physical Page Address

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	
5	
6	
7	Page

Block#1

Chip#1

8	A1
9	B0
10	B2
11	B2'

Block#2

12	
13	
14	
15	

Block#3

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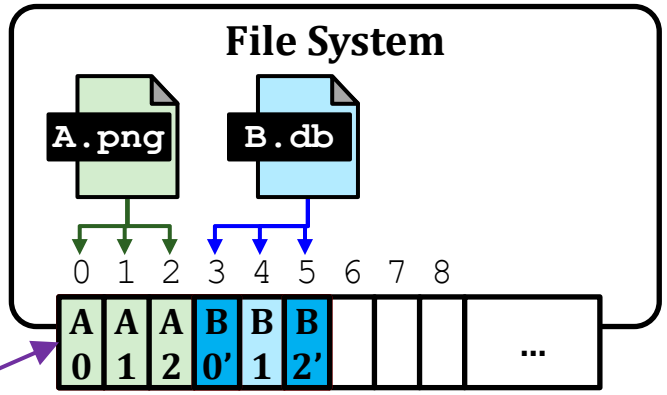

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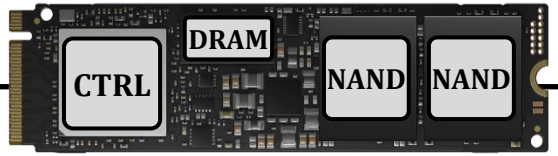

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  Physical Page Address
- **Garbage collection (GC)**
  - Reclaims free pages for future host writes

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	
5	
6	
7	Page

Block#1

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15	

Block#3

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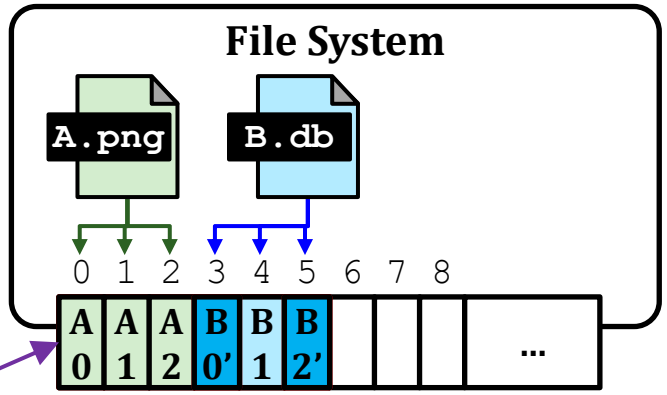

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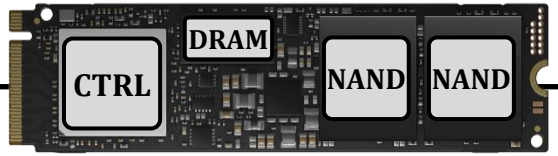

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  - Selects a victim block w/ the smallest number of valid pages
  - Additional copy operations to move valid pages

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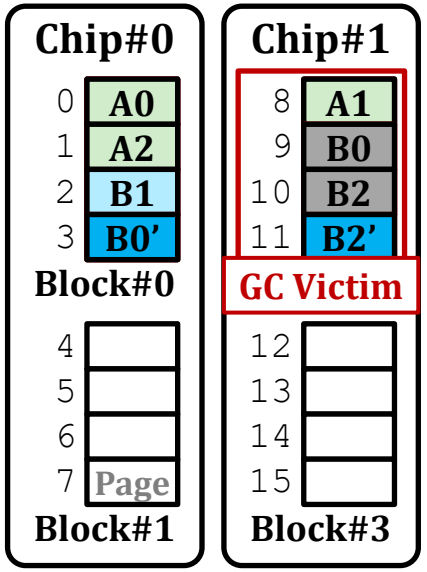

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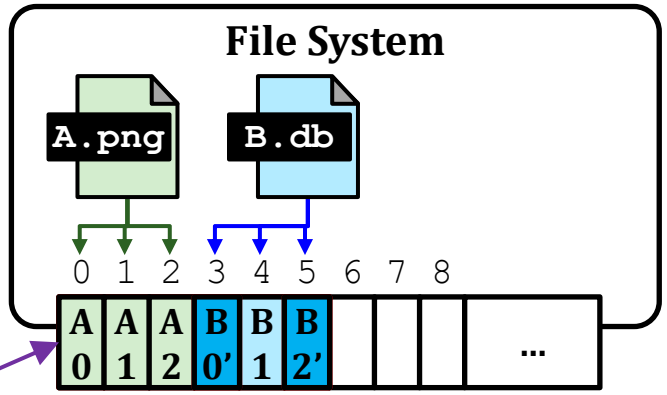

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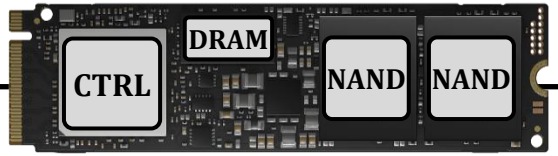

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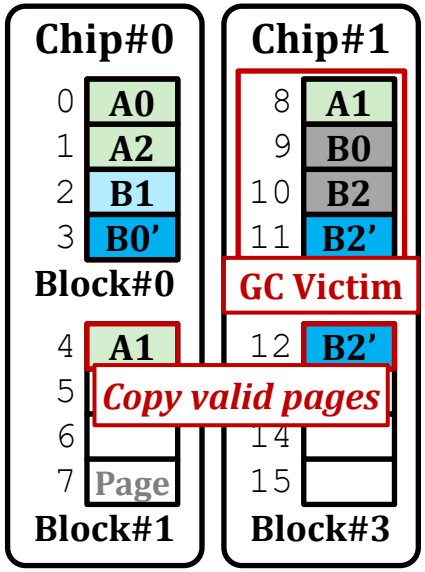

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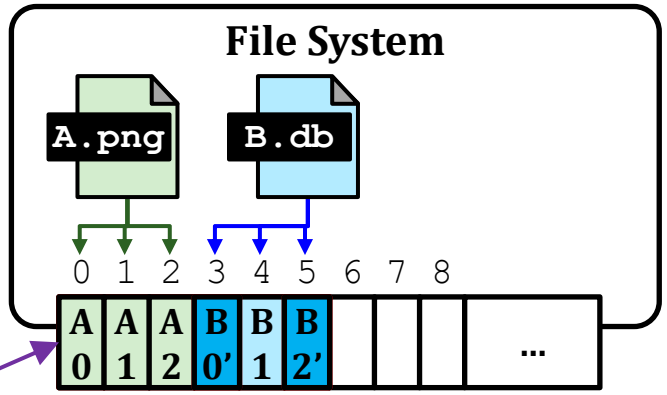
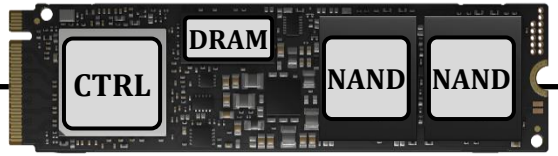


Logical block-device view that supports overwrites



Flash-Based SSD

Flash Translation Layer (FTL)

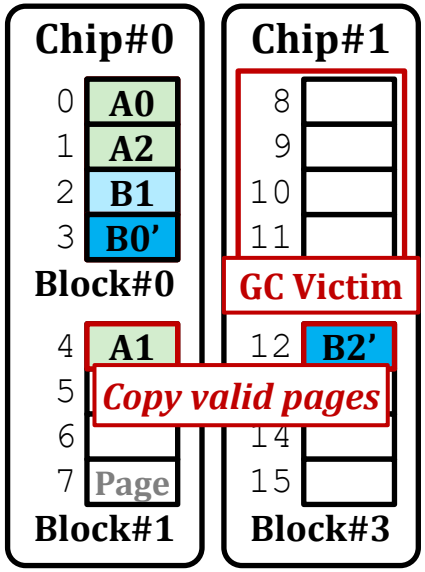
- **Address translation**
  - Distributes host writes to fully exploit internal parallelism
  - Out-of-place updates

  Logical Page Address

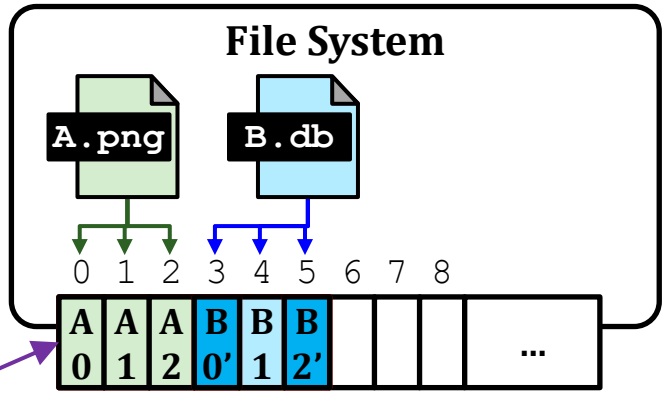
  → Logical-to-physical (L2P) mappings (e.g., LPA 1 → PPA 8)

  Physical Page Address
- **Garbage collection (GC)**
  - Reclaims free pages for future host writes
  - Selects a victim block w/ the smallest number of valid pages
  - Additional copy operations to move valid pages

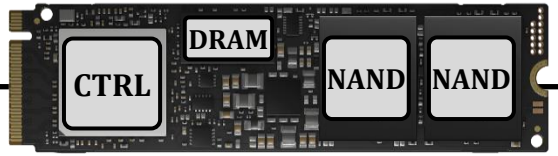
Flash Controller



NAND Flash-Based SSD



Logical block-device view that supports overwrites



Flash-Based SSD

Flash Translation Layer (FTL)

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  - Distributes host writes to fully exploit internal parallelism
  - Out-of-place updates

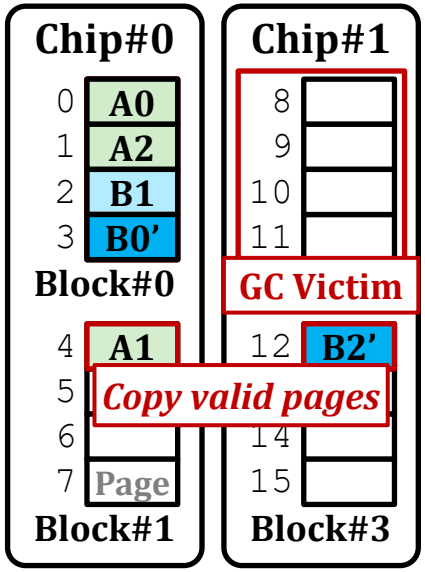
  Logical Page Address

  → Logical-to-physical (L2P) mappings (e.g., LPA 1 → PPA 8)

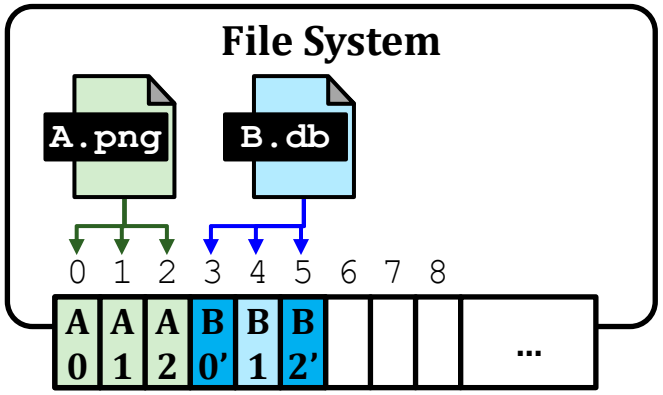
  Physical Page Address
- **Garbage collection (GC)**
  - Reclaims free pages for future host writes
  - Selects a victim block w/ the smallest number of valid pages
  - Additional copy operations to move valid pages

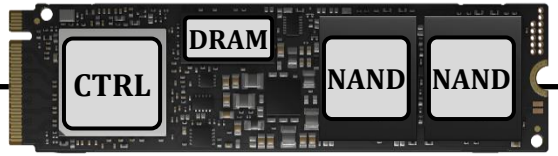
  → Page-status information (e.g., B0: invalid)

Flash Controller



Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	0
1	4
2	1
3	3
4	2
5	12
...	...
11	N/A

L2P Mapping Table

PPA	Status
0	valid
1	valid
2	valid
3	valid
4	valid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	A1
5	
6	
7	

Block#1

Chip#1

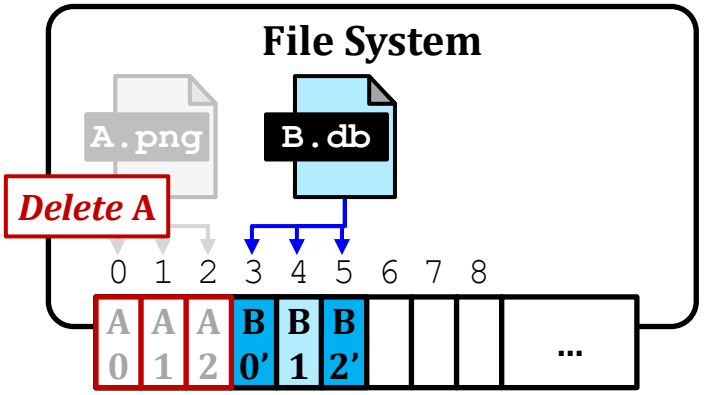
8	
9	
10	
11	

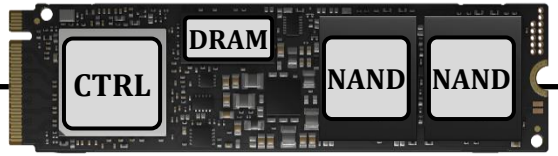
Block#2

12	B2'
13	
14	
15	

Block#3

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

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1	4
2	1
3	3
4	2
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...	...
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PPA	Status
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1	valid
2	valid
3	valid
4	valid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	A1
5	
6	
7	

Block#1

Chip#1

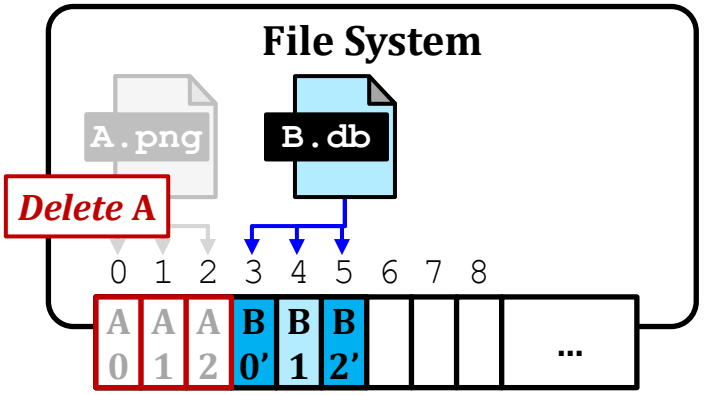
8	
9	
10	
11	

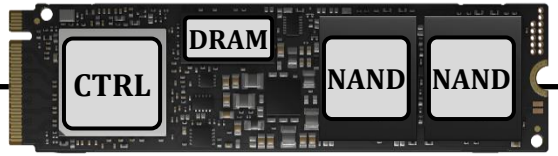
Block#2

12	B2'
13	
14	
15	

Block#3

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	0
1	4
2	1
3	3
4	2
5	12
...	...
11	N/A

L2P Mapping Table

PPA	Status
0	valid
1	valid
2	valid
3	valid
4	valid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	A1
5	
6	
7	

Block#1

Chip#1

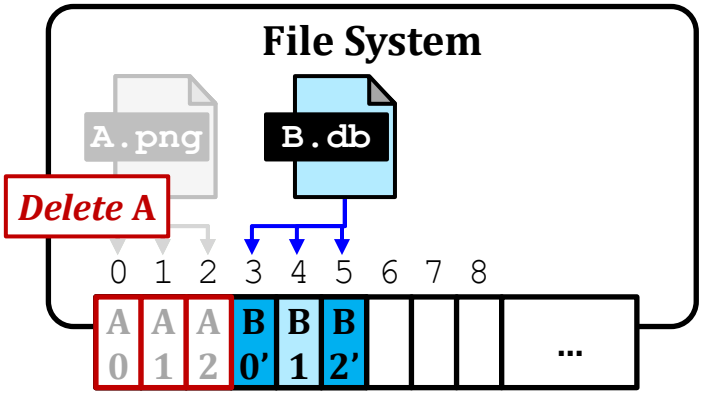
8	
9	
10	
11	

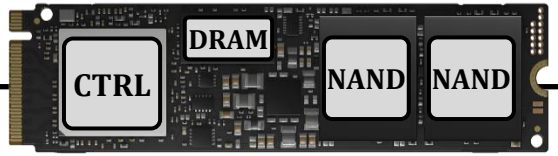
Block#2

12	B2'
13	
14	
15	

Block#3

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	
4	2
5	12
...	...
11	N/A

L2P Mapping Table

Update mapping & status

PPA	Status
0	invalid
1	invalid
2	valid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0'

Block#0

4	A1
5	
6	
7	

Block#1

Chip#1

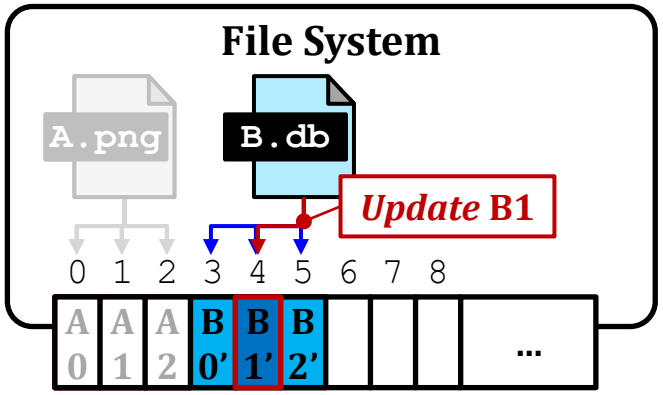
8	
9	
10	
11	

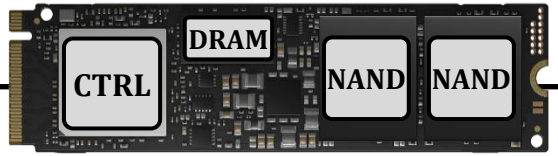
Block#2

12	B2'
13	
14	
15	

Block#3

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	2
5	12
...	...
11	N/A

L2P Mapping Table

PPA	Status
0	invalid
1	invalid
2	valid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

Block#0: 0 A0, 1 A2, 2 B1, 3 B0'

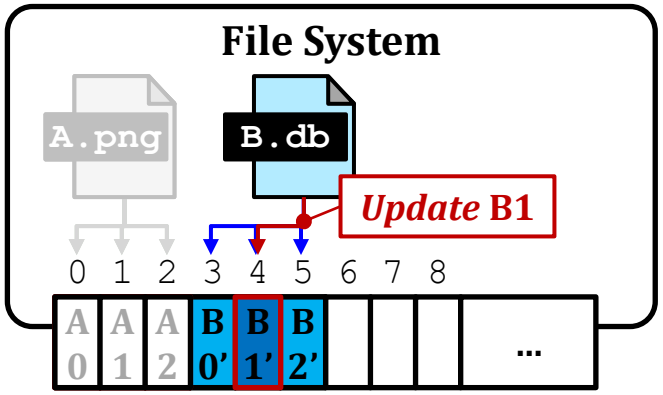
Block#1: 4 A1, 5, 6, 7

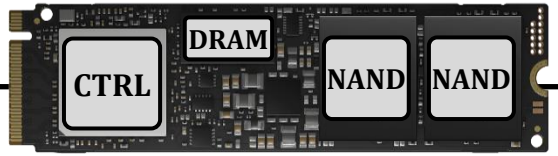
Chip#1

Block#2: 8, 9, 10, 11

Block#3: 12 B2', 13, 14, 15

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	2
5	12
...	...
11	N/A

L2P Mapping Table

PPA	Status
0	invalid
1	invalid
2	valid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

Block#0: 0 A0, 1 A2, 2 B1, 3 B0'

Block#1: 4 A1, 5 B1', 7

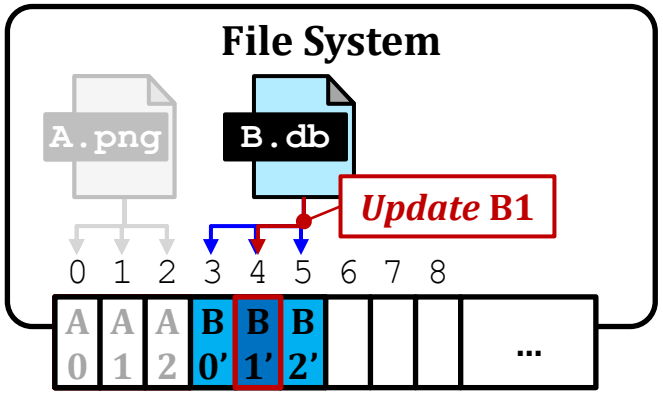
Chip#1

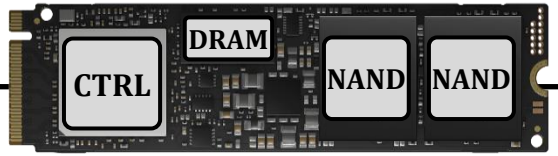
Block#2: 8, 9, 10, 11

Block#3: 12 B2', 13, 15

Out-of-place update

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	2
5	12
...	...
11	N/A

L2P Mapping Table

Update status

PPA	Status
0	invalid
1	invalid
2	invalid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

Out-of-place update

Chip#0

Block#0: 0 A0, 1 A2, 2 B1, 3 B0'

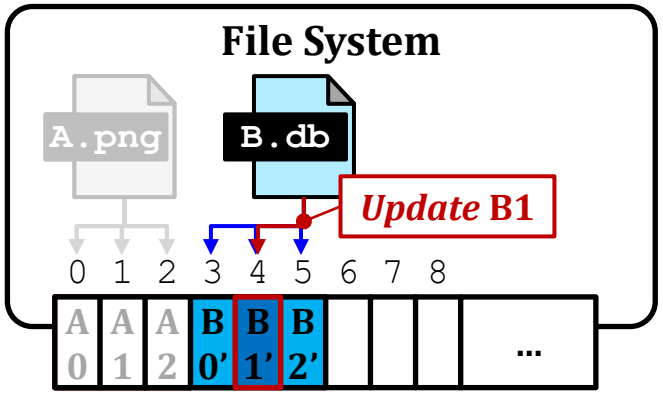
Block#1: 4 A1, 5 B1', 7

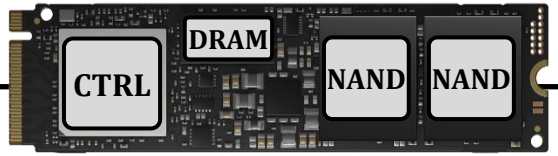
Chip#1

Block#2: 8, 9, 10, 11

Block#3: 12 B2', 13, 15

Data Deletion in NAND Flash-Based Storage Systems





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	5
5	
...	
11	N/A

L2P Mapping Table

Update mapping

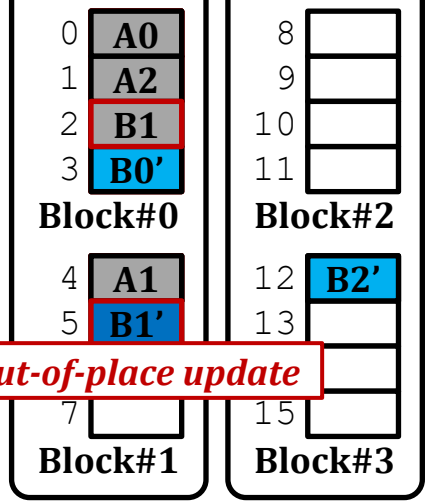
Update status

PPA	Status
0	invalid
1	invalid
2	invalid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

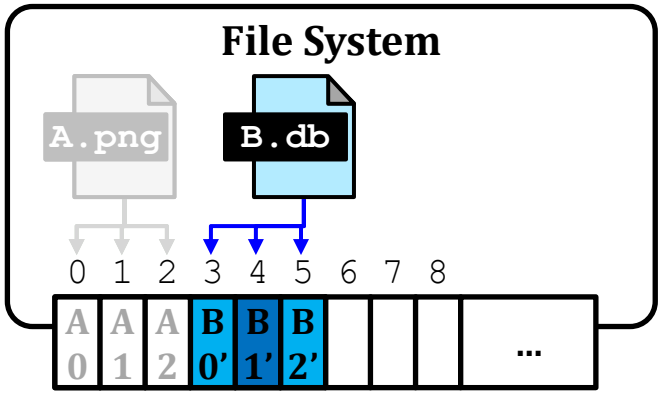
Out-of-place update

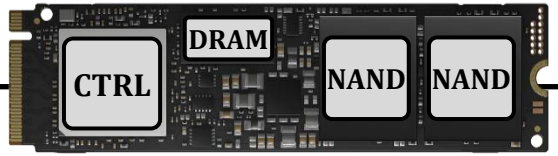


Data Deletion in NAND Flash-Based Storage Systems

Invalid data remains in NAND flash chips
until GC erases the corresponding block(s)

Security Vulnerability of NAND Flash-Based SSDs





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	5
5	12
...	...
11	N/A

L2P Mapping Table

PPA	Status
0	invalid
1	invalid
2	invalid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

0 A0
1 A2
2 B1
3 B0'

Block#0

4 A1
5 B1'
6
7

Block#1

Chip#1

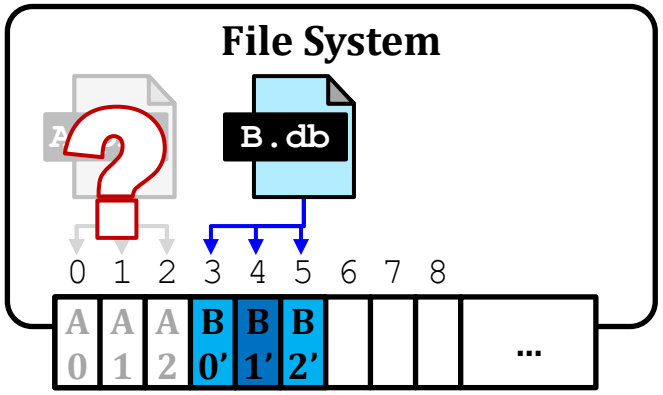
8
9
10
11

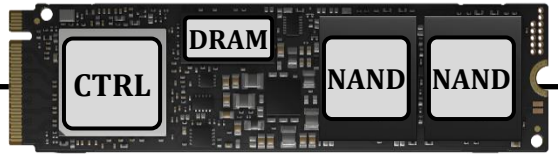
Block#2

12 B2'
13
14
15

Block#3

Security Vulnerability of NAND Flash-Based SSDs





Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	5
5	12
...	...
11	N/A

L2P Mapping Table

PPA	Status
0	invalid
1	invalid
2	invalid
3	valid
4	invalid
5	free
...	...
15	free

Page Status Table

Flash Controller

Chip#0

0 A0
1 A2
2 B1
3 B0'

Block#0

4 A1
5 B1'
6
7

Block#1

Chip#1

8
9
10
11

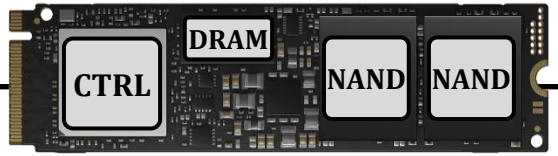
Block#2

12 B2'
13
14
15

Block#3

Security Vulnerability of NAND Flash-Based SSDs

Direct access to SSD



Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	5
5	12
…	…
11	N/A

L2P Mapping Table

PPA	Status
0	invalid
1	invalid
2	invalid
3	valid
4	invalid
5	free
…	…
15	free

Page Status Table

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0’

Block#0

4	A1
5	B1’
6	
7	

Block#1

Chip#1

8	
9	
10	
11	

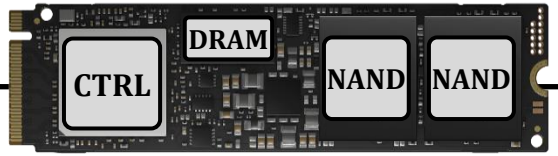
Block#2

12	B2’
13	
14	
15	

Block#3

Security Vulnerability of NAND Flash-Based SSDs

Direct access to SSD



Flash-Based SSD

Flash Translation Layer (FTL)

LPA	PPA
0	N/A
1	N/A
2	N/A
3	3
4	5
5	12
…	…
11	N/A

L2P Mapping Table

No mappings to invalid PPAs

PPA	Status
0	invalid
1	invalid
2	invalid
3	valid
4	invalid
5	free
…	…
15	free

Page Status Table

Flash Controller

Chip#0

0	A0
1	A2
2	B1
3	B0’

Block#0

4	A1
5	B1’
6	
7	

Block#1

Chip#1

8	
9	
10	
11	

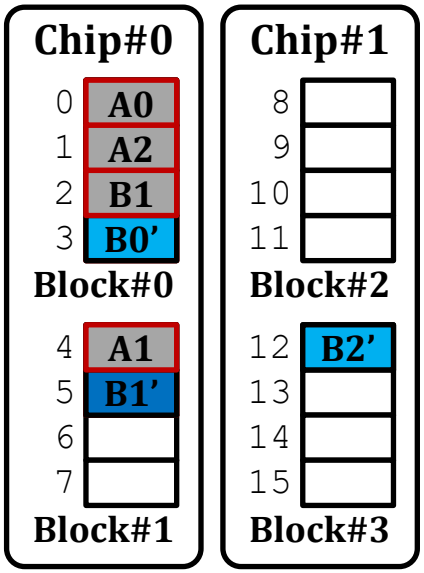
Block#2

12	B2’
13	
14	
15	

Block#3

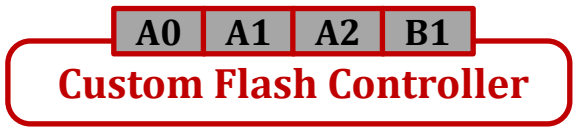
Security Vulnerability of NAND Flash-Based SSDs

De-solder

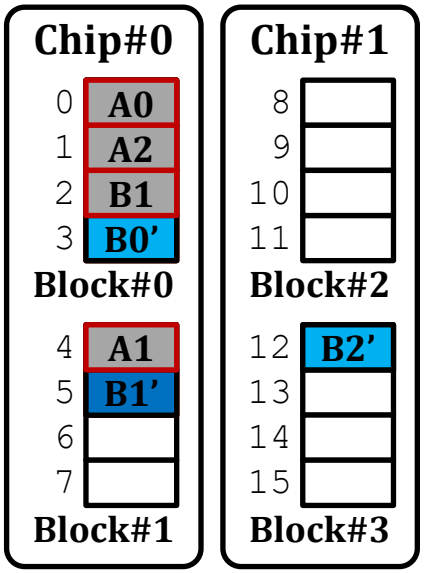


Security Vulnerability of NAND Flash-Based SSDs

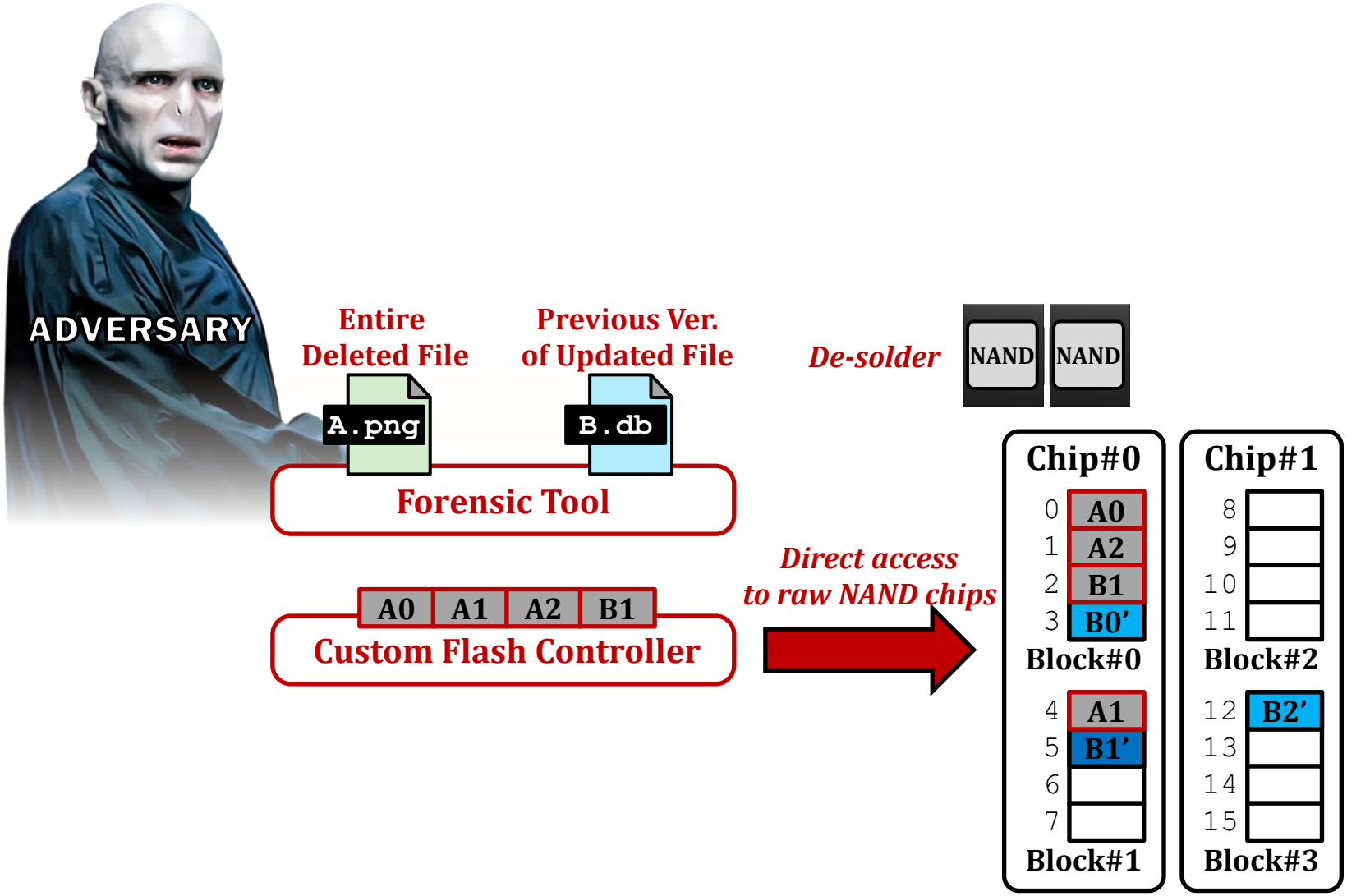
De-solder



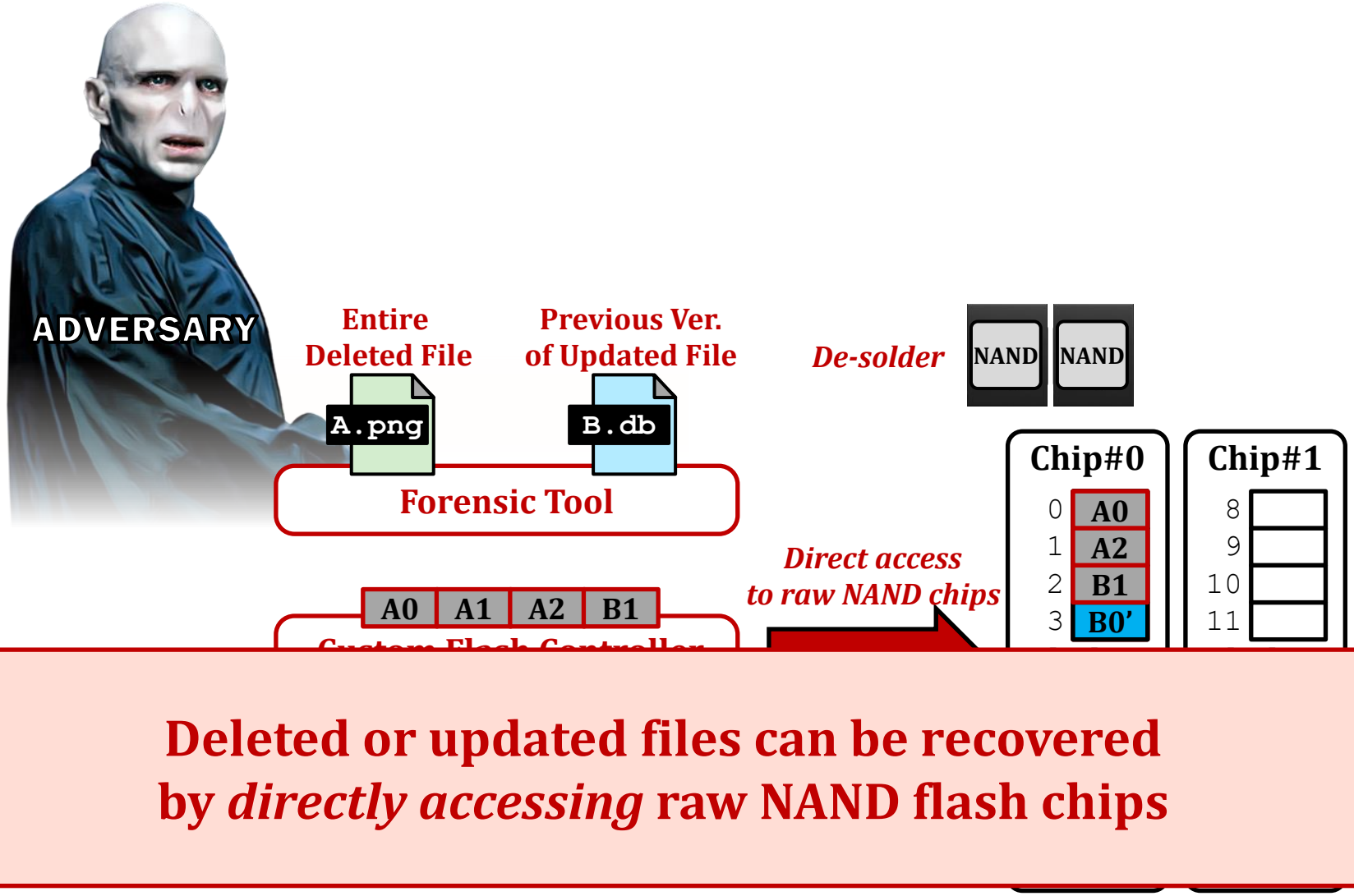
Direct access to raw NAND chips



Security Vulnerability of NAND Flash-Based SSDs



Security Vulnerability of NAND Flash-Based SSDs



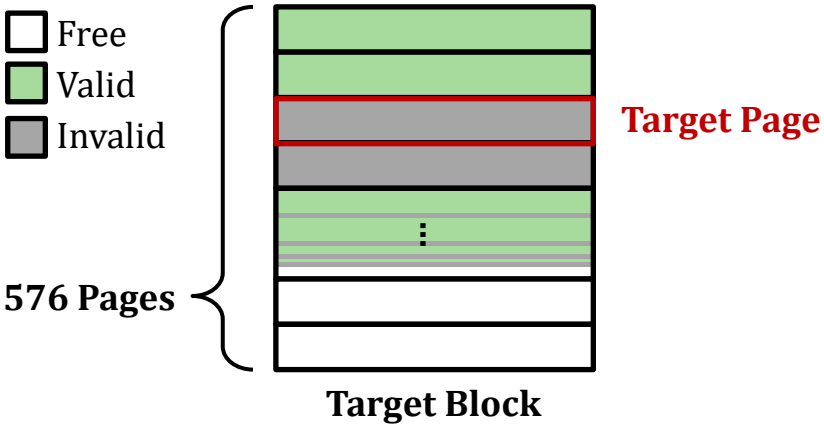
Deleted or updated files can be recovered by *directly accessing* raw NAND flash chips

Existing Solution: Immediate Block Erasure

- Immediately erases the block that stores data to be sanitized

Existing Solution: Immediate Block Erasure

- Immediately erases the block that stores data to be sanitized
  - High performance and lifetime overheads due to *Erase-before-write property*
    - Needs to copy all the valid pages stored in the same block



Existing Solution: Immediate Block Erasure

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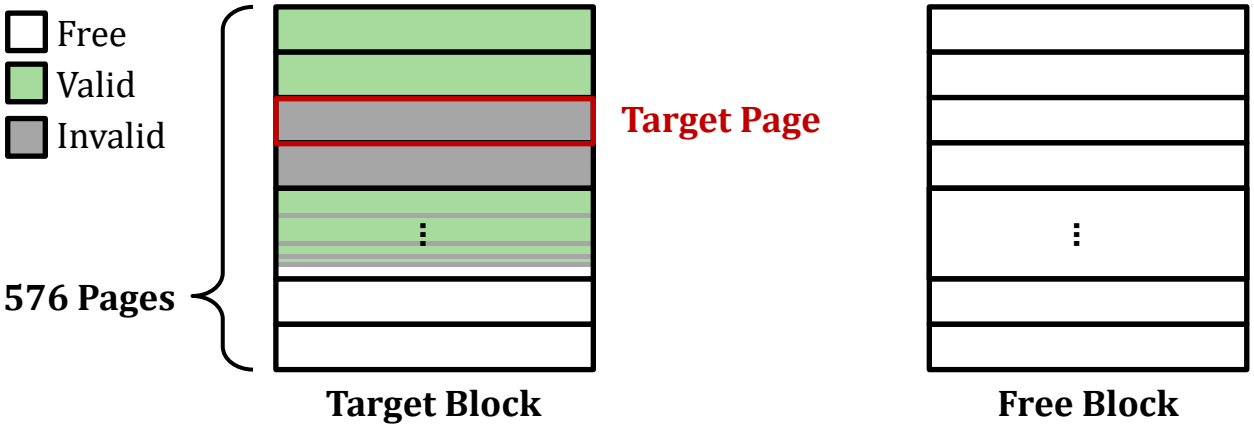

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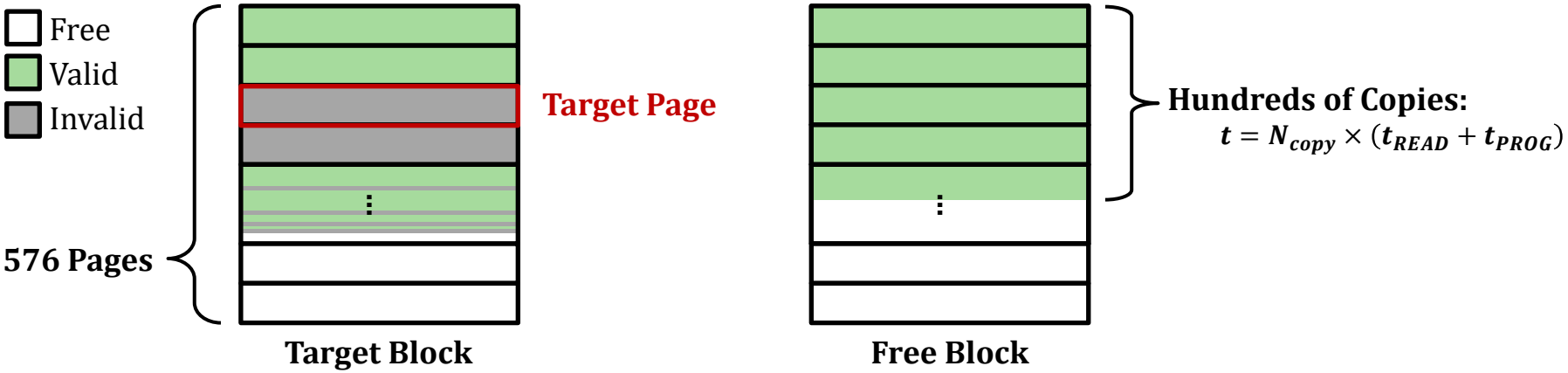

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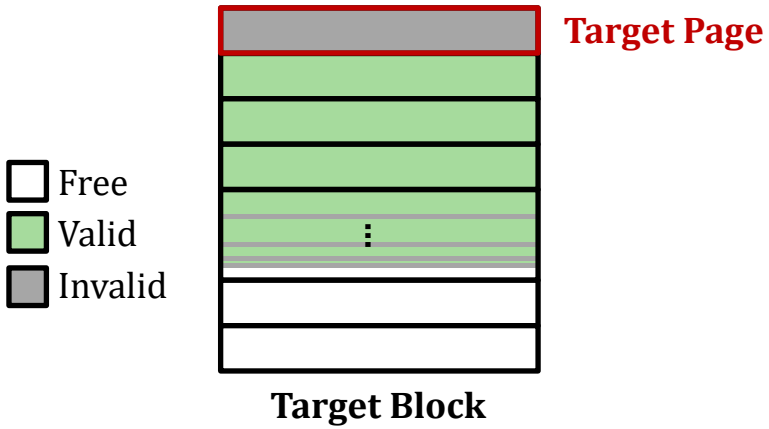

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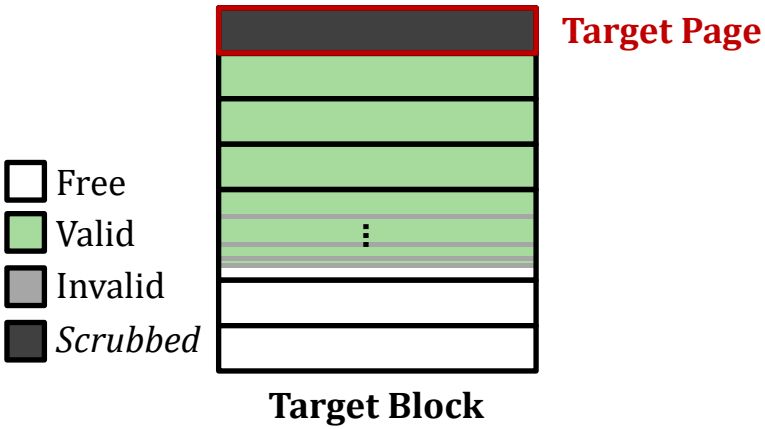

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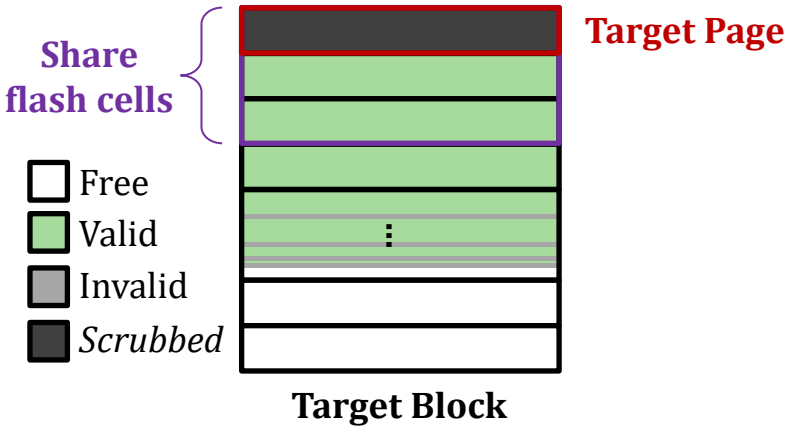

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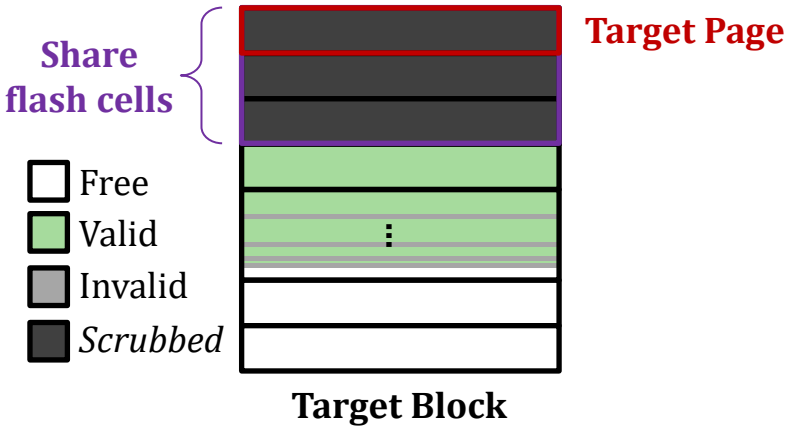

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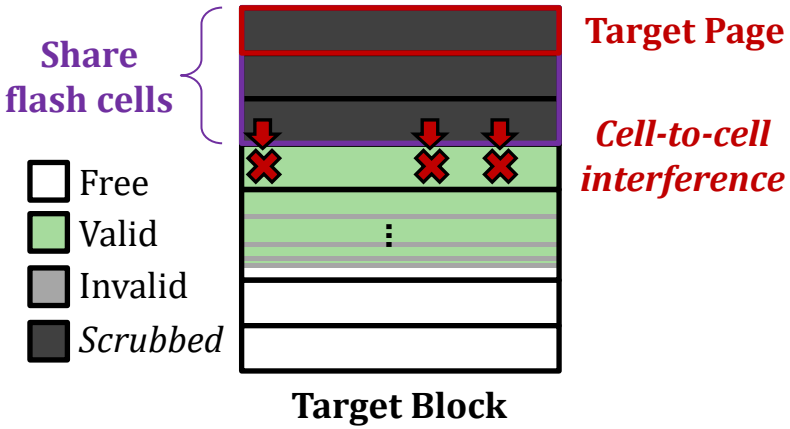

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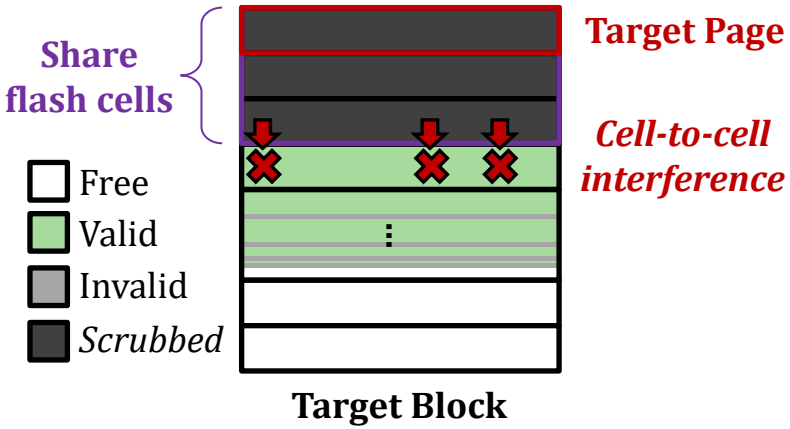

Existing solutions incur
***performance, lifetime, and reliability* problems**
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- Secure Deletion in NAND Flash-Based SSDs
- **Evanesco: Lock-Based Data Sanitization**
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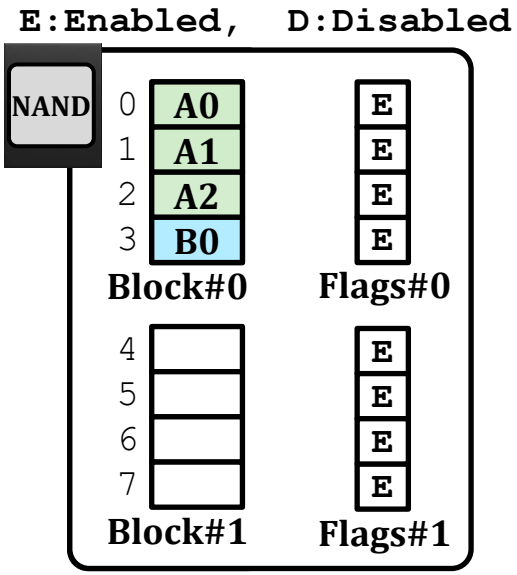

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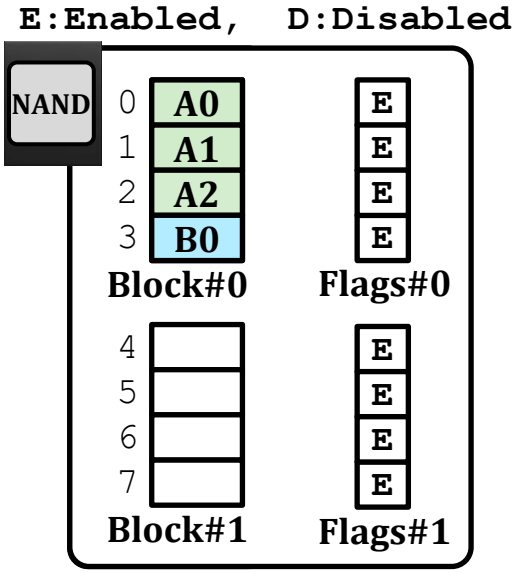

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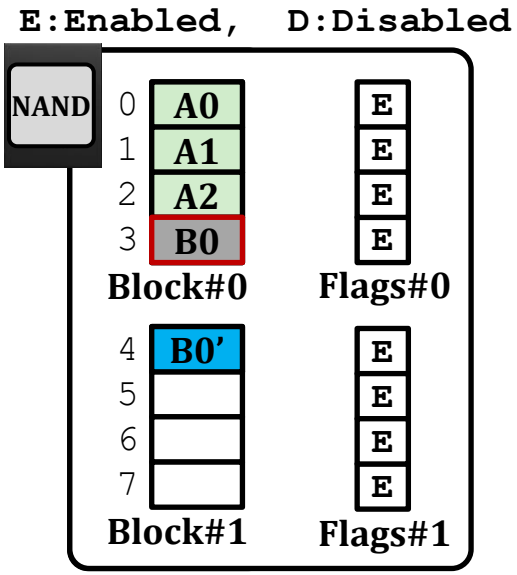

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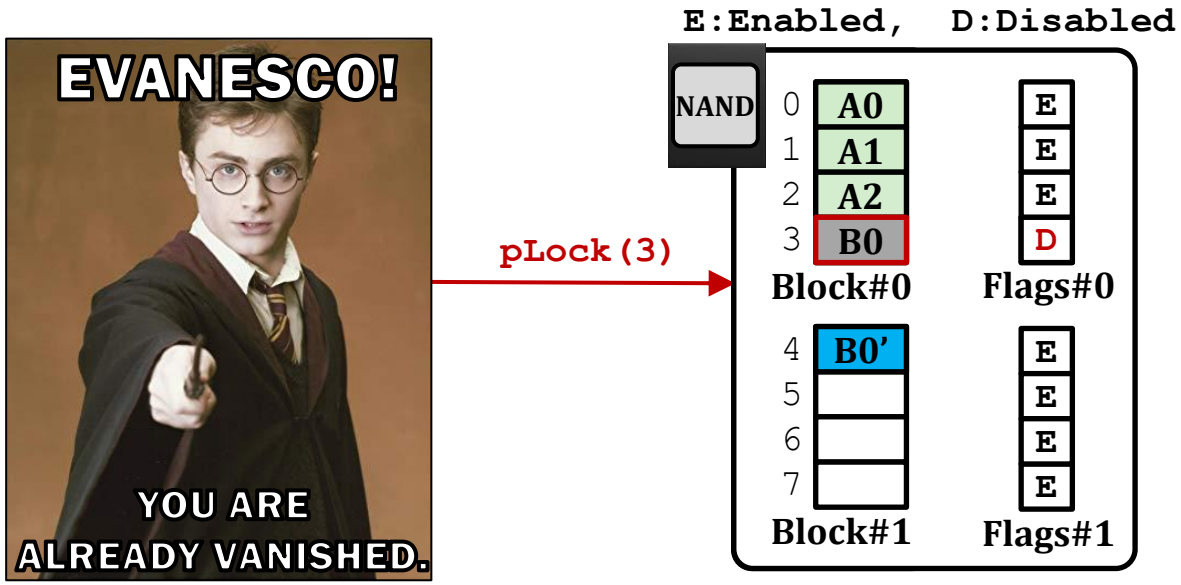

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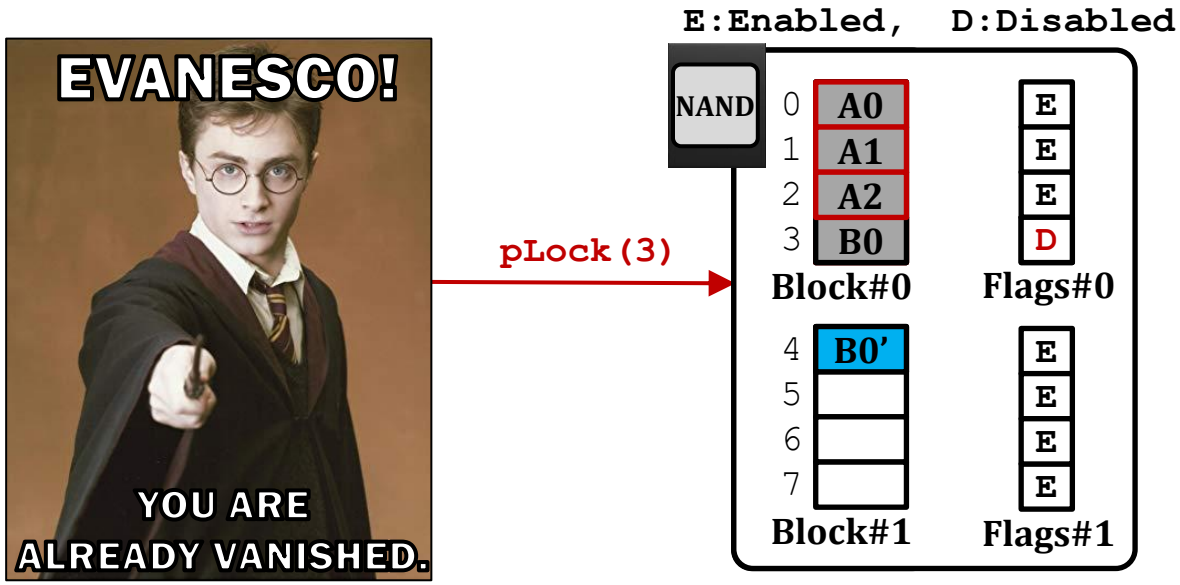

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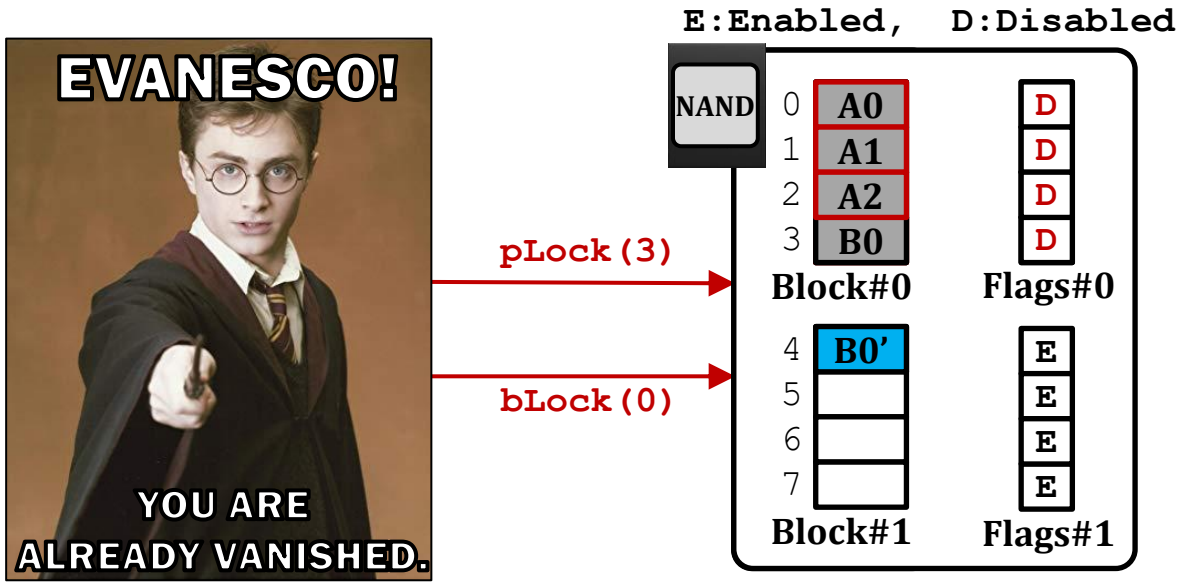

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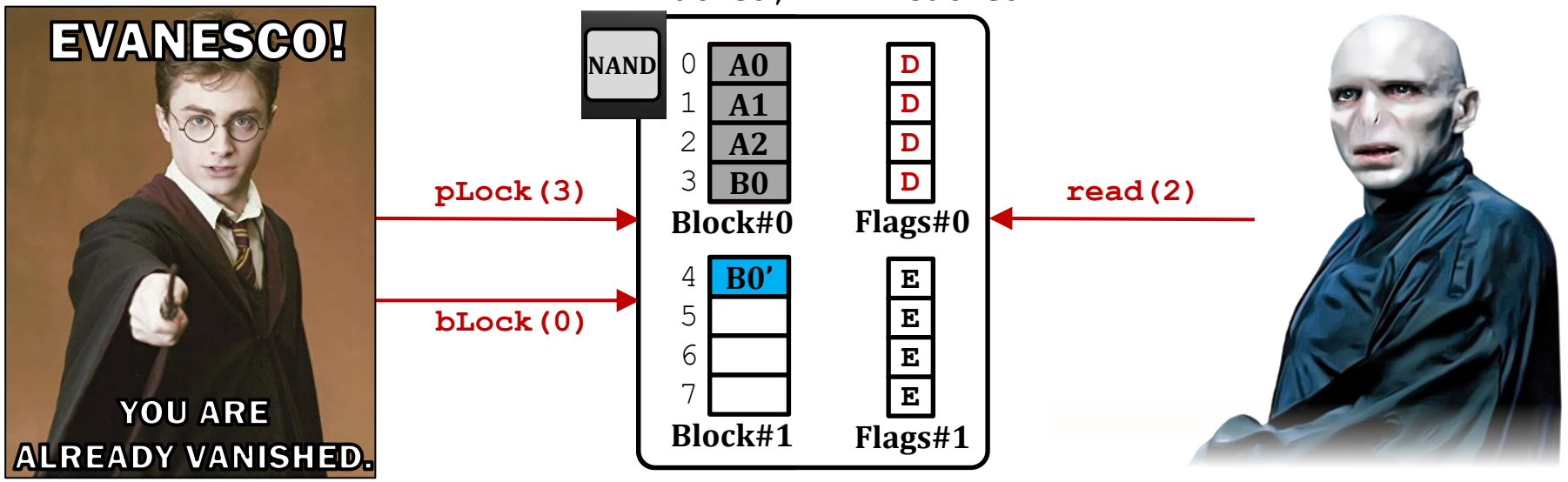

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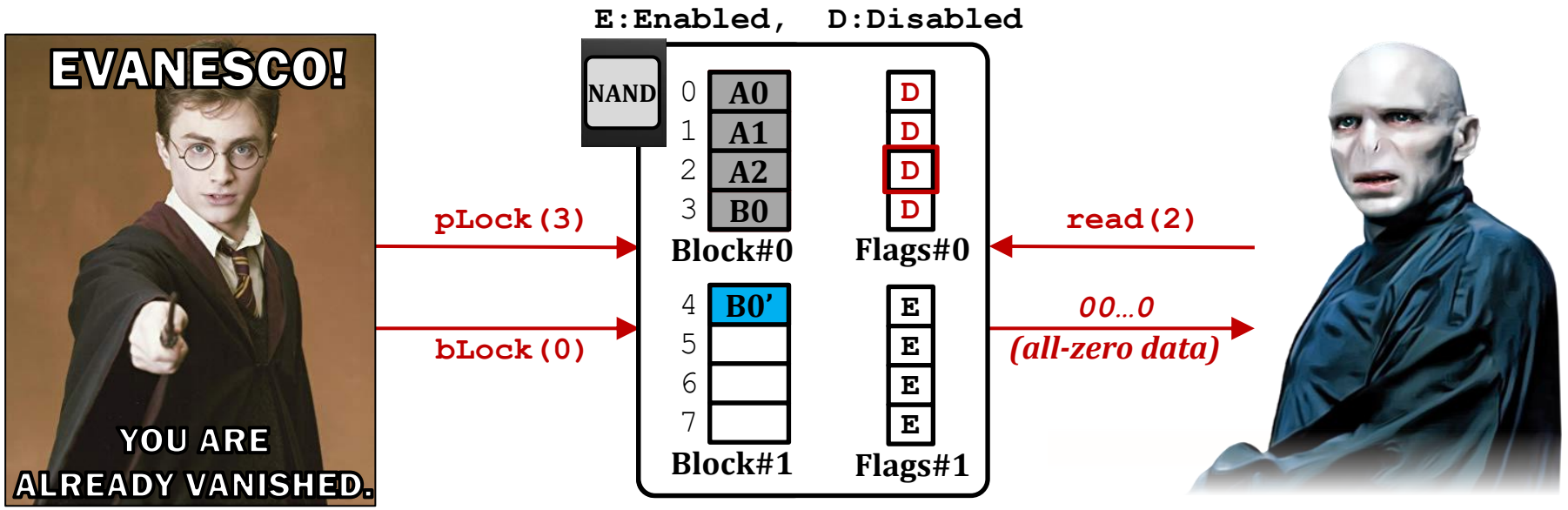

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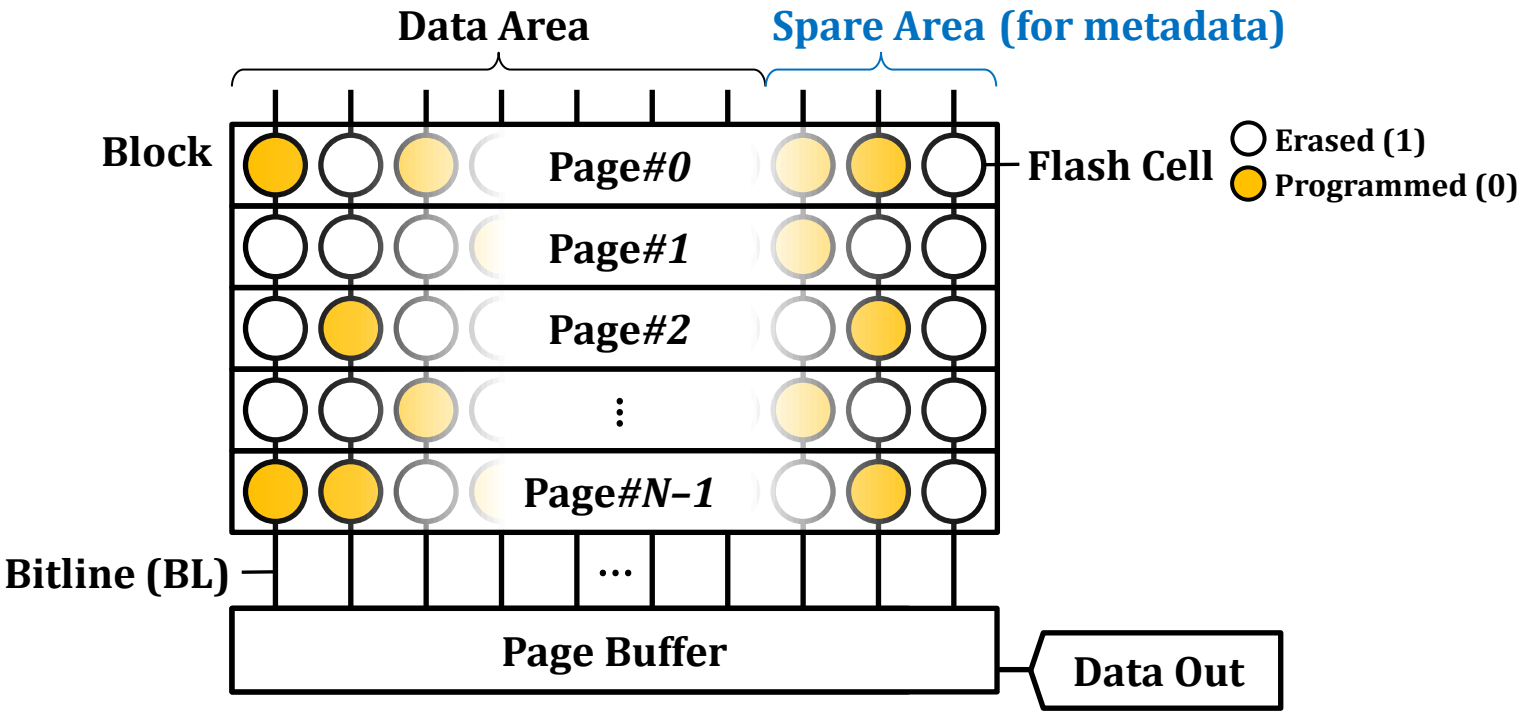

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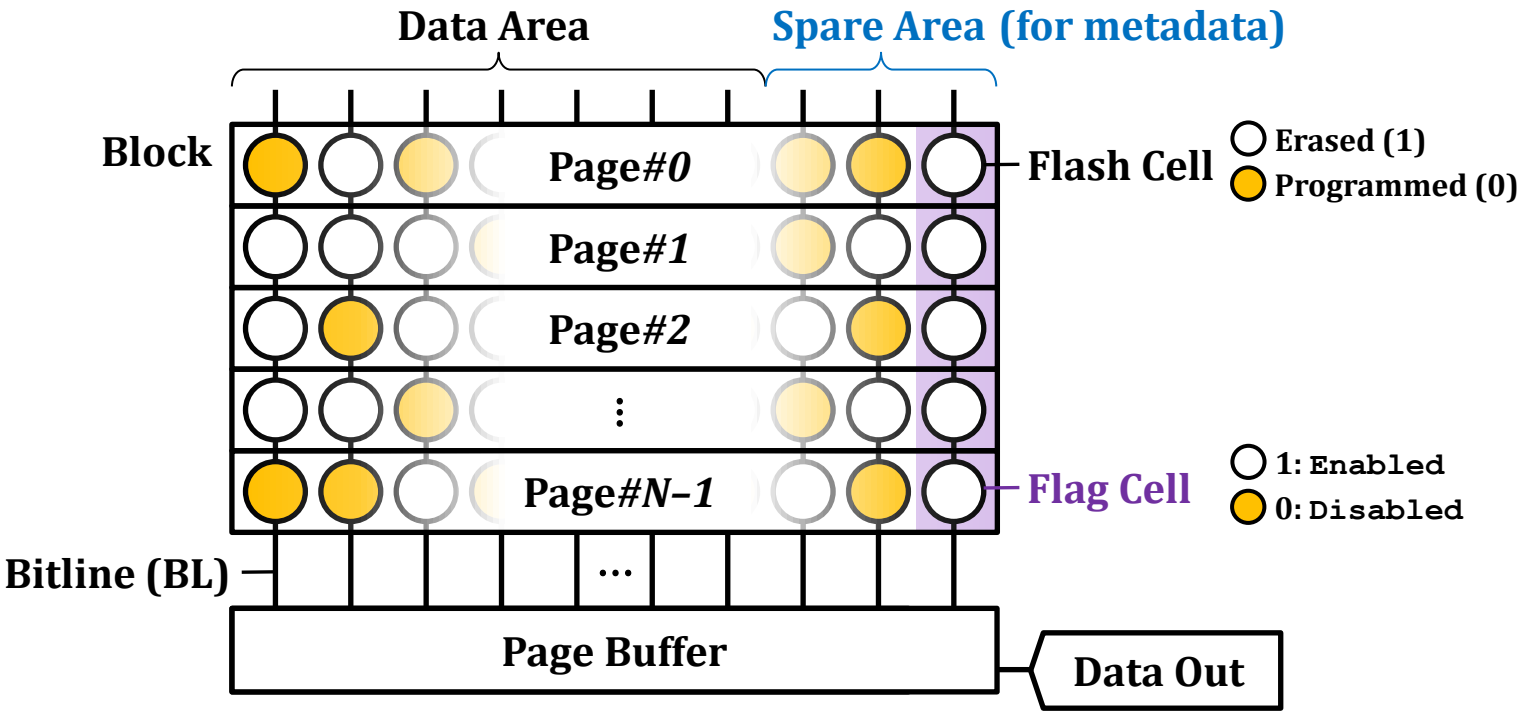

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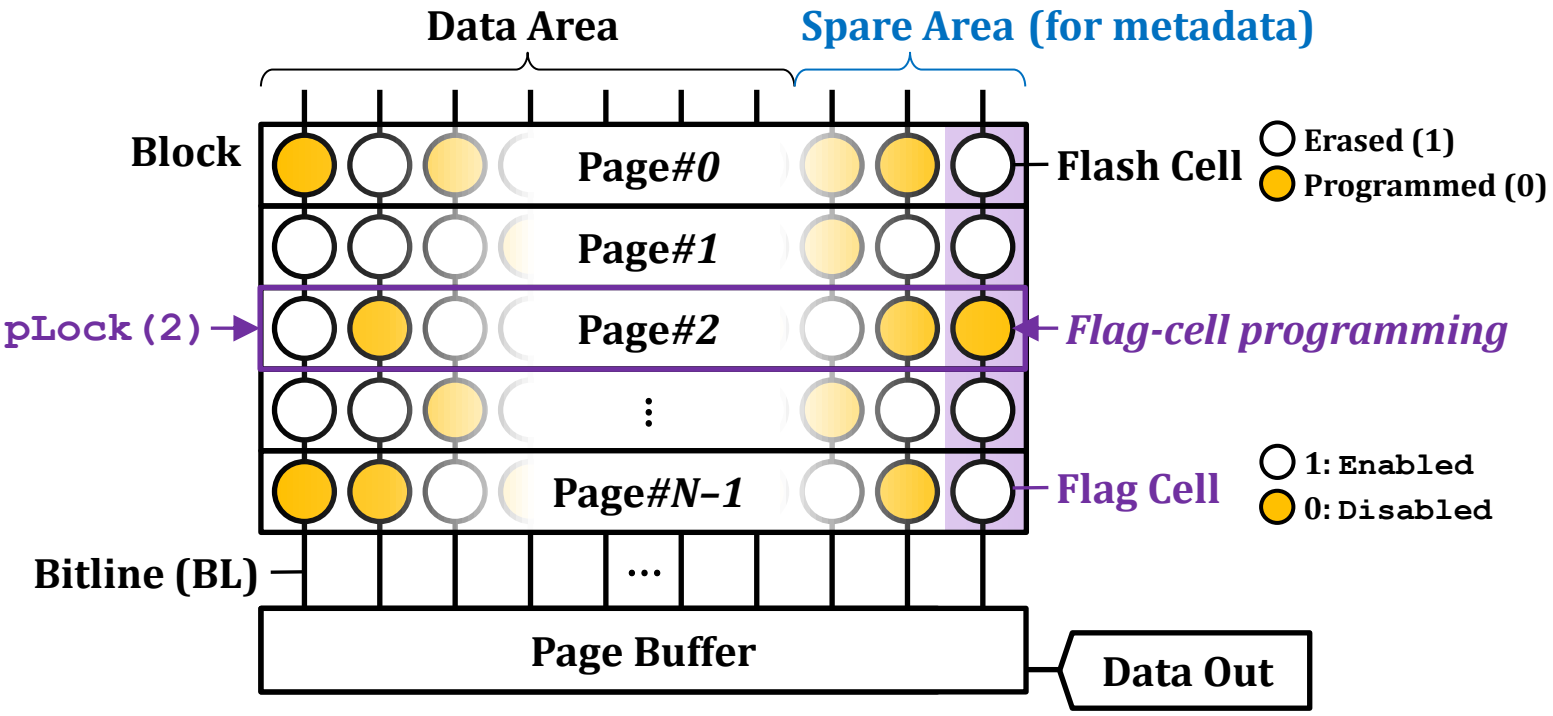

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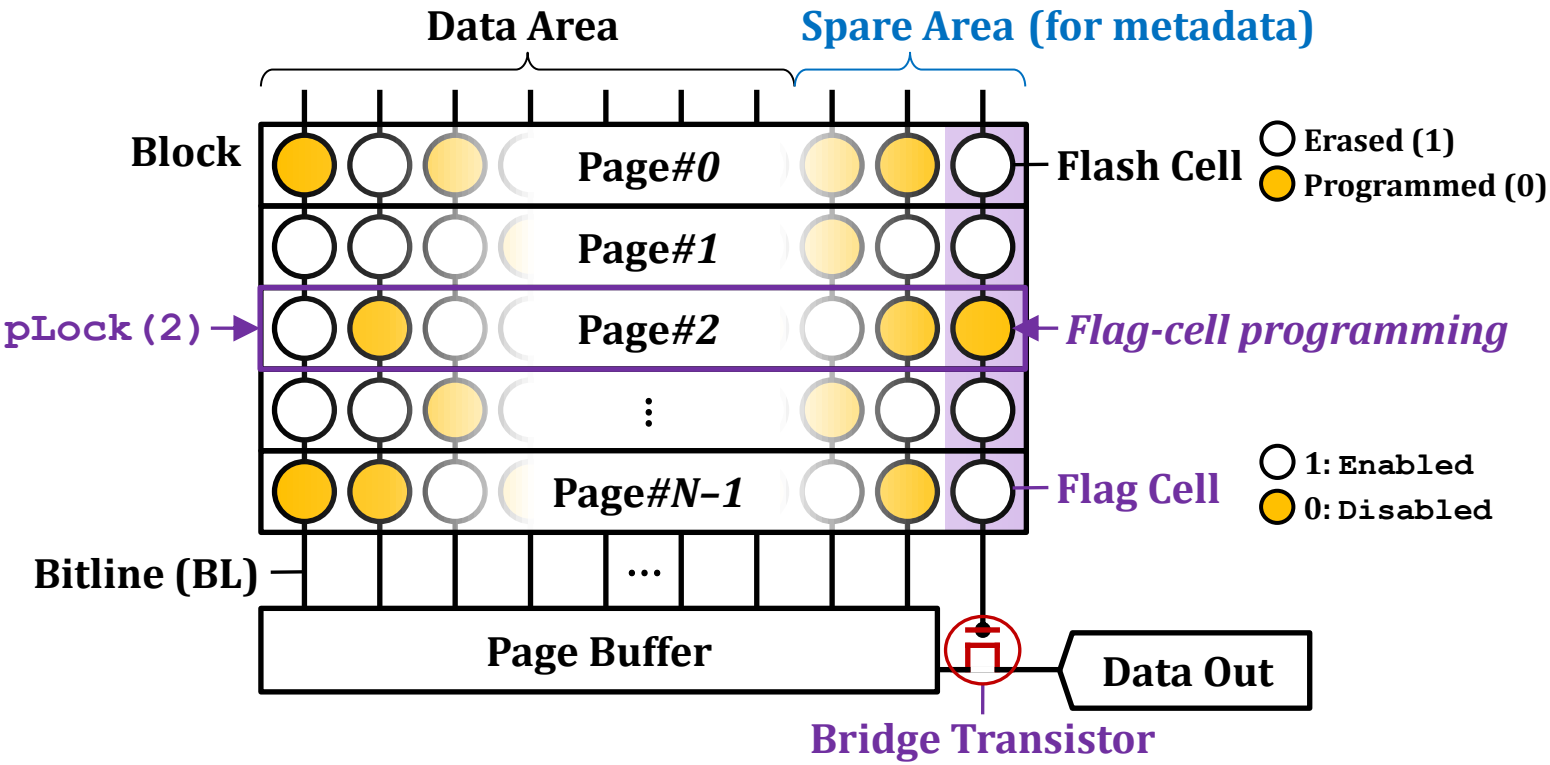

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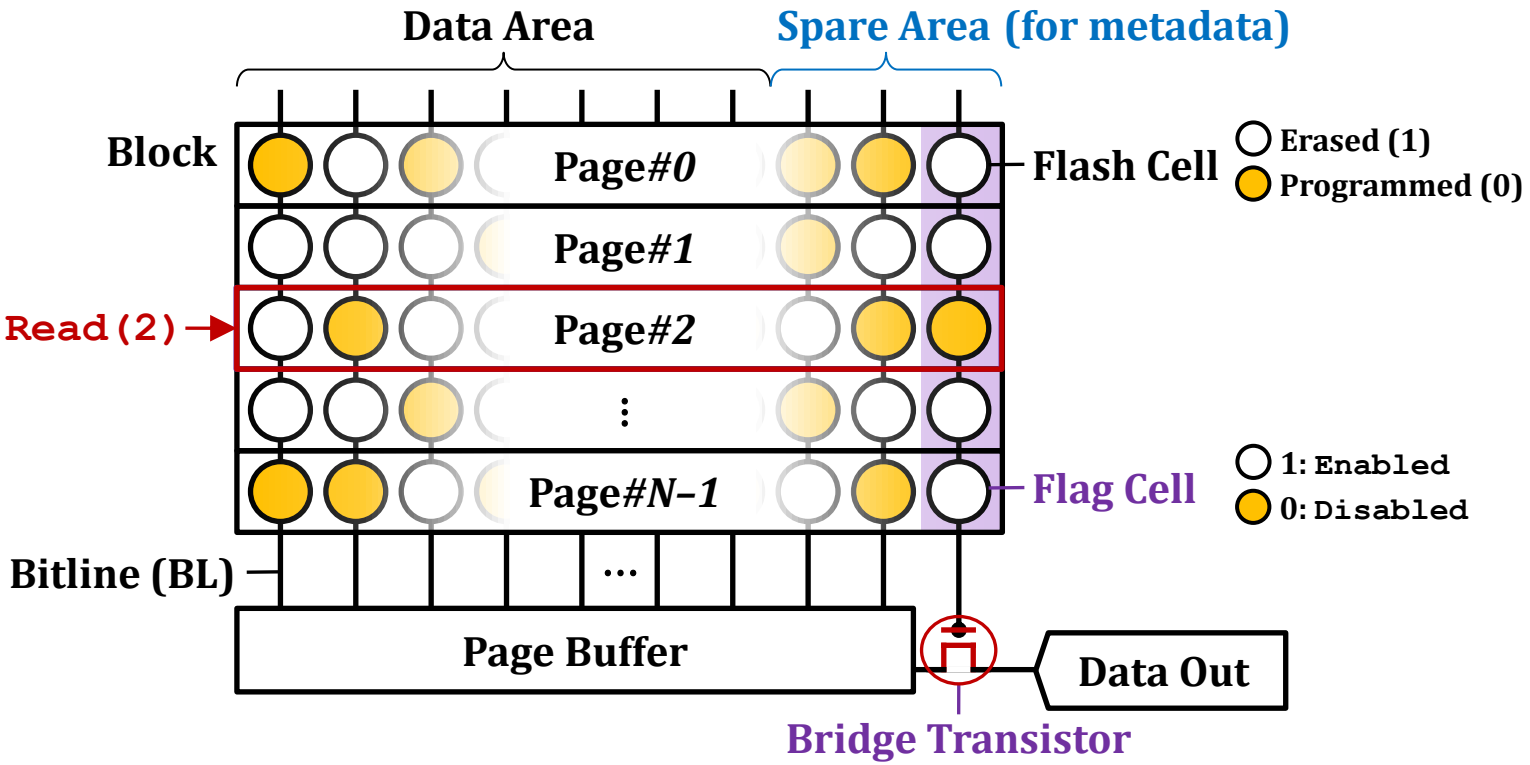

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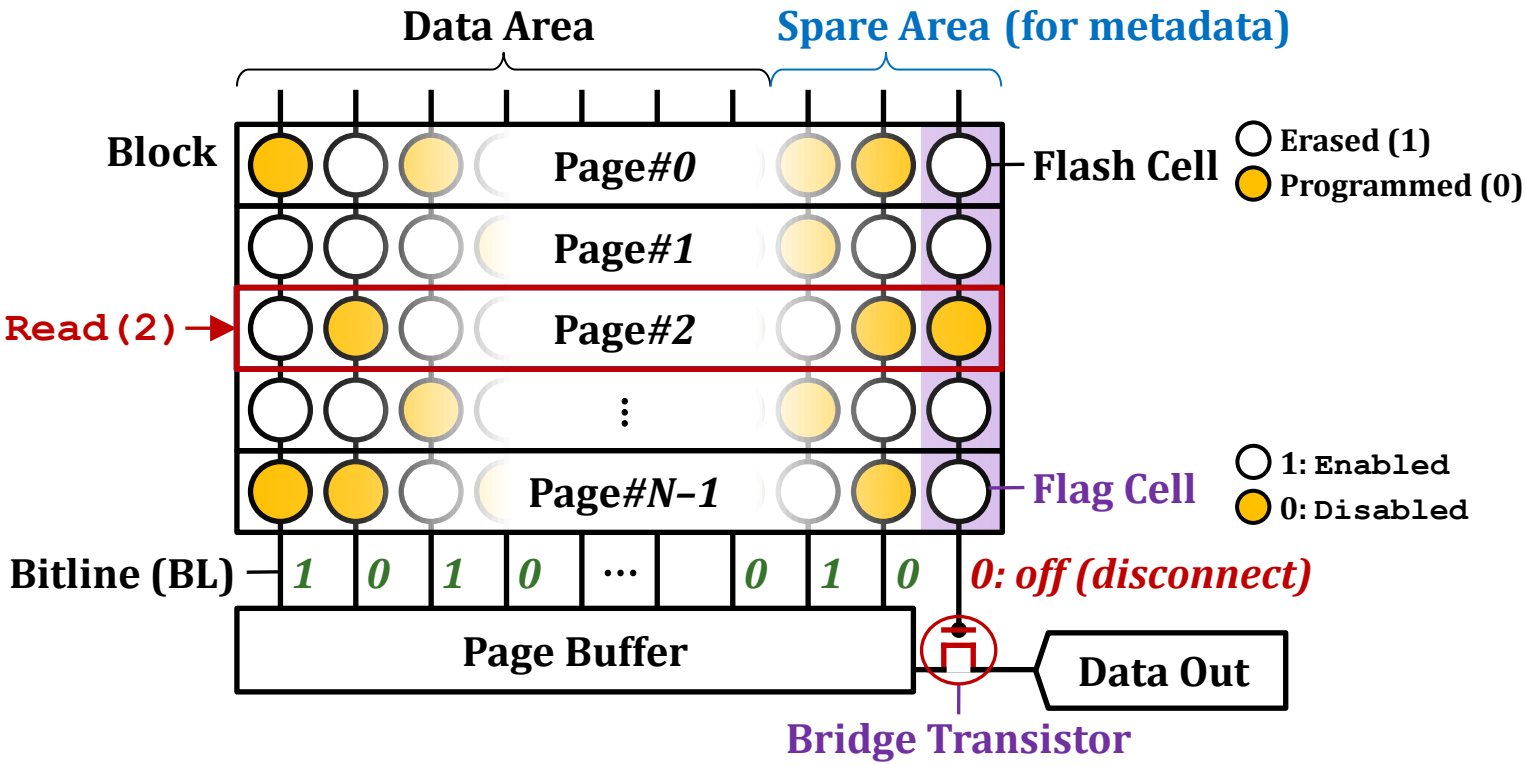

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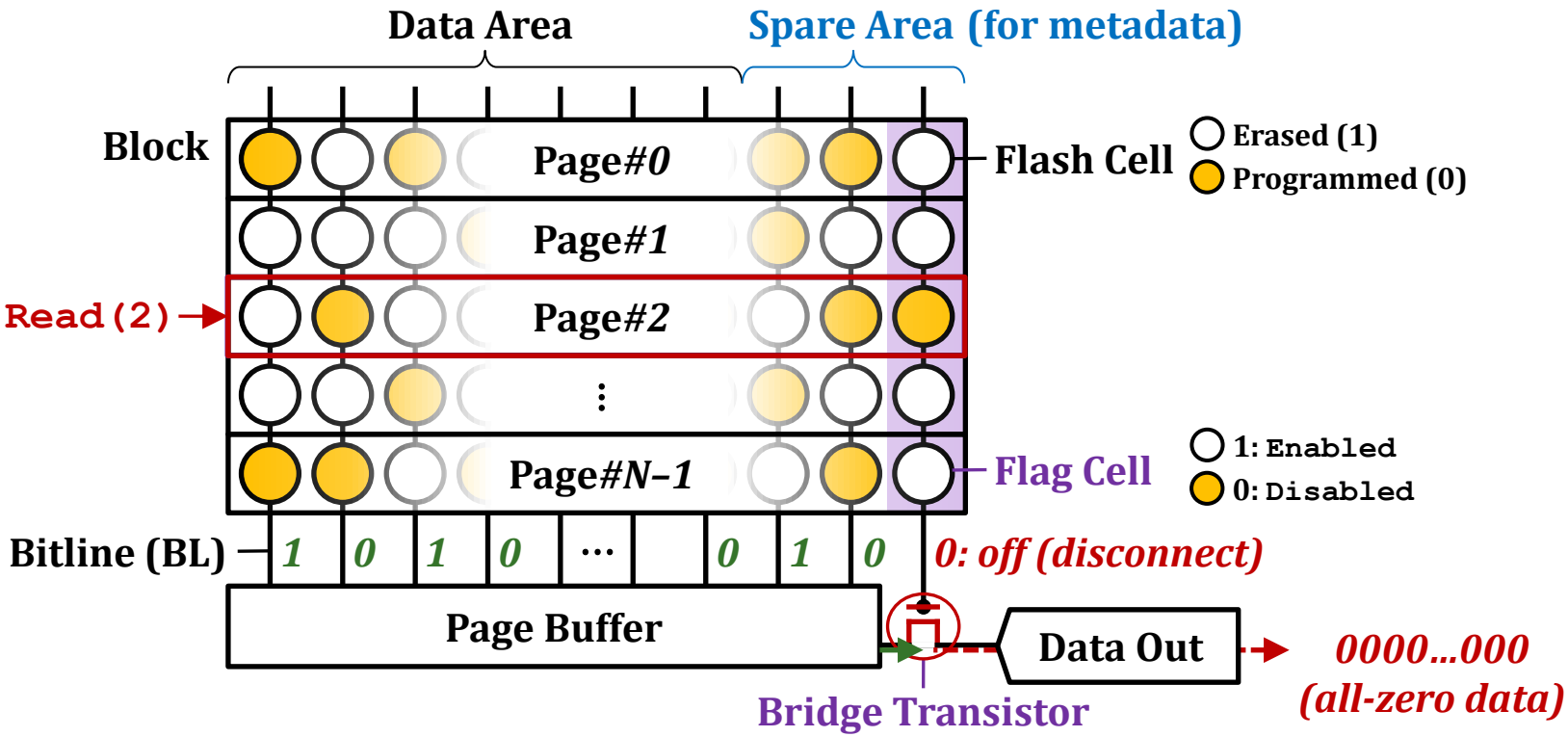

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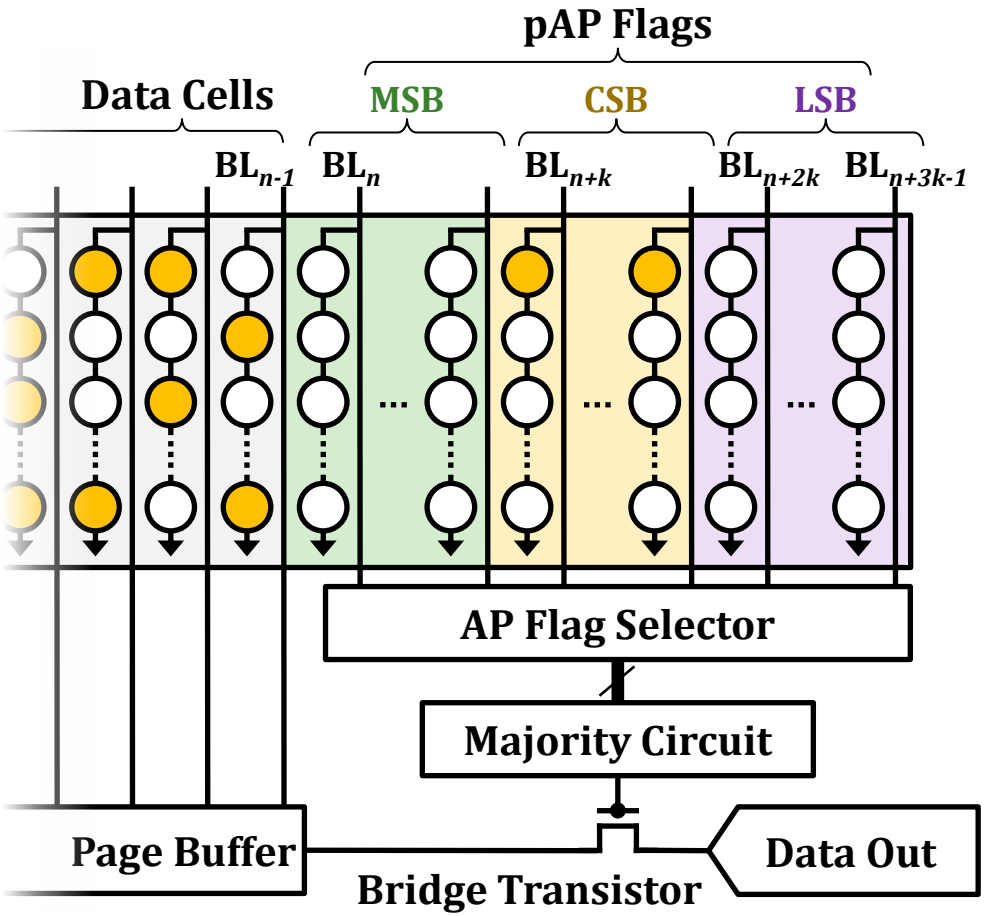

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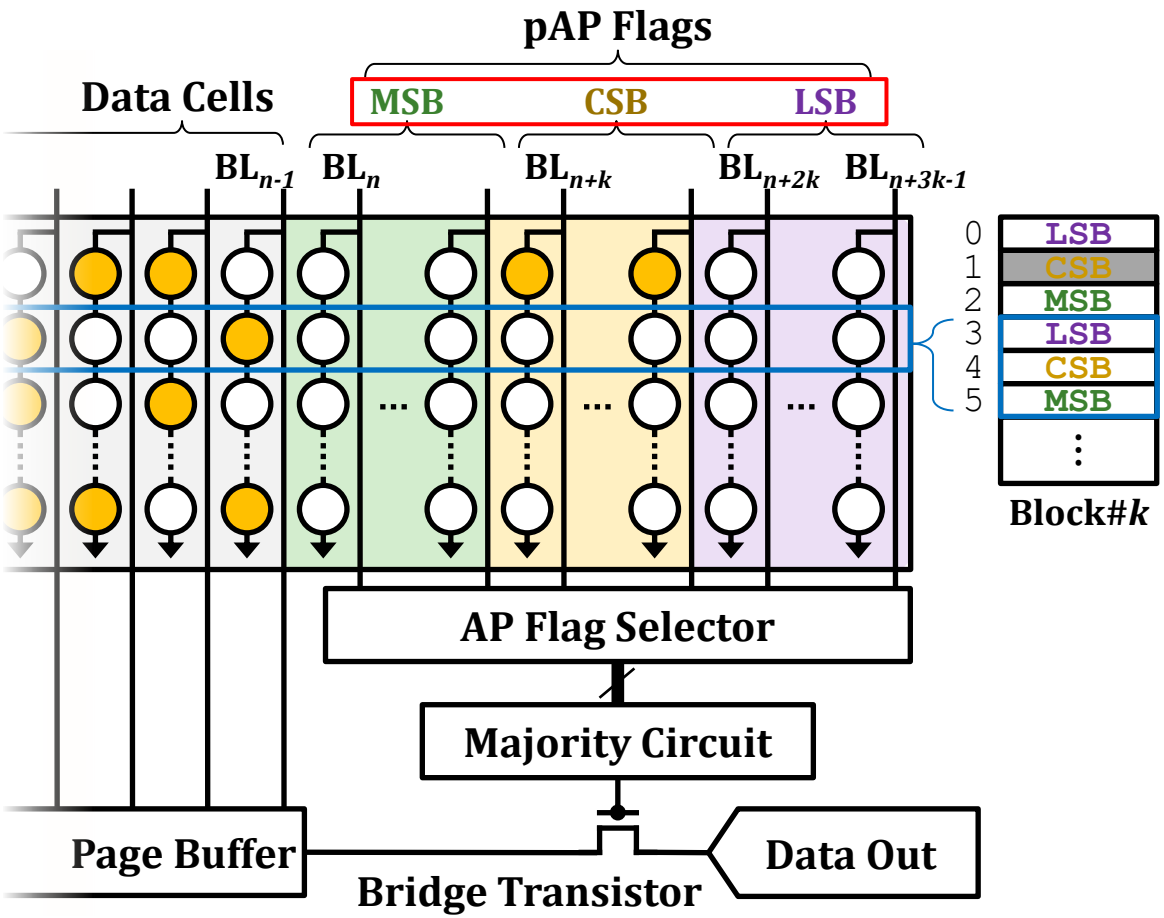

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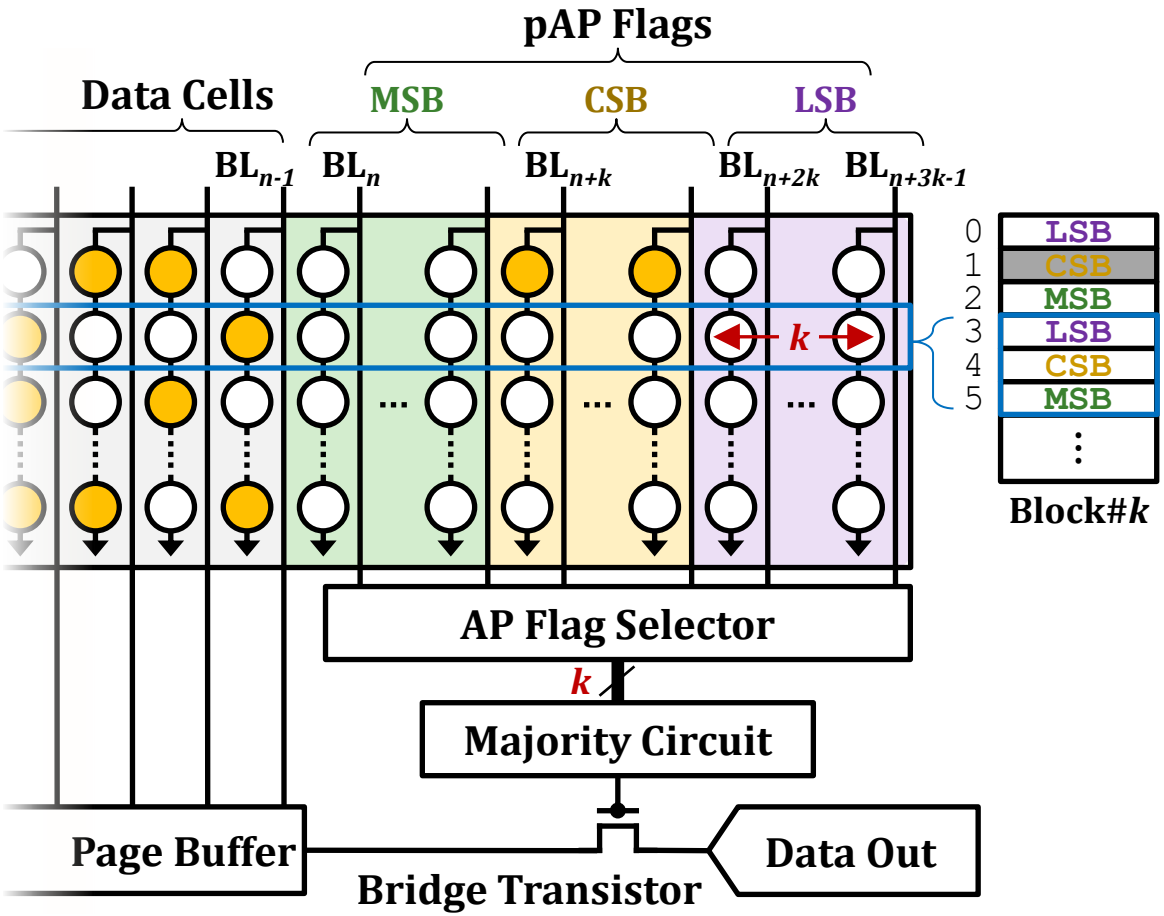

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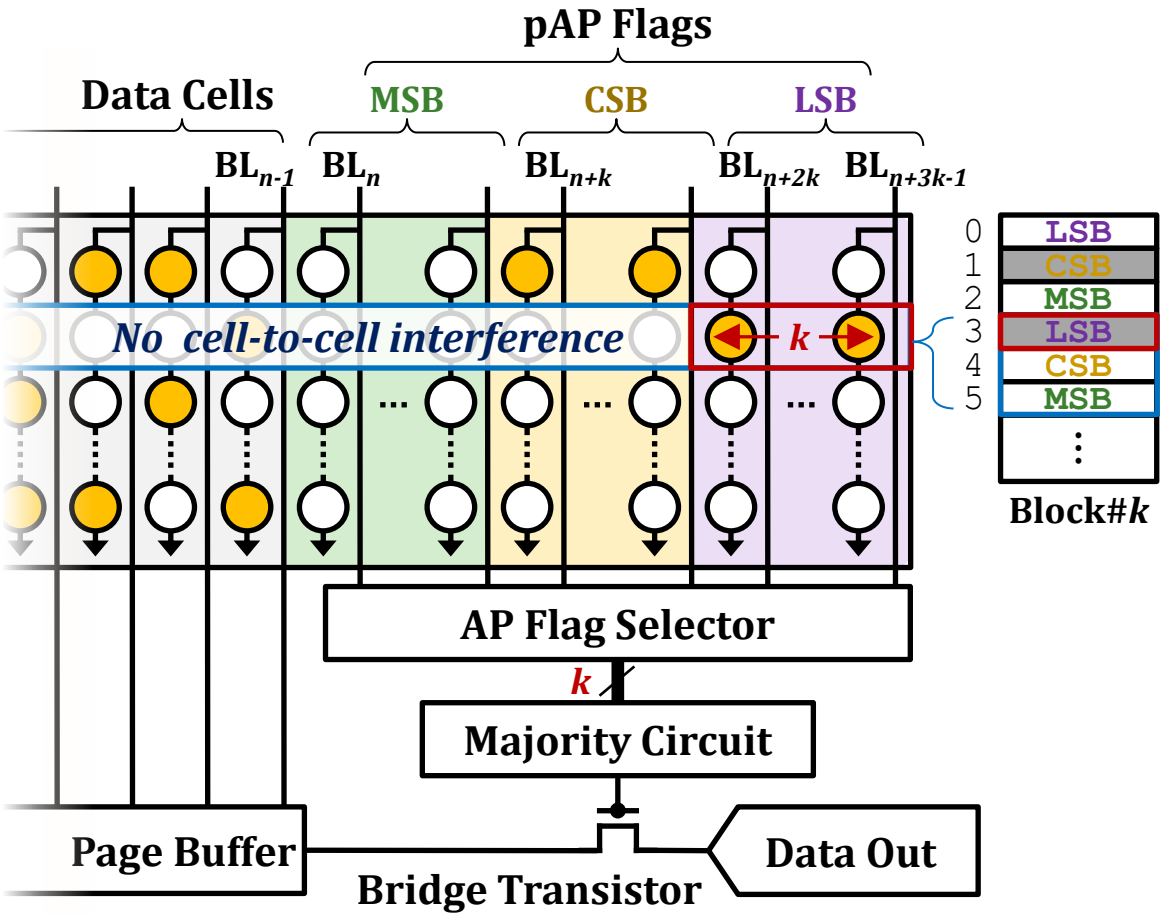

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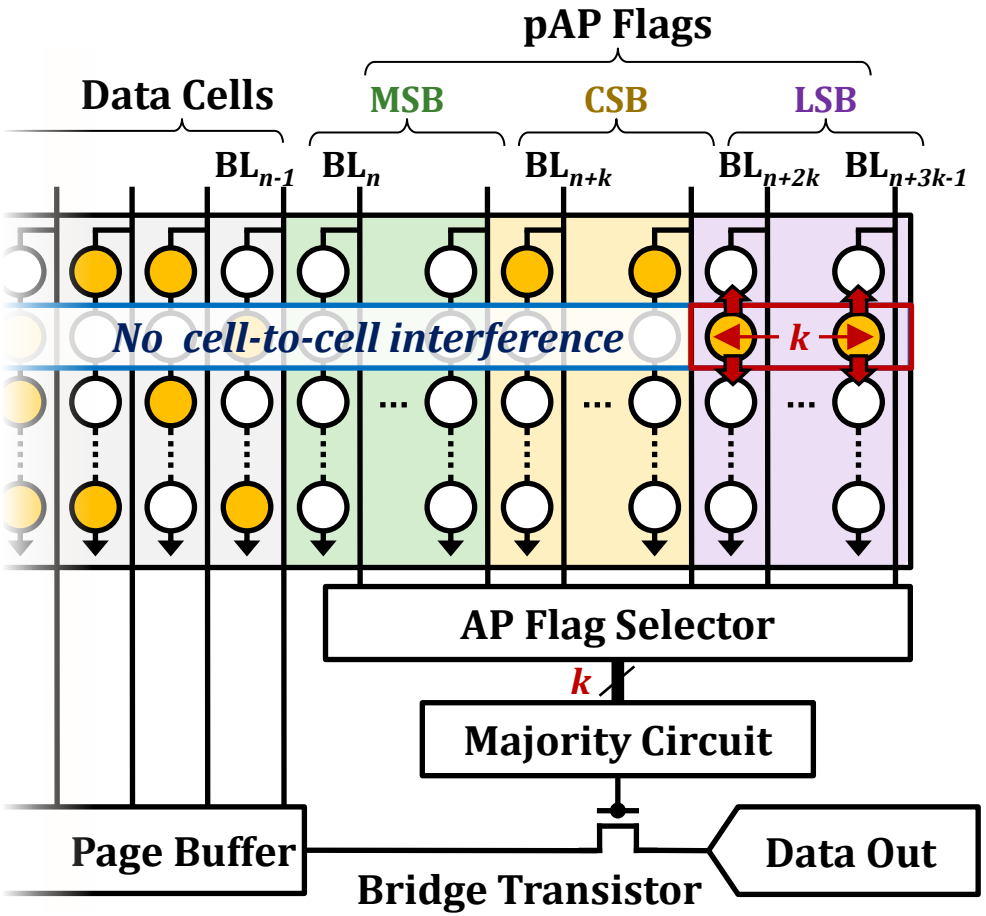

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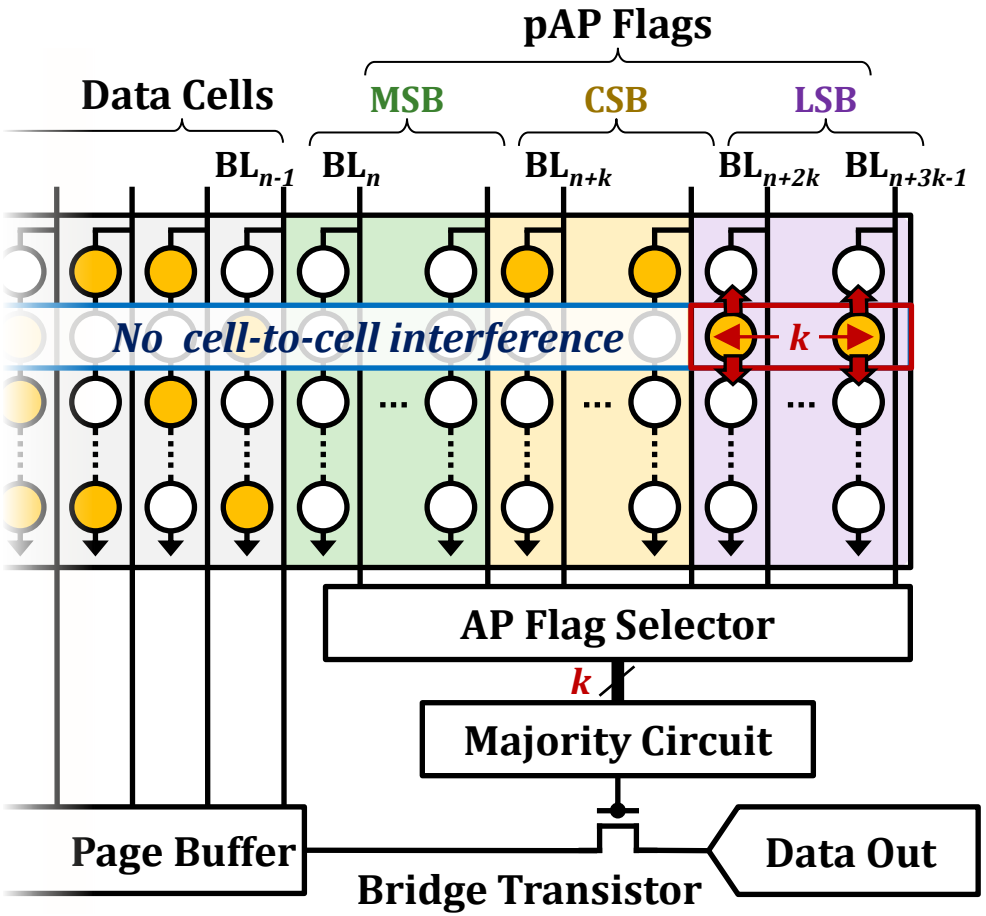

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1. Use flag cells in single-level cell (SLC) mode
   - More robust to interference and disturbance
   - Reduces pLock latency
2. One-shot programming w/ low voltage
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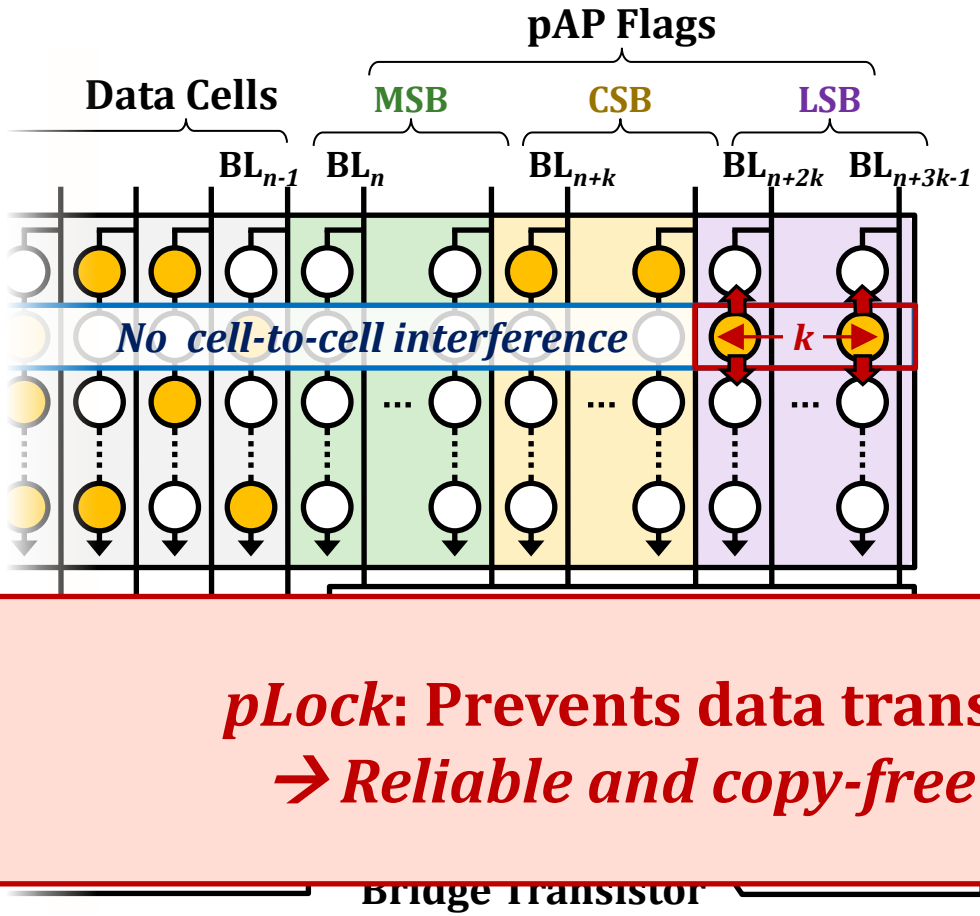

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→ *Reliable and copy-free per-page sanitization*

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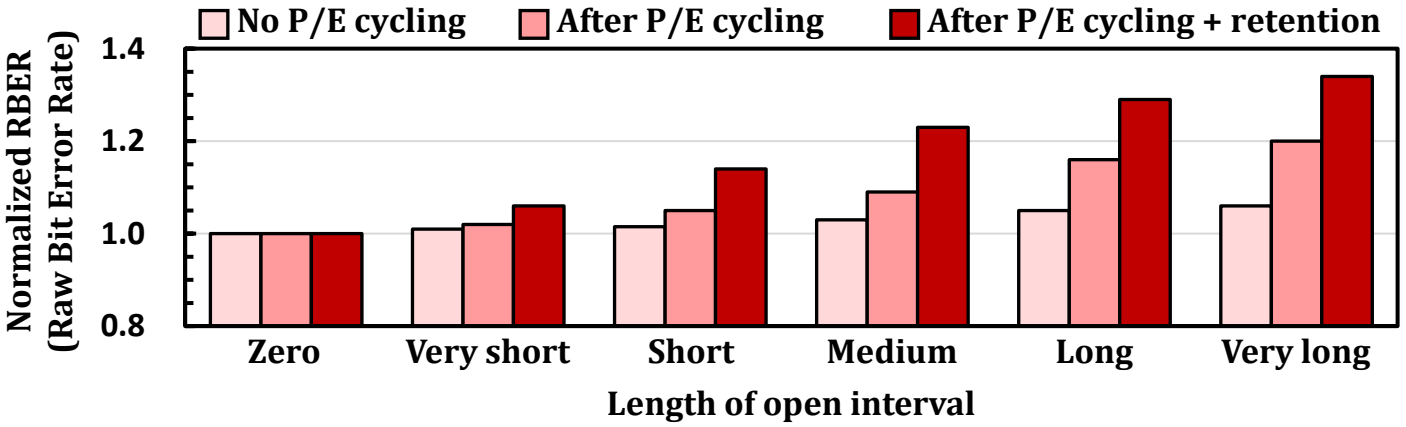
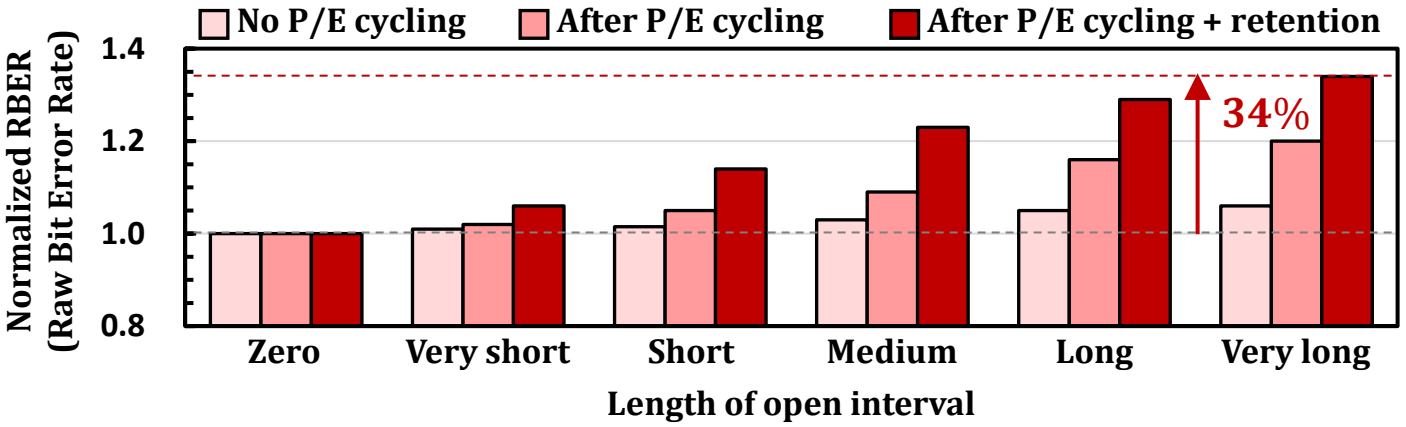


Problem with Page-Level Sanitization

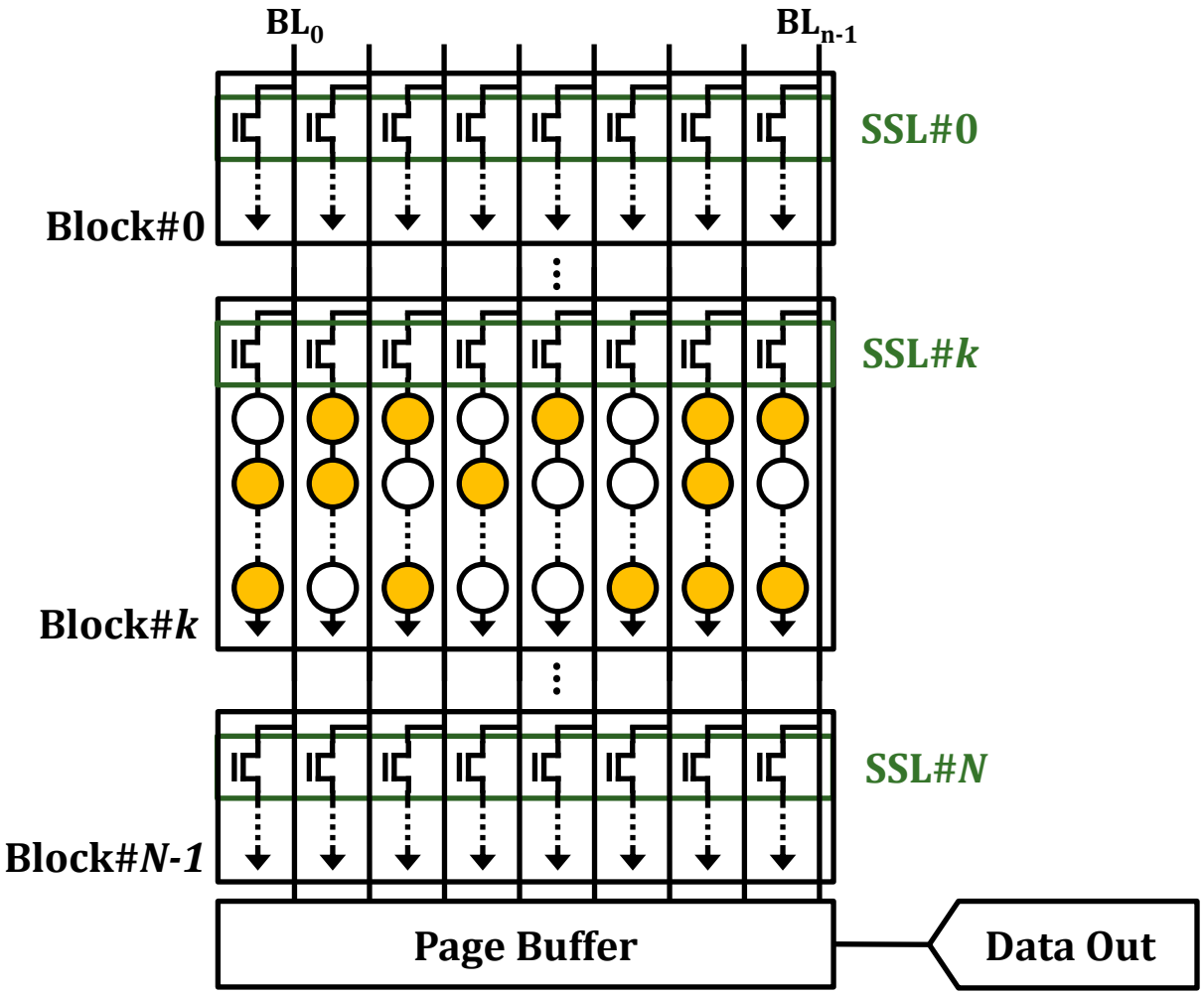
- Nontrivial performance overhead in invalidating an entire block
  - Deleting a 1-GiB video → 65,536 pLock operations (page size = 16 KiB)
  - Invalidating blocks in SSD management tasks (GC, wear-leveling, …)

- Immediate block erasure is not feasible in 3D NAND flash memory.
  - **Open-block problem:** Reliability degradation due to a long time interval b/w erasing and programming a block → A block should be erased *lazily*.



bLock: Block-Level Sanitization

- **Key idea:** Program the *string-select line* (SSL) of a block



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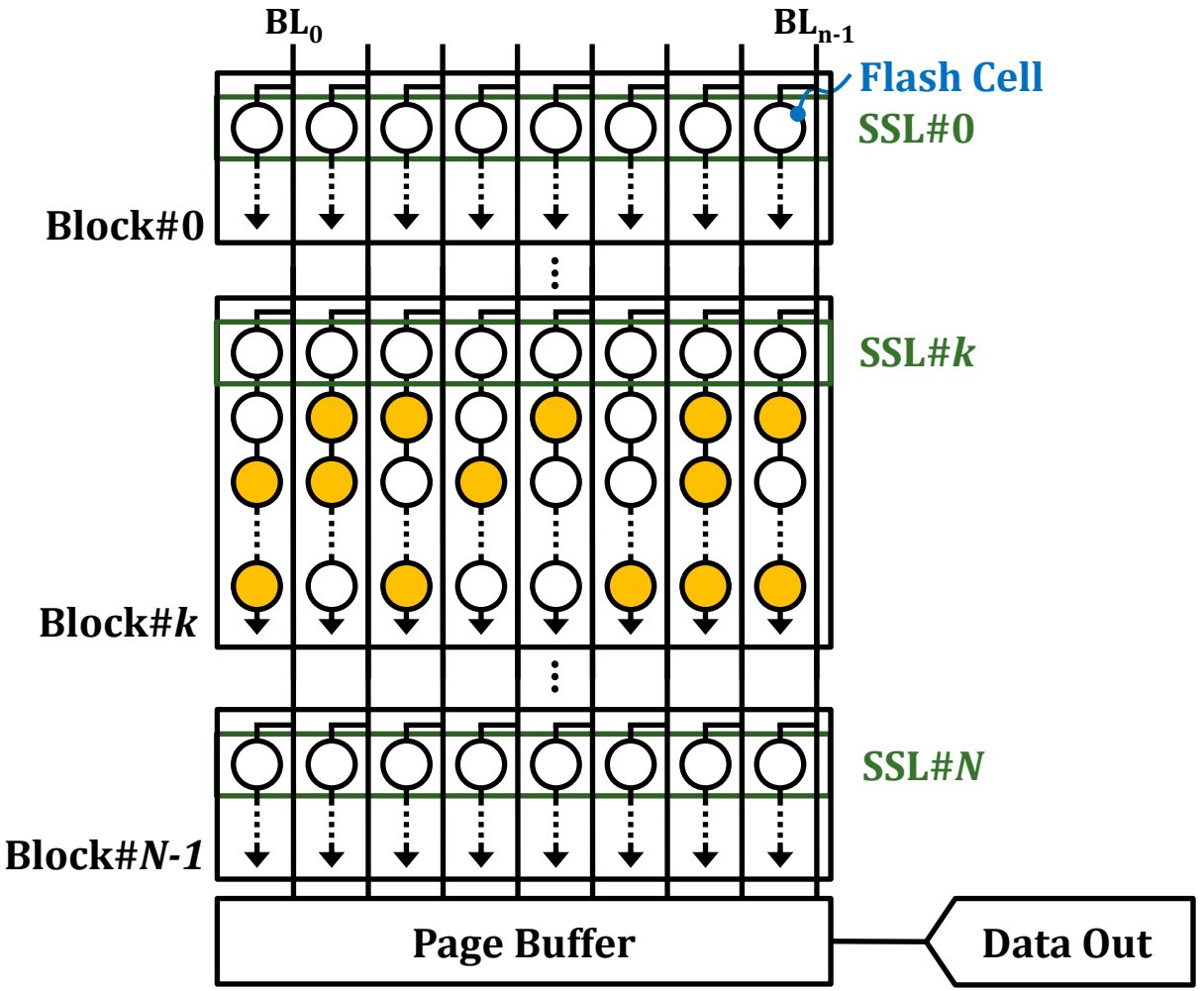

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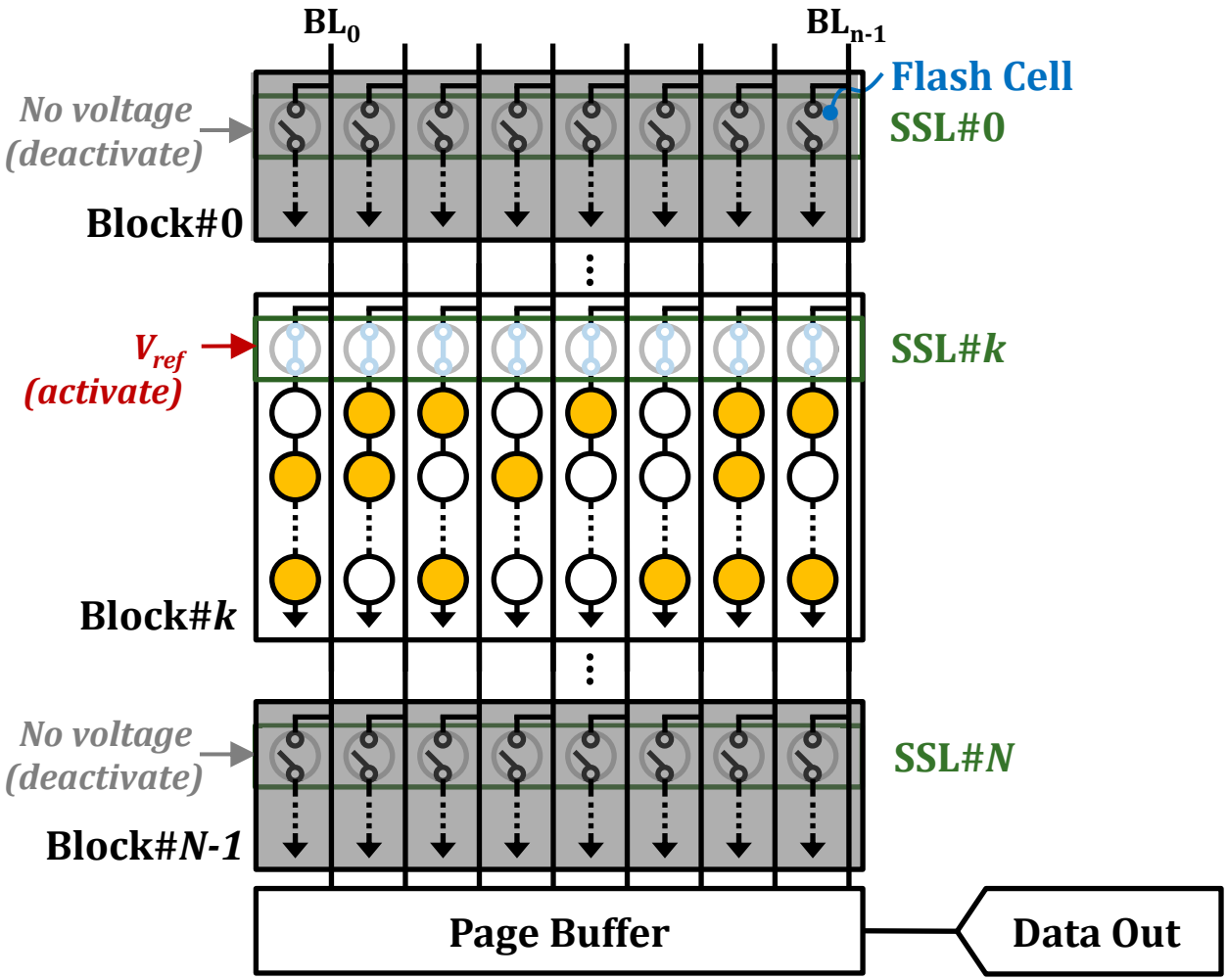

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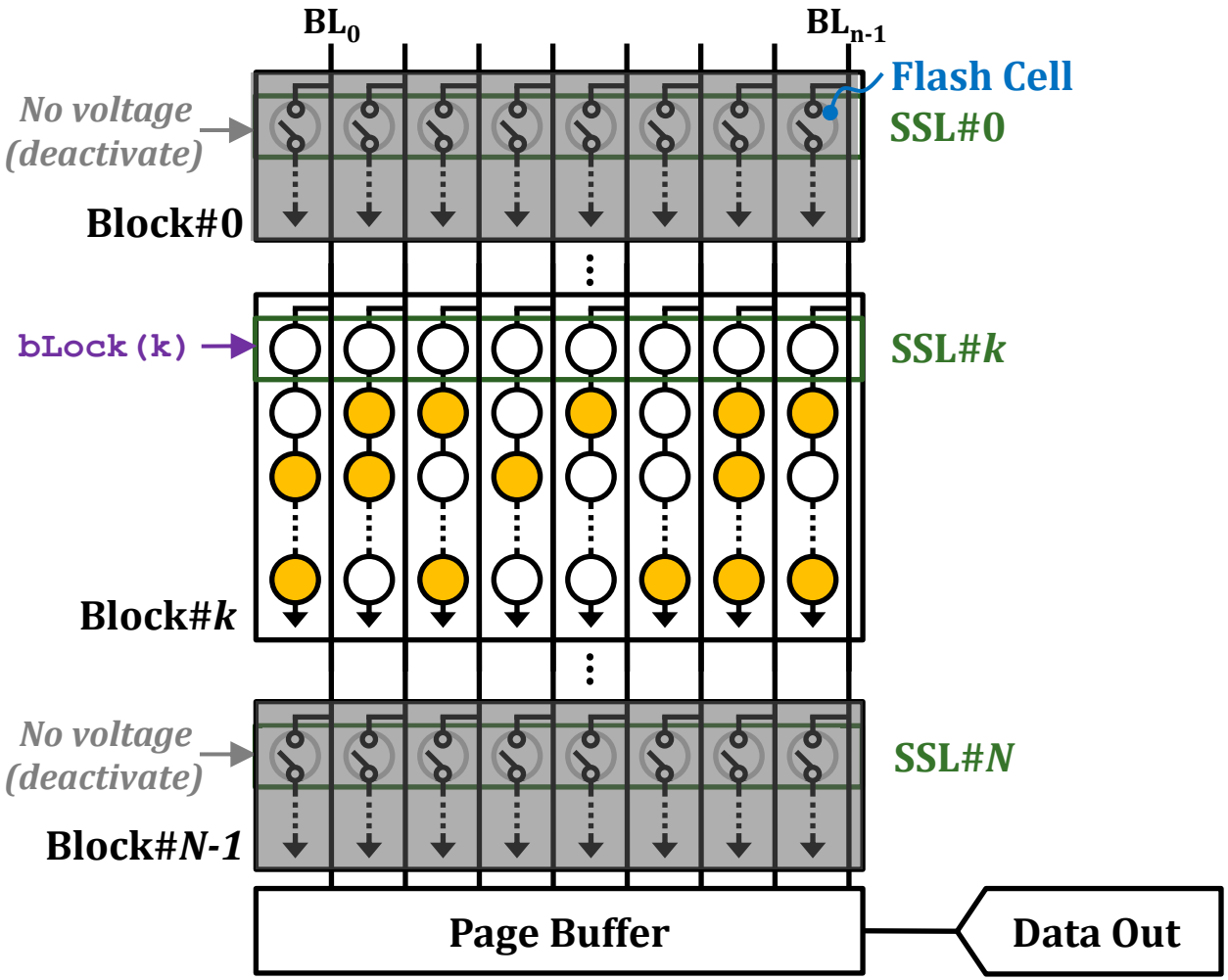

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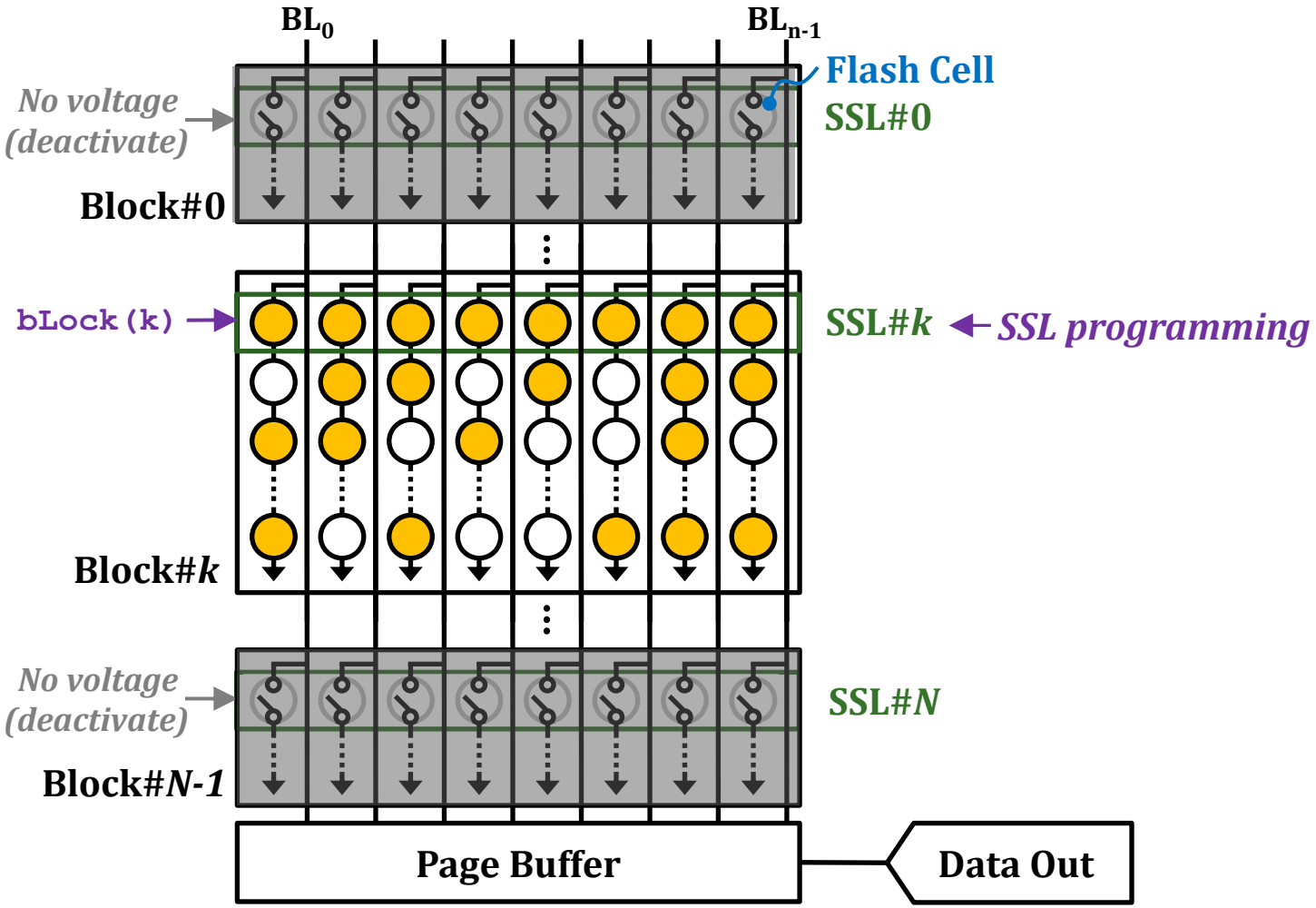

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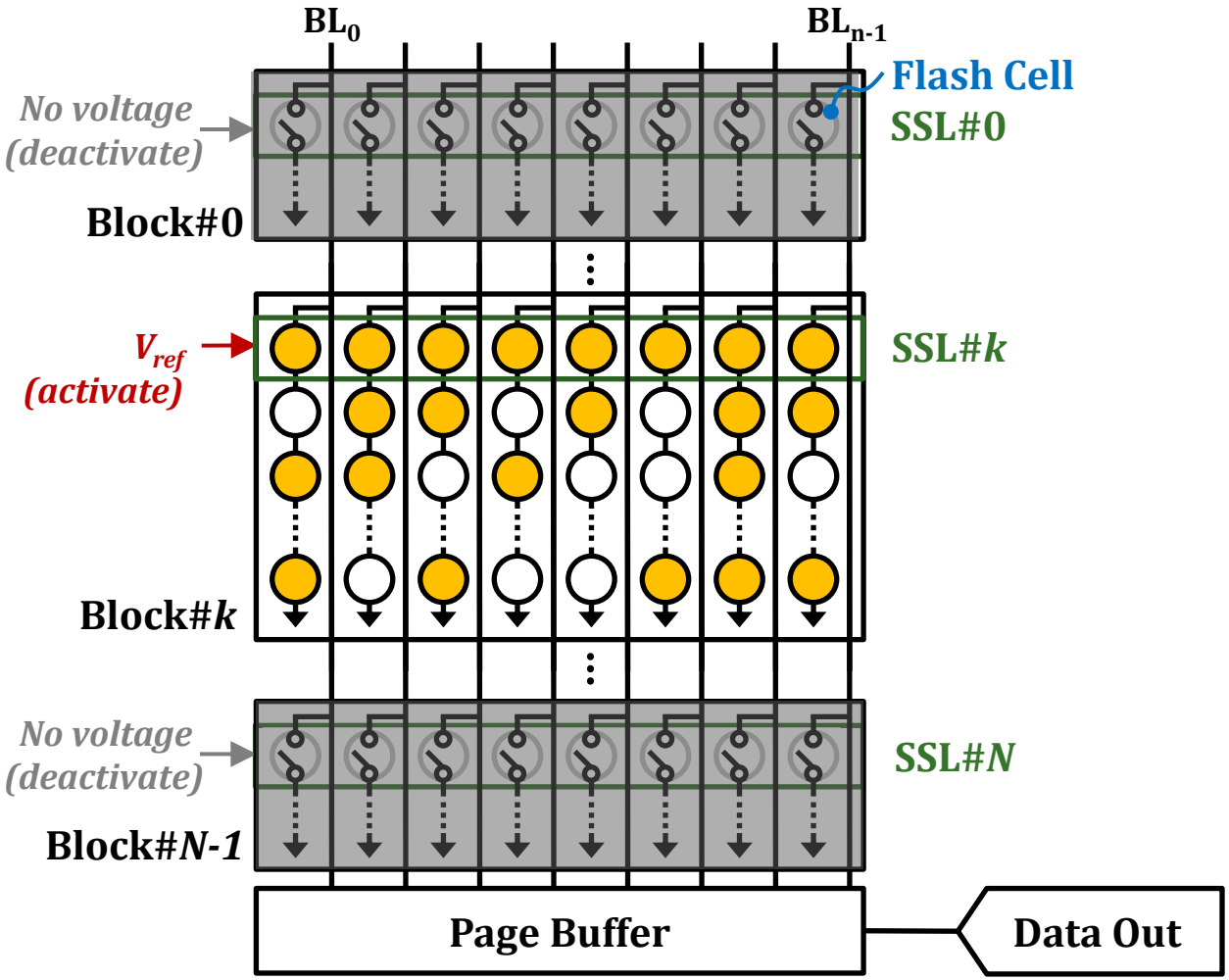

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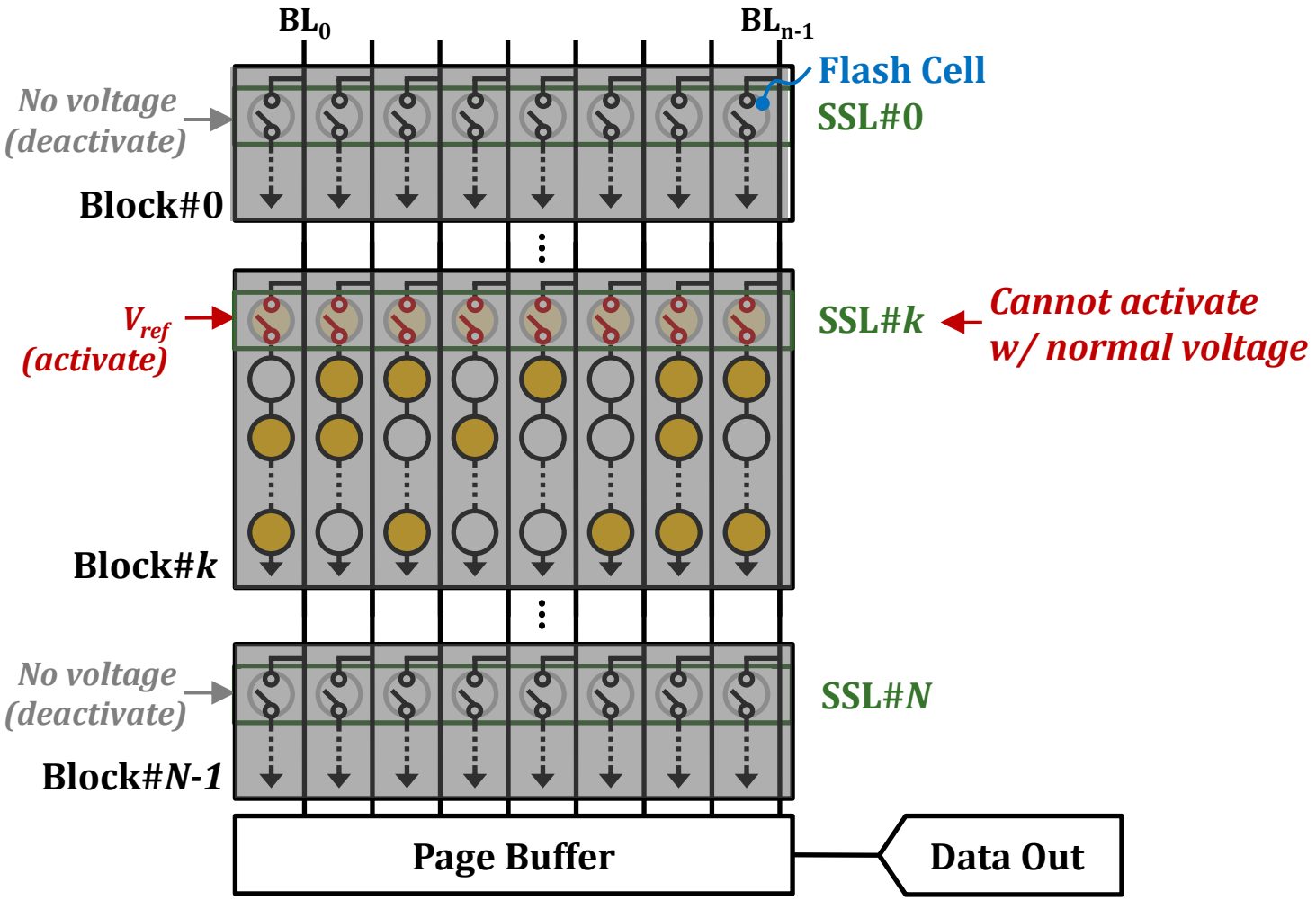

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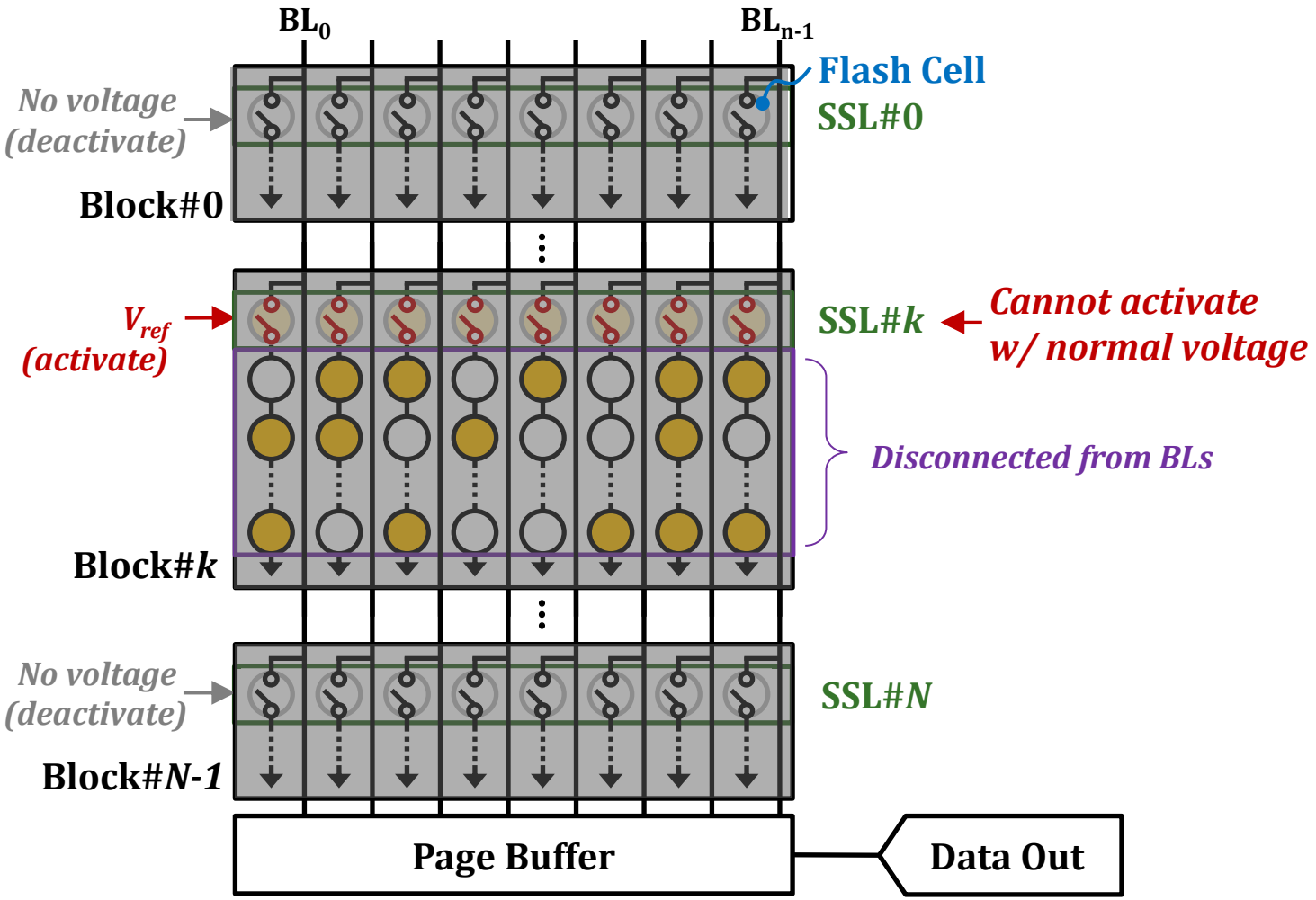

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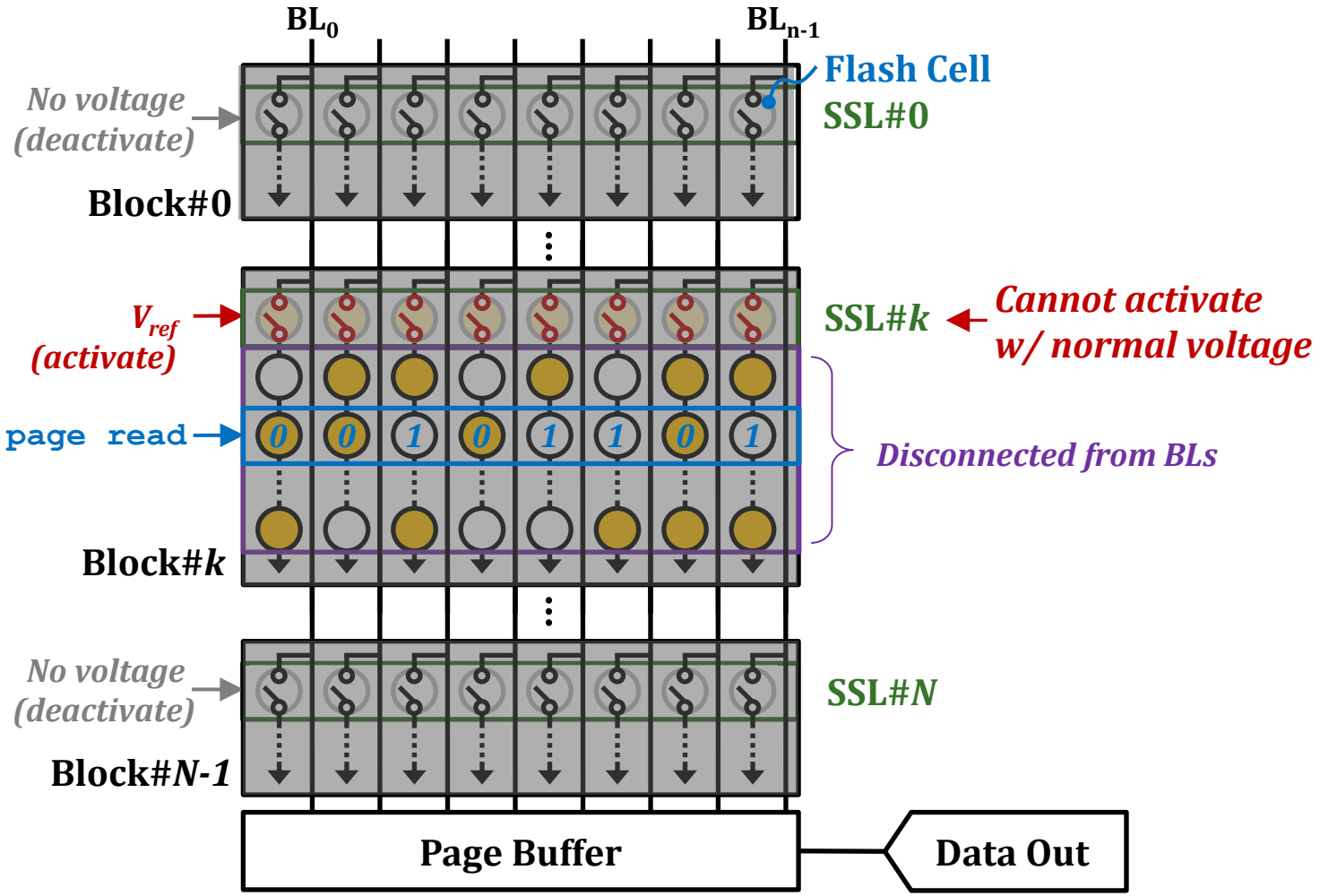

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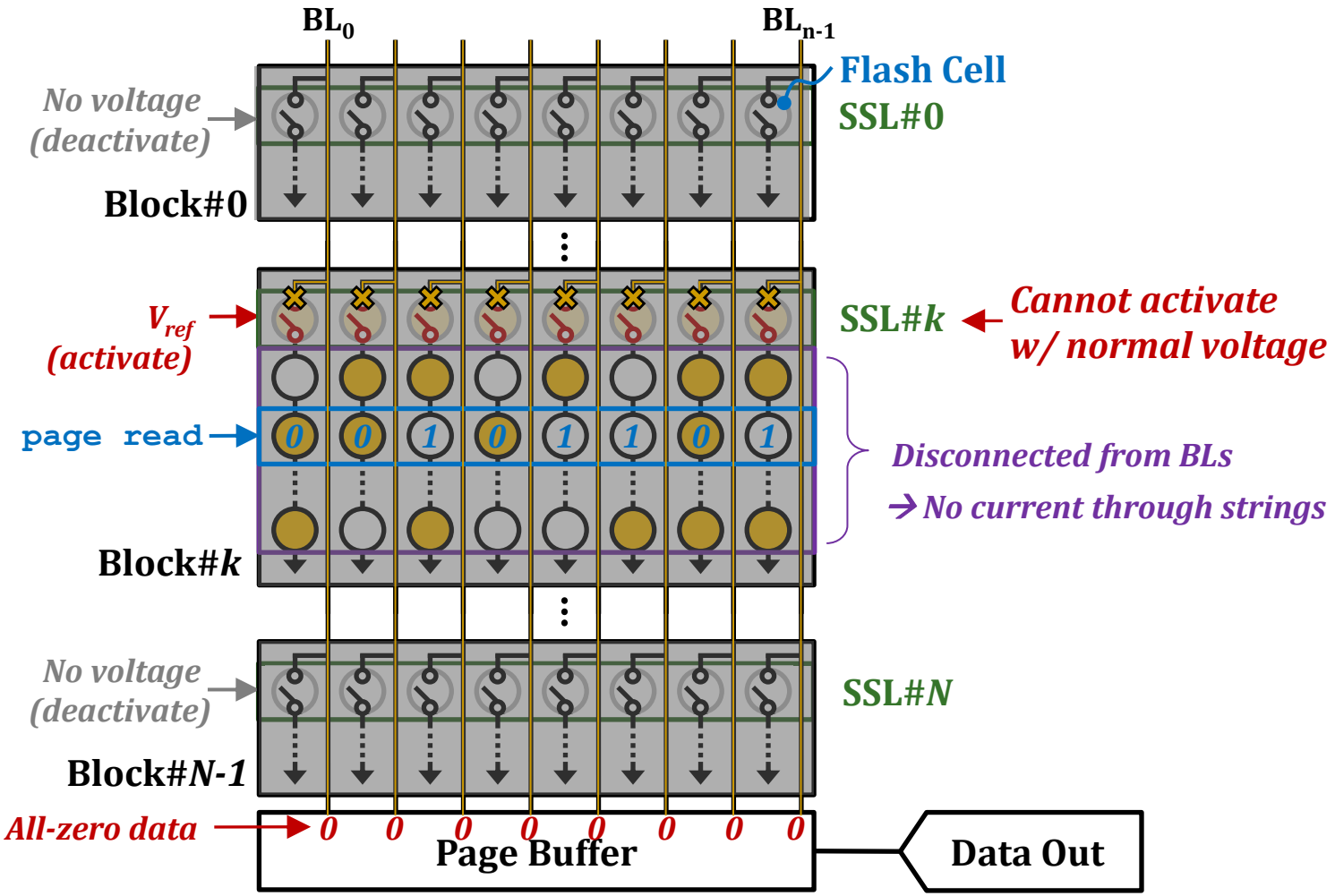

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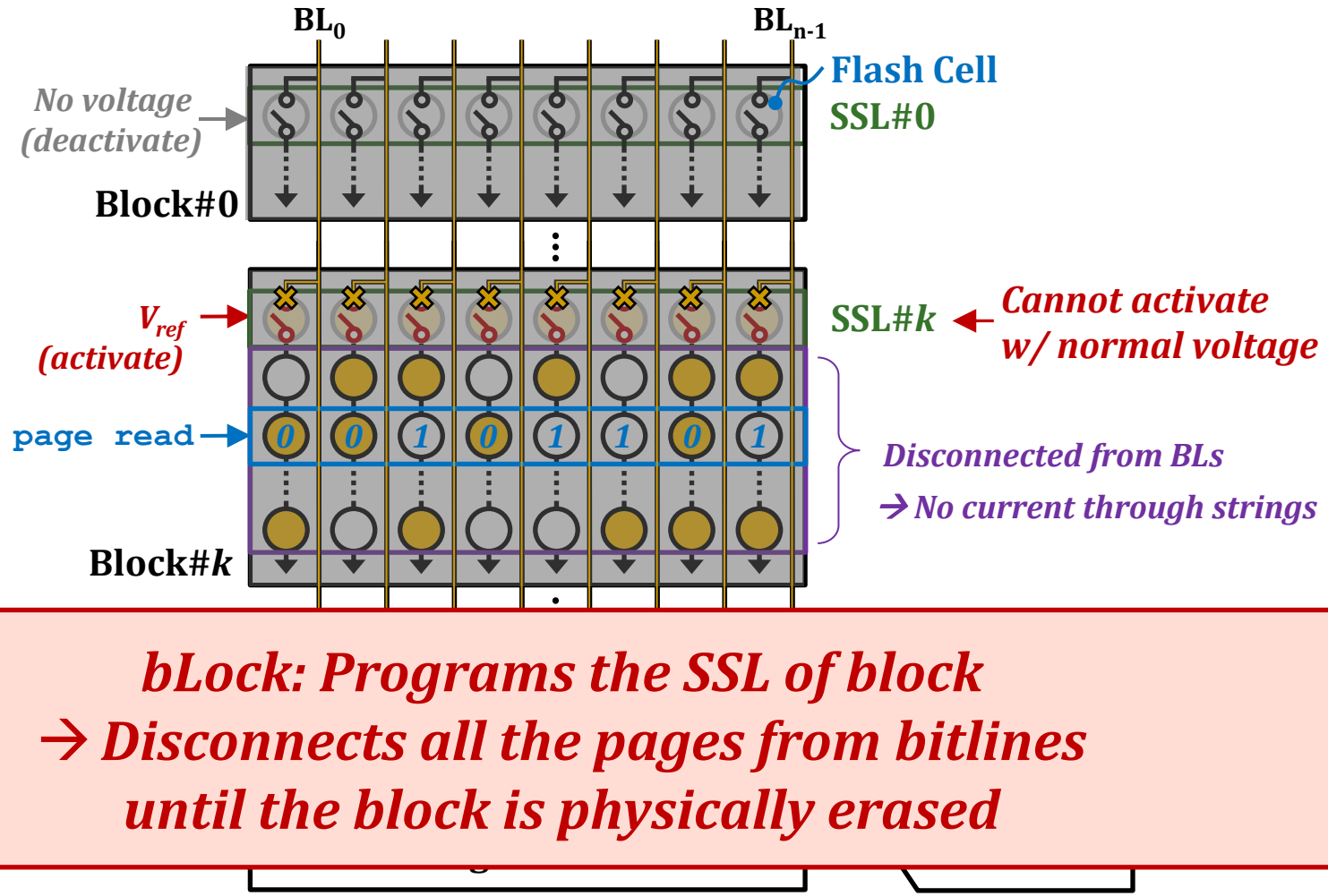


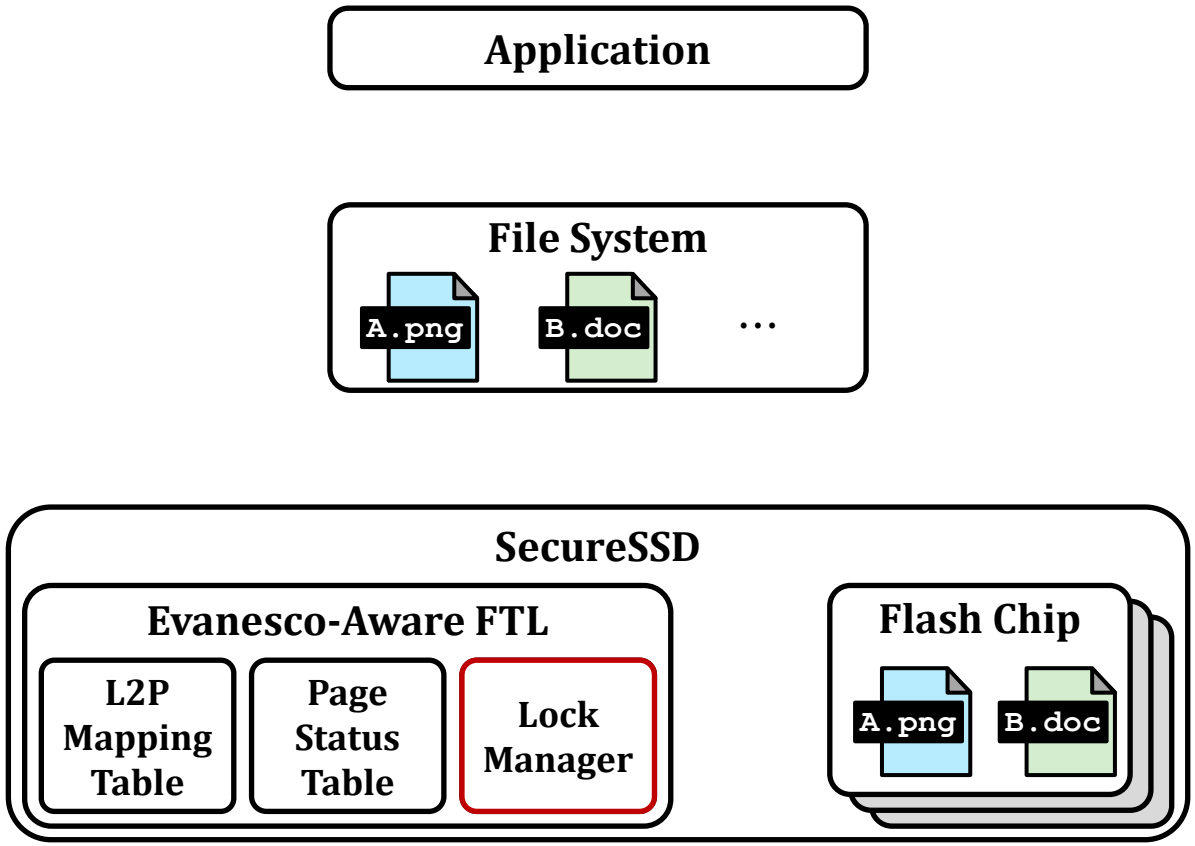
bLock: Programs the SSL of block
→ Disconnects all the pages from bitlines
until the block is physically erased

Outline

- Secure Deletion in NAND Flash-Based SSDs
- **Evanesco: Lock-Based Data Sanitization**
  - pageLock: Page-Level Data Sanitization
  - blockLock: Block-Level Data Sanitization
  - SecureSSD: An Evanesco-Enabled SSD
- Evaluation
- Conclusion

SecureSSD: An Evanesco-Enabled SSD

- An SSD that supports immediate data sanitization of updated or deleted data
  - Lock manager issues pLock and bLock commands depending on the block's status.



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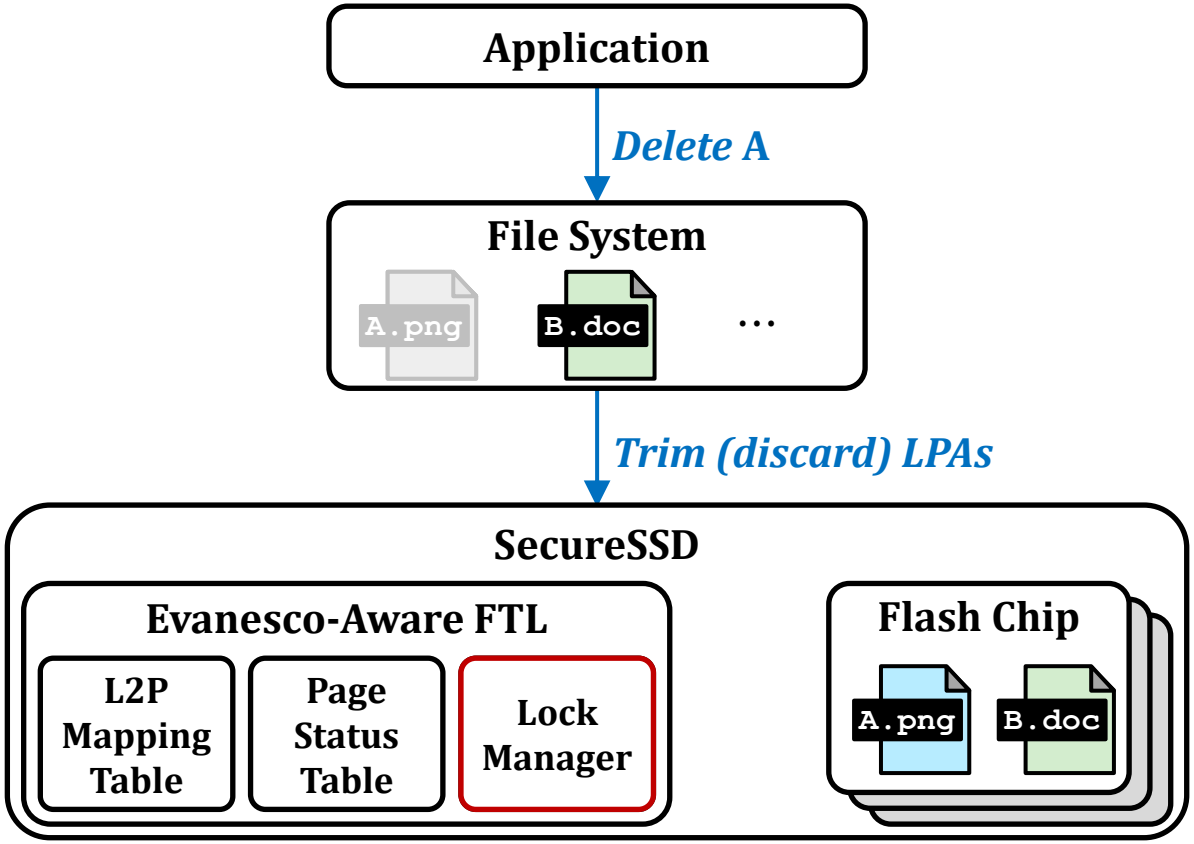

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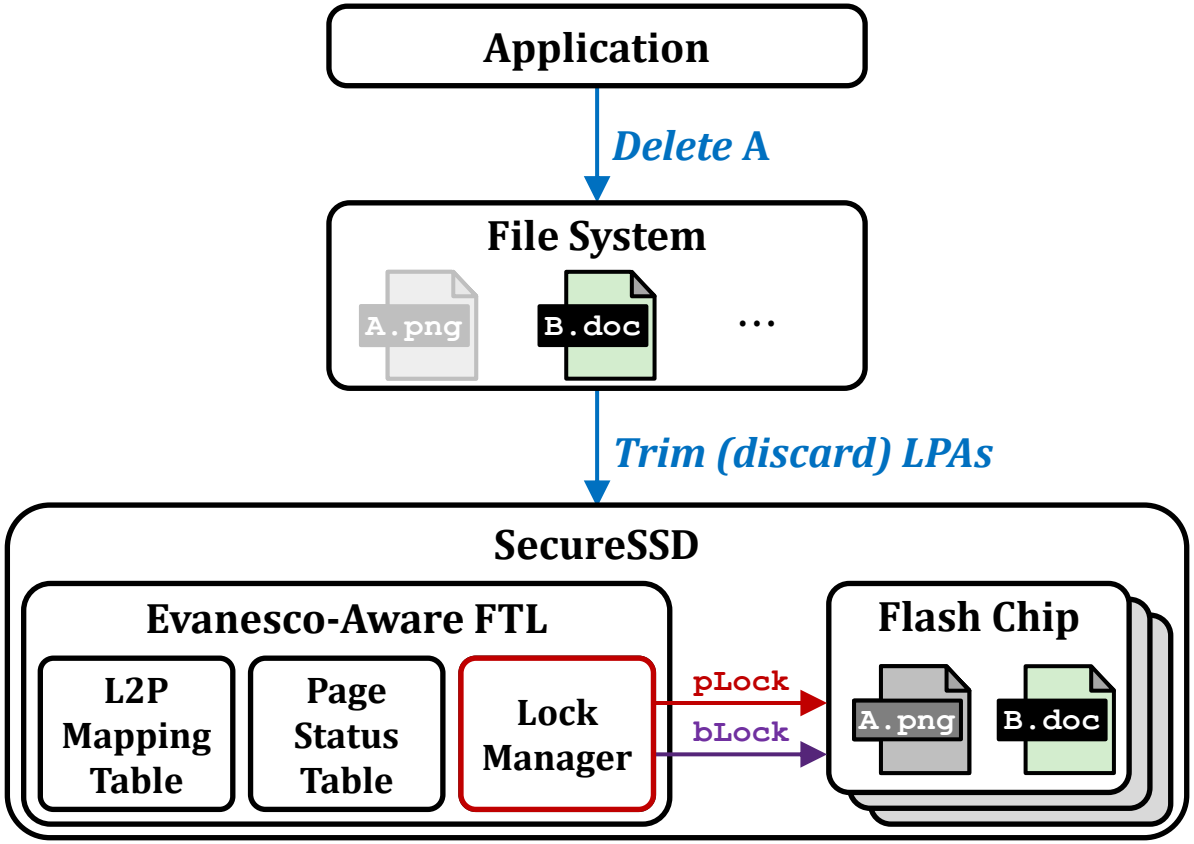

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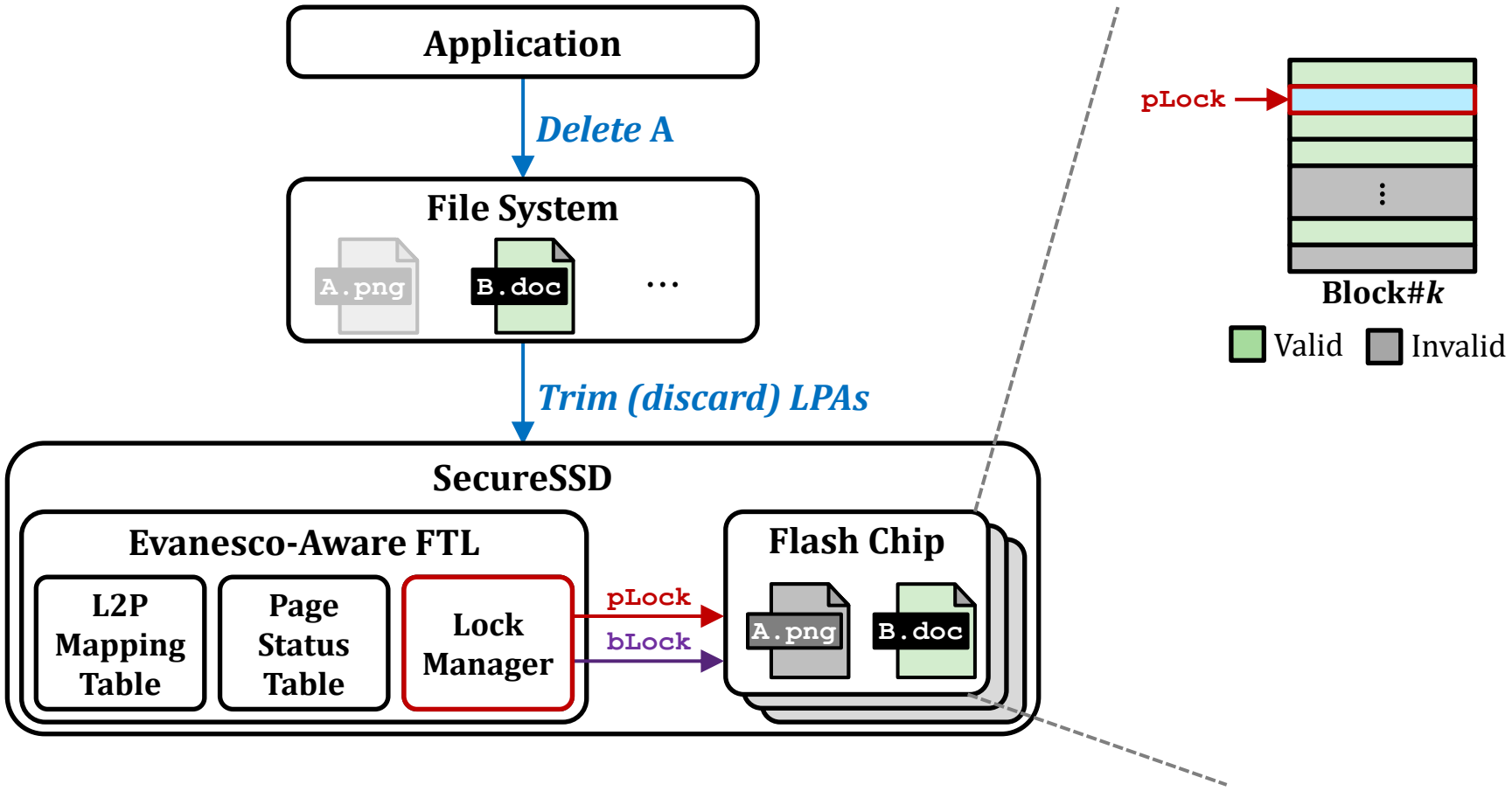

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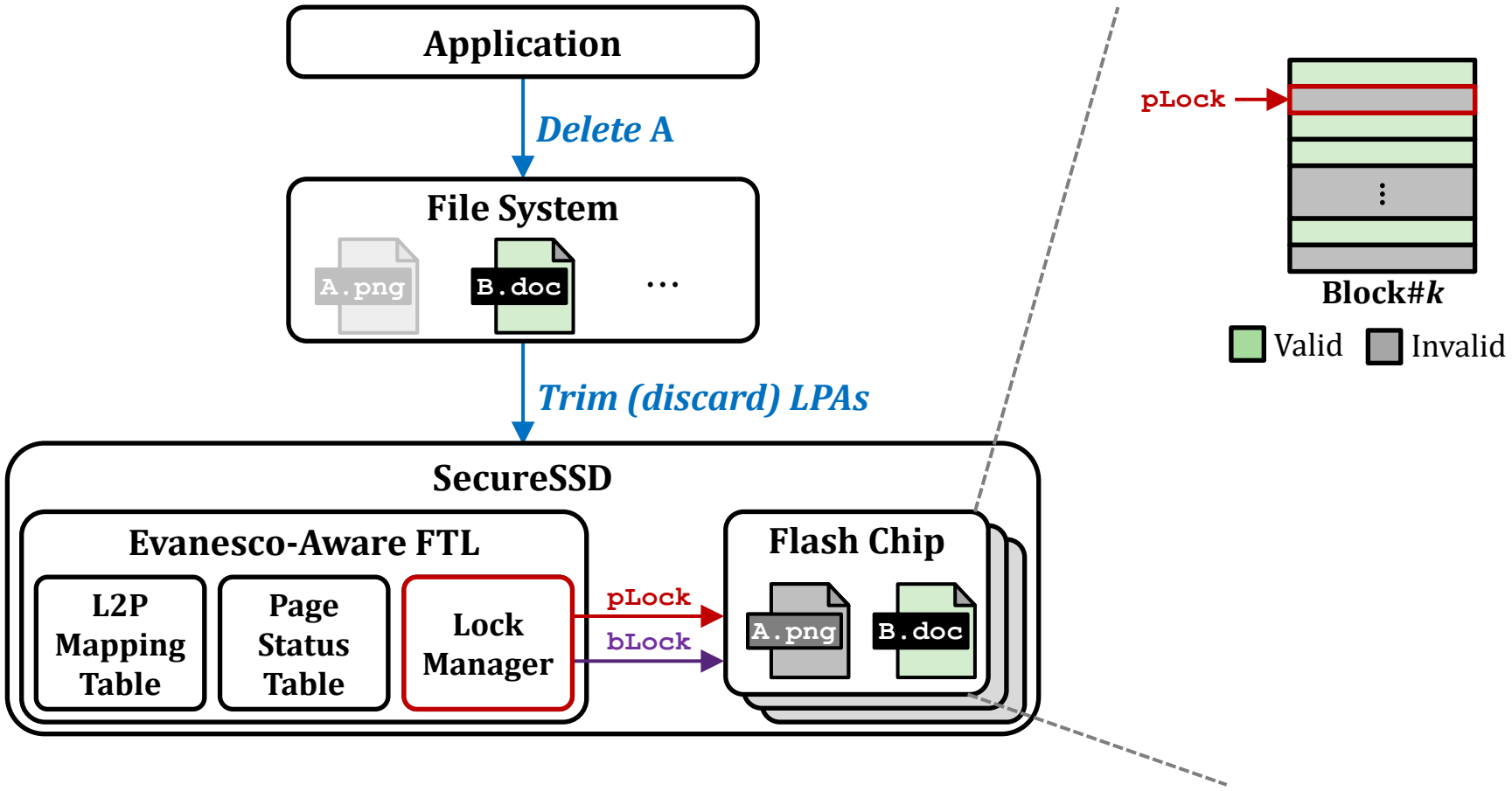

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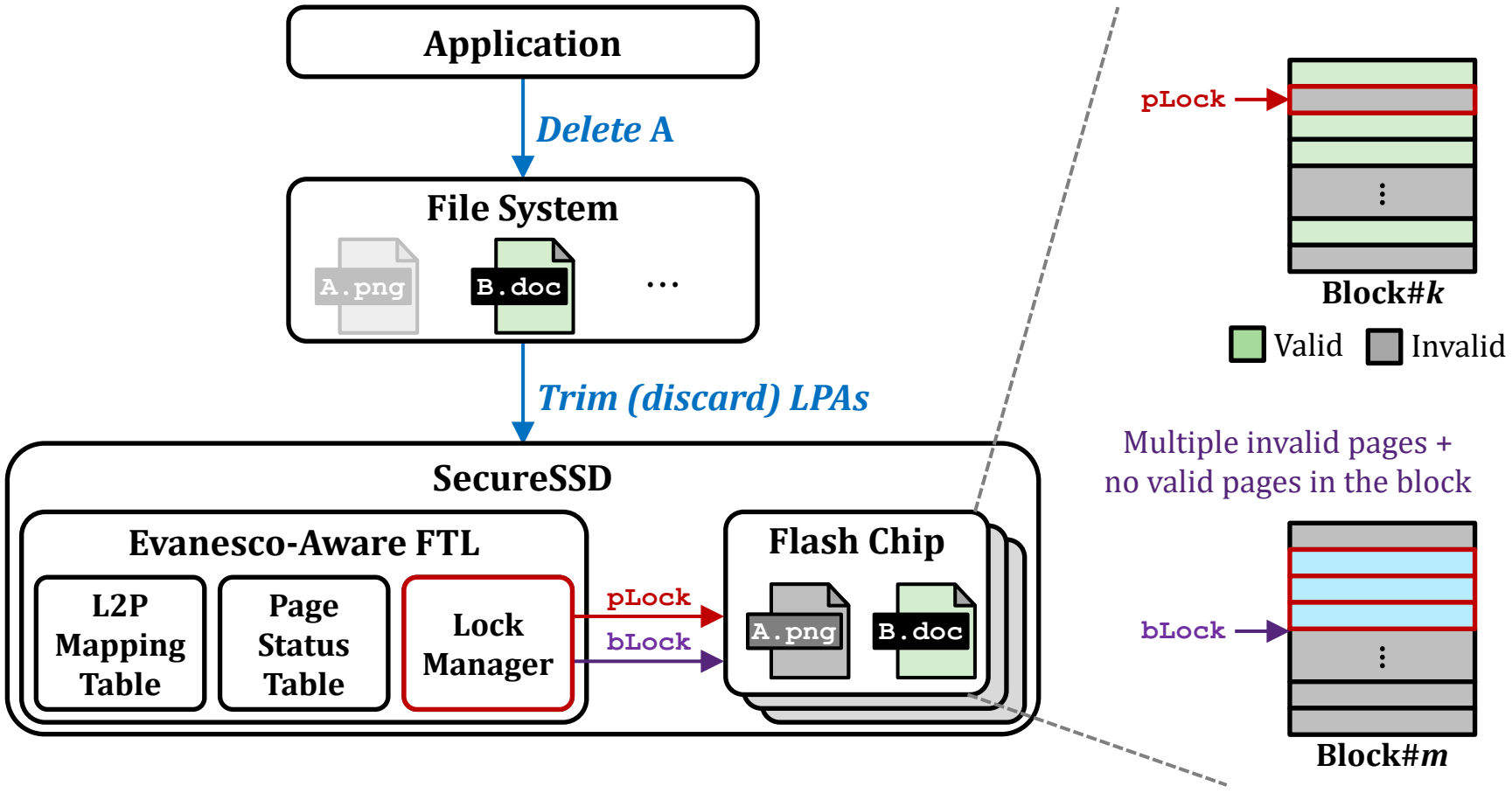

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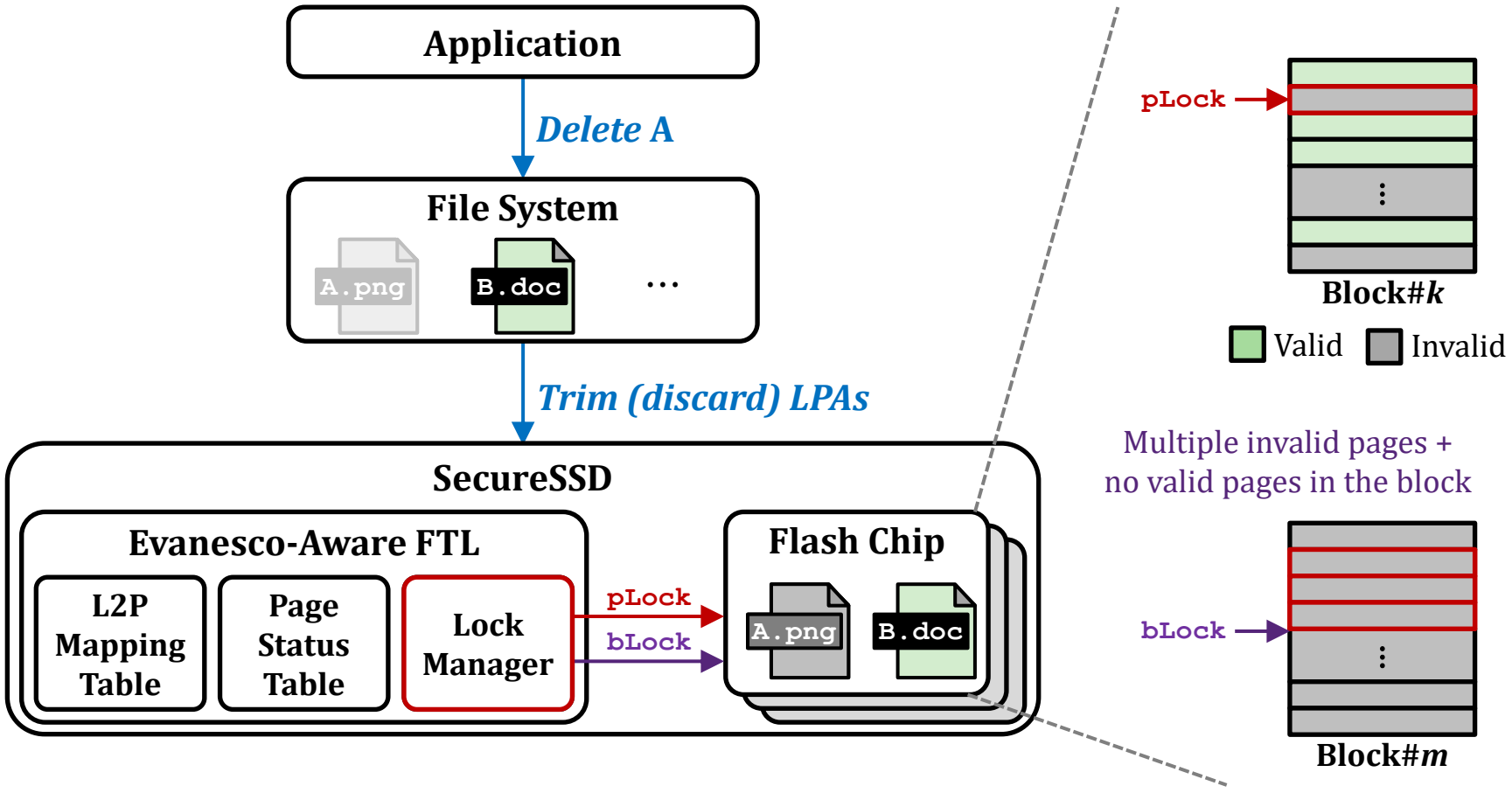
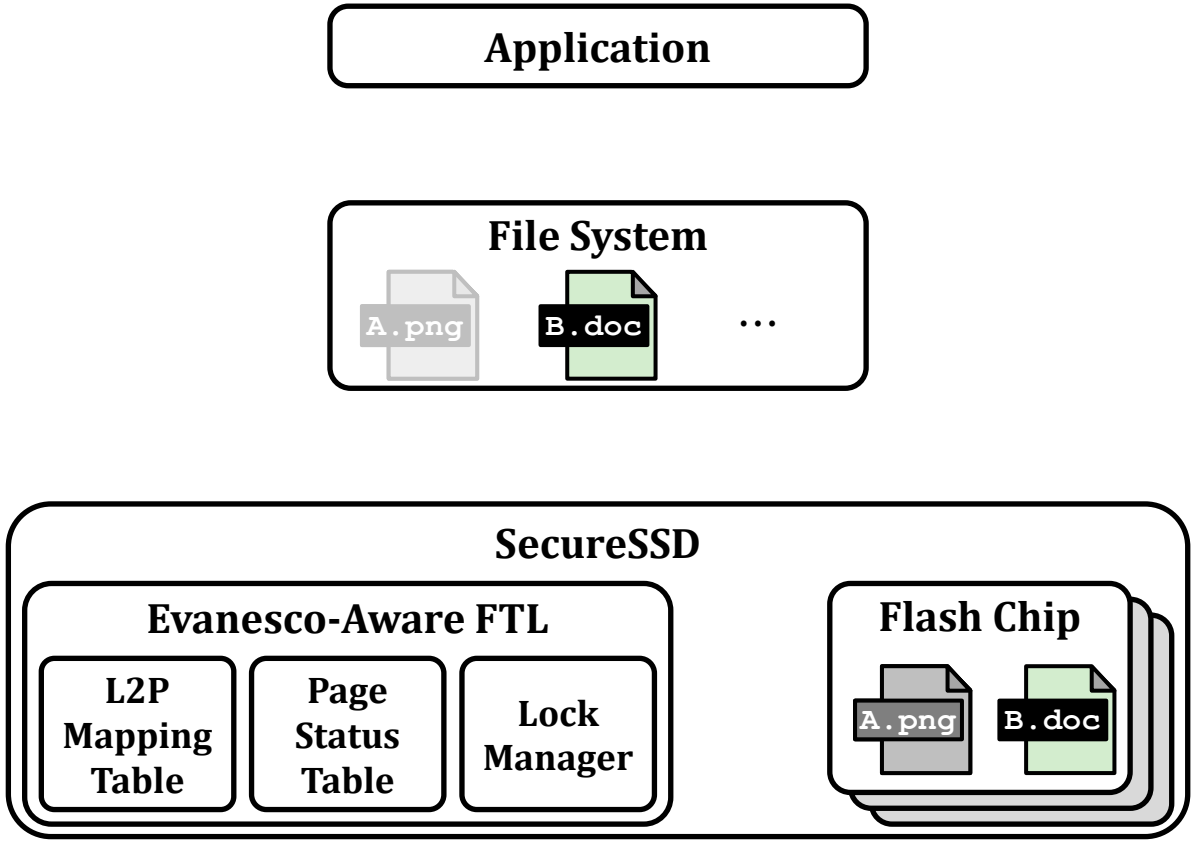


SecureSSD: Selective Data Sanitization

- SecureSSD avoids unnecessary pLock and bLock for security-insensitive data.
  - A user sets the security requirements of written data w/ extended I/O interfaces.



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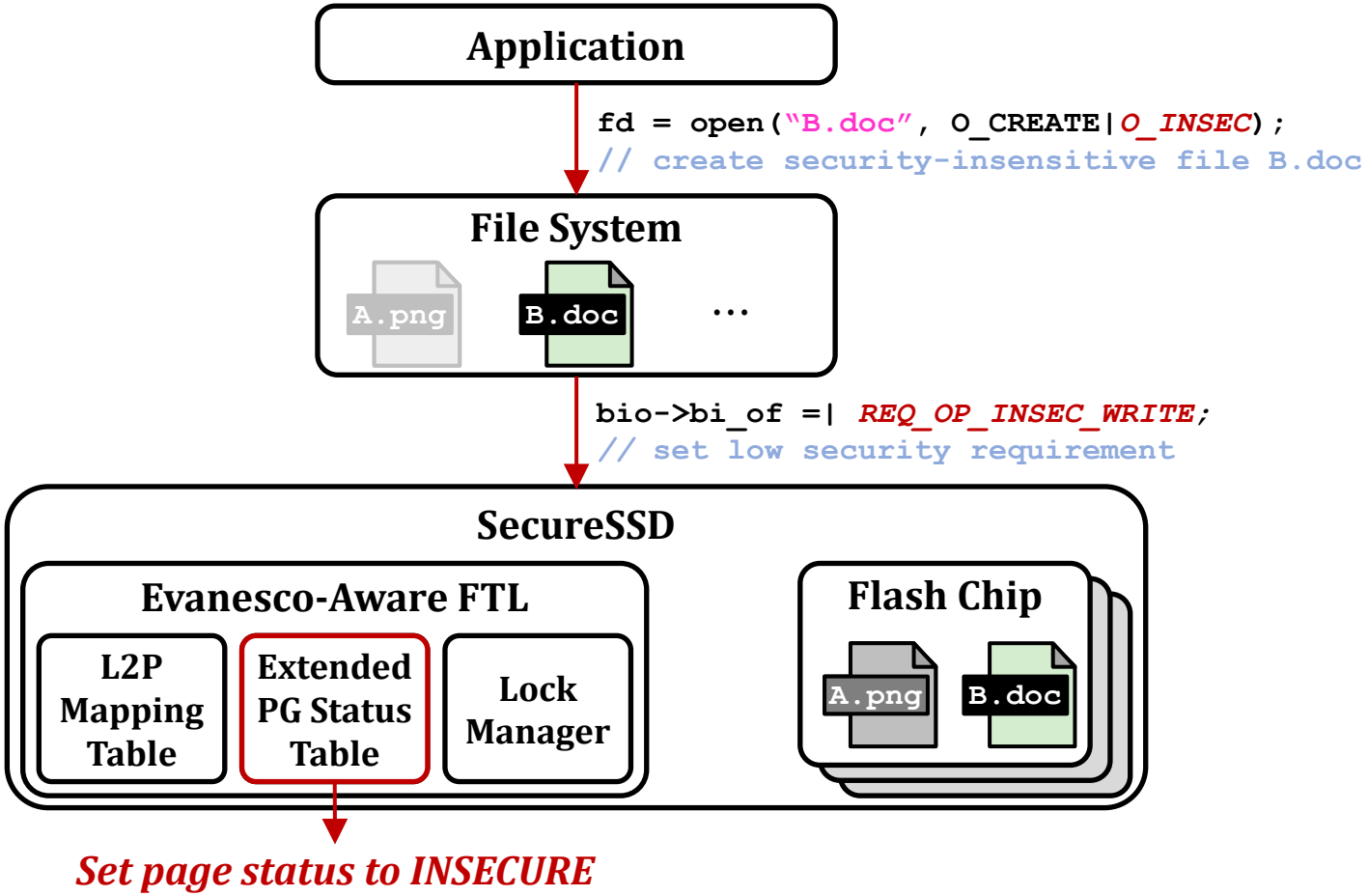

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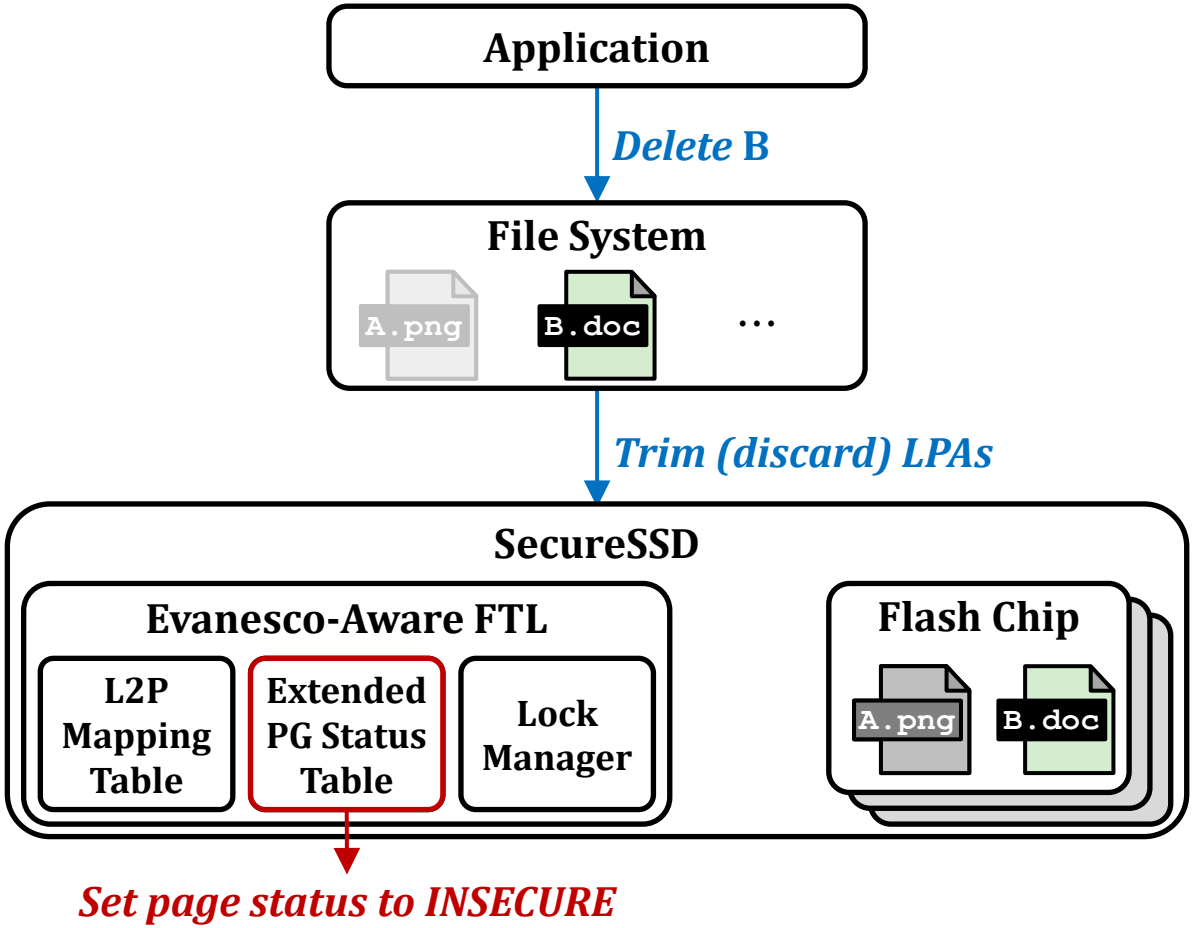

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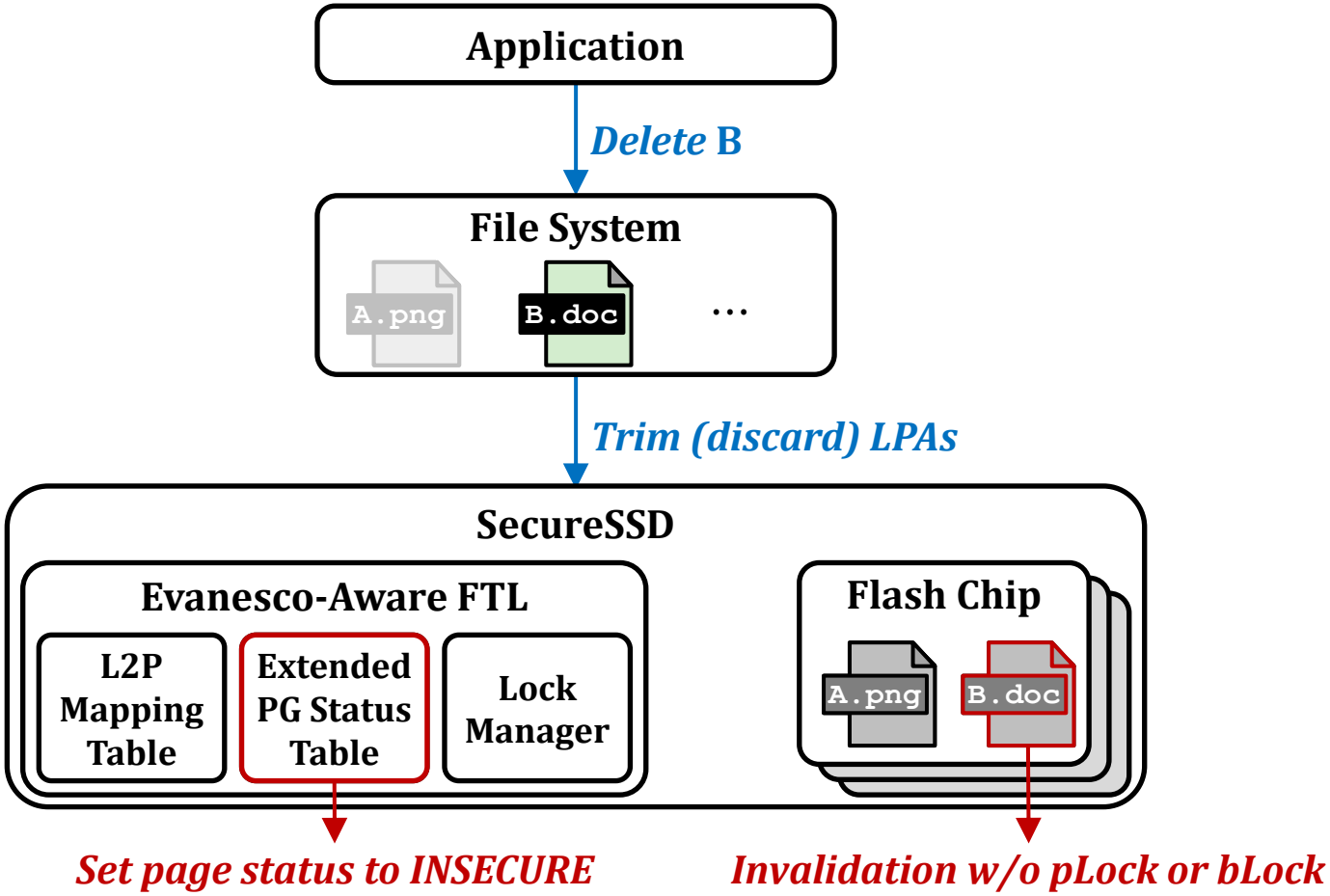

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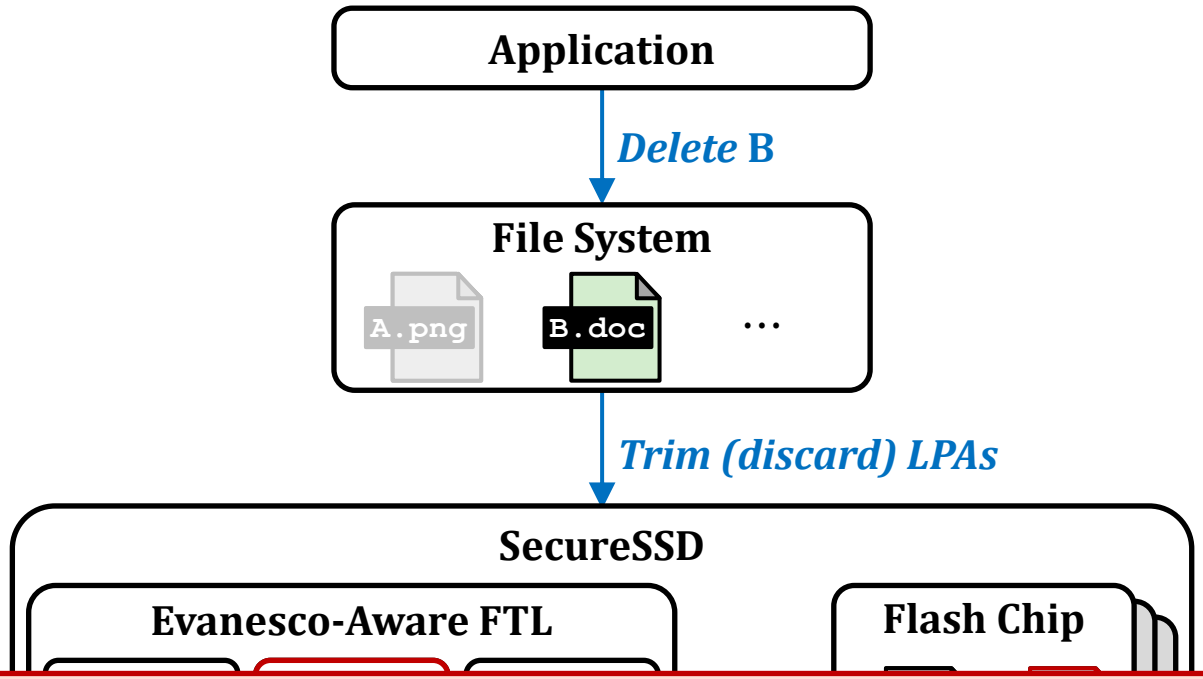

SecureSSD minimizes data-sanitization overheads

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- Evanesco: Lock-Based Data Sanitization
  - pageLock: Page-Level Data Sanitization
  - blockLock: Block-Level Data Sanitization
  - SecureSSD: An Evanesco-Enabled SSD
- **Evaluation**
- Conclusion

Methodology

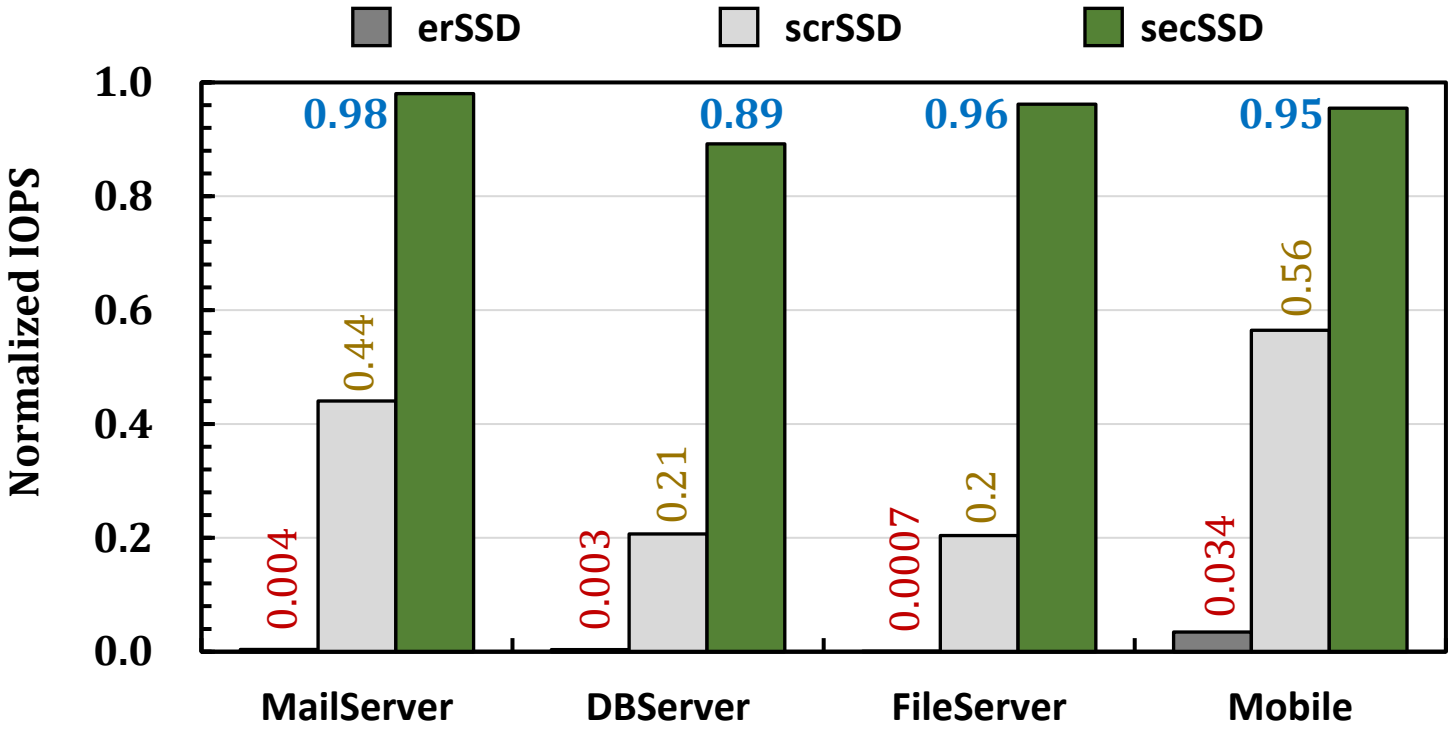
- **Design space exploration for pLock and bLock**
  - Using 160 real state-of-the-art 3D triple-level-cell (TLC) NAND flash chips
  - To find the best operation parameters w/o reliability degradation
    - **pLock:** 100-us latency w/ 9 flag cells per page
    - **bLock:** 300-us latency
    - tREAD = 100 us, tPROG = 700 us, tBERS = 3.5 ms

- **Simulator:** Open SSD-development platform (FlashBench [Lee+, RSP'2012])
  - 32-GiB storage capacity
  - 576 pages per block
  - 16-KiB page size

- **Compared SSDs**
  - **erSSD:** Erases the entire block after copying valid pages in the block
  - **scrSSD:** Performs scrubbing after copying valid pages in the same cells [Wei+, FAST'2011]

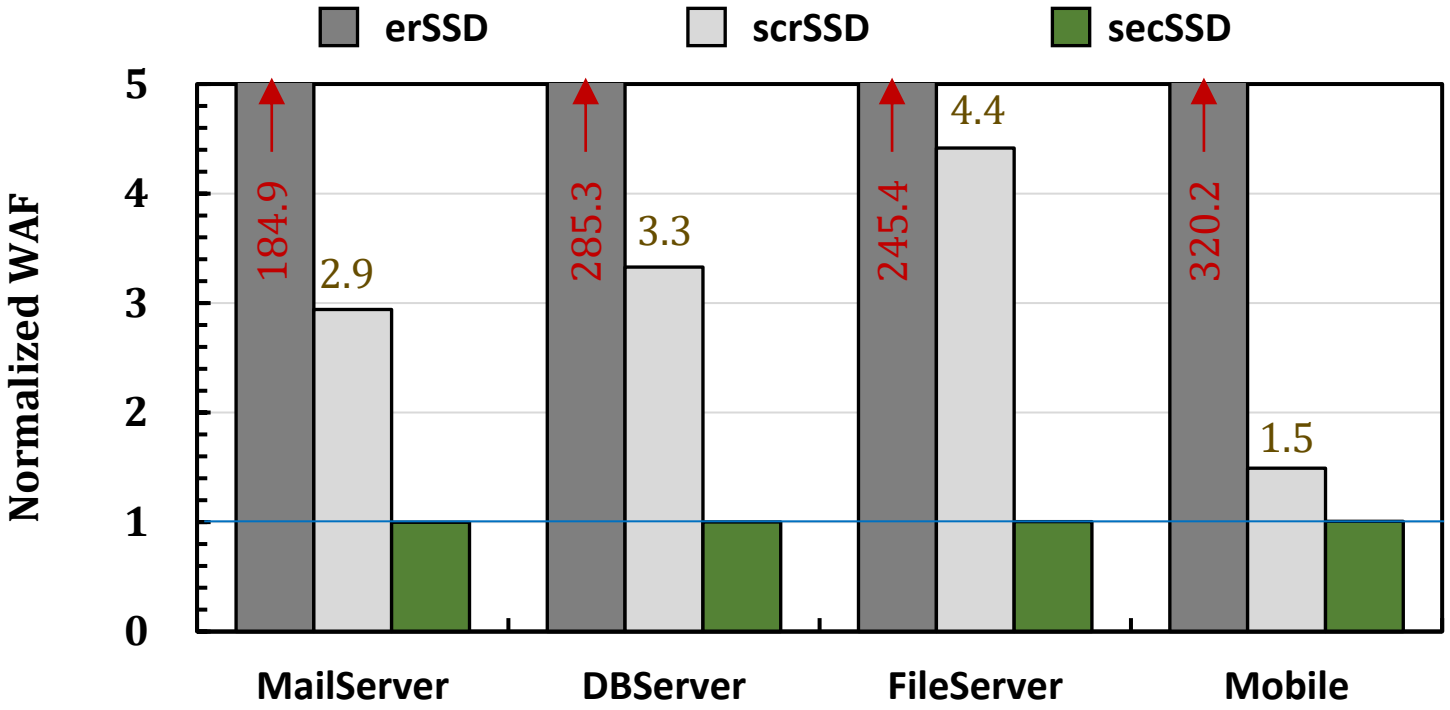
- **Workloads**
  - Three server workloads: MailServer, DBServer, FileServer
  - Mobile workload collected from an Android smartphone (Samsung Galaxy S2)

Results: Performance



SecureSSD significantly reduces performance overhead of data sanitization (11% slowdown at most)

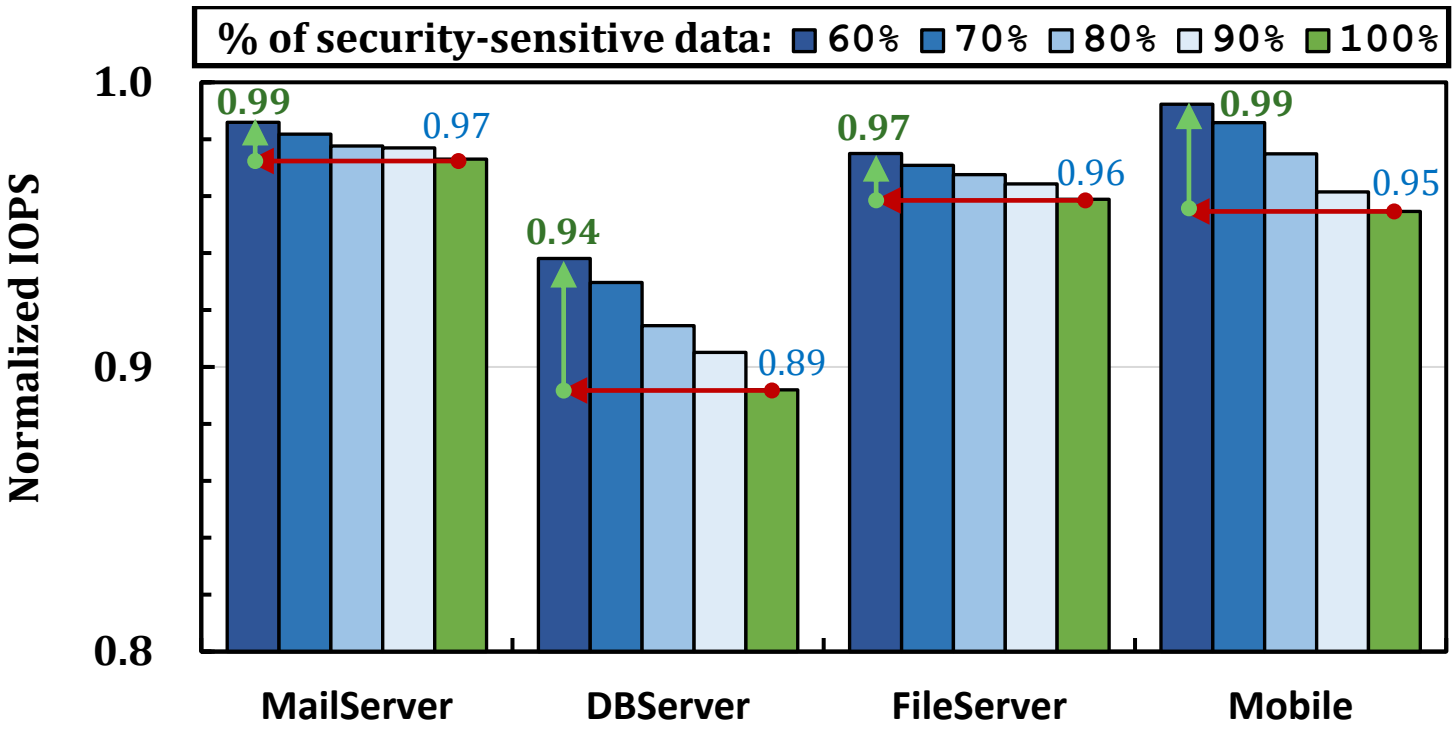
Results: Lifetime



$$Write\ Amplification\ Factor\ (WAF) = \frac{\#\ of\ logical\ pages\ written\ by\ the\ host\ system}{\#\ of\ physical\ pages\ written\ by\ the\ SSD}$$

No additional copy in SecureSSD: No lifetime overhead

Results: Effect of Selective Data Sanitization



Selective data sanitization minimizes performance overheads (6% slowdown at most with 60% security-sensitive data)

Other Analyses in the Paper

- **Empirical Study on Invalid Data in SSDs**
- **Reliability Issues in Physical Data Destruction**
- **Design Space Exploration for pLock and bLock**
- **Effectiveness of bLock command**

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Conclusion

- **Challenges of data sanitization** in NAND flash-based SSDs:
  - **Erase-before-write property** → no overwrite on stored data
  - **Physical data destruction** → high performance & reliability overheads

- **Evanesco:** Uses on-chip access-control mechanisms
  - **pLock:** Page-level data sanitization
    - Implements the access-permission flag of each page using spare cells
  - **bLock:** Block-level data sanitization
    - Programs the SSL of a block to disconnect all pages
  - **SecureSSD:** An Evanesco-Enabled SSD
    - Supports selective data sanitization to reduce performance overheads

- **Results**
  - Provides the same level of reliability of an unmodified SSD
    - Validated w/ 160 real state-of-the-art 3D NAND flash chips
  - Significantly improves performance and lifetime over existing data-sanitization techniques
    - Provides comparable (94.5%) performance with an unmodified SSD

Evanesco: Architectural Support for Efficient Data Sanitization in Modern Flash-Based Storage Systems

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ASPLOS 2020

**M. Kim and J. Park equally contributed.*