Flash Memory

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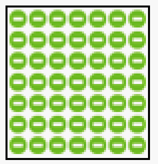
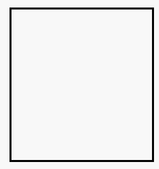
Spring 2023

Flash Memory Basics

- Two states based on the presence of electrons

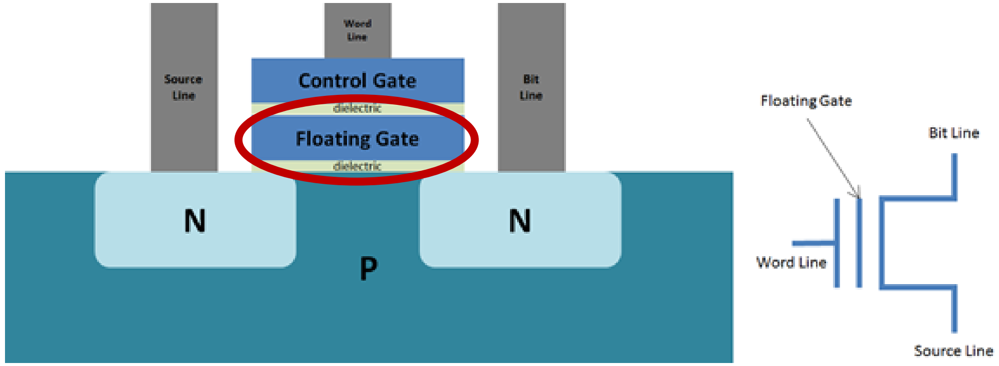


0 = Electrons present



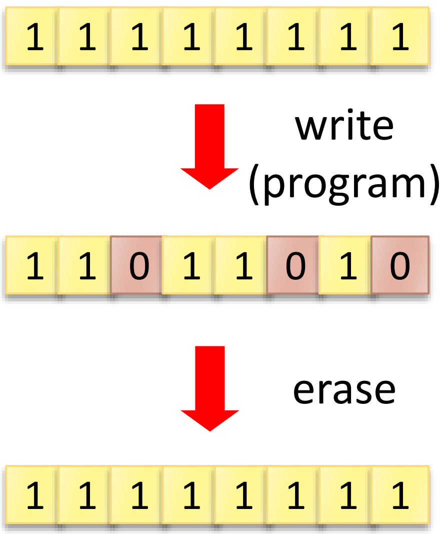
1 = No electrons

- Challenges
  - How to attract or expel electrons?
  - How to find out whether there are electrons or not?
  - How to keep electrons without any power?



Flash Memory Characteristics

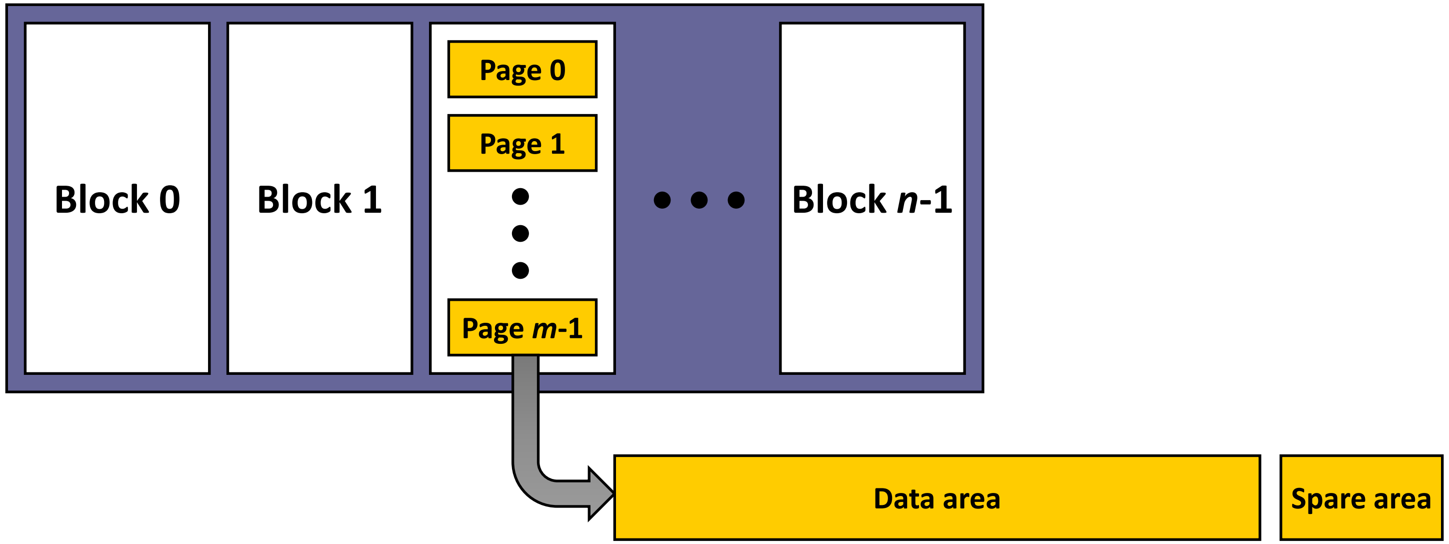
- Erase-before-write
  - Read
  - Write or Program: 1 → 0
  - Erase: 0 → 1



- Bulk erase
  - Read/program unit
    - NOR: byte or word
    - NAND: page
  - Erase unit: block

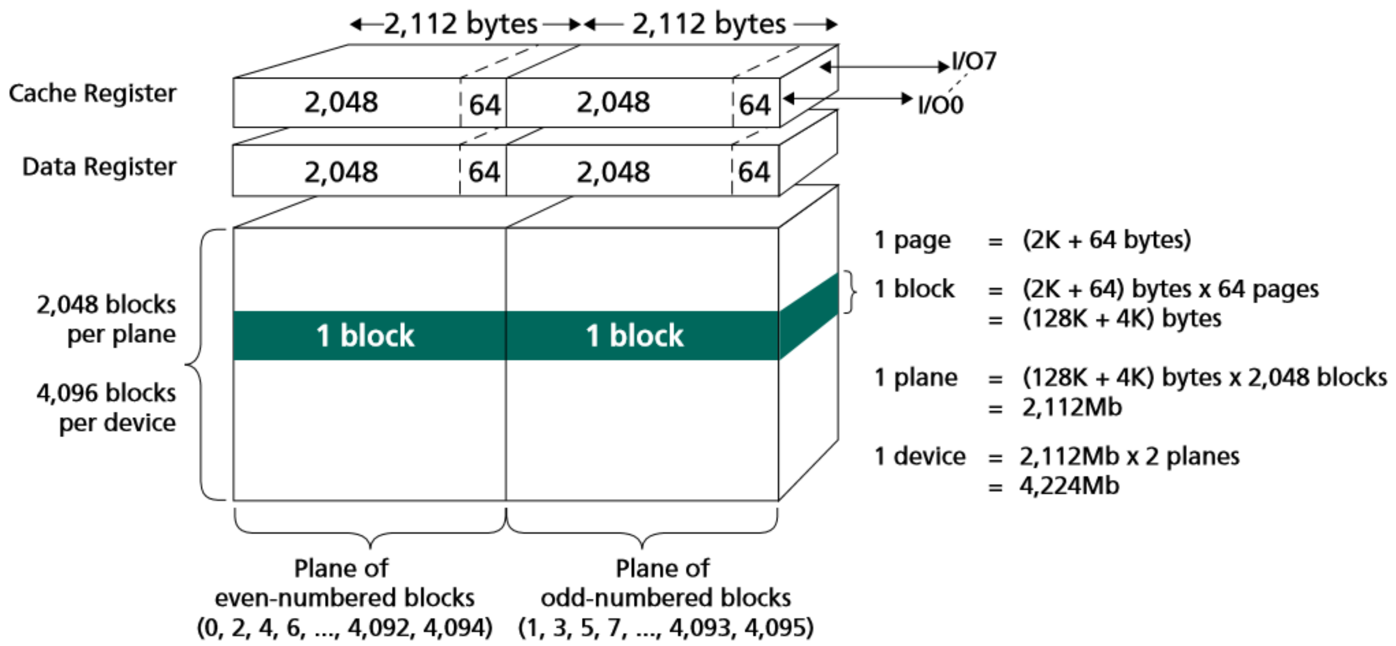
Logical View of NAND Flash

- A collection of blocks
- Each block has a number of pages
- The size of a block or a page depends on the technology (but, it's getting larger)



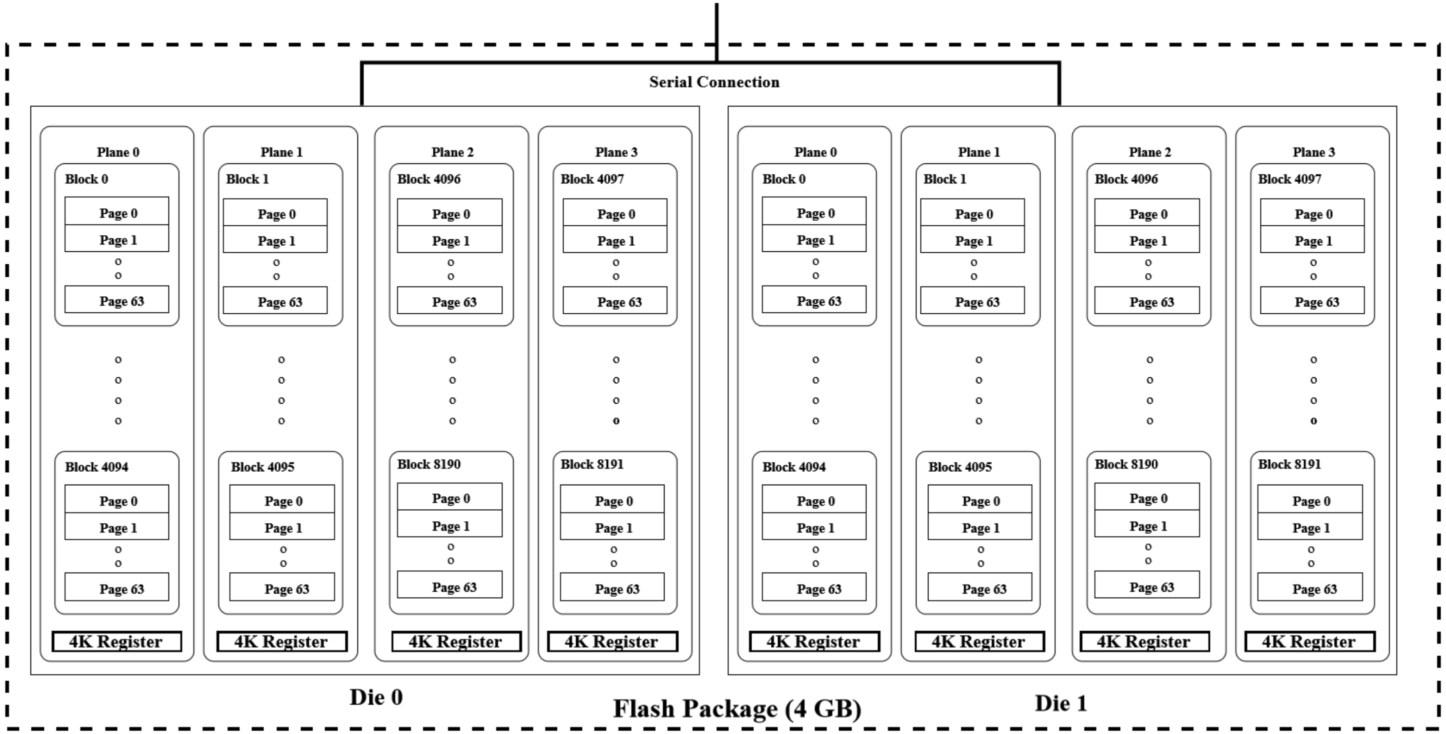
Plane

- Each plane has its own page register and cache register
- Pages can be programmed or read at once
- Optional feature: 1, 2, 4, 8, … planes



Die / Chip

- Each chip has multiple dies (can be stacked)
- + extra circuits, chip enable signal, ready/busy signal

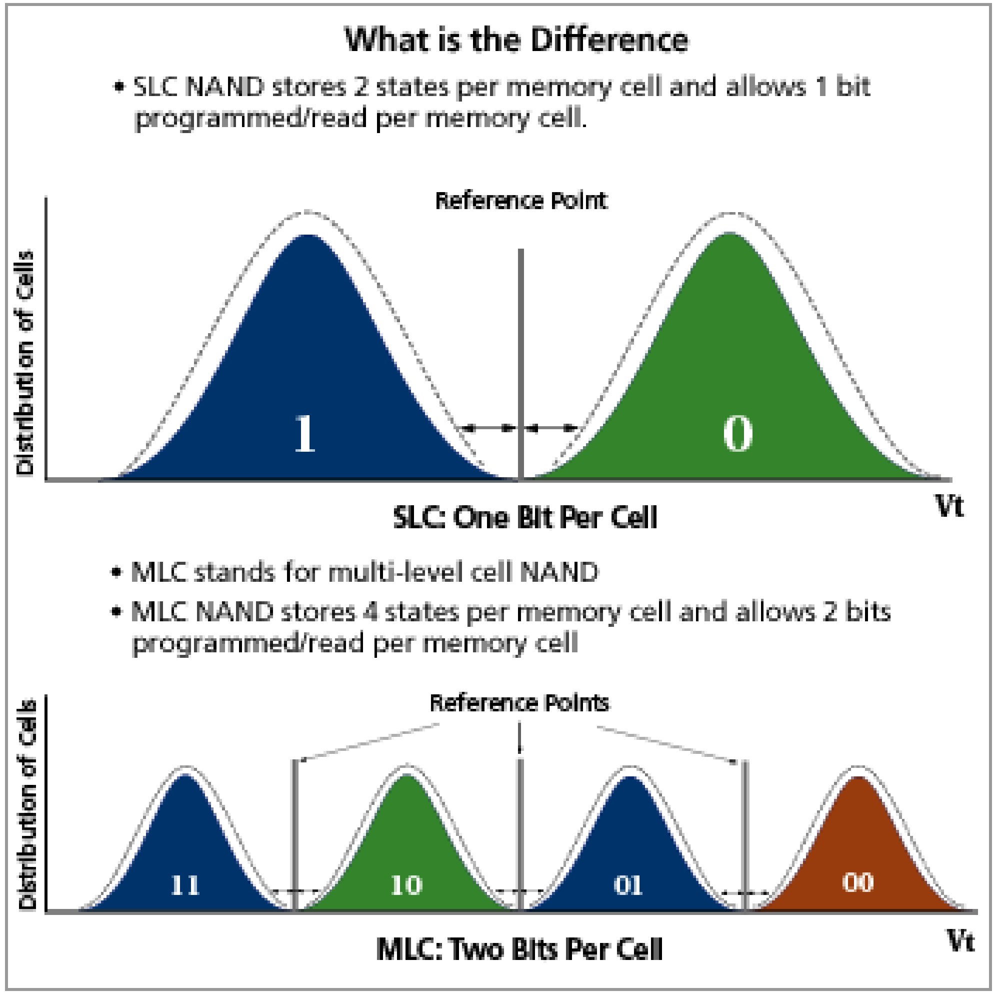


N. Agrawal, Design Tradeoffs for SSD Performance, USENIX ATC, 2008.

NAND Flash Types

- SLC NAND
  - Single Level Cell (1 bit/cell)
- MLC NAND
  - Multi Level Cell (2 bits/cell)
- TLC NAND
  - Triple Level Cell (3 bits/cell)
- QLC NAND
  - Quad Level Cell (4 bits/cell)

- 3D NAND (or V-NAND)



Source: Micron Technology, Inc.

Characteristics of NAND Flash

Erase-Before-Write

- In-place update (overwrite) is not allowed
- Pages must be erased before new data is programmed
- The erase unit is much larger than the read/write unit
  - Read/write unit: page (4KB, 8KB, 16KB, …)
  - Erase unit: block (64-512 pages)

- What if there are live pages in the block we wish to erase?

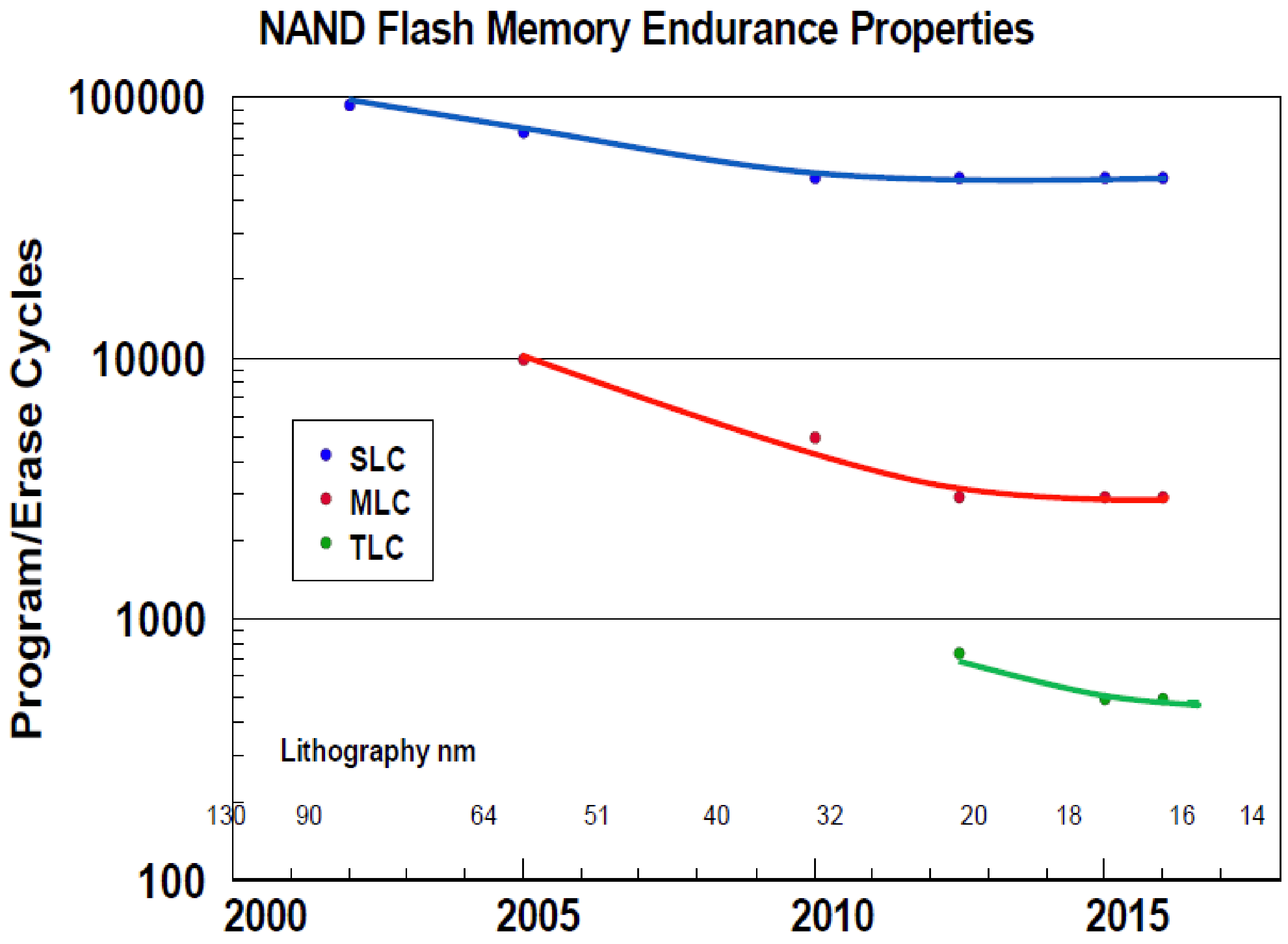
Limited Lifetime

- The number of times NAND flash blocks can reliably be programmed and erased (P/E cycle) is limited
  - SLCs: 50,000 ~ 100,000
  - MLCs: 1,500 ~ 5,000
  - eMLCs (Enterprise MLCs): 10,000 ~ 30,000
  - TLCs: < 1,000
  - QLCs: ???

Old Data

- High voltage applied to cell degrades oxide
  - Electrons are trapped in oxide
  - Break down of the oxide structure
- Requires ______________

Flash Endurance



E. Grochowski et al., Future Technology Challenges for NAND Flash and HDD Products, FMS, 2012.

Asymmetric Read/Write Latency

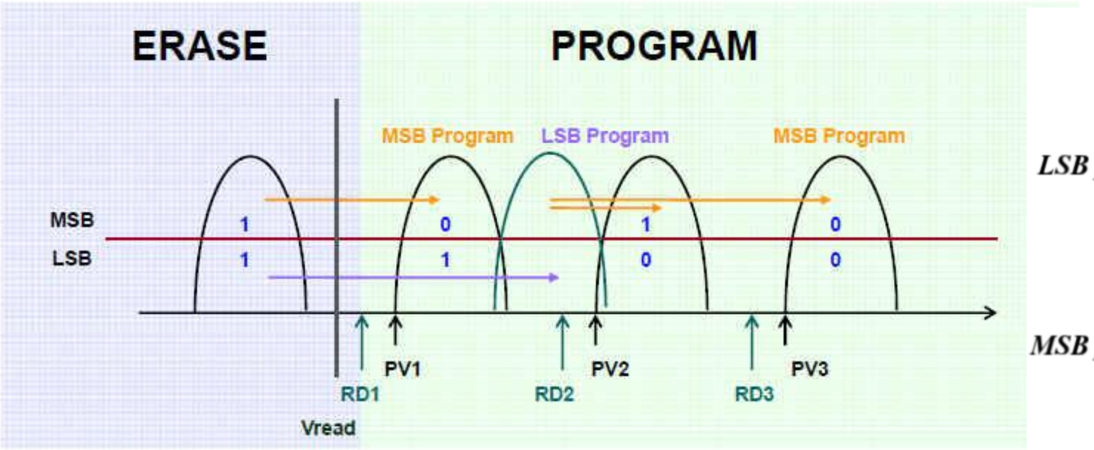
- Reading a page is faster than programming it
- Usually more than 10x
  - e.g., 1ynm MLC[1]: Read 45μs, Program 1350μs, Erase 4ms
- Programming a page should go through multiple steps of Program & Verify phases

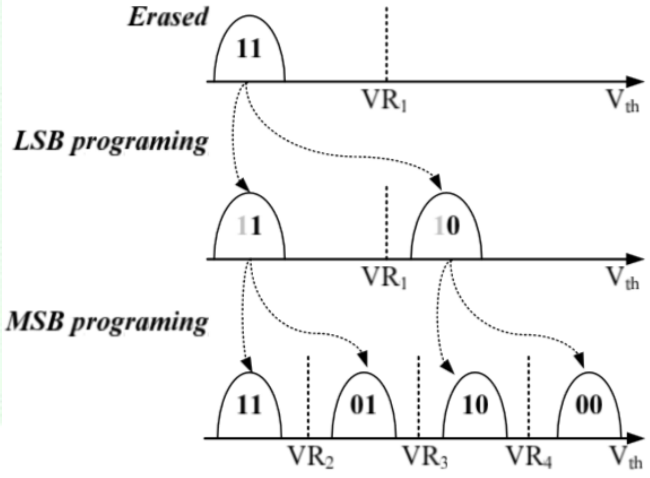
- As the technology shrinks, read/write latency tends to increase
- MLC and TLC make it even worse

[1] *D. Sharma, System Design for Mainstream TLC SSD, FMS, 2014.*

MLC Programming

- LSB programmed first
  - Cell cannot move to the lower voltage before erase





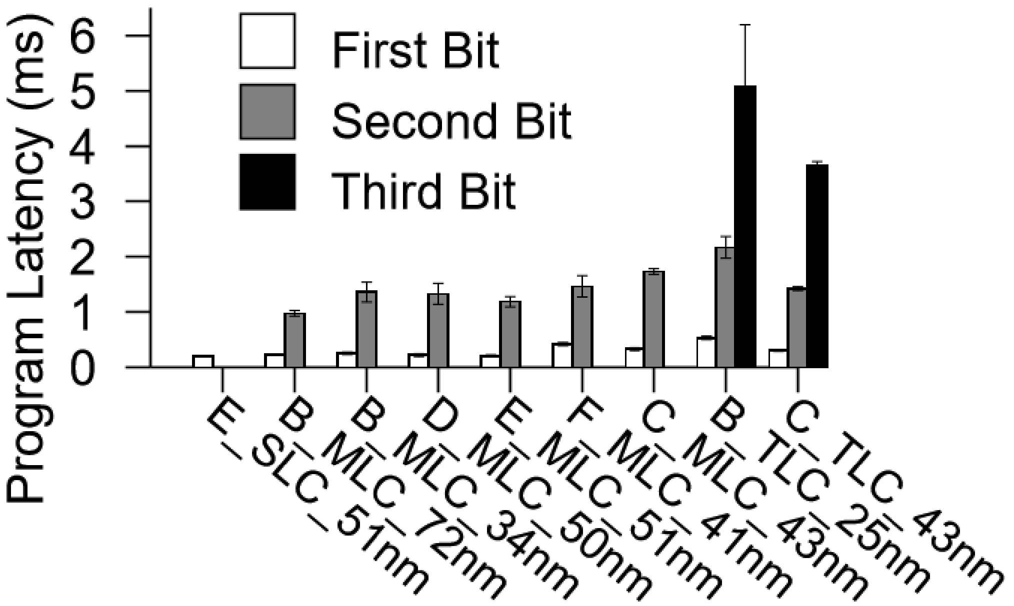
Program : "1"(Erase) → "0"(Program)

LSB Program : 1) Erase → Erase, 2) Erase → LSB

MSB Program: 1) Erase → Erase, 2) Erase → PV1, 3) LSB → PV2, 4) LSB → PV3

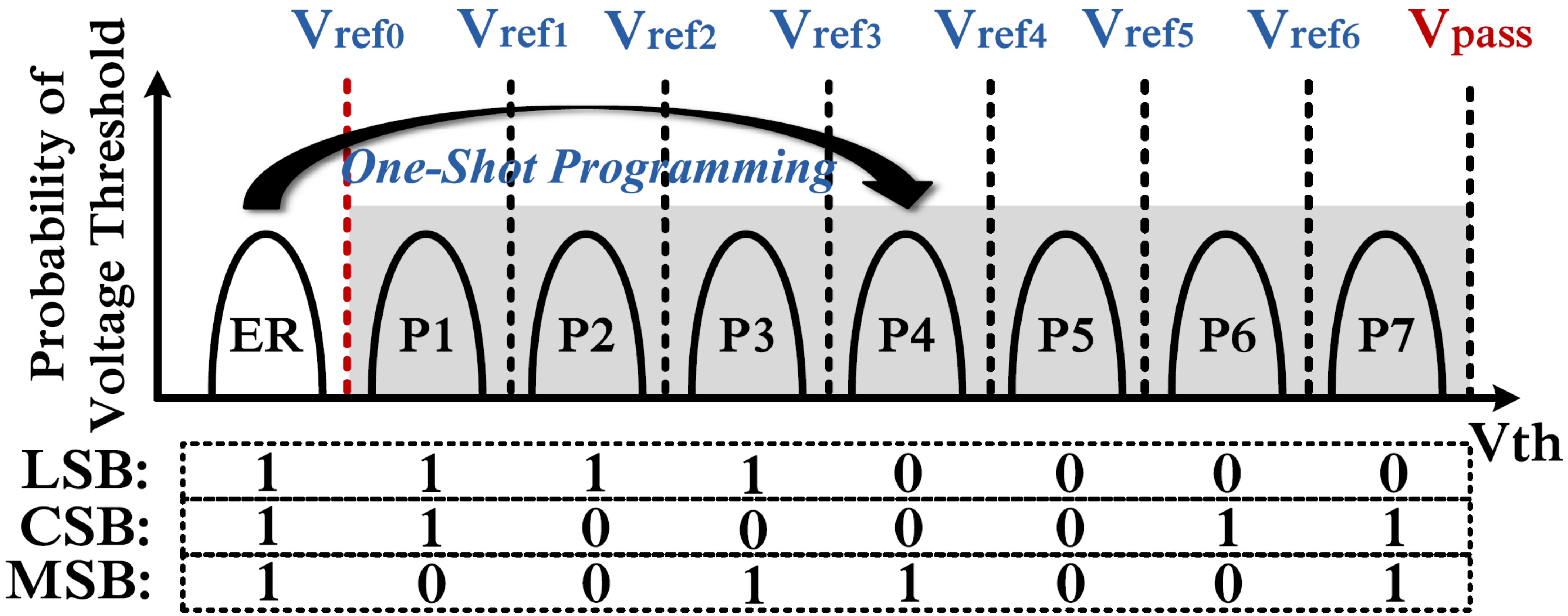
Paired Pages in MLC

- One cell represents two or three bits in paired pages
  - LSB: low voltage, fast program, less error
  - MSB: high voltage, slow program, more error
- Performance difference
- LSB page can be corrupted when MSB page programming is interrupted



L. M. Grupp et al., The Harey Tortoise: Managing Heterogeneous Write Performance in SSDs, USENIX ATC, 2013.

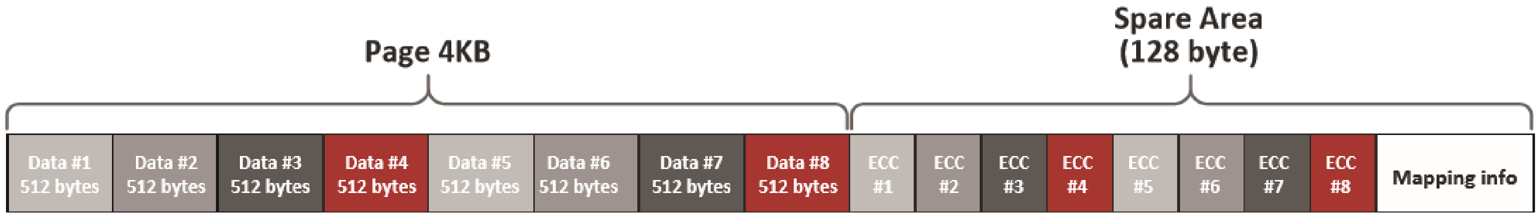
TLC One-Shot Programming



C. Gao et al., "Reprogramming 3D TLC Flash Memory based Solid State Drives", ACM TOS 2022.

Bit Errors

- Bits are flipping frequently
- Error Correction Code (ECC) in spare area

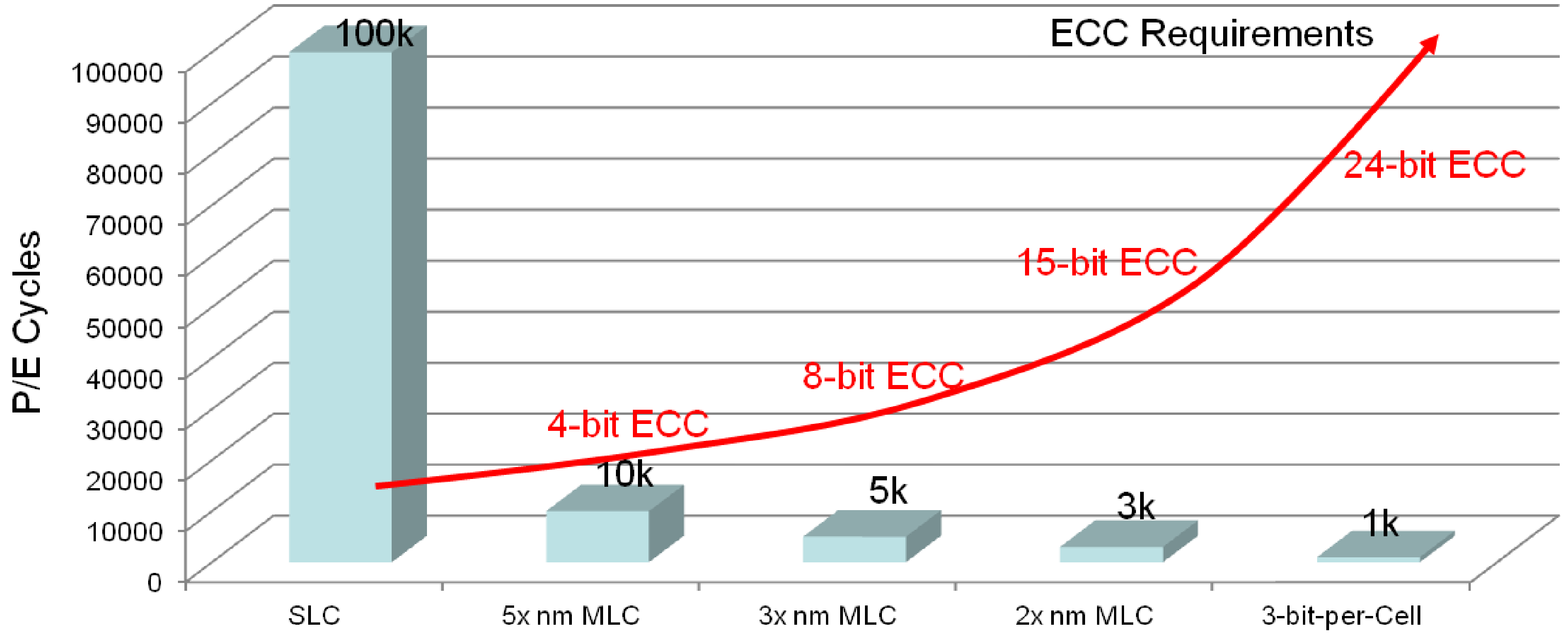


Error Correction Level	Bits Required in the NAND Flash Spare Area		
	Hamming	Reed-Solomon	BCH
1	13	18	13
2	N/A	36	26
3	N/A	54	39
4	N/A	72	52
5	N/A	90	65
6	N/A	108	78
7	N/A	126	91
8	N/A	144	104
9	N/A	162	117
10	N/A	180	130

Source: Micron Technology, Inc.

ECC Requirements

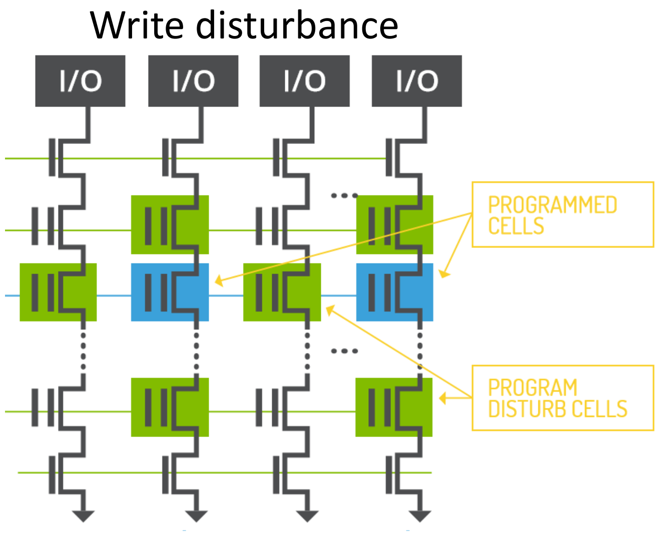
- Endurance continues to deteriorate
- Stronger ECCs are required: RS, BCH, LDPC

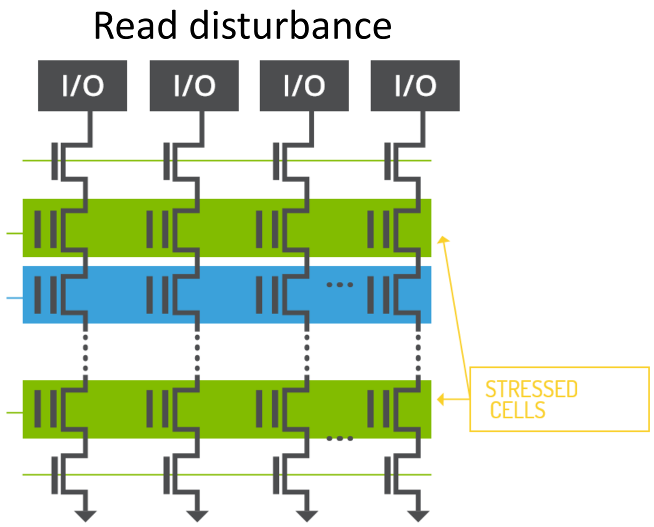


Y. Cai et al., Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis, DATE, 2012.

Reliability

- **Write disturbance**
  - When a page is programmed, adjacent calls receive elevated voltage stress
- **Read disturbance**
  - Repeated reading from one page can alter the values stored in other unread pages
- ___________ error
  - Threshold voltage shifts down due to charge leakage from the floating gate





Bad Blocks

- Initial bad blocks
  - Due to production yield constraints and the pressure to keep costs low
  - SLCs: up to 2%
  - MLCs: up to 5%
- Run-time bad blocks
  - Read, write, or erase failure
  - Permanent shift in the voltage levels of the cells due to trapped electrons
- Requires run-time bad block management

Page Programming Constraints

- NOP
  - The number of partial-page programming is limited
  - 1 / sector for most SLCs (4 for 2KB page)
  - 1 / page for most MLCs and TLCs
- Sequential page programming
  - Pages should be programmed sequentially inside a block
  - For large block SLCs, MLCs, and TLCs
- SLC mode
  - Possible to use only LSB pages in MLCs and TLCs
  - Faster and more reliable, higher P/E cycles

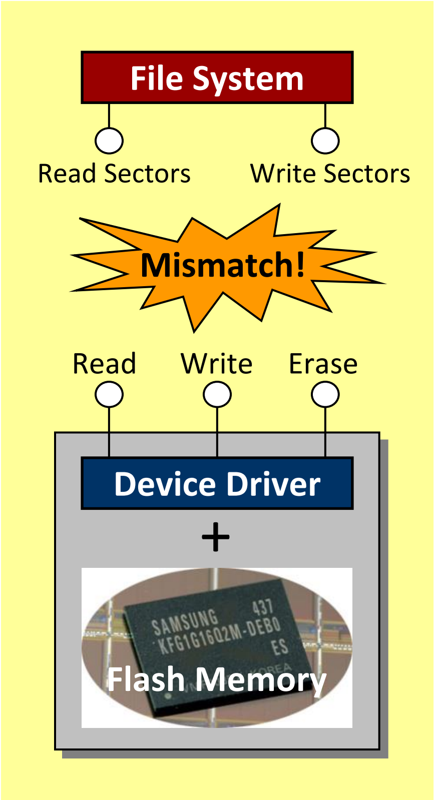
Beauty and the Beast

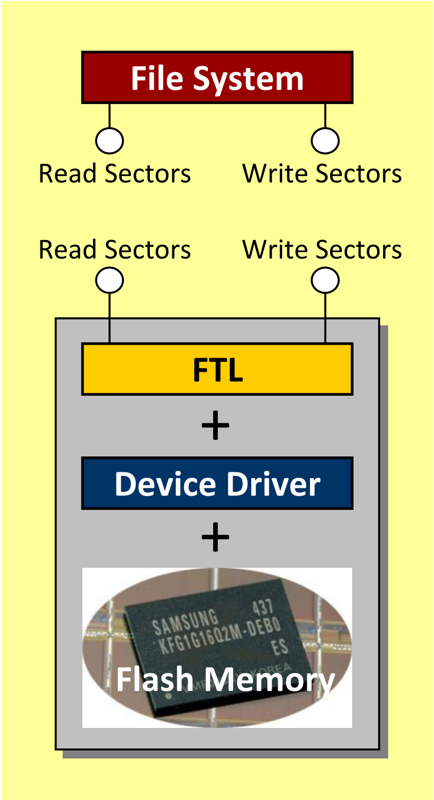
- NAND Flash memory is a beauty
  - Small, light-weight, robust, low-cost, low-power non-volatile device
- NAND Flash memory is a beast
  - Much slower program/erase operations
  - No in-place-update
  - Erase unit > write unit
  - Limited lifetime
  - Bit errors, bad blocks, …
- Software support is essential for performance and reliability!

Page Mapping FTL

What is FTL?

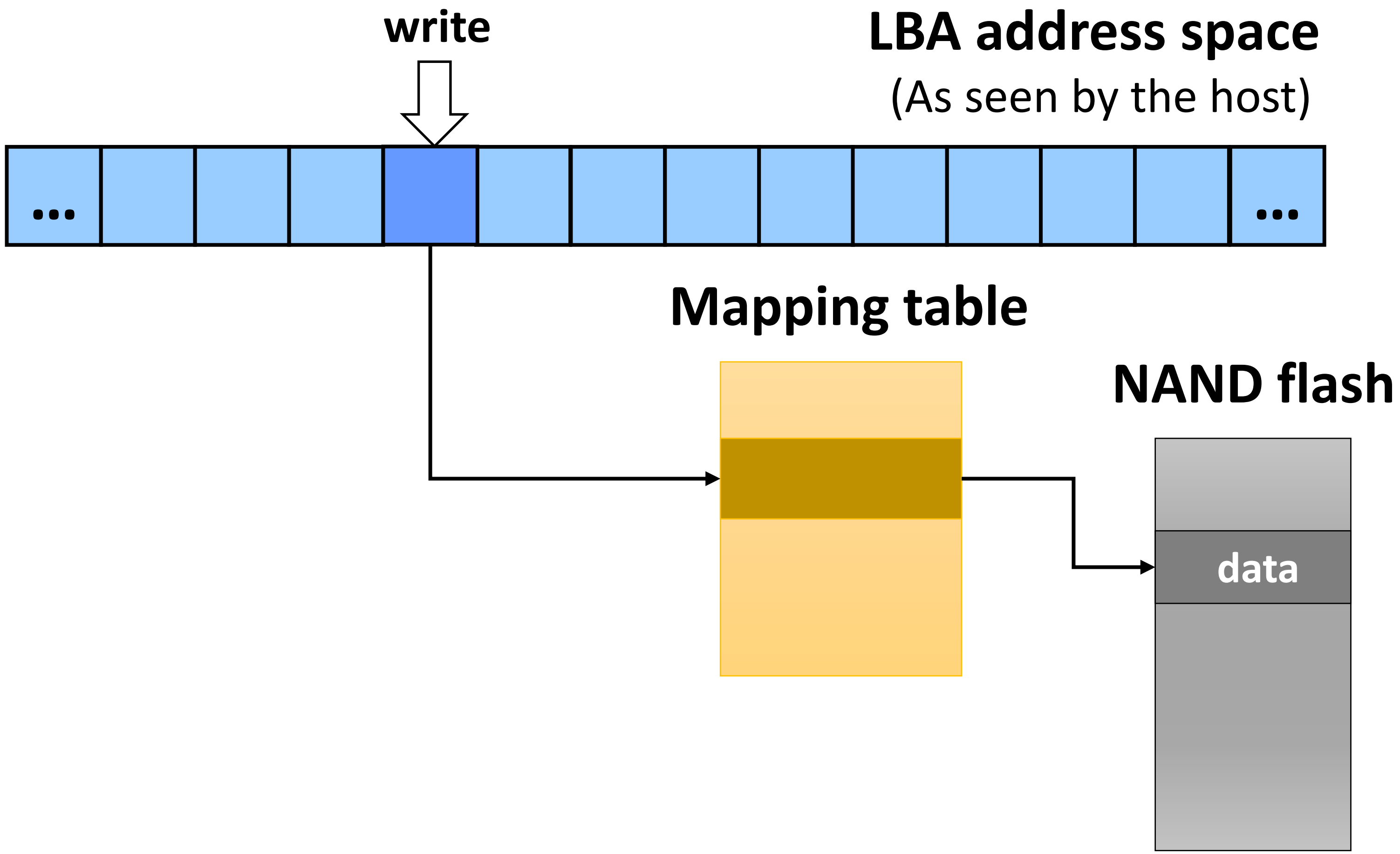
- A software layer to make NAND flash fully emulate traditional block devices (or disks)





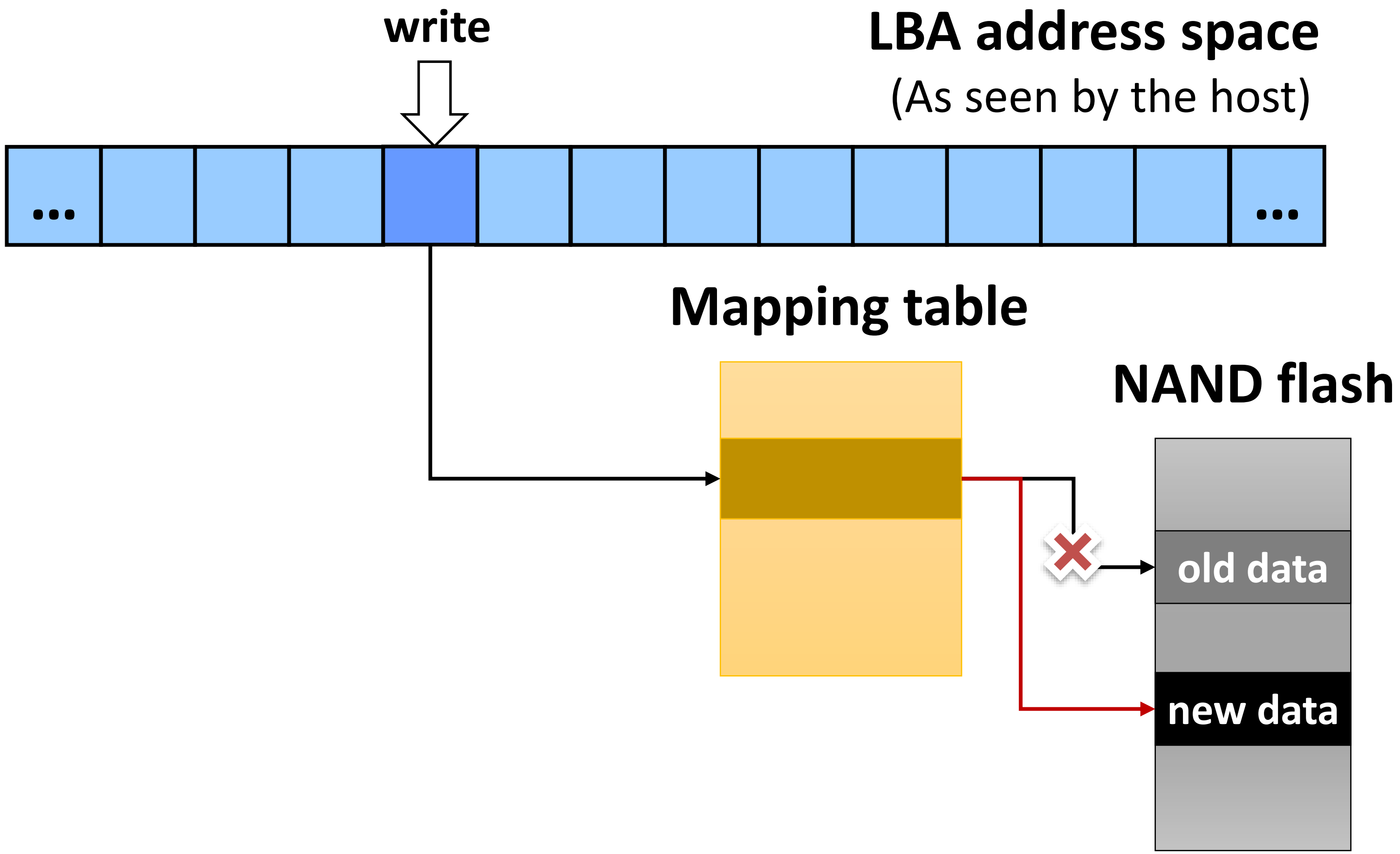
Source: Zeen Info. Tech.

Address Mapping



Address Mapping

- Required due to "no overwrite" characteristic



Plethora of FTLs

HFTL

SAST SFTL MS FTL BPLRU

BFTL AFTL FAST LazyFTL

KAST

Chameleon CNFTL DFTL

LAST MNFTL

super-block scheme CFTL

Log block scheme

GFTL μ-FTL JFTL zFTL

Hydra FTL Vanilla FTL Replacement block scheme

YanusFTL

Reconfigurable FTL

..........and so on

WAFTL UFTL

E. H. Nam, HIL: FTL Design Framework with Provably-correct Crash Recovery, NVRAMOS, 2013.

Mapping Schemes

- Page mapping
  - Fine-granularity page-level map table
  - Hugh amount of memory space required for the map table
- Block mapping
  - Coarse-granularity block-level map table
  - Small amount of memory space required for the map table
- ___________ mapping
  - Use both page-level and block-level map tables
  - Higher algorithm complexity

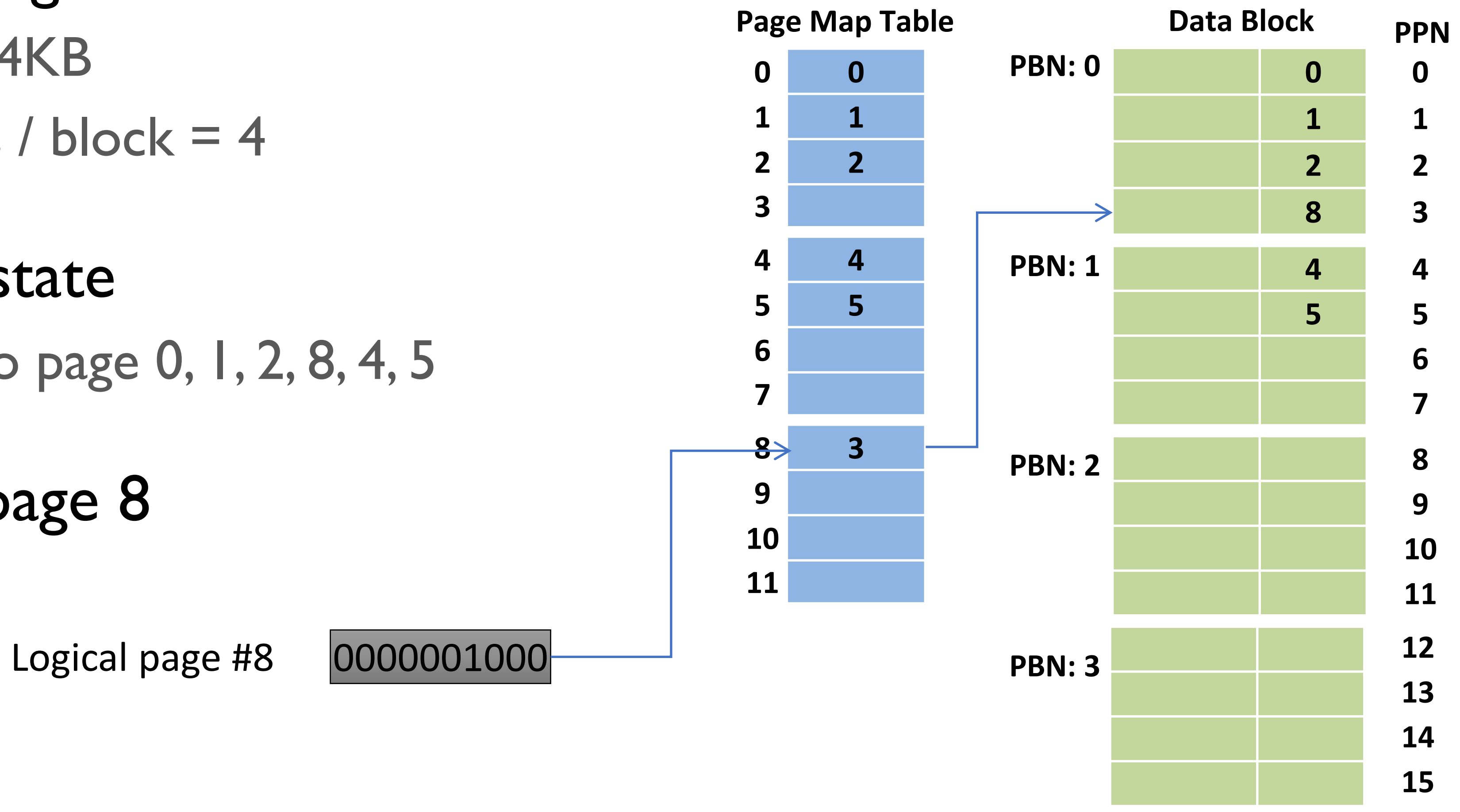
Page Mapping

- Mapping in page-level
  - Logical page number → physical page number
  - Page mapping table (PMT) required
  - # entries in PMT == # pages visible to OS

- Translation
  - Step 1: logical sector number (LSN) → logical page number (LPN)
  - Step 2: LPN → physical page number (PPN) via PMT

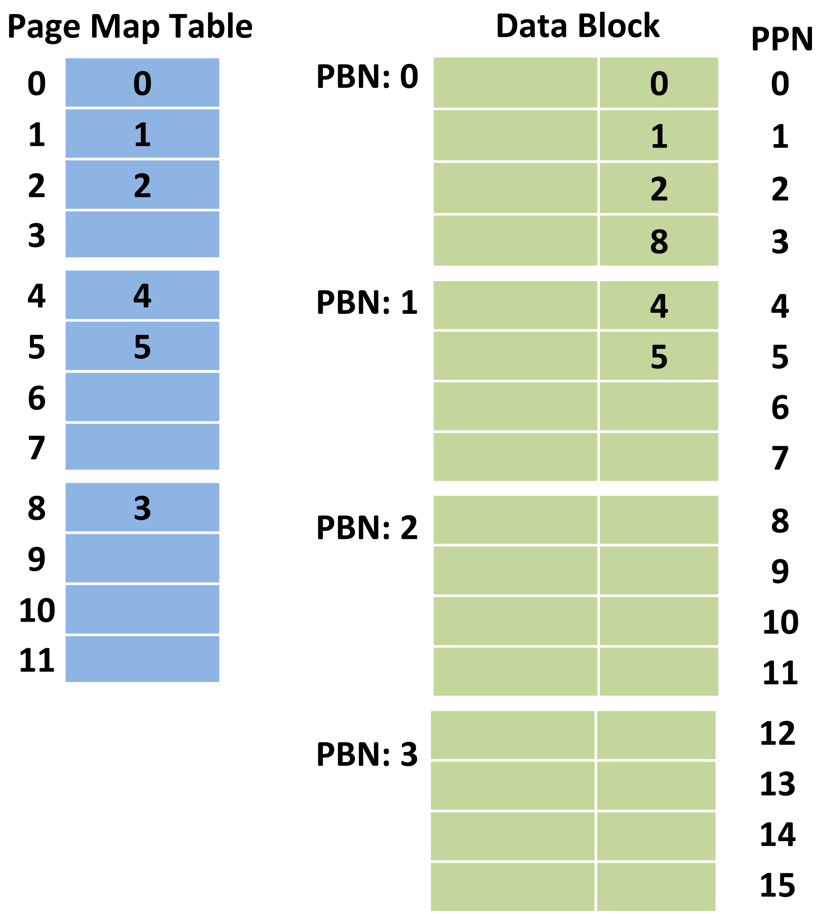
Example: Page Mapping

- Flash configuration
  - Page size: 4KB
  - # of pages / block = 4
- Current state
  - Written to page 0, 1, 2, 8, 4, 5
- Reading page 8



Example: Page Mapping

- **Flash configuration**
  - Page size: 4KB
  - # of pages / block = 4
- **Current state**
  - Written to page 0, 1, 2, 8, 4, 5
- **New requests (in order)**
  - Write to page 9
  - Write to page 3
  - Write to page 5



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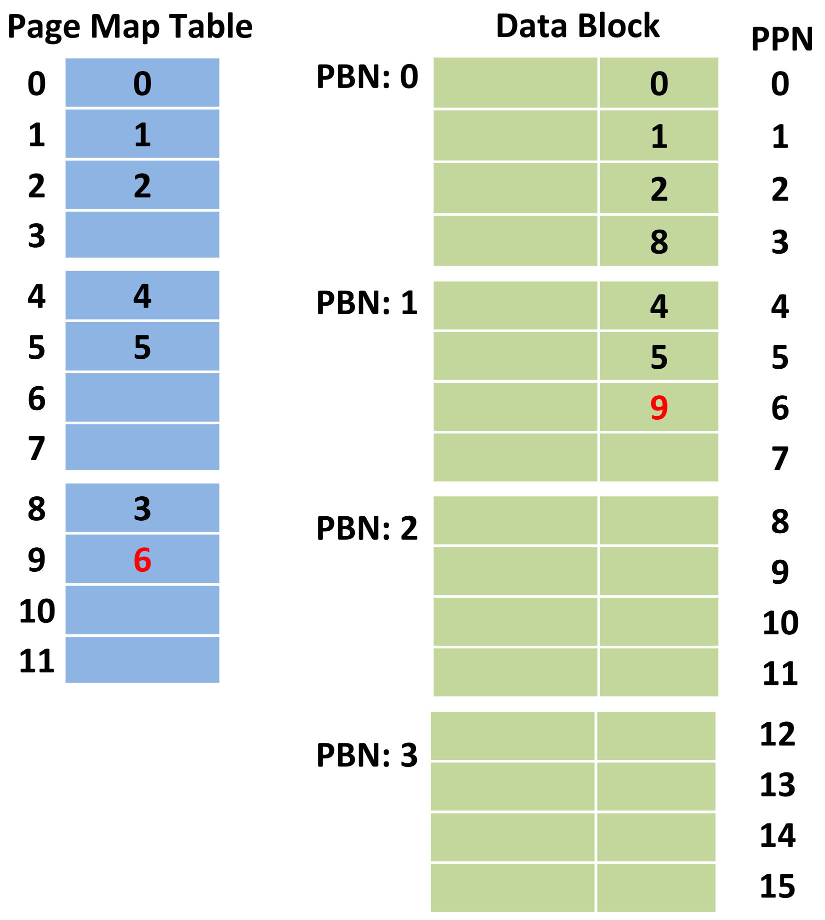

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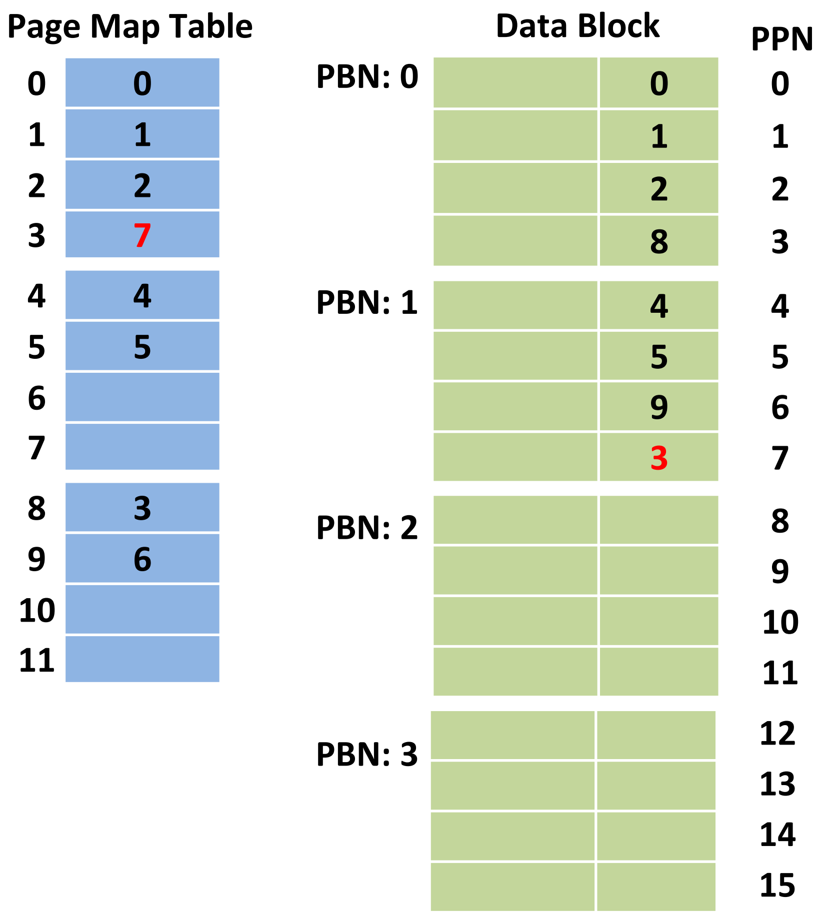

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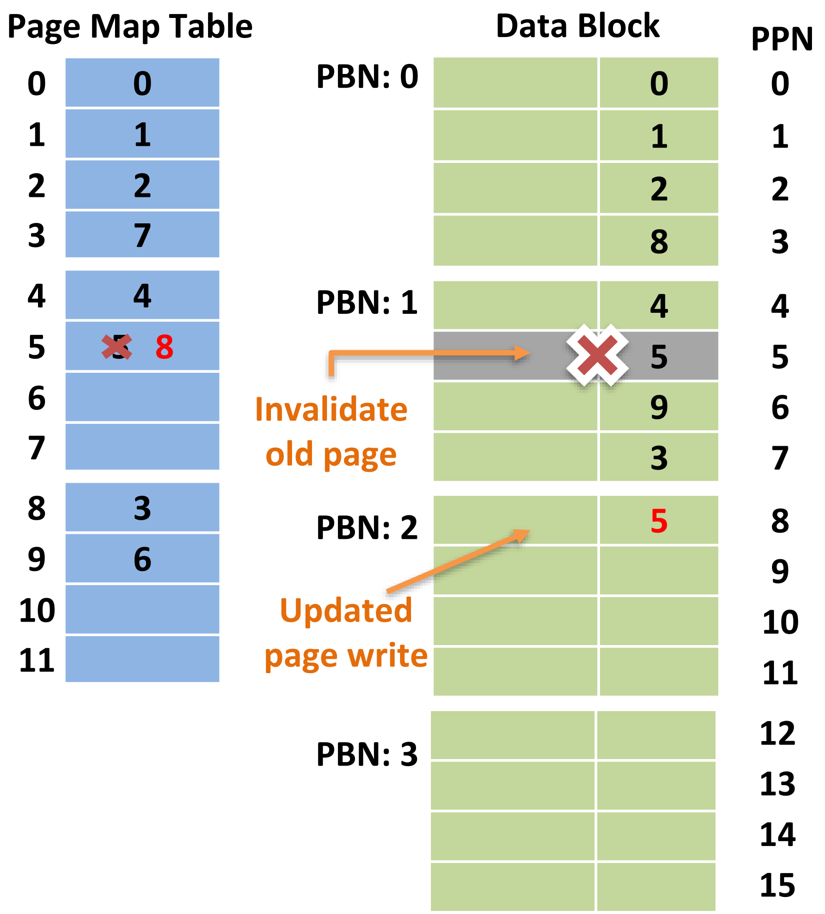
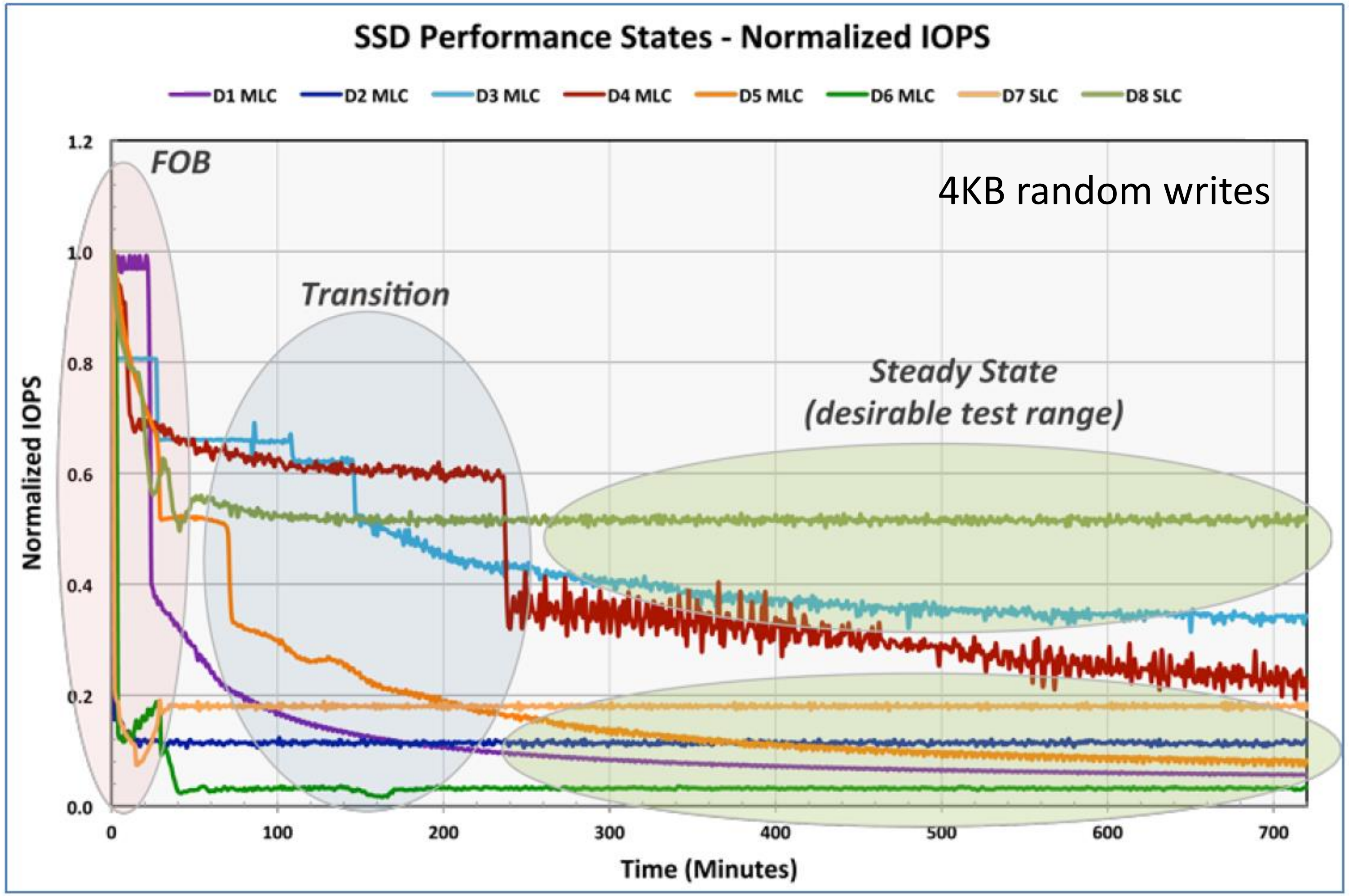


Page Mapping

- Pros
  - Most flexible
  - Efficient handling of small random writes
    - A logical page can be located anywhere within the flash storage
    - Updated page can be written to any free page
- Cons
  - Large memory footprint
    - One page mapping entry per page
    - 32MB for 32GB (4KB page)
  - Sensitive to the amount of reserved blocks
  - Performance affected as the system ages

Why?



http://tfindelkind.com/2015/08/20/

Garbage Collection

- Garbage collection (GC)
  - Eventually, FTL will run out of blocks to write to
  - GC must be performed to reclaim free space
  - Actual GC procedure depends on the mapping scheme

- GC in page-mapping FTL
  - Select victim block(s)
  - Copy all valid pages of victim block(s) to free block
  - Erase victim block(s)
  - Note: At least one free block should be reserved for GC

Example: GC in Page Mapping

- Current state
  - Written to page 0, 1, 2, 8, 4, 5
  - Written to page 9, 3, 5
- New requests (in order)
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  - Write to page 3
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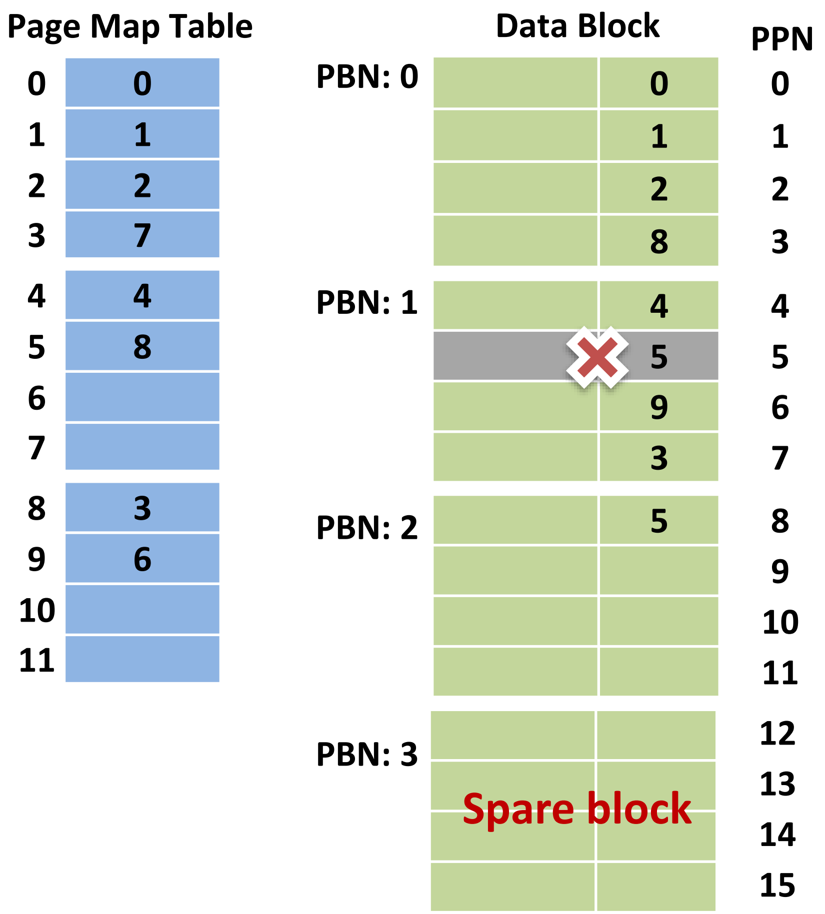
  - Write to page 4



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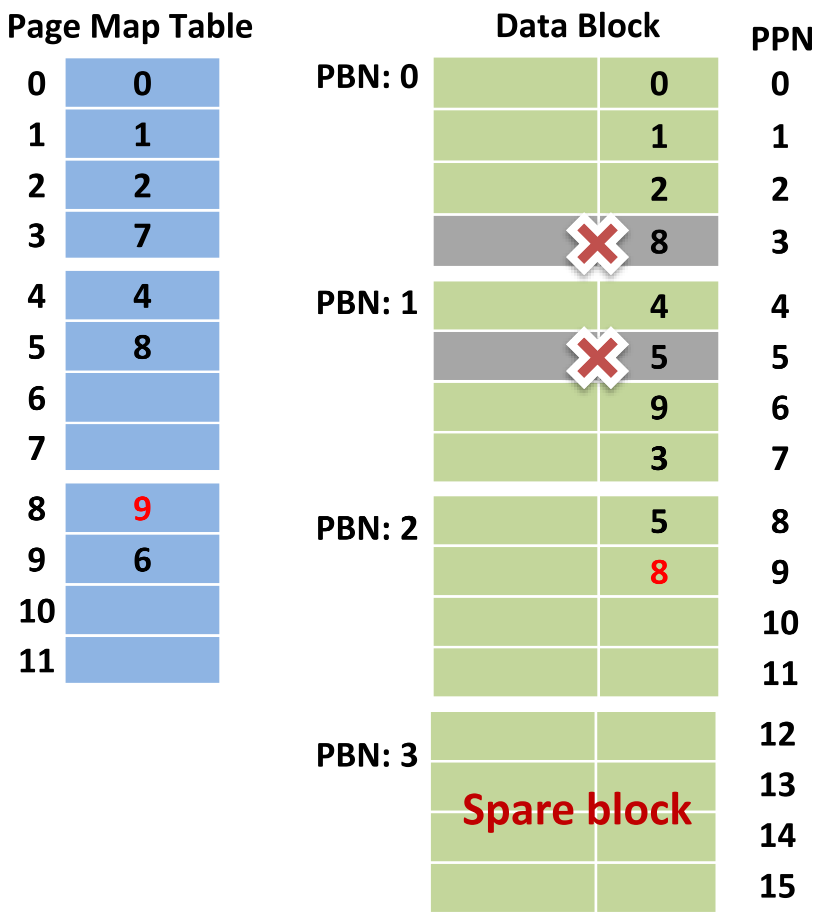

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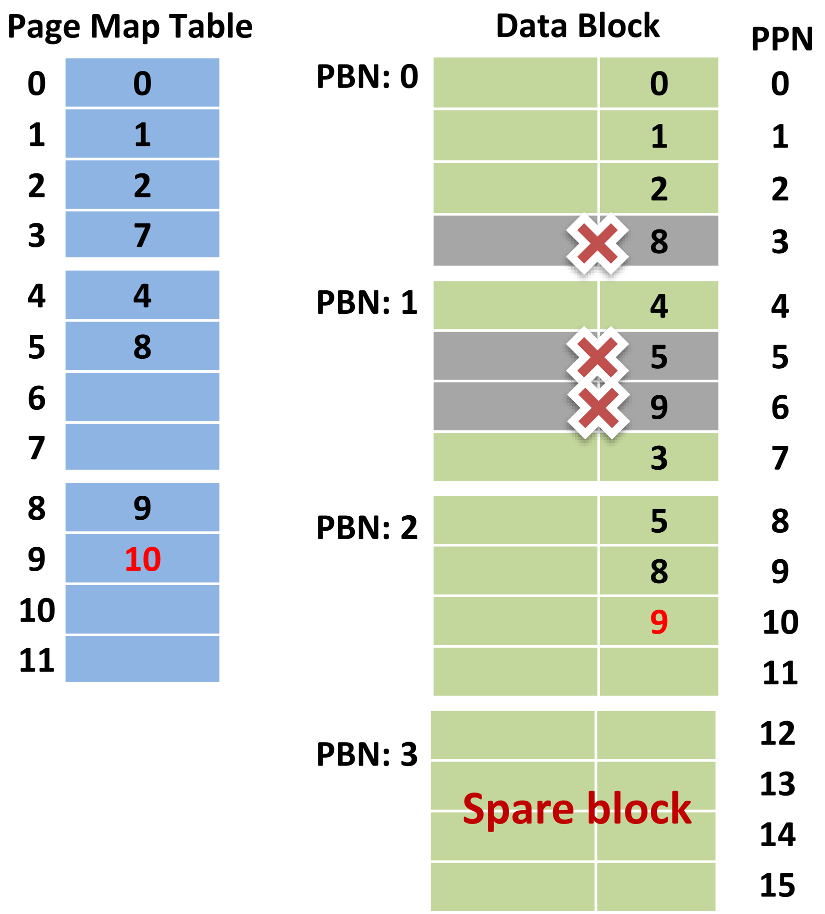

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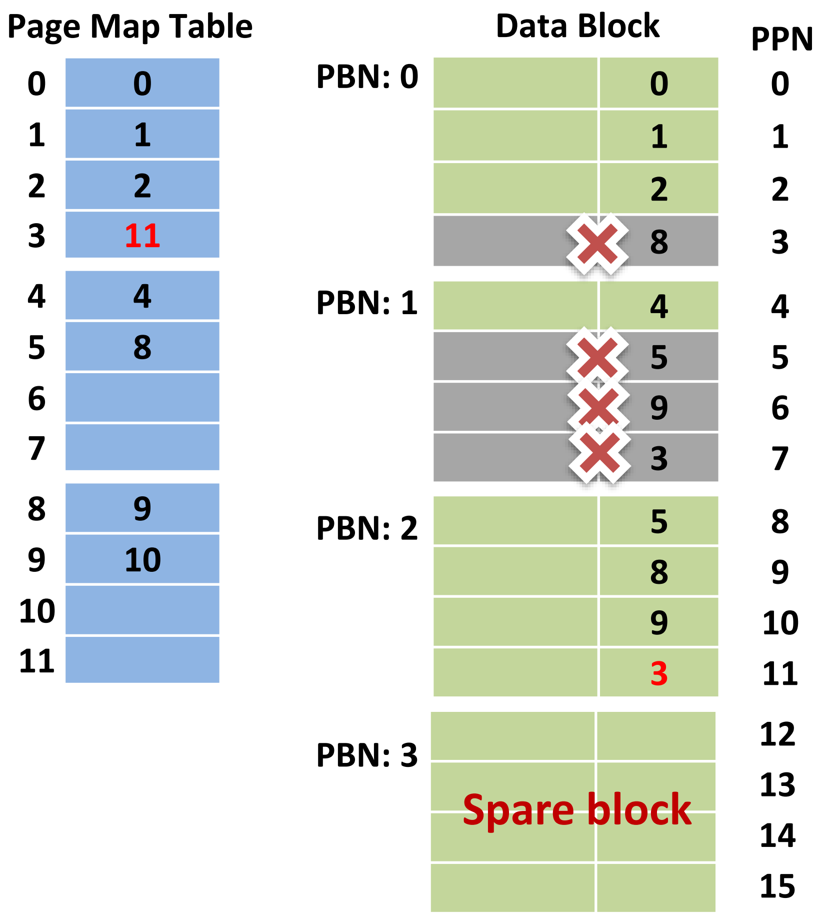

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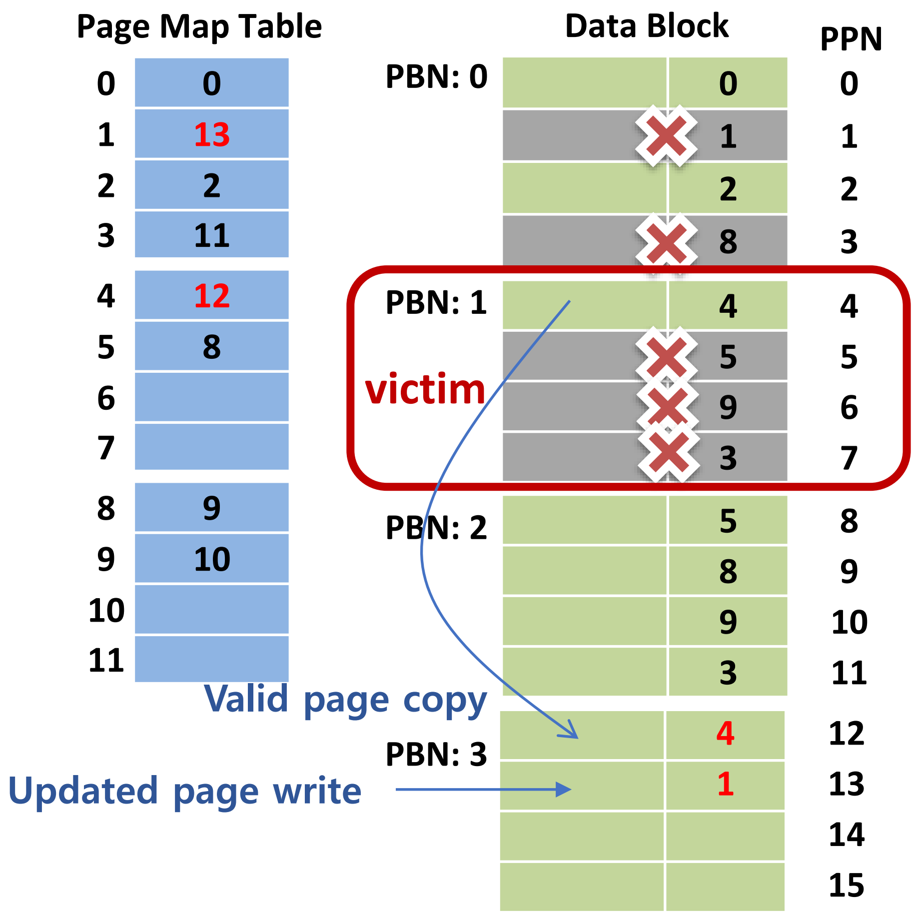

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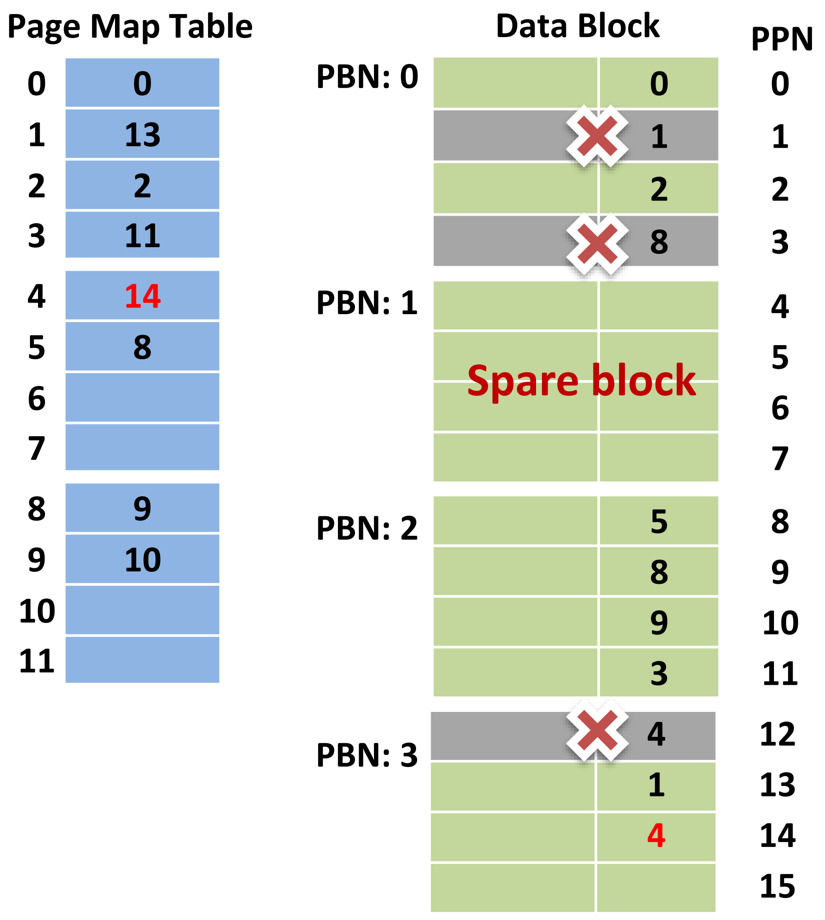


Write Amplification

- Ratio of data written to flash to data written from host

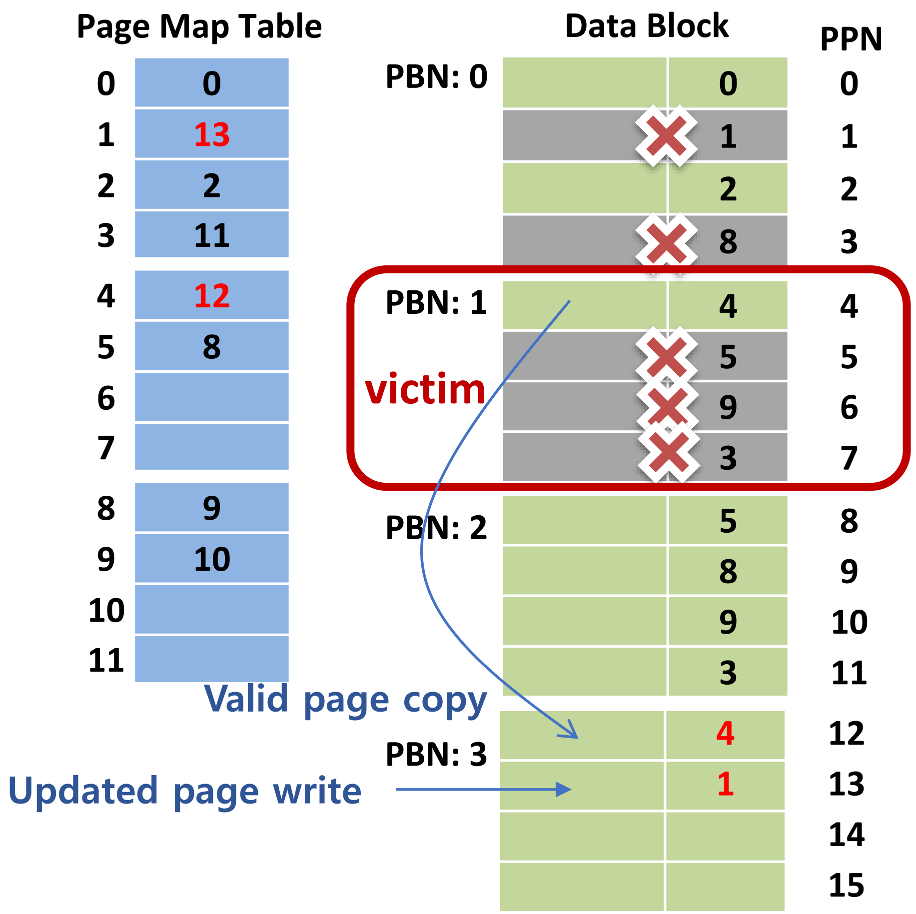
- Write Amplification Factor (WAF)

$$= \frac{Bytes\ written\ to\ Flash}{Bytes\ written\ from\ Host} = \frac{Bytes\ written\ from\ Host + Bytes\ written\ during\ GC}{Bytes\ writen\ from\ Host}$$

- Generally, WAF is greater than one in flash storage
  - Due to valid page copies made from victim block to free block during GC
  - WAF is one of metrics that shows the efficiency of GC

Example: Write Amplification

- Current state
  - Written to page 0, 1, 2, 8, 4, 5
  - Written to page 9, 3, 5
- New requests (in order)
  - Write to page 8, 9, 3, 1
- WAF = 1.08
  - Total host writes: 13
  - Total flash writes: 14



Victim Selection Policy: Greedy

- Selects a block with the largest amount of invalid data
- A block with the ___________ utilization *u*

$$u = \frac{Number\ of\ valid\ pages\ in\ a\ block}{Number\ of\ Pages\ in\ a\ block}$$

- ***Pros?***

- ***Cons?***

Victim Selection Policy: Cost-Benefit

- Selects a block with the ___________

$$\frac{Benefit}{Cost} = \frac{(1-u)}{2u} \times age$$

  - u: utilization
  - age: the time since the last modification

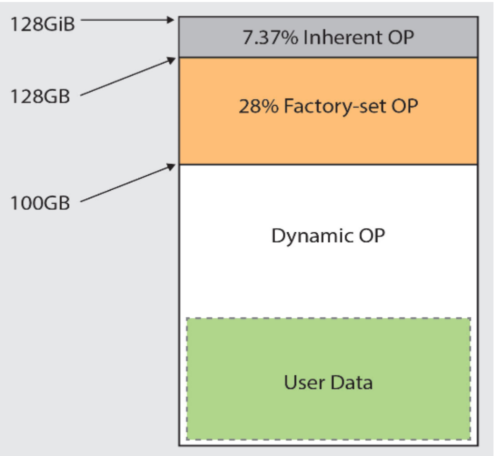
- ***Pros?***

- ***Cons?***

Over-Provisioning

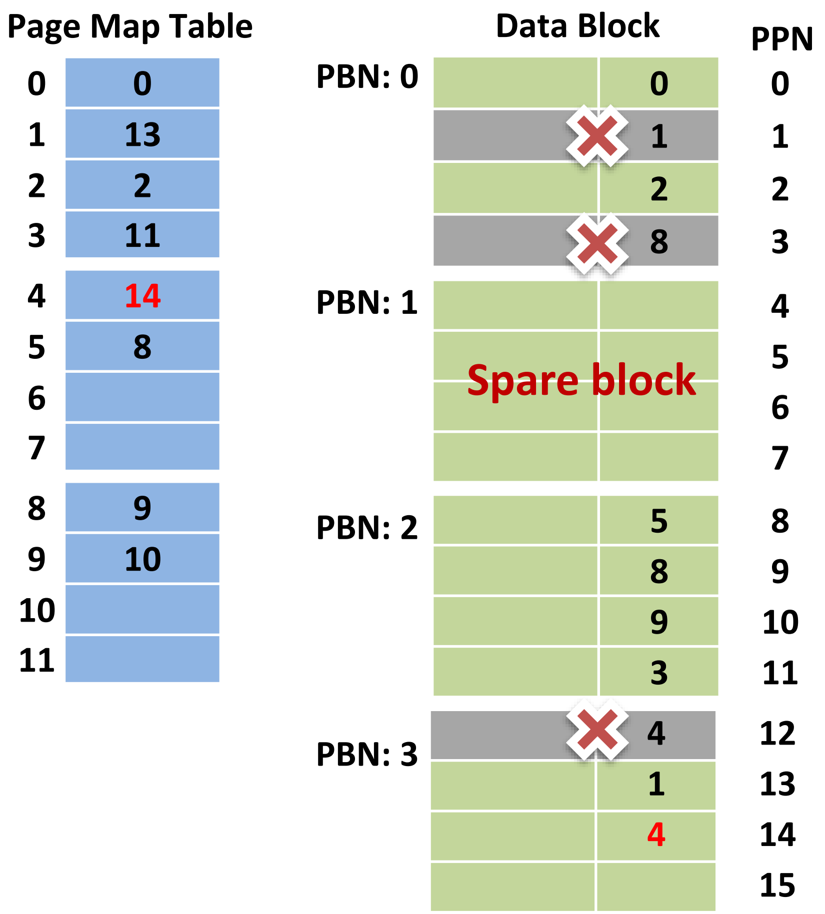
- OP (Over-Provisioning) = $\frac{Physical\ Capacity}{Logical\ Capacity} - 1$
  - Extra media space on an SSD that does not contain user data

- Typical SSDs have more space than is advertised
  - Consumer SSDs: ~ 7%
    - 1 Gigabyte (GB) = 10^9 bytes = 1,000,000,000 bytes
    - 1 Gibibyte (GiB) = 2^{30} bytes = 1,073,741,824 bytes
  - Enterprise SSDs: > 25%
    - 100GB user space on 128GiB SSD: 37.4%



Example: Over-Provisioning

- OP = 33%
  - Logical capacity: 3 blocks
  - Physical capacity: 4 blocks



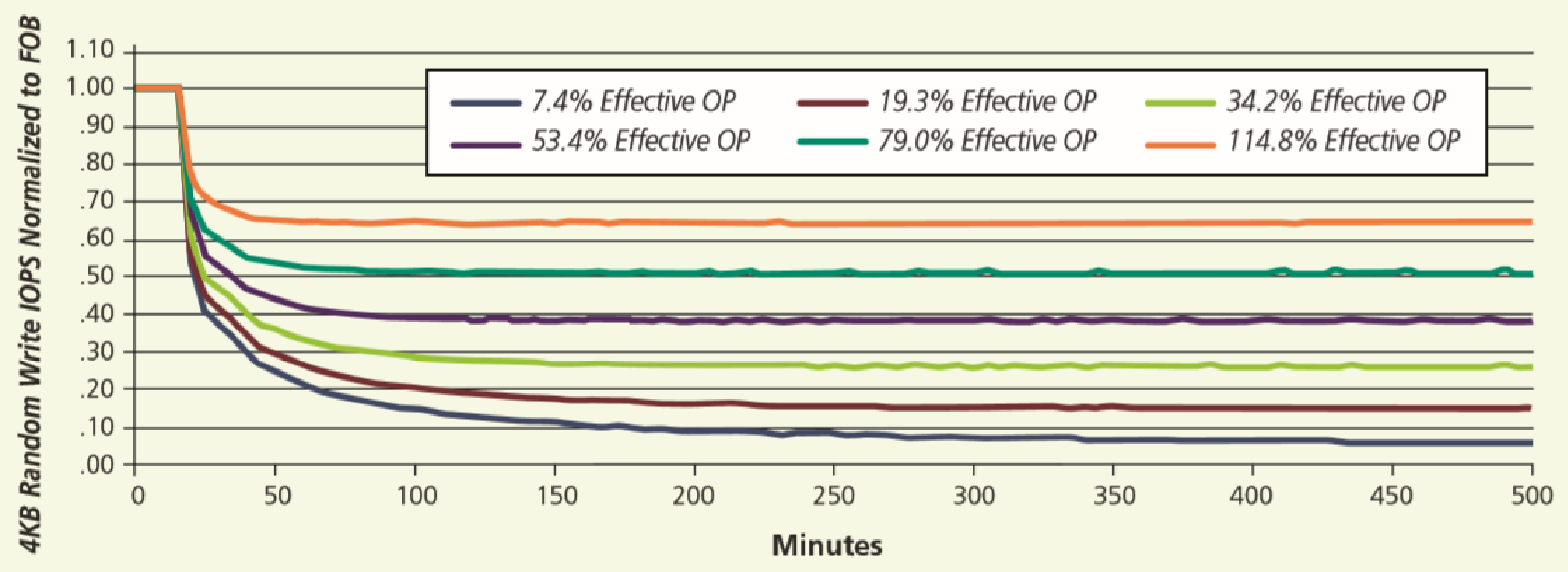
Why Over-Provisioning?

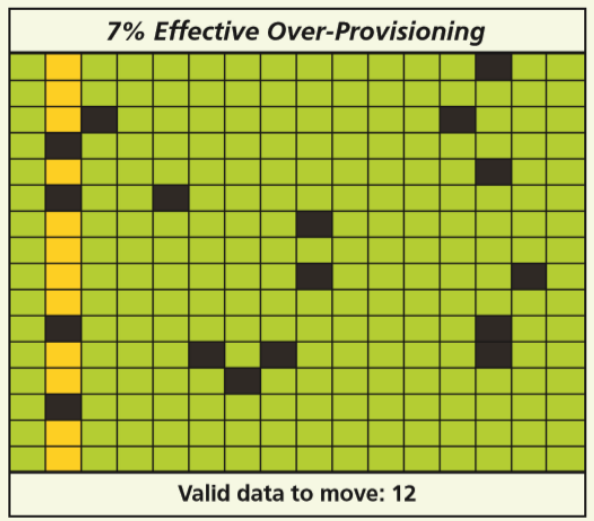
- Over-Provisioning Space (OPS) is used for
  - Write buffers
  - ______________
  - ______________
  - ______________

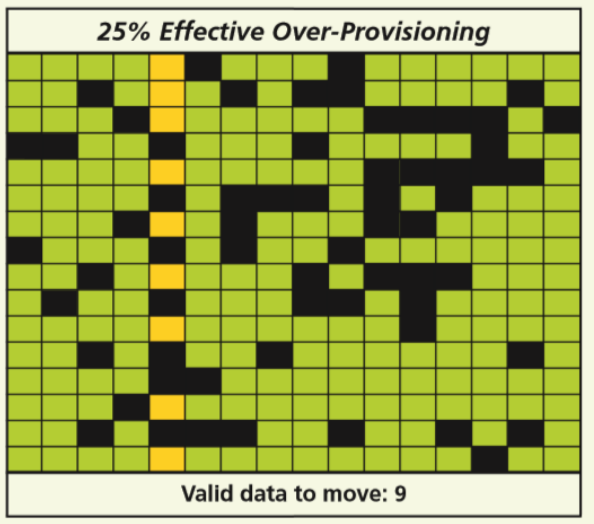
- Garbage collection cost
  - Affected by utilization of SSD space and Over-Provisioning
  - _______ utilization → Better performance
  - _______ OP → Better performance

Over-Provisioning and GC

- IOPS for random write workloads
  - What about for sequential write workloads?







D. Glen, Differences in Personal vs. Enterprise SSD Performance, Micron Technology, Inc.