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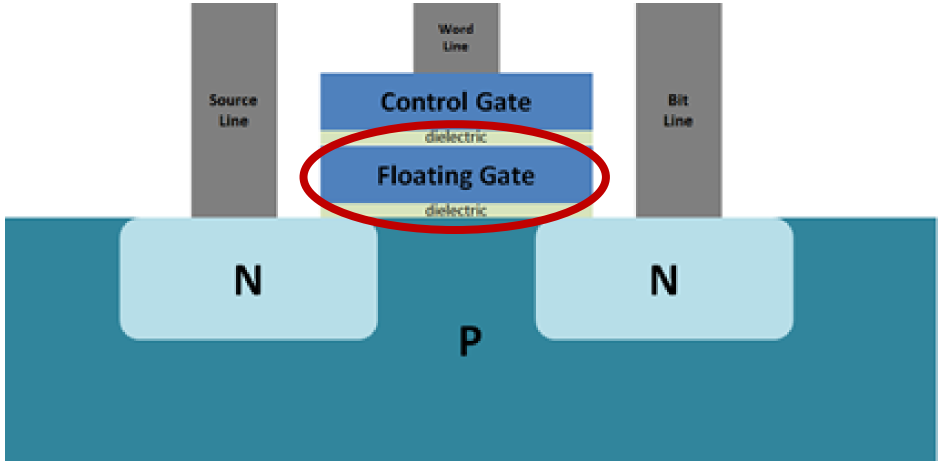
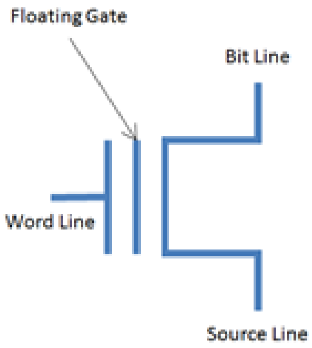
Solid State Drives (SSDs)

Flash Memory Cell

- Transistor with floating gate
  - The floating gate is insulated all around with an oxide layer
  - Electrons trapped in the floating gate can remain for up to years

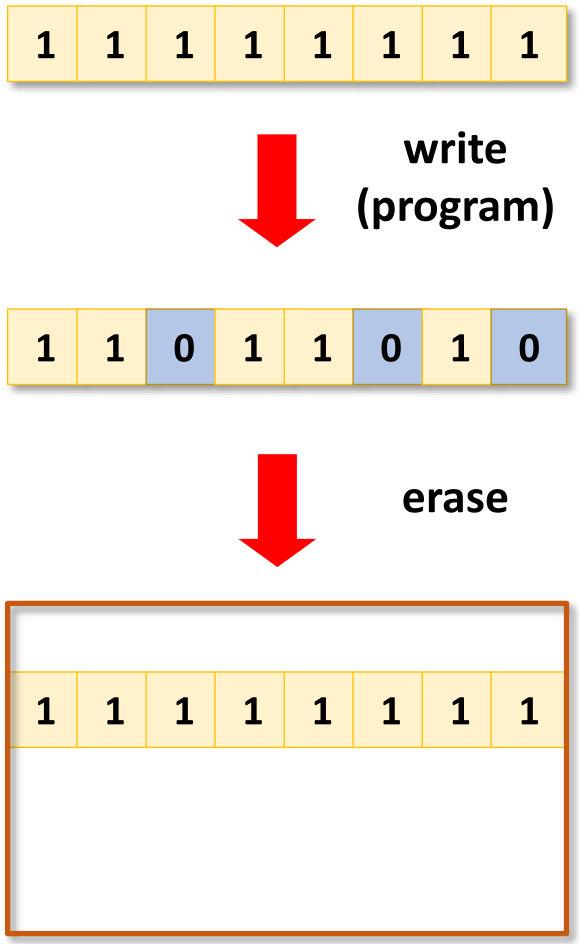




http://www.thenandflash.com

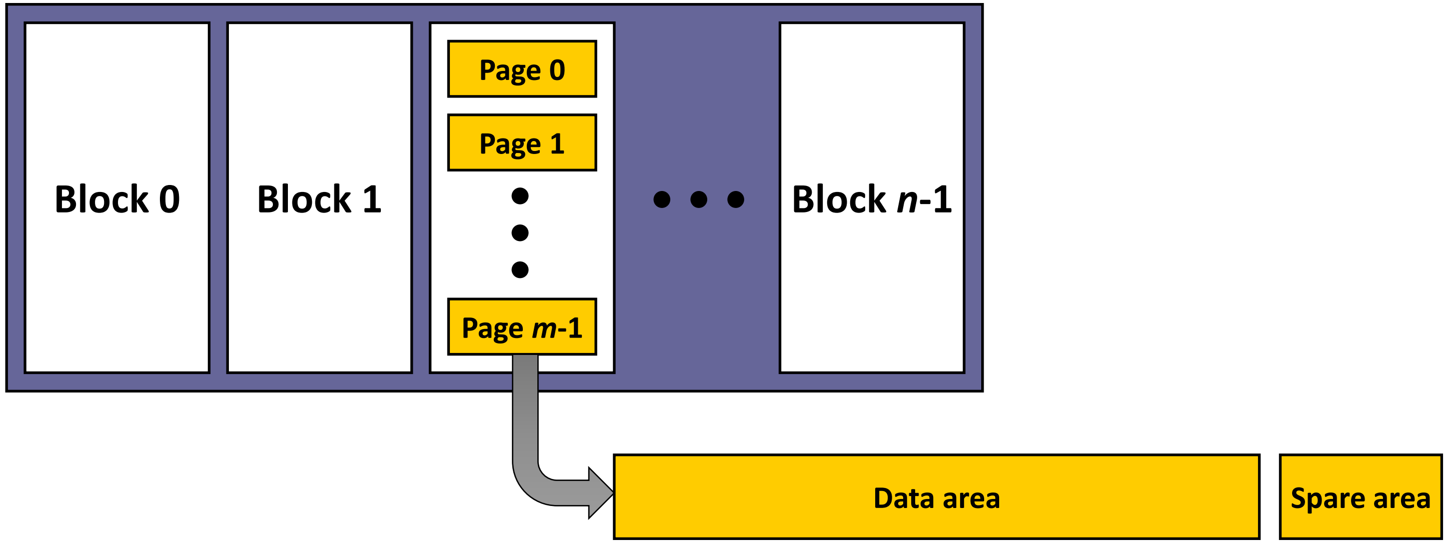
Flash Memory Characteristics

- **Erase-before-write**
  - Read
  - Write or Program: 1 → 0
  - Erase: 0 → 1
- **Bulk erase**
  - Program unit:
    - NOR: byte or word
    - NAND: page
  - Erase unit: ____________



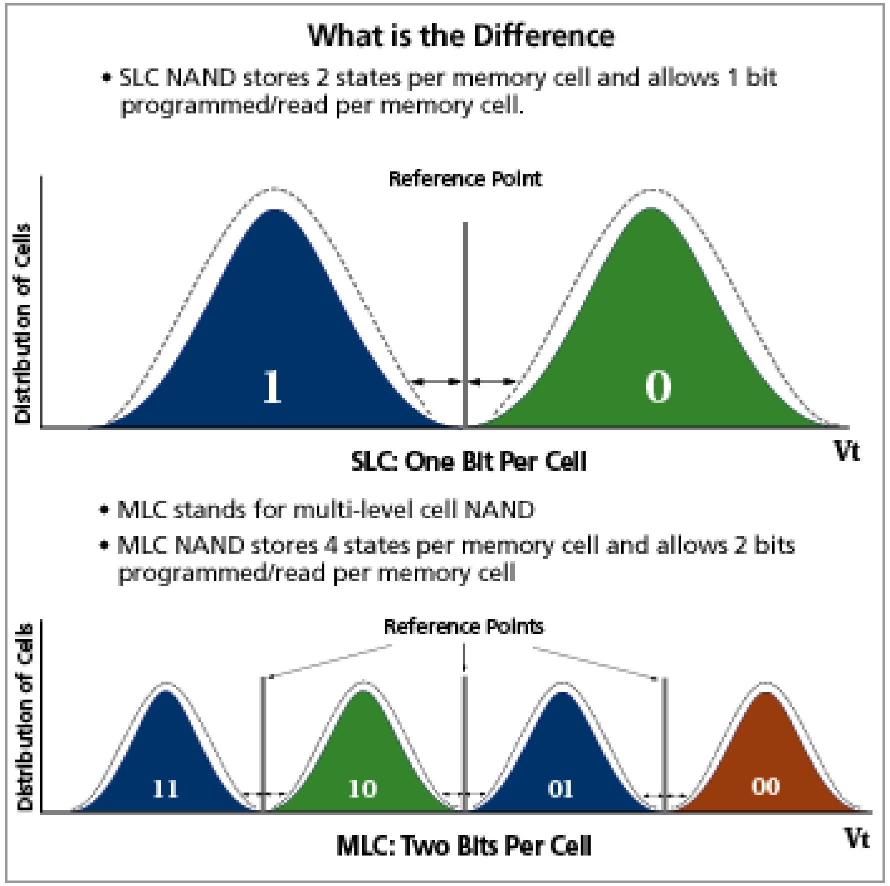
Logical View of NAND Flash

- 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)



NAND Flash Types

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



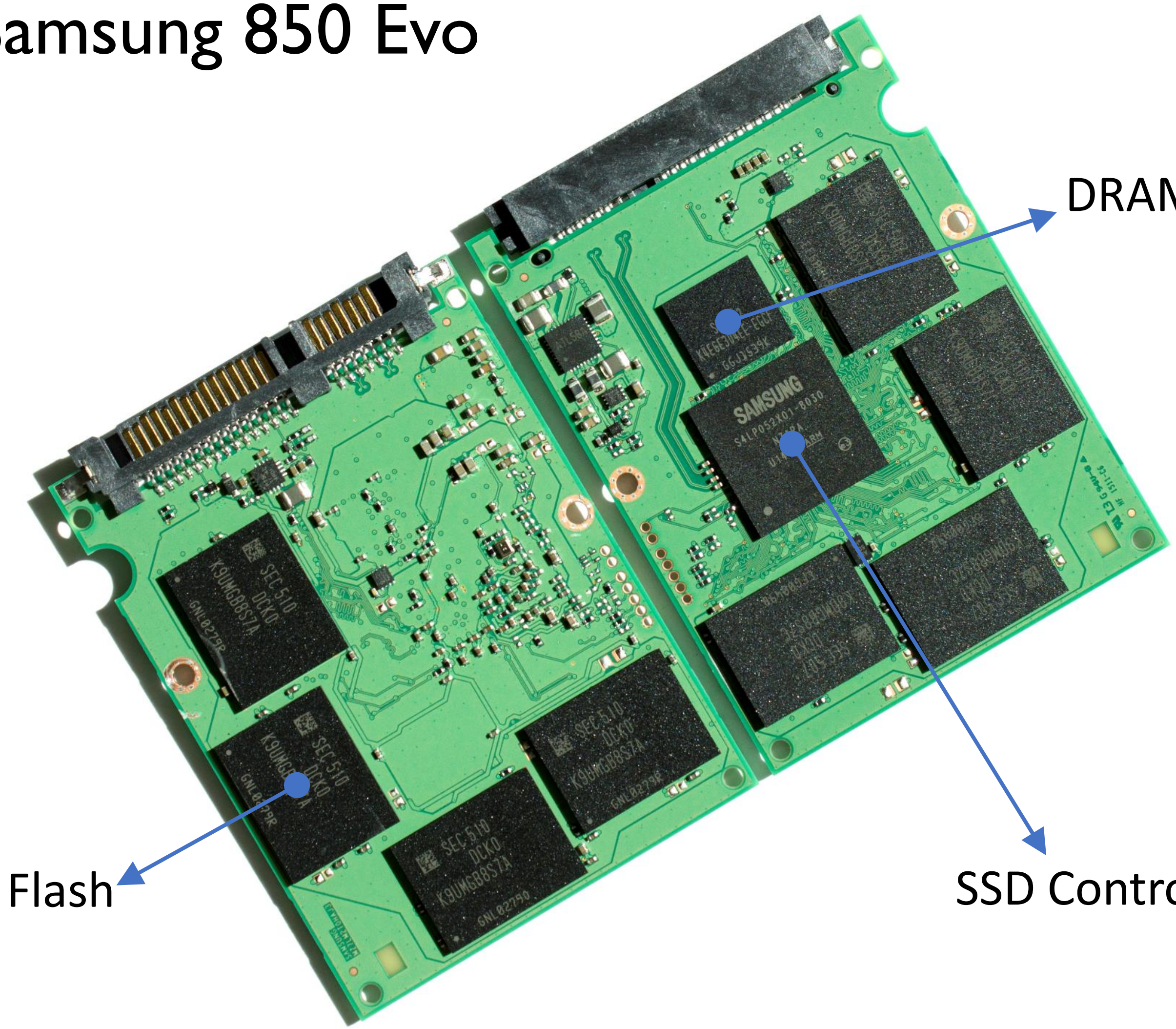
Source: Micron Technology, Inc.

NAND Applications

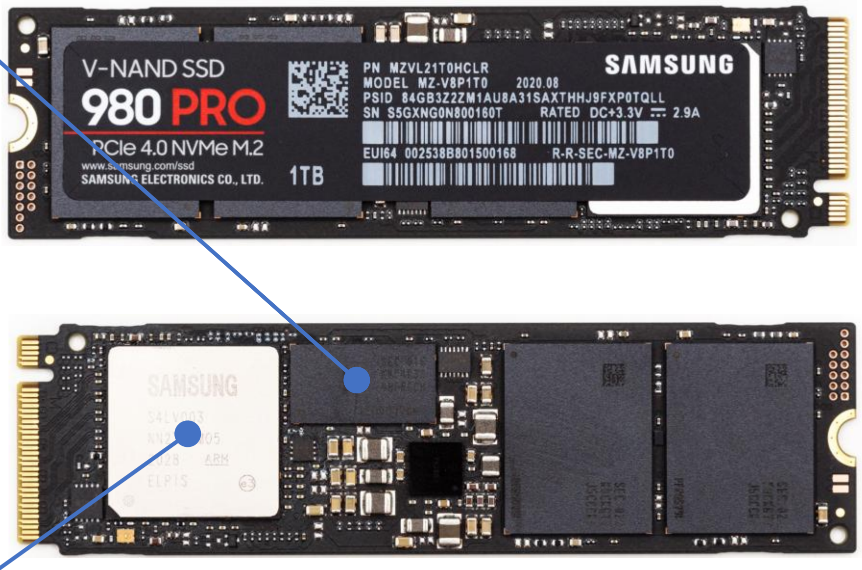
- Universal Flash Drives (UFDs)
- Flash cards
  - CompactFlash, MMC, SD, Memory stick, …
- Smartphones
  - eMMC (Embedded MMC)
  - UFS (Universal Flash Storage)
- SSDs (Solid State Drives)
- Other embedded devices
  - MP3 players, Digital TVs, Set-top boxes, Car navigators, …

Anatomy of an SSD

- Samsung 850 Evo

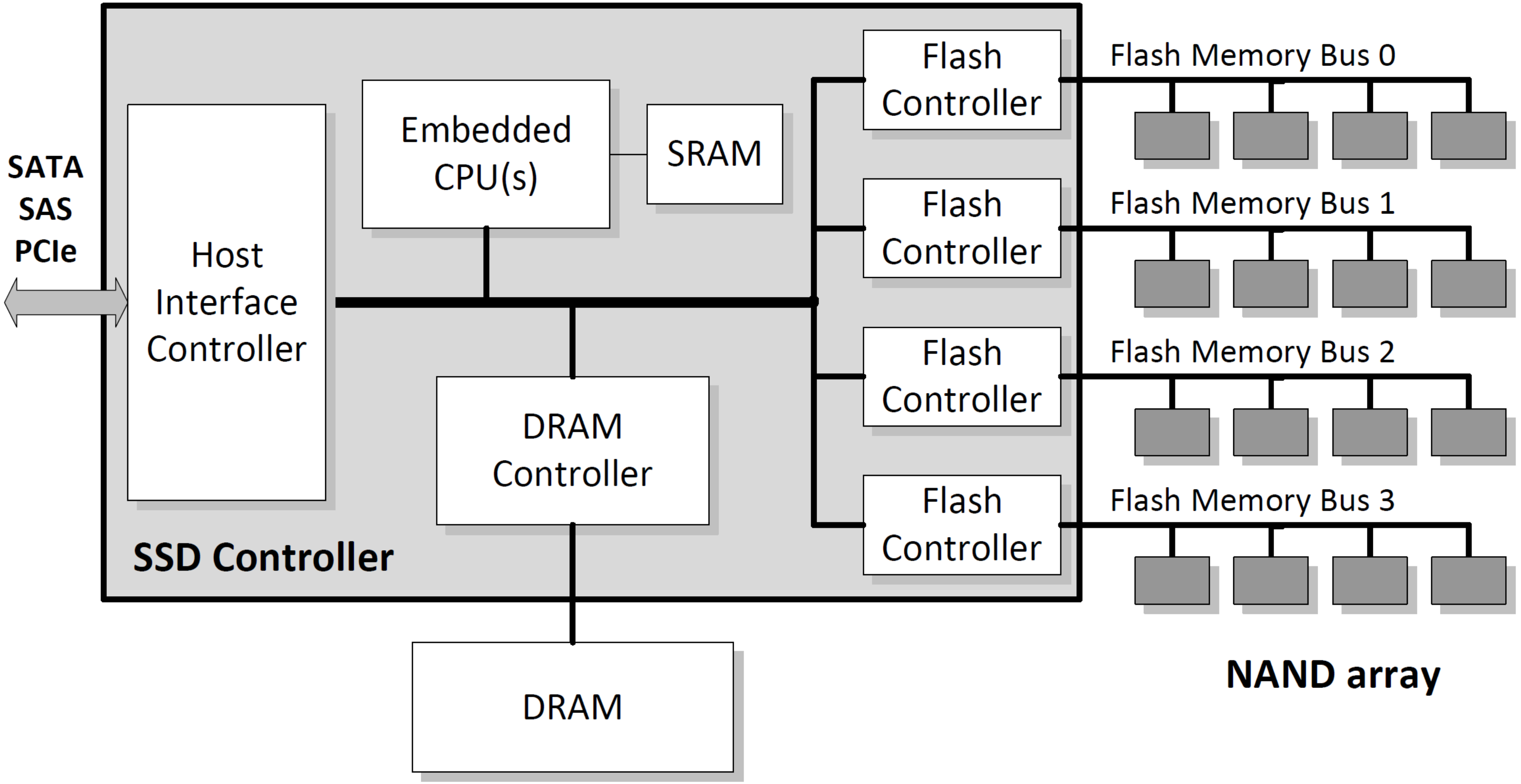


- Samsung 980 Pro



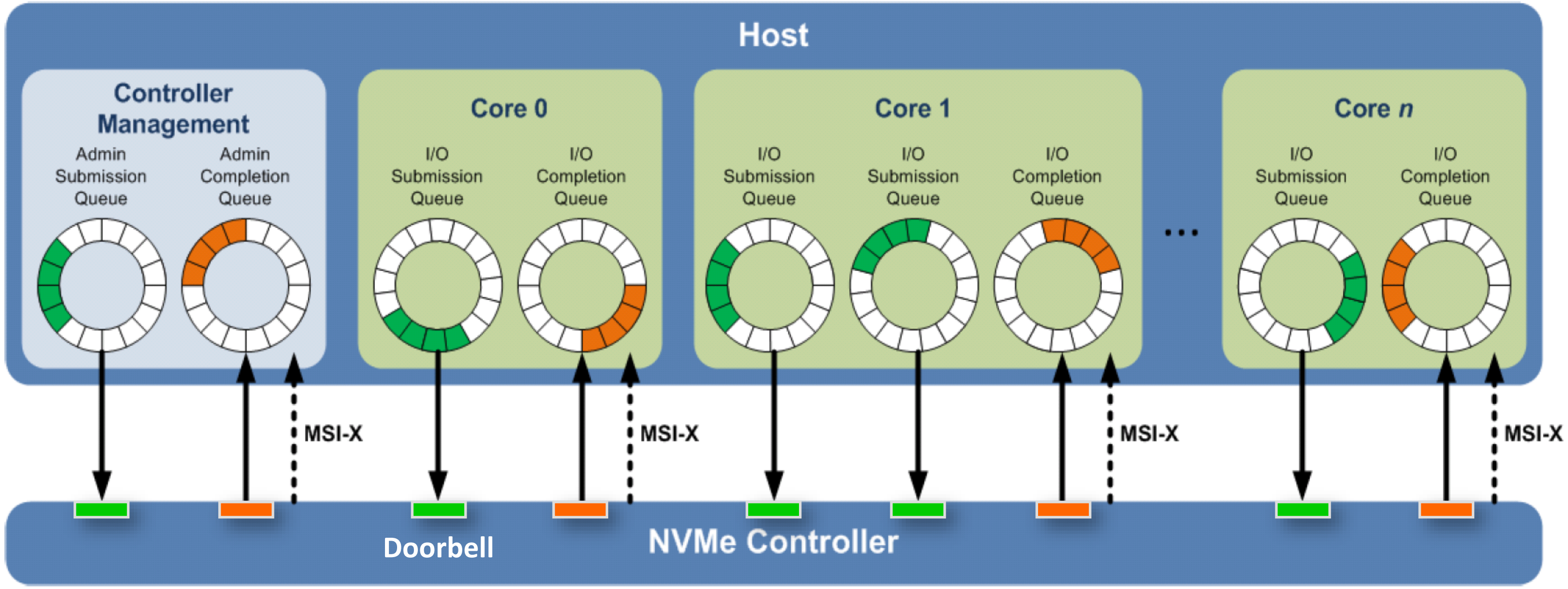
http://www.anandtech.com/show/9451/the-2tb-samsung-850-pro-evo-ssd-review
https://www.tomshardware.com/reviews/samsung-980-pro-m-2-nvme-ssd-review

SSD Internals



NVMe SSD

- PCIe-based (PCIe Gen. 3: 1GB/s per lane, up to 32 lanes)
- Deep queue: 64K commands per queue, up to 64K queues
- Streamlined command set: only 13 required commands
- One register write to issue a command (“doorbell”)



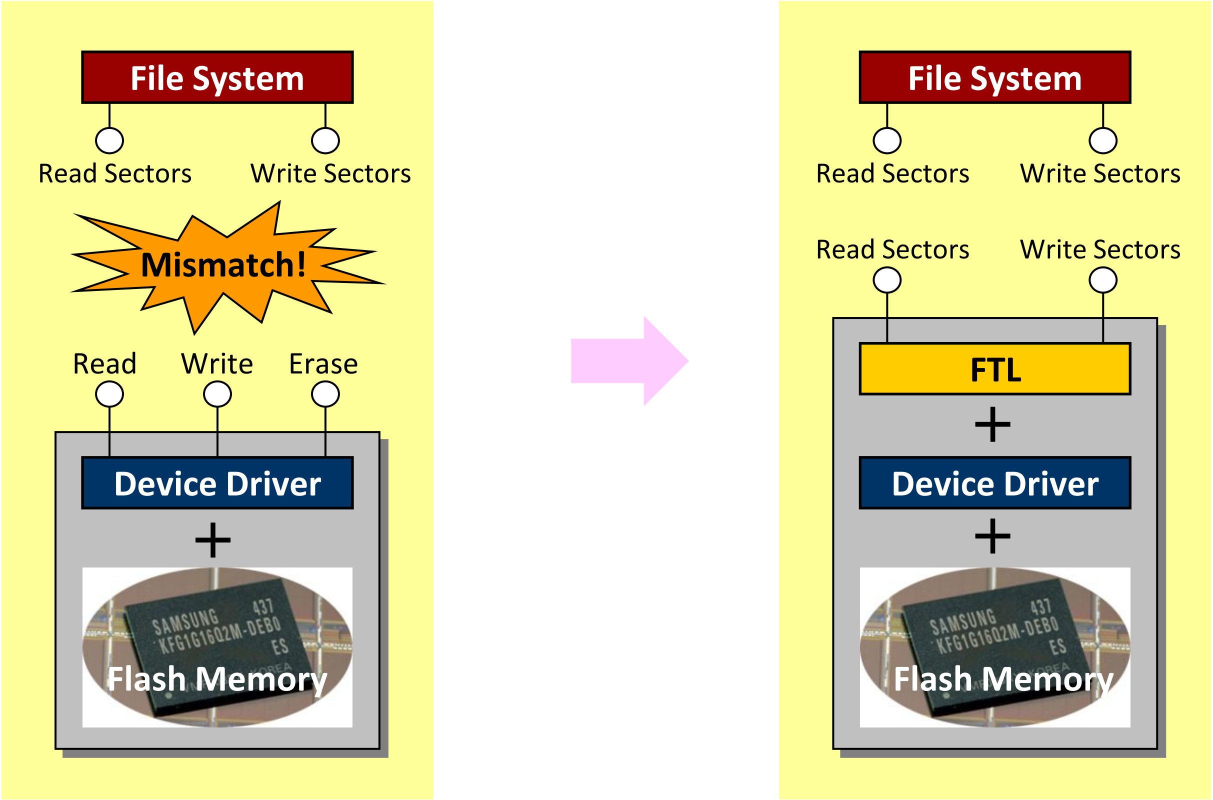
HDDs vs. SSDs

Feature	SSD (Samsung)	HDD (Seagate)
Model	MZ-V8P2T0 (980 Pro)	ST2000LM003 (SpinPoint M9T)
Capacity	2TB (512Gb 128-Layer 3D V-NAND TLC x 16 dies/chip x 2 chips)	2TB (3 Discs, 6 Heads, 5400 RPM)
Form factor	M.2 (2280), 55g	2.5”, 130g
DRAM	2 GB	32 MB
Host interface	NVMe (PCIe 4.0 x 4, 8GB/s)	SATA-3 (600 MB/s)
Power consumption (Active / Idle / Sleep)	6.1 W/ 0.035 W / 0.005 W	2.3 W / 0.7 W / 0.18 W
Performance	Sequential read: 7000 MB/s Sequential write: 5100 MB/s Random read: 1,000K IOPS (QD32) Random write: 1,000K IOPS (QD32) Random read: 22,000 IOPS (QD1) Random write: 60,000 IOPS (QD1)	Sequential read: 124 MB/s Sequential write: 124 MB/s Random read: 56 IOPS Random write: 98 IOPS Power-on to ready: 3.5 sec Average seek: 12/14 ms Average latency: 5.6 ms
Price[1]	243,050 won (123won/GB)	66,000 won (33won/GB)

[1] http://www.danawa.com (As of Nov. 29, 2023)

Flash Translation Layer (FTL)

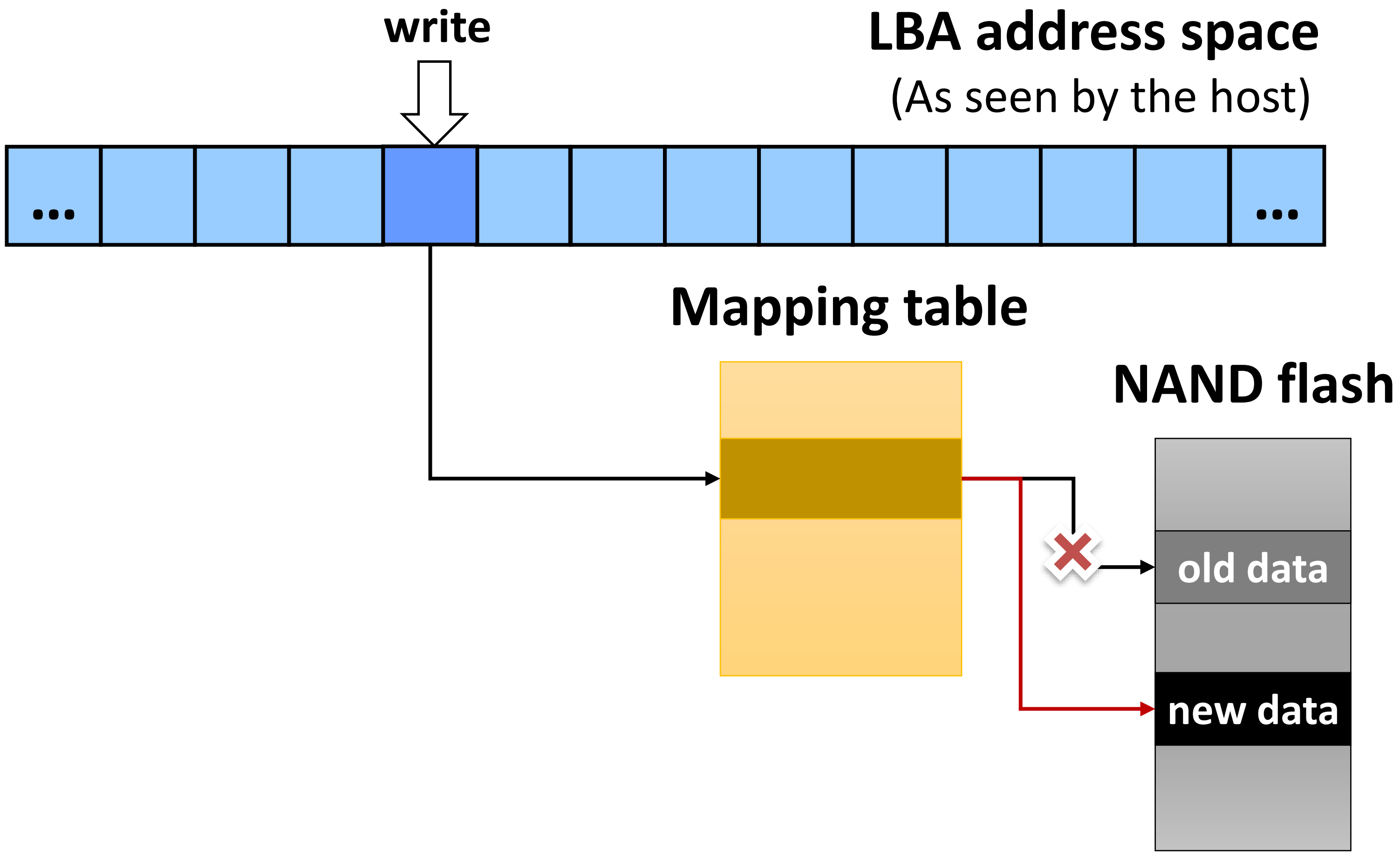
- A software layer to make NAND flash fully emulate traditional block devices (e.g., disks)



Source: Zeen Info. Tech.

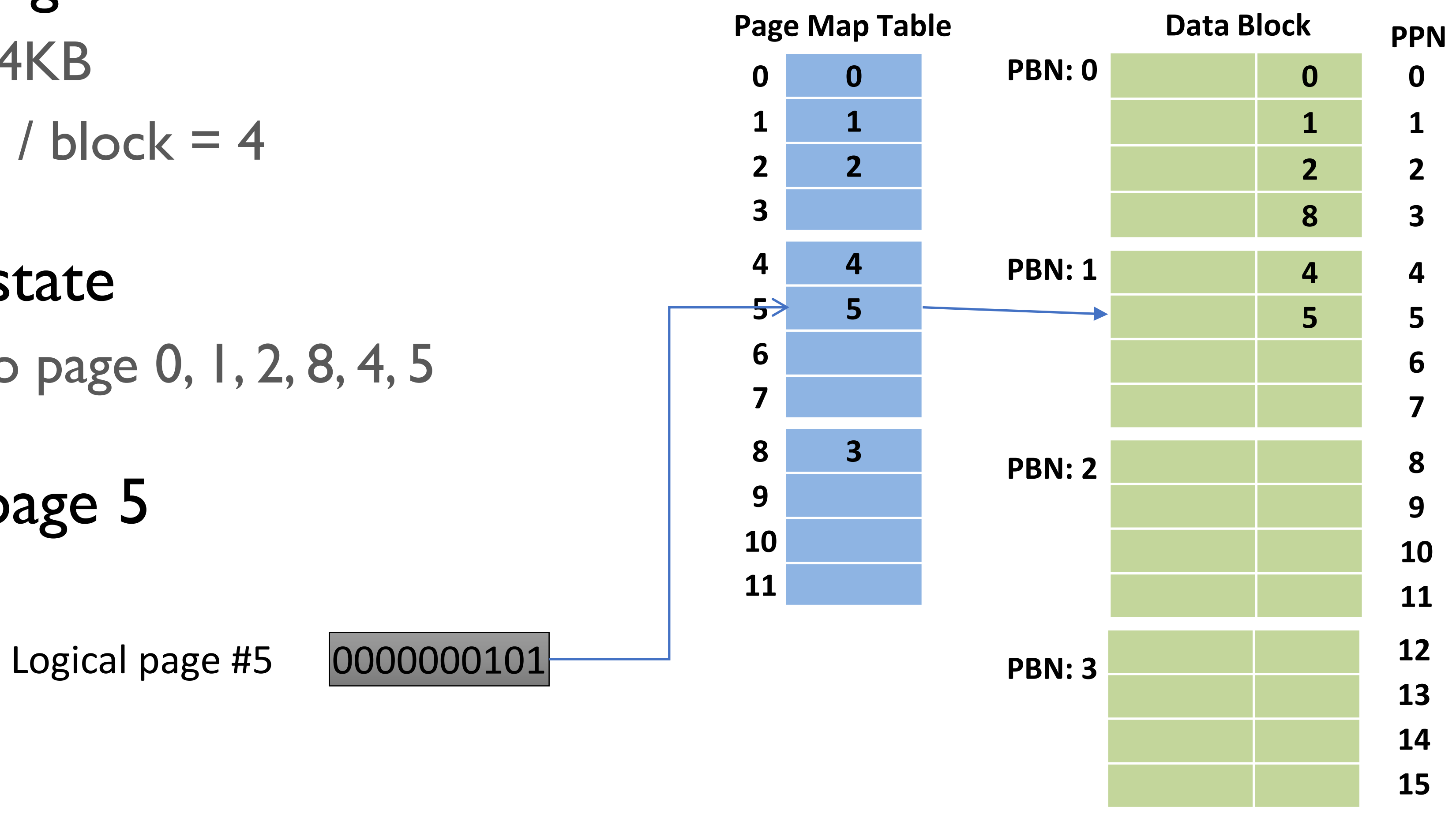
Address Mapping

- Required since flash pages cannot be overwritten



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 5



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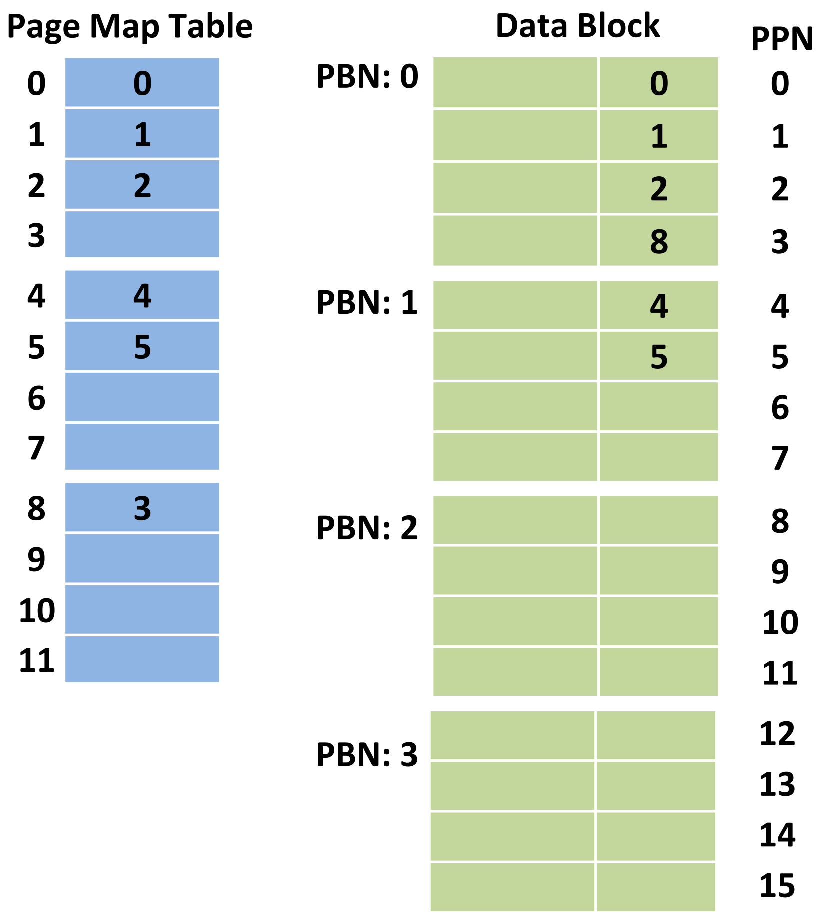
- Flash configuration
  - Page size: 4KB
  - # of pages / block = 4
- Current state
  - Written to page 0, 1, 2, 8, 4, 5
- New requests (in order)
  - Write to page 9
  - Write to page 3
  - Write to page 5



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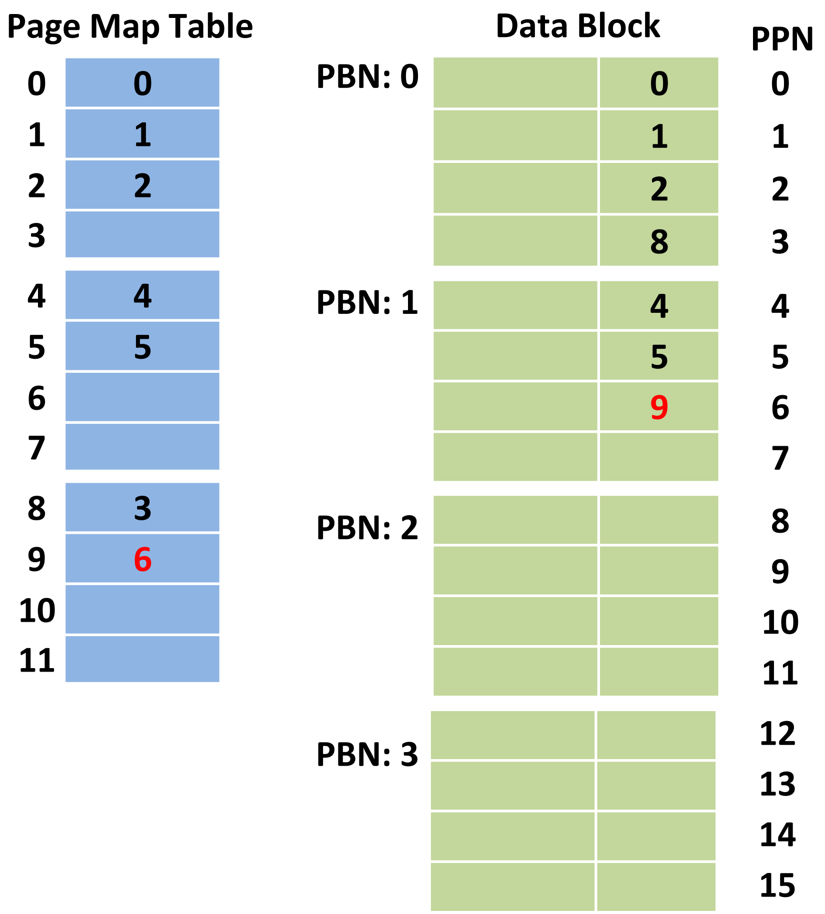

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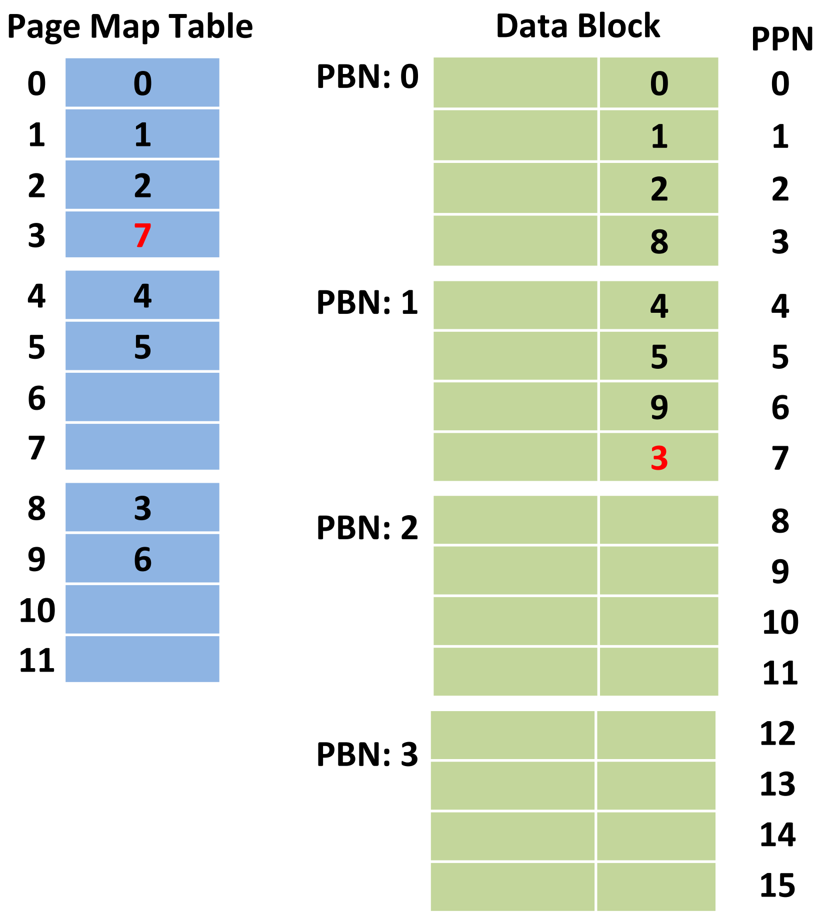

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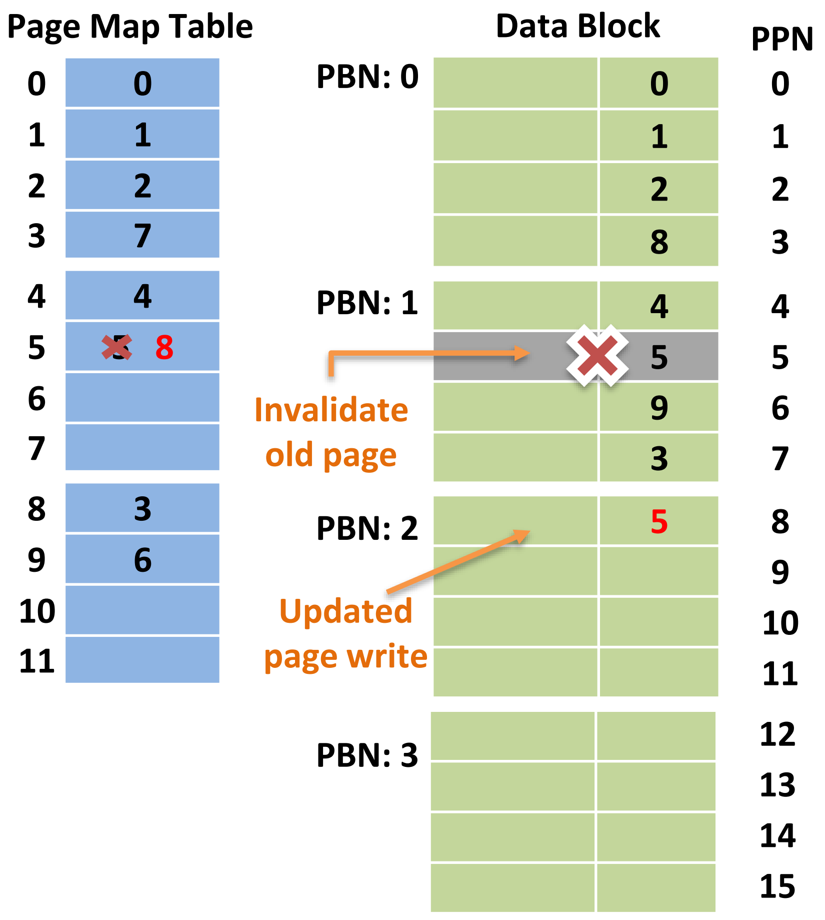

Garbage Collection

- 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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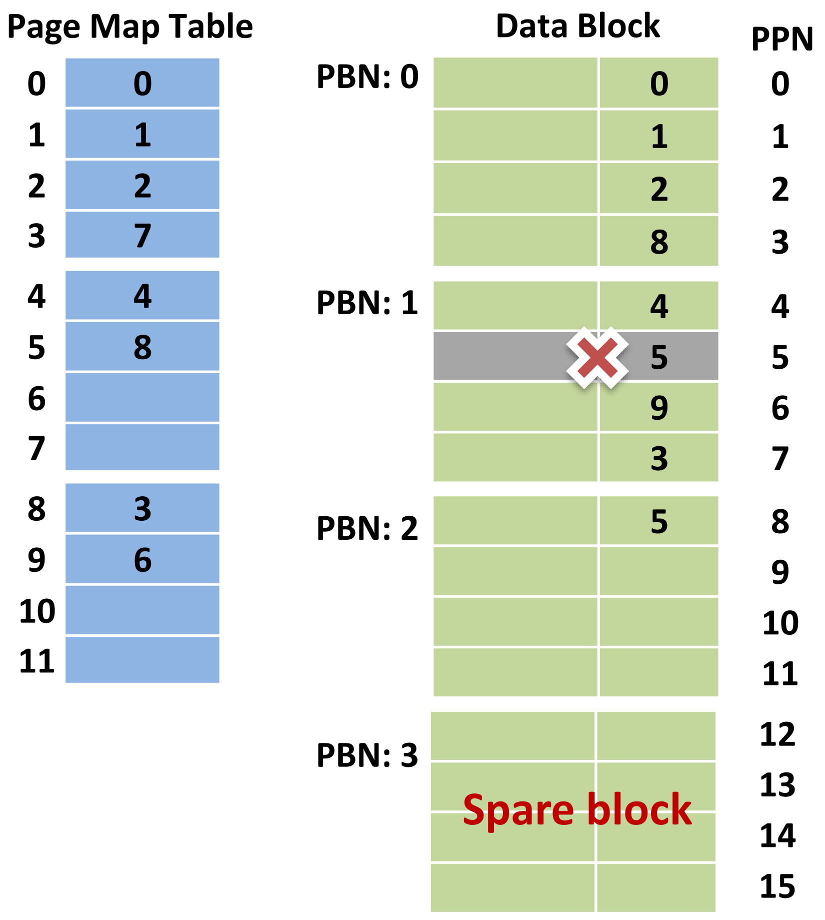

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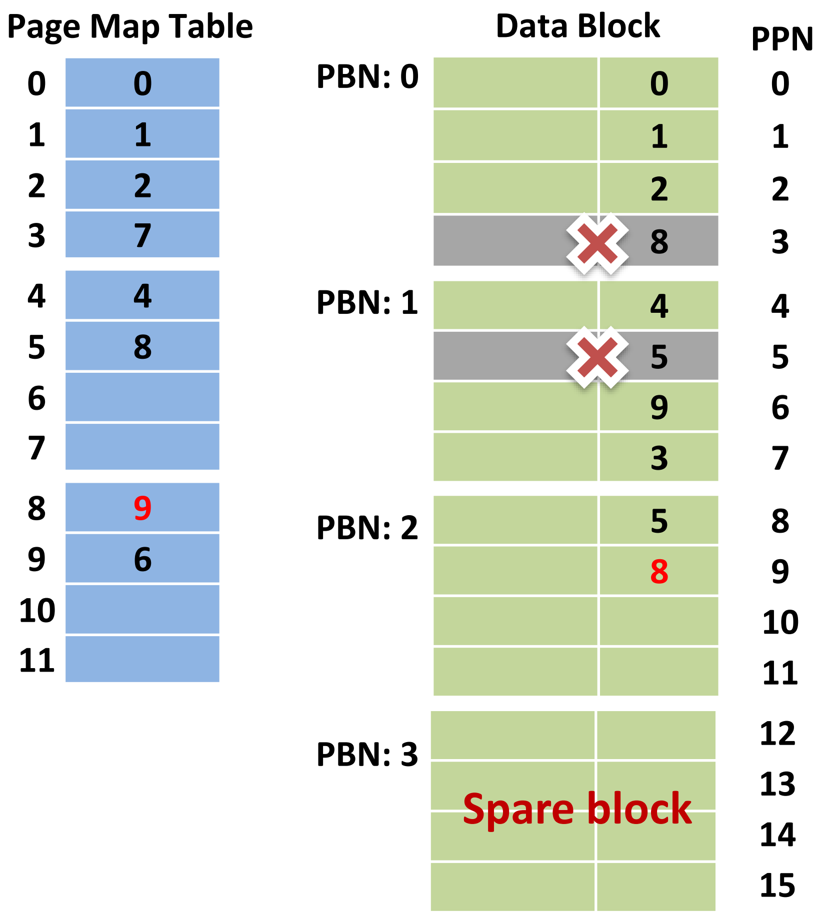

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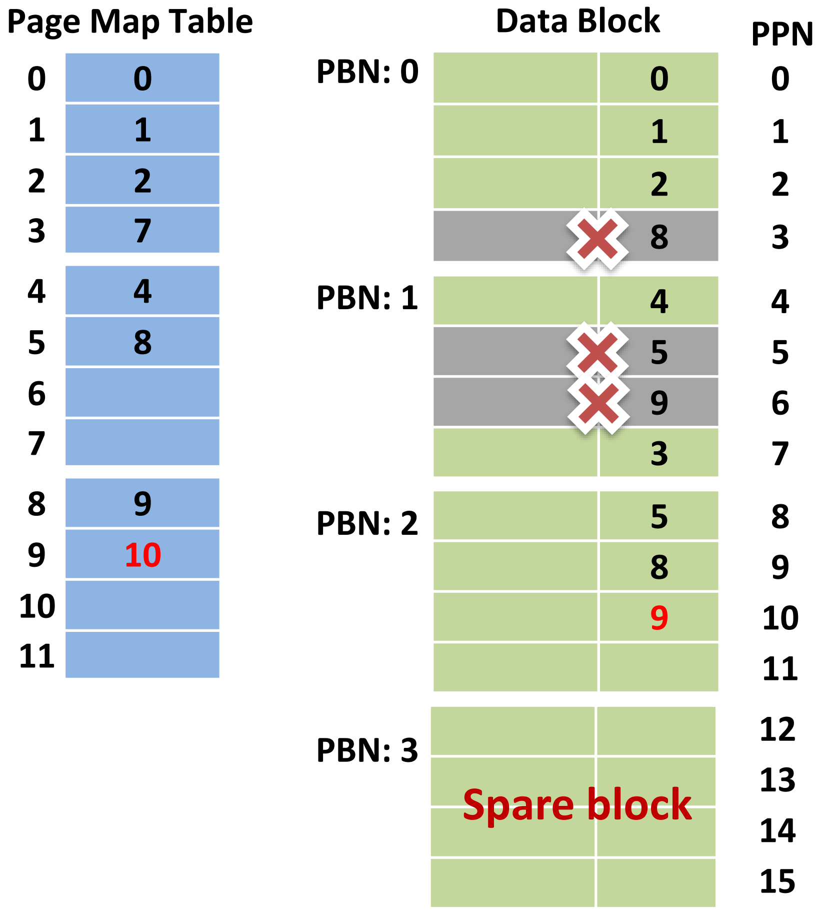

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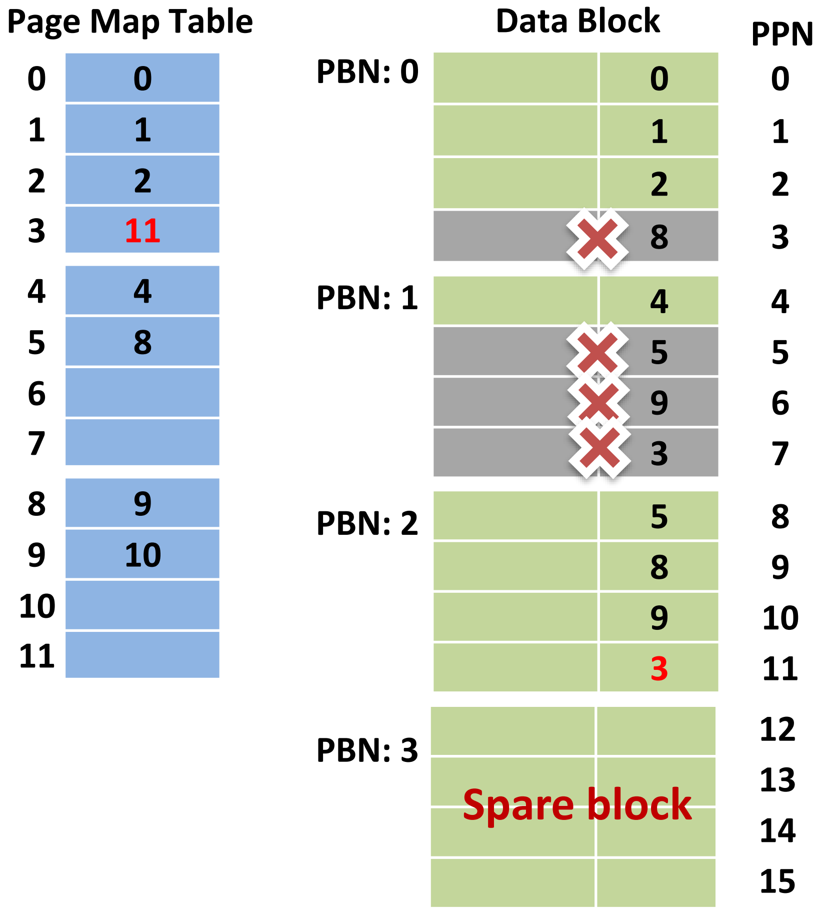

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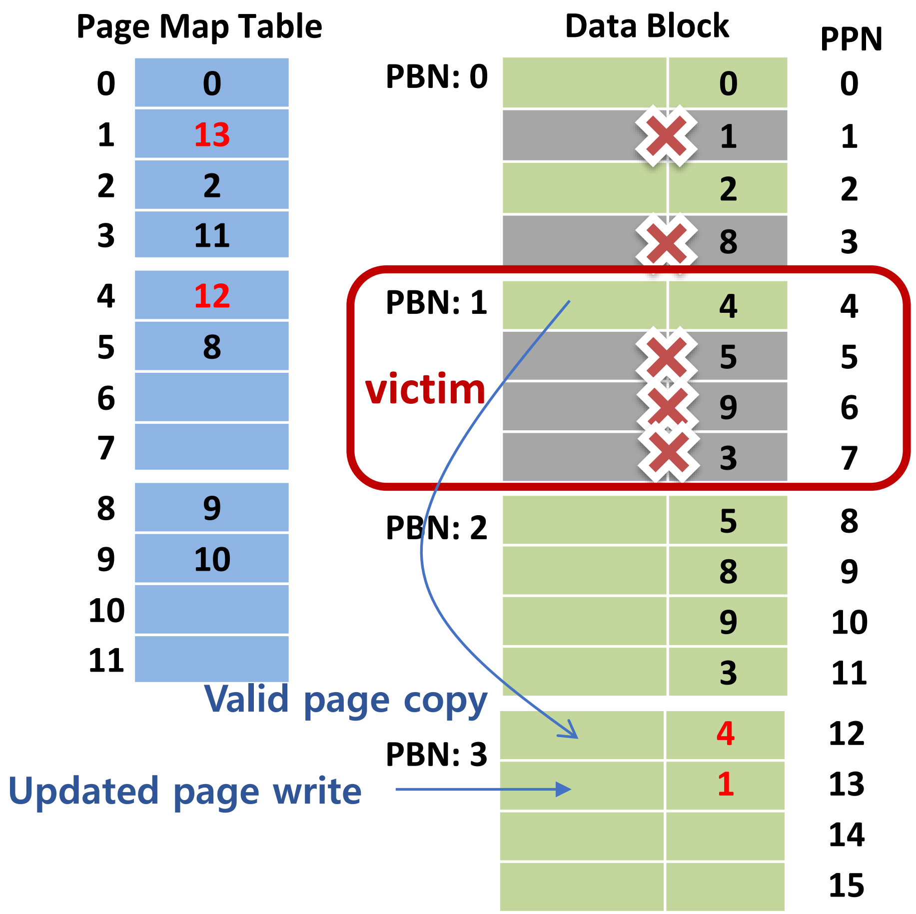

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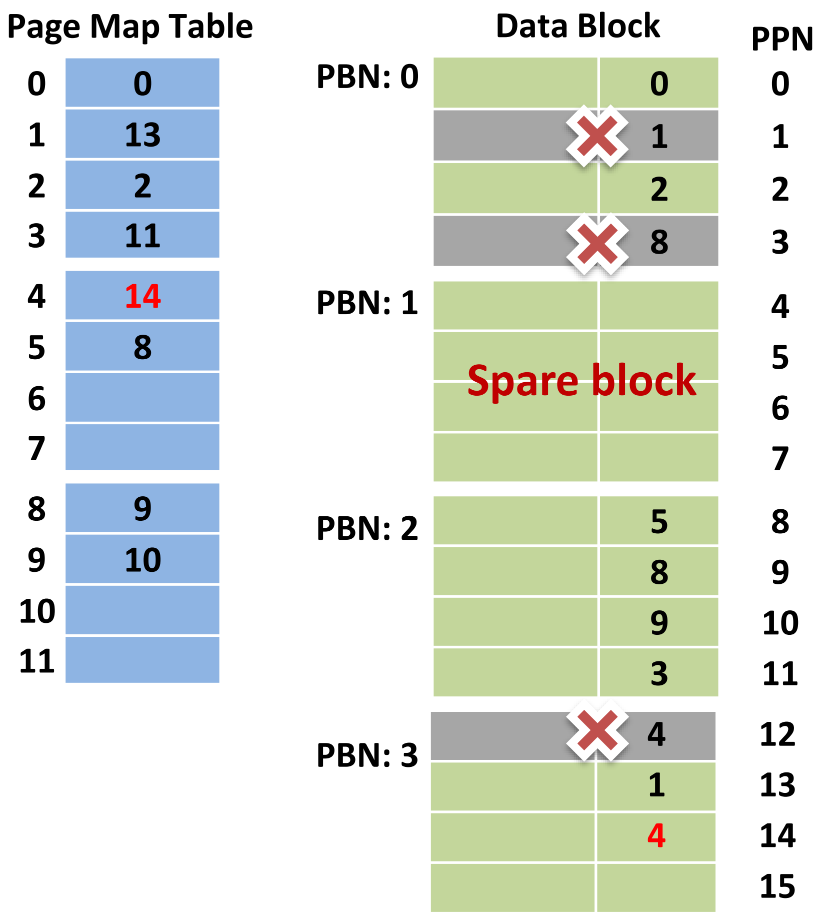
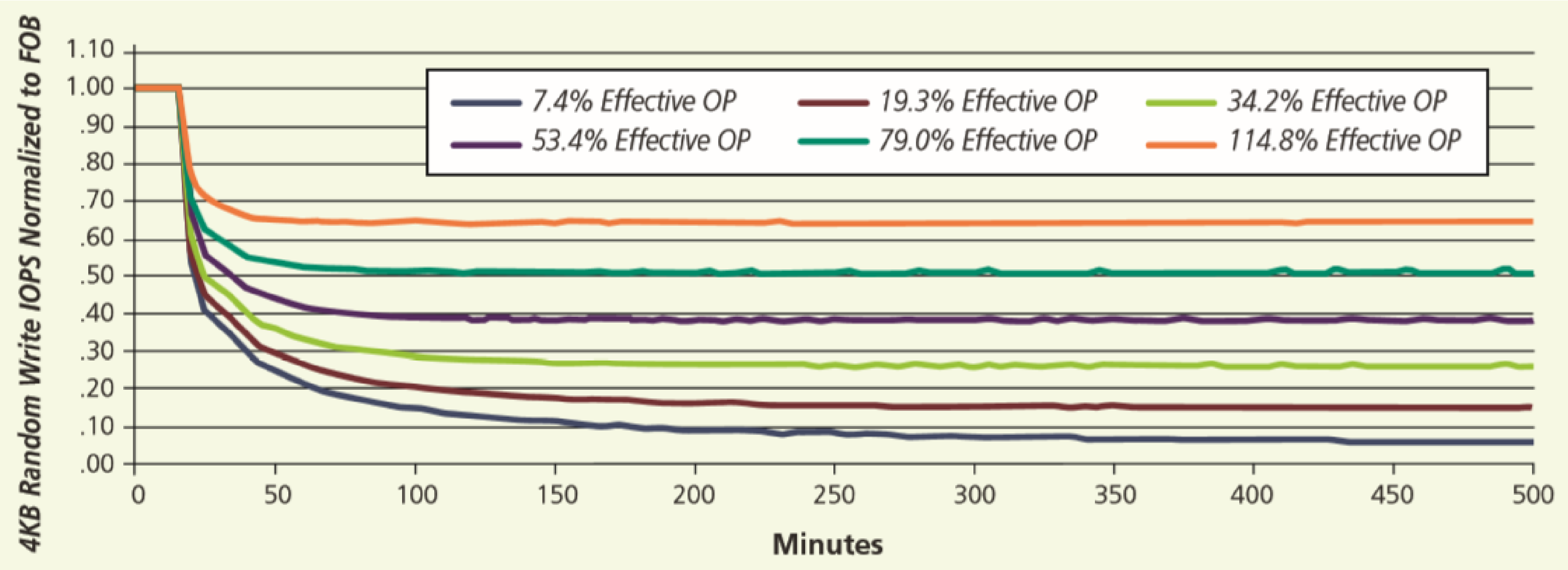
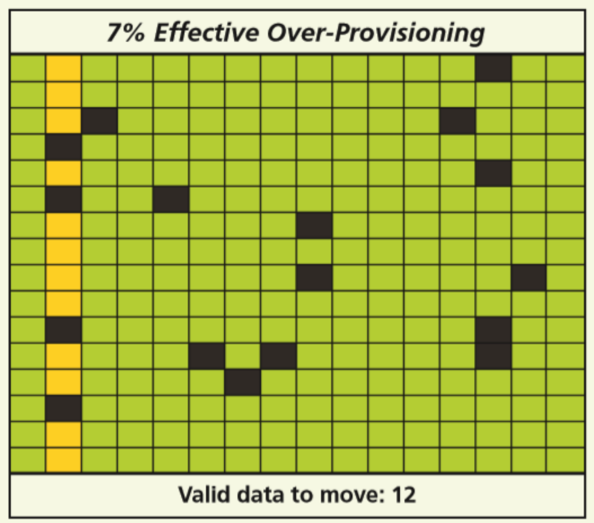
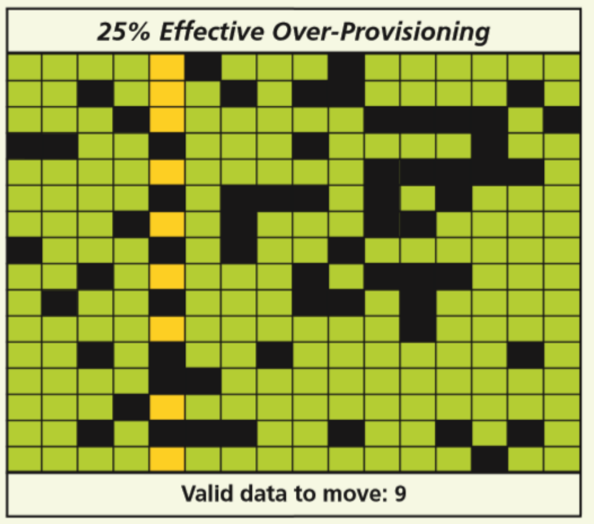


Over-Provisioning and GC

- IOPS for random write workloads
  - OP (Over-Provisioning) = $\frac{Physical\ Capacity}{Logical\ Capacity} - 1$
  - What about for sequential write workloads?







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

Challenges

No in-place update	Address mapping, Garbage collection (with hot/cold separation)
Limited P/E cycles	Wear leveling
Bit errors	ECC
Bad blocks	Bad block remapping
Read/write disturbance Retention errors	Background activity for data integrity
Multiple planes/dies/channels	Exploiting parallelism, prefetching
Slower & more power-consuming program/erase operations	Hiding latency, power throttling
Sudden power failure	Power loss protection

OS Implications

- NAND flash has different characteristics compared to disks
  - High throughput with low latency
  - No seek time
  - No in-place-update
  - Asymmetric read/write access times
  - Good sequential read/write and random read performance, but bad random write performance
  - Background garbage collection and wear-leveling
  - …
  - Traditional operating systems have been optimized for disks. What should be changed?

SSD Support in OS & Applications

- Align file system partition with SSD layout
- Larger block size (4KB)
- Turn off "defragmentation" for SSDs
- New "TRIM" command (remove-on-delete)
- Simpler & scalable I/O scheduler
- Flash-aware file systems (e.g., F2FS in Linux/Android)
- New "multi-stream" interface
- User-level storage access (e.g., SPDK)
- Fairness, isolation, etc.

New NVMe SSD Proposals

	Interfaces	Data placement	Flash management	Overwrite	Data movement	Host CPU utilization	Hardware complexity	Computation capability	Software modification
Conventional SSD	Block (SATA, SAS, NVMe)	Host	Device	Yes	-	-	-	No	-
ZNS SSD **FDP SSD**	Restricted Block (NVMe)	**ZNS**: Host **FDP**: Host + Device	**ZNS**: Host **FDP**: Host + Device	**ZNS**: No **FDP**: Yes	High	High	Low	No	High
KV-SSD	Key-value (NVMe)	Device	Device	Yes	Low	Low	Medium	Some	Very High
SmartSSD	FPGA + Block (NVMe)	Host	Device	Yes	Low	Low	High	Yes	Very High
Computational Storage	Compute + Block? (NVMe)	Host or device?	Device	Yes	Low	Low	High	Yes	Very High

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
  - No in-place-update
  - Much slower program/erase operations
  - Erase unit > read/write unit
  - Bit errors
  - Limited lifetime etc.
- Software support is essential for performance and reliability!