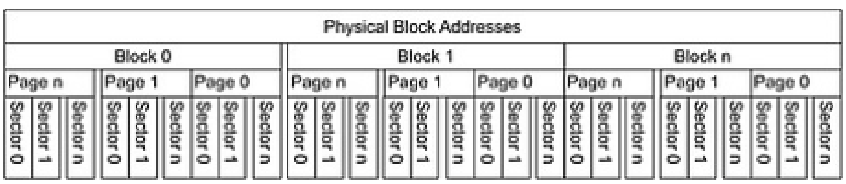
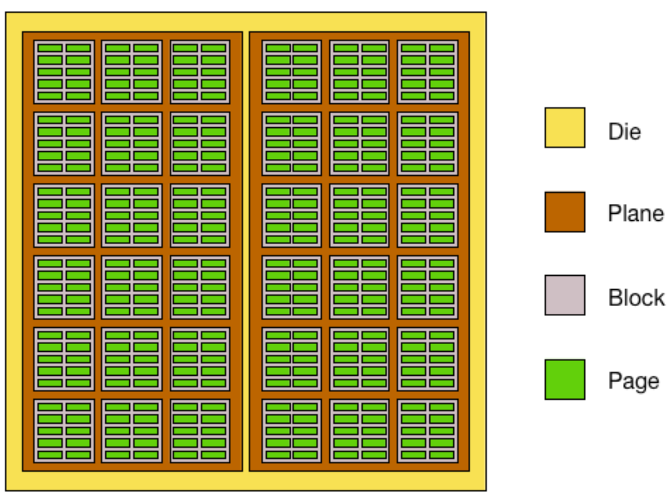
1 Flash-Based SSDs

<u>Vocabularies</u>

1. **Flash Solid-State Storage**
   - Is a type of non-volatile computer storage that stores and retrieves digital information using only electronic circuits, without any involvement of moving mechanical parts
2. **NAND-Based Flash**
   - Is an electronic non-volatile computer memory storage medium using NAND-gate that can be electrically erased and reprogrammed.
3. **Flash Page**
   - Is the smallest unit that can be programmed into flash
4. **Flash Block**
   - Is a group of pages and <u>the smallest unit that can be erased</u>.

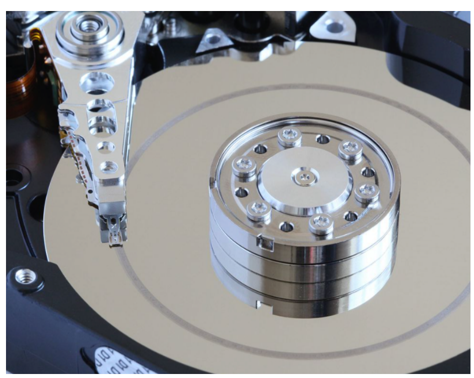




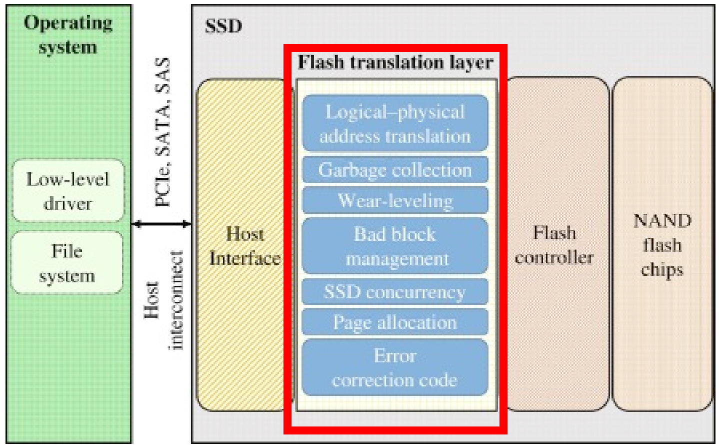
5. **Wear Out**

   - Is similar to going past **expiration date**
   - Means it has exceeded their endurance rating

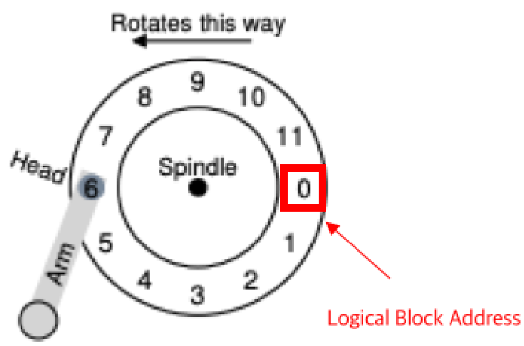
6. **Single-Level Cell**
   - Is a type of cell in solid-state storage that stores one bit of data per transister (0 or 1)
7. **Multi-Level Cell**
   - Is a type of cell in solid-state storage that stores two bits of data (i.e 00, 01, 10, 11) per cell using two different levels of charge
8. **Triple-Level Cell**
   - Is a type of cell in solid-state storage that stores three bits of data per cell (i.e 000, 001, 010, 011, 100, 101, 110, 111)
9. **Bank / Plane**
   - Is a group of large number of cells
10. **Head Crash**
    - Is a condition where the drive head makes contact with the recording surface



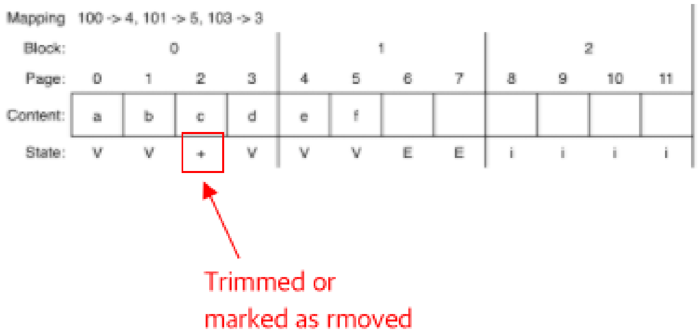
11. **Disturbance**
    - Is also known as **read disturbance** or **program disturbance**
    - Is a condition where accesing a bit in a page causes some bits to get flipped in neighboring pages
12. **Flash Transition Layer**
    - Is an intermediate system made up software and hardware that manages SSD operations



13. **Wear Leveling**
    - Is a technique for prolonging the service life of some kinds of erasable computer storage media, such as flash memory, which is used in solid-state drives (SSDs)
14. **Direct Mapped**
    - Is a simplest organization of an **Flash Transition Layer** that maps read of logical page N directly to read of playsical page N.
15. **Logging**
    - Is a concept in **log-structured file system** that buffer all writes (data + metadata) using an in-memory segment; once the segment is full, write the segment to a log
16. **Mapping Table**
    - Is a table that stores the physical address of each logical block in the system
17. **Logical Block Address**
    - Is a common scheme used for specifying the location of blocks of data stored on computer storage devices, generally in secondary storage system

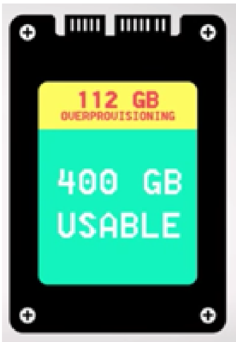


18. **In-Memory Mapping Table**
    - Is a table inside the memory of the secondary storage device (is persistent in some form) that stores the physical address of each logical block in the system
19. **Garbage Block**
    - Is also called **Dead Block**
    - Is old version of block in secondary storage, such as solid state drive
20. **Garbage Collection**
    - Is the process of finding garbage blocks and reclaiming them for future use
21. **Cache Flush**
    - Is the process of clearing out sections of memory to ensure writes have actually been persisted in solid state drive
22. **Trim**
    - Is an operation that takes an address (and possibly a length) and informs the device that the block(s) specified by the address (and length) have been deleted



23. **Overprovision**

- Is an extra amount of flash space used to reduce the cost of **garbage collection**, increase the logitivity of flash drive, and prevents the device from slowing down



24. **Page-Level FTL**

- Is an intermediate system made of software and hardware that manages SSD operations at page-level.
  - It does not write a full block
  - Only writes the necessary page(s) of data along with the FTL metadata that must be written to track of the new position of the data

25. **Hybrid Mapping**

- Is a mapping technique used in **Flash Transition Layer** that utilizes both block-based mapping and page-based mapping to enable flexible writing but also reduce mapping costs

26. **Log Blocks**
    - Are blocks in solid state storage where contents are erased and all writes are directed
27. **Switch Merge**
    - This will be revisited when reading related section
28. **Partial Merge**
    - This will be revisited when reading related section
29. **Full Merge**
    - This will be revisited when reading related section

1.1 Flash-Based SSDs

- Has two interesting problems to overcome
  1. To write a small chunk (called **flash page**), a bigger chunk (**flash block**) must be erased first
  2. Writing too often would cause a page to **wear out**

1.2 Storing a Single Bit

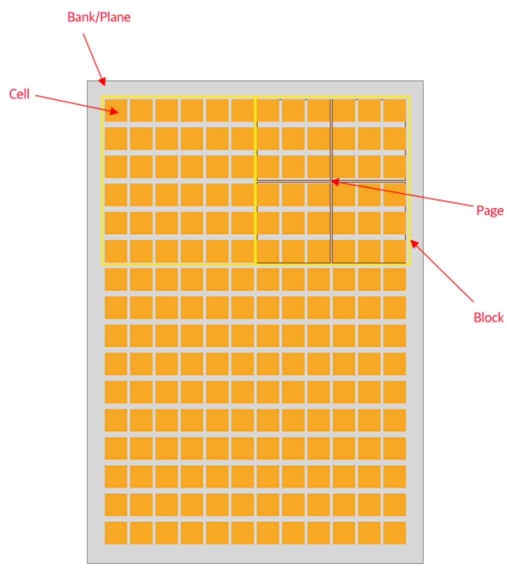
- **Single-level cell** → 1 bit per cell
- **Multi-level cell** → 2 bits per cell
- **Triple-level cell** → 3 bits per cell
- **Single-level cell** has higher performance and are more expensive
  - More 촘촘하다
- How SLC, MLC, TLC works → Physics!!

1.3 From Bits to Banks / Planes

Question Is conent in a flash chip a cell? How many bits can be stored per content?

Question I should ask clarification from professor about why Samsung and other tech giants are producing higher level cells if SLC is better in performance

- In each plane/bank, there are large number of blocks
- In each block, there are a large number of pages



1.4 Basic Flash Operations

- **Read (a page):**
  - Is fast (10 μs)
  - Can access any location uniformly
    - flash-based SSD is a **random access device**
- **Erase (a block):**
  - Is most expensive
  - **block** must be erased before erasing a **page**

- **Program (a page):**
  - Is used to change some of the 1's within a page to 0's and vice versa
  - Is less expensive then erasing a block
  - Is more costly than reading a page
  - Before overwriting any page within a block, we must first move any data we care about to another location
    * Frequent repeatitions of program/erase cycle cause flash chips to **wear out**
- Page starts in `INVALID` state
- Erasing block results in pages with `ERASED` state
  - resets contents in page
  - makes contents re-programmable
- Programming a page results in `VALID` state
  - Contents are set and can be read
  - Only way to change it's content is to erase the entire block

		iiii	*Initial: pages in block are invalid* (i)
Erase()	→	EEEE	*State of pages in block set to erased* (E)
Program(0)	→	VEEE	*Program page 0; state set to valid* (V)
Program(0)	→	**error**	*Cannot re-program page after programming*
Program(1)	→	VVEE	*Program page 1*
Erase()	→	EEEE	*Contents erased; all pages programmable*

1.5 Flash Performance and Reliability

- **Performance**

	Device	Read (μs)	Program (μs)	Erase (μs)
Single-layer cell	SLC	25	200-300	1500-2000
Multi-layer cell	MLC	50	600-900	~3000
Triple-layer cell	TLC	~75	~900-1350	~4500

Slower as more bits packed per cell

- **Reliability Concerns**
  - **Wear Out**
    - Accures a bit of extra charge when flash block is erased and programmed
    - Over time, 0 and 1 become difficult to distinguish
    - Becomes unusable at the point where it becomes impossible to distinguish
  - **Disturbance**
    - Access a page within a flash may cause some bits to get flipped in neighboring pages
    - **Disturbance** while programming → **Program Disturbance**
    - **Disturbance** while reading → **Read Disturbance**

1.6 From Raw Flash to Flash-Based SSDs

- Addresses the question "How to turn a basic set of flash chips into something that looks like a typical storage device"
- Hardware Requirements
  - Flash chips
  - Some volatile memory for caching (e.g. SRAM)
  - Control logic to orchestrate device operation
- Other Requirements
  - **Flash Transition Layer**
    - Is made up of both hardware and software
    - Takes read and write requests on logical blocks
    - Turns contents in logical blocks into low-level read, erase, and program commands on the underlying *physical page* and *physical block*
    - FTL should accomplish this task with the goal of excellent performance and high reliability

      1. Performance

· Running in **parallel** - using multiple chips internally boosts performance

Is similar to using multiple disk arm on HDD

2. Reliability

· **Wear Leveling** - Spreading writes across the blcoks of flash as evenly as possible

- Address **wear out**
- Slows the buildup of charge

· Writing page in order from low page to high page

- Minimize **disturbance**

1.7 FTL Organization: A Bad Approach

- **Direct Mapped**
  - How it works
    - Read
      - Directly translates the read of logical page N to a read of physical page N
    - Write
      - Read in the entire block page N is contained within
      - Erase the block
      - Program the old page as well as the new one
  - Creates **write amplification** (performance problem)
    - Write is proportional to number of pages in a block
      - Reading entire block is costly, Erasing it is costly, and programming it is costily
    - Results in terrible write performance
    - Is slower than typical hard drives
  - Doesn't follow **wear leveling** (reliability problem)
    - User file data is repeatedly over written
    - Results in **wear out** and potentially loses data

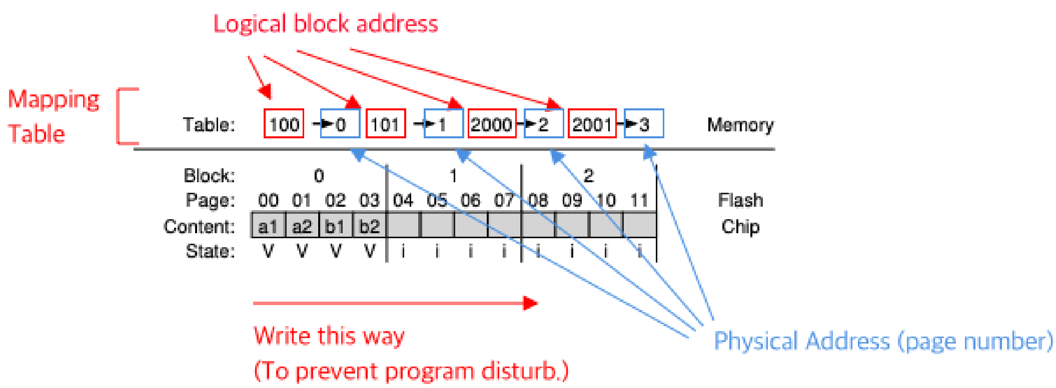
1.8 A Log Structured FTL

- Works similarly as **log structured file system**
- Is useful in storage device and file system
- How it works

- Keeps a **logical block** N
  - To append the write to the next free spot in the currently-being-written block
- Keeps a **mapping table**
- Translate contents from logical address to physical address
  - Is done when logical block is full

Example

- Write logical address (100) with content `a1`
- Write logical address (101) with content `a2`
- Write logical address (2000) with content `b1`
- Write logical address (2001) with content `b2`



- Advantages
  - Improves performance
  - Greatly enhances reliability

1.9 Garbage Collection

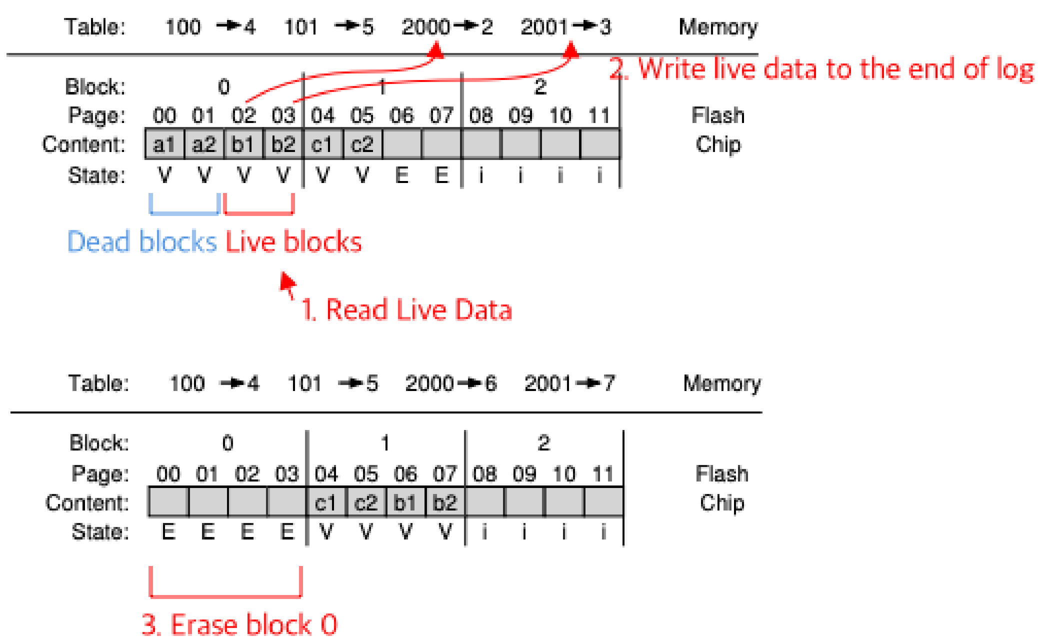
Note Mapping not on **mapping table** is considered a garbage

Question I should ask professor if durability is the issue, why can't we clean the build of charge by moving block to overprovisioned space and then discharging the block?

- How it works
  - Find a block with one or more garbage pages
  - Read in the live (non-garbage) pages from the block
  - Write out those live pages to the log

– Reclaim the entire block for use in writing

Example



- Disadvantage
  - Is expensive
    - Reading (25 - 75 μs / operation) + Re-writing live blocks (200 - 1360 μs / operation)
    - Cost is reduced via **overprovision**
      - Moves to-be-deleted items to this background space
      - **Garbage Collection** is done when the device is less busy

1.10 Mapping Table Size

- Addresses the second problem of log structuring - a huge mapping table
  - 4 TB of space with 4KB page with 4 byte per entry requires 1 GB of memory
  - Page-level FTL is impractical
- Solutions
  1. **Block-based mapping**
     - Has a pointer per block (not one pointer per page)
     - Reduces mapping amount

- Does not work very well

  1. Small write
     * Must read a large amount of live data from old block before moving to a new one
     * Increases **write amplification**
     * Dereases performance

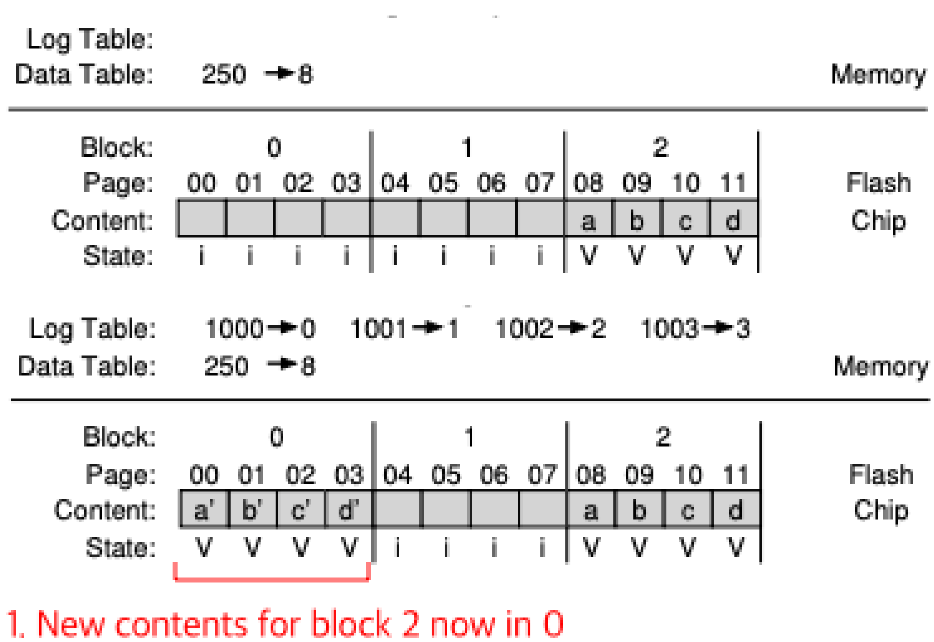
2. **Hybrid mapping**
   - Is the most used mapping method today
   - Enables flexible writing but reduces mapping costs
   - How it works
     * Keep pointers for both page and block
       · Has <u>small</u> set of per-page mapping in **log table**

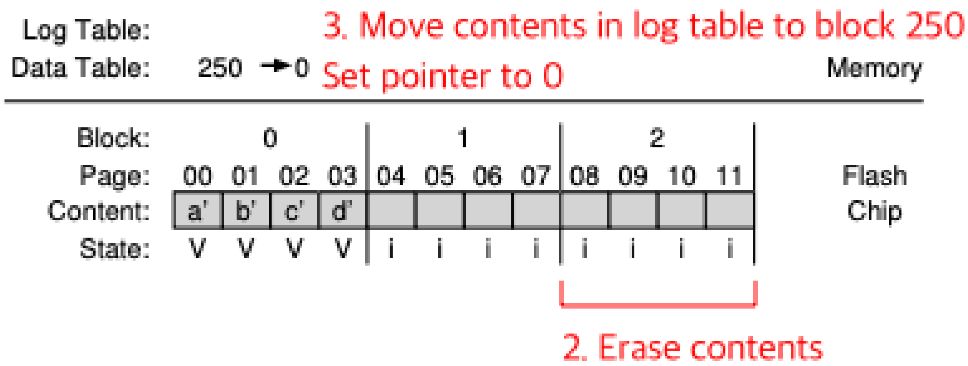
         Note <u>Small</u> is the key to hybrid mapping

       · Has larger set of per-block mapping in **data table**
     * Periodically examine **log blocks**
     * When sufficient, switch them into blocks that can be pointed to by only a single block pointer

   <u>Example (Switch Merge):</u>

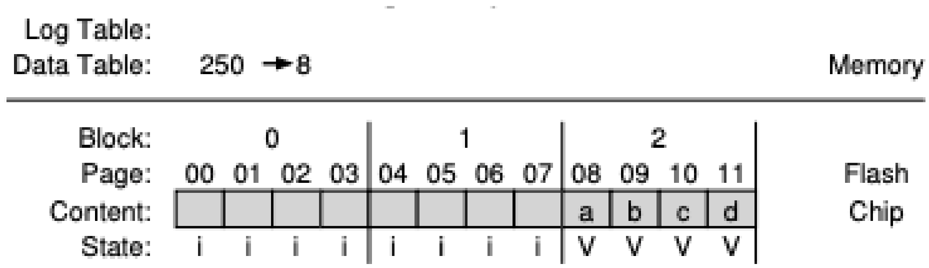
   - Contents of the writes to 1000,1001,1002,1003 are `a`, `b`, `c`, `d` respectively
   - Client overwrites the contents `a`, `b`, `c`, `d` to `a'`, `b'`, `c'`, `d'`

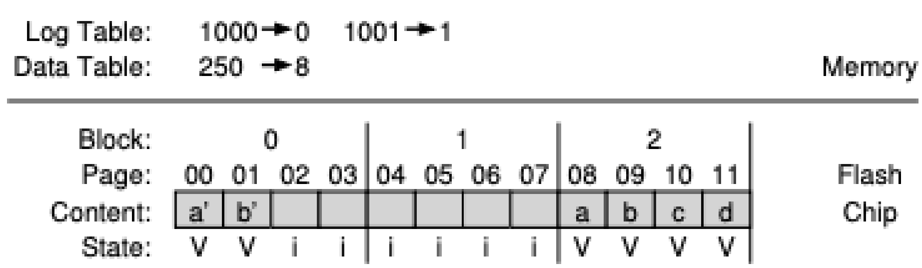




Example (Partial Merge):

- Contents of the writes to 1000,1001,1002,1003 are `a`, `b`, `c`, `d` respectively
- Client overwrites the contents `a`, `b` to `a'`, `b'`





- Read logical blocks 1002 and 1003 from physical block 2
- Append read blocks to the log
- Entries in **log table** moved to **data table** only when filled

1.11 Wear Leveling

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1.12 SSD Performance And Cost