Flash storage

COS 518: *Advanced Computer Systems*
Lecture 8

Michael Freedman

~2016

Seagate ($50)
1TB HDD 7200RPM
Model: STD1000DM003-1SB10C

Operation	HDD Performance
Sequential Read	176 MB/s
Sequential Write	190 MB/s
Random Read 4KiB	0.495 MB/s 121 IOPS
Random Write 4KiB	0.919 MB/s 224 IOPS
DQ Random Read 4KiB	1.198 MB/s 292 IOPS
DQ Random Write 4KiB	0.929 MB/s 227 IOPS

http://www.tomshardware.com/answers/id-3201572/good-normal-read-write-speed-hdd.html

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Seagate ($50)
1TB HDD 7200RPM
Model: STD1000DM003-1SB10C

Samsung ($330)
512 GB 960 Pro NVMe PCIe M.2
Model: MZ-V6P512BW

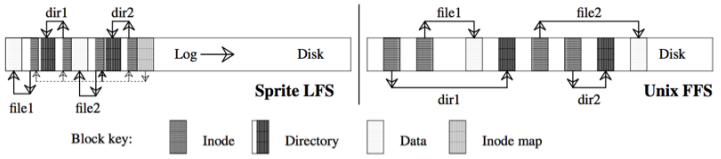
Operation	HDD Performance	SSD Performance
Sequential Read	176 MB/s	2268 MB/s
Sequential Write	190 MB/s	1696 MB/s
Random Read 4KiB	0.495 MB/s 121 IOPS	44.9 MB/s 10,962 IOPS
Random Write 4KiB	0.919 MB/s 224 IOPS	151 MB/s 36,865 IOPS
DQ Random Read 4KiB	1.198 MB/s 292 IOPS	348 MB/s 84961 IOPS
DQ Random Write 4KiB	0.929 MB/s 227 IOPS	399 MB/s 97,412 IOPS

http://www.tomshardware.com/answers/id-3201572/good-normal-read-write-speed-hdd.html
http://ssd.userbenchmark.com/SpeedTest/182182/Samsung-SSD-960-PRO-512GB

The Design and Implementation of a Log-Structured File System

Mendel Rosenblum and John K. Ousterhout

- **Idea:** Traditionally disks laid out with spatial locality due to cost of seeks
- **Observation:** main memory getting bigger → most reads from memory
- **Implication:** Disk workloads now write-heavy → avoid seeks → write log
- **New problem:** Many seeks to read, need to occasionally defragment
- **New tech solution:** SSDs → seeks cheap, erase blocks change defrag



This paper will appear in the *Proceedings of the 13th ACM Symposium on Operating Systems Principles* and the February 1992 *ACM Transactions on Computer Systems*.

Flash: Storing individual bits

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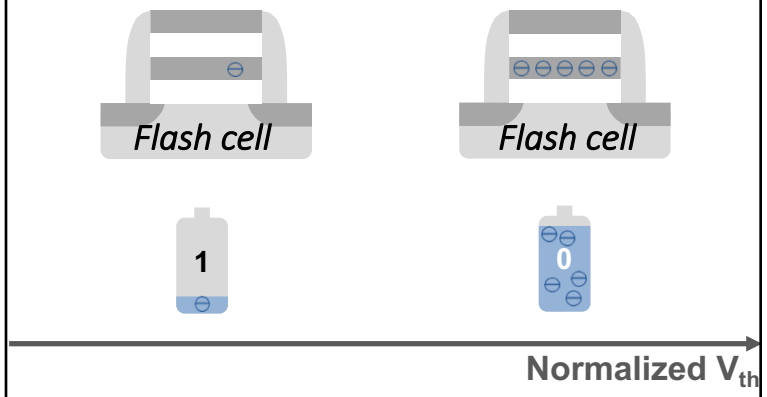
Threshold Voltage (V_{th})



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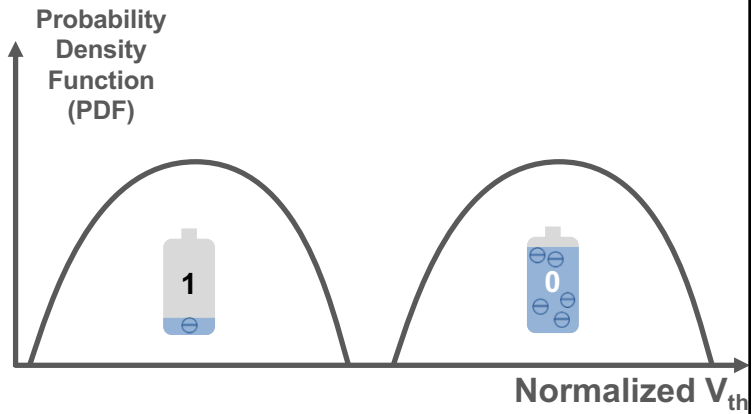
Threshold Voltage (V_{th}) Distribution



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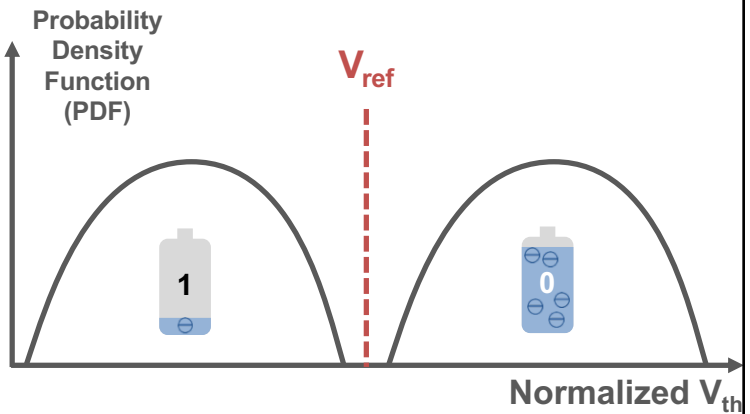
Read Reference Voltage (V_{ref})



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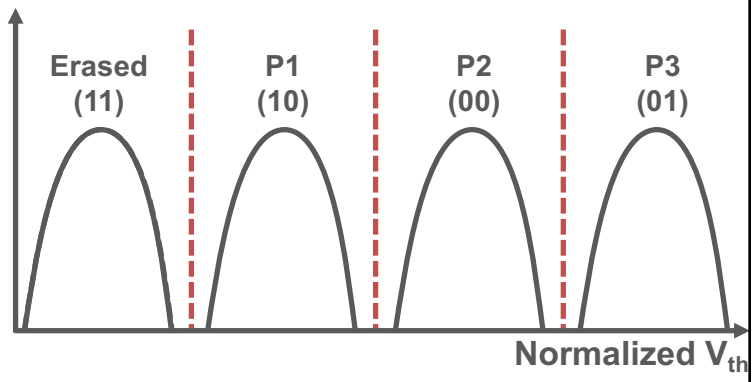
Multi-Level Cell (MLC)



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Flash: Storing many bits

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Flash: Bit vs. page-level access

- NOR flash
  - Cells connected in parallel to bit lines
  - Cells can be read and written to individually
- NAND flash
  - Cells connected in series, consuming less space
  - Smaller area needed to implement certain capacity
    - Reduce cost per bit, increase max chip capacity
  - Cells can only be written and read at the page level

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NAND Flash: Architecture

- **Architecture:**
  - Pages: 8-16 KB, assembled into
  - Blocks: 4-8 MB

Block 1000 (data)

PPN	data
0	x
1	y
2	z
3	

Block 2000 (free)

PPN	data
0	
1	
2	
3	

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NAND Flash: Reading / writing

- **Always read an entire page:**
  - Can only read entire aligned page from SSD
- **Always write an entire page:**
  - To change single byte, need to write entire page
- **Pages cannot be overwritten**
  - Page can be written only if the "free" state.
  - **Updating**: **Read** page to internal register, **modify**, then **write** to free page
- **Erases are aligned on block size**
  - To make a page "free", need to erase it
  - Erasures can only occur at block boundary

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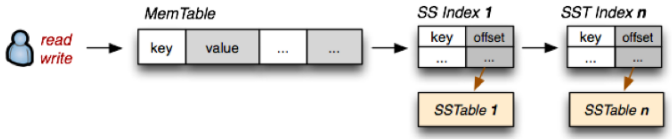
Why Erase then Write? Hardware limitation

- A freshly erased, blank page of NAND flash has no charged gates; it stores all 1s.
- 1s can be turned into 0s at the page level, but one-way process.
  - Turning 0s back into 1s is a difficult operation b/c it uses high voltages.
  - Difficult to confine the effect only to desired cells; high voltages can change adjacent cells.

Implication: Buffer small writes

- To maximize throughput:
  - Keep small writes into a buffer in RAM
  - Perform large batch write when buffer full
- Suited well for log-structured write (e.g., LSM trees)



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SSD architecture

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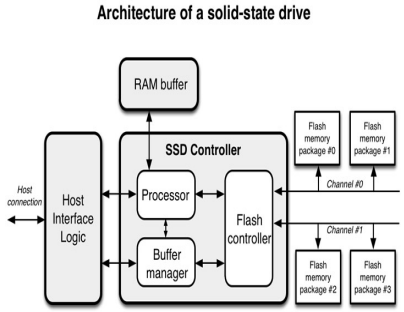
SSD: Solid State Driver

- Host Interface Logic
- SSD Controller
- RAM Buffer
- Flash Memory Package



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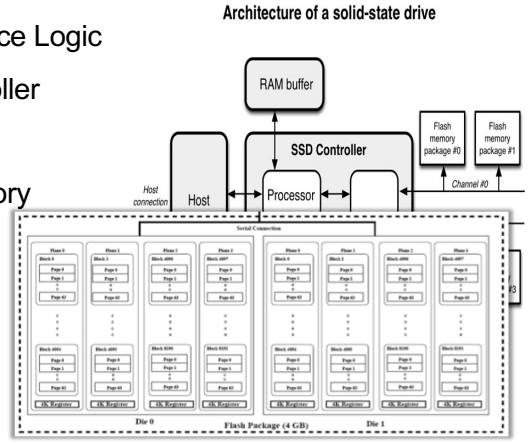

Last twist

- Disk lifetime: each page can only be written some fixed number of times:
  - SLC: 100,000 P/E cycles
  - MLC: 3,000 P/E cycles
  - TLC: 100 P/E cycles
- When blocks get bad, take them out of rotation
  - Need indirection layer to not use bad pages
- Want to load balance writes over pages!
  - FTL: Flash-Translation Layer for “wear leveling”

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