15-410
“...What goes around comes around...”

Storage
Oct. 22, 2018

Dave Eckhardt
Dave O'Hallaron

Contributions from
- Garth Gibson
- Brian Railing & Steve Muckle
- Eno Thereska, Rahul Iyer
- 15-213
- “How Stuff Works” web site
Overview

What is “storage”? 

Anatomy of a Hard Drive

SSD's

What you should know
Storage

Where is your stuff when you turn your machine off?
Storage

Where is your stuff when you turn your machine off?

- In “the cloud”!
Storage

Where is your stuff when you turn your machine off?
- In “the cloud”!

Where does the cloud store your stuff?
Storage

Where is your stuff when you turn your machine off?
- In “the cloud”!

Where does the cloud store your stuff?

http://xkcd.com/908/
Storage

Where is your stuff when you turn your machine off?
- In “the cloud”!

Where does the cloud store your stuff?

http://xkcd.com/908/
Storage

Where is your stuff when you turn your machine off?
- In “the cloud”!

Where does the cloud store your stuff?

http://xkcd.com/908/
Storage

Where is your stuff when you turn your machine off?
- In “the cloud”!

Where does *the cloud* store your stuff?

http://xkcd.com/908/
Storage

Various devices
- “Drum”
- Magnetic tape
- “Hard disk”
- Floppy disc
- CD-ROM
- Magneto-Optical (MO) disk
- Flash memory
- “3D XPoint”

What do they have in common?
How do they differ?
Storage Features

“Non-volatile”
- Remembers without electricity

Slow (compared to RAM)
- Milliseconds or seconds instead of nanoseconds
- Can't execute programs from it (must fetch first)

“Block oriented”
- Fetch and store large clumps of data
  - Floppy: 128/256/512 bytes
  - Spinning disk: 512/4096 bytes
  - CD-ROM: 2048 bytes
  - Flash: “hard to say”
- Time to fetch 1 byte == time to fetch 1 block
Storage Model

“Non-volatile”
- Write; power-off; read: should return same value
  - Years later!

Address space
- Each block has a number
  - Ancient times: (C,H,S) tuple
    - C, H, S were geometric features of old disks
  - Modern: (LBA)
    - “Logical Block Address” runs from 0..N
Storage Model

Reading and writing

- Read-block(N) ⇒ [huge delay] ⇒ block else failure
- Sometimes a re-try helps (usually not)
Storage Model

Reading and writing

- Read-block(N) ⇒ [huge delay] ⇒ block else failure
  - Sometimes a re-try helps (usually not)
- Write-block(N) ⇒ [huge delay] ⇒ “ok” else failure
  - Failures usually indicate “obvious” bad things
    - The disk motor stopped
  - “Ok” doesn't guarantee a later read
- Devices usually contain a power buffer
  - A write operation either completes or has no effect
Storage Model

Reading and writing

- Read-block(N) ⇒ [huge delay] ⇒ block else failure
  - Sometimes a re-try helps (usually not)
- Write-block(N) ⇒ [huge delay] ⇒ “ok” else failure
  - Failures usually indicate “obvious” bad things
    - The disk motor stopped
  - “Ok” doesn't guarantee a later read
- Devices usually contain a power buffer
  - A write operation either completes or has no effect
- Modern devices support “tagged command queueing”
  - OS can issue multiple requests, each has a “tag”
  - Device can return results in any order, with the OS's tag
Command Queueing In Action

Disks serve read requests out of order

- OS queues: “read 37”, “read 83”, “read 2”
  - Disk returns 37, 2, 83
    - Great! That's why we buy smart disks and queue multiple requests
- OS queues: “read 37”, “read 38”, “read 39”
  - Disk does one seek, reads 37-40, plus also 40-72 while it's in the neighborhood
  - Sends sectors 37-39 to OS as they become available
Command Queueing In Action

Disks serve read requests out of order
- OS queues: “read 37”, “read 83”, “read 2”
  - Disk returns 37, 2, 83
    - Great! That's why we buy smart disks and queue multiple requests
- OS queues: “read 37”, “read 38”, “read 39”
  - Disk does one seek, reads 37-40, plus also 40-72 while it's in the neighborhood
  - Sends sectors 37-39 to OS as they become available

Disks serve write requests out of order, too
- OS queues “write 23”, “write 24”, “write 1000”, “read 4-8”, ...
  - Disk writes 24, 23 (!!), gives you 4, 5, 6, 7, 8, writes 1000
    - What if power fails before last write?
    - What if power fails between the first two writes?
Command Queueing In Action

How can OS ensure data-structure integrity?

- Special commands
  - “Flush all pending writes”
    - Think “my disk is 'modern'”, think “disk barrier”
    - Can even queue a flush to apply to all before now
    - Can apply these “barrier” flushes to subsets of requests
    - Rarely used by operating system
  - “Disable write cache”
    - Think “please don't be quite so modern”
Examples

“Hard drive”
- Parts
- Execution model

NAND flash memory
- Challenges
  - Write amplification
  - Wear leveling
Anatomy of a Hard Drive

On the outside, a hard drive looks like this

Taken from “How Hard Disks Work”
http://computer.howstuffworks.com/hard-disk2.htm
Anatomy of a Hard Drive

If we take the cover off, we see that there actually is a “hard disk” inside

Taken from “How Hard Disks Work”
http://computer.howstuffworks.com/hard-disk2.htm
Anatomy of a Hard Drive

A hard drive usually contains multiple disks, called *platters*

These spin at thousands of RPM (5400, 7200, 10000, ...)

Slower disks use less power

Taken from “How Hard Disks Work”
http://computer.howstuffworks.com/hard-disk2.htm
Anatomy of a Hard Drive

Information is written to and read from the platters by the **read/write heads** on the end of the **disk arm**.

Taken from “How Hard Disks Work”
http://computer.howstuffworks.com/hard-disk2.htm
Anatomy of a Hard Drive

The arm is moved by a voice coil actuator

Slow, as computers go
- Acceleration time
- Travel time

Taken from “Hard Disk Drives”
http://www.pcguide.com/ref/hdd
Anatomy of a Hard Drive

Both sides of each platter store information.

Each side of a platter is called a surface.

Each surface has its own read/write head.

Taken from “How Hard Disks Work”
http://computer.howstuffworks.com/hard-disk2.htm
Anatomy of a Hard Drive

How are the surfaces organized?

a surface
Anatomy of a Hard Drive

Each surface is divided by concentric circles, creating **tracks**
Anatomy of a Hard Drive

These tracks are further divided into sectors
Anatomy of a Hard Drive

These tracks are further divided into sectors

A sector is the smallest unit of data transfer to or from the disk

- 512 bytes – traditional disks
- 2048 bytes – CD-ROMs
- 4096 bytes – 2010 disks
  - (pretend to be 512!)
Disk Cylinder

Matching tracks across surfaces are collectively called a cylinder
Anatomy of a Hard Drive

These tracks are further divided into sectors

A sector is the smallest unit of data transfer to or from the disk
- 512 bytes – traditional disks
- 2048 bytes – CD-ROMs
- 4096 bytes – 2010 disks
  - (pretend to be 512!)

“Sector address”
- “C/H/S”

Gee, those outer sectors look bigger...?
Anatomy of a Hard Drive, Really

Modern hard drives use **zoned bit recording**

- Disk has tables to map track# to #sectors
- Sectors are all roughly the same linear length
- LBA “sector address” names a sector, like “page number” names a frame

Taken from “Reference Guide – Hard Disk Drives”
http://www.storagereview.com/map/lm.cgi/zone
Anatomy of a Hard Drive

Let's read in a sector from the disk

disk rotates counter-clockwise

read/write head

desired sector
Anatomy of a Hard Drive

We need to do two things to transfer a sector

- Move the read/write head to the appropriate track ("seek time")
- Wait until the desired sector spins around ("rotational delay" or "rotational latency")

Observe

- Average seeks are 2 – 10 msec
- Rotation of 5400/7200/10K/15K rpm means rotational delay of 11/8/6/4 msec
- Rotation dominates short seeks, matches average seeks
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a Hard Drive

Let's read in a sector from the disk

read/write head
Anatomy of a “Sector”

Finding a sector involves real work
Locate correct track; scan sector headers for number

After sector is read, compare data to checksum
Disk Cylinder

Matching tracks form a cylinder.
Access Within A Cylinder is Faster

Heads share one single arm
- All heads always on same cylinder
- Active head is aligned, others are “close”

Switching heads is “cheap”
- Deactivate head I, activate J
- Read a few sector headers to fine-tune arm position for J's track

Optimal transfer rate?
1. Transfer all sectors on a track
2. Transfer all tracks on a cylinder
3. *Then* move the arm
Access Time

On average, we will have to move the read/write head over one third of the tracks

- The time to do this is the “average seek time”
  - 5400 rpm: ~10 ms
  - 7200 rpm: ~8.5 ms

We will also must wait half a rotation, on average

- The time to do this is “average rotational delay”
  - 5400 rpm: ~5.5 ms
  - 7200 rpm: ~4 ms

These numbers don't exactly add

- While arm moves sideways, disk spins below it
Access Time

Total random access time is ~7 to 20 milliseconds
Access Time

Total random access time is $\sim$7 to 20 milliseconds

- $1000 \text{ ms/second, } 20 \text{ ms/access} = 50 \text{ accesses/second}$
Access Time

**Total random access time is ~7 to 20 milliseconds**
- 1000 ms/second, 20 ms/access = 50 accesses/second
- 50 ½-kilobyte transfers per second = 25 KByte/sec
- Oh man, disks are slow!
  - That's slower than DSL!!!
Access Time

Total random access time is ~7 to 20 milliseconds
- 1000 ms/second, 20 ms/access = 50 accesses/second
- 50 ½-kilobyte transfers per second = 25 KByte/sec
- Oh man, disks are slow!
  - That's slower than DSL!!!
  - But wait! Disk transfer rates are hundreds of MBytes/sec!
Access Time

Total random access time is ~7 to 20 milliseconds
- 1000 ms/second, 20 ms/access = 50 accesses/second
- 50 ½-kilobyte transfers per second = 25 KByte/sec
- Oh man, disks are slow!
  - That's slower than DSL!!!
  - But wait! Disk transfer rates are hundreds of MBytes/sec!

What can we, as OS programmers, do about this?
- Read/write more per seek (multi-sector transfers)
  - Disk cache can read ahead and delay/coalesce writes
- Don't seek so randomly
  - Place data near also-relevant data
  - Re-order requests
    - OS may do “disk scheduling” instead of a FIFO queue
    - Historically very important; recently, less
    - (Disks internally schedule too)
Solid-State Disks (SSD)

What is “solid state”?
- Original meaning: “no vacuum tubes”
- Modern meaning: ?
Solid-State Disks (SSD)

What is “solid state”?
- Original meaning: “no vacuum tubes”
- Modern meaning: “no moving parts”
Solid-State Disks (SSD)

What is “solid state” storage?
- RAM backed by a battery!
- “NOR flash”
- “NAND flash”
- Newer things
Solid-State Disks (SSD)

What is “solid state” storage?

- RAM backed by a battery!
  - Fast
  - Legato “Prestoserve”, 1989 ($8,000 for 1 MB)
  - Allowed NFS servers to complete write RPCs without waiting for disk

- “NOR flash”
  - Word-accessible
  - Writes are slow, density is low
  - Used to boot embedded devices, store configuration

- “NAND flash”
  - Read/write “pages” (512 B), erase “blocks” (16 KB)
  - Most SSDs today are NAND flash

- Newer things
  - “Phase-change” memory (melting), magnetic RAM, “Memristor” memory
  - Intel's new “3D XPoint” / “Optane”
Newer Things

What is “solid state” storage?

- “Phase-change” memory (melting)
- Magnetic RAM
- “Memristor” memory
- Intel's new “3D XPoint” / “Optane”
  - How it works isn't widely known
  - Characteristics
    - Word addressable (small random accesses are fast)
    - Slower than RAM, faster than NAND flash
    - Less power than RAM, more power than NAND flash
    - May not have write amplification
    - Wear is less of a threat
    - Price is a multiple of NAND flash
  - Initially packaged as “Optane” SSD
  - Expected to be packaged later as DIMMs
    - Exact usage model unclear
Solid-State Disks (SSD)

Architectural features of NAND flash
- No moving parts means no “seek time” / “rotational delay”
- Read is faster than write
- Write and “erase” are different
  - A blank page can be written to (just once)
  - A written page must be “erased” before rewriting
Solid-State Disks (SSD)

Architectural features of NAND flash

- No moving parts means no “seek time” / “rotational delay”
- Read is faster than write
- Write and “erase” are different
  - A blank page can be written to (just once)
  - A written page must be “erased” before rewriting
  - But pages can't be individually erased!
    - “Erase” works on multi-page blocks (16 KB)
    - “Erase” is very slow
    - “Erase” damages the block each time

Implications

- “Write amplification”
- “Wear leveling”
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)

Copy to RAM
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)
“Write Amplification”

Goal: update 8 pages (4 KB) in a block (16 KB)

Result
- Logical: wrote 4 KB
- Physical: erased-and-wrote 16 KB
- “Amplification factor”: 4
  - Why do we care? Device will wear out 4X faster!
Hot-Spot Wear

The bad case
- File systems like to write the same block repeatedly
- Erasing damages part of the flash
  - ~10,000 erases destroys a block

Strategy: ?
Managing - Wear Leveling

The bad case
- File systems like to write the same block repeatedly
- Erasing damages part of the flash
  - ~10,000 erases destroys a block

Strategy: lie to the OS!
- Host believes it is writing to specific “disk blocks” - LBA
- Store the information somewhere else!
  - Secretly re-map host address onto NAND address
  - FTL - “flash translation layer”
Managing - Wear Leveling

The bad case

- File systems like to write the same block repeatedly
- Erasing damages part of the flash
  - ~10,000 erases destroys a block

Strategy: lie to the OS!

- Host believes it is writing to specific “disk blocks” - LBA
- Store the information somewhere else!
  - Secretly re-map host address onto NAND address
  - FTL - “flash translation layer”
- Each part of the “disk” moves from one part of the flash to another over time
- “Over-provision”
  - Advertise less space than there really is
  - Use spare space to replace worn-out blocks
- Use up overprovisioning as blocks wear out
  - Device eventually gets slower and then fails
Wear Leveling - FTL

FTL is a **computer**
- CPU, RAM
- Access to lots of flash for code & data structures & user data
Managing - Write Amplification

The bad case
- Small random writes

Strategy: ?
Managing - Write Amplification

The bad case
- Small random writes

Strategy: lie to the OS!
- Host believes it is writing to specific “disk blocks” - LBA
- Store the information somewhere else!
  - Secretly re-map host address onto NAND address
  - FTL - “flash translation layer”
- Group multiple small writes into full blocks
  - Write at sequential write rates
- To update a “disk block”, store a new copy somewhere else
  - Leaves “holes” in other blocks (stale old block versions)
  - At some point, “clean out” the holes by reading a bunch of old blocks and writing back a smaller number of whole pages
- Rate of cleaning depends amount of unallocated space
  - Controller reserves X% hidden space (ie. 10, 20, 50%)
SSD Summary

SSD vs. disk

😊 SSD's implement "regular disk" model
  - LBA sectors
  - Write-sector, read-sector, "park heads", etc.

😊 Read operations are extremely fast (100X faster), no "seek time" or "rotational delay" (every sector is "nearby")

.Scanner.Write operations “vary widely” (maybe 100X faster, maybe not faster at all)

😊 SSD's use less power than actual disks (~1/5?)

😊 SSD's are shock-resistant

—including Writing to an SSD wears it out much faster than a disk

😊 SSD's are expensive (20X or more)
SSD Summary

Opportunity & threat
- “TRIM” command speeds up writes!
  - “Dear FTL, logically zero-fill these blocks”
- “Securely erase disk” may or may not be possible

The future?
- Lots more SSD's
- Lots more disks too
- Hybrid systems to take advantage of best features of both
What You Should Know

**Storage is slow**
- Whatever you want to do may take *milliseconds*

**Storage lies**
- You get some number of “disk blocks”
- There is no way to know where on the “disk” they are
- LBA is a faint approximation of proximity

**Failure model**
- Sometimes a read fails (sorry!)
- Writing to that block will cause the device to re-map
  - Both spinning-disk and SSD
- When re-map space is exhausted, device refuses to write

**Security**
- Actually erasing information from flash is uncertain
- Suggestion: encrypt
Summary

What is “storage”?  

Anatomy of a Hard Drive  

SSD's  

What you should know
Further Reading

Reliably Erasing Data from Flash-based Solid State Drives
Wei et al., UCSD
FAST '11

A Conversation with Jim Gray
Dave Patterson
ACM Queue, June 2003
http://queue.acm.org/detail.cfm?id=864078

Terabyte Territory
Brian Hayes
American Scientist, May/June 2002
http://www.americanscientist.org/issues/pub/terabyte-territory