CS 422/522 Design & Implementation of Operating Systems

Lecture 15: Storage Devices

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The big picture

- Lectures before the fall break:
  - Management of CPU & concurrency
  - Management of main memory & virtual memory
- Current topics --- "Management of I/O devices"
  - Last lecture: I/O devices & device drivers
  - This lecture: storage devices
  - Next week: file systems
    - File system structure
    - Naming and directories
    - Efficiency and performance
    - Reliability and protection

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Main points

- File systems
  - Useful abstractions on top of physical devices
- Storage hardware characteristics
  - Disks and flash memory
- File system usage patterns

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File systems

- Abstraction on top of persistent storage
  - Magnetic disk
  - Flash memory (e.g., USB thumb drive)
- Devices provide
  - Storage that (usually) survives across machine crashes
  - Block level (random) access
  - Large capacity at low cost
  - Relatively slow performance
    - * Magnetic disk read takes 10-20M processor instructions

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File system as illusionist: hide limitations of physical storage

- Persistence of data stored in file system:
  - Even if crash happens during an update
  - Even if disk block becomes corrupted
  - Even if flash memory wears out
- Naming:
  - Named data instead of disk block numbers
  - Directories instead of flat storage
  - Byte addressable data even though devices are block-oriented
- Performance:
  - Cached data
  - Data placement and data structure organization
- Controlled access to shared data

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File system abstraction

- File system
  - Persistent, named data
  - Hierarchical organization (directories, subdirectories)
  - Access control on data
- File: named collection of data
  - Linear sequence of bytes (or a set of sequences)
  - Read/write or memory mapped
- Crash and storage error tolerance
  - Operating system crashes (and disk errors) leave file system in a valid state
- Performance
  - Achieve close to the hardware limit in the average case

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Storage devices

- Magnetic disks
  - Storage that rarely becomes corrupted
  - Large capacity at low cost
  - Block level random access
  - Slow performance for random access
  - Better performance for streaming access
- Flash memory
  - Storage that rarely becomes corrupted
  - Capacity at intermediate cost (50x disk)
  - Block level random access
  - Good performance for reads; worse for random writes

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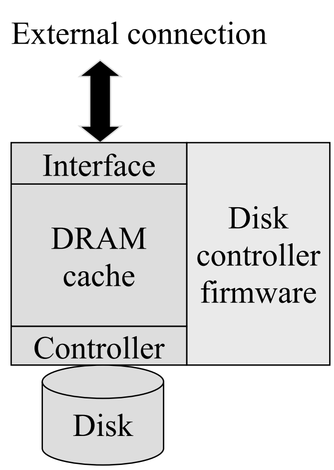
A typical disk controller

- External connection
  - IDE / ATA, SATA
  - SCSI, SCSI-2, Ultra SCSI, Ultra-160 SCSI, Ultra-320 SCSI
  - Fibre channel (FC)
- Cache
  - Buffer data between disk and the I/O bus
- Controller
  - Details of read/write
  - Cache replacement algorithm
  - Failure detection and recovery



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Caching inside a disk controller

- Method
  - Disk controller has DRAM to cache recently accessed blocks
    - Hitachi disk has 16MB
    - Some of the RAM space stores "firmware" (an embedded OS)
  - Blocks are replaced usually in an LRU order
- Pros
  - Good for reads if accesses have locality
- Cons
  - Expensive
  - Need to deal with reliable writes

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Magnetic disk

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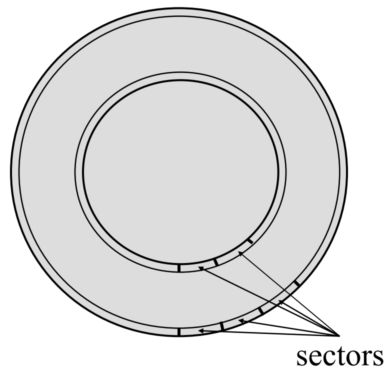
Disk organization

- Disk surface
  - Circular disk coated with magnetic material
- Tracks
  - Concentric rings around disk surface, bits laid out serially along each track
- Sectors
  - Each track is split into arc of track (min unit of transfer)



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Disk tracks

- ~ 1 micron wide
  - Wavelength of light is ~ 0.5 micron
  - Resolution of human eye: 50 microns
  - 100K tracks on a typical 2.5" disk
- Separated by unused guard regions
  - Reduces likelihood neighboring tracks are corrupted during writes (still a small non-zero chance)
- Track length varies across disk
  - Outside: More sectors per track, higher bandwidth
  - Disk is organized into regions of tracks with same # of sectors/track
  - Only outer half of radius is used
    - * Most of the disk area in the outer regions of the disk

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Sectors

- Sectors contain sophisticated error correcting codes
  - Disk head magnet has a field wider than track
  - Hide corruptions due to neighboring track writes
- Sector sparing
  - Remap bad sectors transparently to spare sectors on the same surface
- Slip sparing
  - Remap all sectors (when there is a bad sector) to preserve sequential behavior
- Track skewing
  - Sector numbers offset from one track to the next, to allow for disk head movement for sequential ops

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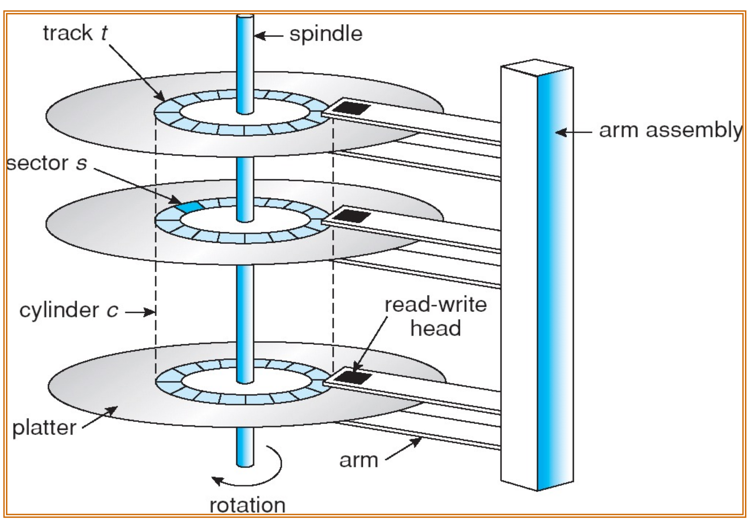
Moving-head disk mechanism



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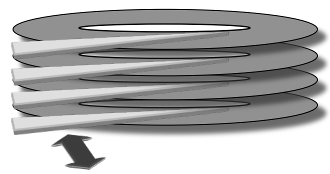
Disk cylinder and arm

- CD's and floppies come individually, but magnetic disks come organized in a disk pack
- Cylinder
  - Certain track of the platter
- Disk arm
  - A disk arm carries disk heads
- Read/write operation
  - Disk controller receives a command with <track#, sector#>
  - Seek the right cylinder (tracks)
  - Wait until the right sector comes
  - Perform read/write



seek a cylinder

Disk performance

Disk Latency =

Seek Time + Rotation Time + Transfer Time

Seek Time: time to move disk arm over track (1-20ms)

Fine-grained position adjustment necessary for head to "settle"

Head switch time ~ track switch time (on modern disks)

Rotation Time: time to wait for disk to rotate under disk head

Disk rotation: 4 – 15ms (depending on price of disk)

On average, only need to wait half a rotation

Transfer Time: time to transfer data onto/off of disk

Disk head transfer rate: 50-100MB/s (5-10 usec/sector)

Host transfer rate dependent on I/O connector (USB, SATA, …)

Toshiba disk (2008)

Size	
Platters/Heads	2/4
Capacity	320 GB
Performance	
Spindle speed	7200 RPM
Average seek time read/write	10.5 ms/ 12.0 ms
Maximum seek time	19 ms
Track-to-track seek time	1 ms
Transfer rate (surface to buffer)	54–128 MB/s
Transfer rate (buffer to host)	375 MB/s
Buffer memory	16 MB
Power	
Typical	16.35 W
Idle	11.68 W

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Question

- How long to complete 500 random disk reads, in FIFO order?

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Question

- How long to complete 500 random disk reads, in FIFO order?
  - Seek: average 10.5 msec
  - Rotation: average 4.15 msec
  - Transfer: 5-10 usec
- 500 * (10.5 + 4.15 + 0.01)/1000 = 7.3 seconds

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Question

- How long to complete 500 sequential disk reads?

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Question

- How long to complete 500 sequential disk reads?
  - Seek Time: 10.5 ms (to reach first sector)
  - Rotation Time: 4.15 ms (to reach first sector)
  - Transfer Time: (outer track)
    - 500 sectors * 512 bytes / 128MB/sec = 2ms

Total: 10.5 + 4.15 + 2 = 16.7 ms

Might need an extra head or track switch (+1ms)

Track buffer may allow some sectors to be read off disk out of order (-2ms)

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Question

- How large a transfer is needed to achieve 80% of the max disk transfer rate?

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Question

- How large a transfer is needed to achieve 80% of the max disk transfer rate?

  Assume x rotations are needed, then solve for x:

  0.8 (10.5 ms + (1ms + 8.5ms) x) = 8.5ms x

Total: x = 9.1 rotations, 9.8MB

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Disk scheduling

- FIFO
  - Schedule disk operations in order they arrive
  - Downsides?

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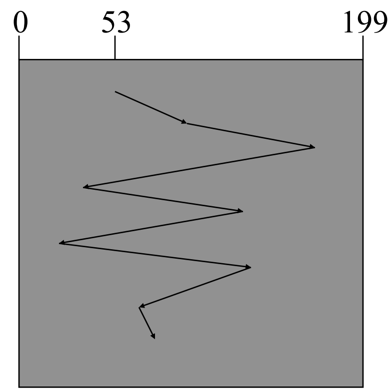
FIFO (FCFS) order

- Method
  - First come first serve
- Pros
  - Fairness among requests
  - In the order applications expect
- Cons
  - Arrival may be on random spots on the disk (long seeks)
  - Wild swing can happen



98, 183, 37, 122, 14, 124, 65, 67

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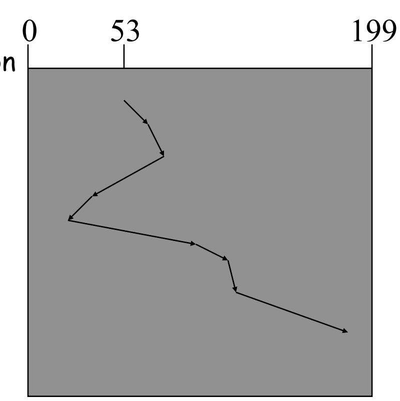
SSTF (Shortest Seek Time First)

- Method
  - Pick the one closest on disk
  - Rotational delay is in calculation
- Pros
  - Try to minimize seek time
- Cons
  - Starvation
- Question
  - Is SSTF optimal?
  - Can we avoid the starvation?



98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 37, 14, 98, 122, 124, 183)

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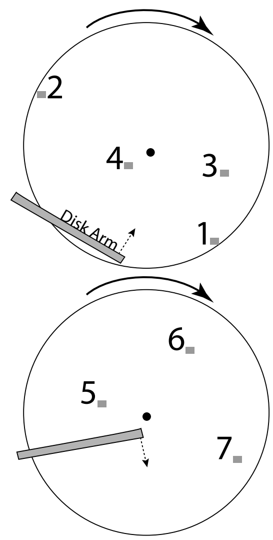
Disk scheduling

- SCAN: move disk arm in one direction, until all requests satisfied, then reverse direction
- Also called "elevator scheduling"



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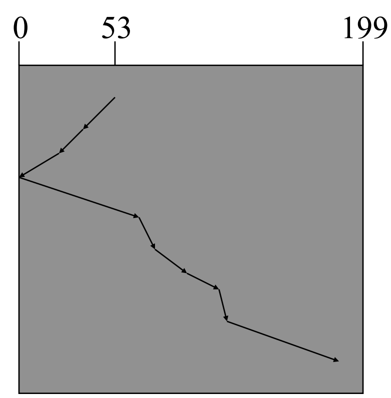
Elevator (SCAN)

- Method
  - Take the closest request in the direction of travel
  - Real implementations do not go to the end (called LOOK)
- Pros
  - Bounded time for each request
- Cons
  - Request at the other end will take a while



98, 183, 37, 122, 14, 124, 65, 67
(37, 14, 65, 67, 98, 122, 124, 183)

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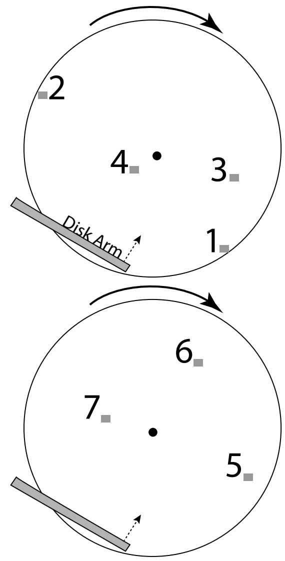
Disk scheduling

- CSCAN: move disk arm in one direction, until all requests satisfied, then start again from farthest request



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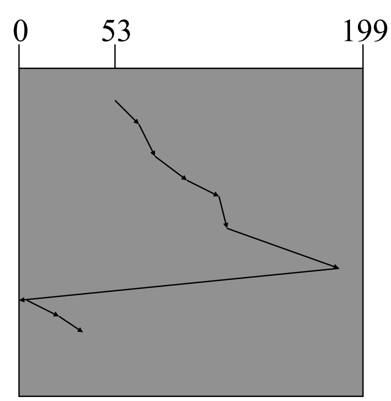
C-SCAN (Circular SCAN)

- Method
  - Like SCAN
  - But, wrap around
  - Real implementation doesn't go to the end (C-LOOK)
- Pros
  - Uniform service time
- Cons
  - Do nothing on the return



98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 98, 122, 124, 183, 14, 37)

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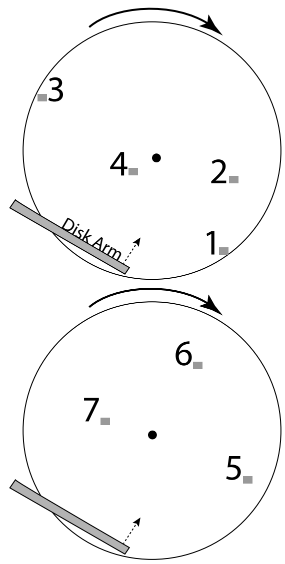
Disk scheduling

- R-CSCAN: CSCAN but take into account that short track switch is < rotational delay



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Question

- How long to complete 500 random disk reads, in any order?

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Question

- How long to complete 500 random disk reads, in any order?
  - Disk seek: 1ms (most will be short)
  - Rotation: 4.15ms
  - Transfer: 5-10usec
- Total: 500 * (1 + 4.15 + 0.01) = 2.2 seconds
  - Would be a bit shorter with R-CSCAN
  - vs. 7.3 seconds if FIFO order

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Question

- How long to read all of the bytes off of a disk?

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Question

- How long to read all of the bytes off of a disk?
  - Disk capacity: 320GB
  - Disk bandwidth: 54-128MB/s
- Transfer time =

  Disk capacity / average disk bandwidth

  ~ 3500 seconds (1 hour)

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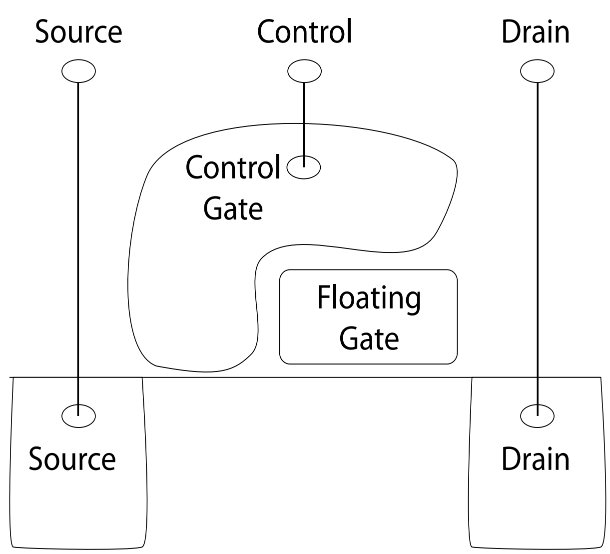
Flash memory



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Flash memory

- Writes must be to "clean" cells; no update in place
  - Large block erasure required before write
  - Erasure block: 128 – 512 KB
  - Erasure time: Several milliseconds
- Write/read page (2-4KB)
  - 50-100 usec

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Flash drive (2011)

Size	
Capacity	300 GB
Page Size	4KB
Performance	
Bandwidth (Sequential Reads)	270 MB/s
Bandwidth (Sequential Writes)	210 MB/s
Read/Write Latency	75 μs
Random Reads Per Second	38,500
Random Writes Per Second	2,000 (2,400 with 20% space reserve)
Interface	SATA 3 Gb/s
Endurance	
Endurance	1.1 PB (1.5 PB with 20% space reserve)
Power	
Power Consumption Active/Idle	3.7 W / 0.7 W

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Question

- Why are random writes so slow?
  - Random write: 2000/sec
  - Random read: 38500/sec

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Flash translation layer

- Flash device firmware maps logical page # to a physical location
  - Garbage collect erasure block by copying live pages to new location, then erase
    - More efficient if blocks stored at same time are deleted at same time (e.g., keep blocks of a file together)
  - Wear-leveling: only write each physical page a limited number of times
  - Remap pages that no longer work (sector sparing)
- Transparent to the device user

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File system – flash

- How does Flash device know which blocks are live?
  - Live blocks must be remapped to a new location during erasure
- TRIM command
  - File system tells device when blocks are no longer in use

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File system workload

- File sizes
  - Are most files small or large?
  - Which accounts for more total storage: small or large files?

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File system workload

- File sizes
  - Are most files small or large?
    - SMALL
  - Which accounts for more total storage: small or large files?
    - LARGE

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File system workload

- File access
  - Are most accesses to small or large files?
  - Which accounts for more total I/O bytes: small or large files?

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File system workload

- File access
  - Are most accesses to small or large files?
    - SMALL
  - Which accounts for more total I/O bytes: small or large files?
    - LARGE

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File system workload

- How are files used?
  - Most files are read/written sequentially
  - Some files are read/written randomly
    - Ex: database files, swap files
  - Some files have a pre-defined size at creation
  - Some files start small and grow over time
    - Ex: program stdout, system logs

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File system design

- For small files:
  - Small blocks for storage efficiency
  - Concurrent ops more efficient than sequential
  - Files used together should be stored together
- For large files:
  - Storage efficient (large blocks)
  - Contiguous allocation for sequential access
  - Efficient lookup for random access
- May not know at file creation
  - Whether file will become small or large
  - Whether file is persistent or temporary
  - Whether file will be used sequentially or randomly

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File system abstraction

- Directory
  - Group of named files or subdirectories
  - Mapping from file name to file metadata location
- Path
  - String that uniquely identifies file or directory
  - Ex: /cse/www/education/courses/cse451/12au
- Links
  - Hard link: link from name to metadata location
  - Soft link: link from name to alternate name
- Mount
  - Mapping from name in one file system to root of another

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UNIX file system API

- create, link, unlink, createdir, rmdir
  - Create file, link to file, remove link
  - Create directory, remove directory
- open, close, read, write, seek
  - Open/close a file for reading/writing
  - Seek resets current position
- fsync
  - File modifications can be cached
  - fsync forces modifications to disk (like a memory barrier)

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File system interface

- UNIX file open is a Swiss Army knife:
  - Open the file, return file descriptor
  - Options:
    - if file doesn't exist, return an error
    - If file doesn't exist, create file and open it
    - If file does exist, return an error
    - If file does exist, open file
    - If file exists but isn't empty, nix it then open
    - If file exists but isn't empty, return an error
    - …

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Interface design question

- Why not separate syscalls for open/create/exists?
  - Would be more modular!

```
if (!exists(name))
    create(name);   // can create fail?
fd = open(name);   // does the file exist?
```

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