CS61C
Anatomy of I/O Devices: Magnetic Disks

Lecture 15

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www-inst.eecs.berkeley.edu/~cs61c/schedule.html

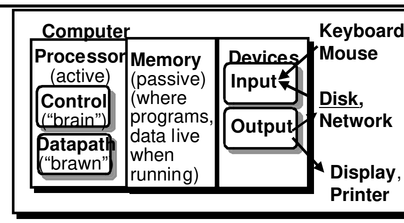
"Review.." 1/2

- **Protocol suites allow heterogeneous networking**
  - Another use of principle of abstraction
  - Protocols ⇒ operation in presence of failures
  - Standardization key for LAN, WAN
- **Integrated circuit revolutionizing network switches as well as processors**
  - Switch just a specialized computer
- **High bandwidth networks with slow SW overheads don't deliver their promise**

Outline

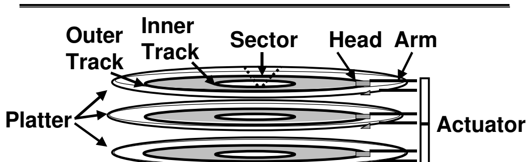
- Basic Terms/ Mechanical Operation
- History
- Disk Performance
- Administrivia, "What's this Stuff Good for"
- Disk Trends
- Disk Arrays, Reliability
- RAID
- Conclusion

Magnetic Disks



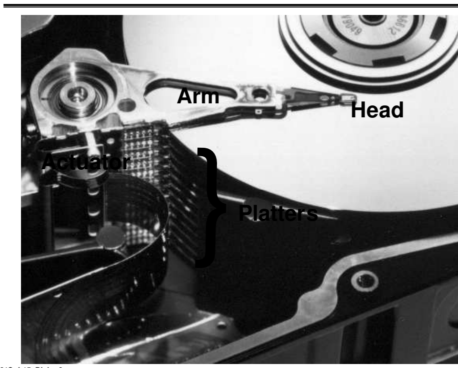
- **Purpose:**
  - Long-term, nonvolatile, inexpensive storage for files
  - Large, inexpensive, slow level in the memory hierarchy (discuss later)

Disk Device Terminology

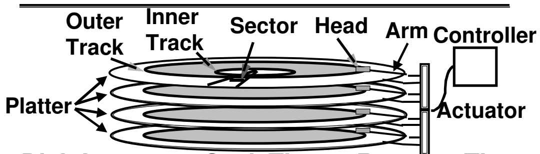


- Several <u>platters</u>, with information recorded magnetically on both <u>surfaces</u> (usually)
- Bits recorded in <u>tracks</u>, which in turn divided into <u>sectors</u> (e.g., 512 Bytes)
- <u>Actuator</u> moves <u>head</u> (end of <u>arm</u>,1/surface) over track (<u>"seek"</u>), select <u>surface</u>, wait for <u>sector</u> rotate under <u>head</u>, then read or write
  - "<u>Cylinder</u>": all tracks under heads

Photo of Disk Head, Arm, Actuator



Disk Device Performance



- Disk Latency = Seek Time + Rotation Time + Transfer Time + Controller Overhead
  - Seek Time? depends no. tracks move arm, seek speed of disk
  - Rotation Time? depends on speed disk rotates, how far sector is from head
  - Transfer Time? depends on data rate (bandwidth) of disk, size of request

Disk Device Performance

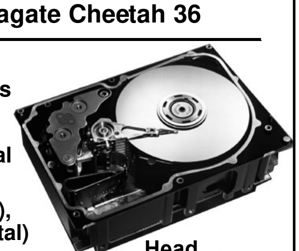
- Average distance sector from head?
- 1/2 time of a rotation
  - 7200 Revolutions Per Minute $\Rightarrow$ 120 Rev/sec
  - 1 revolution = 1/120 sec $\Rightarrow$ 8.33 milliseconds
  - 1/2 rotation $\Rightarrow$ 4.16 ms
- Average no. tracks move arm?
  - Calculate all possible seek distances from all possible tracks
  - Answer: about 1/3 number of tracks
  - (Disk industry standard benchmark)

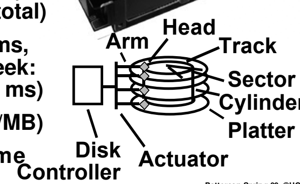
Data Rate: Inner vs. Outer Track

- To keep things simple, orginally kept same number of sectors per track
  - Since outer track longer, lower bits per inch
- As competition grew, decided to keep BPI the same for all tracks ("constant bit density")
  - More capacity per disk
  - more of sectors per track towards edge
- Since disk spins at constant speed, outer track has faster data rate
  - 1.5X outer track vs. inner track!

State of the Art: Seagate Cheetah 36

- 36.4 GB, 3.5 inch disk
- 12 platters, 24 surfaces
- 10,000 RPM
- 18.3 to 28 MB/s internal media transfer rate
- 9772 cylinders (tracks), (71,132,960 sectors total)
- Avg. seek: read 5.2 ms, write 6.0 ms (Max. seek: 12/13,1 track: 0.6/0.9 ms)
- \$2100 or 17MB/\$ (6¢/MB)
- 0.15 ms controller time





source: www.seagate.com

Disk Performance Example

- Calculate time to read 1 sector (512B) for Cheetah 36 using advertised performance; sector is on outer track

Disk latency = average seek time + average rotational delay + transfer time + controller overhead

= 5.2 ms + 0.5 * 1/(10000 RPM) + 0.5 KB / (28 MB/s) + 0.15 ms

= 5.2 ms + 0.5 /(10000 RPM/(60000ms/M)) + 0.5 KB / (28 KB/ms) + 0.15 ms

= 5.2 + 3.0 + 0.18 + 0.15 ms = 8.53 ms

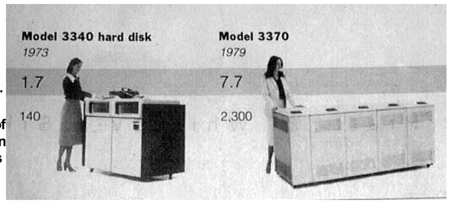
Areal Density

- Bits records along track
  - Metric is Bits Per Inch (BPI)
- Number of tracks per surface
  - Metric is Tracks Per Inch (TPI)
- Care about bit density per units area
  - Metric is Bits Per Square Inch
  - Called Areal Density
  - Areal Density = BPI x TPI

Disk History (IBM)

Data density Mbit/sq. in.

Capacity of Unit Shown Megabytes

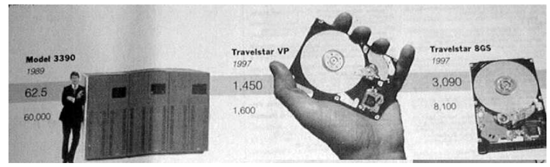


1973:
1. 7 Mbit/sq. in
140 MBytes

1979:
7. 7 Mbit/sq. in
2,300 MBytes

source: New York Times, 2/23/98, page C3,
"Makers of disk drives crowd even more data into even smaller spaces"

Disk History



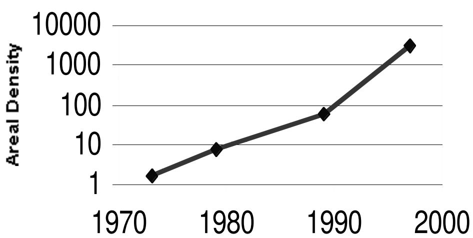
1989:
63 Mbit/sq. in
60,000 MBytes

1997:
1450 Mbit/sq. in
2300 MBytes

1997:
3090 Mbit/sq. in
8100 MBytes

source: New York Times, 2/23/98, page C3,
"Makers of disk drives crowd even more data into even smaller spaces"

Areal Density



- **Areal Density = BPI x TPI**
- **Change slope 30%/yr to 60%/yr about 1991**

Historical Perspective

- **Form factor plus capacity drives market, not so much performance**
- **1970s: Mainframes ⇒ 14 inch disks**
- **1980s: Minicomputers, Servers ⇒ 8", 5.25" disks**
- **Late 1980s/Early 1990s:**
  - **Laptops, notebooks,**
  - **3.5 inch, 2.5 inch**
  - **Palmtops didn't use disks, so 1.8 inch disks didn't make it**

1 inch disk drive!

- **1999 IBM MicroDrive:**
  - **1.7" x 1.4" x 0.2"**
  - **340 MB, 5400 RPM, 5 MB/s, 15 ms seek**
  - **Digital camera, PalmPC?**
- **2006 MicroDrive?**
  - **Assuming its found place in successful product**
  - **Assuming past trends continue**
  - **9 GB, 50 MB/s!**

Administrivia

- **6th homework: Due Today (8AM tomorrow)**
- **4th Project: Friday 3/12 7PM (absolute latest: 3/13 8AM)**
- **Readings: Cache Memory 7.1, 7.2**
- **Upcoming events**
  - **Midterm Review Sunday 3/14 2PM, 1 Pimentel**
  - **Midterm on Wed. 3/17 5pm-8PM, 1 Pimentel**
  - **Friday before Break 3/19: video tape by Gordon Moore, "Nanometers and Gigabucks"**
- **Copies of lecture slides in 271 Soda? Copies before midterm in Copy Central?**

"What's This Stuff Good For?"

Computers with wireless modems let drivers keep in touch with headquarters through E-mail. Companies can send out fleetwide communications, and drivers can tell dispatchers about any delays.

A truck using this Global Positioning System (GPS) technology sends signals to satellites, which send the truck's position to system's manufacturer, Qualcomm. That information is relayed to trucking company dispatchers. Collision-avoidance systems based on radar make alarms go off if a truck gets too close to another vehicle, giving the driver time to take evasive action. Such systems can also track whether a driver habitually tailgates and pass that information along to the company. N.Y. Times, 3/4/99

Fallacy: Use Data Sheet "Average Seek" Time

- Manufacturers needed standard for fair comparison ("benchmark")
  - Calculate all seeks from all tracks, divide by number of seeks = "average"
- Real average would be based on how data laid out on disk, where seek in real applications, measure performance
  - Usually, tend to seek to tracks nearby, not to random track
- Rule of Thumb: observed average seek time is typically 25% to 33% of quoted seek time (i.e., 3X-4X faster)
  - Cheetah 36 avg: 5.2 ms seek => 1.7 ms seek

Fallacy: Use Data Sheet Transfer Rate

- Manufacturers quote the speed off the data rate off the disk
- Sectors contain an error detection and correction field as well as data (can be 20% of sector)
- There are gaps between sectors on track
- Rule of Thumb: disks deliver about 75% of internal media rate (1.3X slower)
- For example, Cheetah 36 quotes 28 to 18 MB/s internal media rate
- Expect 21 to 14 MB/s user data rate

Disk Performance Example

- Calculate time to read 1 sector for Cheetah 36 again, this time using 1/3 quoted seek time, 75% of internal outer track bandwidth; (before it was 8.53 ms)

Disk latency = average seek time + average rotational delay + transfer time + controller overhead

= (0.33 * 5.2 ms) + 0.5 * 1/(10000 RPM) + 0.5 KB / (0.75 * 28 MB/s) + 0.15 ms

= 1.73 ms + 0.5 /(10000 RPM/(60000ms/M)) + 0.5 KB / (21 KB/ms) + 0.15 ms

= 1.73 + 3.0 + 0.24 + 0.15 ms = 4.73 ms

Disk Performance Model /Trends

- Capacity
  - + 60%/year (2X / 1.5 yrs)
- Transfer rate (BW)
  - + 40%/year (2X / 2.0 yrs)
- Rotation + Seek time
  - – 8%/ year (1/2 in 10 yrs)
- MB/$
  - > 60%/year (2X / <1.5 yrs)
  - Fewer chips + areal density

Disk Size and Performance

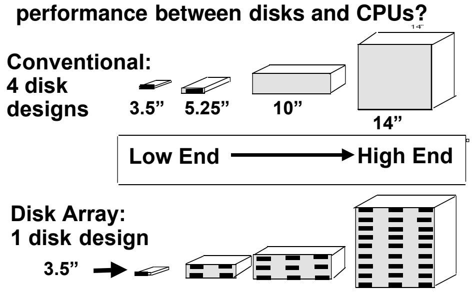
- Continued advance in capacity (60%/yr) and bandwidth (40%/yr.)
- Slow improvement in seek, rotation (8%/yr)
- Time to read whole disk

Year	Sequentially	Randomly
1990	4 minutes	6 hours
2000	12 minutes	1 week

- 3.5" form factor still make sense in 5 years?

Use Arrays of Small Disks?

- Randy Katz and myself asked in 1987:
  - Can smaller disks be used to close gap in performance between disks and CPUs?



Replace Small Number of Large Disks with Large Number of Small Disks! (1988 Disks)

	IBM 3390K	IBM 3.5" 0061	x70
Capacity	20 GBytes	320 MBytes	23 GBytes
Volume	97 cu. ft.	0.1 cu. ft.	11 cu. ft.
Power	3 KW	11 W	1 KW
Data Rate	15 MB/s	1.5 MB/s	120 MB/s
I/O Rate	600 I/Os/s	55 I/Os/s	3900 IOs/s
MTTF	250 KHrs	50 KHrs	??? Hrs
Cost	$250K	$2K	$150K

Disk Arrays have potential for large data and I/O rates, high MB per cu. ft., high MB per KW, but what about reliability?

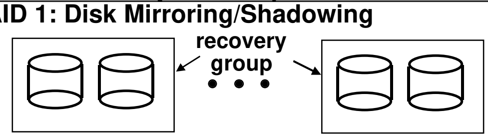
Array Reliability

- Reliability - whether or not a component has failed
  - measured as Mean Time To Failure (MTTF)
- Reliability of N disks = Reliability of 1 Disk ÷ N
  - 50,000 Hours ÷ 70 disks = 700 hour
- Disk system MTTF: Drops from 6 years to 1 month!
- Arrays too unreliable to be useful!

Redundant Arrays of (Inexpensive) Disks

- Files are "striped" across multiple disks
- Redundancy yields high data availability
  - Availability: service still provided to user, even if some components failed
- Disks will still fail
- Contents reconstructed from data redundantly stored in the array
  - ⇒ Capacity penalty to store redundant info
  - ⇒ Bandwidth penalty to update redundant info

Redundant Arrays of Inexpensive Disks
RAID 1: Disk Mirroring/Shadowing

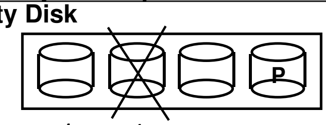


- Each disk is fully duplicated onto its "shadow"
  Very high availability can be achieved
- Bandwidth sacrifice on write:
  Logical write = two physical writes
  - Reads may be optimized
- Most expensive solution: 100% capacity overhead
- (RAID 2 not interesting, so skip)

Redundant Array of Inexpensive Disks
RAID 3: Parity Disk

10010011
11001101
10010011
. . .

logical record



Striped physical records

1	1	1	1
0	1	0	1
0	0	0	0
1	0	1	0
0	1	0	1
0	1	0	1
1	0	1	1
1	1	1	1

P contains sum of other disks per stripe

If disk fails, subtract P from sum of other disks to find missing information

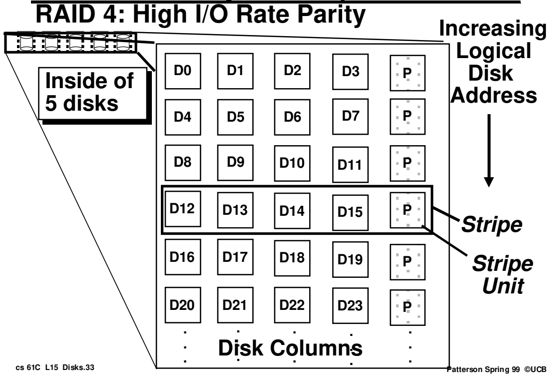
RAID 3

- Sum computed across recovery group to protect against hard disk failures, stored in P disk
- Arms logically synchronized, spindles rotationally synchronized
- Logically a single high capacity, high transfer rate disk: good for large transfers
- Wider arrays reduce capacity costs, but decreases availability, increases repair time
- 33% capacity cost for parity in this configuration

Inspiration for RAID 4

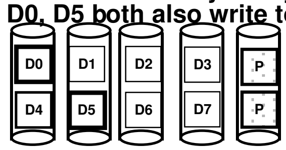
- RAID 3 relies on Check bits to discover errors on Read
- But every sector has an error detection field
- Rely on error detection field to catch errors on read, not on check disk
- Allows independent reads to different disks simultaneously

Redundant Arrays of Inexpensive Disks RAID 4: High I/O Rate Parity

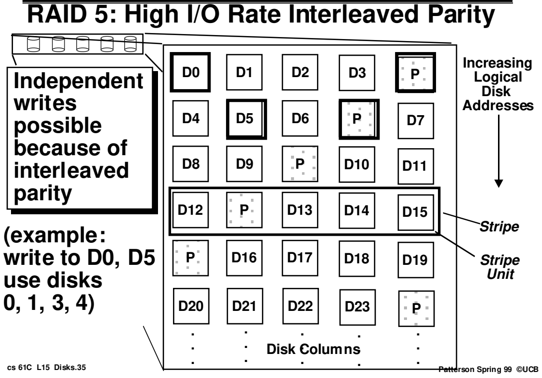


Inspiration for RAID 5

- RAID 4 works well for small reads
- Small writes (write to one disk):
  - Option 1: read other data disks, create new sum and write to Parity Disk
  - Option 2: since P has old sum, compare old data to new data, add the difference to P
- Small writes are limited by Parity Disk: Write to D0, D5 both also write to P disk



Redundant Arrays of Inexpensive Disks RAID 5: High I/O Rate Interleaved Parity



(example: write to D0, D5 use disks 0, 1, 3, 4)

Berkeley History: RAID-I

- RAID-I (1989)
  - Consisted of a Sun 4/280 workstation with 128 MB of DRAM, four dual-string SCSI controllers, 28 5.25-inch SCSI disks and specialized disk striping software
- Today RAID is multi billion dollar industry, > 50 companies, from PCs to mainframes

“And in Conclusion..” 1/1

- **Magnetic Disks continue rapid advance: 60%/yr capacity, 40%/yr bandwidth, slow on seek, rotation improvements, MB/$ improving 100%/yr?**
  - Designs to fit high volume form factor
  - Quoted seek times too conservative, data rates too optimistic for use in system
- **RAID**
  - Higher performance with more disk arms per $
  - Adds availability option at modest cost
- **Next: Introduction to Caches, Review of 1st Half 61C**