CS61C - Machine Structures

Lecture 16 - Disks

October 20, 2000

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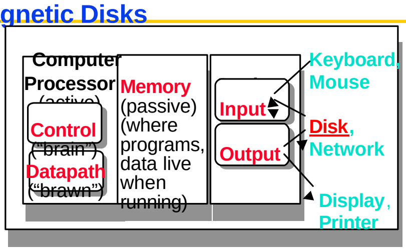
Review

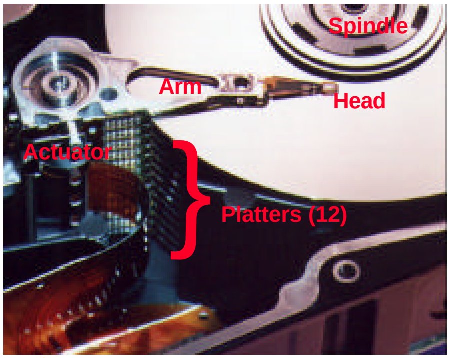
- Protocol suites allow heterogeneous networking
  - Another form of principle of abstraction
  - Protocols Þ operation in presence of failures
  - Standardization key for LAN, WAN
- Integrated circuit revolutionizing network switches as well as processors
  - Switch just a specialized computer
- Trend from shared to switched networks to get faster links and scalable bandwidth

Magnetic Disks

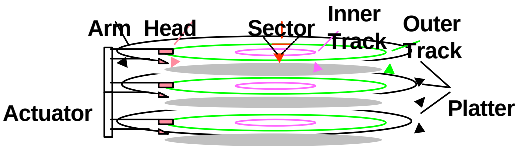


- Purpose:
  - Long-term, nonvolatile, inexpensive storage for files
  - Large, inexpensive, slow level in the memory hierarchy (discuss later)

Photo of Disk Head, Arm, Actuator

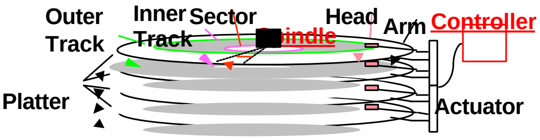


Disk Device Terminology



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

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 (bit density), size of request

Disk Device Performance

- ° Average distance sector from head?
- ° 1/2 time of a rotation
  - 7200 Revolutions Per Minute Þ 120 Rev/sec
  - 1 revolution = 1/120 sec Þ 8.33 milliseconds
  - 1/2 rotation (revolution) Þ 4.16 ms
- ° Average no. tracks move arm?
  - Sum all possible seek distances from all possible tracks / # possible
    - Assumes average seek distance is random
  - Disk industry standard benchmark

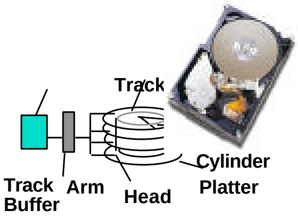
Data Rate: Inner vs. Outer Tracks

- ° To keep things simple, orginally kept same number of sectors per track
  - Since outer track longer, lower bits per inch
- ° Competition Þ decided to keep BPI the same for all tracks ("constant bit density")
  - Þ More capacity per disk
  - Þ More of sectors per track towards edge
  - Þ Since disk spins at constant speed, outer tracks have faster data rate
- ° Bandwidth outer track 1.7X inner track!

Disk Performance Model /Trends

- ° Capacity
  - \+ 100%/year (2X / 1.0 yrs)
- ° Transfer rate (BW)
  - \+ 40%/year (2X / 2.0 yrs)
- ° Rotation + Seek time
  - – 8%/ year (1/2 in 10 yrs)
- ° MB/$
  - \> 100%/year (2X / <1.5 yrs)
  - Fewer chips + areal density

State of the Art: Ultrastar 72ZX



Latency =

per access + per byte { Queuing Time + Controller time + Seek Time + Rotation Time + Size / Bandwidth

- 73.4 GB, 3.5 inch disk
- 2¢/MB
- 10,000 RPM; 3 ms = 1/2 rotation
- 11 platters, 22 surfaces
- 15,110 cylinders
- 7 Gbit/sq. in. areal den
- 17 watts (idle)
- 0.1 ms controller time
- 5.3 ms avg. seek
- 50 to 29 MB/s(internal)

source: www.ibm.com; www.pricewatch.com; 2/14/00

Disk Performance Example (will fix later)

- ° Calculate time to read 1 sector (512B) for UltraStar 72 using advertised performance; sector is on outer track

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

= 5.3 ms + 0.5 * 1/(10000 RPM) + 0.5 KB / (50 MB/s) + 0.15 ms

= 5.3 ms + 0.5 /(10000 RPM/(60000ms/M)) + 0.5 KB / (50 KB/ms) + 0.15 ms

= 5.3 + 3.0 + 0.10 + 0.15 ms = 8.55 ms

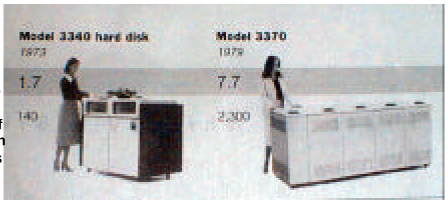
Areal Density

- ° Bits recorded along a track
  - Metric is Bits Per Inch (BPI)
- ° Number of tracks per surface
  - Metric is Tracks Per Inch (TPI)
- ° Care about bit density per unit 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

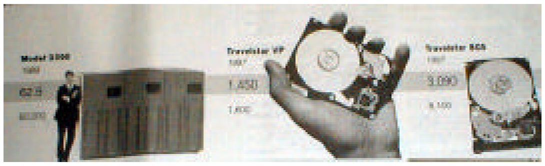


1973:
1. 7 Mbit/sq. in
140 MBytes

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



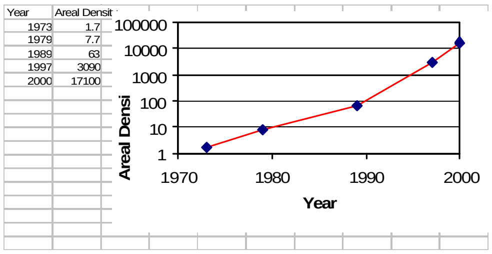
1989:
63 Mbit/sq. in
60,000 MBytes

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



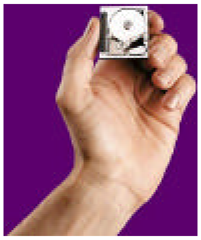
Year	Areal Densit
1973	1.7
1979	7.7
1989	63
1997	3090
2000	17100

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

Historical Perspective

- **Form factor and capacity drives market, more than performance**
- **1970s: Mainframes Þ 14 inch diameter disks**
- **1980s: Minicomputers, Servers Þ 8", 5.25" diameter disks**
- **Late 1980s/Early 1990s:**
  - **Pizzabox PCs Þ 3.5 inch diameter disks**
  - **Laptops, notebooks Þ 2.5 inch disks**
  - **Palmtops didn't use disks, so 1.8 inch diameter disks didn't make it**

1 inch disk drive!



- **2000 IBM MicroDrive:**
  - **1.7" x 1.4" x 0.2"**
  - **1 GB, 3600 RPM, 5 MB/s, 15 ms seek**
  - **Digital camera, PalmPC?**
- **2006 MicroDrive?**
- **9 GB, 50 MB/s!**
  - **Assuming it finds a niche in a successful product**
  - **Assuming past trends continue**

Administrivia

- **Midterm Review Sunday Oct 22 starting 2 PM in155 Dwinelle**
- **Midterm will be Wed Oct 25 5-8 P.M.**
  - **1 Pimintel**
  - **Midterm conflicts? Talk to TA about taking early midterm ("beta tester")**
  - **Pencils**
  - **2 sides of paper with handwritten notes**
  - **no calculators**
  - **Sample midterm online, old midterms online**

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, then measure performance
  - Usually, tend to seek to tracks nearby, not to random track
- Rule of Thumb: observed average seek time is typically about 1/4 to 1/3 of quoted seek time (i.e., 3X-4X faster)
  - UltraStar 72 avg. seek: 5.3 ms Þ 1.7 ms

Fallacy: Use Data Sheet Transfer Rate

- Manufacturers quote the speed off the data rate off the surface of the disk
- Sectors contain an error detection and correction field (can be 20% of sector size) plus sector number as well as data
- There are gaps between sectors on track
- Rule of Thumb: disks deliver about 3/4 of internal media rate (1.3X slower) for data
- For example, UlstraStar 72 quotes 50 to 29 MB/s internal media rate

Þ Expect 37 to 22 MB/s user data rate

Disk Performance Example

- Calculate time to read 1 sector for UltraStar 72 again, this time using 1/3 quoted seek time, 3/4 of internal outer track bandwidth; (8.55 ms before)

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

= (0.33 * 5.3 ms) + 0.5 * 1/(10000 RPM) + 0.5 KB / (0.75 * 50 MB/s) + 0.15 ms

= 1.77 ms + 0.5 /(10000 RPM/(60000ms/M)) + 0.5 KB / (37 KB/ms) + 0.15 ms

= 1.73 + 3.0 + 0.14 + 0.15 ms = 5.02 ms

Future Disk Size and Performance

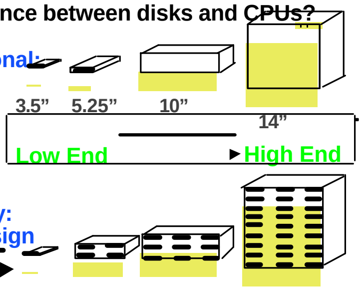
- Continued advance in capacity (60%/yr) and bandwidth (40%/yr)
- Slow improvement in seek, rotation (8%/yr)
- Time to read whole disk

Year	Sequentially	Randomly (1 sector/seek)
1990	4 minutes	6 hours
2000	12 minutes	1 week(!)

- 3.5” form factor make sense in 5-7 yrs?

Use Arrays of Small Disks?

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



Conventional: 4 disk designs

Disk Array: 1 disk design

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.	9X
Power	3 KW	11 W	1 KW	3X
Data Rate	15 MB/s	1.5 MB/s	120 MB/s	8X
I/O Rate	600 I/Os/s	55 I/Os/s	3900 IOs/s	6X
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
  (assuming failures independent)
  - 50,000 Hours ÷ 70 disks = 700 hour
- °Disk system MTTF:
  Drops from 6 years to 1 month!
- °Arrays too unreliable to be useful!

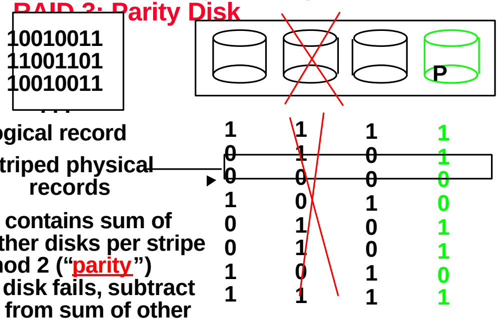
Redundant Arrays of (Inexpensive) Disks

- °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
  - Þ Capacity penalty to store redundant info
  - Þ Bandwidth penalty to update redundant info

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

- Each disk is fully duplicated onto its "**mirror**"
  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



logical record

Striped physical records

P contains sum of other disks per stripe mod 2 ("**parity**")
If disk fails, subtract P from sum of other disks to find missing information

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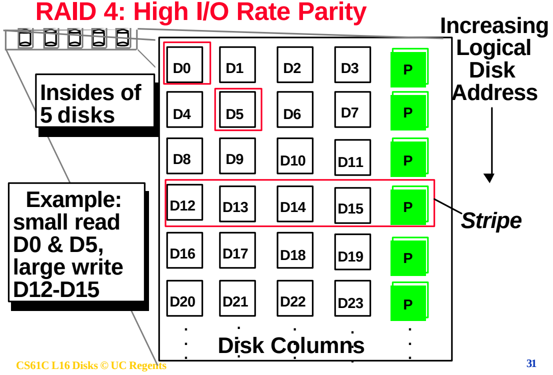
RAID 3

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

Inspiration for RAID 4

- °RAID 3 relies on parity disk 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 the parity disk
- °Allows independent reads to different disks simultaneously

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



Insides of 5 disks

Example: small read D0 & D5, large write D12-D15

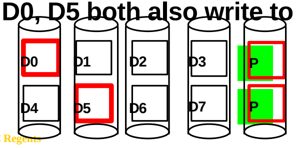
Increasing Logical Disk Address

Stripe

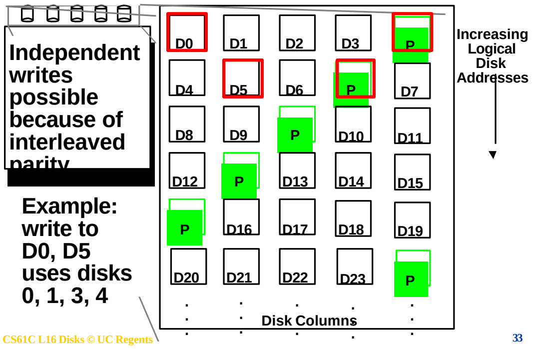
Disk Columns

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



Independent writes possible because of interleaved parity

Example: write to D0, D5 uses disks 0, 1, 3, 4

Increasing Logical Disk Addresses

Disk Columns

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 $19 billion dollar industry, 80% nonPC disks sold in RAIDs

“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 for small number of extra disks