Lecturer SOE
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UCB CS61C : Machine Structures

Lecture 37 – Disks
2008-04-28

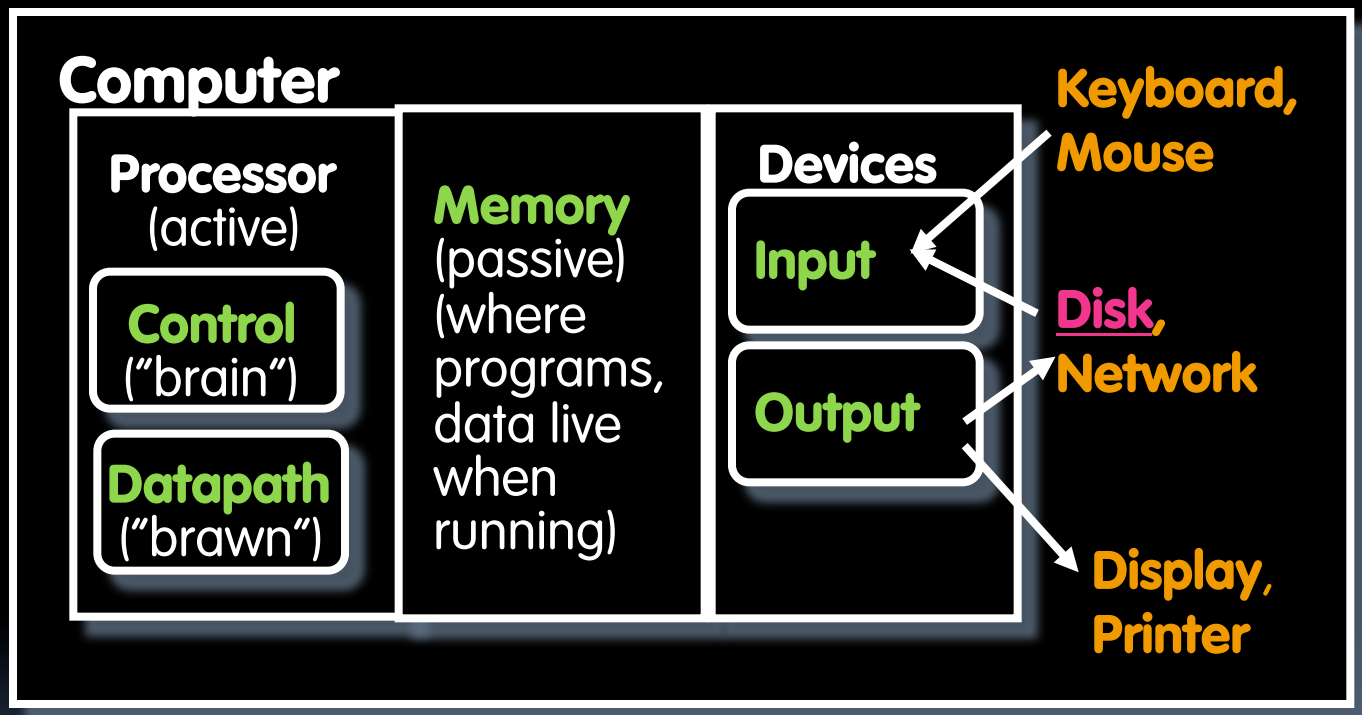
How much storage do YOU have?

SEAGATE SHIPS BILLIONTH DRIVE!

The ST506 was their first drive in 1979 (shown here), weighed 5 lbs, cost $1,500 and held 5 MeB. Today's drives hold 1 TB, and are available for less than $200.

1b.seagatestorage.com

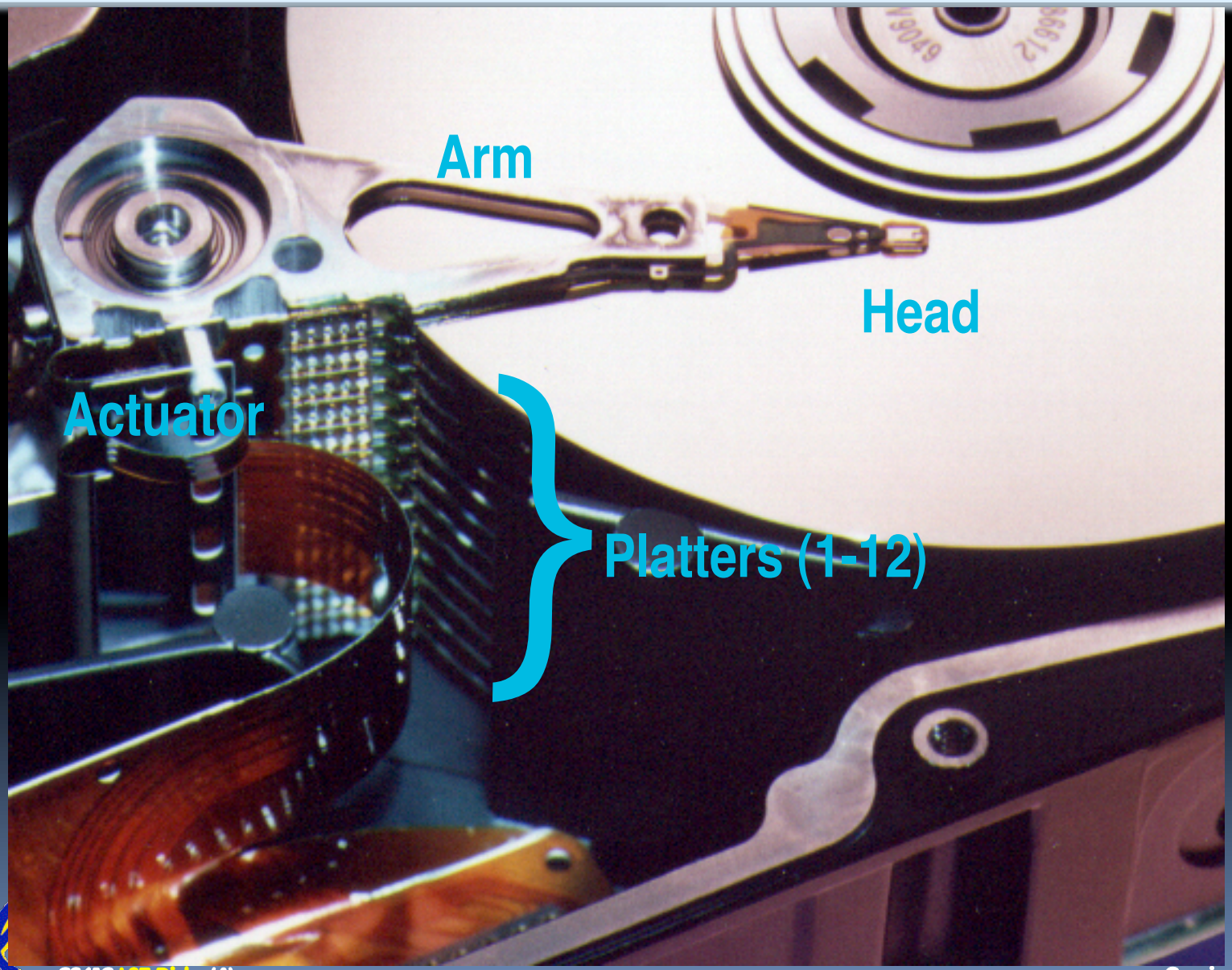
Magnetic Disk – common I/O device



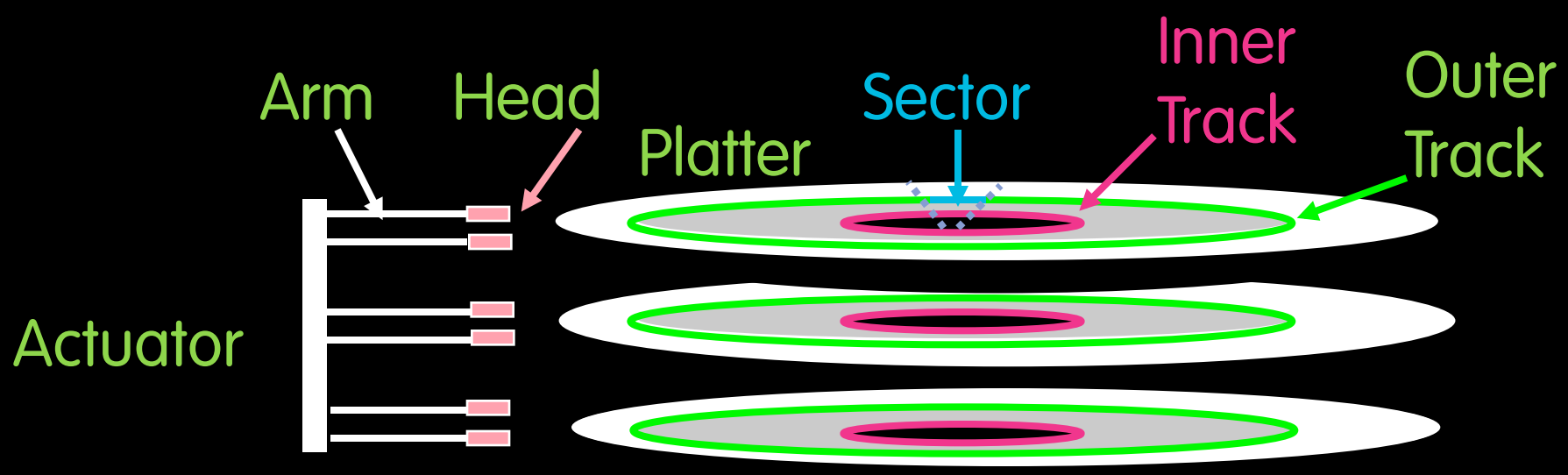
Magnetic Disk – common I/O device

- **A kind of computer memory**
  - Information stored by magnetizing ferrite material on surface of rotating disk
    - similar to tape recorder except digital rather than analog data
- **Nonvolatile storage**
  - retains its value without applying power to disk.
- **Two Types**
  - Floppy disks – slower, less dense, removable.
  - Hard Disk Drives (HDD) – faster, more dense, non-removable.
- **Purpose in computer systems (Hard Drive):**
  - Long-term, inexpensive storage for files
  - "Backup" for main-memory. Large, inexpensive, slow level in the memory hierarchy (virtual memory)

Photo of Disk Head, Arm, Actuator

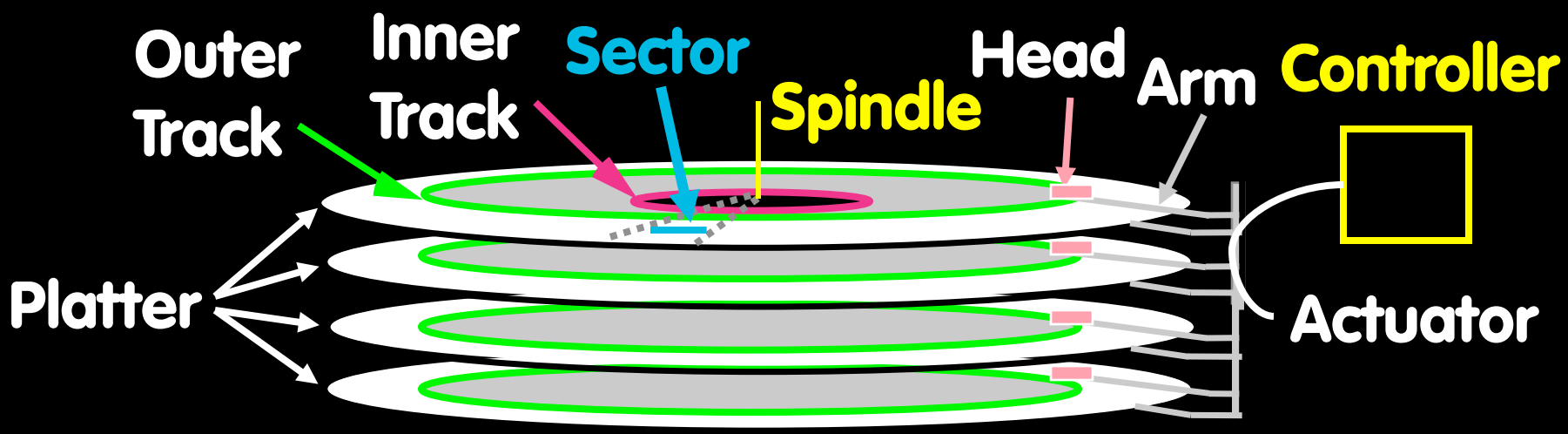


Disk Device Terminology



- 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) over track ("seek"), wait for sector rotate under head, then read or write

Disk Device Performance (1/2)



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

Disk Device Performance (2/2)

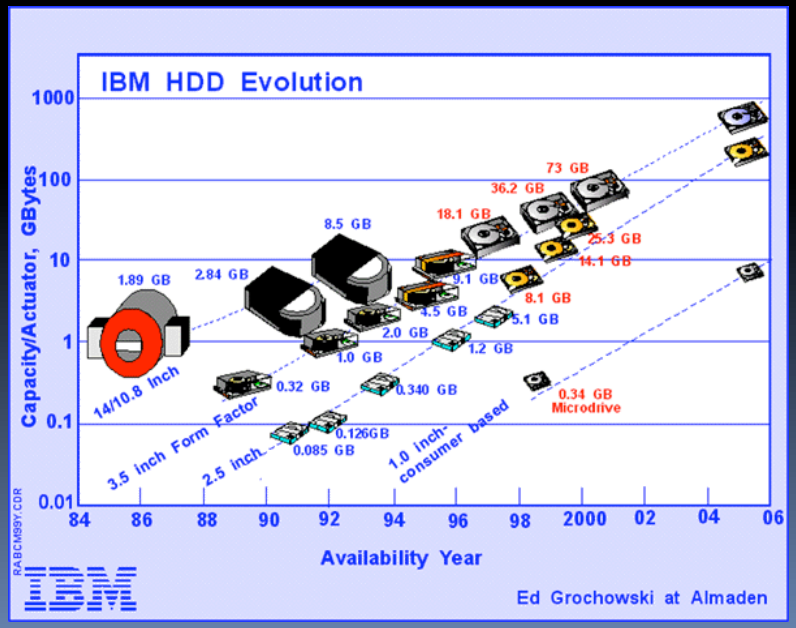
- **Average distance of sector from head?**
- **1/2 time of a rotation**
  - 7200 Revolutions Per Minute ⇒ 120 Rev/sec
  - 1 revolution = 1/120 sec ⇒ 8.33 milliseconds
  - 1/2 rotation (revolution) ⇒ 4.17 ms
- **Average no. tracks to move arm?**
  - Disk industry standard benchmark:
    - Sum all time for all possible seek distances from all possible tracks / # possible
    - Assumes average seek distance is random
- **Size of Disk cache can strongly affect perf!**
  - Cache built into disk system, OS knows nothing

Data Rate: Inner vs. Outer Tracks

- **To keep things simple, originally same number of sectors per track**
  - Since outer track longer, lower bits per inch
- **Competition ⇒ decided to keep bits per inch (BPI) high for all tracks ("constant bit density")**
  - ⇒ More capacity per disk
  - ⇒ More sectors per track towards edge
  - ⇒ 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)**
  - Over time, grown so fast that # of platters has reduced (some even use only 1 now!)
- **Transfer rate (BW) : + 40%/yr (2X / 2 yrs)**
- **Rotation+Seek time : – 8%/yr (1/2 in 10 yrs)**
- **Areal Density**
  - Bits recorded along a track: Bits/Inch (BPI)
  - # of tracks per surface: Tracks/Inch (TPI)
  - We care about bit density per unit area Bits/Inch^2
  - Called Areal Density = BPI x TPI
  - "~120 Gb/In^2 is longitudinal limit"
  - "230 Gb/In^2 now with perpendicular"
- **GB/$: > 100%/year (2X / 1.0 yrs)**
  - Fewer chips + areal density



State of the Art: Two camps (2008)

- **Performance**
  - Enterprise apps, servers
- **E.g., Seagate Cheetah 15K.6**
  - 3 Gb/s, Serial Attached SCSI, Fibre Channel
  - 450 GB, 3.5-inch disk
  - 4 disks, 8 heads
  - 15,000 RPM
  - 12-17 watts (idle-normal)
  - 3.4 ms avg. seek
  - 164 MB/s transfer rate
  - 1.6 Million Hrs MTBF
  - 5 year warrantee
  - $1000 = $3.30 / GB

- **Capacity**
  - Mainstream, home uses
- **E.g., Seagate Barracuda 7200.11**
  - SATA 3Gb/s NCQ, SATA 1.5Gb/s NCQ
  - 1 TB, 3.5-inch disk
  - 4 disks, 8 heads
  - 7,200 RPM
  - 8-12 watts (idle-normal)
  - ?? ms avg. seek (last one 8.5)
  - 115 MB/s transfer rate
  - 0.75 Million Hrs MTBF
  - 5 year warrantee
  - $200 = $0.20 / GB

These use Perpendicular Magnetic Recording (PMR)!!

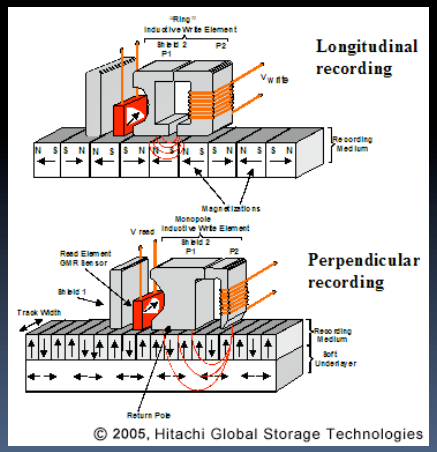
source: www.seagate.com

1 inch disk drive!

- **Hitachi 2007 release**
  - Development driven by iPods & digital cameras
  - 8GB, 5-10MB/s (higher?)
  - 42.8 x 36.4 x 5 mm

HITACHI
Inspire the Next

- **Perpendicular Magnetic Recording (PMR)**
  - FUNDAMENTAL new technique
  - Evolution from Longitudinal
    - Starting to hit physical limit due to superparamagnetism
  - They say 10x improvement



www.hitachi.com/New/cnews/050405.html
www.hitachigst.com/hdd/research/recording_head/pr/

Where does Flash memory come in?

- **Microdrives and Flash memory (e.g., CompactFlash) are going head-to-head**
  - Both non-volatile (no power, data ok)
  - Flash benefits: durable & lower power (no moving parts, need to spin µdrives up/down)
  - Flash limitations: finite number of write cycles (wear on the insulating oxide layer around the charge storage mechanism)

- **How does Flash memory work?**
  - NMOS transistor with an additional conductor between gate and source/drain which "traps" electrons. The presence/absence is a 1 or 0.

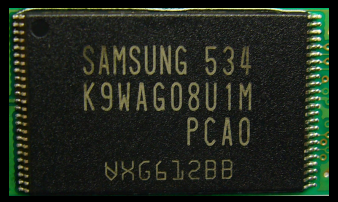
`en.wikipedia.org/wiki/Flash_memory`

en.wikipedia.org/wiki/Ipod www.apple.com/ipod

What does Apple put in its iPods?

Toshiba flash
1, 2GB

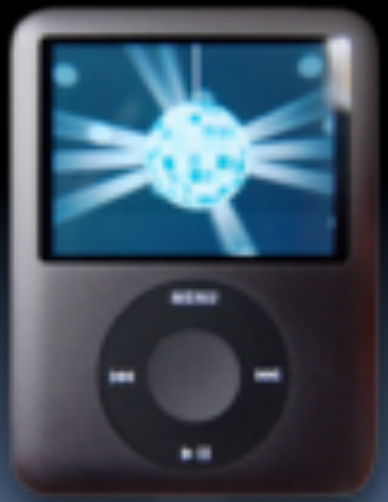
Samsung flash
4, 8GB



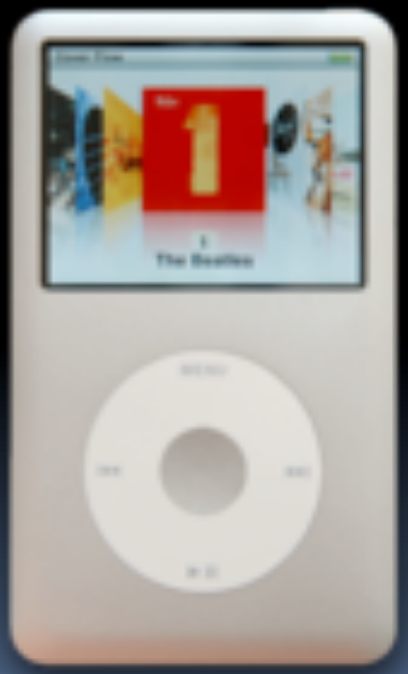
Toshiba flash
8, 16, 32GB

Toshiba 1.8-inch HDD
80, 160GB

shuffle,



nano,



classic,

touch

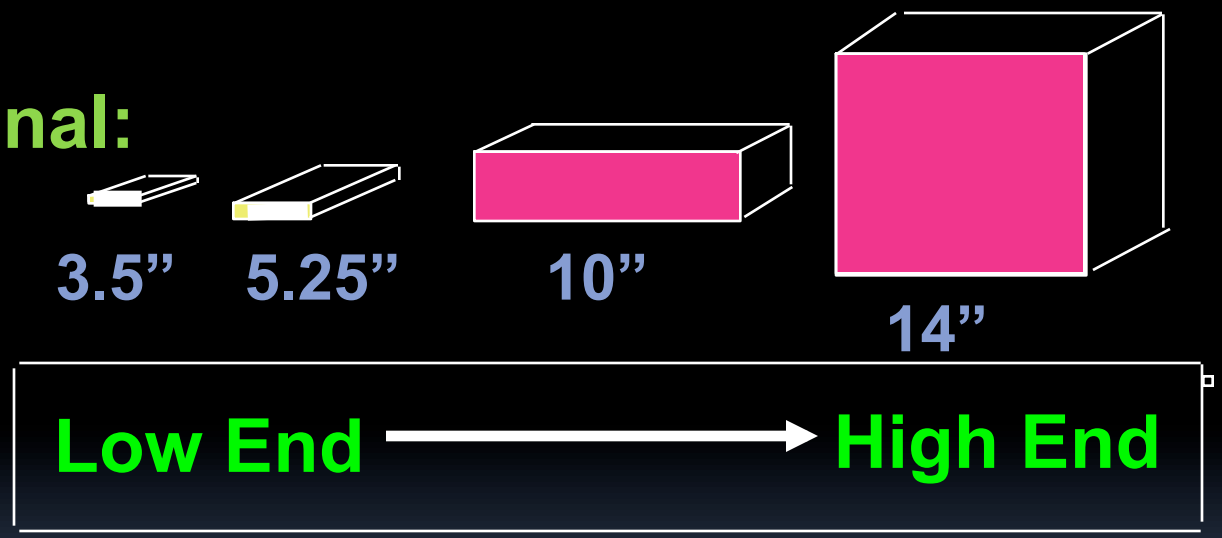
Upcoming Calendar

Week #	Mon	Wed	Thu Lab	Fri
#15 This week	I/O Disks	Performance	I/O Polling P4 due	Writing really fast code (Casey)
#16 Next week	Parallelism in Processor Design	IntRA-machine Parallelism (Matt)	Parallel	IntER-machine Parallelism Perf comp due
#17 Last week o' classes	LAST CLASS Summary, Review, & HKN Evals			
#18 FINAL REVIEW Sun @ 2-5pm 10 Evans	FINAL EXAM Mon 5-8pm 1 Pimintel			

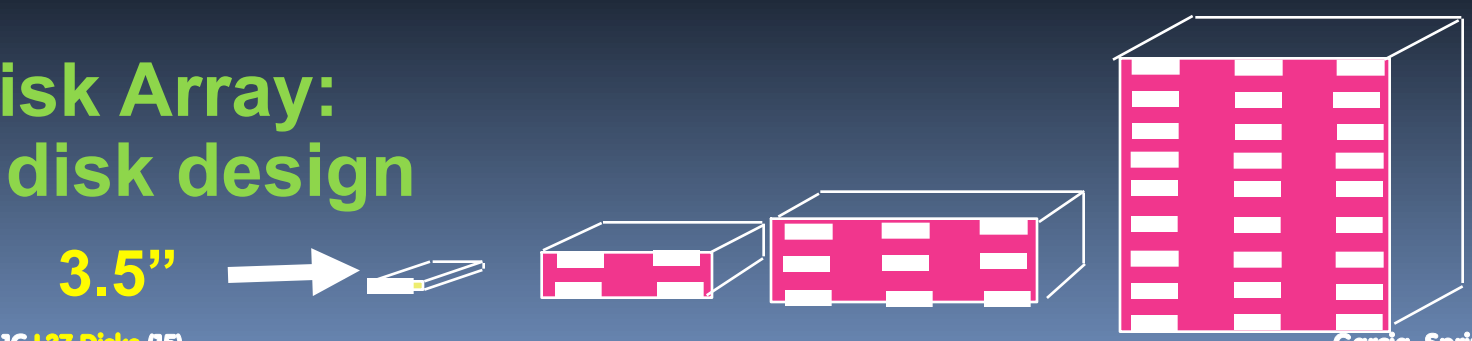
Use Arrays of Small Disks…

- 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 # of Large Disks with Large # of Small!

(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 I/Os/s	6X
MTTF	250 KHrs	50 KHrs	??? Hrs	
Cost	$250K	$2K	$150K	

Disk Arrays potentially high performance, 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!
- **Disk 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**

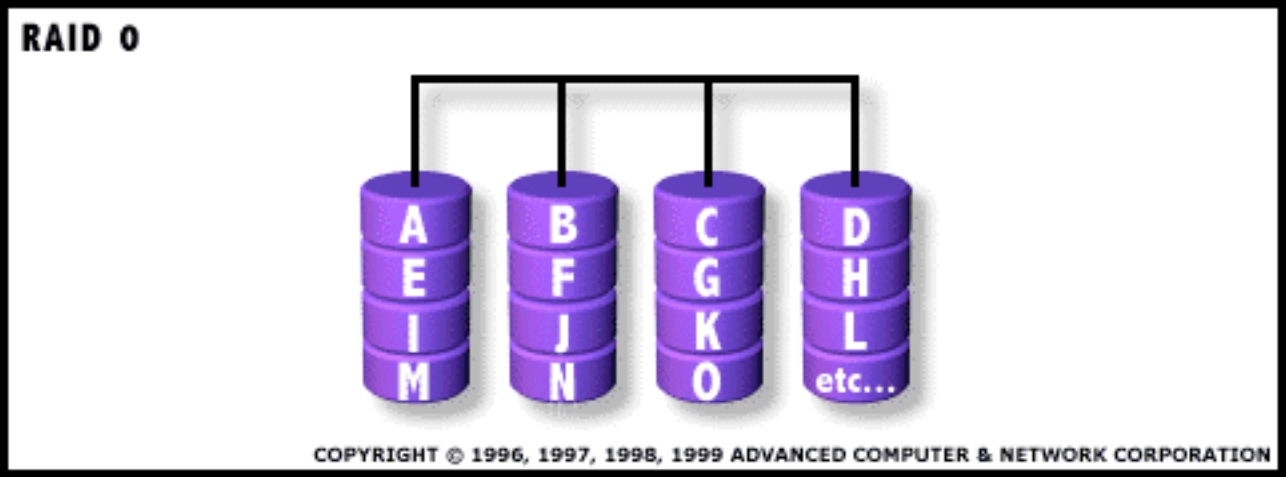
  ⇒ Capacity penalty to store redundant info

  ⇒ Bandwidth penalty to update redundant info

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 > tens billion dollar industry, 80% nonPC disks sold in RAIDs**

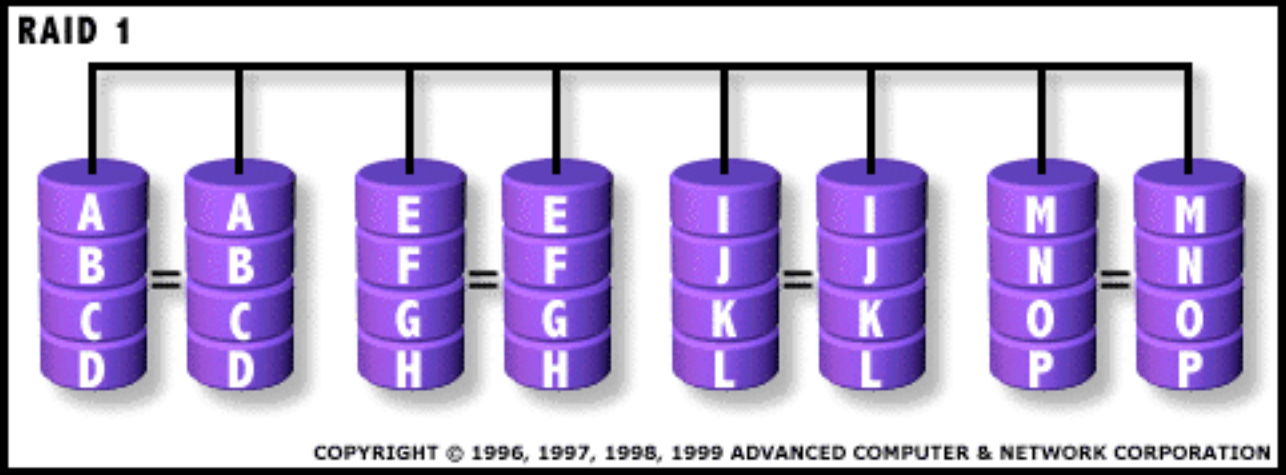
"RAID 0": No redundancy = "AID"



- Assume have 4 disks of data for this example, organized in blocks
- Large accesses faster since transfer from several disks at once

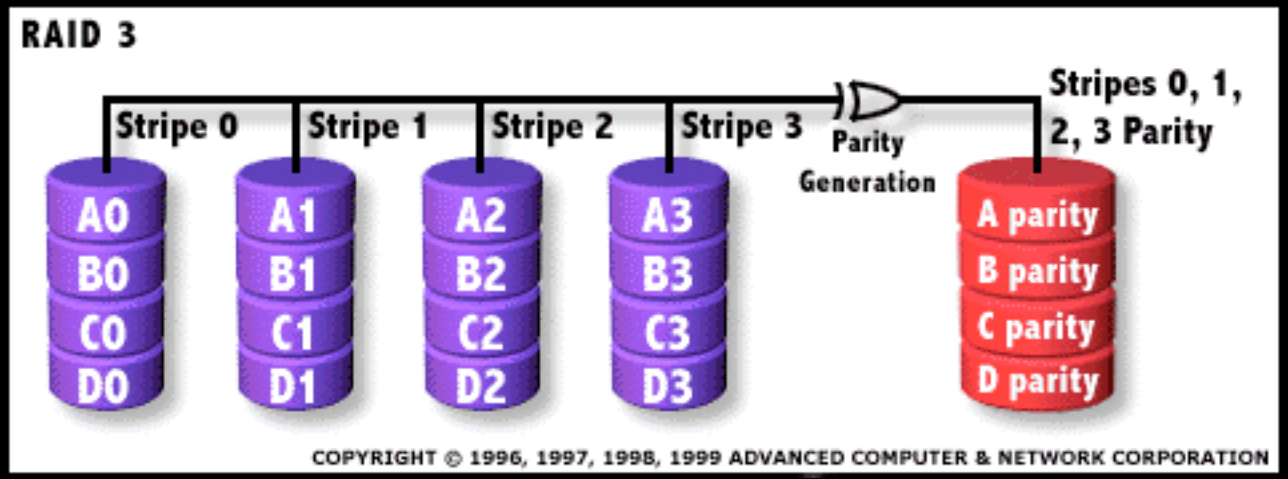
This and next 5 slides from `RAID.edu`, `http://www.acnc.com/04_01_00.html`
`http://www.raid.com/04_00.html` also has a great tutorial

RAID 1: Mirror data



- **Each disk is fully duplicated onto its "mirror"**
  - Very high availability can be achieved
- **Bandwidth reduced on write:**
  - 1 Logical write = 2 physical writes
- **Most expensive solution: 100% capacity overhead**

RAID 3: Parity

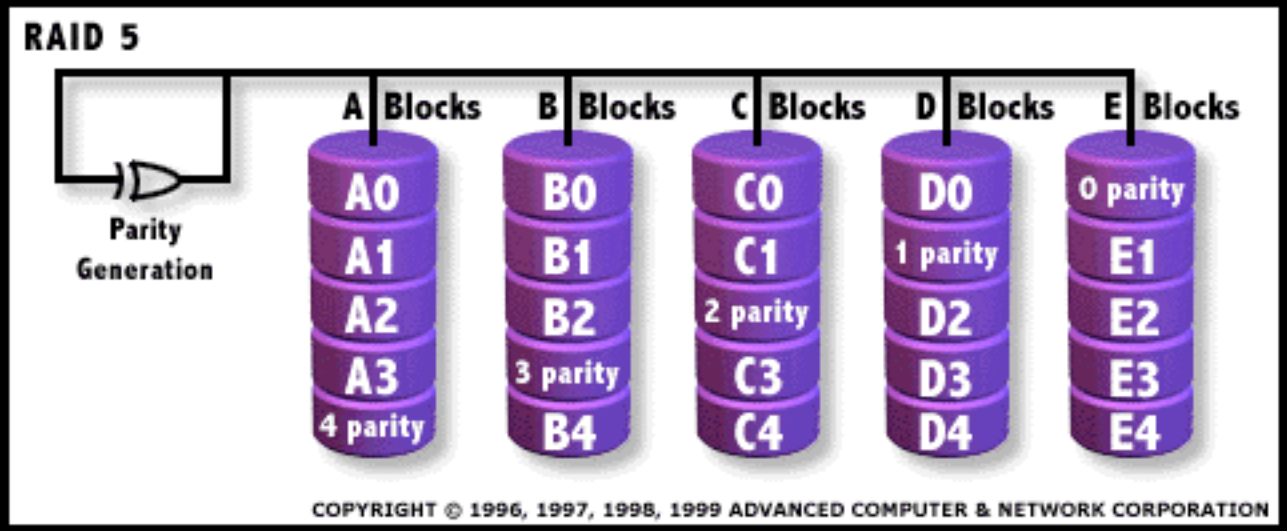


- Parity computed across group to protect against hard disk failures, stored in P disk
- Logically, a single high capacity, high transfer rate disk
- 25% capacity cost for parity in this example vs. 100% for RAID 1 (5 disks vs. 8 disks)

Inspiration for RAID 5 (RAID 4 block-striping)

- **Small writes (write to one disk):**
  - Option 1: read other data disks, create new sum and write to Parity Disk (access all disks)
  - Option 2: since P has old sum, compare old data to new data, add the difference to P:
    1 logical write = 2 physical reads + 2 physical writes to 2 disks
- **Parity Disk is bottleneck for Small writes: Write to A0, B1 → both write to P disk**

RAID 5: Rotated Parity, faster small writes



- **Independent writes possible because of interleaved parity**
  - Example: write to A0, B1 uses disks 0, 1, 4, 5, so can proceed in parallel
  - Still 1 small write = 4 physical disk accesses

en.wikipedia.org/wiki/Redundant_array_of_independent_disks

Peer Instruction

1. RAID 1 (mirror) and 5 (rotated parity) help with performance and availability
2. RAID 1 has higher cost than RAID 5
3. Small writes on RAID 5 are slower than on RAID 1

	ABC
0 :	FFF
1 :	FFT
2 :	FTF
3 :	FTT
4 :	TFF
5 :	TFT
6 :	TTF
7 :	TTT

"And In conclusion…"

- **Magnetic Disks continue rapid advance: 60%/yr capacity, 40%/yr bandwidth, slow seek, rotation improvements, MB/$ improving 100%/yr?**
  - Designs to fit high volume form factor
  - PMR a fundamental new technology
    - breaks through barrier
- **RAID**
  - Higher performance with more disk arms per $
  - Adds option for small # of extra disks
  - Can nest RAID levels
  - Today RAID is > tens-billion dollar industry, 80% nonPC disks sold in RAIDs, started at Cal

Bonus slides

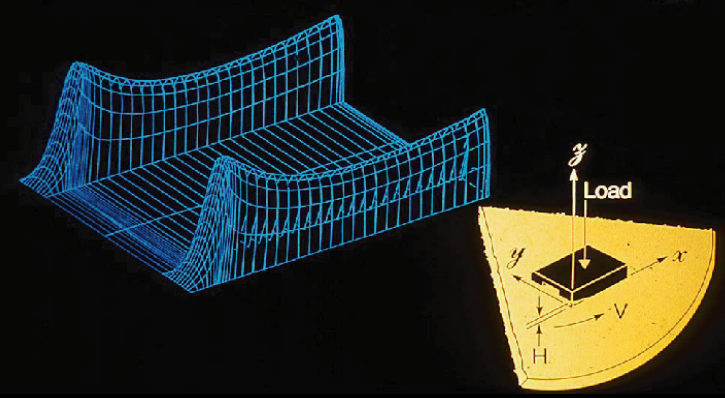
- These are extra slides that used to be included in lecture notes, but have been moved to this, the "bonus" area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation

Bonus

BONUS : Hard Drives are Sealed. Why?

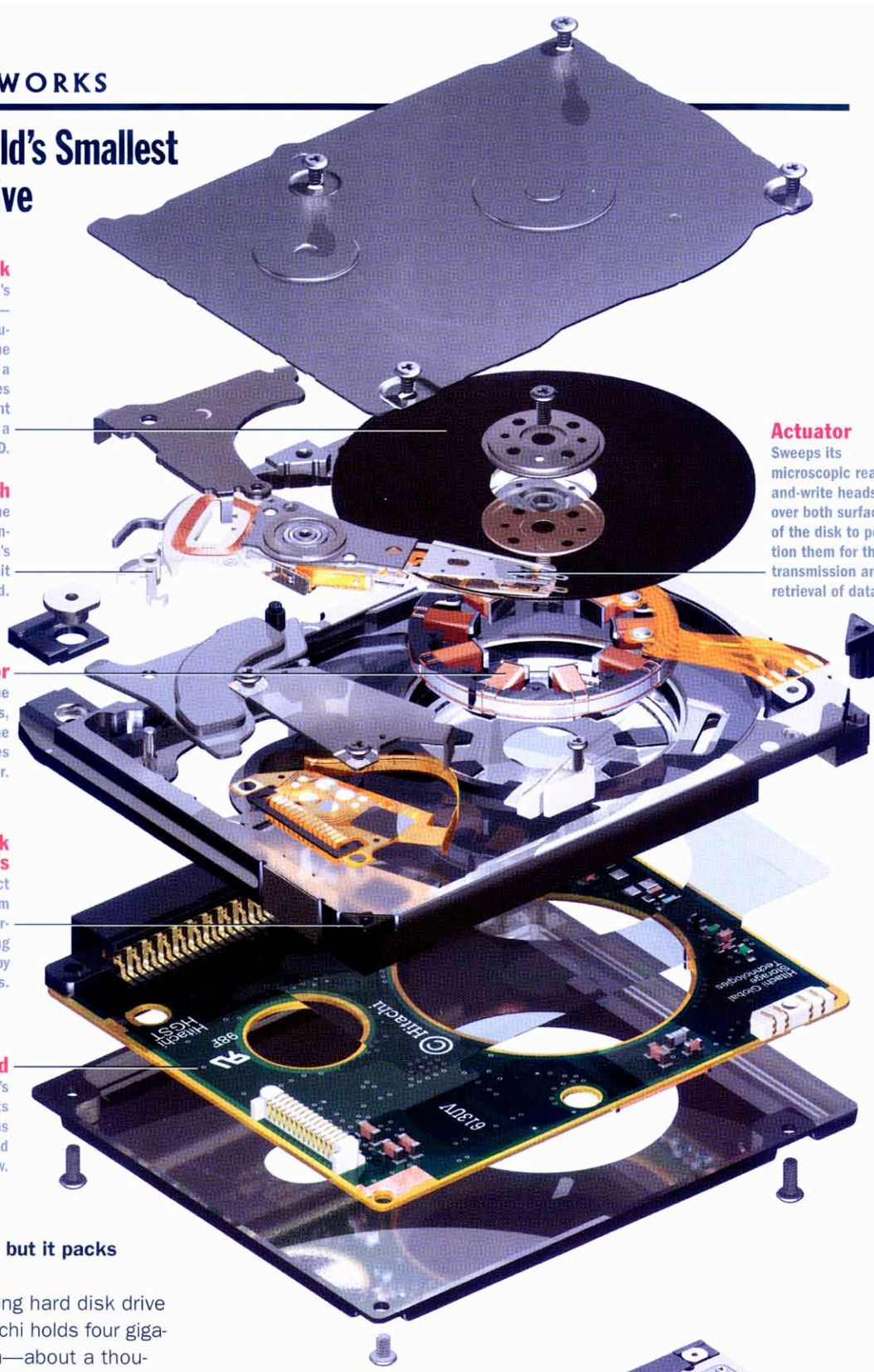
- **The closer the head to the disk, the smaller the "spot size" and thus the denser the recording.**
  - Measured in Gbit/in2. ~60 is state of the art.
- **Disks are sealed to keep the dust out.**
  - Heads are designed to "fly" at around 5-20nm above the surface of the disk.
  - 99.999% of the head/arm weight is supported by the air bearing force (air cushion) developed between the disk and the head.

$$\nabla\cdot\left[H^3P\nabla P + 6\lambda_a P_a H^2\nabla P - 6\mu\, VPH\right] = 12\mu\,\frac{\partial(PH)}{\partial t}$$



INNERWORKS

The World's Smallest Hard Drive



It's bite-size, but it packs a huge byte.

A new inch-long hard disk drive made by Hitachi holds four gigabytes of data—about a thousand times the drive capacity of a desktop computer 20 years ago. It's the latest in a family of hard drives built to store data in handheld devices from PDAs to digital cameras. The hardest part of working small: Getting the actuator to move across the disk a mere 2,500,000th of an inch from its surface.

—Michael Klesius

ART BY GRIFF WASON

Historical Perspective

- Form factor and capacity are more important in the marketplace than is performance
- Form factor evolution:

  1970s: Mainframes ⇒ 14 inch diameter disks

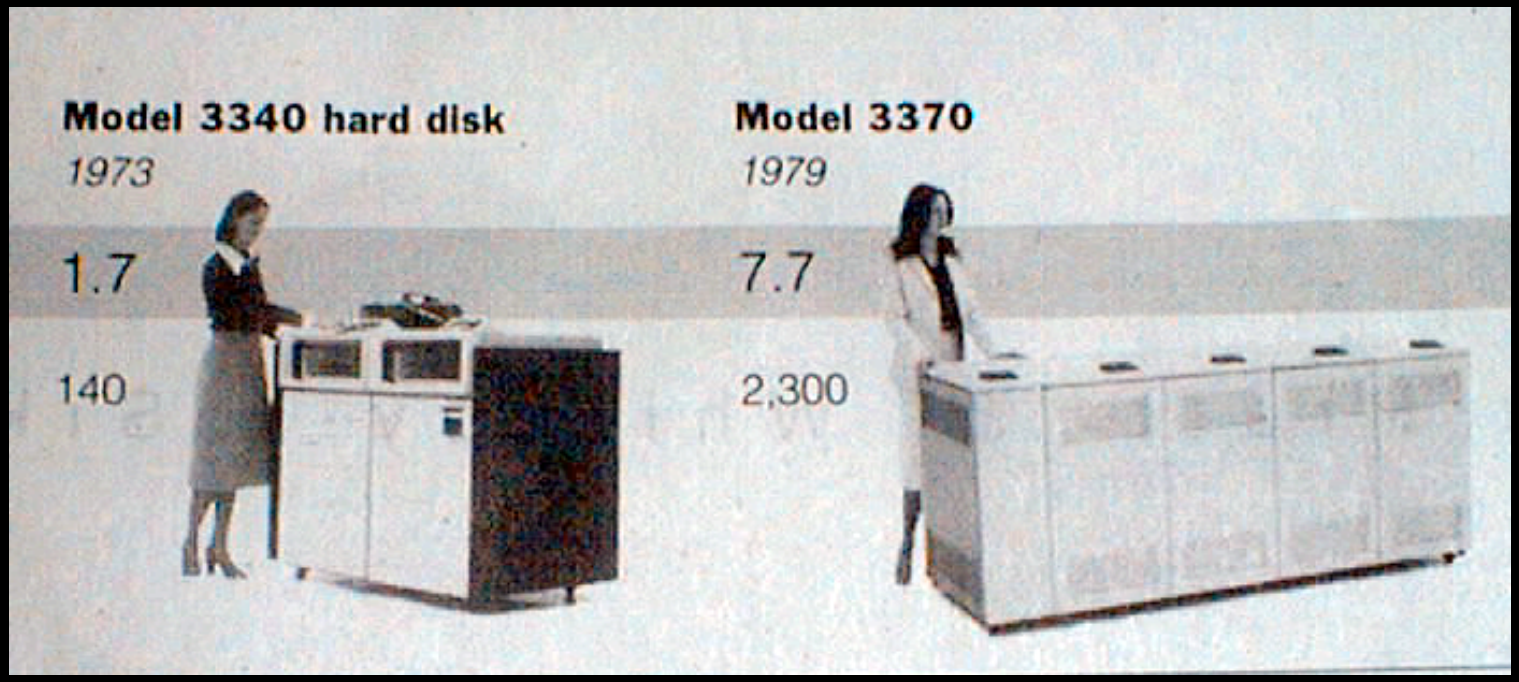
  1980s: Minicomputers, Servers ⇒ 8", 5.25" diameter disks

  Late 1980s/Early 1990s:
  - PCs ⇒ 3.5 inch diameter disks
  - Laptops, notebooks ⇒ 2.5 inch disks
  - Palmtops didn't use disks, so 1.8 inch diameter disks didn't make it
- Early 2000s:
  - MP3 players ⇒ 1 inch disks

Early Disk History (IBM)

Data density Mbit/sq. in.

Capacity of unit shown Megabytes

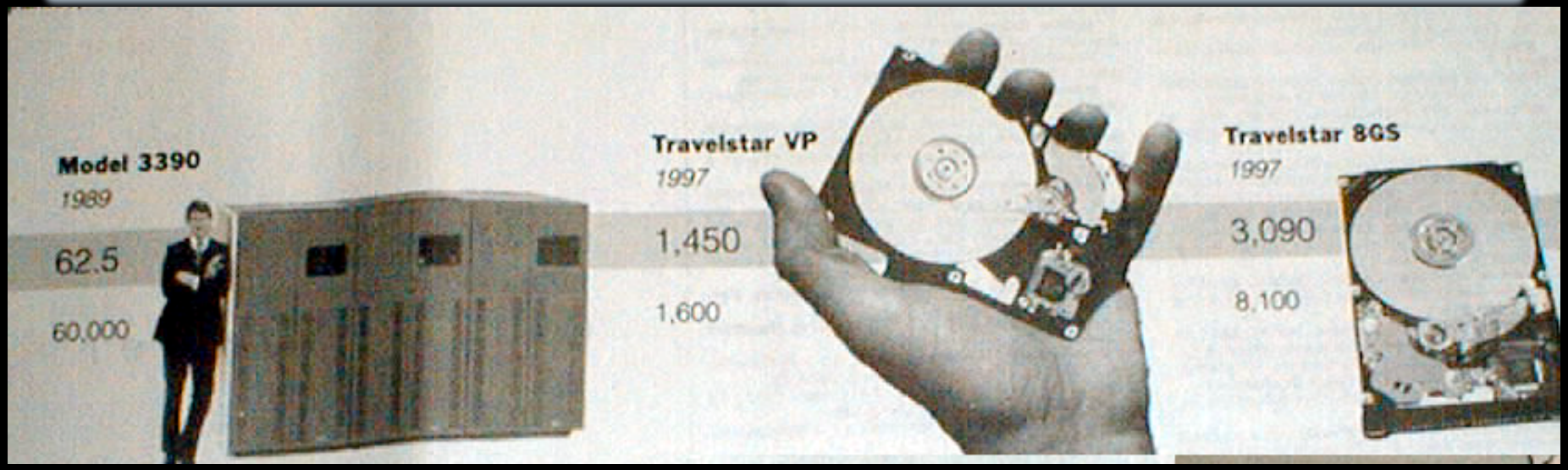


1973:
1. 7 Mbit/sq. in
140 MBytes

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"

Early Disk History



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

1997:
1450 Mbit/sq. in
1600 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"

Disk Performance Example

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

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

= 8.5 ms + 0.5 * 1/(7200 RPM)
  + 0.5 KB / (100 MB/s) + 0.1 ms

= 8.5 ms + 0.5 /(7200 RPM/(60000ms/M))
  + 0.5 KB / (100 KB/ms) + 0.1 ms

= 8.5 + 4.17 + 0.005 + 0.1 ms = 12.77 ms

- How many CPU clock cycles is this?