magnetic information storage

IBM 350 RAMAC, the first hard disk
it stored about 4.4Mb

wikipedia.org - "RAMAC"
what do I mean by magnetic recording?
what do I mean by magnetic recording?
what do I mean by magnetic recording?

hard disks.

mostly hard disks.
why do we use hard disks?

what is their role in a computer?

benefits?

disadvantages?

and the real reason .. $$$
basic PC architecture

- access time
- latency
- volatility
- cost / GB
basic PC architecture

- CPU
- access time
- latency
- cost / GB
- volatility
basic PC architecture

- CPU
- caches

\( \wedge \) access time
\( \wedge \) latency

\( \vee \) cost / GB
\( \vee \) volatility
basic PC architecture

- CPU
- caches
- SRAM / DRAM

▼ access time ▼ latency ▼ cost / GB ▼ volatility
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk

> access time
> latency

> cost / GB
> volatility
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk
- floppy tape
- DVD CD-ROM

Access time < Latency

Cost / GB > Volatility
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk
- floppy
- tape
- DVD
- CD-ROM

▲ access time
▲ latency
▼ volatility
▼ cost / GB
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk
- floppy
- tape
- DVD
- CD-ROM

> access time
> latency

> cost / GB
> volatility
terminology

RAM
random access memory

ROM
read-only memory

access time & latency?
time between request for info & info returned

$ / GB
primary figure of merit.
most other things can be worked around

nonvolatility?
retains data without power

45nm SRAM die intel.com
every bit has a role

cache - reduce latency to main memory
  small memories close to CPU
even faster than main memory
temp storage of frequently accessed items

SRAM / DRAM - main memory
  blazingly fast
  relatively large
  voltaile!!

HDD - mass storage
  higher latency
  enormous capacity
  nonvolatile

removable
  portability
  backup
  large ROM

future paradigm shifts? distributed net storage?

EDSAC / wikipedia.org
the need for hard disks (tech)

volatility of semiconductor memories!
  some sort of nonvolatile storage necessary
  why not just battery backup of SRAM?

cost per GB
  SRAM/DRAM are too expensive
  Flash is too expensive
  cache RAM is more expensive

size & throughput
  higher latency, but bandwidth is huge
  enormous sizes

endurance
  essentially unlimited cycling
  radiation hard

punched cards are nonvolatile
Back in the day, disks were expensive.

Sometimes, we would trick the system into using RAM as a disk to avoid swapping floppies.

now RAM disks make a comeback ...
the need for mass storage (human)

sound
several MB per minute / lossy
tens of MB per minute / “lossless”

pictures
several MB per image

video
~ 1 MB per sec
several GB per movie
with lossy compression!

data mining
enormous sizes

apple.com
how do hard disks work, more or less?

spinning (~10^4 rpm) part holds data. sliding part reads and writes data.

wikipedia.org - “Hard_Disk”
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

Magnetic medium

Read-write head

Voice-coil actuator

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
The diagram illustrates a hard disk drive's components:

- **Magnetic medium**
- **Read-write head**
- **Spindle motor**
- **Voice-coil actuator**

Additionally, it mentions an 160 Gbit 2.5” perpendicular drive for laptops.

Images from M. Coey

---

THE UNIVERSITY OF ALABAMA

CENTER FOR MATERIALS FOR INFORMATION TECHNOLOGY
An NSF Science and Engineering Center
hard disk drives

8 Gbit 1” drive for cameras

160 Gbit 2.5” perpendicular drive for laptops

Magnetic medium
Read-write head
Spindle motor
Voice-coil actuator

images from M. Coey
media basics

Hard disk
- tiny magnetized regions
- direction (N/S) stores bit
- magnetic sensor reads bits

LP records
- tiny bumps
- needle moves

CDs
- pits store bits
- optical reflectivity

actual record grooves

actual CD surface
media basics

hard disk platters are round.

so how is data arranged?

*tracks* = concentric circles

*sectors* = wedge of a track

sector has fixed # bytes
media basics

CoCrPt alloy platters - Al or glass substrate
typical magnetic region
  ~200-250 nm wide,  ~25-30 nm down-track
  100 billion bits (Gigabits) per in$^2$

reading and writing basics

(longitudinal recording)

sensor - magnetoresistive

reading and writing basics

(\textit{perpendicular recording})

soft underlayer becomes part of the flux guide

... careful concentration of flux ...

read head (and its reflection)
wikipedia.org - “Hard_Disk”
positioning basics

- current powers voice coil\(^\dagger\)
- field generated moves head L or R
- more precise than stepper motor

\[^\dagger\] this is the same way a speaker cone moves

www.pcguide.com/ref/hdd/op/actActuator-c.html
positioning basics

- current powers voice coil†
- field generated moves head L or R
- more precise than stepper motor

IBM 62PC "Piccolo" HDD, ~1979 - an early 8" disk

† this is the same way a speaker cone moves
why magnets?

magnets remember their state
once magnetized, they stay that way

with a little bit of energy, we can control them
switch from N to S
why magnets?

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with a little bit of energy, we can control them
switch from N to S
why magnets?

what happens when you break a magnet?

you get two magnets

now: do this 25 more times

→ 33 million magnets, all 50nm across

about 1,000 times thinner than a hair

we can make really tiny magnets

smaller is better, to a point
technology timeline

- **1950**: RAMAC - first hard-disc drive; inductive head
- **1960**: TMR discovered
- **1970**: AMR discovered
- **1980**: GMR discovered
- **1990**: AMR head
- **2000**: Spin-valve head (CIP)
- **2010**: TMR head

In-plane


perpendicular

AMR discovered (1857)

images and text from M. Coey
technology timeline

<table>
<thead>
<tr>
<th>year</th>
<th>capacity</th>
<th>platters</th>
<th>size</th>
<th>rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>40 Mb</td>
<td>50x2</td>
<td>24&quot;</td>
<td>1200</td>
</tr>
<tr>
<td>2005</td>
<td>160 Gb</td>
<td>1</td>
<td>2.5&quot;</td>
<td>18000</td>
</tr>
</tbody>
</table>

images and text from M. Coey
the incredible shrinking hard disk

E. Grochowski and R.D. Halem
*IBM Systems Journal*, **42** (2), 2003
the incredible shrinking hard disk

E. Grochowski and R.D. Halem
*IBM Systems Journal, 42* (2), 2003
growth of areal density

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E. Grochowski and R.D. Halem
IBM Systems Journal, 42 (2), 2003
growth of areal density

E. Grochowski and R.D. Halem
*IBM Systems Journal, 42* (2), 2003
areal density vs. DRAM
The incredible shrinking bit!
Predicted relative sizes of HDD storage bits

2002

(assumes areal densities continue to double yearly)
The incredible shrinking bit!
Predicted relative sizes of HDD storage bits

(assumes areal densities continue to double yearly)
The incredible shrinking bit!
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(assumes areal densities continue to double yearly)
The incredible shrinking bit!
Predicted relative sizes of HDD storage bits

(assumes areal densities continue to double yearly)

2002: 50 nm

2004

2006

2008

2010

2012: 4.4 nm x 4.4 nm
The incredible shrinking bit!
Predicted relative sizes of HDD storage bits

- 2002: 400 nm x 50 nm
- 2004
- 2006
- 2008
- 2010
- 2012: 4.4 nm x 4.4 nm (this will probably not happen)

(assumes areal densities continue to double yearly)
50 TB per square inch on a quarter ...

- over 3.4 million high-resolution photos, or …
- 2,800 audio CDs, or…
- 1,600 hours of television, or …
50 TB per square inch on a quarter ...

• over 3.4 million high-resolution photos, or …
• 2,800 audio CDs, or…
• 1,600 hours of television, or …

• the entire printed collection of the U.S. Library of Congress

Library of Congress, Jefferson building
so what’s the problem?

at some point, they are no longer stable

heat makes them ‘wiggle’
   like drops of water on a griddle

bits are no longer reliable

so we need stronger magnets ...  
   ... which need more field to magnetize
   ... which needs more power

HUGE challenge in nanoscale materials science!

1 bit needs $k_B T$ ...
$\$\$ vs flash and DRAM

![Chart](chart.png)
$\$$ vs flash and DRAM

E. Grochowski and R.D. Halem
IBM Systems Journal, 42 (2), 2003
seek time

E. Grochowski and R.D. Halem
IBM Systems Journal, 42 (2), 2003
seek time

far higher than DRAM/SRAM (~nsec) reduction limited by mechanics!
throughput
throughput

areal density growing faster than data rate problem, or no?
density metrics

Track, Areal, Linear Density Perspective

Hard Disk Drive Products
Circles = Server products
Squares = Mobile products

Track Density CGR = 50%
Areal Density CGR = 100%
Linear Density CGR = 30%

Ed Grochowski
density metrics

This is why we quote areal density.
head-media spacing

![Graph showing the relationship between spacing and areal density for different types of hard drives. The graph plots head/media spacing in nanometers on the x-axis and areal density in Gbits/in² on the y-axis. Different markers represent various types of hard drives, including lab demos, 2.5 inch mobile HDDs, 3.5 inch server HDDs, and 3.5 inch desktop HDDs. The data points show a decreasing trend as spacing decreases.]
head-media spacing

tribology ...

we are basically in contact
physical spacing
<table>
<thead>
<tr>
<th></th>
<th>SRAM</th>
<th>DRAM</th>
<th>Flash</th>
<th>FeRAM</th>
<th>MRAM</th>
<th>PCRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read speed</td>
<td>Fast</td>
<td>Medium</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
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<tr>
<td>Write speed</td>
<td>Fast</td>
<td>Medium</td>
<td>Slow</td>
<td>Medium</td>
<td>Fast</td>
<td>Medium</td>
</tr>
<tr>
<td>Array efficiency</td>
<td>High</td>
<td>High</td>
<td>Medium/low</td>
<td>Medium</td>
<td>Medium/high</td>
<td>Medium/high</td>
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<tr>
<td>Future scalability</td>
<td>Good</td>
<td>Limited</td>
<td>Limited</td>
<td>Limited</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Cell density</td>
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<td>High</td>
<td>High</td>
<td>Medium</td>
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<tr>
<td>Nonvolatility</td>
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<td>No</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Endurance</td>
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<td>Infinite</td>
<td>Limited</td>
<td>Limited</td>
<td>Infinite</td>
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<tr>
<td>Cell leakage</td>
<td>Increasing</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>Low voltage</td>
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<td>Limited</td>
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<td>Yes</td>
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</tr>
<tr>
<td>Complexity</td>
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<td>Medium</td>
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## PCRAM Medium competition?

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price is the real advantage.
price is the real advantage.

flash is beating the 1” HDD in some apps
e.g., mp3, camera
price is the real advantage.

flash is beating the 1” HDD in some apps

e.g., mp3, camera

power consumption may be the larger issue
power consumption is not an advantage

latency ...

fundamental limits of magnetism?
power consumption is not an advantage

latency ...  

fundamental limits of magnetism?

more importantly ...
power consumption is not an advantage

latency ...

fundamental limits of magnetism?

more importantly ...
will we get “scooped” like bubbles?
SO!

what about the competition?

how does flash work?
the basics of Flash

NOR Cell

- \( V_G < 0 \) channel pinched
- \( V_G > 0 \) channel open

- like a MOSFET
- uses 2 gates
writing

“hot electron injection”

- ~7V to drain
  pull e⁻ through channel
- ~12V to control gate / open channel
  injects e⁻ into floating gate through tunnel oxide
- floating gate now charged
writing

“hot electron injection”

• ~7V to drain
  pull e\textsuperscript{−} through channel

• ~12V to control gate / open channel
  injects e\textsuperscript{−} into floating gate through tunnel oxide

• floating gate now charged
**writing**

“hot electron injection”

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"hot electron injection"

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**writing**

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“hot electron injection”

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• ~7V to drain
  pull e⁻ through channel
erasing

reset all bits to “0”

-9V to control
  pinch off channel
~6V to source
  suck electrons out of floating gate into source
  Fowler-Nordheim tunneling
erasing

reset all bits to “1”

-9V

-9V to control
pinch off channel

~6V to source

suck electrons out of floating gate into source
Fowler-Nordheim tunneling
erasing

reset all bits to “1”

-9V

control gate

floating gate

e-

source

drain

• -9V to control
pinch off channel

• ~6V to source

• suck electrons out of floating gate into source
  Fowler-Nordheim tunneling
erasing

reset all bits to "1"

-9V

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Fowler-Nordheim tunneling

source

drain

control gate

floating gate
reset all bits to “1”

-9V

~6V

control gate

floating gate

source

-9V to control
pinch off channel

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suck electrons out of floating gate into source

Fowler-Nordheim tunneling

OPEN

drain

erasing
erasing

reset all bits to “1”

-9V

~6V

OPEN

control gate

floating gate

source

e-
e-
e-

drain

e-

• -9V to control
  pinch off channel
• ~6V to source
• suck electrons out of floating gate into source
  Fowler-Nordheim tunneling
floating gate

control gate

source

e

e

drain

• 5V to control
• 1V to drain
• floating gate charged = channel is pinched off = “0”
• floating gate discharged = channel open = “1”

presence of charge modulates $I_{SD}$!
reading

- 5V to control
- 1V to drain
- floating gate charged = channel is pinched off = “0”
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Presence of charge modulates $I_{SD}$!
the basics of Flash
the basics of Flash

+ no mechanical limitations

+ lower latency
  
  = attractive for speed, noise, power consumption, reliability.
the basics of Flash

+ no mechanical limitations

+ lower latency
  = attractive for speed, noise, power consumption, reliability.

- cost/GB still significantly higher (but decreasing rapidly!)

- finite number of erase/write (typically $10^6$ cycles guaranteed)
  unable to support an OS (swap!)

  warranties on flash-based disks trending $\geq$ HDD
http://bama.ua.edu/~pleclair/PH587/

PDF version of these slides