**Project:**
Your project will be to assess the prospects of a future information storage or memory technology.

Some possible technologies to consider (choose one):

- Ferroelectric Random Access Memory
- Optical Storage
- Holographic Storage
- Flash Memory
- Phase Change Memory (PC-RAM)
- Resistive Random Access Memory
- Probe Based Storage Devices
- Molecular Memory Devices
Introduction to Magnetic Recording

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.

only 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

Arrows indicate:
- Up: cost per GB
- Down: access time, latency

The pyramid illustrates the trade-offs in computer architecture, focusing on CPU and cache layers.
basic PC architecture

- CPU
- Caches
- SRAM / DRAM

\[ \text{access time} \quad \text{> latency} \]

\[ \text{> volatility} \quad \text{> cost / GB} \]
basic PC architecture

- CPU
- caches
- SRAM / DRAM
- hard disk

\[ \text{access time} \searrow \text{latency} \swarrow \text{cost / GB} \swarrow \text{volatility} \]
basic PC architecture

- CPUs
- 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 disk
- DVD
- CD-ROM

> access time
> latency
> cost / GB
> volatility

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basic PC architecture

- CPU
- Caches
- SRAM / DRAM
- Hard disk
- Floppy
disk
- 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
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?
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.
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

Magnetic medium

160 Gbit 2.5” perpendicular drive for laptops

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

Magnetic medium

Read-write head

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

Magnetic medium
Read-write head
Voice-coil actuator

images from M. Coey
hard disk drives

160 Gbit 2.5” perpendicular drive for laptops

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

images from M. Coey
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
 sector = wedge of a track

sector has fixed # bytes
media basics

**mfm image**

sees transition field

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

(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†
- field generated moves head L or R
- more precise than stepper motor

† this is the same way a speaker cone moves
positioning basics

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

† this is the same way a speaker cone moves

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

wikipedia.org - “Hard_Disk”
why magnets?

microscopic view

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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---

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CENTER FOR MATERIALS FOR INFORMATION TECHNOLOGY
An NSF Science and Engineering Center
why magnets?

what happens when you break a magnet?
you get two magnets

now: do this 25 more times

$\Rightarrow$ 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

- In-plane (1950-1970)
  - RAMAC - first hard-disc drive; inductive head

- Perpendicular (1980-2010)
  - TMR discovered
  - GMR discovered
  - AMR head
  - Spin-valve head (CIP)
  - TMR head

- AMR discovered (1857)

Images and text from M. Coey
technology timeline

- RAMAC - first hard-disc drive; inductive head
- TMR discovered
- GMR discovered
- Spin-valve head (CIP)
- TMR head

AMR discovered (1857)

<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”</td>
<td>1200</td>
</tr>
<tr>
<td>2005</td>
<td>160 Gb</td>
<td>1</td>
<td>2.5”</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
growth of areal density

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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

(assumes areal densities continue to double yearly)
The incredible shrinking bit!
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2002

2004

2006

2008

2010

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

(assumes areal densities continue to double yearly)

2002

2004

2006

2008

2010

2012: 4.4 nm x 4.4 nm

this will probably not happen
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!
$\$$ vs flash and DRAM

Average Price of Storage

Year


Price/MB, Dollars

0.00001 0.0001 0.01 1 10 100

HDD DRAM Flash Paper/Film

Ed Grochowski

The University of Alabama

Center for Materials for Information Technology

An NSF Science and Engineering Center
$$\text{vs}$$ 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
density metrics

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

![Graph showing the relationship between head/media spacing and areal density.](image)

- **Label:** Head/Media Spacing, nm
- **Y-axis:** Areal Density, Gbits/in²
- **Legend:**
  - Lab Demos
  - 2.5 inch Mobile HDD
  - 3.5 inch Server HDD
  - 3.5 inch Desktop HDD

**Source:** Ed Grochowski
head-media spacing

tribology ...
we are basically in contact
physical spacing

**Physical spacing and disk surface evolution**

- **Physical Spacing, nm**
  - Slider/Coat
  - Magnetic Element
  - Recession
  - Physical Spacing

- **Overcoat**
  - Magnetic Film
  - Disk Substrate

**Year**
- 1992
- 1994
- 1996
- 1998
- 2000
- 2002
- 2004
- 2006

- **Server Products - 3.5 Inches**
- **Mobile Products - 2.5**
- **Lab Demos**

**Data Points**
- **Travelstar LP** 3 Gbits/in^2
- **Travelstar 2XP**
- **Travelstar 30GN**
- **Travelstar 6GN** 12.1 Gbits/in^2
- **Travelstar 4GT** 5 Gbits/in^2
- **Travelstar 6GT** 26.3 Gbits/in^2 demo
- **Travelstar 36GX**
- **Travelstar 73LZS**
- **Travelstar 40GN**
- **Travelstar 36PX**
- **Travelstar 18GX**
- **Travelstar 18GT**
- **Travelstar 18ZX**
- **Travelstar 36GX**
- **Travelstar 80GN**

**Text**: Smooth Disk Load/Unload

**Legend**: Textured Disk
### PCRAM Competition?

<table>
<thead>
<tr>
<th></th>
<th>SRAM</th>
<th>DRAM</th>
<th>Flash</th>
<th>FeRAM</th>
<th>MRAM</th>
<th>PCRAM</th>
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<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>
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<tr>
<td>Future scalability</td>
<td>Good</td>
<td>Limited</td>
<td>Limited</td>
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<td>Good</td>
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</tr>
<tr>
<td>Cell density</td>
<td>Low</td>
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</tr>
<tr>
<td>Nonvolatility</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Endurance</td>
<td>Infinite</td>
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<td>Limited</td>
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<td>Infinite</td>
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<tr>
<td>Cell leakage</td>
<td>Increasing</td>
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<td>Low</td>
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<tr>
<td>Low voltage</td>
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<td>Yes</td>
<td>Yes</td>
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<td>Complexity</td>
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PCRAM competition?
price is our real advantage.
price is our real advantage.

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

before we get into alternatives ...

how does what we have work?
SO!

before we get into magnetic recording details ... how does flash work?
**the basics of Flash**

**NOR Cell**

- control gate
- floating gate
- source
- drain
- channel
- p substrate
- n^+

- $V_G < 0$ channel pinched
- $V_G > 0$ channel open

- like a MOSFET
- uses 2 gates

- isolation oxide
- tunnel oxide
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
“hot electron injection”

- ~7V to drain
  - pull e\(^-\) through channel
- ~12V to control gate / open channel
  - injects e\(^-\) into floating gate through tunnel oxide
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**writing**

"hot electron injection"

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writing

“hot electron injection”

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  pull \(e^-\) through channel

• floating gate now charged
writing

“hot electron injection”

- ~7V to drain
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- floating gate now charged
erasing

reset all bits to “1”

-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

OPEN

e-

source

• -9V to control
  pinch off channel
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  Fowler-Nordheim tunneling

Floating gate

drain
erasing

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reset all bits to “1”

-9V

~6V

OPEN

source

e-
e-

drain

e-

control gate

floating gate

-9V to control
pinch off channel

~6V to source

suck electrons out of floating gate into source

Fowler-Nordheim tunneling
reading

- 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
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THE UNIVERSITY OF ALABAMA
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Presence of charge modulates $I_{SD}$!
Floating Gate

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- 1V to drain
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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
the basics of *phase change memory*

this is your homework ...

in 3 pages:

how does phase-change memory work?
advantages and disadvantages?
could it be disruptive?
who are the major players?

places to start:
Transcript

http://bama.ua.edu/~pleclair/PH587/

PDF version of these slides