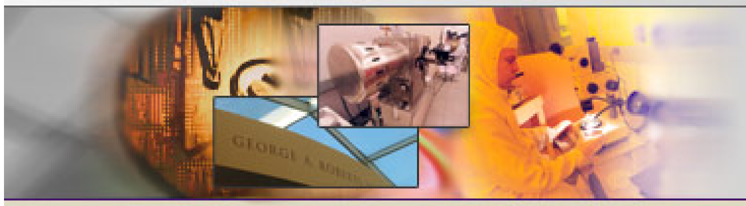
Information Storage and Nanotechnology

T.E. Schlesinger
Professor and Head
Department of Electrical and Computer Engineering
Carnegie Mellon University
Pittsburgh, PA, USA



DSSC
The Data Storage Systems Center

Electrical & Computer ENGINEERING

16 April 2005

Carnegie Mellon

Acknowledgments

Jim Bain, Gary Fedder, Larry Pileggi

Department of Electrical and Computer Engineering

Carnegie Mellon University

Pittsburgh, PA

15213

A Report from the U.S. National Science Foundation
Blue Ribbon Panel on Cyberinfrastructure
Daniel E. Atkins
The University of Michigan
Chair, NSF Panel on Cyberinfrastructure
January 2003

"….cyberinfrastructure refers to infrastructure based upon distributed computer, information and communication technology. If infrastructure is required for an industrial economy, then we could say that cyberinfrastructure is required for a knowledge economy….. The base technologies underlying cyberinfrastructure are the integrated electro-optical components of computation, storage, and communication that continue to advance in raw capacity at exponential rates."

I want to consider the future…

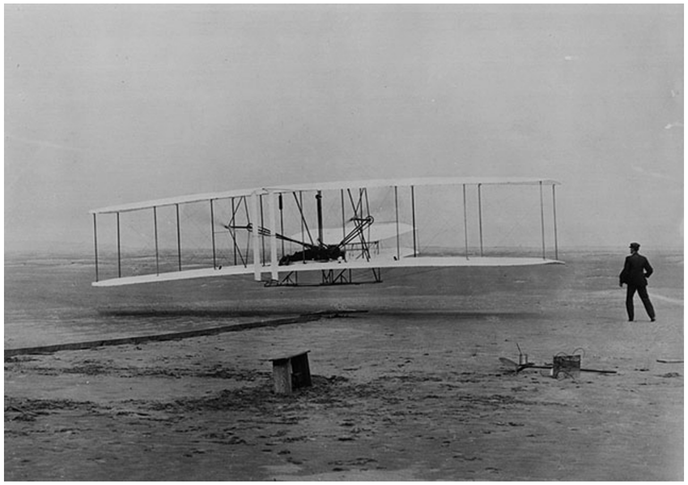
Prediction is very difficult, especially of the future. - Niels Bohr

This statement has been confirmed over time….

…in aviation….

"I have not the smallest molecule of faith in aerial navigation other than ballooning." – Lord Kelvin 1870

"The [flying] machines will eventually be fast; they will be used in sport but they should not be thought of as commercial carriers."- Octave Chanute, 1910



1903

The first civilian, sustained and regular domestic airline service began on 22 Februay 1919 by the German airline Deutshe Luft Reederi (D.L.R.) using AEG biplanes daily between Berlin and Weimar.

1926, 8 passengers, 164 mph

…in communication….

"While theoretically and technically television may be feasible, commercially and financially I consider it an impossibility, a development of which we need waste little time dreaming." – Lee DeForest, 1926

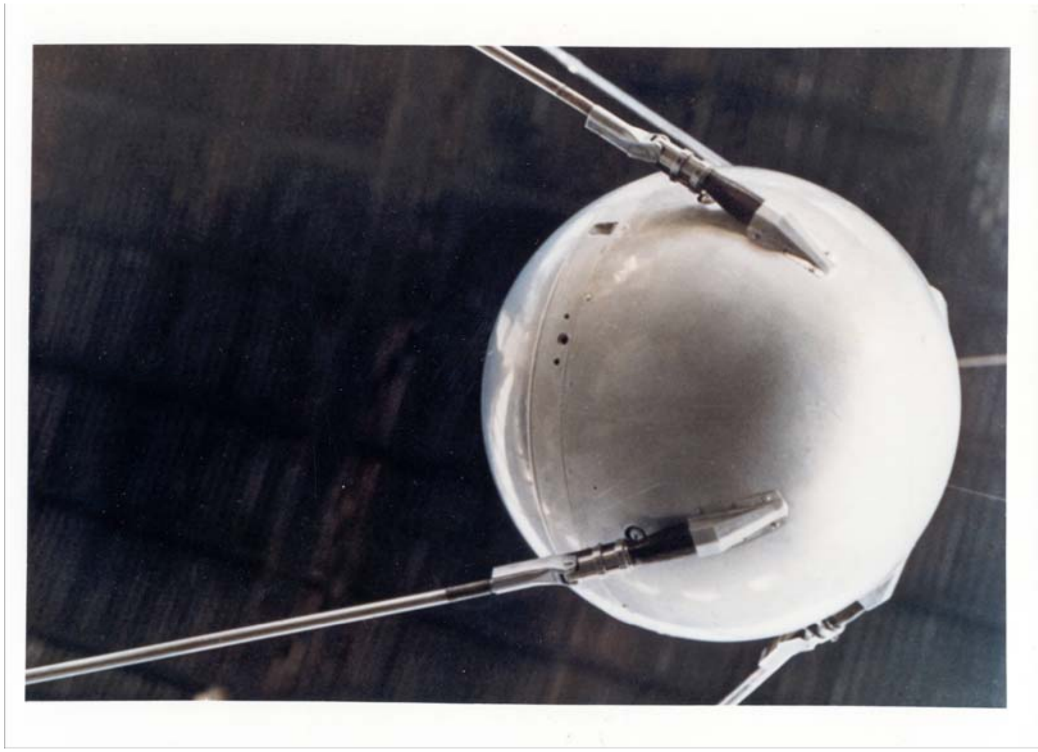
1928 G.E. Scanning Disk Television Set (closed-open)

Early T.V. circa 1928

(c) TVhistory.TV Library

…in space….

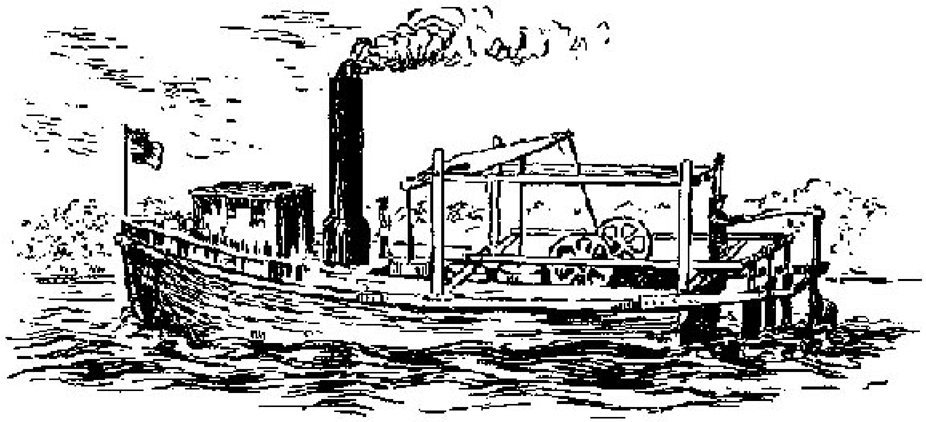
"Space travel is utter bilge." – Sir Richard van der Riet Wooley, The Astronomer Royal 1956



October 4, 1957, the Soviet Union successfully launches Sputnik I

…sometimes it is even difficult to predict the past...

“What, sir, would you make a ship sail against the wind and currents by lighting a bonfire under her deck? I pray you excuse me. I have no time to such nonsense.” – Napoleon to Robert Fulton ca. 1800



JOHN FITCH'S STEAMBOAT, THE FIRST STEAM VEHICLE EMPLOYED IN THE BUSINESS OF TRANSPORTATION. IT MADE TRIAL TRIPS IN 1788, AND REGULAR TRIPS BETWEEN TRENTON AND PHILADELPHIA IN 1790.

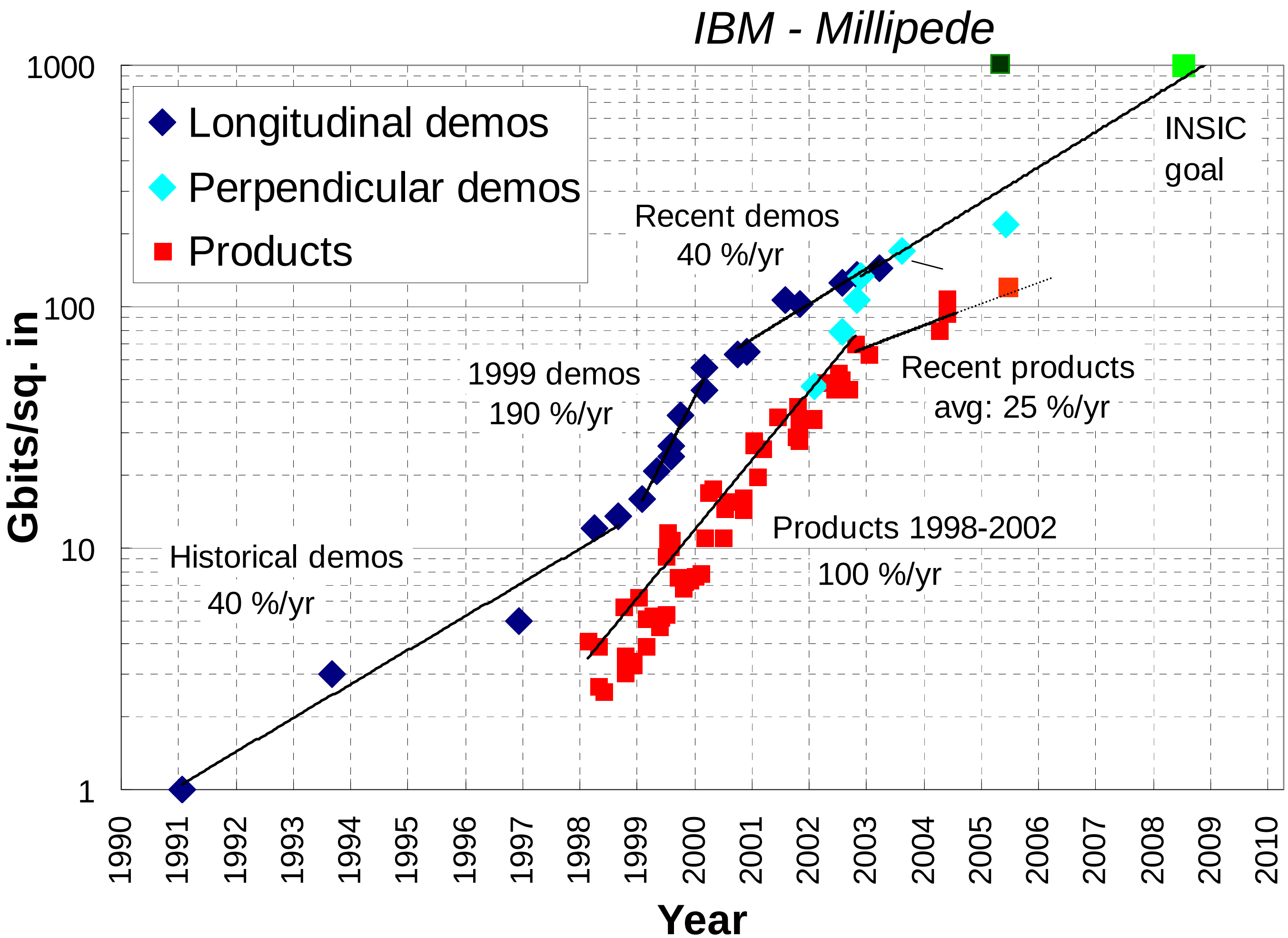
1786 John Fitch invents a steamboat

Robert Fulton is credited with turning the steamboat into a commercial success. On August 7, 1807, Robert Fulton's Clermont went from New York City to Albany making history with a 150-mile trip taking 32 hours at an average speed of about 5 miles-per-hour.

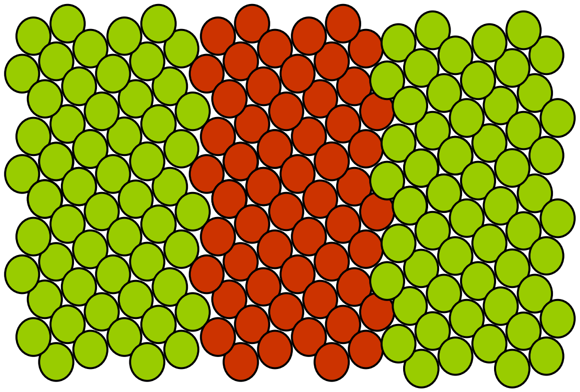
Before looking to the future…

- *Look at what's happening today*

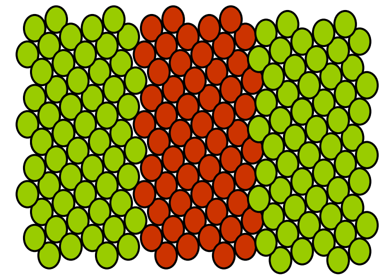
Magnetic Hard Disk Drives



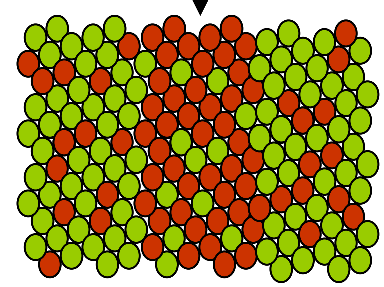
Superparamagnetic Limit

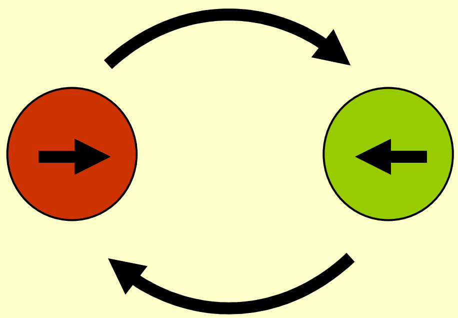


To preserve SNR, number of grains in a bit must be constant. Therefore higher densities require smaller grains



The smaller bits have a higher probability of flipping and the data is unstable





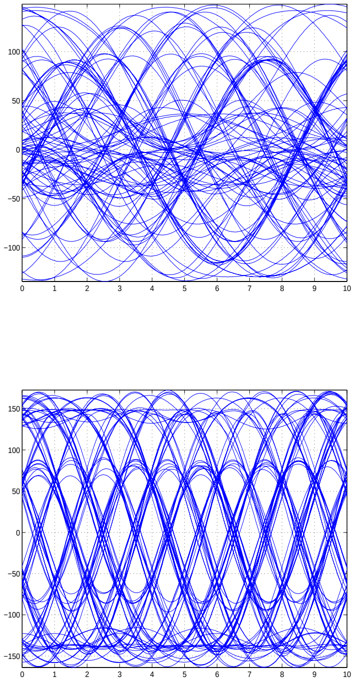
High areal density means small volume

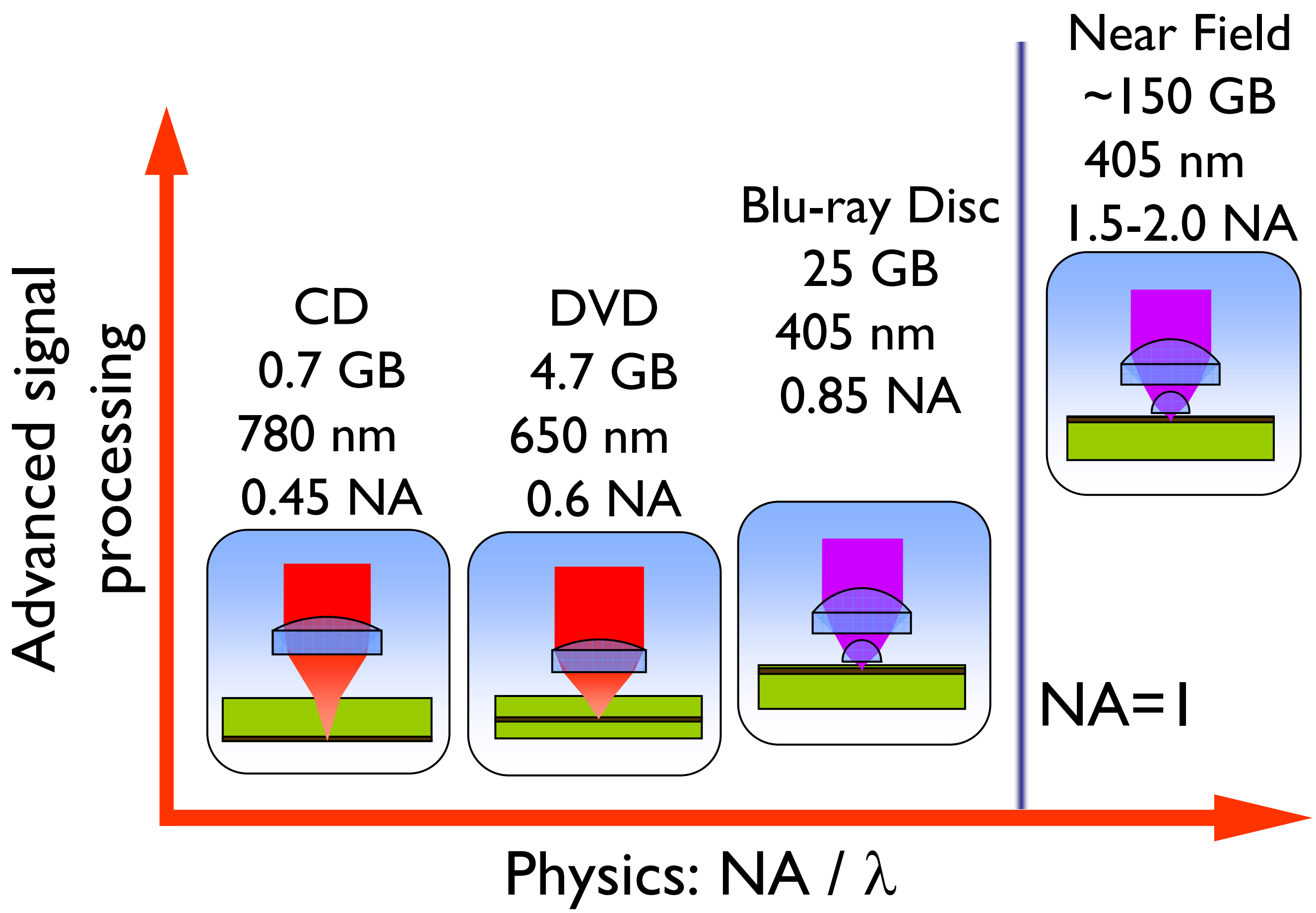
$$\text{Probability of a flip} \propto e^{-\frac{K_u V}{kT}}$$

$K_u V = 40kT$ is considered acceptable

"Thermal Stability of Recorded Information at High Densities", S.H. Charap, P.-L. Lu, Y. He, *IEEE Trans. Mag* **33,** 978(1997).

Optical Storage Limits





Courtesy Philips Research

Room for pessimism…

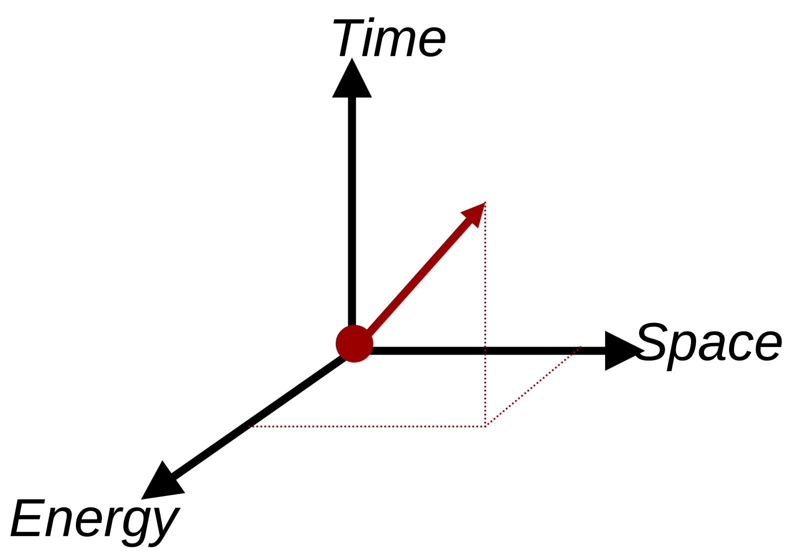
- ***Current information storage paradigms are reaching engineering limits***
  - *Superparamagnetic limit*
  - *Diffraction limits*
  - *Scaling limits*
- ***So we might ask:***
  - *Can we go any further than we have and do we need to?*
  - *Can we do more than squeeze out a few more percent improvements in "performance"?*
  - *Will we see new "revolutionary" or "game changing" developments that are going to take place in the field of information storage?*

It would seem that some people might answer "no" to all the above.

…but the answer is "YES"

- *We can create orders of magnitude more storage capacity than is available today.*
- *The world needs much more information storage capacity.*
- *The creation of this capacity will change society.*
- *Beyond storage alone the integration of information storage and information processing will change the type of systems we will create and use.*

Are We Reaching Fundamental Limits?



We would like to be as close to the origin in terms of space-time-energy as possible when writing and reading a bit:

- ***Zero time***
- ***Zero space***
- ***Zero energy***

But nature does place some constraints on us.

So how close can we get?

"Fundamental" Limits

***Space:* Planck length, lengths smaller than this do not make any physical sense, according to current theories of physics.**

$$\left(\frac{\hbar G}{c^3}\right)^{1/2} = 1.6\times10^{-35} m$$

Implies an "ultimate" storage density of 10^{66} bits/inch^2

***Time:* Planck time, there are no shorter physically meaningful times according to current theories of physics**

$$\left(\frac{\hbar G}{c^5}\right)^{1/2} = 5.4\times10^{-44}\,\sec$$

***Energy:* Thermodynamics says that the minimum energy required to establish the state of a two state system is:**

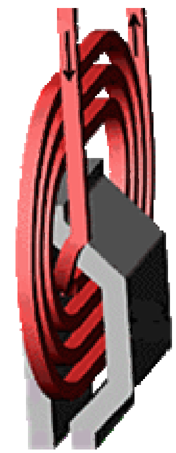
$$k_b T \log 2 \approx 10^{-2} eV$$

Are we near "fundamental" limits?

***Space:* State-of-the-art storage densities > 200 Gbits/in^2 = 2.00 x 10^{11} bits/inch^2.**

***Time:* Present day data rates about 10^9 bits/second**

Energy:



I =	50 ma
R =	6 Ω
t =	1 nsec

$$E = I^2 R \times t = (50\times10^{-3})^2 \times 6\times10^{-9}\,J$$

$$E = 1.5\times10^{-11}\,J = 10^{8}\,eV$$

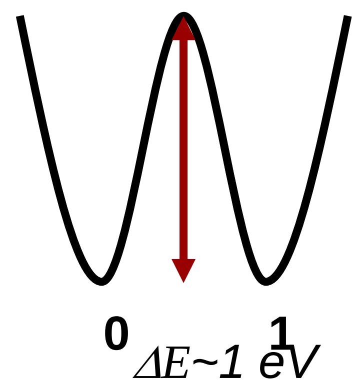
Assume one dissipates 1 eV during each transition.
(But no more)

$$\Delta E \Delta t \geq \hbar$$

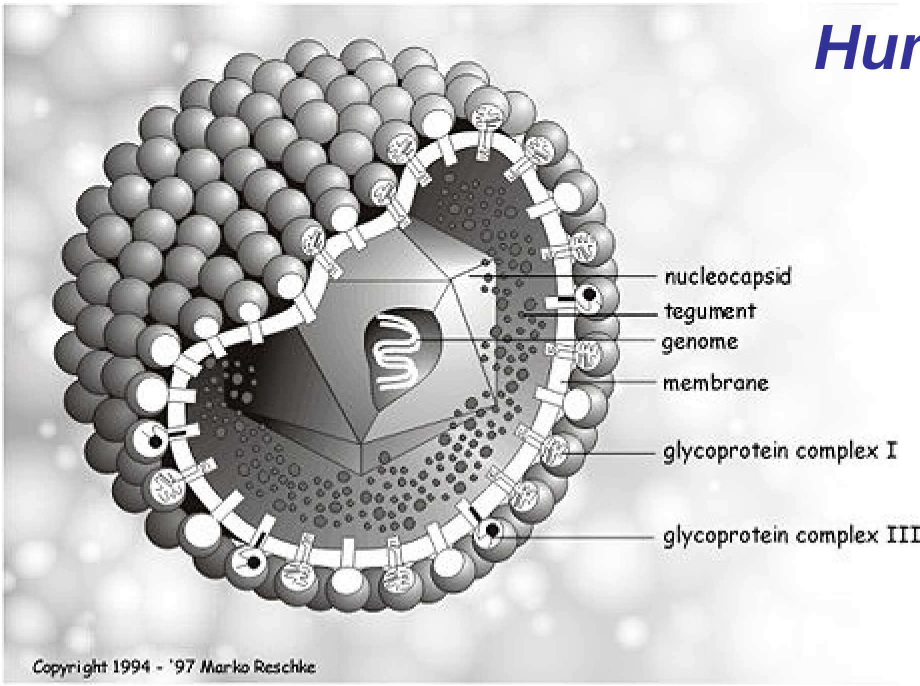
$$(1eV)(\Delta t) \geq 10^{-34}\,J\cdot\sec$$

$$\Delta t \geq \frac{10^{-34}}{1.6\times10^{-19}} \approx 10^{-15}\sec$$

Energy Barrier



An example from nature



Human Cytomegalovirus (CMV):

200,000 base pairs
Nucleocapsid ~ 100 nm diameter

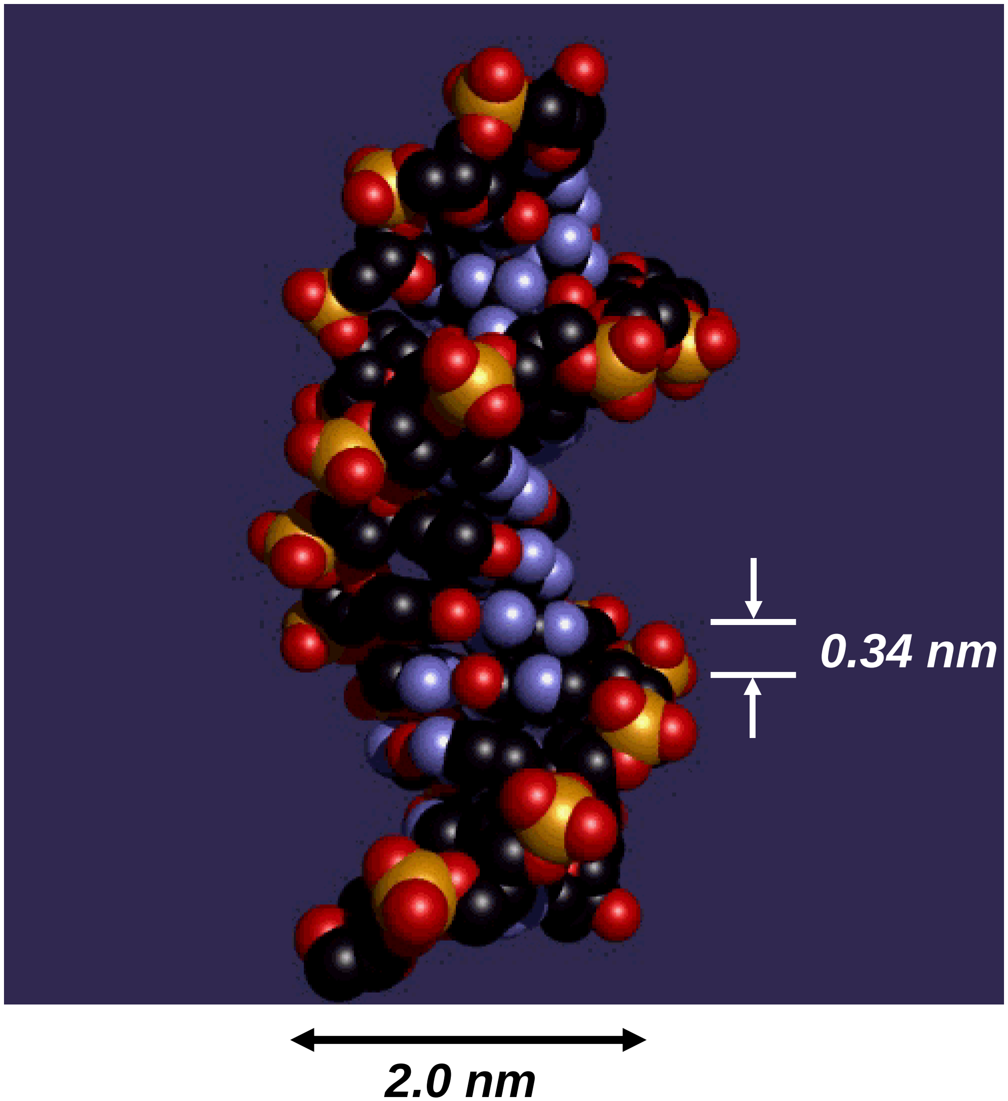
Information storage density $4x10^5$ bits per $\pi(50x10^{-9})^2$ m^{-2}

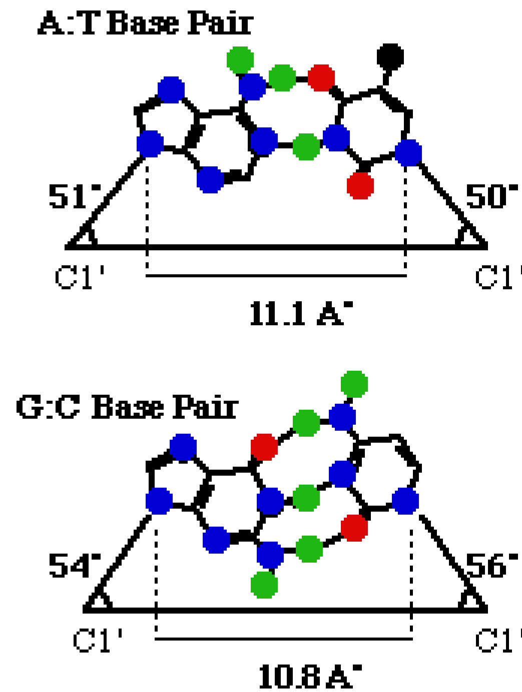
or about $3x10^{16}$ bits/inch^2

A factor of 10^5 times today's state-of-the-art

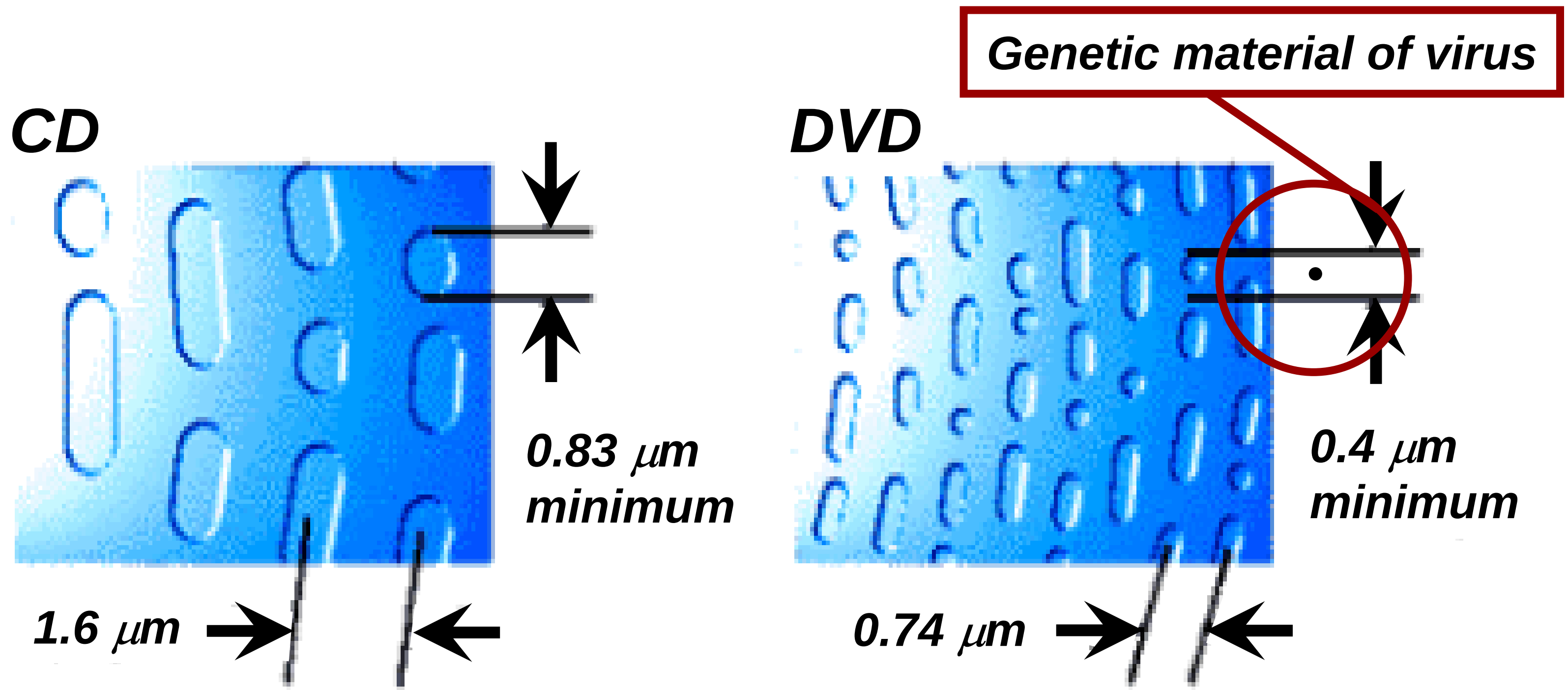
or equivalent to > 30 years of development

DNA has a structure defined at the Nanoscale





Relative Sizes



Can we learn too much from nature?

Bald Eagle in flight

F-15 Eagle in flight

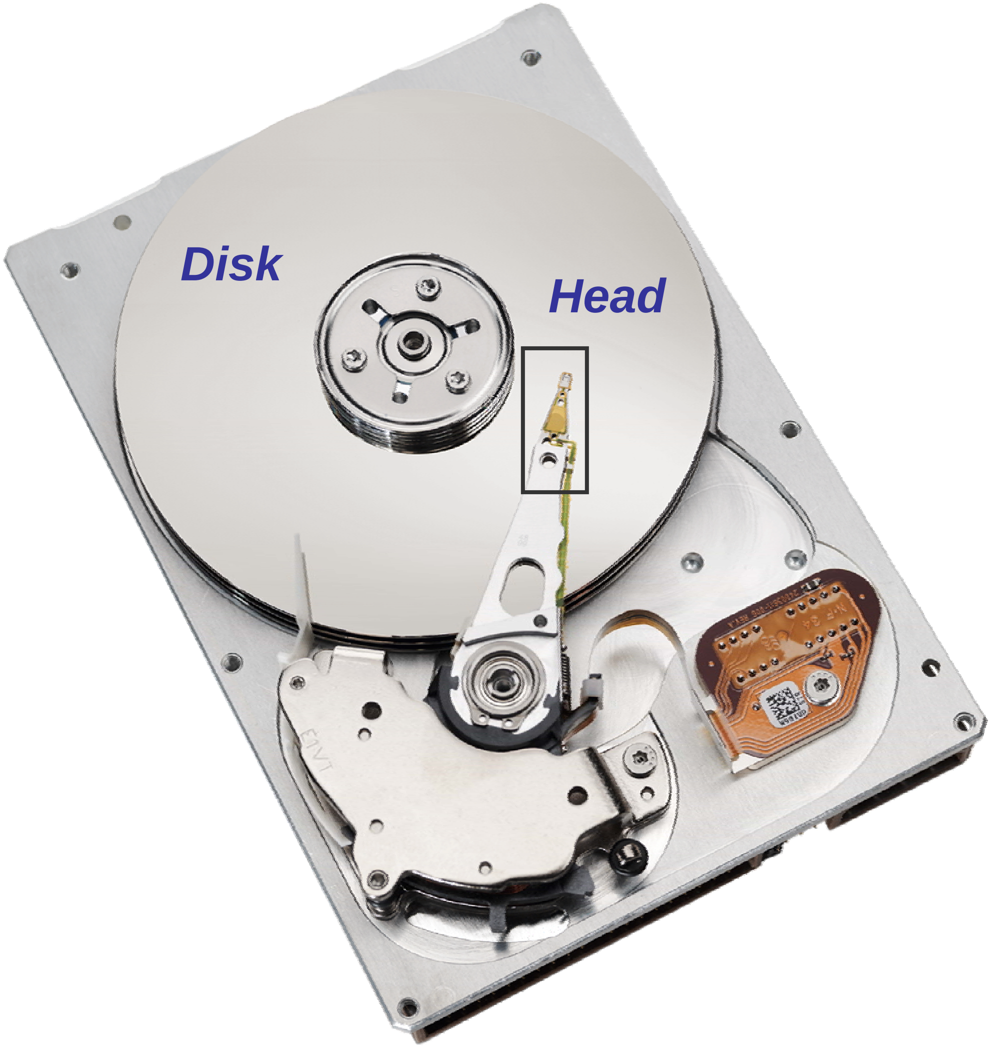
Heavier than air flight is possible…..

Using the examples from nature…

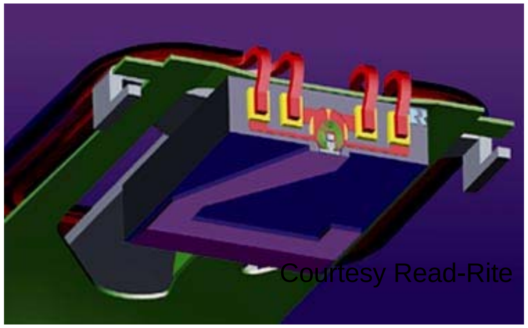
- ***We should exploit nanoscale phenomena for information storage….but we can, eventually, do even better than nature….***

- ***Question:* *What is nanotechnology and can we exploit it in a practical system?***
- ***Answer:* *We already are….***

Inside a disk drive

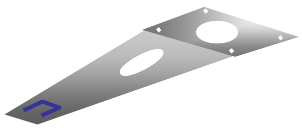


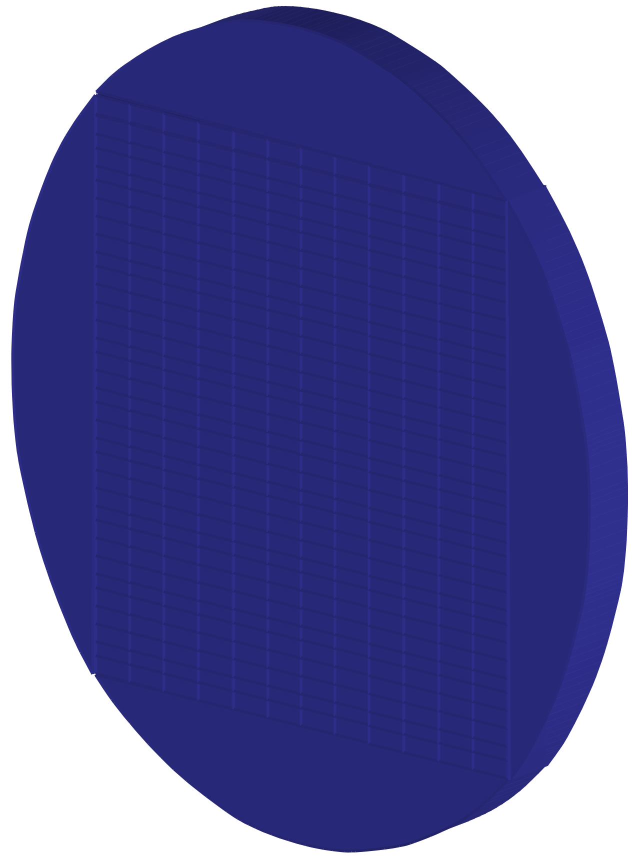
Seagate Barracuda ATA II



Head

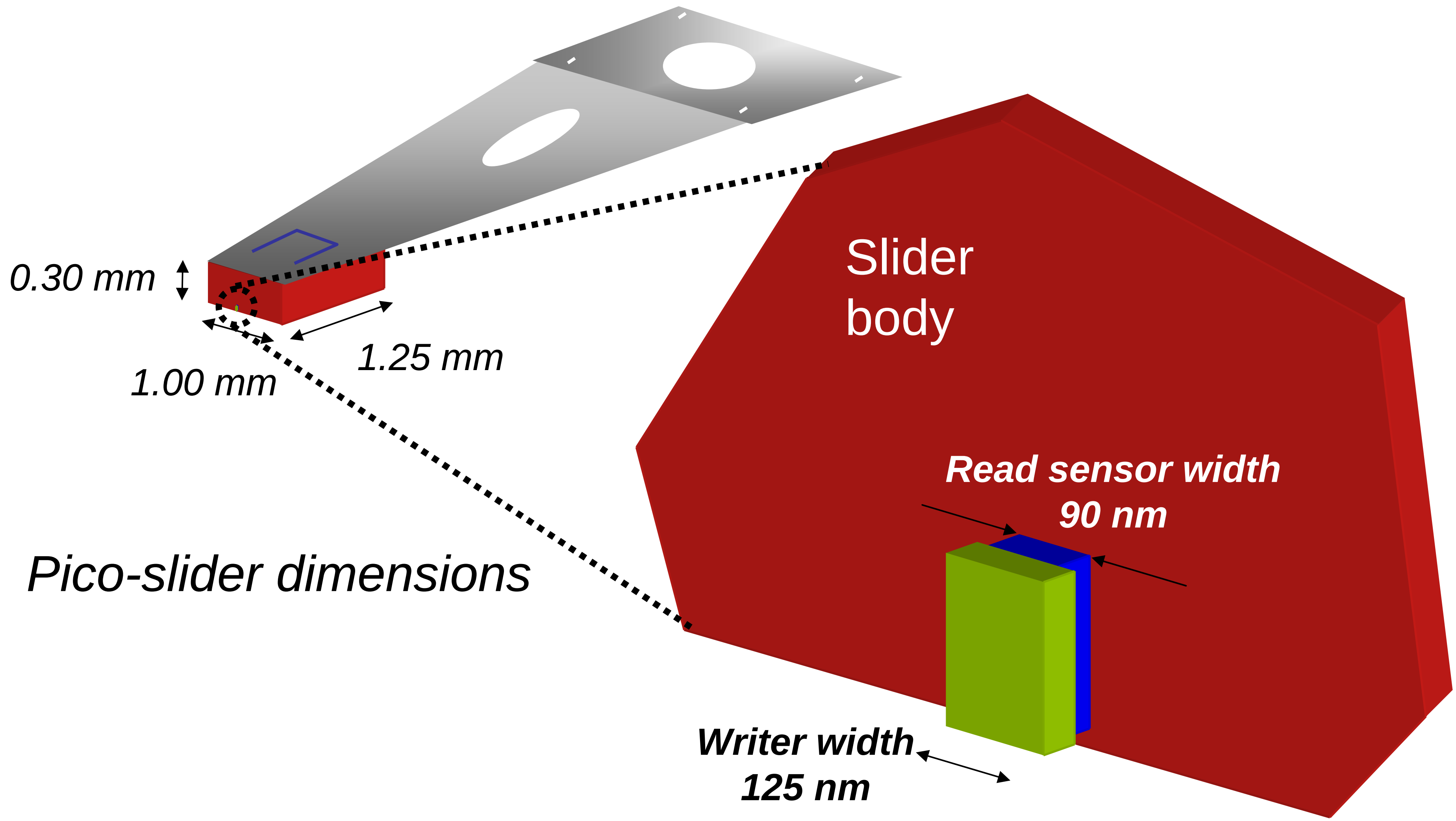
Slider Fabrication (HDD)





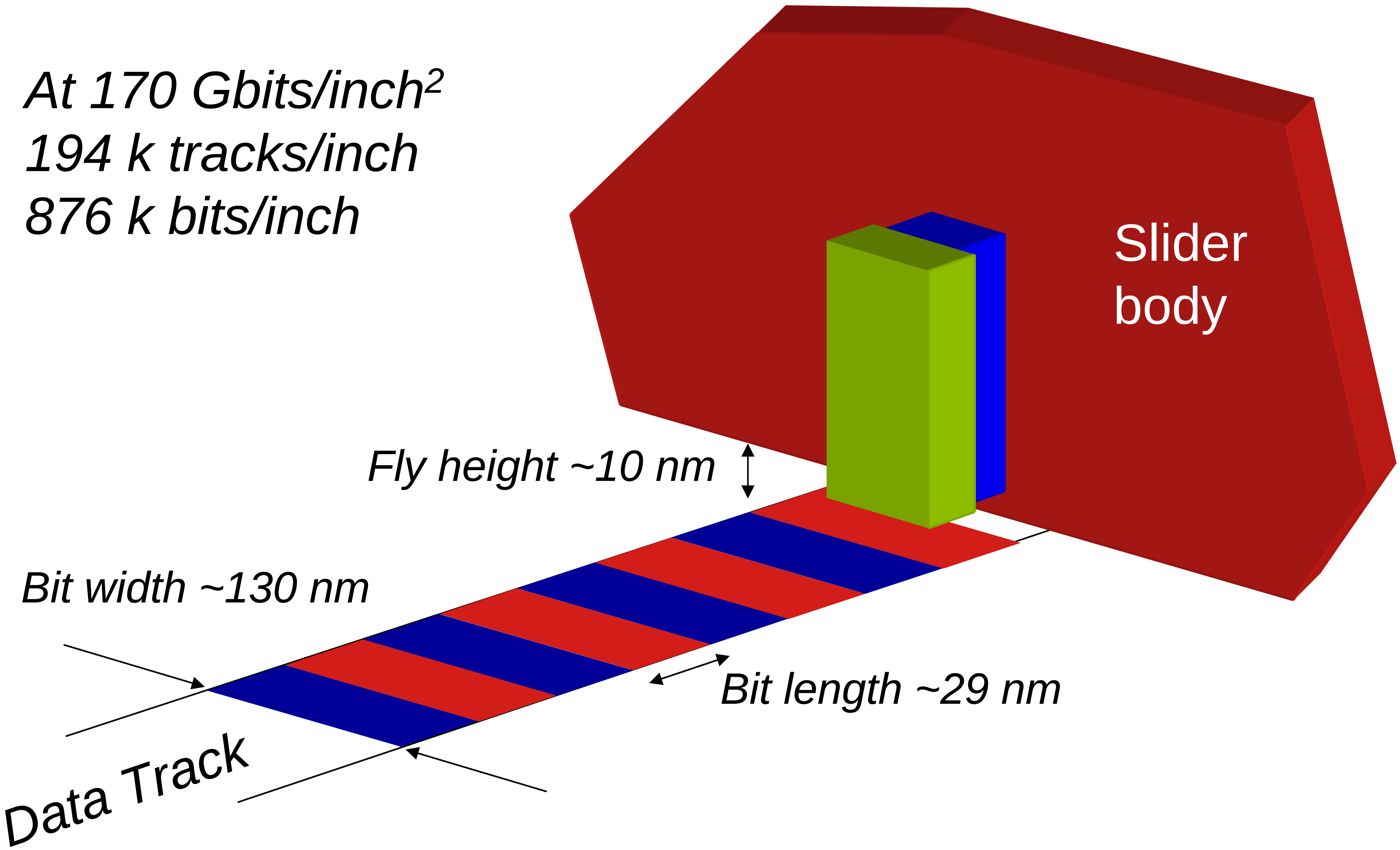
Sliders are cut from substrate and mounted to a suspension

Industrial demo: 170 Gbit/inch²



This is nanotechnology...

At 170 Gbits/inch^2
194 k tracks/inch
876 k bits/inch



Highly Developed Packaging*

***From the Toshiba Press release:** "Toshiba's 0.85-inch HDD, announced in January 2004, is the first hard disk drive to deliver multi-gigabyte data storage in a sub-one-inch form factor. The 0.85-inch measurement refers to the diameter of the magnetic disk to which data is recorded. With initial capacities of 2 to 4 gigabytes (GB) the drive delivers enhanced storage to smaller, lighter, more efficient products, such as mobile phones, digital camcorders and portable storage devices. Toshiba expects to start sampling the drive in summer 2004 and to start mass production in autumn 2004."*

Toshiba (2004)

Not 170 Gbits/inch^2

Nanotechnology

The manipulation of materials at the nanoscale in a deterministic manner to achieve new properties and functions.

What does an information storage system do?

It can move precisely with sub nanometer accuracy to a predetermined location, it can change the physical state of the material at that location at the nanoscale. It can then move away from that location and then return to that very same physical location years later and interogate the state of that very same nanoscale object.

Nanoparticles

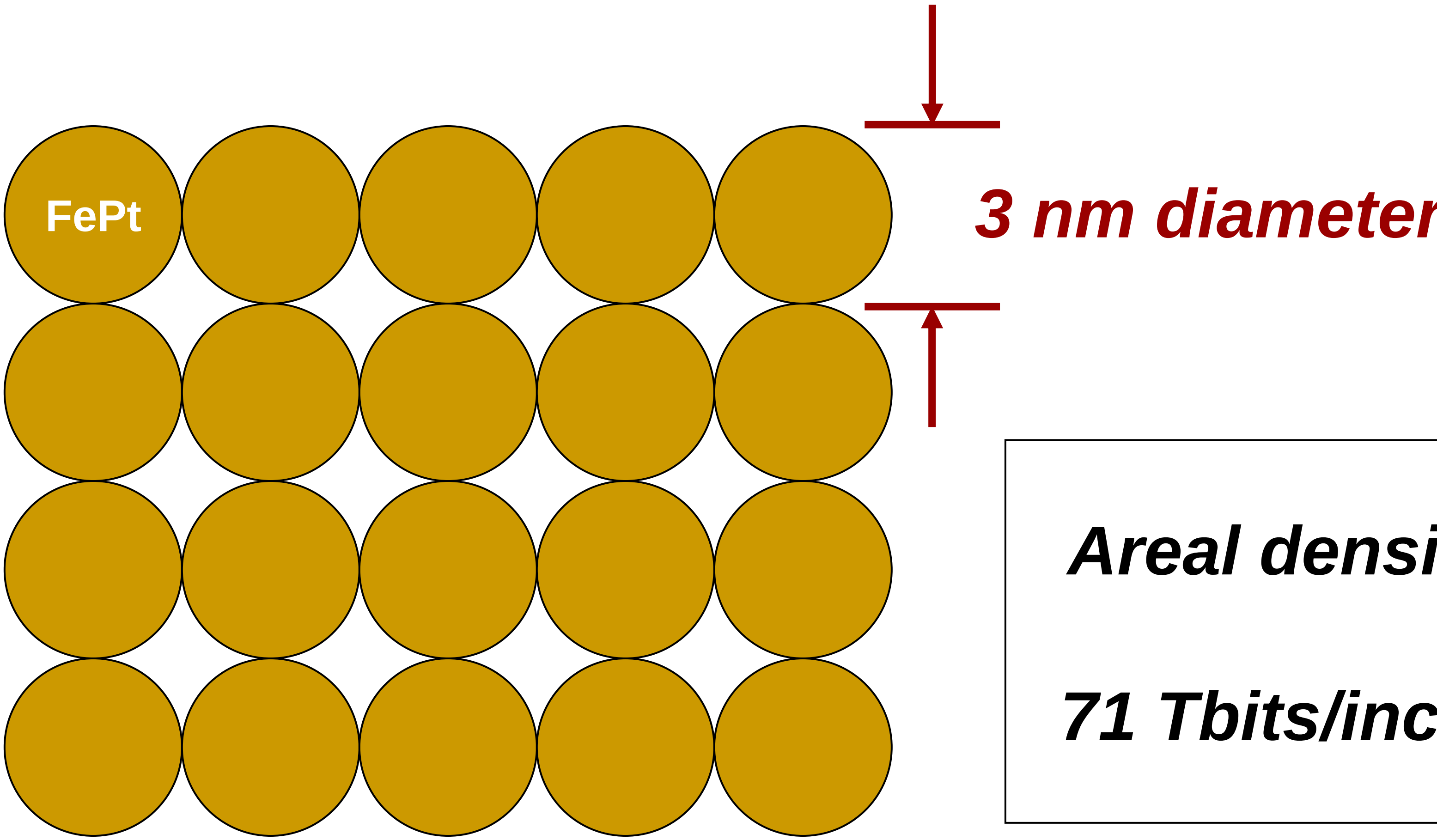
3 nm

- anisotropy field: $H_K = 2K_u/M_S$;
- domain wall width: $\delta_W = \pi\,(A/K_u)^{½}$
- domain wall energy: $\gamma_W \cong 4\,(A \cdot K_u)^{½}$
- single particle domain size: $D_C = 1.4\,\gamma_W / M_S^2$
- exchange coupling constant $A = 10^{-6}$ erg/cm
- minimal stable grain size: $D_p = (60\,k_B T/K_u)^{1/3}$ (τ=10 years)

alloy system	material	K_u (10^7erg/cm^3)	M_S (emu/cm^3)	H_K (kOe)	T_C(K)	δ_W (Å)	γ (erg/cm^3)	D_C (um)	D_p (nm)
	CoPtCr	0.20	298	13.7	--	222	5.7	.89	10.4
Co-alloys	Co	0.45	1400	6.4	1404	148	8.5	.06	8.0
	Co_3Pt	2.0	1100	36	--	70	18	.21	4.8
	FePd	1.8	1100	33	760	75	17	.20	5.0
$L1_0$	FePt	6.6-10	1140	116	750	39	32	.34	3.3-2.8
phases	CoPt	4.9	800	123	840	45	28	.61	3.6
	MnAl	1.7	560	69	650	77	16	.71	5.1
rare-earth	$Fe_{14}Nd_2B$	4.6	1270	73	585	46	27	.23	3.7
transition metals	$SmCo_5$	11-20	910	240-400	1000	22-30	42-57	.71-.96	2.7-2.2

** "High K_u Materials Approach to 100 Gbits/in^2" D. Weller, A. Moser, L. Folks, M. E. Best, W. Lee, M. F. Toney, M. Schwickert, J.-U. Thiele, M. F. Doerner, IEEE Trans. Magn. **36**, 10(2000).*

Areal Density

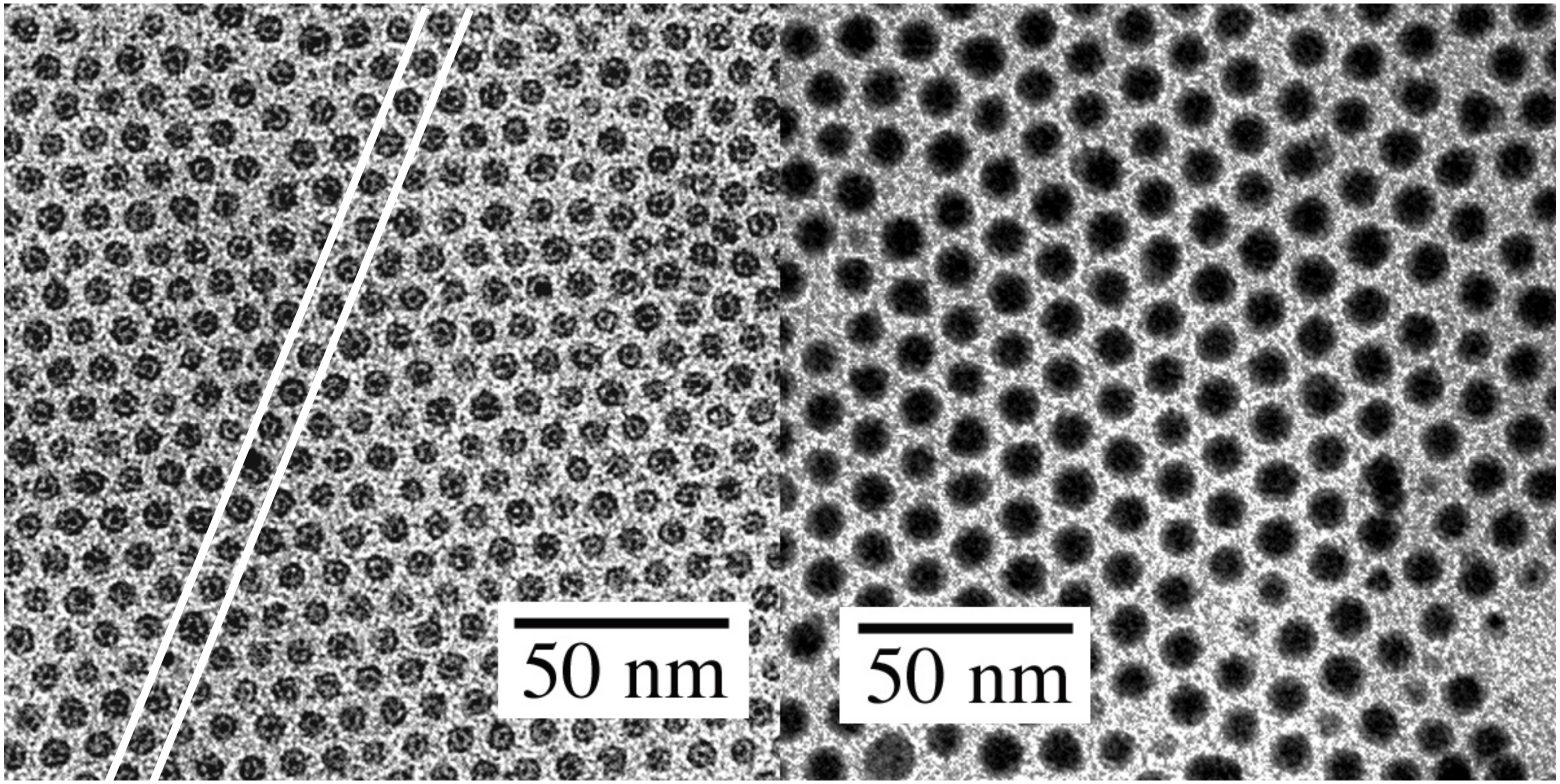


Areal density

71 Tbits/inch^2

Nanoparticle Arrays (Size)

S. Majetich



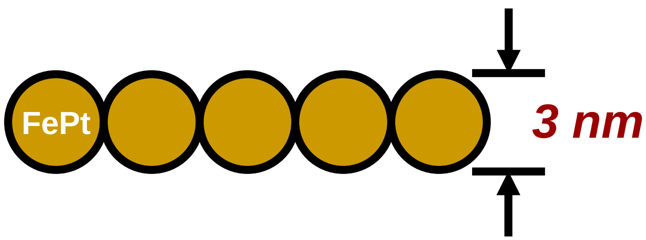
7.0 ± 0.8 nm *9.2 ±0.7 nm*

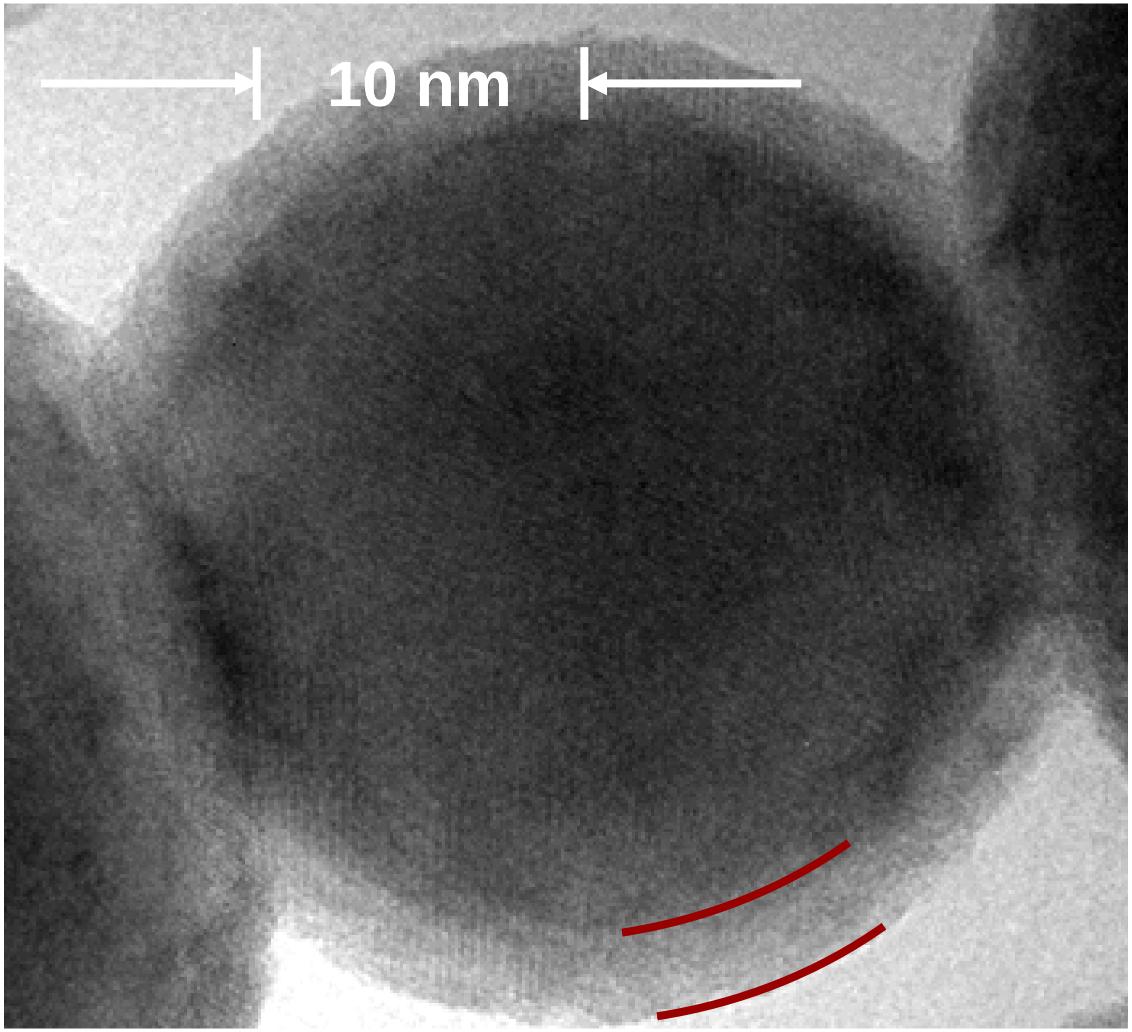
"Preparation and Characterization of Monodispersed Fe Nanoparticles", D. Farrell, S.A. Majetich, J.P. Wilcoxon, J. Phys. Chem. ***107****, 11022(2003).*

Nanoparticles (Structure)

M. McHenry

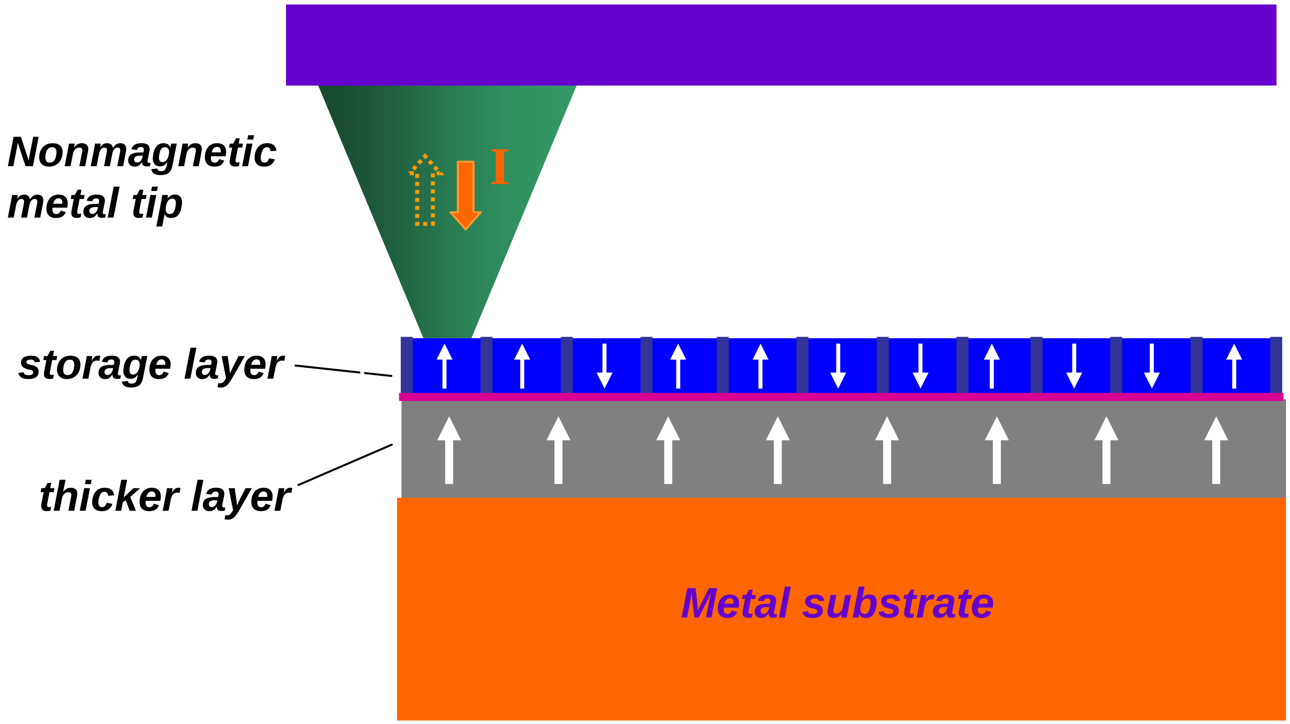
FeCo/Co-Ferrite Nanoparticles





"Magnetic Properties and Microstructural Observation of Oxide Coated FeCo Nanocrystals Before and After Compaction" Z. Turgut, N.T. Nuhfer, H.R. Piehler, M.E. McHenry, J.Appl. Phys. ***85****, 4406(1999).*

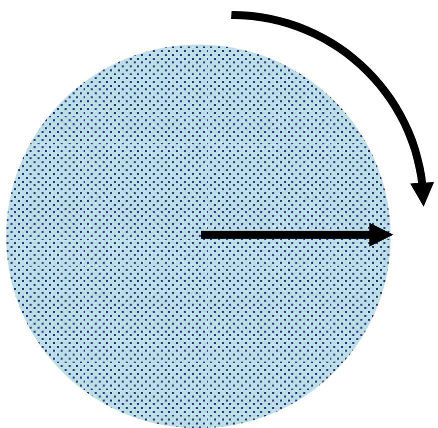
Writing/Reading by Electron Spin Manipulation (Spintronics)



Courtesy J. Zhu

Capacity

- ***Limit capacity to 1 Terabyte (8 Terabits)***
  - *Implies an area of 0.16 inch^2 (1 cm^2 media)*
- ***For 1 msec rotational latency***
  - *1 kHz vibration or 60,000 rpm*



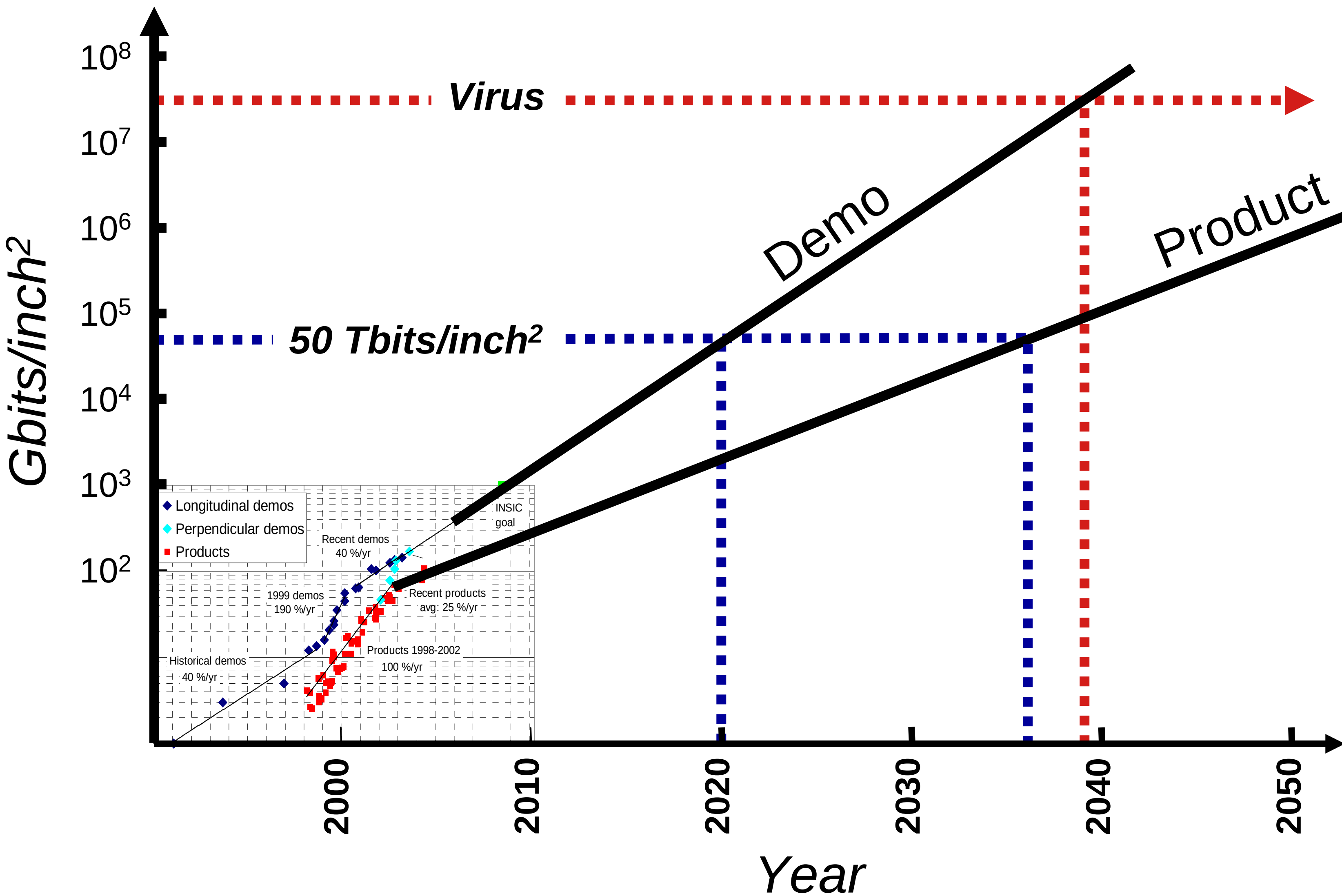
r = 0.564 cm

v = ωr = 2πx1000x0.564

= 35 m/sec

Data rate: 10 Gbits/sec

Competing with Viruses



The Need for Storage

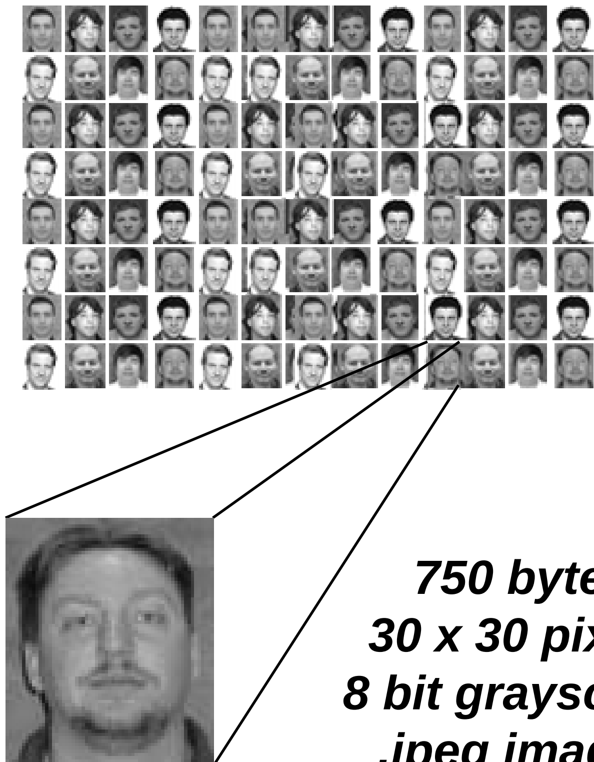
- ***New stored information grew about 30% a year between 1999 and 2002.***

- ***Information flows through electronic channels -- telephone, radio, TV, and the Internet -- contained almost 18 exabytes (exabyte=10^{18} bytes) of new information in 2002, three and a half times more than is recorded in storage media. Ninety eight percent of this total is the information sent and received in telephone calls - including both voice and data on both fixed lines and wireless.***

- ***The World Wide Web contains about 170 terabytes of information on its surface; in volume this is seventeen times the size of the Library of Congress print collections.***

http://www.sims.berkeley.edu/research/projects/how-much-info-2003/printable_report.pdf

What is a Tera-bit?



750 byte
30 x 30 pixel
8 bit grayscale
.jpeg image

Technology goal today 1 Tbit/in^2

What does that mean?

At 1 Tbit/in^2 you can save a picture of every man, women and child on earth on a disk the size of a Compact Disk

Individuals will own libraries of information

Courtesy: T. Rausch

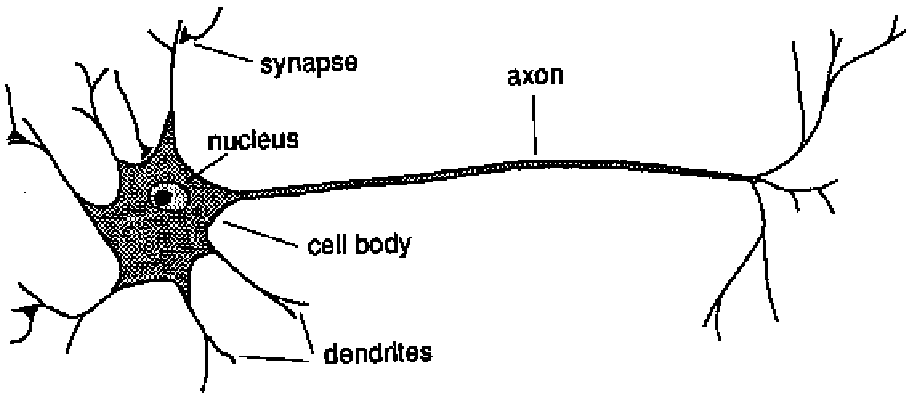
Libraries of Information

- ***What are the social implications of putting "libraries" of information in the hands of individuals?***
  - *The policeman on the corner can have a hand held device containing a photo and fingerprint of every person in the country*
  - *…*
- ***We know from history that when capabilities reserved for institutions are put into the hands of individuals great social changes have occurred***
  - *The printing press*
  - *The personal computer*
  - *…*
- ***Will information storage systems be "regulated"?***

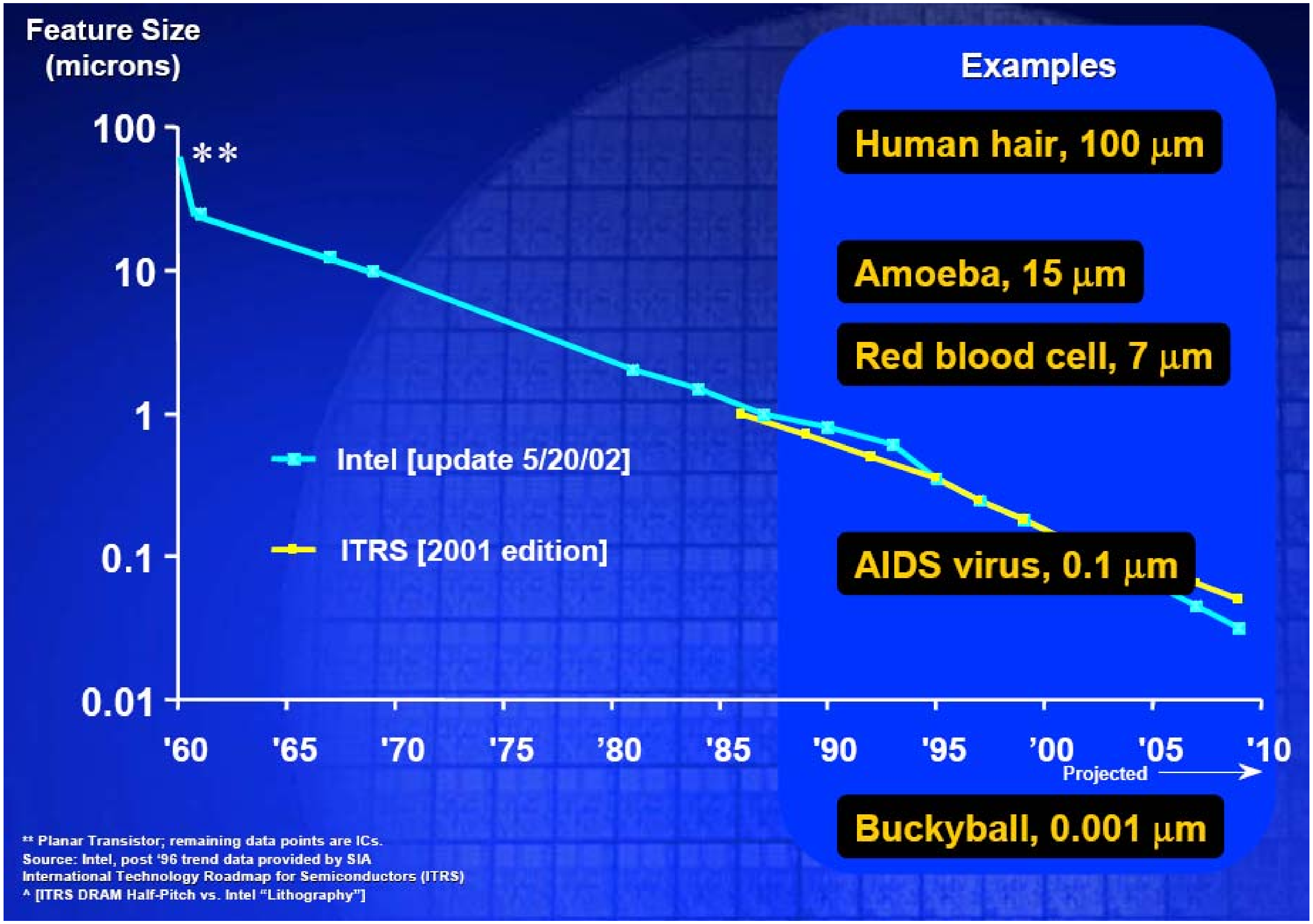
Beyond Storage Alone….

Human Brain – Integrated storage and processing

- Switching a neuron requires 10^{-16} Joules ($\sim 10^3$ eV)
- Propagating a nerve impulse a distance of 1 millimeter requires about 5×10^{-15} Joules. (3×10^4 eV)
- Total energy dissipated by the brain is about 10 watts.
- Given an estimate for the distance between synapses one can estimate how many synapse operations per second the brain can perform; 10^{13} to 10^{16} operations per second.

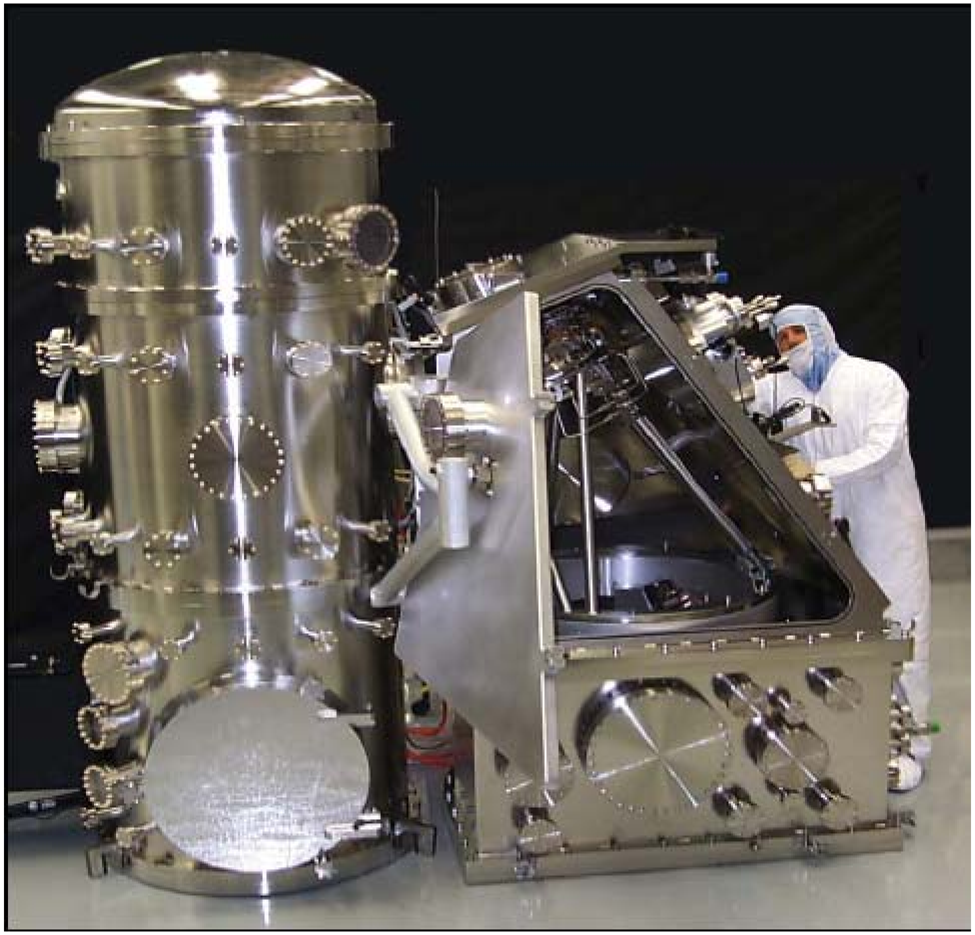


Minimum Feature Size in IC Technology (Scaling)



Gordon Moore ISSCC 2003

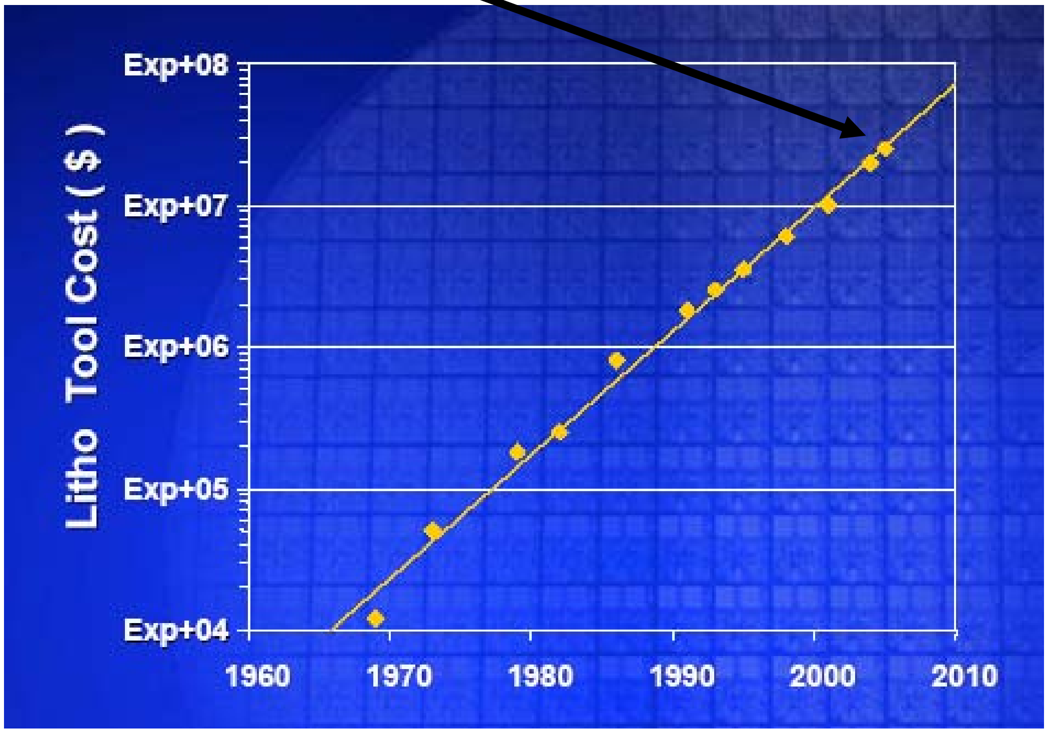
Extreme Ultraviolet Lithography



Cost of Production

- $30 M/tool today
- $250 M/tool in ten years
- $1 B/tool in twenty years!

This can't go on forever!



*Fabs cost 100x the tool cost

Gordon Moore ISSCC 2003

The late economist Herb Stein said "anything that can't go on forever, won't."

The solution?

Self assembled arrays of nanodevices…..

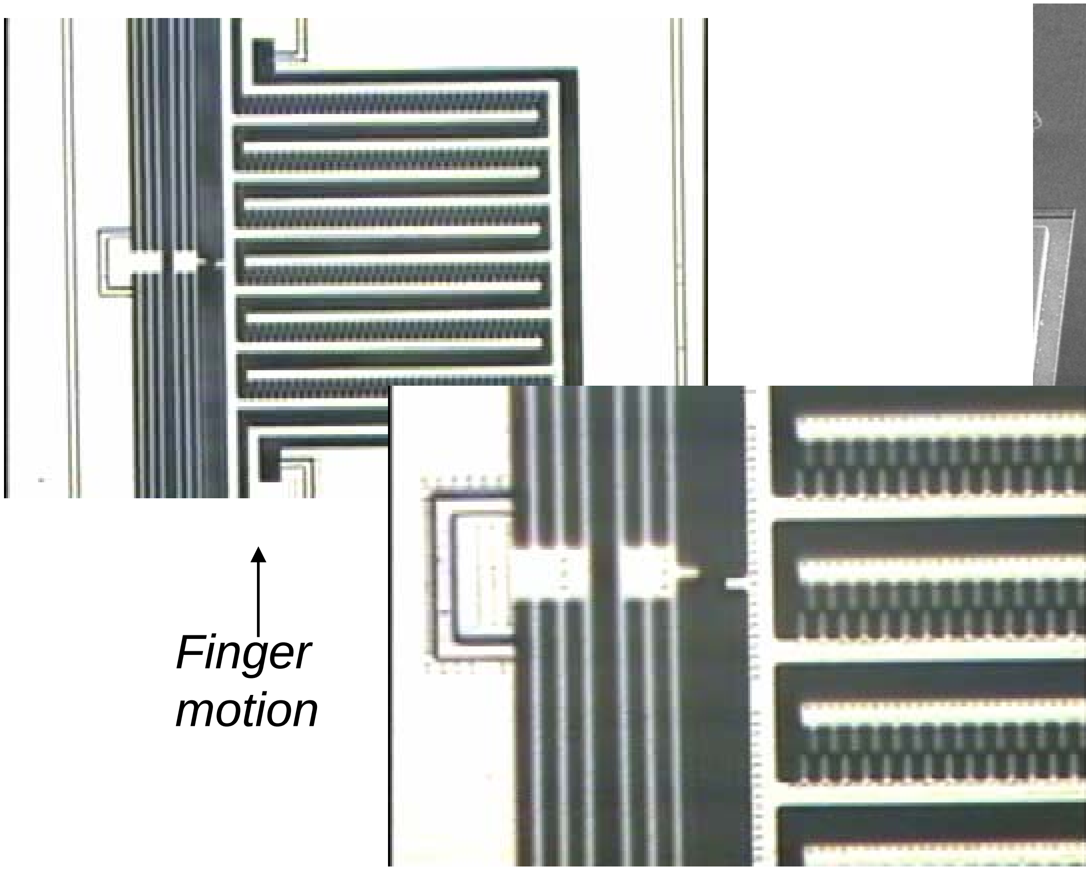
Only half the solution….since one has to input the "information"….

CMOS MEMS at CMU

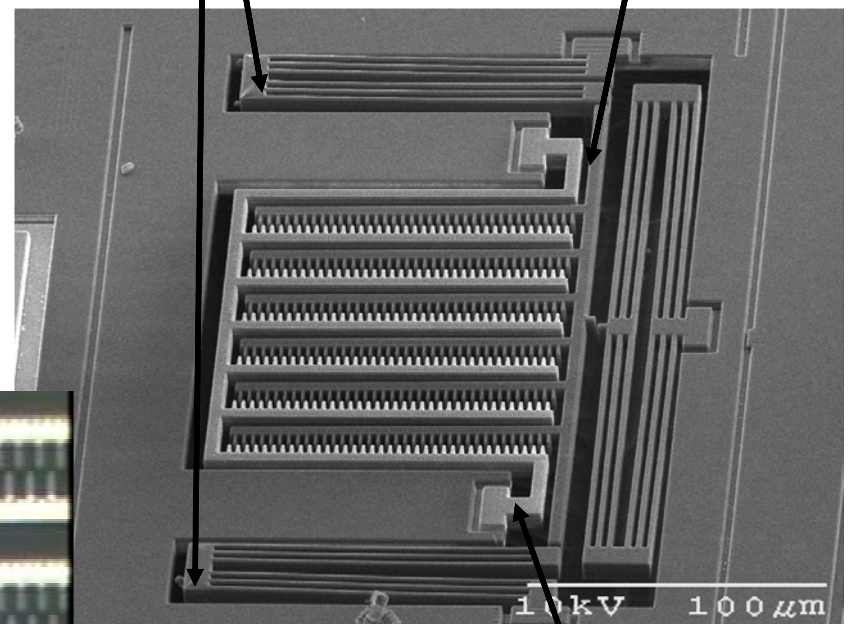
- ***Moving capacitor in 0.35 µm CMOS***
- ***Dense comb array provides variable capacitance***

Electro-thermal actuators

Yoke for moving fingers



Finger motion

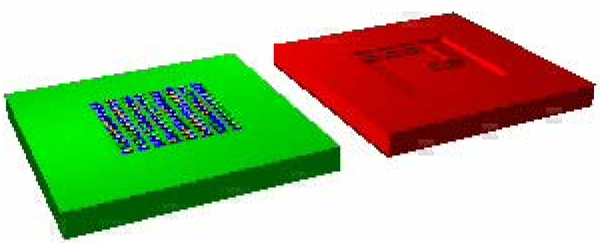


Finger motion

Yoke for static fingers

A. Oz, G. K. Fedder, IEEE Transducers 2003 & MTT-S RFIC 2003, June 2003

Memory Intensive Self Configuring Integrated Circuits (MISC IC's)



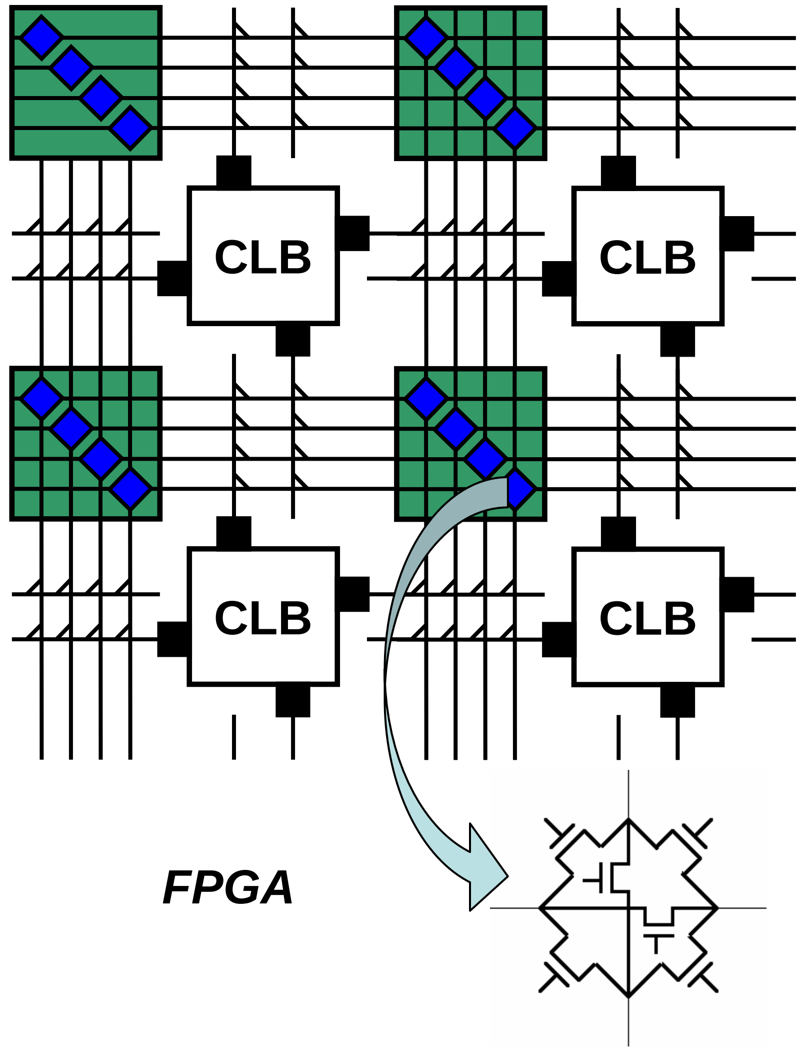
This technology integrates memory and processing technology, is able to tolerate defects and irregularities, and is reconfigurable in the field and most importantly allows IC systems to move beyond CMOS and its scaling paradigm.

Field Programmable Gate Array

Switch boxes

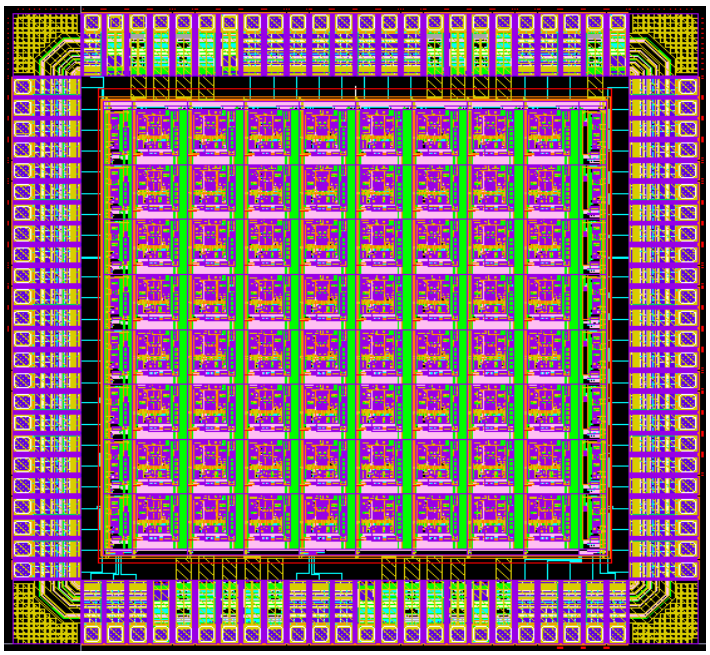
and

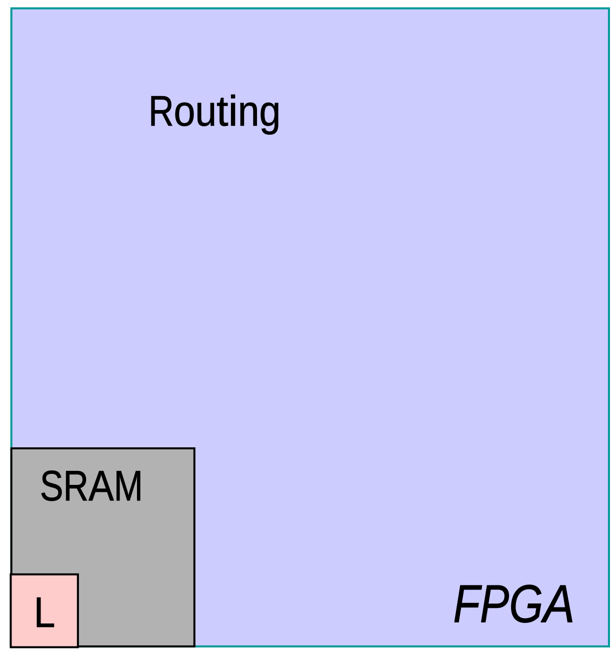
Configurable Logic Blocks (CLB)



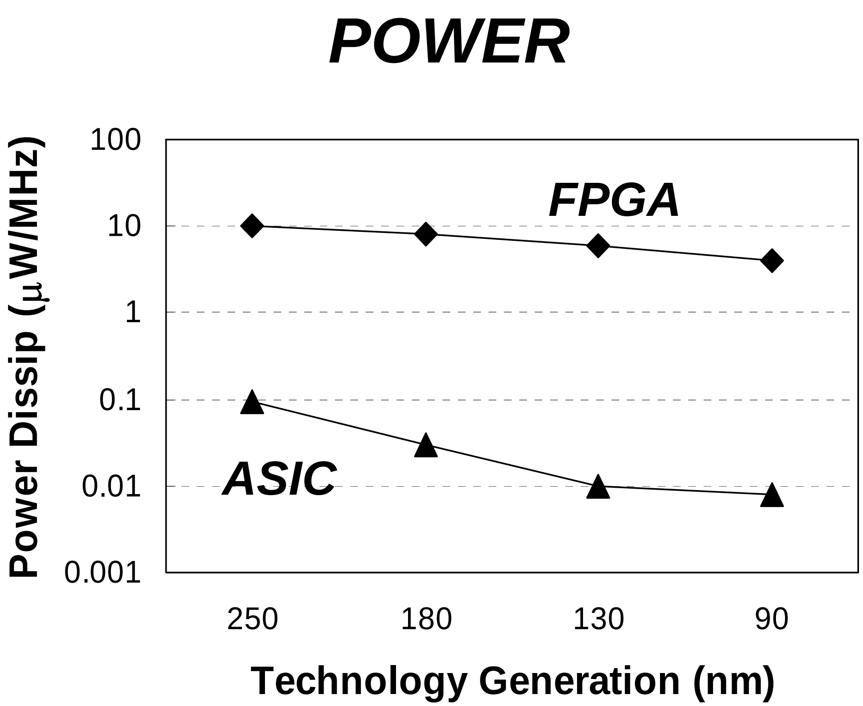
FPGA

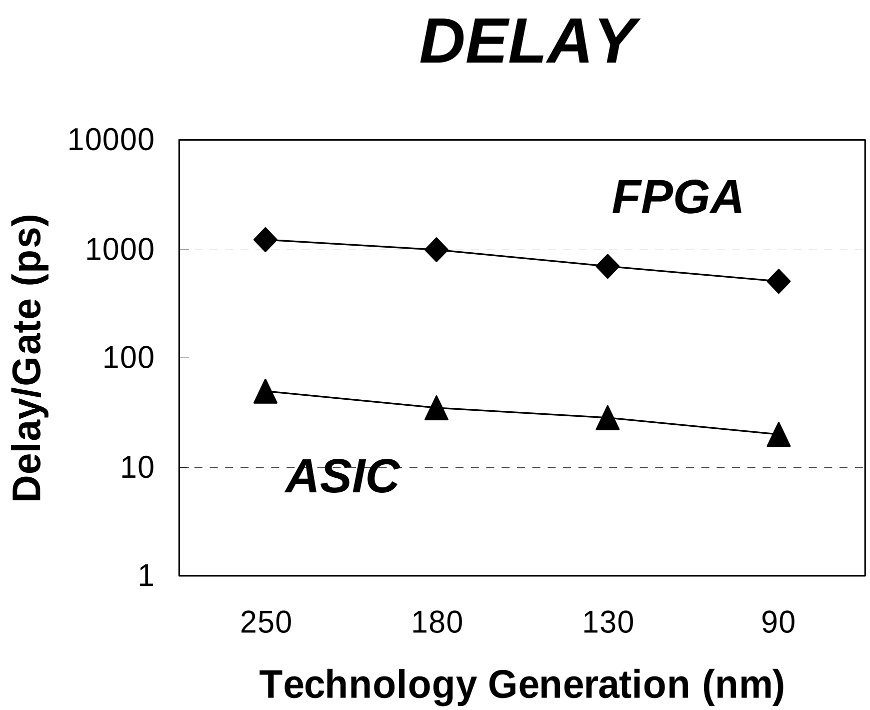
- ***Proportional diagram of relative area for components of FPGA***





FPGA vs ASIC Performance

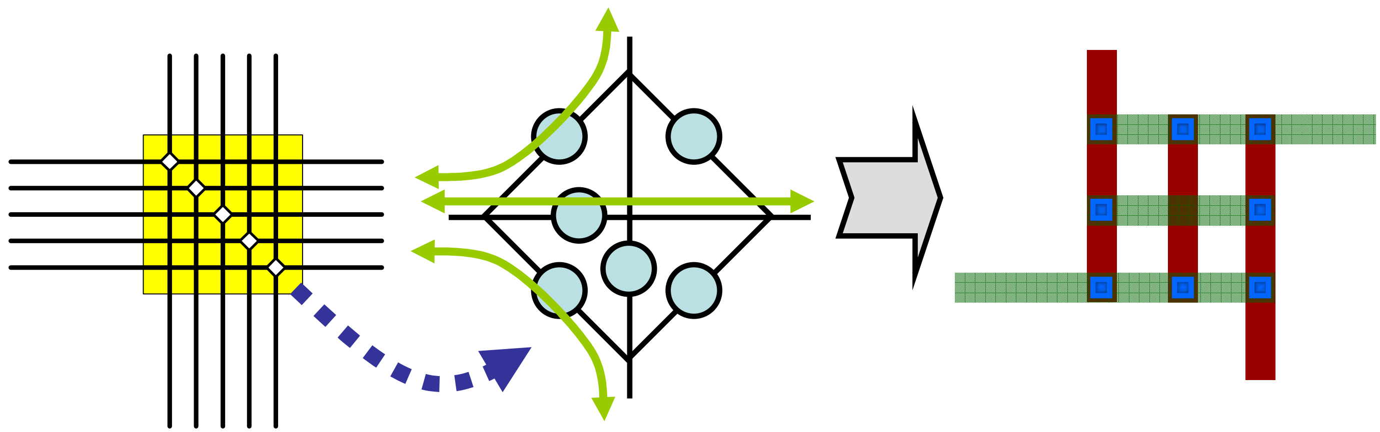




Source: IBM

Switchbox

- *A switchbox has to be able to route in all directions, w/o wiping out other tracks*
- *An FPGA does this with SRAM storage and pass-gates in a configuration something like that shown here:*

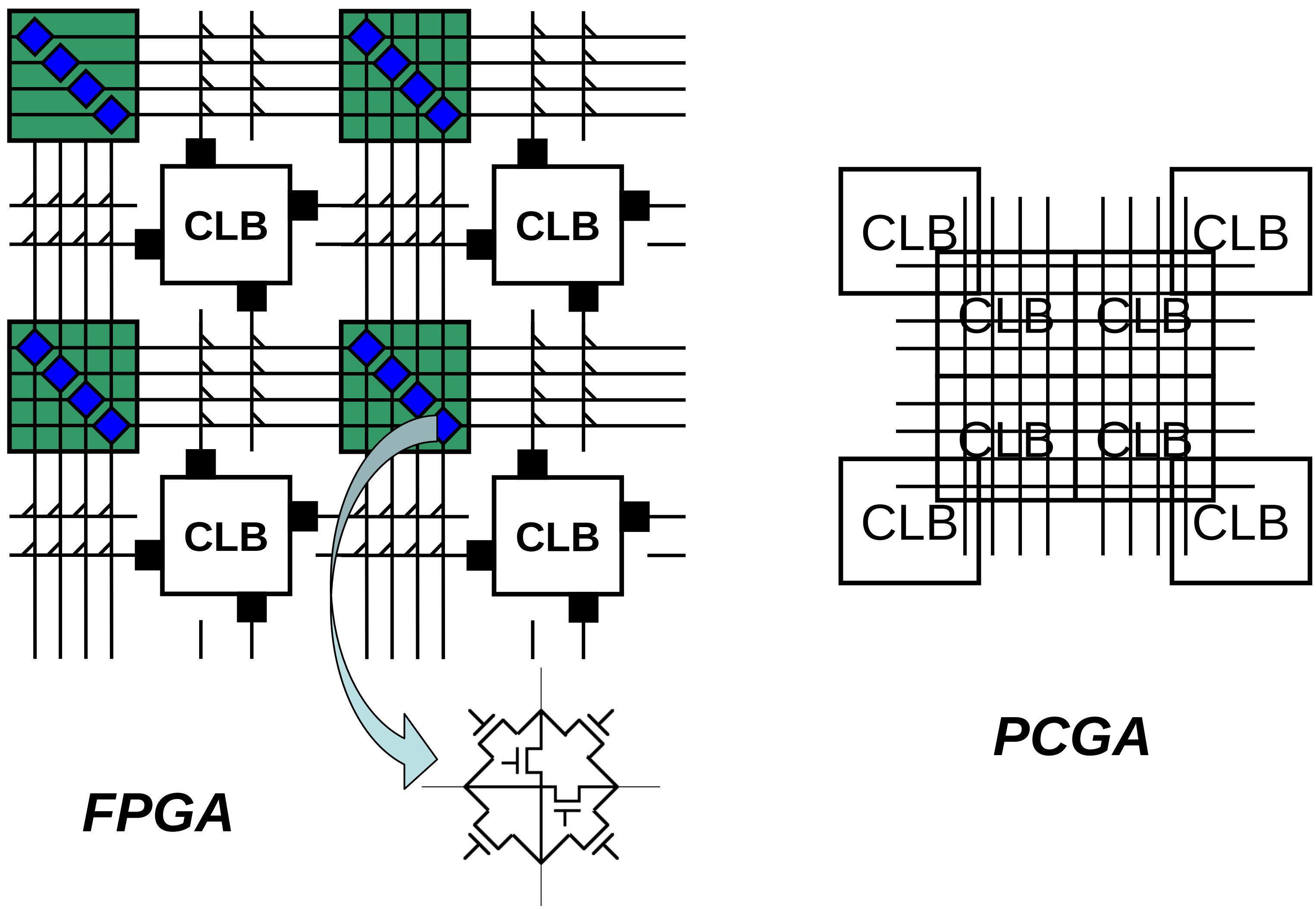


- *We can actually use vias instead of transistor-switches for configuration*
  - *E.g. replace 36-120 transistors switchbox with 8 potential vias*

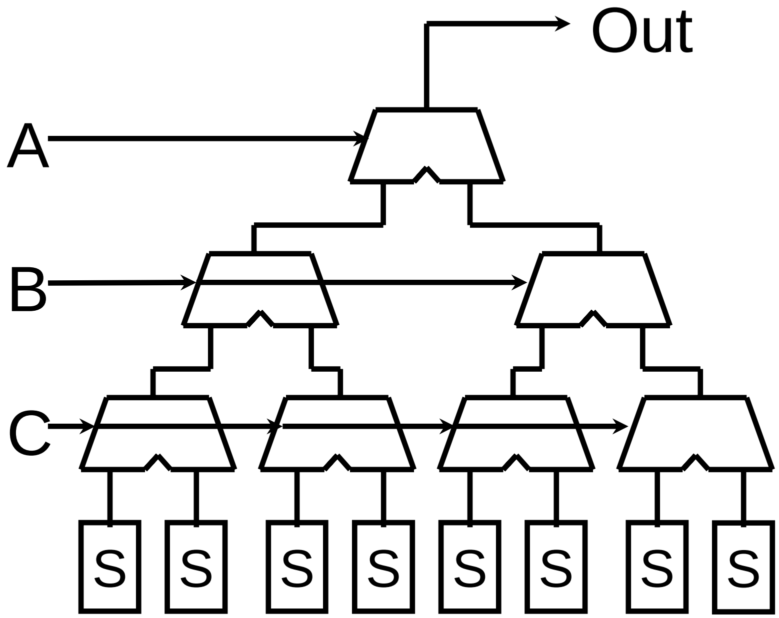
Advantages Using Probes

- *Signal lines do not carry high current*
- *Some architectures simply will not work without probe access (separate access)*
- *Two-probe architecture that allows for the configuration of vias in pairs (with current) also possible*

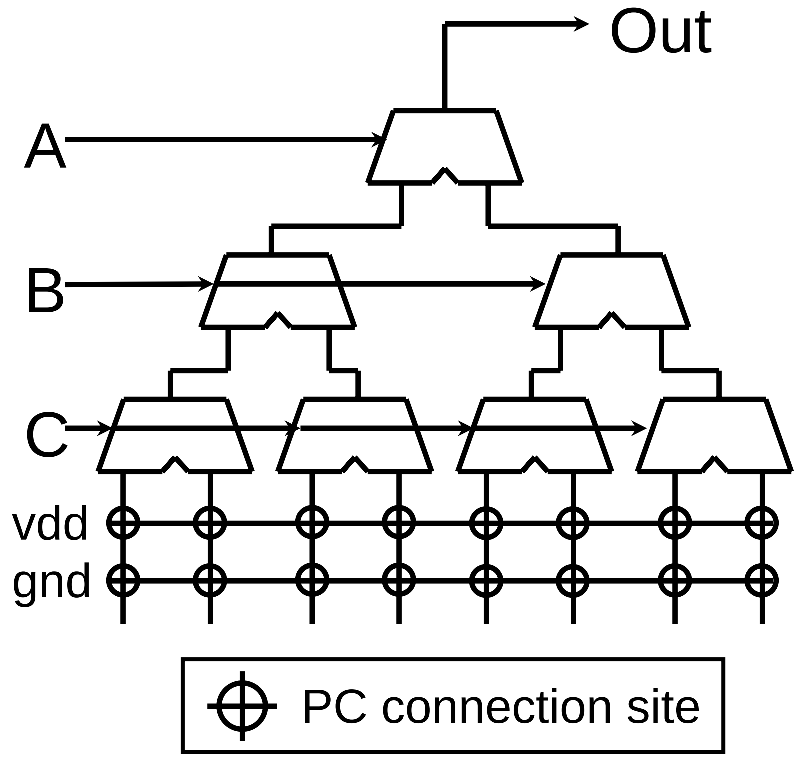
FPGA vs PCPGA



FPGA vs. PCGA LUTs

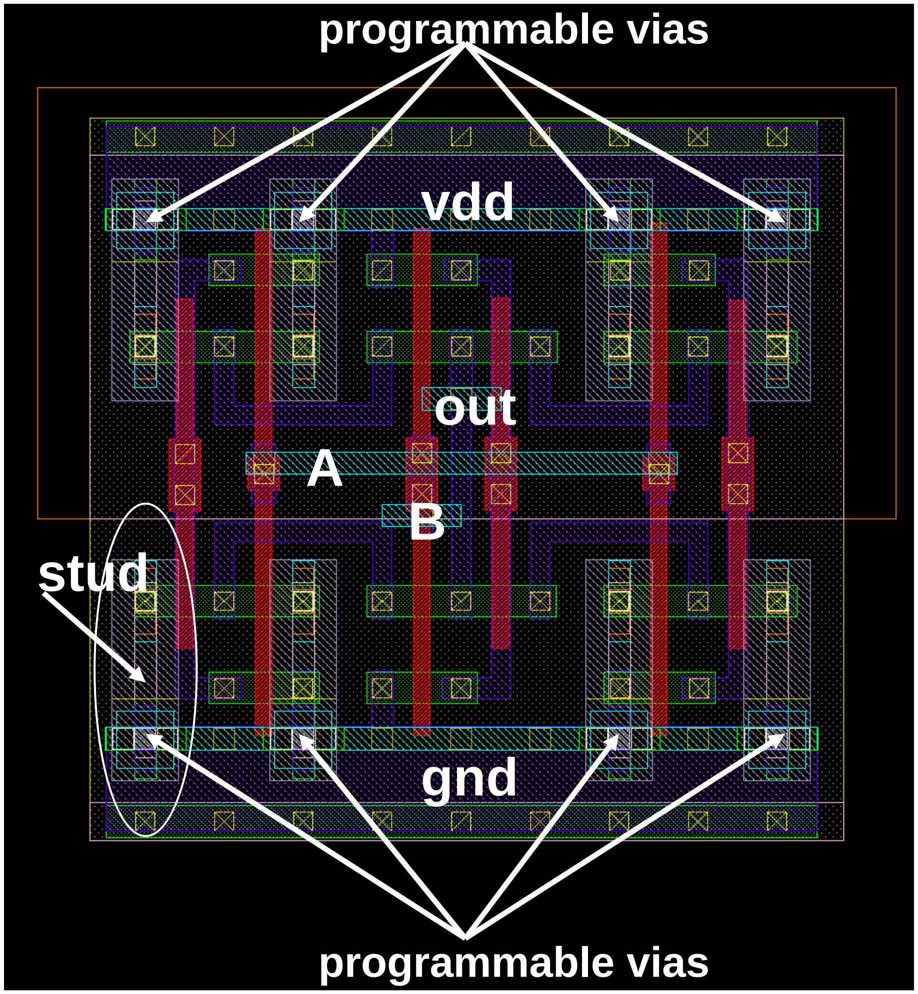


FPGA



PCGA

Example Two Input Layout

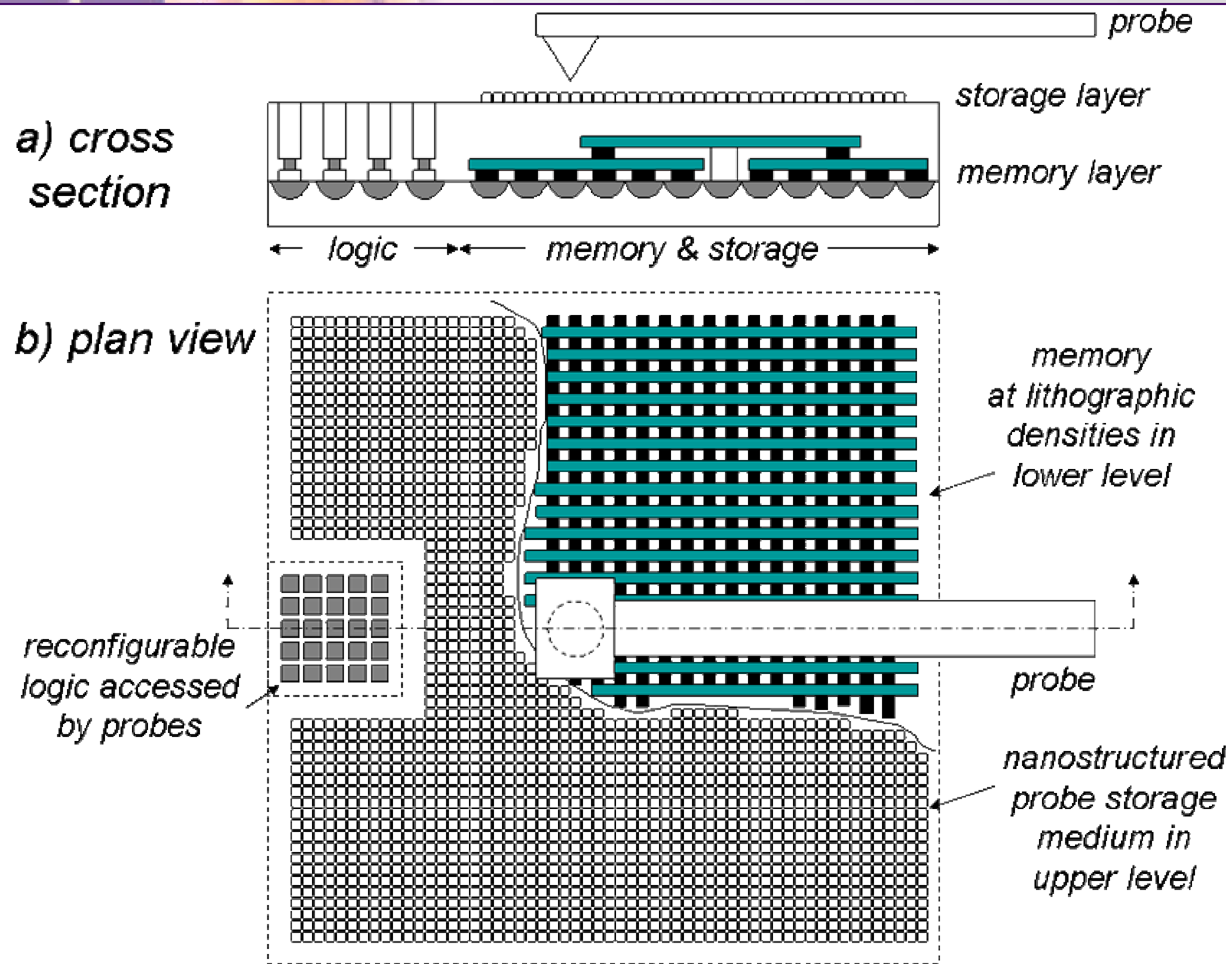


Advantages of MISC IC's VS FPGA

- ***Reduced parasitics***
- ***Potential 100x decrease in wiring complexity***
- ***Potential 100x decrease in power dissipation***
- ***Potential 100x reduction in cost***

- ***Nearly ASIC like performance***

A next generation MISC IC



Under certain assumptions, at the 45 nm technology node, a 1 cm square chip could have: 1 million gates, 1 GByte of memory (access times < 100 ns) and 100 GBytes of storage (access times <500 μs).

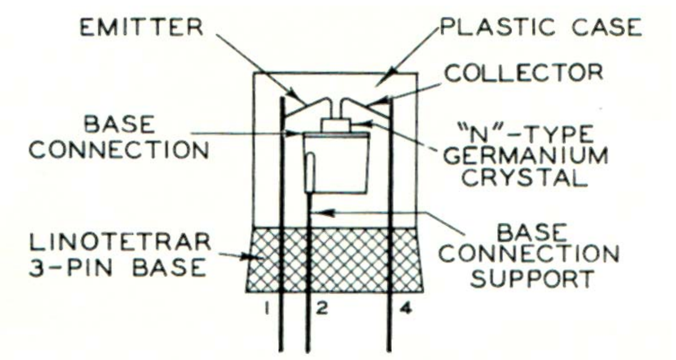
MISC ICs*

- Specific architecture where the technology of information storage systems is applied to and merged with IC technology
- A paradigm that moves IC's beyond current scaling limitations for performance improvement
- Integration of storage, memory, and information processing technology

NSF ERC Proposal to be submitted

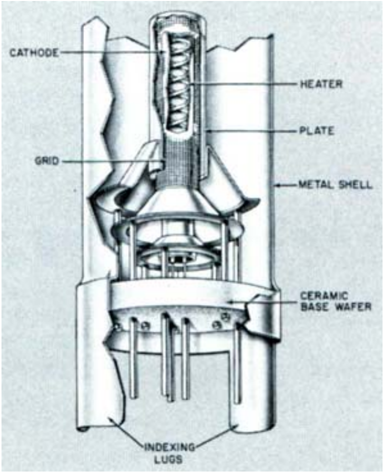
Crude? Consider: First RCA Transistor and Last RCA Vacuum Tube

Point Contact Germanium Triode Transistor (2N33) Introduced 1953



INITIAL PRICE: $32.00
QUANTITY MADE: Low 1000s
APPLICATIONS: High Freq Oscillator
MAX SUPPLY VOLTAGE: 8.5V
OPERATING FREQ: 50 MHz
POWER OUTPUT: 30 mw Max
HEATER POWER: None Required
OPERATING TEMP: 40 C Max
ENV REQ: Poor Tolerance to Vibration, Moisture and Temp Changes

Nuvistor Triode Vacuum Tube (6CW4) Introduced 1960



INITIAL PRICE: $20.00
QUANTITY MADE: Low 100,000s/year
APPLICATIONS: RF Amp for FM/TV
MAX SUPPLY VOLTAGE: 300V (70 TYP)
OPERATING FREQ: 500 MHz
POWER OUTPUT: 1 Watt Max
HEATER POWER: 6.3V @ .13A
OPERATING TEMP: 125 C Max
ENV REQ: Excellent Tolerance to Vibration, Moisture and Temp Changes

What new inventions will be required? Consider…

- ***March 1905***
  - *Einstein sends to the Annalen der Physik, the leading German physics journal, a paper with a new understanding of the structure of light. Einstein showed that light quanta, as he called the particles of energy, could help to explain phenomena being studied by experimental physicists. For example, he made clear how light ejects electrons from metals*
- ***May 1905***
  - *The Annalen der Physik received another paper from Einstein. Einstein explained Brownian motion in detail. He had reinforced the kinetic theory, and he had created a powerful new tool for studying the movement of atoms.*
- ***June 1905***
  - *Einstein sent the Annalen der Physik a paper on electromagnetism and motion. Since the time of Galileo and Newton, physicists had known that laboratory measurements of mechanical processes could never show any difference between an apparatus at rest and an apparatus moving at constant speed in a straight line (Principle of Relativity). But according to the electromagnetic theory, developed by Maxwell and refined by Lorentz, light should not obey this principle. Einstein found a way to show that this principle was compatible with electromagnetic theory. His new theory was later called the special theory of relativity.*
- ***September 1905***
  - *Einstein reported a remarkable consequence of his special theory of relativity: if a body emits a certain amount of energy, then the mass of that body must decrease by a proportionate amount. The relationship is expressed as an equation: $E=mc^2$.*

http://www.aip.org/history/einstein/great1.htm

…the message….

- ***The ideas which Einstein explained and which in some sense form the basis of modern science were based (3 out of 4) on phenomena and experiments already in existence and being investigated by others….***

Summary

- *Engineering limits in information storage systems are being approached but these are not fundamental in the sense of insurmountable laws of nature.*
- *These "limits" may bring to an end particular engineering paradigms we use today to store information but not the development of new storage paradigms and hence new storage systems with improved capabilities.*
- *Information storage today is an application of nanotechnology.*
- *Further advances in nanotechnology will bring unprecedented storage capacity that will fundamentally change the way we think about information.*
- *The integration of information storage and information processing will make for new applications and completely new metrics of performance*

Final Thought

We are living in a time of change…..

In times of change, learners inherit the Earth, while the learned find themselves beautifully equipped to deal with a world that no longer exists. – Eric Hoffer