CS295-6 Introduction to Nanocomputing

The Emergence of Nanotechnology

John E Savage

How Small is a Nanometer?

- In PhD thesis Einstein estimated size of sugar molecule to be about one nanometer (nm).
- One hydrogen atom has diameter of 0.1 nm (one angstrom).
- A bacterium has a length of about 1,000 nms.
- A nanometer is very small!

What is Nanotechnology?

- Materials have at least one dimension that is one to 100 nms in length.
- They are designed through processes that exhibit fundamental control over the physical and chemical attributes of molecular-scale structures.
- They can be combined to form larger structures.

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“There's Plenty of Room at the Bottom” Richard Feynman, 1959

- Richard Feynman gave a talk at 1959 APS meeting arguing for exploration of the nanometer world.
- Envisioned vast amounts of data in small space
  - 120,000 Caltech volumes on a library card
- Forecast tiny machines manufacturing even tinier ones through multiple stages.
  - Is his vision realistic?

The Drexlerian Vision

- In ***Engines of Creation***. K. Eric Drexler, 1986, extended Feynman's vision.
  - "Molecular assemblers will bring a revolution without parallel …" and "… can help life spread beyond Earth …"
  - "These revolutions will bring dangers and opportunities too vast for the human imagination to grasp …"
- These ideas are the source of controversies.
  - Nobelist Smalley and Drexler debate molecular manufacturing.
  - Drexler's forecasts trouble Bill Joy of Sun Microsystems.

New Science and Technology Emerge

- Nanotechnology operates at new scale.
- "Nanotechnology" coined by Tokyo Science University Professor Norio Taniguchi in 1974.
- Objects are so small that their properties lie between classical and quantum physics.
- Placement of such objects can be done either
  - Deterministically but very slowly – e.g., with the atomic force microscope (AFM).
  - Nondeterministically and fast using processes that introduce randomness.

Examples of New Nano Materials

- Carbon nanotubes
  - Used to make strong, light materials
- Silicon nanowires
  - Proposed for use in crossbar memories and ultra-sensitive detection of antibodies.
- Porous materials with nanometer-sized pores
  - Useful in filtration of micro-organisms.
- Nanometer-sized Zinc Oxide particles
  - Used in transparent sunscreens.

Computational Nanotechnology

- The goals:
  - To make ever smaller computing components.
  - To understand computing under uncertainty and with faults.
- The challenge:
  - To model and analyze non-deterministic assembly
  - To cope with faults
  - To communicate with physical nanotechnologists

Moore's Law Clashes with Murphy's Law

- **Moore's Law**: The number of transistors on a chip approximately doubles every two years.
- **Murphy's Law**: If something can wrong, it will.
- As chip densities increase, it is inevitable that chip designs are no longer predictable.
- Chip assembly becomes stochastic!

Emerging Models of Computation

- Nanoelectronic Computing
- DNA Computing and Templating
- Synthetic Biology
- Quantum Computing

Most Exciting Research Results

- Nanoelectronic device development
- Device integration into simple architectures
- Architectural and performance analysis

Most Exciting Open Research Areas

- Fault tolerance
- Stochastic Assembly
- New emerging models

Overview of the Course

- Focus primarily on nanoelectronic computing
  - Crossbars, related technologies and analysis

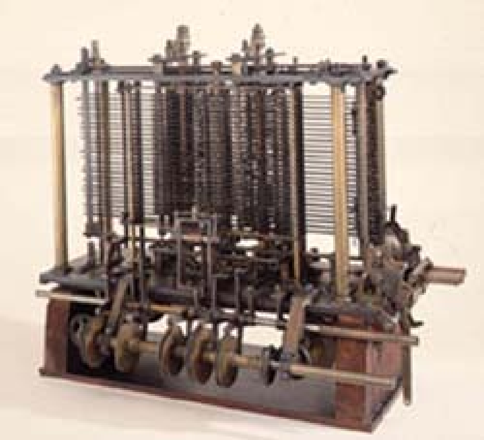
- Exposure provided to
  - DNA Computing and Templating
  - Synthetic Biology
  - Quantum Computing
    - Basic introduction
    - Schor’s theorem

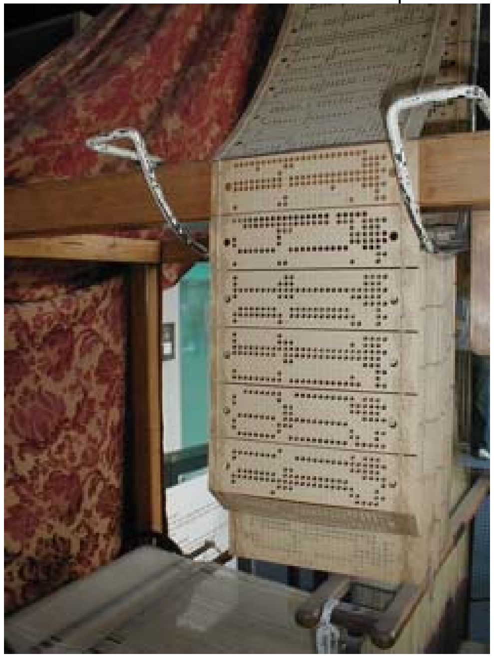
A Brief History of Computer Technologies

- Let’s look at some of the key signposts in the development of computer technology.

Early Computers

- [Jacquard Loom](#) – 1746
  - Punched cards control weaving

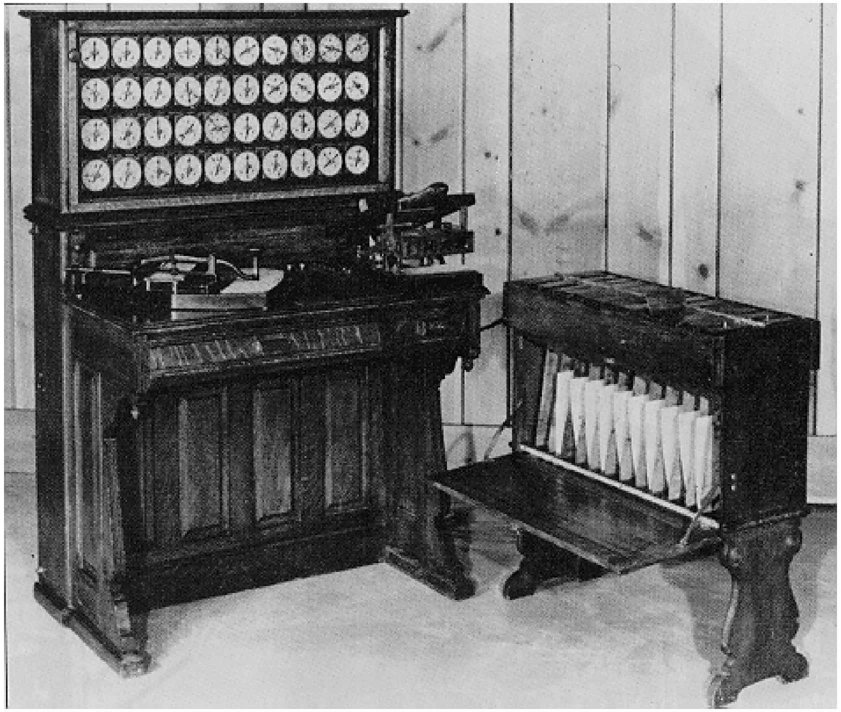




- [Babbage's Analytical Engine](#) – 1834
  - Mechanical computer, punched-card data input
  - Mill is shown above

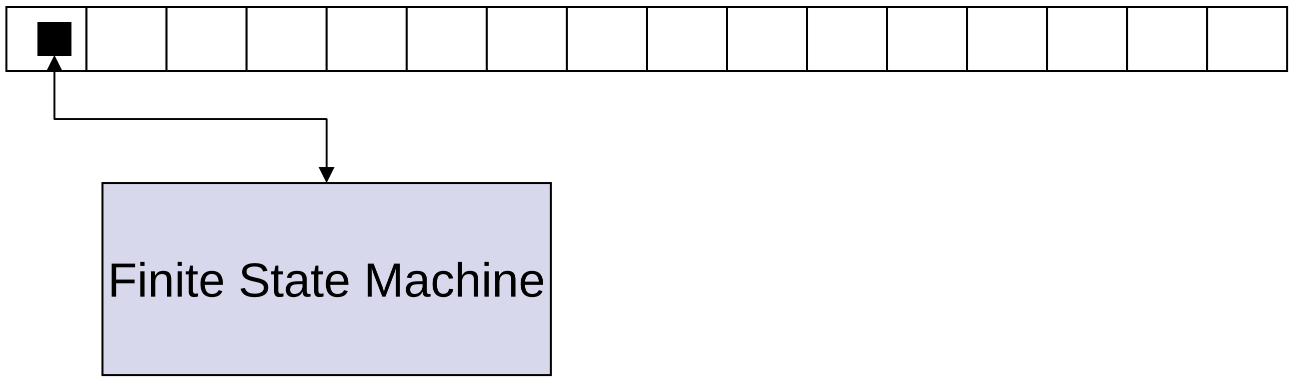
Early Computers

- Hollerith electric tabulator/sorter
  - Punched-card sorter – collated 1890 census data that was forecast to take more than 10 years!



Computers in the 20th Century

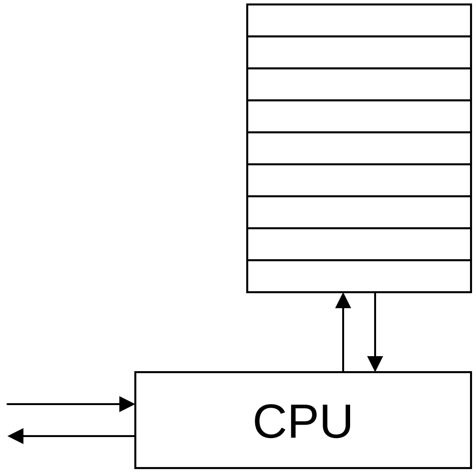
- Turing machine
  - Two-way tape for data input and storage and finite-state machine for reading/writing on tape.



- Thousands of “computers” existed in 1940s

Computers in the 20th Century

- The von Neumann model



- Stored programs
- Fetch-execute cycle

20^{th} Century *Programmable* Computers

- Atanasoff (1940) – linear eqn. solver, tube-based
- Zuse's Z3 (1941) – relay-based computer
- Colossus (1943) – broke Enigma code, tube-based
- Mark I (1944) – general-purpose, relay-based
- ENIAC (1946) – general-purpose, tube-based

The Computer Revolution Begins

- Transistor invented at Bell Labs in 1947
  - Semiconductor switch – replaced vacuum tube.

- By 1958 IBM was selling the 7070, a transistor-based computer.

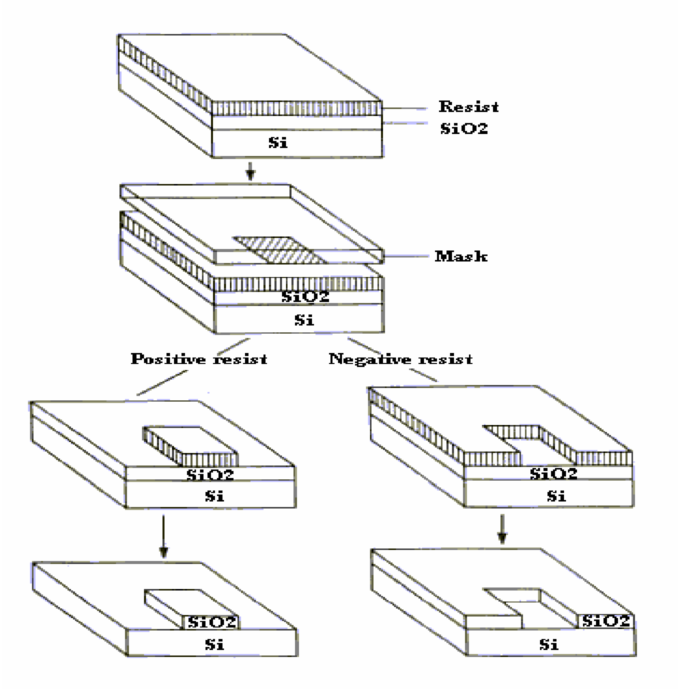
The Integrated Circuit

- Integrated circuits invented independently in 1959 by Jack Kilby and Robert Noyce
  - Transistors and wires combined on a chip through photolithography.

  - *"What we didn't realize then was that the integrated circuit would reduce the cost of electronic functions by a factor of a million to one, nothing had ever done that for anything before"* - Jack Kilby

Photolithography

- This is the process of transferring a pattern to the surface of a chip using light.



The VLSI Revolution

- Intel 4004 CPU placed on a chip – 1969
- By late 1970s very complicated chips were being assembled.
- New challenges were encountered:
  - Specifying large chip designs simply
  - Simulating the electronics
  - Laying out chips
  - Designing area efficient algorithms
  - Understanding tradeoffs through analysis

VLSI Emerges as an Academic Area in Late 1970s

- Publication of **Introduction to VLSI** by Carver Mead and Lynn Conway in 1980.
- Specifying large chip designs
  - Hardware design languages invented
- Simulating the electronics
  - Electronic simulators, such as Spice, developed
- Laying out chips
  - Computer-aided design emerges
- Area-efficient algorithms and theory
  - VLSI layouts and AT^2 lower bounds developed

The VLSI Model

- Wires have width, gates have area.
  - The **feature size** of a VLSI technology is the size of the smallest feature (wire width/separation)
- The area of gates is comparable to the square of feature size
  - The area occupied by wires often dominates the area of gates.

The VLSI Crisis

- Moore's Law – doubling of # transistors/chip every 18 months – coming to an end.

- Chip factories now cost $3-5 billion to construct!

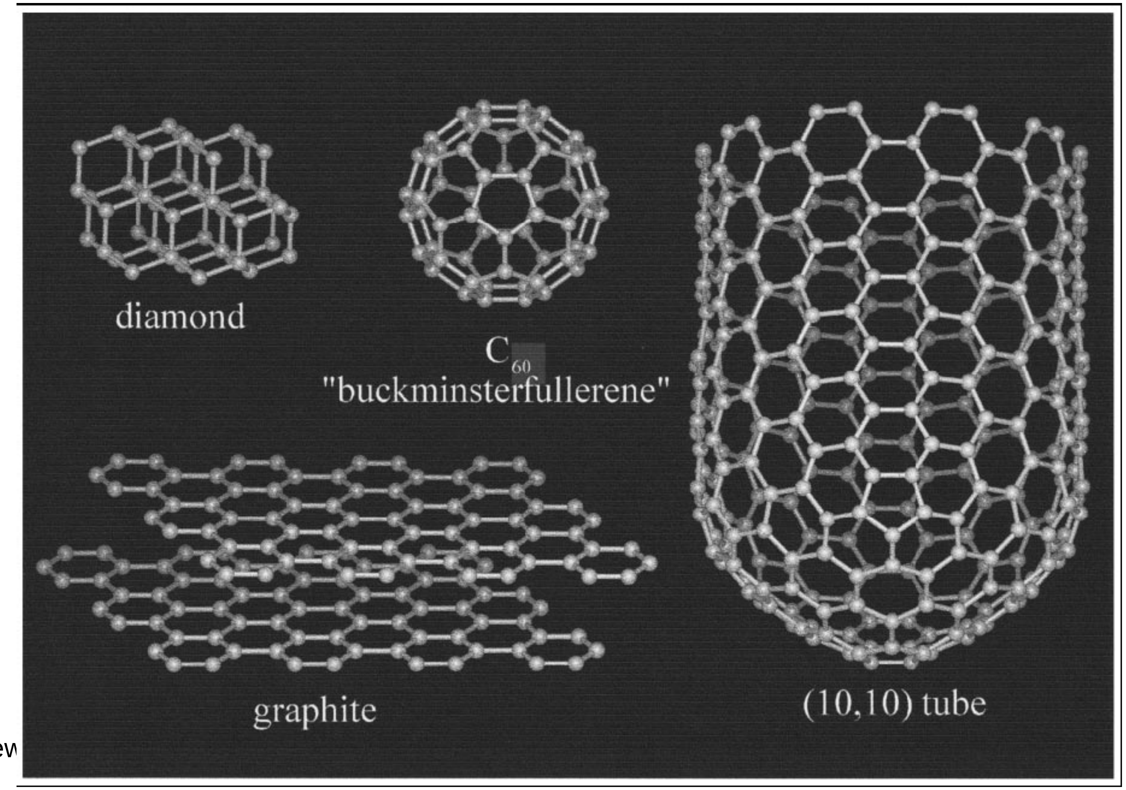
- Devices are so small that electronic models are no longer accurate; expensive redesign needed to meet systems requirements.

What’s Next?

- Nanotechnology of course!
- Nanotechnology is a broad term that includes biological elements, molecular electronics, and quantum computing.
- We give an overview of these technologies but focus primarily on the systems issues arising from nano-electronics.

Emergence of Nanotechnology

- Bucky balls (C_{60}) discovered at Rice in 1985
- Iijima discovers carbon nanotubes in 1991

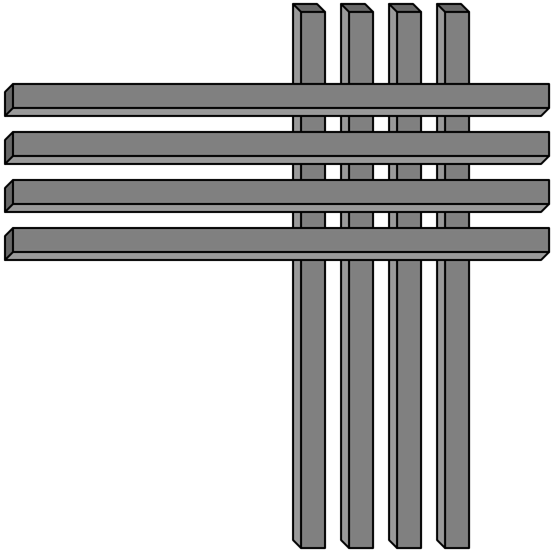


Properties of Nanotechnologies

- Methods of assembly are either very slow and precise or fast and non-deterministic.
- Fast assembly is good at creating fairly regular structures.
- There is hope that through DNA templating non-regular structures will be possible

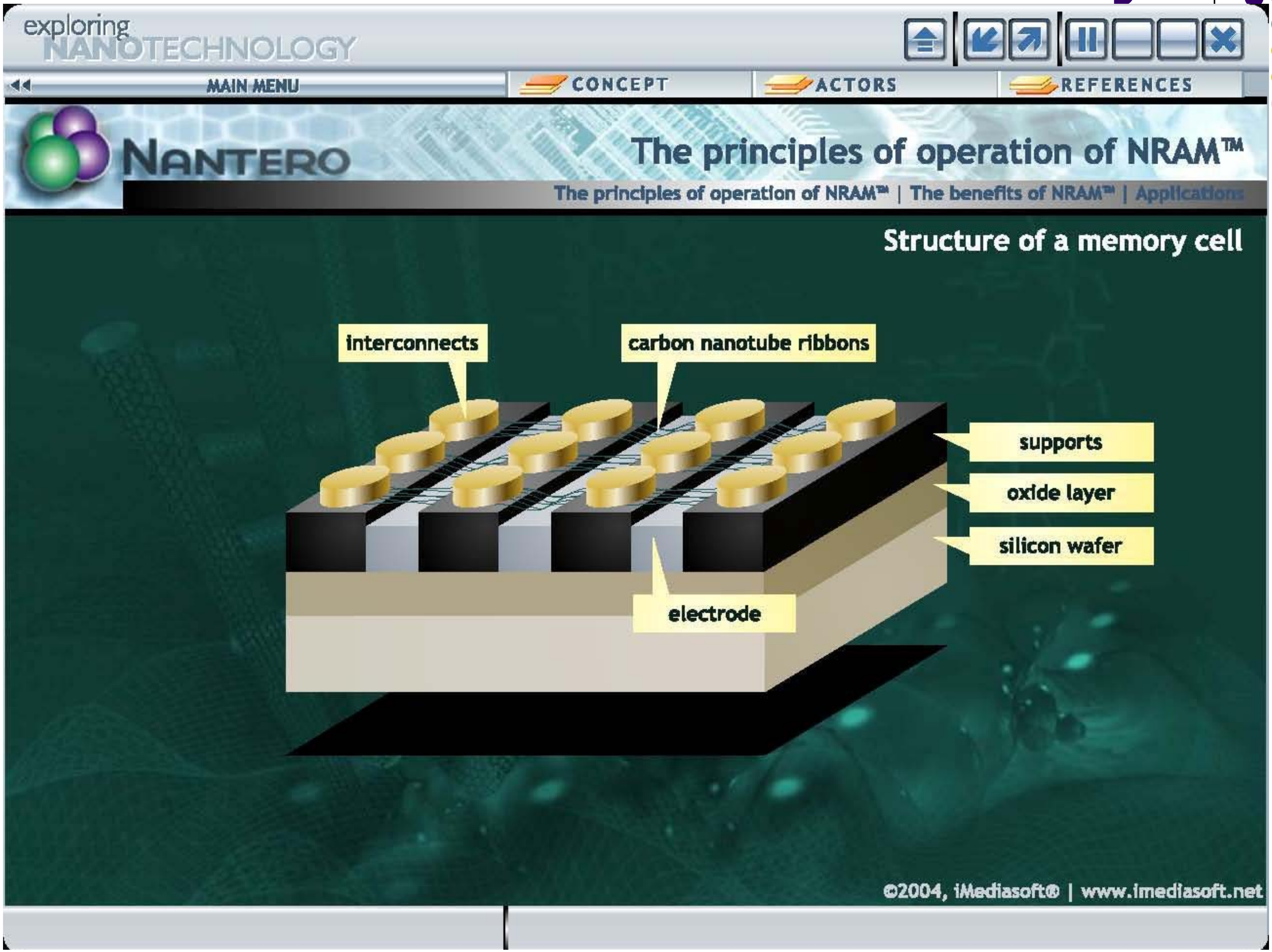
The Crossbar – A Promising Nanotechnology

- Two sets of parallel wires with switches at their intersections.



- Crossbars are used as routers and memories today.

Mechanical Crossbar Memory



NRAM – Nonvolatile RAM Crossbars of Carbon Nanotubes

- Electrostatic attraction used to make contacts, repulsion breaks them.
- Nantero’s claims:
  - Permanently nonvolatile memory
  - Speed comparable to DRAM/SRAM
  - Density comparable to DRAM
  - Unlimited lifetime
  - Immune to soft errors
- No behavioral models yet presented

Many Other Examples of Computational Nanotechnology

- Crossbars realized with silicon nanowires (NWs).
- Many issues concerning controlling NWs with mesoscale wires (MWs).
- Reliable computation with unreliable elements.

Goals of the US National Nanotechnology Initiative

- Maintain a world-class research and development program aimed at realizing the full potential of nanotechnology;
- Facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit;
- Develop educational resources, a skilled workforce, and the supporting infrastructure and tools to advance nanotechnology; and,
- Support responsible development of nanotechnology.

CS Seminar Monday on Molecular Self-Assembly

Efficient Discrete-Event Simulations

of Molecular Self-Assembly

by

Russell Schwartz

Monday Sept 12, 4-5pm in CIT 368