CSCI 2570 Introduction to Nanocomputing

The Emergence of Nanotechnology

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Purpose of the Course

- The end of Moore's Law is in sight.
- Researchers are now exploring replacements for standard methods for assembling chips.
- This course provides an introduction to emerging methods of computation.

Course Outline

- Lectures on nanoelectronic computing
  - Crossbars technologies and analysis
  - Coded computation
  - Reconfigurable computing
- Lectures on other methods of computing
  - 1D and 2D DNA Computing
  - Synthetic biology
  - Quantum Computing
- Introductions to probability theory, finite fields, error-correcting codes.

Schedule

- Intro to nanotechnologies
- Crossbar-based architectures
- Reconfigurable computing
- Review of probability theory
- Intro to information theory
- 1D DNA computing
- DNA tiling – 2D DNA computing
- Intro to NW decoders

Schedule (cont.)

- Analysis of NW decoders
- Coping with errors in crossbars
- Reliable crossbar-based computation
- Reliable computation via replication
- Codes and finite fields
- Coded computation
- Quantum computation
- Student presentations

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!

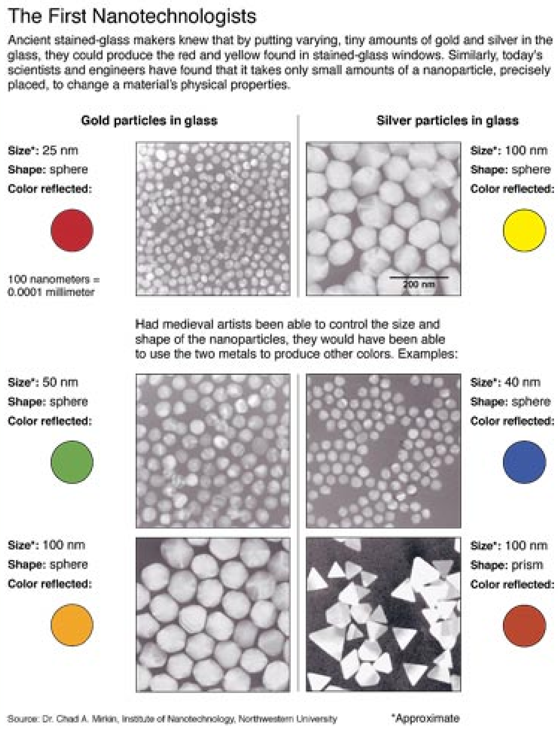
What is Nanotechnology?

- Materials with one dimension of length [1-100] nm.
- Materials designed through processes that exhibit fundamental control over the physical and chemical attributes of molecular-scale structures.
- Materials that can be combined to form larger structures.

Mihail C. Rocco
NSF

Nanotechnology in the Cathedrals of Europe

- The brilliant colors of stained glass are made by small clusters of gold and silver atoms (25-100 nm) that were mixed into the glass.

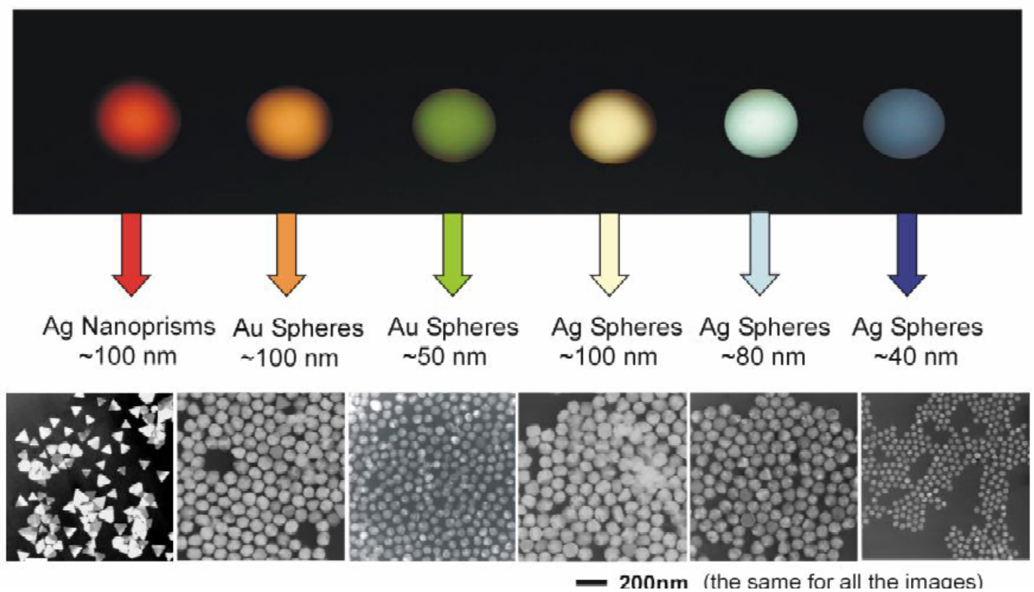


The First Nanotechnologists
Ancient stained-glass makers knew that by putting varying, tiny amounts of gold and silver in the glass, they could produce the red and yellow found in stained-glass windows. Similarly, today's scientists and engineers have found that it takes only small amounts of a nanoparticle, precisely placed, to change a material's physical properties.
Gold particles in glass
Silver particles in glass
Size*: 25 nm
Shape: sphere
Color reflected:
100 nanometers = 0.0001 millimeter
Size*: 100 nm
Shape: sphere
Color reflected:
200 nm
Had medieval artists been able to control the size and shape of the nanoparticles, they would have been able to use the two metals to produce other colors. Examples:
Size*: 50 nm
Shape: sphere
Color reflected:
Size*: 40 nm
Shape: sphere
Color reflected:
Size*: 100 nm
Shape: sphere
Color reflected:
Size*: 100 nm
Shape: prism
Color reflected:
Source: Dr. Chad A. Mirkin, Institute of Nanotechnology, Northwestern University
*Approximate

Size Matters at the Nanoscale

- When objects are larger than the wavelength of light, their size has no effect on their color.
- When smaller, size and shape determine color

700 nm



400 nm

Figure due to Mark Ratner, Northwestern U.

“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.

Seeing Small Things

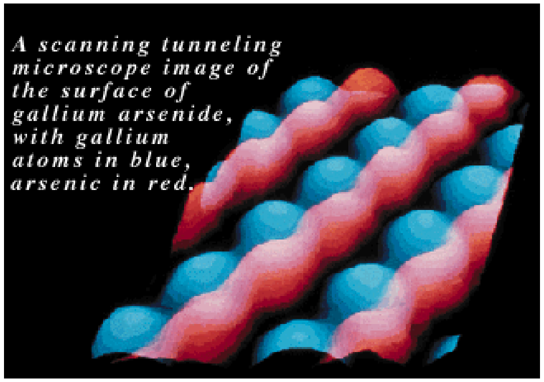
- Optical microscopes use light to see objects as small as 200 nm.
  - Invented in 1600s.

- Electron microscopes use beams of electrons to **see through** objects as small as 0.1 nm.
  - Produces 2D image.
  - Requires objects be in a vacuum.
  - Invented in 1931.

Seeing Small Things

- Scanning probe microscope (SPM) **sense** very small objects (.2nm)
  - Produce 3D image – sense heights
  - Does not require vacuum.
  - Can move molecules around.
  - Invented in 1981.

- Led to an explosion in nanotechnology research.

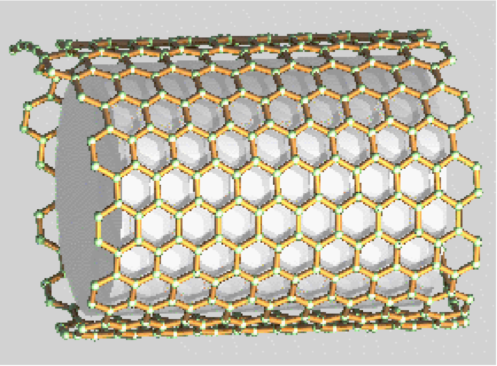


Source

Chemists and Nanotechnology

- 1986 discovery of buckminsterfullerenes
  - Spheres of 60 carbon atoms (C_{60})
  - At Rice University
  - Known as "buckyballs"

- 1991 discovery of carbon nanotubes by Iijima
  - Extremely strong
  - Lightweight



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.

Examples of Nano Materials

- DNA – both single and double stranded
  - Compute with 1D and 2D DNA

- Synthesize new molecular processes

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

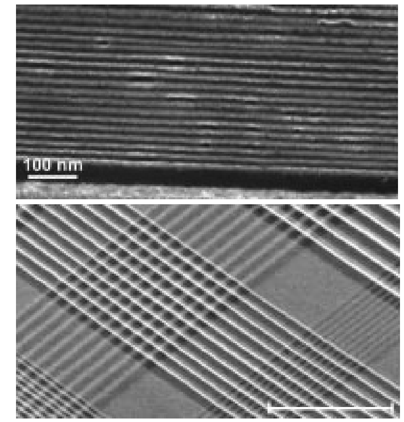
- Fault tolerance
- Stochastic Assembly
- New emerging models

An Introduction to Nanowire-Based Computing

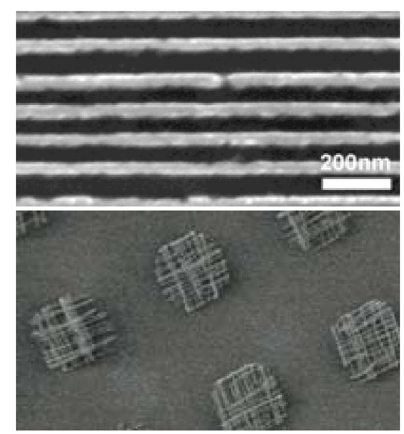
- Crossbars can serve as a basis for both memories and circuits.
- **Semiconductor nanowires (NWs)** can be stochastically assembled into crossbars
- NW-based crossbars must interface with lithographically produced technology.
- Decoders provide an efficient defect-tolerant interface.

Nanowires

- Uniform NWs can be produced using a stamping process.
- Non-uniform NWs can be grown off-chip with chemical vapor deposition.
- In both cases NWs are assembled into crossbars.
- To use these crossbar many NWs must be individually addressable.



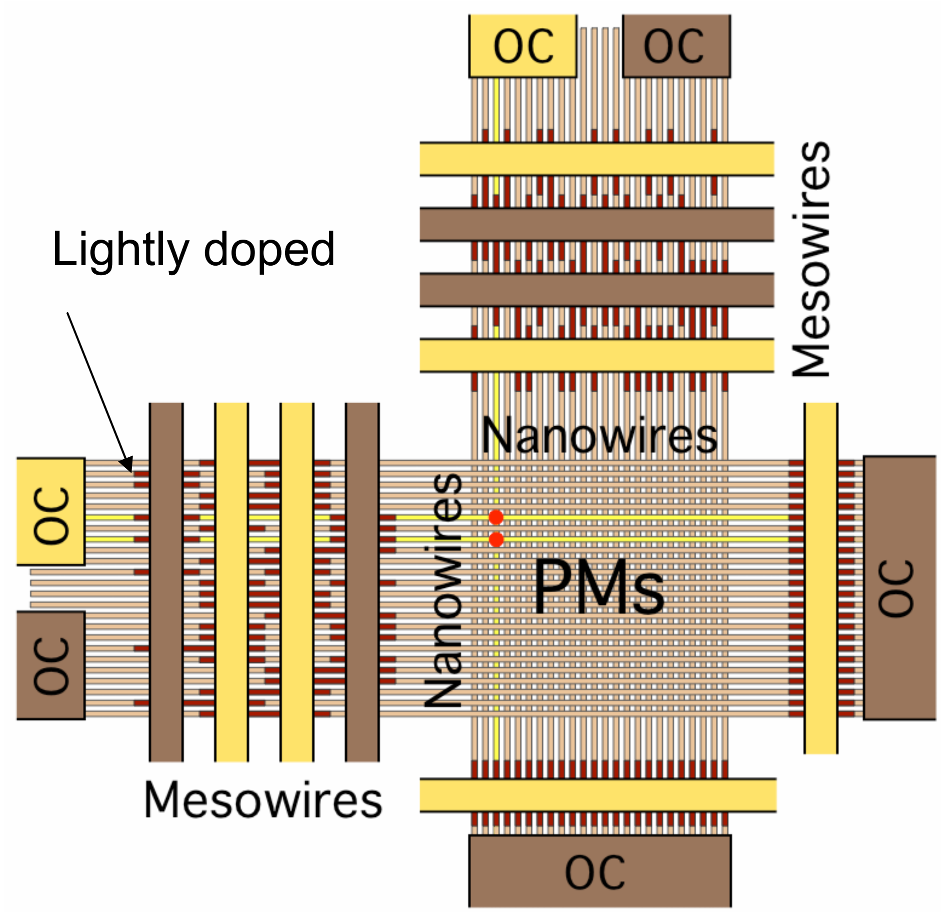
SNAP NWs
(Heath, Caltech)



CVD NWs
(Lieber, Harvard)

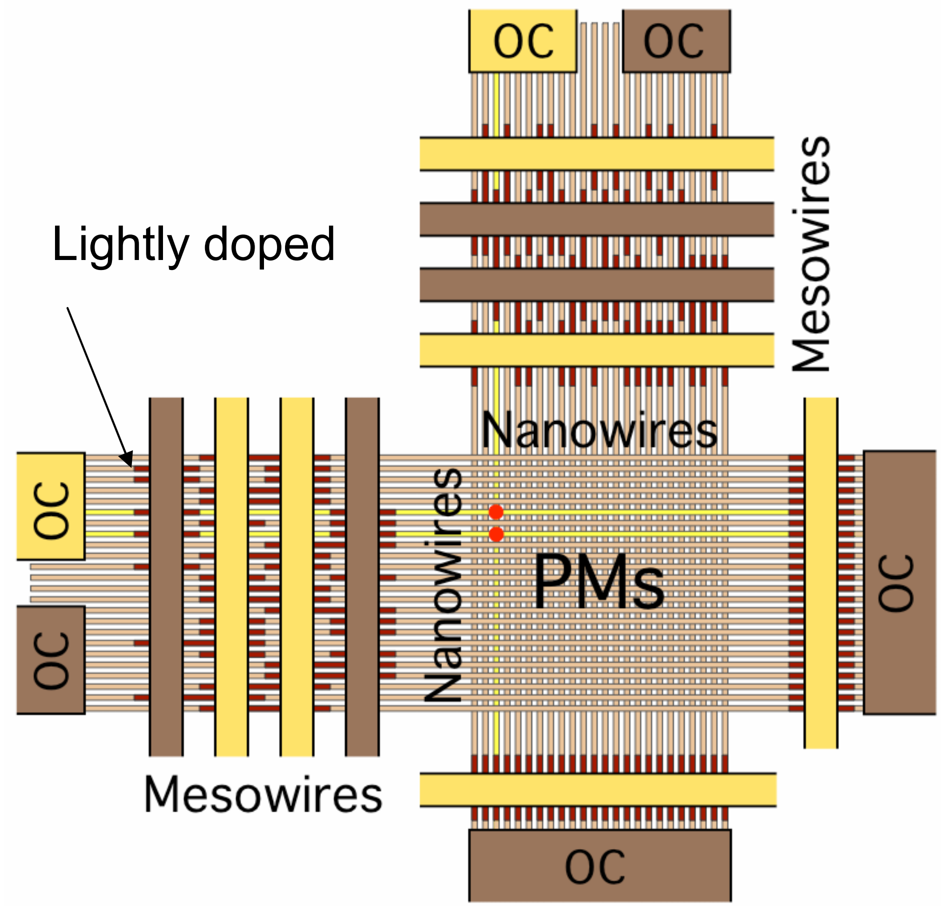
Controlling NWs with Mesoscale Wires (MWs)

- **Ohmic contacts (OCs)** place a voltage across consecutive NWs.
- **Mesoscale address wires (MWs)** turn off NWs within each group.
- Lightly doped regions couple MWs to NWs.



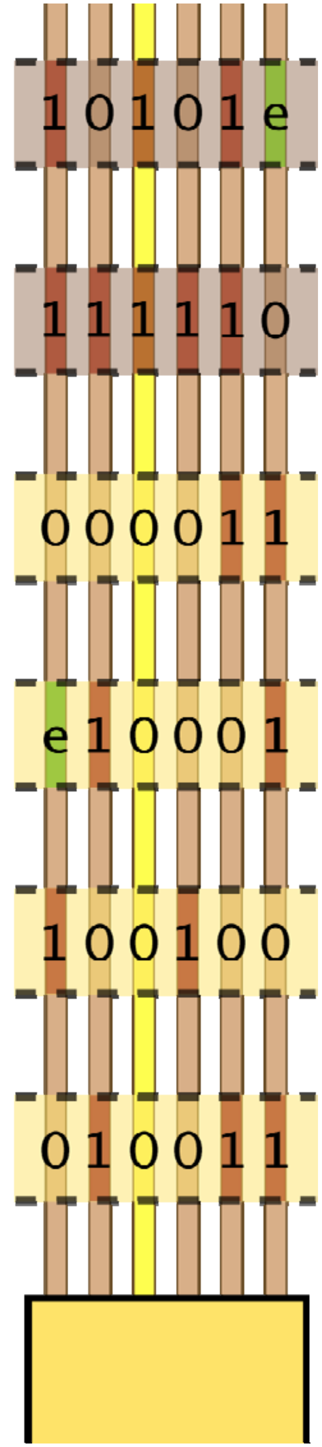
Read/Write Operations

- Perpendicular NWs provide control over molecular devices.
- Larger voltages set the conductivity of crosspoints.
- Smaller voltages measure conductivity.



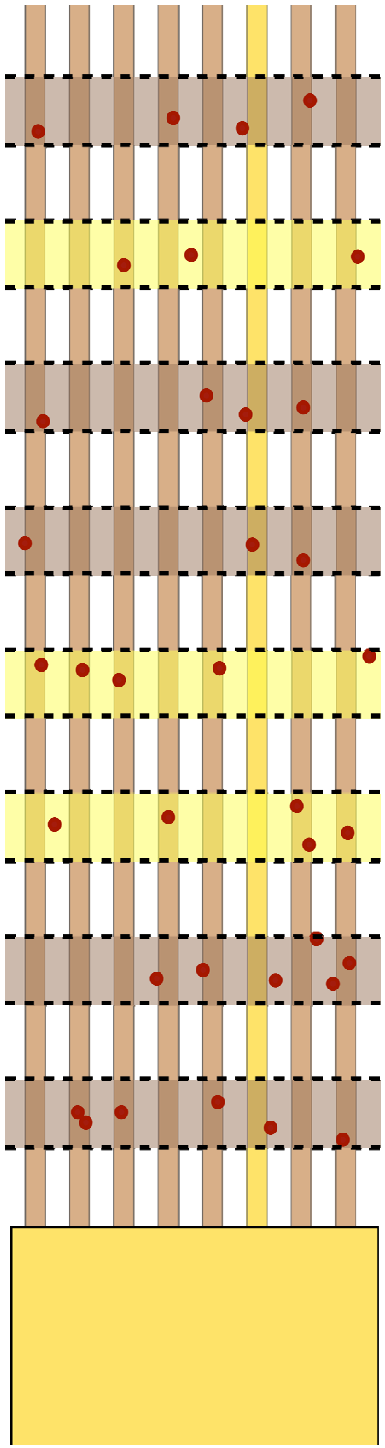
Nanowire Decoders

- The interface circuit between N NWs and M MWs is called a **NW decoder**.
- Each MW provides control over a subset of NWs.
- We associate an M-bit **codeword, c_i** with each NW. Let $c_{i,j}$ be the jth bit of c_i.
  - $c_{i,j} = 1$ if the jth MW <u>controls</u> the ith NW.
  - $c_{i,j} = 0$ if the jth MW <u>has no effect on</u> the ith NW.
  - $c_{i,j} = e$ if the jth MW <u>partially controls</u> the ith NW.



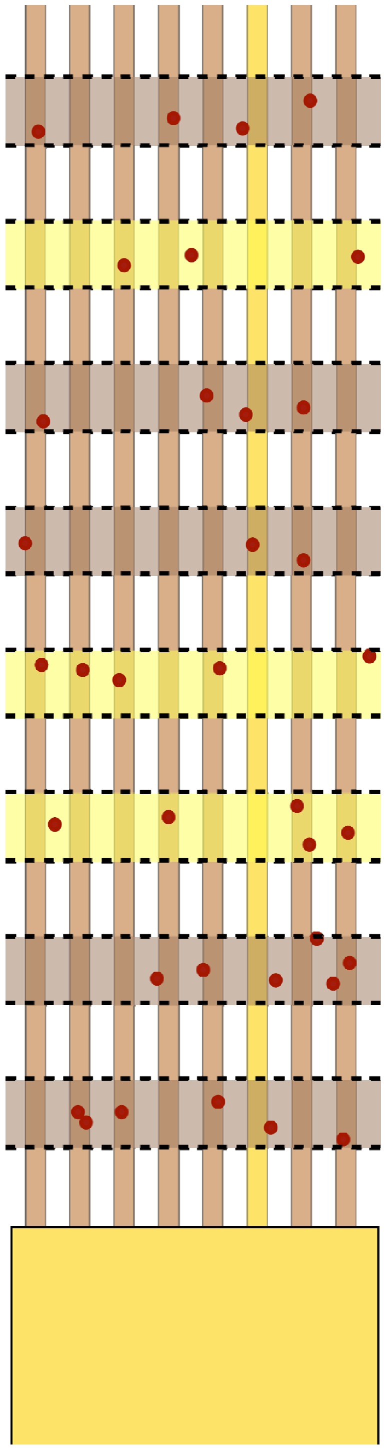
Types of NW Decoder

- Decoders exist for
  - uniform NWs
  - Encoded NWs
- Connections between NWs and MWs is random
  - Type of randomness varies with type of decoder



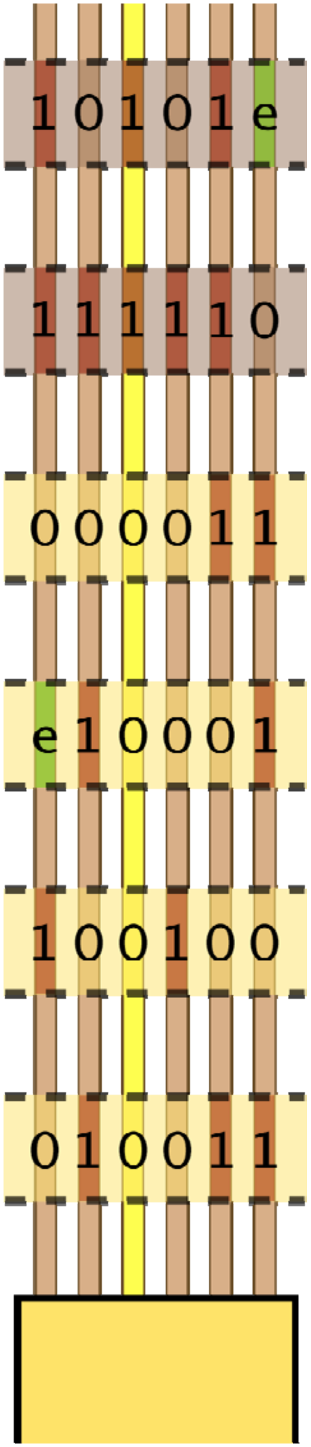
Types of NW Decoder

- NW codewords allow us to model each of the proposed NW decoders.
- When a decoder is manufactured, codewords are randomly assigned to NWs according to some distribution.



Individually Addressable Nanowires

- A NW is **individually addressable** if it can be turned on while all other NWs are turned off.
- Most NWs connected to an OC should be individually addressable.
- If the number of MWs is sufficiently large, many NWs will be individually addressable with high probability.



Bounding the Number of MWs

- We develop bounds on the number of NWs that are individually addressable with a probability ≥ 1-e.
- Decoders are compared on the number of MWs needed to address N_a NWs with probability ≥ 1-e.
  - A superior decoder uses fewer MWs.
  - Analysis uses advanced probabilistic methods.
- Several types of decoder have been proposed. Some use many more MWs than others.

Errors in Computation

- Sources of nanoscale error:
  - Crosspoints may not be responsive
  - Mesocale wire/nanowire junctions may be unreliable.
  - Transistors/gates and memory cells may fail.
  - Memory cells may fail.

- How should area be allocated between big, reliable gates and small unreliable ones?

Assigned Work

- Short written assignments for each lecture
- 30-minute student presentations on one or two research papers
- Final project
  - Long research or research summary paper

Evaluation

Homework	60%
Seminar Presentation	15%
Final Project	20%
Class participation	5%