PHYS 5300-019

First lecture – August 25, 2022

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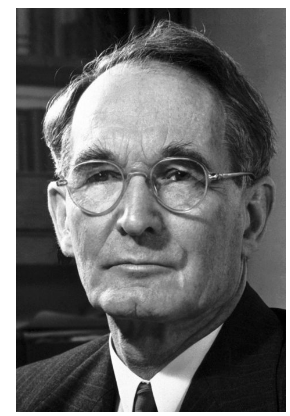
Today, August 25, 2022

- Introduction to nanoscience and to quantum sensing
- Detailed discussion of Feynman's "There's Plenty of Room at the Bottom"
- Review syllabus
  - Grading: term paper and class participation
  - Location of course materials
  - Day-by-day agenda
- Brief mention of the 2010 Decadal Survey on Biological and Physical Sciences in Space (optional, but interesting)

Discussion of Feynman's 1959 paper

- K. Onnes and LT Physics – the "First Quantum Revolution"
  - Winner of the 1913 Nobel Prize in Physics
  - Liquid helium, superconductivity in Hg (1908)
  - Led to superfluidity in ^{4}He (1942) and ^{3}He (1972) and …
  - https://en.wikipedia.org/wiki/Superfluid_helium-4



- P. Bridgman and High-Pressure Physics
  - Winner of the 1946 Nobel Prize in Physics
  - Airplane doors, other practical applications
  - Metallic hydrogen, many other discoveries
  - https://www.nobelprize.org/prizes/physics/1946/summary/

The Encyclopedia on the head of a pin?

- 25,000 magnification required to read / reduction to write
- 32 atoms per pixel
- Suggested a method to read / duplicate based on plastic metallization followed by electron-beam microscopy: quite doable in 1959!
- BUT no way to write this on the head of a pin in 1959
  - Feynman suggests running the electron microscope ‘backwards’
  - This is known as Focused Ion Beam (FIB) machining today
  - Developed first by Orloff and Swanson in 1975
  - Suggested what would later become Xerography, but not at this scale
  - https://en.wikipedia.org/wiki/Focused_ion_beam
  - All books in 1959 printed on 35 pages at this reduced scale!
  - Doable today without violation of what we fundamentally understand in physics

Information storage at a much smaller scale

- Prediction of data storage in ‘bits’
  - Say each ‘bit’ requires 5x5x5 = 125 atoms to avoid diffusion, etc.
  - In 1959, 10^{15} bits of information exist, so a cube 1/200 of an inch on a side would be required to store all known information in 1959!
  - Storage densities have not reached this level yet, but its not ‘impossible’!
  - Storage has not moved into three-dimensions yet, so we are still stuck with areal densities for our digital record
    - Highest area storage density today is 100TB/inch^2 = 1.6×10^{13} bits per cm^2
    - https://en.wikipedia.org/wiki/Density_(computer_storage)
    - So it would have required ~ 100 cm^2 to store all of the world’s information in 1959 with today’s technology
    - There is a staggering ~ 10^{24} bits of information today! This would require 6×10^{10} cm^2 to store today. See: https://theconversation.com/the-worlds-data-explained-how-much-were-producing-and-where-its-all-stored-159964
  - Biophysics: 50 atoms per nucleotide, which is a biological ‘bit’

Better electron microscopes

- Make the e-microscope 100 times better in resolution
  - This has occurred to 10 times better, but the higher energy electrons disturb soft molecules that they attempt to image
  - Other diagnostics, like EDS, EBD, FIB, etc. have made great advances
- Make a much larger numerical aperture
  - Aperture corrections have advanced to the diffraction limit, but the electronic lenses remain axially-symmetric
  - The big advance has been the use of many different detectors in various geometries to give 3D reconstruction and better depth of field
- Encourages genetic sequencing by e-microscopes
  - Molecular mass spectroscopy has worked better instead – sequencing
  - The advantages of improved biological imaging have been realized
- Wonderful advances in chemical analysis and synthesis have occurred

Biological machines / miniaturization

- Feynman's suggestions of making biological machines has excelled!
  - See Synthetic Biology, Venter Institute: https://www.jcvi.org
  - Langton, Artificial Life: https://en.wikipedia.org/wiki/Artificial_life
- Feynman called for much greater miniaturization via lithography
  - His goal of 1 nm lines are almost realized today.
  - Moore's Law: https://www.synopsys.com/glossary/what-is-moores-law.html
- He went on to discuss miniaturization of everything
  - Thermal diffusivity scales as d^2/D_T, so very small things cool differently
  - Engineering principles change with scale dramatically
    - Viscosity, thermal conductivity, Brownian motion, onset of quantum behaviors
    - We will discuss this extensively in this class

More on miniaturization

- As the size decreases, the material properties generally become more important than their loading
  - True for homogenous materials, like plastics, glass, amorphous materials, etc.
  - As r becomes smaller, $\omega^2 r$ limits permit ω to become greater as $r^{1/2}$
  - Not true for materials with grain / domain structures like metals and magnets
- As you get smaller, your air drag ~ r^2, but your mass ~ r^3
  - So your terminal velocity ~ r (bugs do better than people in free fall!)
  - If you are a bacterium, then you live in a very viscid world
- Making a very small car?
  - Cooling by conduction is very rapid, so combustion vehicles fail as they become very small
  - Lubrication is not necessary, since conductive cooling wins out over convection
  - New designs are needed with lower machining tollerences
- Fantastic Voyage: Tiny medical devices (from Albert Hibbs)
  - Colonoscopy, laparoscopic surgery, etc., exist today.
  - <u>Great</u> potential for advancement in this field of nano-medicine

How do you make this work?

- Feynman extends the 'Hot Cell' concept to small scale manufacturing
  - Consider the Leonardo robotic surgical device, or FIB and reactive etching machining
  - https://www.davincisurgery.com
  - Ga / Xe FIB machining and metallization patterning are good to ± 20 nm
- The need to improve precision and accuracy as you get smaller
  - The miniature lathe example
  - Feynman introduces mechanical concepts, but electronic approaches with outstanding vibration isolation systems have achieved this today
- Feynman introduces massive parallelization as you scale down
  - 'A hundred tiny hands' concept → Billions of tiny hands → Billions of lathes!
  - Scaling challenges: Van der Waals forces, etc.
  - Computer architectures use this today, and this is the basis of lithography

Rearranging the atoms

- Feynman calls for individual atomic configurations
  - Quantum Corrals: https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Quantum_Tutorials_(Rioux)/Quantum_Fundamentals/70%3A_Quantum_Corrals_-_Electrons_within_a_Ring
  - Quantum properties dominate when electronic $\lambda_{dB} = h/p$ ~ the atom spacing
  - Atom spacing at this scale can turn quantum effects 'on and off'
- Predicted the development of metamaterials
  - Scaling concern: ω increases as 1/d, but EM penetration depth ~ $\omega^{-1/2}$
  - EM dissipation problems? Superconductivity doesn't save us!

Atoms in a small world

- Designer quantum phenomena
- Predictions of hetero-structures, and designer electronic properties
- Advantage: Perfect atomic replication
  - Key to integrated circuit up-scaling to billions of transistors
- Feynman Competitions
  - Today, we have few-atom molecules that walk chain molecular backbones
    - Genetic editing (CRISPR), etc.
    - Viruses have rotary motors that invade cells. Like 'H1N1' reference in influenza