

OU Condensed Matter Physics



Physics you can touch.

*Well, more than in astrophysics,
high energy and all those other
fields...*



The Department of Physics and Astronomy has 29 faculty in
four major areas of research:

- Astrophysics
- Atomic, Molecular and Chemical Physics
- High Energy Physics
- Solid State and Applied Physics.

A.k.a. Condensed Matter Physics

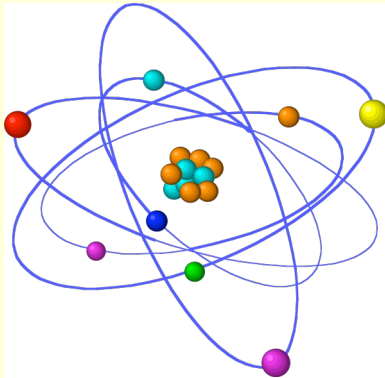
What is this condensed matter stuff?

Who does it?

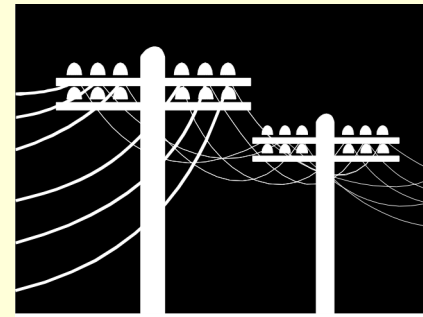
What does it involve?

Goal of Condensed Matter Physics:

Given all the properties of individual atoms, be able to predict or explain the properties of dense collections of atoms.



A copper atom is not a conductor.



10^{23} copper atoms do conduct.

Formerly known as solid state physics, condensed matter physics includes liquids, gels, plastics, glasses and suspensions.

High Energy Theory:

“Given our one universe, what is H?”

Condensed matter theory:

“Given H, what is possible in our universe?”

$$H = \sum_{j=1}^N \frac{p_j^2}{2m_j} + \frac{1}{2} K \sum_{i \neq j} \frac{q_i q_j}{|\vec{r}_i - \vec{r}_j|^2} + \frac{1}{2} G \sum_{i \neq j} \frac{m_i m_j}{|\vec{r}_i - \vec{r}_j|^2}$$

$$H\Psi = E\Psi$$

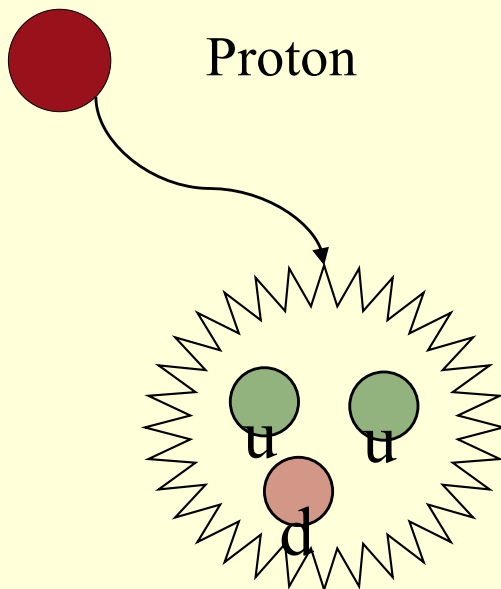
So far answers include:

- Superconductors
- Superfluids
- ferromagnets
- liquids, solids, vapors
- glasses and amorphous solids
- quantum Hall effect
- Topological insulators
- Topological superconductors
- "Strange" metals...

A difference in perspective:

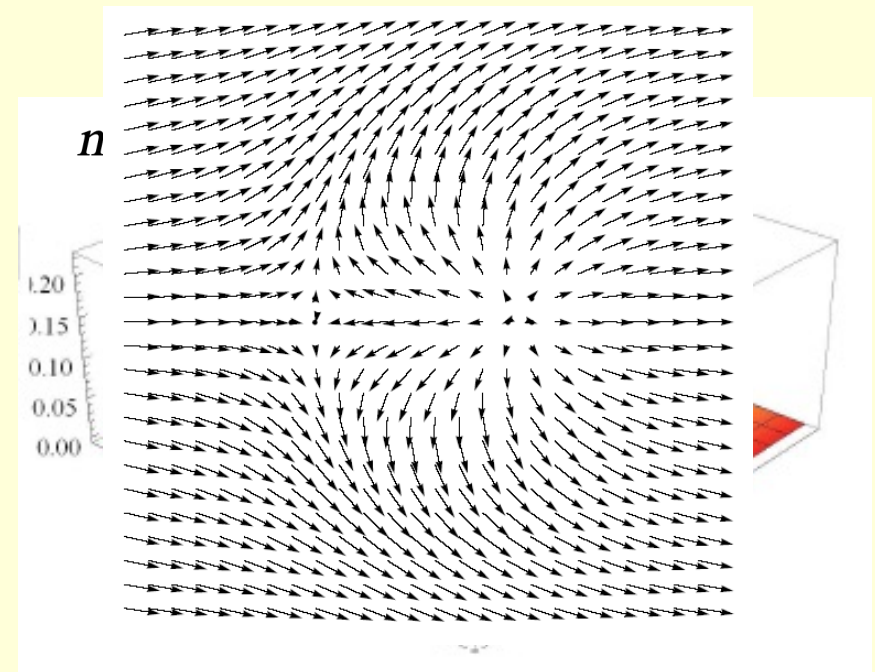
High Energy:

- At “long times” we see integer charges.
- At short times we see exotic particles and fractional charges.



Condensed Matter

- At “*short* times” we see integer charges.
- At long times we see exotic particles and fractional charges.



Where are the “Frontiers of Physics?”

Very small: Look for smaller particles

(Reductionism)

Very large: Look at the night sky

(Cosmology)

A frontier is a boundary: there are many
unexplored frontiers:

- Nanotechnology: the crossover between the classical and quantum world.
- Nonequilibrium dynamics
- Designer materials: creating structures that never existed in nature.
- Low temperatures: examining matter at energies that never existed before.

What are some current topics of research in Condensed Matter Physics?

- Semiconductor electronics
- Semiconductor lasers
- Optical storage materials
- Electro-optical computing
- Quantum Computing
- Quantum Communication
- High temperature superconductors
- Biomaterials
- Strange metals
- Micromachines
- Nonequilibrium phenomena
- Fullerenes and Nanotubes
- Topological insulators and superconductors.
- Weyl metals.
- Altermagnetism.

What do you need to know to do CMP?

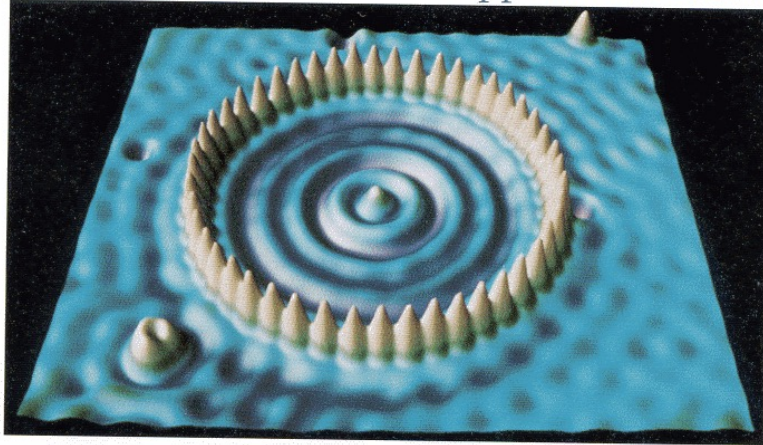
- Classical Mechanics
- Electricity and Magnetism
- Statistical Mechanics
- Thermodynamics
- Quantum Mechanics

Condensed matter requires a knowledge
of all the fundamental subjects in Physics.

In addition, it has the advantage of being closely tied
to experiments, and
and to applications.

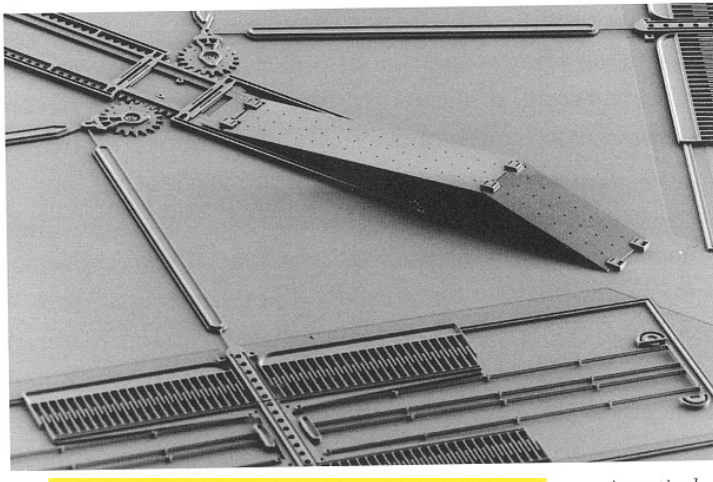
Research: 1990s

Application: 2020?



Electron Corral

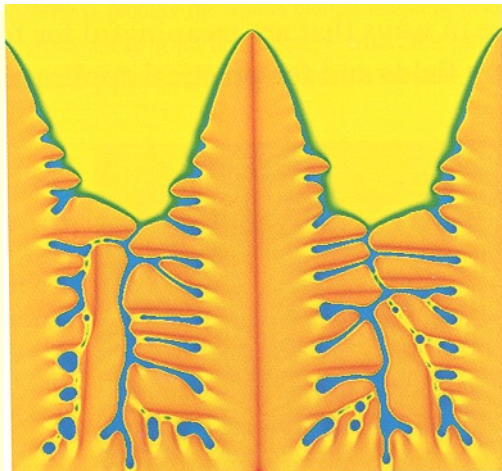
size: 14nm



Micro-machines

Gear size:

50 microns



Nonequilibrium crystal
growth of metals with
impurities.

How important is Condensed Matter to Physics?

Nobel Prizes in Physics since 2000:

- 2000: Semiconductor heterostructures in high-speed- and opto-electronics
- 2003: Superconductivity and Superfluidity.
- 2007: Giant magneto-resistance.
- 2009: CCD cameras and fiber optics.
- 2010: Two dimensional graphene
- 2014: Light emitting diodes
- 2016: Topological properties in condensed matter
- 2018: Optical tweezers and chirped pulse lasers
- 2021: Disorder in statistical mechanics and the replica trick
- 2023: Attosecond pulses of light to study of electron dynamics in matter
- 2024: Invention of neural nets as a statistical mechanics model of brains
- 2025: Macroscopic tunnelling and energy quantisation in an electric circuit

Who does condensed matter physics?

Industrial Physicists:

- Research Labs (AT&T, IBM, GM)
- Production Scientists (TI, Intel)

Government labs:

- Naval Research Lab, JPL
- Sandia, Livermore. National Inst. Standards and Tech.

Academic Researchers:

- Professors
- Technicians and Postdocs

Over 50% of recent Ph.Ds are in CMP or adjacent fields.

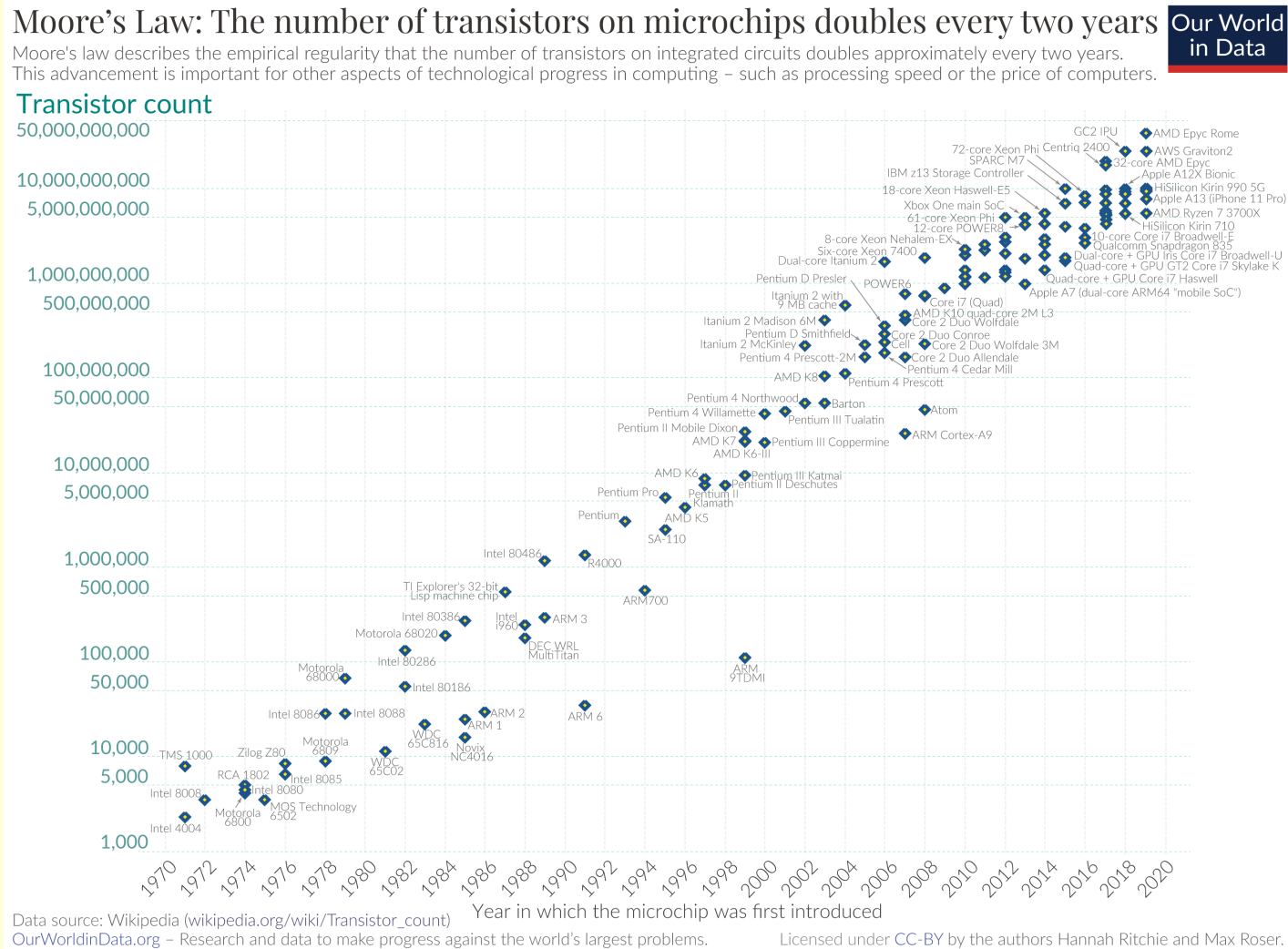
Over 25% of APS membership is in CMP division.

Grand Challenges in CMP

1. How do complex phenomena emerge from simple ingredients?
2. What is the physics of life?
3. What happens far from equilibrium and why?
4. What new discoveries await us in the nano-world?
5. How will the information technology revolution be extended?

-- National Academy of Studies, “Condensed Matter and Materials Physics: The Science of the World Around Us,” (NA Press 2007)

Nanotechnology: Let's get small...



By Max Roser, Hannah Ritchie –

<https://ourworldindata.org/uploads/2020/11/Transistor-Count-over-time.png>, CC BY 4.0,

<https://commons.wikimedia.org/w/index.php?curid=98219918>

The Scale of Things -- Nanometers and More

Things Natural



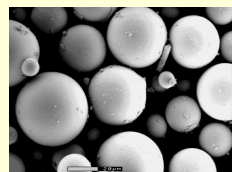
Dust mite
200 μm



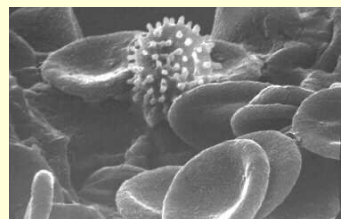
Human hair
~10-50 μm wide



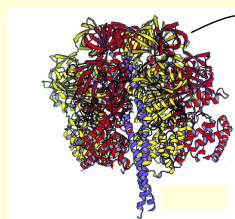
Ant
~5 mm



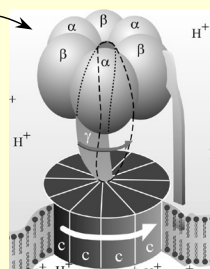
Fly ash
~10-20 μm



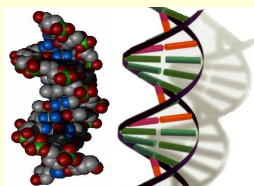
Red blood cells
with white cell
~2-5 μm



~10 nm diameter



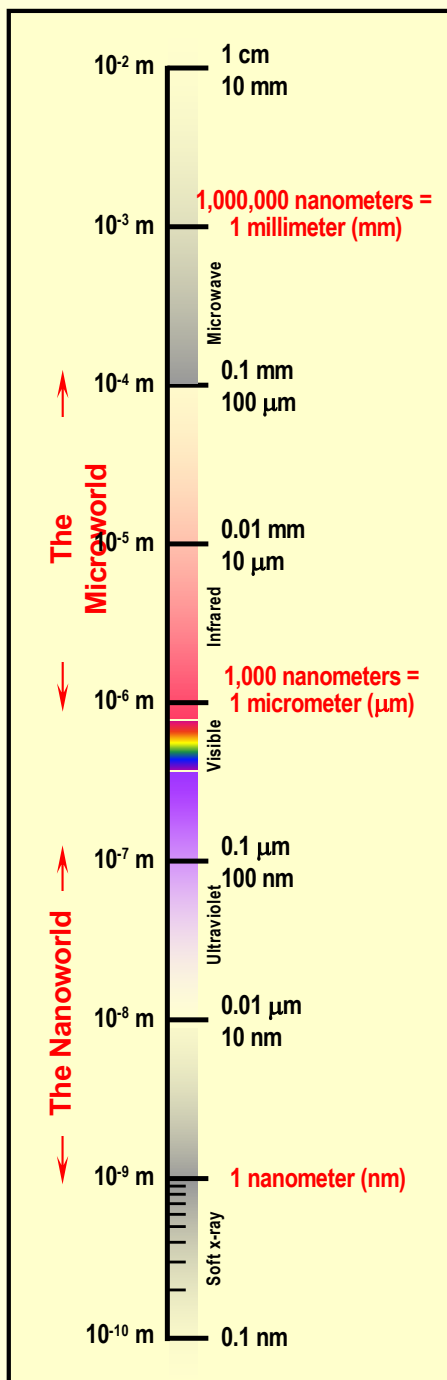
ATP synthase



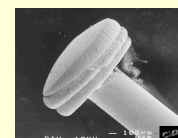
DNA
~2-1/2 nm diameter



Atoms of silicon
spacing ~tenths of nm

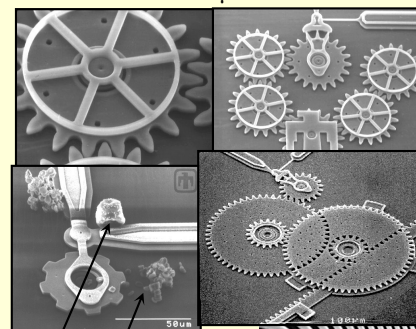


Things Manmade



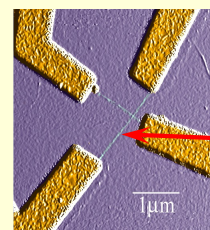
Head of a pin
1-2 mm

MicroElectroMechanical devices
10 -100 μm wide

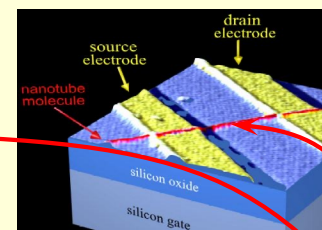


Red blood cells
Pollen grain

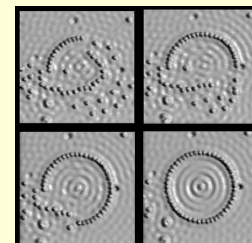
Zone plate x-ray "lens"
Outermost ring spacing
~35 nm



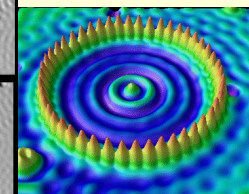
Nanotube electrode



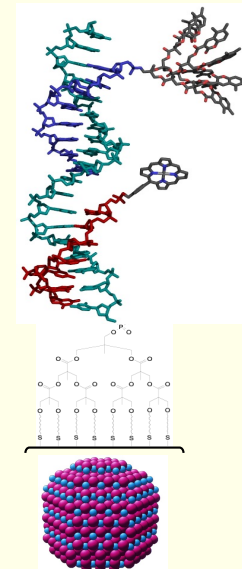
Nanotube transistor



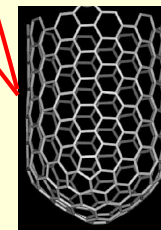
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm



21st Century Challenge



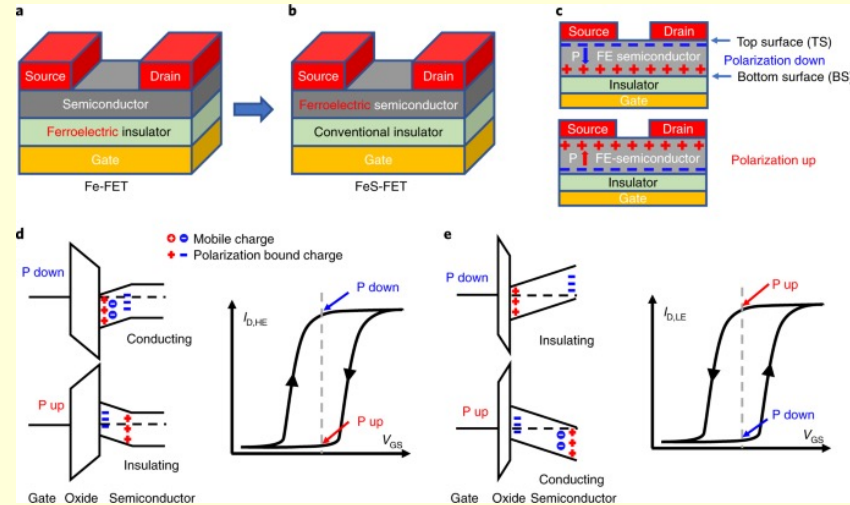
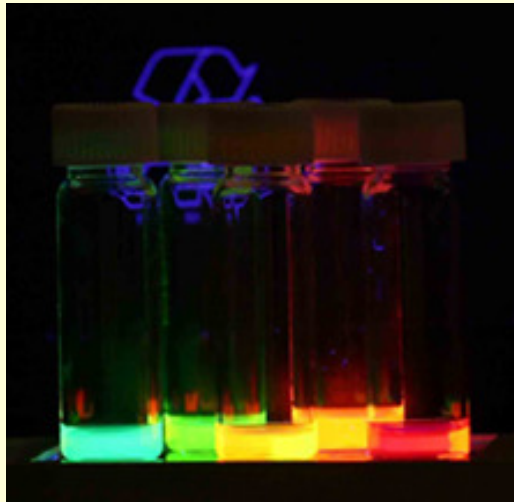
Combine nanoscale building blocks to make novel functional devices, e.g., a photosynthetic reaction center with integral semiconductor storage



Carbon nanotube
~2 nm diameter

Quantum technology revolutions

The ability to control matter on the nanoscale has allowed us to control the flow of energy and charge for applications.



The ability to control coherent quantum states will allow new applications based on their entanglement.

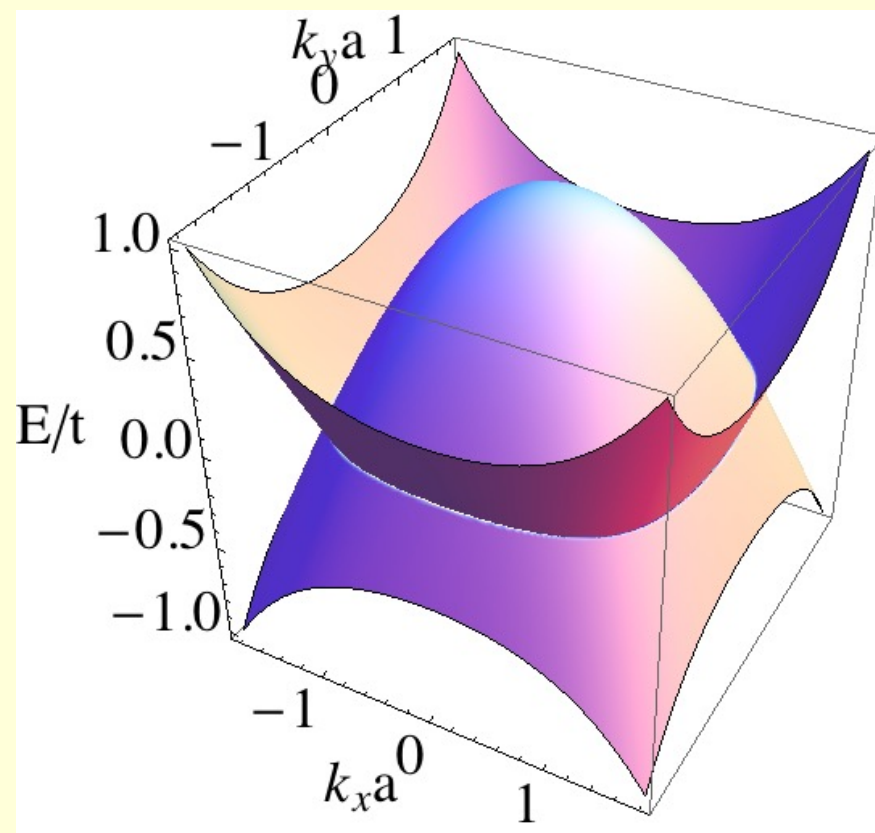
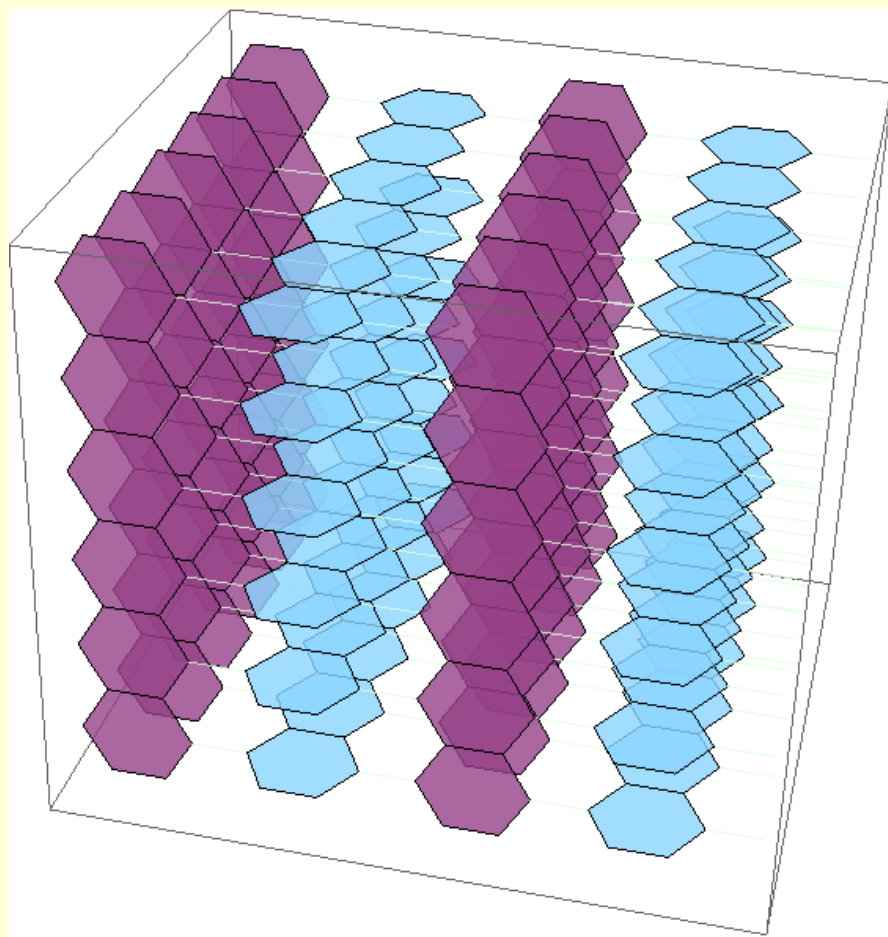


Personal View of CM Research

Condensed matter physics consists mostly of:

- Discovering *materials*,
- Determining the *properties* of materials, new and old,
- Discovering the properties of *structures* of materials.
- Blurring the line between materials and structures.

New Materials: “Latticene”

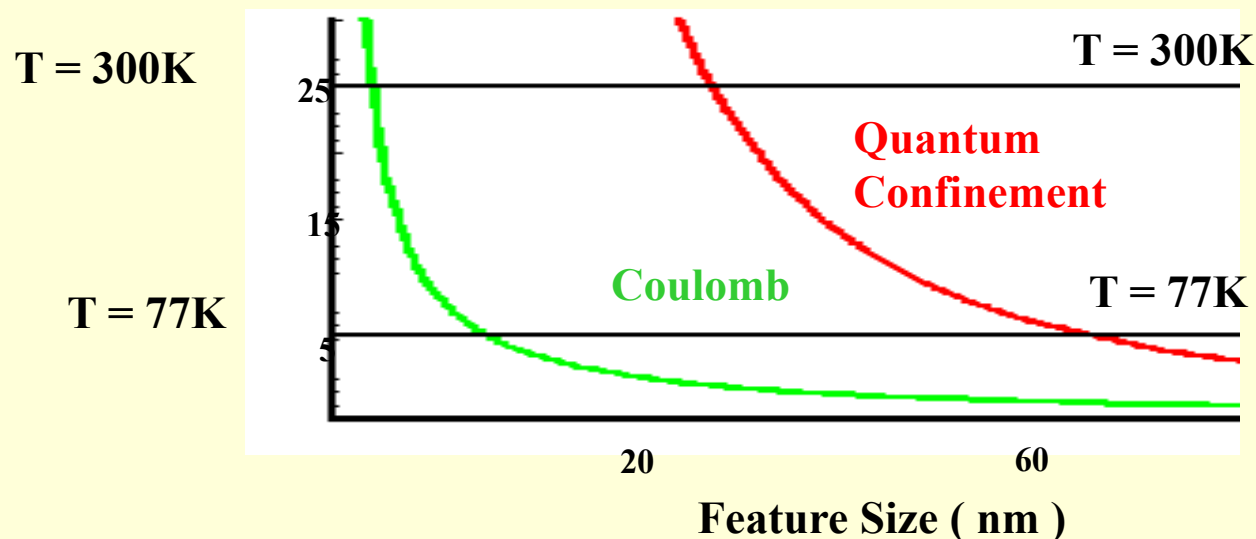


Material Properties: Indium Arsenide

Demonstrated material growth with InSb

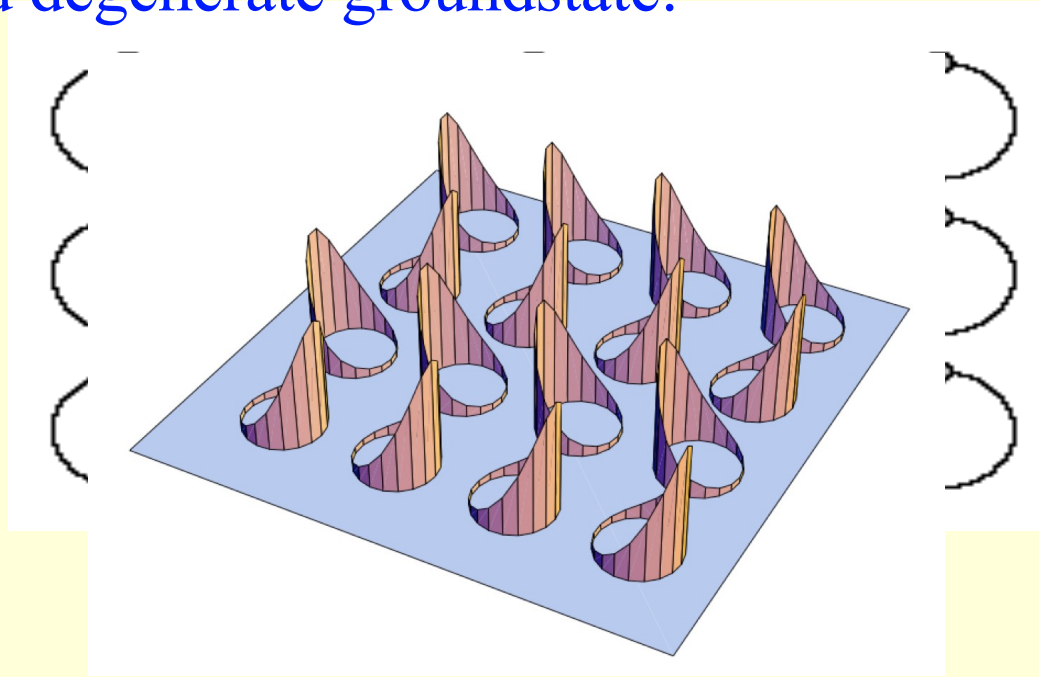
- Device design and fabrication of InSb/AlInSb system
- Its *effective* parameters are among the most extreme in semiconductors.
 - Small electron effective mass ($0.0145 m_0$)
 - High electron mobility ($41,000 \text{ cm}^2 / \text{V sec}$)
 - Huge g-factor for large Zeeman energy ($g = 51$).

InSb Energy Scales

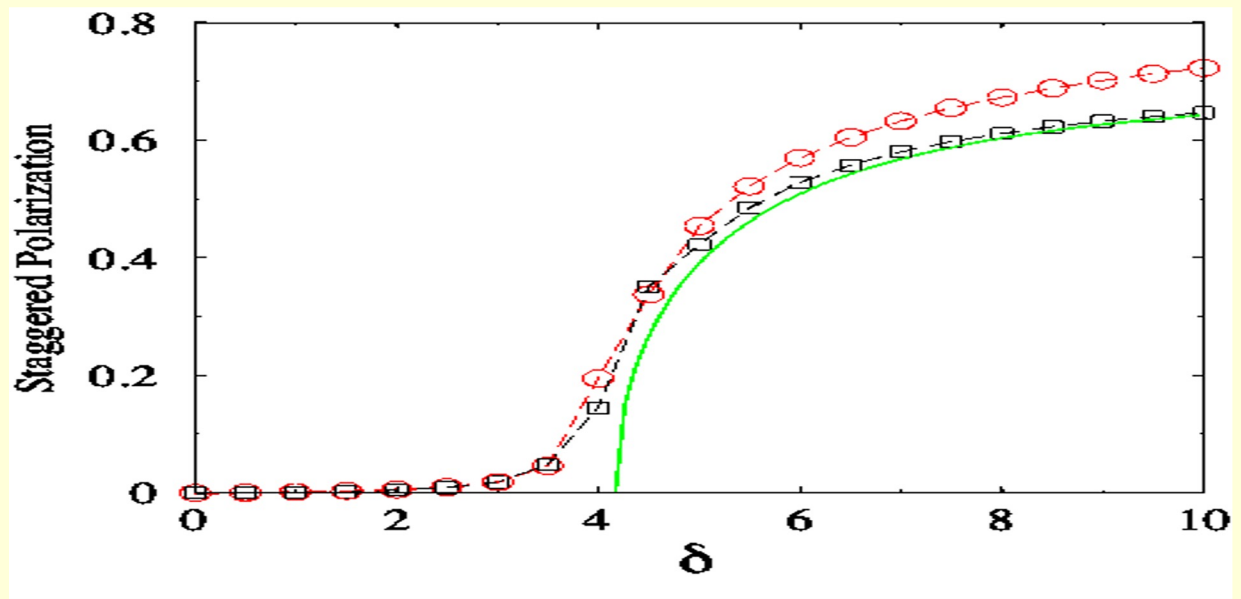


New Structures: Quantum Rings

Four fold degenerate groundstate:

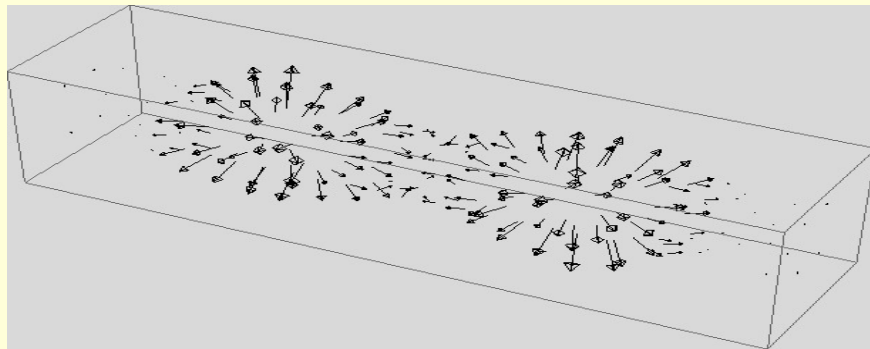
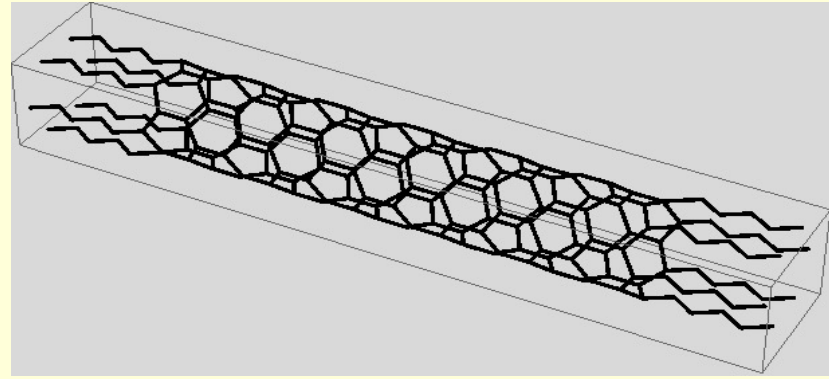


$$P_s = \sum_{ij} (-1)^i P_{ij}$$

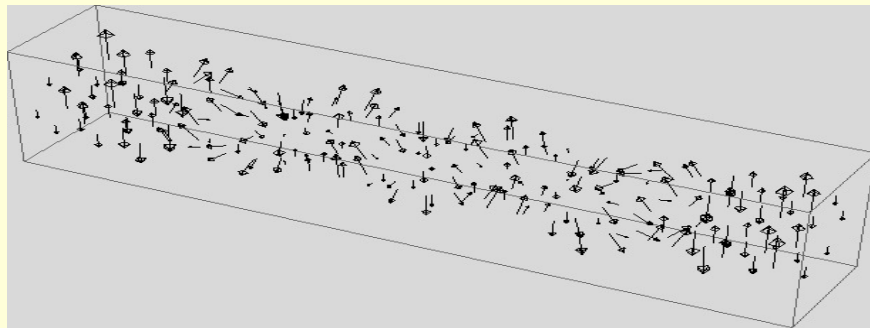


Material or Structure?

Right: A carbon nanotube with terminating alkane side-chains to improve phonon transfer. →



← A “bad” normal mode in which all motion is confined to the CNT.



← A “good” normal mode in which energy in the chains is transferred through the CNT.

Concluding thoughts

- Course areas $\neq$ Research Areas
- Course areas = Research *Tools*
- Most jobs in physics are outside of academia
- Bets for the future:
 - Interface materials
 - Bio-technical materials
 - Quantum coherent technology
 - Whatever the !&\$# experimentalists stumble upon..