Quantum Physics and Topology: The next revolution in computing?

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(for references see end of presentation)

A Question: Physics anyone?

Anything look familiar?

A Question: Physics anyone?

- Most likely, everyone here uses physics every day.

Quantum physics anyone?

- Most likely, everyone here uses physics every day.
- In fact, probably everyone here uses *quantum physics* every day.

Outline

- Why do we care about physics?
- What is quantum physics?
- What exactly does a theoretical physicist do?
- What is topology?
- What does quantum physics and topology have to do with computing?

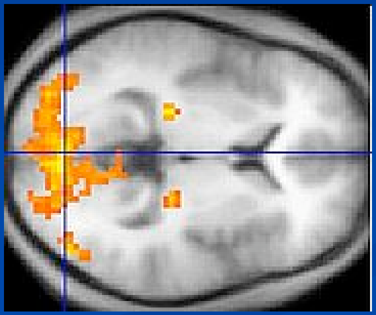
Why do we care about physics?

- Medical advances and applications.
- Energy conservation & reduction of carbon footprint.
- Prediction and early detection of natural disasters.
- Tools for the unfolding revolution in biology.
- National Security.

Physics and Medical Advances

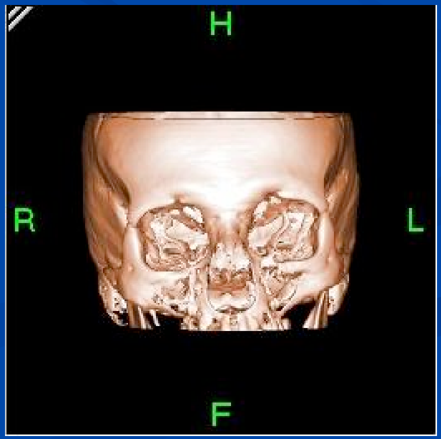
- Nuclear Magnetic Resonance (a.k.a. MRI)

MRI



fMRI

- X-rays and CT scans



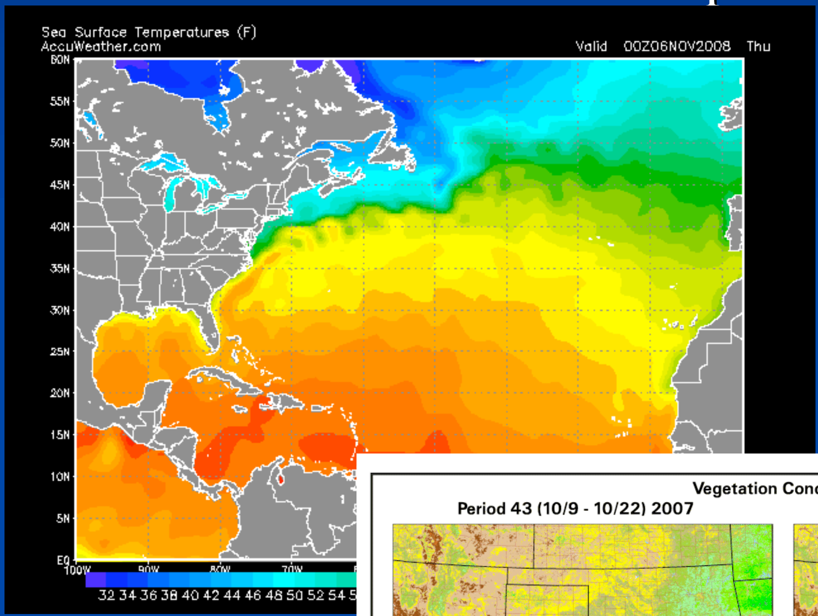
Non-carbon based energy

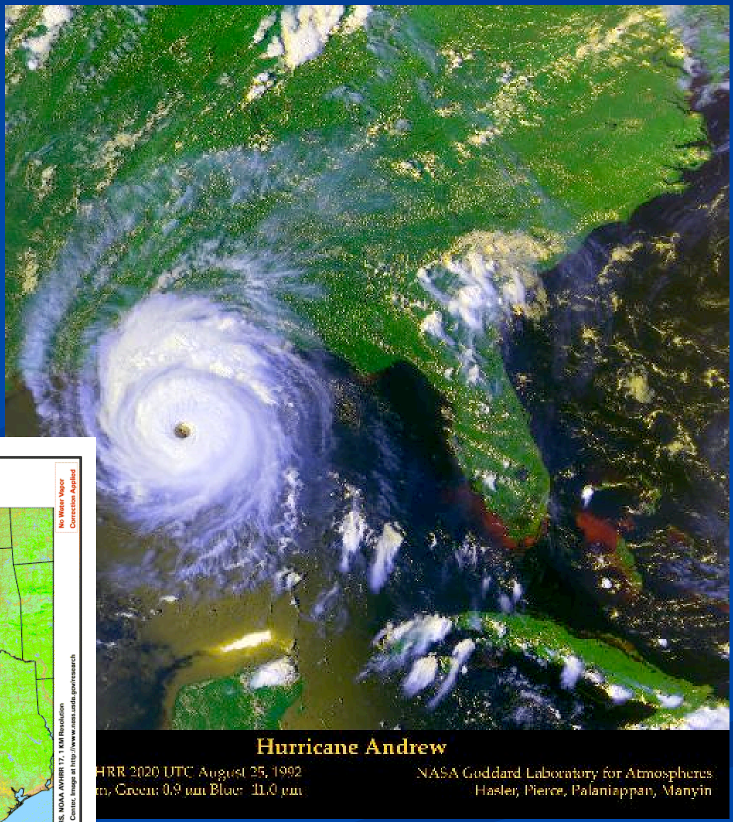
- Solar Power

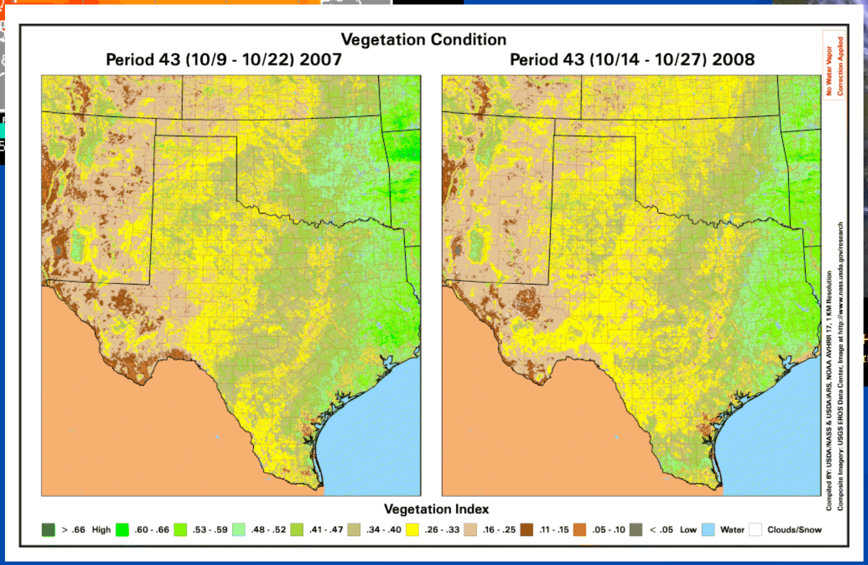
- Nuclear Power

Global environmental changes and early warning for natural disaster

- Ocean surface temperatures, hurricanes, vegetation



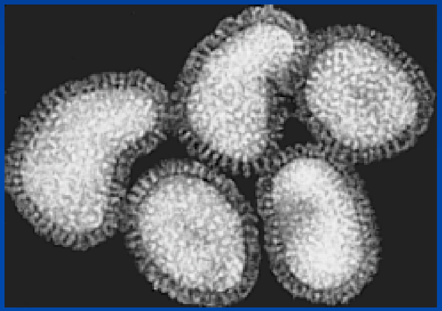




Tools for biology

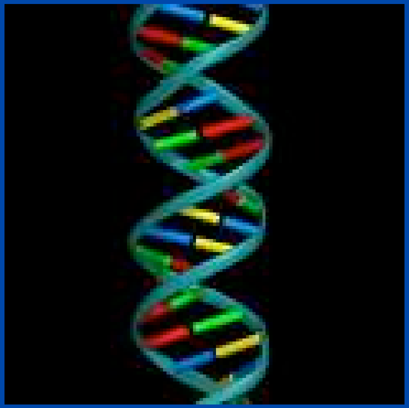
- Imaging methods: Electron microscope

Ant

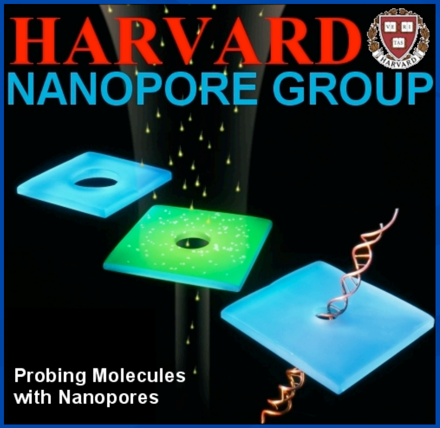


Influenza virus

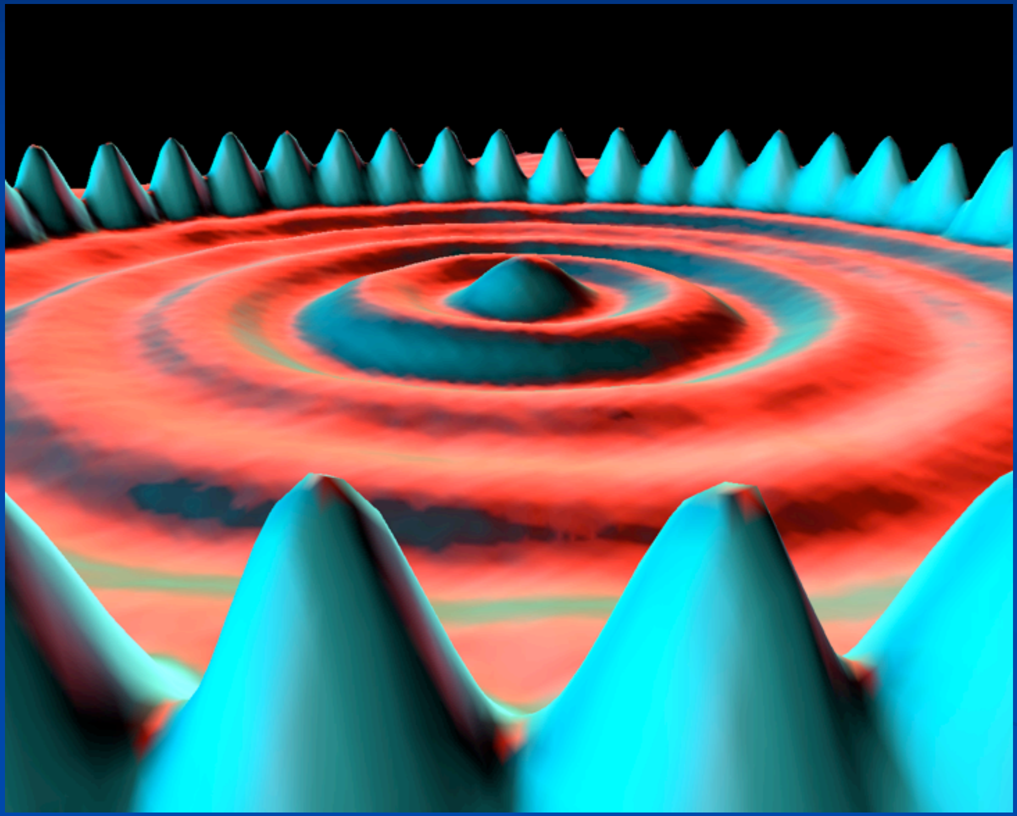
- Structure of molecules: X-ray scattering



DNA

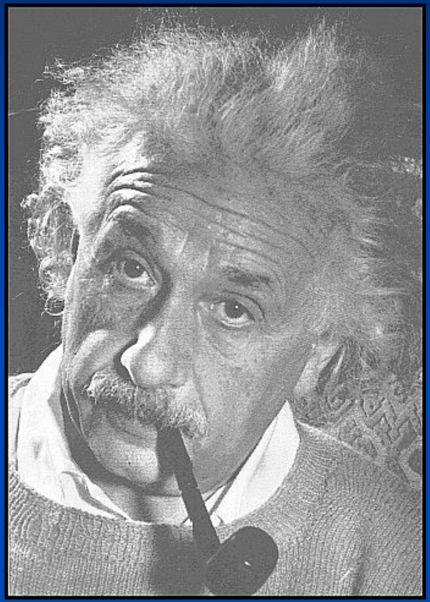


Tools for physics!



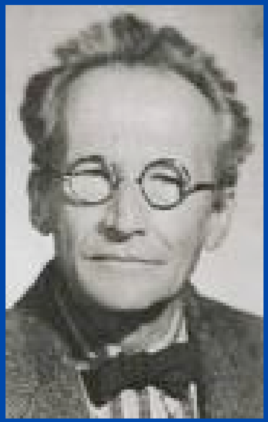
Scanning Tunneling Microscope image of Iron atoms and electron waves on a Copper surface

What is quantum physics?



Properties of matter exist in discrete "quanta" or "packets".

Light waves behave like particles: "photons".



Particles behave like waves: wave mechanics, wave equation.

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi$$

Key Physical Principles of QM

- Theory intrinsically probabilistic.
- There exists a Heisenberg Uncertainty Principle.
- Particles are indistinguishable and have a "statistics" quantum number.
- Wavefunction must be single valued--this combined with wave nature implies quantization.

- System seeks to minimize energy.
- Modulus squared of wavefunction gives probability for finding a particle locally.

What exactly does a theoretical physicist do?

- Construct and test models to describe nature.
- Consult and discuss with experimentalists and other theorists.
- Submit ideas and results for peer review in the scientific community before publishing.

What is topology?

- Branch of mathematics that deals with properties of space that are unchanged under continuous deformations: the number of holes.

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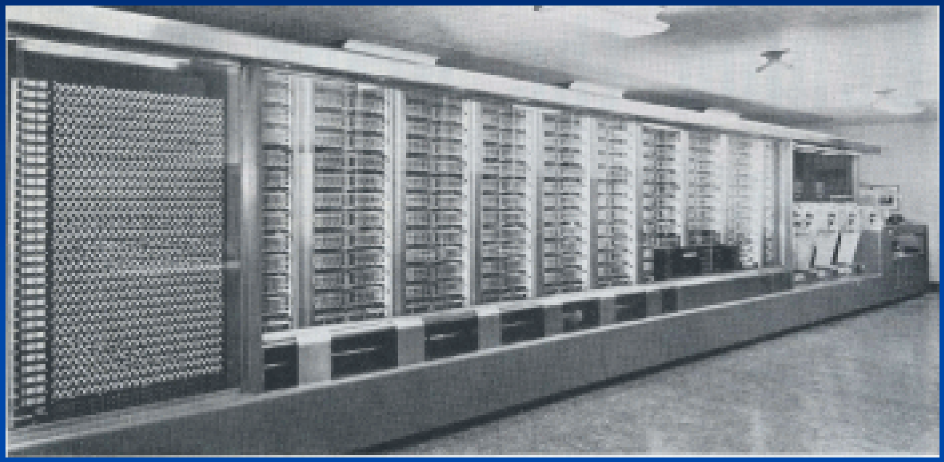
Coffee cup topologically equivalent to doughnut!

Didn't this talk have something to do with computing?

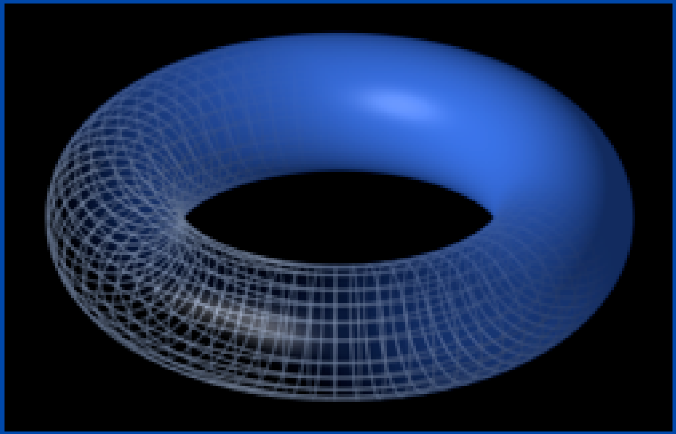
"It looks like that motherboard you installed is starting to act up again!"

How far we've come!



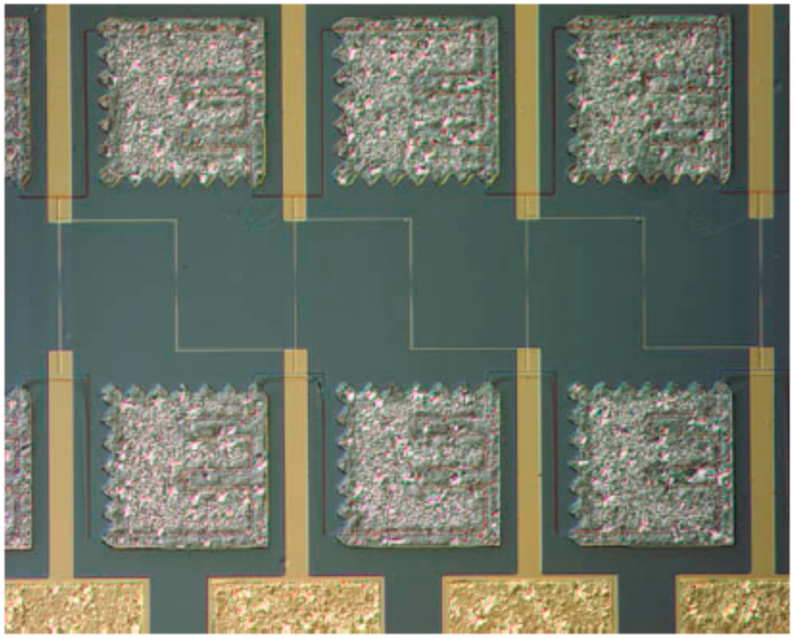
Where we are headed: topology + tiny quantum electronic devices.

Mobius Strip



Torus = Coffee cup

+



Top-gate defined quantum point contacts on an etch-defined Hall bar with Ohmic contacts.

Electronic devices smaller than the width of a human hair

Why Quantum Computing?

- Certain problems, like factoring large numbers, have efficient quantum algorithms.
- Naturally "parallel".
- Can be used to solve physical models that an ordinary computer cannot: physics simulates itself.

Why combine topology and quantum physics?

- Quantum mechanics is usually fragile, but topological quantum states circumvent this.
- Heating in small devices is a major problem, topological states can transport energy and information without dissipation.
- Certain topological states contain the necessary ingredients for universal quantum computation.

How does topology appear in physics? It's usually an emergent property.

- Many topological states are described by a topological quantum field theory. An example of which is Chern-Simons theory:

$$S_{CS} = \frac{k}{4\pi}\int d^2\mathbf{r}dt\epsilon^{\mu\nu\rho}a_\mu\partial_\nu a_\rho$$

- Topological theories generally have fractional charges and statistics.
- Topological theories are non-dynamical in the bulk, but there may be dynamics on the boundary.

What kind of systems exhibit topological behavior?

- Quantum Hall systems, particularly fractional quantum Hall systems.
- Certain band insulators with spin-orbit coupling.
- Some magnetic systems.
- Superconductors of a certain type.
- Possible some cold atomic gases in atomic traps.

Where is the research frontier?

- How do we classify topological states?
- What are the general conditions under which they occur?
- How do we experimentally establish their existence?
- How can we best exploit them in applications?

Summary

- We all use quantum physics everyday.
- Physics is a foundational science that enables advances in chemistry, biology, medicine, earth and space science, anthropology, etc.
- Topological quantum systems hold exceptional promise in quantum computing and tiny quantum devices.

Useful references

- Accessible article discussing topological quantum computing and non-Abelian fractional quantum Hall states: S. Das Sarma, M. Freedman, and C. Nayak, "Topological quantum computation", Physics Today Vol 59, Issue 7, page 32 (2006).
- Research level review article on the same topic: C. Nayak, S. Simon, A. Stern, M. Freedman, S. Das Sarma, "Non-Abelian anyons and topological quantum computation", Reviews of Modern Physics, Vol. 80, page 1083 (2008).