Condensed matter physics: More is different!

(and how to study it by high-performance computing)

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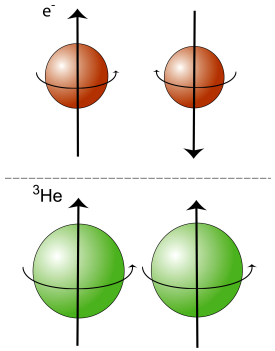
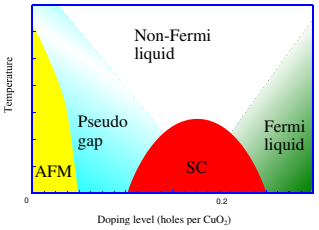
Outline



What is condensed matter physics?
Emerging phenomena and the axis of complexity
Current projects

High-performance computing in scientific research
Monte Carlo simulations



What is condensed matter physics?

Condensed Matter Physics:

> *field of physics that deals with the macroscopic properties of matter; in particular ... the "condensed" phases that appear whenever the number of constituents in a system is large and their interactions ... are strong.*

Traditionally: Physics of solids and liquids

- What is the structure of crystals?
- How do solids melt or liquids evaporate?
- Why do some materials conduct an electric current and others do not?

Today: all systems consisting of a large number of interacting constituents

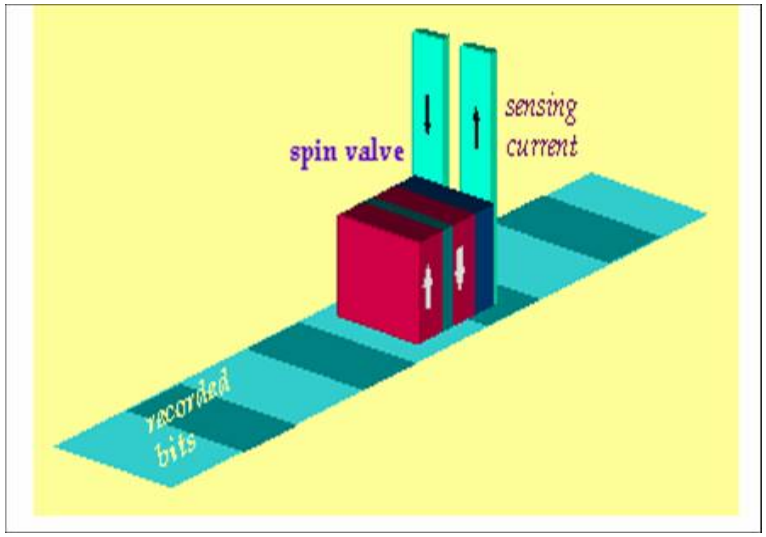
- biological systems: biomolecules, DNA, membranes, cells
- geological systems: earthquakes
- economical systems: fluctuations of stock markets, currencies

Why condensed matter physics?

Applications: "Helps you to make stuff."

- semiconductors, transistors, microchips
- magnetic recording devices
- liquid crystal displays
- plastic and composite materials

Maglev train using levitation by superconducting magnets, can go faster than 350 mph

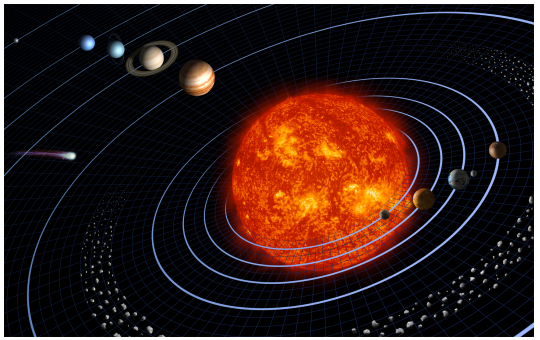


Magnetic read head, based on Giant Magneto-resistance effect (Physics Nobel Prize 2007)

Why condensed matter physics II

Directions of fundamental physics research :

Astrophysics and cosmology:
increasing length and time scales

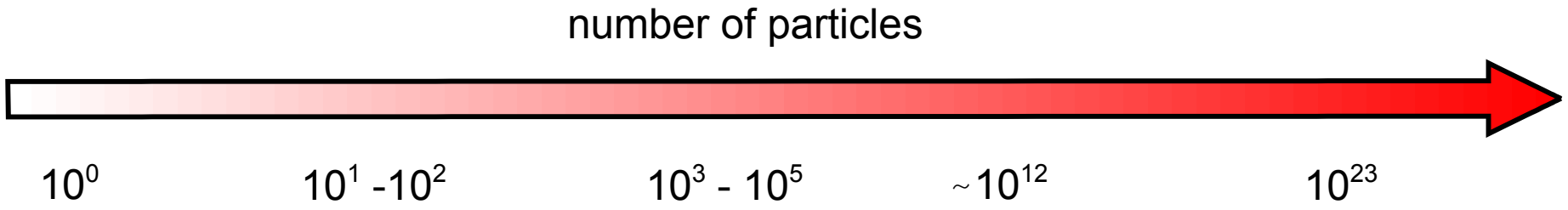


Atomic, nuclear and elementary particle physics:
decreasing length and time scales

Particle accelerator at Fermilab

What direction does condensed matter research explore?

Emerging phenomena and the axis of complexity



elementary particles	atoms, molecules	cluster	mesoscopic systems	macroscopic solid or liquid
	chemical prop. (periodic table) optical prop. (e.g., color)	mechanical properties (rigidity, solid vs. liquid)	transport properties (conductivity)	phases and phase transitions (ferromagnetism) ... biology, life

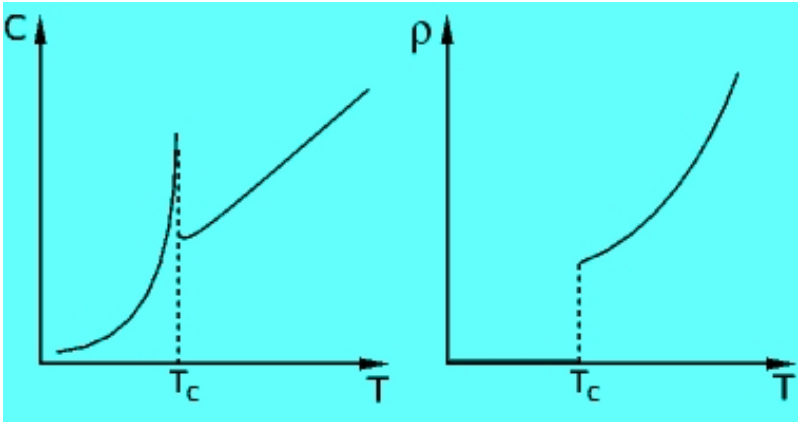
Emerging phenomena:

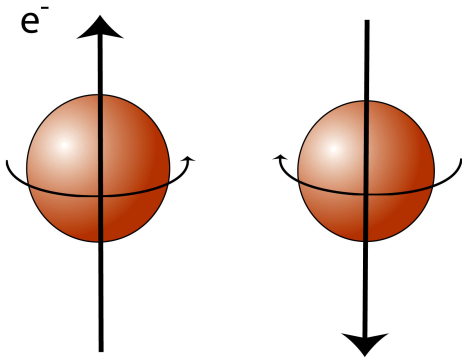
When **large numbers** of particles strongly **interact**, qualitatively new properties of matter **emerge** at every level of complexity

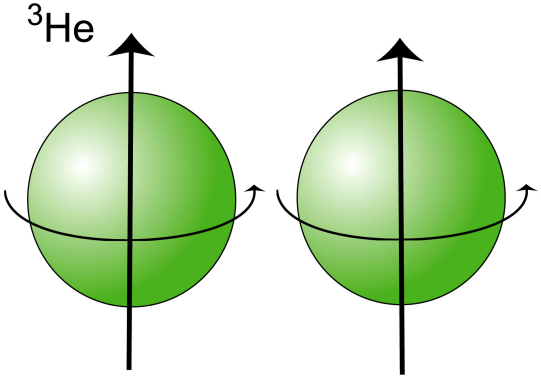
Superconductivity

Superconductivity

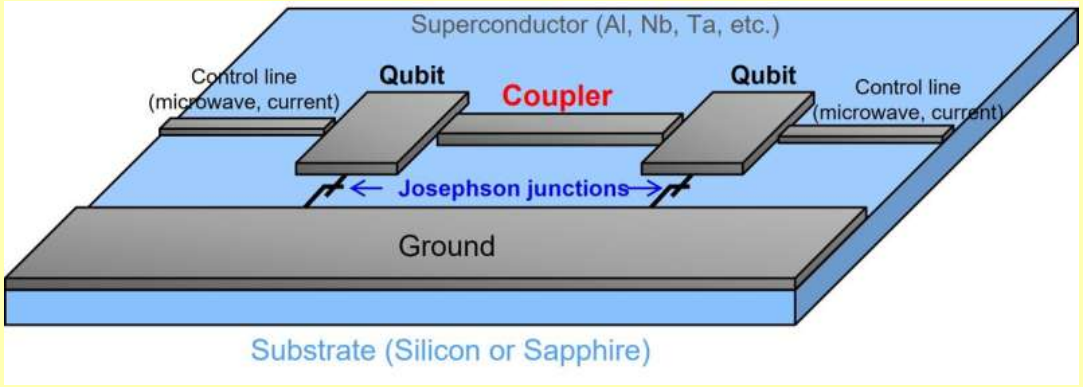
- zero electrical resistance below a certain temperature
- electrons form Cooper pairs







superconducting qubits for quantum computing

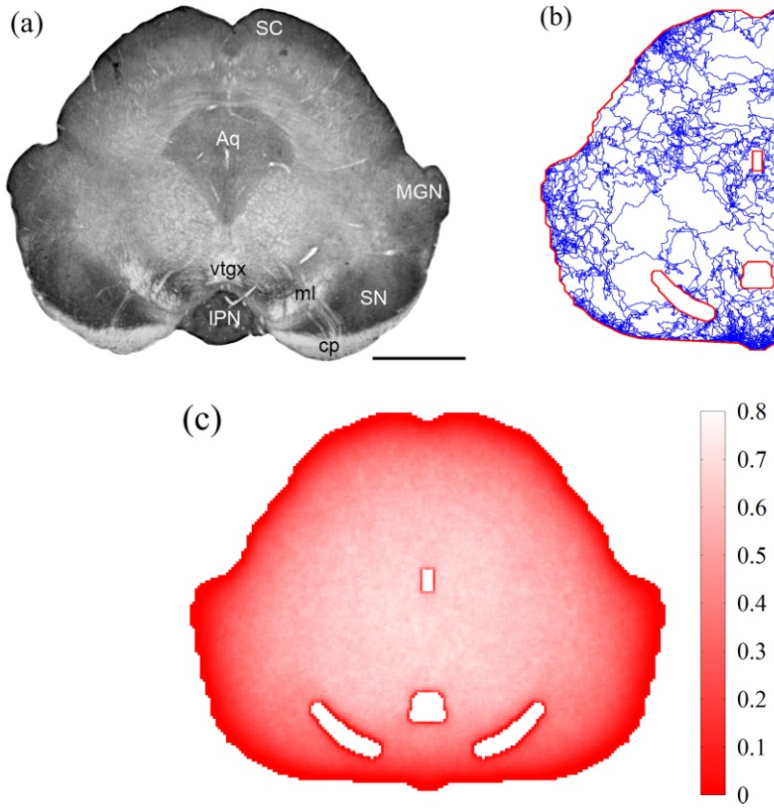


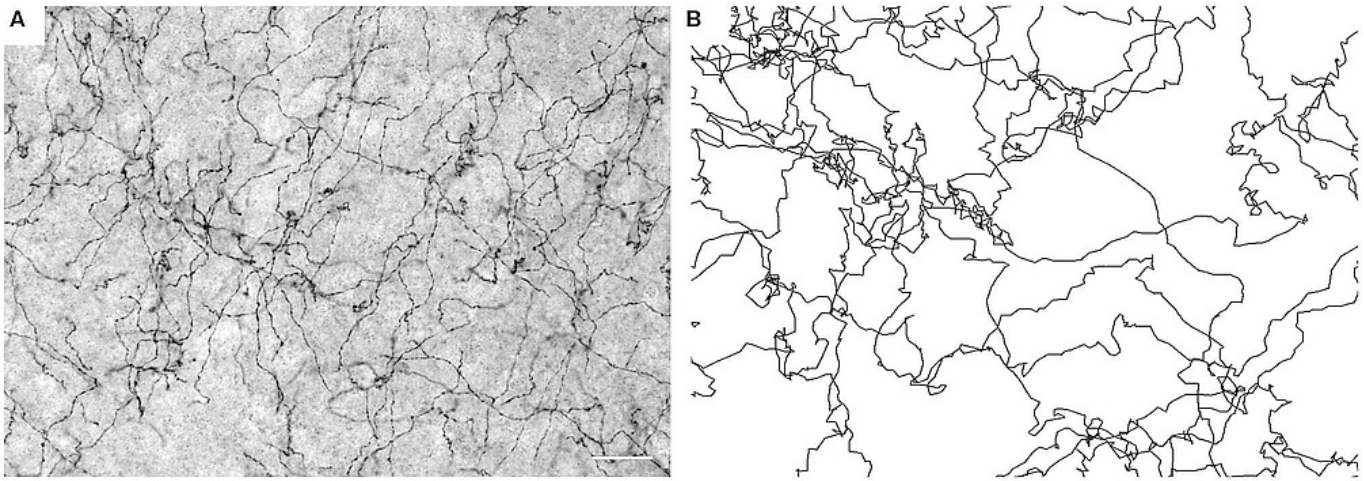
Many-particle physics meets neuroscience

Serotonergic fibers in vertebrate brains:

- serotonergic fibers: special neurons that transport **serotonin**
- form inhomogeneous random network

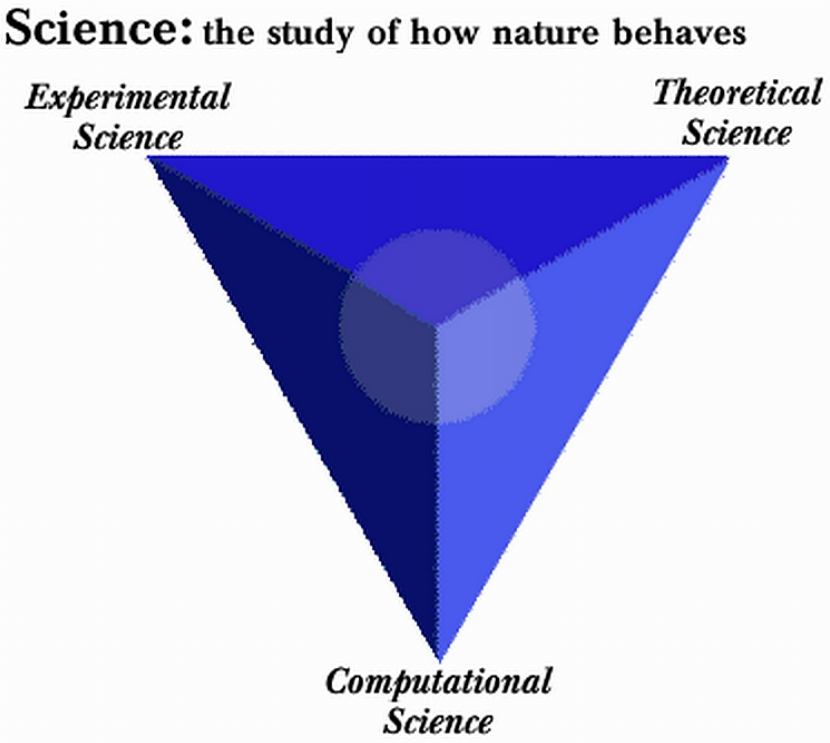
What causes varying fiber densities?





Computational Science

Application of computational and numerical techniques to solve large and complex science problems



3rd independent scientific methodology

has arisen over the last 30 years or so

shares characteristics with both theory and experiment

requires interdisciplinary skills in science, mathematics, computer science

Computational Science $\neq$ Computer Science

Top 500 supercomputer list

In the latest list (June 2025):

- about 86% of the 500 fastest computers in the world are clusters
- top cluster system in the US (rank 5): Eagle, Microsoft Azure, 2,073,600 CPUs

Frontera (Texas Advanced Computing Center)

- at Missouri S&T: The Mill cluster, 15,200 CPUs

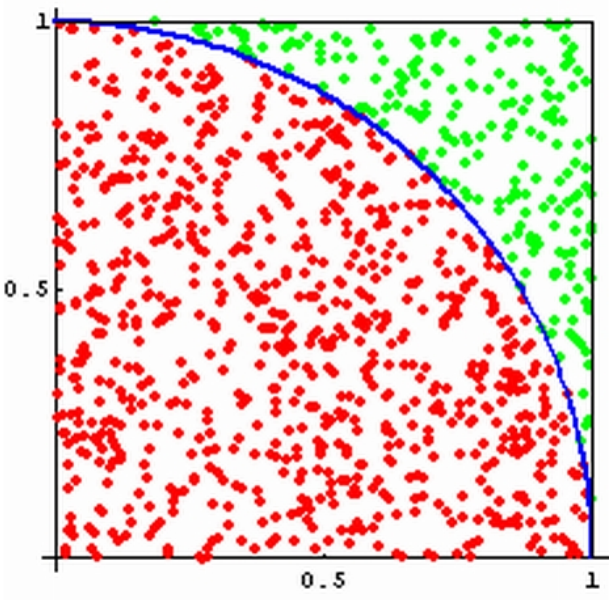
Monte Carlo simulations

Monte Carlo method:

class of computational algorithms for simulating various physical and mathematical systems; they are ... stochastic, usually by using random numbers.

Example: Monte Carlo calculation of Pi

- fire random data points at a circle inscribed within a square
- ratio of the areas of circle and square is $\pi/4$
- ratio can be estimated as the number of hits in the circle and the total number of points in the square



Research opportunities for undergraduates

Computational Physics Projects:

- some **programming experience** in required
- projects involve:
  developing Monte Carlo programs,
  running large-scale parallel simulations,
  analyzing and visualizing numerical data