

# Lecture 26 Review of Course

## The Great Ideas of Physics A Review

**Quantum Mechanics**

**Classical Physics**

**Relativity**

## General Comments

- What have we done this semester?
  - We have studied the most important developments in physics, stressing **conceptual** understanding.
  - Science since antiquity (mostly Western)
  - Revolutions in thought:
    - Scientific Method, Classical Physics ~ 1300 – 1900
    - Space Time, Quantum Behavior Key advances 1900- 1930
- This review does NOT cover the entire semester in detail
  - We have had two previous summaries.
  - Today:
    - The overall picture
    - More detail on the last part of the course: Quantum mechanics and the last 2 lectures.

## Scientific Knowledge

- Framework for Understanding:
  - “Logical Approach”
    - Induction vs. Deduction (Bacon vs Descartes)
    - The Problem of Induction: How to go beyond a collection of facts to new concepts?
    - The problem of Deduction: How to demonstrate that an abstract idea applies to nature?
  - “Historical Approach”
    - Normal science → crisis → extraordinary science (Kuhn)
      - Paradigm
      - Anomalies exist only in the context of a paradigm
      - Revolution leads to a new paradigm
- We have followed historical approach
  - Documented “Revolutions”
  - Set stage for understanding the way science worked and works in practice

## Timeline

- “Classical Physics” was complete around 1880
- See Timeline description of lives of various scientists on WWW pages.

## Astronomy

- Initial Paradigm: **The Two Sphere Universe**
  - Large sphere containing the stars on its surface rotates about a small sphere, the Earth, with a period = 1 day.
- Anomaly: **The Problem of the Planets**
  - Five planets exhibit anomalous (within 2 sphere paradigm) motion. *ie* for some part of the year, planets go “backwards”.
- Normal Science Response: **Ptolemy** → **Tycho**
  - Planets move on circles (epicycles) centered on another circle (deferent = Sun for Tycho) which moves uniformly around the Earth.
- Extraordinary Response: **Copernicus** → **Kepler**
  - **Copernicus**: All planets (including the Earth) move about the Sun.
  - **Kepler**: abandons paradigm of uniform circular motion: Elliptical orbits (Sun at one focus) with a varying speed (equal areas in equal times)

## The Copernican Revolution

- The Renaissance was a “rebirth” of knowledge in many ways
  - Science and especially physics was at the center
  - Re-examination of the “ultimate questions” of cosmology and the “practical questions” of understanding what we observe in nature
- Is the earth the center of the universe or only a planet orbiting the sun?
  - **Ptolemy vs. Copernicus**
  - Resolved by the simple description of Kepler, the earth and other planets move in ellipses
  - Copernican revolution
- Affects our understanding of our place in the universe – our world view

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## The Classical Revolution

- Continuing the Copernican revolution
- How do we understand motion on earth?
  - Galileo (mathematician) introduces the experimental method and quantitative mathematical analysis
  - Describes motion on earth by simple laws
  - Applies also to the heavens – the earth moves!
- Basis for later developments ==> Newton
  - Next slide

## The Classical Revolution

- Newton and Maxwell define “Classical Physics”
- Newton’s Three Laws
  - Inertia:
    - “Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by a force impressed on it.”
  - Force & Acceleration:
    - “The change in motion [rate of change of momentum] is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.
  - Action = Reaction:
    - “To every action [change of momentum] there is always opposed an equal reaction; or, the mutual actions of two bodies are always equal, and directed to contrary parts.”

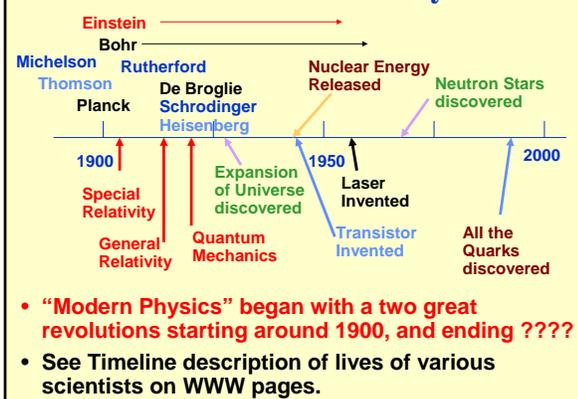
## Forces & Fields

- Forces:
  - Free Fall (Galileo-->Newton)
    - Galileo: All bodies fall downward with the same acceleration
    - Newton:  $F = m a$  + force of gravity near earth is  $F_g = m g$
  - Universal Gravitation (Kepler-->Newton)
    - Kepler: Described motion of planets  $T^2 = k R^3$
    - Newton:  $F = m a$  + Universal law of gravity  $F_m = G m_1 m_2 / R^2$
- Conservation Laws:
  - Conservation of Momentum:
    - Newton’s 3rd & 2nd Laws => total momentum ( $p=mv$ ) of interacting objects is conserved (does not change in time).
  - Conservation of Energy:
    - Energy changes form but the total is always conserved
- Fields: (Newton ==> Faraday ==> Maxwell)
  - Electric Fields created by charges.
  - Magnetic Fields created by charges in motion.
  - Electromagnetic waves (speed = c)

## Paradigm of Classical Physics: Space & Time, Particles & Waves

- Experimental method
  - Galileo, ..... Test theories under controlled conditions
- Space & Time
  - Time is absolute (the same in all reference frames)
- Particles
  - Particles have mass which is conserved
  - Particles obey Newton’s equations
  - Examples: Baseballs, electrons
- Waves
  - Waves are moving patterns
  - Waves show interference effects
  - Examples: Light (Maxwell’s equations), Sound
- Nature is Deterministic

## Timeline - Modern Physics



## Space-Time Revolution

- The Initial Paradigm: Classical Physics
  - Light is a wave (thought to be a medium called “ether”)
- The anomaly (crisis) for classical physics: Michelson-Morley Experiment
  - Found Speed of light to be the same in all directions even though the earth is moving around the sun
- Normal response
  - Try to explain the experiment as some anomaly of light
- Extraordinary Response (Revolution)
  - Completely revise our notions of space and time

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## Special Relativity: The Postulates

- A problem for classical physics: **Michelson-Morley Experiment**
  - Found **Speed of light** to be the same in all directions even though the earth is moving around the sun
- **Einstein's Postulates**
  - **Principle of Relativity:**
    - The laws of physics are the same in all frames of reference which are moving at constant velocity
  - **Speed of Light:**
    - Light is always propagated in empty space with the same velocity  $c$  independent of the state of motion of the source or the observer
- **Relative character of "simultaneity"**
  - Adopting an **operational definition** of measurement of time at different places, we find that the meaning of "**simultaneous**" depends upon the relative motion of the observer.
- **Time is not absolute!**

## Special Relativity: The Consequences

- **Proper Time**
  - Time for an object is measured in the reference frame where the object is at rest is called the **proper time interval**,  $\Delta T_{\text{proper}}$ .
- **Space and Time differences**

- $\Delta T_{\text{improper}} = \gamma \Delta T_{\text{proper}} \quad \gamma = 1 / \text{sqrt} ( 1 - (v / c)^2 )$
  - $L_{\text{parallel}}(\text{moving}) = L_{\text{parallel}}(\text{rest}) / \gamma$
  - $L_{\text{perpendicular}}(\text{moving}) = L_{\text{perpendicular}}(\text{rest})$
- **Nature's speed limit**
  - Information cannot travel faster than the speed of light.
  - Enforced by **increase in relativistic mass:**

- $M = \gamma M_0 \quad E = M c^2$
- **Mass and energy are related!**

## Space-time & General Relativity

- **General Relativity**
    - **Equivalence Principle**
      - Inertial mass = gravitational mass
      - "No experiment performed in one place can distinguish a gravitational field from an accelerated reference frame"
    - **Consequences**
      - Light "bends" in a gravitational field.
      - Gravitational "Red Shift": Clocks at lower gravitational potential run slower than those at higher gravitational potential.
      - Leads to objects like "Black Holes"
    - **The Theory**
      - Mass causes space-time itself to be curved
      - Describe gravity not by a force but by motion of bodies in a curved space
- 

## The Quantum Revolution

- **The Initial Paradigm: Classical Physics**
  - All motion is continuous; any energy is possible for particles or waves
  - Particles and waves are completely different
- **The anomaly (crisis) for classical physics: Radiation from Hot bodies; Properties of atoms**
- **Normal response**
  - Completely puzzling
  - Try to explain the experiment as some anomaly of matter
- **Extraordinary Response (Revolution)**
  - Many people pointed the way: **Planck, Einstein, Bohr**
  - **de Broglie** made the giant step: **Particles act like waves!**
  - **Schrodinger** and **Heisenberg** showed that our ideas of determinism have to be completely revised, .....

## Origins of the Quantum Theory

- **The concept of quanta**
  - **Blackbody Radiation:** To get agreement with data, **Planck** assumed light is emitted in packets or "quanta" with energy of each quantum related to the frequency by  $E = h\nu$
  - **Photoelectric effect:** **Einstein** takes Planck seriously. Predicts energy of electrons liberated in photoelectric effect because the light arrives in quanta of energy  $E = h\nu$
- **Atomic models**
  - How can atoms be stable?
    - Completely puzzling in classical physics!
    - Electrons should spiral into nucleus!
  - **Bohr proposed solution**
    - Electrons can only be in certain orbits – quantized states
    - Right idea but not fully correct

## Waves & the Quantum Theory

- **Wave nature of electrons**
  - **de Broglie** proposed an electron has an "associated wave" with wavelength determined by its momentum:  $\lambda = h / p$
  - **Davisson & Germer** showed electrons act like waves- show interference.
- **General wave equation**
  - **Schrodinger** proposed an equation which describes completely the time evolution of the matter wave  $\Psi$ . Probability of finding the particle is given by  $\Psi^2$
- **Successful** -- describes electrons, atoms (periodic table), molecules (chemistry), elementary particles, .....
- **Strange** - The truth is stranger than fiction

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## The Uncertainty Principle

- Basic fact of quantum mechanics
  - Heisenberg** formulates quantum mechanics in terms of "observable quantities only" and obtains fundamental limits on how good an experimenter can be!

$$\Delta p \Delta x > (1/2) h/2\pi \quad \text{or} \quad m \Delta v \Delta x > (1/2) h/2\pi$$

$$\Delta E \Delta t > (1/2) h/2\pi$$

- Fundamental uncertainty in what we observe in nature

## The Quantum Revolution - Interpretation

- Consequence:
  - Calls into question our very notion of "reality"
- Is there a "reality" external to ourselves?
  - How do you know?
  - Do experiments – test!
- Conclusion
  - At the quantum level, the result of the experiment depends upon the experimenter!
- Not understood – a matter of debate

## Scale of Sizes in Nature

Person ~ 1 m



Fundamental particles

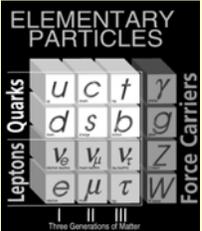
Scale in m:	Scale in 10 <sup>-18</sup> m:
10 <sup>-10</sup> m atom	100,000,000
10 <sup>-14</sup> m nucleus	10,000
10 <sup>-15</sup> m proton	1,000
≤ 10 <sup>-18</sup> m quark	≤ 1

Universe ~ 10<sup>26</sup> m  
 Solar System ~ 10<sup>11</sup> m  
 Earth ~ 10<sup>7</sup> m



## Elementary Particles

- Fermions:** particles with half-integer spin which can be transformed into other fermions or created (or destroyed) only in pairs with its anti-particle
  - Example: electron, quark
- Bosons:** particles with integer spin which can be freely created or destroyed; carries forces between particles
  - Example: photon, gluon
- All matter described by the theory except gravity --- Present theories are incomplete



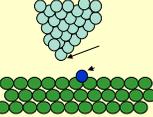
## Important Quantum Effects in Our World

**Lasers** → Due to quantum wave character of photons of light

**Semiconductors - Basis of all modern electronics**  
 Transistor invented at Bell Labs, 1947 (Bardeen, Brattain, Shockley)

Due to quantum wave character of electrons in crystals

**Scanning Tunneling Microscope "Sees atoms and electrons"**  
 Invented at IBM Labs, Switzerland, 1985  
 (Depends on quantum "tunneling")

## The Universe and Cosmology

- Galaxies and stars form from gases (mainly H) pulled together by gravity
  - Stars produce energy from nuclear fuel
- Death of a star
  - Collapse when fuel runs out
  - Becomes a dwarf, neutron star (pulsar) or black hole
  - Rapid collapse causes a supernova
- The Universe is Expanding
  - Hubble (1929) Measured by "Doppler Shift"
  - Expanding in all directions as if it came from a point
  - Estimate for age of universe ~ 15 billion years
- The **BIG BANG**
- Future?
  - Expansion, gradual slowing, or collapse to the **BIG CRUNCH**



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