The Idea of Science

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Lecture 3
Further Reading

• A clear explanation of the history of Einstein’s theory of relativity

• I does have equations but there are reasoned words to go with them

• Taken from lectures
“The Equation”

• We will start at the end

• Probably the most widely know equation
• The idea is much, much more far-reaching than the one equation
Our World

- Our world is Newton’s world. It is:
  - Continuous
  - Observable
Observable

- In ‘Our World’ we observe things from the outside
- What we observe doesn’t change
Frame of Reference

- We observe in a ‘frame of reference’
- All motion is relative
Questions

• The first questions about the completeness of Newton’s description were raised in the late 19\textsuperscript{th} century

• Newton’s Principia
  – Classic Physics
    • Forces and actions
    • Optics
    • Thermodynamics
Late 19th Century

• Industrial revolution
  – Steam/ Heat /Thermodynamics
  – Electricity/ Magnetism / Electromagnetism

• A great deal of development
  – Great financial reward
Late 19\textsuperscript{th} Century

• In the 1870’s everything in physics ‘was known’

• The area of work was the somewhat ‘applied’ field of thermodynamics
  – Practical applications
  – New mathematical tools

\begin{align*}
q_t(V) &= - \int_{\partial V} \mathbf{H}(x) \cdot \mathbf{n}(x) \, dS \\
    &= \int_{\partial V} \mathbf{A}(x) \cdot \nabla u(x) \cdot \mathbf{n}(x) \, dS \\
    &= \int_V \sum_{i,j} \partial_{x_i} (a_{ij}(x) \partial_{x_j} u(x, t)) \, dx
\end{align*}

• There remained a few issues to be ‘tidied up’
Electricity
Late 19th Century

• Some familiar names:
  – Watt
  – Faraday
  – Ampere
  – Coulomb

• All described part of behaviour of electricity

GE generating plant Washington DC circa 1880
Late 19th Century

• Observational tools beyond the microscope
  – Electricity and magnetism detectors
  – Cathode rays/ x-rays
  – Radiation

• Mathematics to describe things we can’t see
  – Calculus in 3 dimensions
  – Quantitative 3D geometry
  – Maxwell’s equations for electromagnetism
Newton’s Optics

- Late 1600’s Newton used prism experiments to show that light was a wave
  - Optiks was first major science publication written in English
- Waves required a medium to propagate
- Aether
- Luminiferous aether
Maxwell’s Unification

- James Clerk Maxwell was a Scottish mathematician.
- At age 28 (1865) he published a description of *The Dynamic Nature of the Electromagnetic Field*.
- He was able to take all the previous work on electricity and magnetism and fields and connect them mathematically.
Maxwell’s Unification

• ‘Maxwell’s Equations’ are seen as the high point of ‘elegance’ in physics
• It firmly grounded the field and methods of mathematical physics
• He showed that
  – Electrical waves and magnetic waves interact
  – That the interaction of the electromagnetic wave(s) allowed propagation of the wave
  – The properties of the propagation (the way it moved) could be related to the properties of the medium it travelled through
    • These properties could be measured
\[ \nabla \cdot \mathbf{B} = 0 \]

\[ \nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \]

\[ \nabla \cdot \mathbf{E} = 4\pi \rho(r, t) \]

\[ \nabla \times \mathbf{B} = \frac{4\pi}{c} \mathbf{J}(r, t) + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} \]
It Turns Out That ...

- The term that included the electric and magnetic properties of material:
  - Had units of velocity (e.g. m/sec)
  - Had a value close to the measured speed of light
  - Maxwell had used the ‘c’ for that constant

\[
\begin{align*}
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \\
\nabla \cdot \mathbf{E} &= 4\pi \rho(r, t) \\
\nabla \times \mathbf{B} &= \frac{4\pi}{c} \mathbf{J}(r, t) + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}
\end{align*}
\]
It Turns Out That ...

- It works ...

- There was no other ‘a priori’ reason

- It has continued to work in all situations where electromagnetic fields have been studied
• But the waves needed a medium to travel through
  – We know this from water waves and sound waves
  – We know that a prism works because of differences of speed of light in different media
• There are observations that support this theory
The Trouble With Maxwell
The Trouble With Maxwell

However

There were discrepancies between the predictions of Maxwell in some specific cases and what would be expected according to Newton

- Stellar aberration from distant stars
Careful measurements found that the aberration did not behave like walking in the rain.
Careful measurements found that the aberration did not behave like walking in the rain.
The Trouble With Maxwell

• The mathematical ‘fix’ to Maxwell’s equations was developed by Hendrik Lorenz and Henri Poincaré

• They added a term to the Newtonian quantities in Maxwell’s equations
  – i.e. the terms in Newton’s Laws
The Trouble With Maxwell

• The ‘corrections’ allowed agreement between the predictions of motion and optics as formulated by Newton and those of Maxwell
• They had to work around the constant speed of light.
  – This meant there was a maximum speed anything could move

*Recall that Newton’s theory shows only relative motion can be measured*
Frame of Reference

• We observe in a ‘frame of reference’
• All motion is relative
Lorenz Corrections

- Lorenz developed a mathematical correction that explained the data
- Worked in all experimental situations

\[ t' = \frac{t - \frac{v}{c^2} x}{\sqrt{1 - \frac{v^2}{c^2}}} \]
\[ x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}} \]
\[ y' = y \]
\[ z' = z \]
Corrections

• It could explain motion of electrons as well
• Cathode ray tubes allowed us to study a ‘stream’ of electrons

• However corrections were necessary
The Trouble With Maxwell

• So now we could predict:
  – How trucks move (Newtonian Mechanics)
  – How light can be focused
  – How a moving electric motor would behave

• The mathematics did, however, lead to some VERY unexpected consequences for objects moving very very fast
  – i.e. close to the speed of light
The Trouble With Maxwell

- When an object is seen to be moving in the x-direction
- Lengths contract
- Time slows down
- In that direction
• This mathematical prediction has been observed experimentally.

• We thus take it as a foundation of the way we describe the fast-paced world.
Cosmic Rays at Earth’s Surface

For reference only

Out of a million particles at 10 km, how many will reach the Earth?

- $\mu$: mass $207\ m_e$
- Charge $+$ or $-$
- Rest half-life: $T_0 = 1.56 \times 10^{-6}\ \text{sec}$

Measure muon flux at 10 km height.

$v = 0.98c$

$L_0 = 10\ \text{km}$

 documentos simultanegraumonitor flux at ground level.

Distance: $L_0 = 10^4\ \text{meters}$

Time: $T = \frac{10^4\ \text{m}}{(0.98)(3 \times 10^8\ \text{m/s})}$

$T = 34 \times 10^{-6}\ \text{s} = 21.8\ \text{halflives}$

Survival rate:

$\frac{1}{L_0} = 2^{-21.8} = 0.27 \times 10^{-6}$

Or only about 0.3 out of a million.

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Albert Einstein

Portrait by Yousef Karsh
Albert Einstein

- Born 1879, German Republic, Died 1955, USA
- Graduated from University in Munich in 1900
- Was unable to obtain a University Position
  - Eventually moved to Switzerland
  - Through a friend obtained a position in the Swiss patent office
- He completed a thesis and received the equivalent of a PhD from Bern University in 1902
Albert Einstein

• He continued to work at the patent office until 1908

• In 1902 he organized a discussion group with some friends ‘The Olympia Academy’ & met regularly to discuss science, including the work of Poincaré, Mach and David Hume
Albert Einstein

• His groundbreaking work occurred ~1905-1915

• In fact in 1905 he published 4 papers all of which were worthy of a Nobel Prize
  – Photoelectric effect
  – Special Relativity
  – Brownian motion (statistical thermodynamics)
  – Matter – Energy equivalence
Einstein circa 1905
Albert Einstein

• Einstein’s greatest skill was to be able to visualize \textit{and} describe mathematically ‘worlds’ we cannot see

• For example: It is believed he could visualize and ‘comfortably inhabit’ a 4-dimensional world
A Canadian Analogy:

*Gretzky sees a picture out there that no one else sees. It’s difficult to describe because I’ve never seen the game he’s looking at.*

Harry Sinden
Shadow of a 4-Dimensional Object
Special Relativity

• Many brilliant scientists had worked on the problems of reconciling Newton and Maxwell
  – Lorentz
  – Pointcaré
  – Michealson
  – Mach
  – Poynting
  – Fitzgerald
  – ........ and many more
Einstein’s Contribution

• Einstein looked at all the data and made the following observations:
  – There is no need for a transmission medium (aether) to describe transmission of an electromagnetic wave (or light)
  – The speed of light is constant to all observers and nothing moves faster than the speed of light
  – Different observers watching the same event need not observe the same thing (!!!)
Speed of Light

- The speed of light is constant to all observers.
Special Relativity

• The third point was referred to as ‘special relativity’
  – To differentiate it from Newtonian relativity

Observation depends only upon the observer
Space-Time

• In a philosophical and mathematical sense Einstein described the world we move in as four dimensions that interact with each other.

• This is difficult for us to comprehend because to us, on our scale, time is independent of position or speed.
  – It is still 2 o’clock, whether sitting, walking or driving.
Time Only Moves in One Direction
Mass Energy Equivalence

• Taking the concept of the constant speed of light one step further, we finally get to the Equation.
Mass Energy Equivalence

- If we apply force to a mass it moves
Mass Energy Equivalence

• If we keep applying the force the mass will increase in velocity

• Newton would tell us if you pushed it for an infinite time the mass would reach an infinite speed

• BUT IT CAN’T

We know why
Mass Energy Equivalence

• So what can change?
• We only have mass and velocity ....
• You can calculate how mass changes with velocity
  – Lorenz Transformations
• You can convert the force into an energy
• You assume that relativistic mass and rest mass are related

\[ e = mc^2 \]
General Relativity
General Relativity

- With a relationship established between mass and energy, the only force (known at the time) not included in the theory was gravity.

- Einstein developed the General Theory of Relativity to ‘unify’ gravity with the special theory of relativity.

In much the same way Maxwell had unified electricity and magnetism.
General Relativity

• In order to develop the theory he needed a new form of mathematics that could describe and manipulate geometries in more than 3 dimensions

• The mathematics was developed by Herman Minkowski
  – One of Einstein’s teachers
While the theory was developed in a different context, with many implications for the modern world, there are two important outcomes with regard to gravity:

1: There is a relationship between mass and energy. That is: anything that has energy also has mass
2: Anything that has mass will be subject to gravitational attraction
General Relativity

• In particular light (which clearly possesses energy) is subject to gravitational attraction.
  – This was an unproven outcome of the theory of general relativity
  – Total eclipse 1919 light from stars behind the moon was visible
Bending of light by the Sun
Gravitation causing bending of starlight as it passes near the sun. The apparent position of the star as seen from Earth is different from the actual position.

Eddington’s experimental proof of general relativity. A telescopic image during an eclipse showing the observed position and actual position when the star is viewed far away from the sun.

“One thing is certain and the rest debate. Light rays, when near the Sun, do not go straight.” (Eddington)
Black Holes

• A star is created by a balance between the energy forces pushing out and the gravitational forces pulling in.
• When the fuel for the nuclear reaction that provides the energy runs out gravity takes over.
• The remaining star material is attracted together.
Black Holes

• If there is enough mass around the star the collapsed star will strongly attract light

• A black hole is formed when there is so much mass that:
  – The ‘space’ between molecules is crushed by gravity
  – There is such a large gravitational force that light cannot escape (much like we are trapped on the Earth)
Formation of a black hole

Artist’s concept. NASA
Formation of a black hole

Cygnus Loop Blast. NASA
The Black End?

• If a black hole attracts everything and nothing can escape what then?
• Will everything get swallowed into a black hole?
• Is this the end of the story?
The Black End?

• Probably not ....

• But this is a far as we can get following the path from the Babylonians to Einstein
The Black End?

• To understand further we need to look at the problem from another perspective:

• Which we will ...... In another lecture
Applications

• Gravitational Anomaly mapping
• GPS accuracy
• Life without gravity
  – Back pain
  – Osteoporosis
  – Developmental Biology
Gravitational Anomaly Mapping

• Gravity force is the attraction between two masses:
  – Based on Center of Mass of the objects
• And the distance between the centre of mass of the two objects
  – Measure weight change
  – Know exact position
Gravitational Anomaly Mapping

Provides information on the Earth’s crust also on higher density rock formations or ice thickness
Global Positioning System

GPS uses a number of satellites to determine the position of a receiver.

It measures the distance from each satellite to the receiver and calculates the position.
GPS

• Distance is actually measured by measuring the transit time.

• Limiting factors on accuracy include
  – Atmospheric effects
  – Multiple reflections
  – Accurate timing
  – Relativistic correction for the path of the radio signal
Failure of Classical Physics

• The ultraviolet catastrophe
  – Heated material gives off light
  – The hotter the material the shorter the ‘more blue’
  – i.e. the hotter = shorter wavelength

• Blackbody radiation
Albert Einstein

• Everyone is familiar with Einstein’s iconic equation:

\[ e = mc^2 \]

• But where did it come from and what does it mean in the context of gravity?
Almost 200 years

1687  A lot of incremental steps by many well know names  1862

- Newton’s Principia
  - Classic Physics
    - Forces and actions
    - Optics
    - Thermodynamics

- Maxwell’s equations
  - The last ‘great problem’
  - Unification of
    - Electricity
    - Magnetism
    - Induction
    - Electromagnetism