Chapter 6: Idea 5

Electromagnetism and Relativity

The ***facts*** are relative,
but the ***law*** is absolute.

↑

When you understand this statement,

then you understand Relativity!

Introduction

- We have taken an historical approach
  - to the study of Physics.
- We are now at the turn of the last century
  - the 20th century that is (so around 1900AD)
- There were three major scientific accomplishments in the 20th century
  - And two of them were in Physics!

The Big Three

- The Structure of DNA
  - Watson and Crick, the Double Helix
- Quantum Mechanics
  - Universe *shaking* Idea #6
  - The physics of the very small: atoms
- The Theory of Relativity
  - Universe *shaking* Idea #5
  - The physics of the very fast

Introduction

- Relativity is an old idea
  - Not invented by Albert Einstein
  - But perfected by him
- Been around in various forms
  - since the Copernican Revolution
- Questions about the moving Earth
  - and the appearance of the night sky

Introduction

- Relativity does ***not*** say

  "Everything is relative."

- In fact it says some things are ***not*** relative
  - and explains the consequences of this
- If offers important new insights
  - on many fundamental quantities
  - Space, Time, Mass, Gravity

Introduction

- The modern Theory of Relativity
  - is Einstein's resolution to some problems
  - Some inconsistencies in Physics
- It changed our understanding of basic ideas

  Space and Time ↔ Motion

  Gravity ↔ Space

- And it changed how we think about them…

Introduction

- The Theory of Relativity
  - describes how different observers view an event
- Description depends upon your point of view
  - Depends on the ***Relative Velocity*** between the observer and the event
- By "different observers" we mean observers
  - with different Relative Velocity to the event

Introduction

- So Relativity is a theory about motion!
  - Different observers ⇔ different description
  - "Different" ⇒ different Relative Velocity
- To understand Relativity
  - we need to understand Motion
- So we need to understand Space and Time!

Relativity

- Motion: moving through Space and Time

$$\text{Velocity} = \frac{\text{Distance Traveled}}{\text{Elapsed Time}}$$

Distance Traveled $\Rightarrow$ a change in Position
$\Rightarrow$ a Space Interval
Elapsed Time $\Rightarrow$ a Time Interval

$$\text{Velocity} = \frac{\text{Space Interval}}{\text{Time Interval}}$$

Relative Velocity

- Position, Time, Velocity
  – are all measured relative to something
- We describe our Position (Location) as
  – 10 miles due east of somewhere
  – Or with Latitude, Longitude, Altitude
  – relative to the Earth's center
- The distance traveled is the Space Interval
  – between start and finish

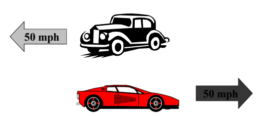
Relative Velocity

- We measure Time relative
  – to some starting reference point
  – Relative to some date: 0 AD
  – Relative to some time: Class started at 11 AM
- We measure the elapsed Time
  – from when the clock starts to when it stops
- The elapsed Time is the Time Interval
  – between start and finish

Relative Velocity

- When we say our speed is 65 mph
  – we mean 65 mph with respect to the road
- What is the relative speed between two cars?
  – One going north at 50 mph relative to the road
  – One going south at 50 mph relative to the road
- Let's see…

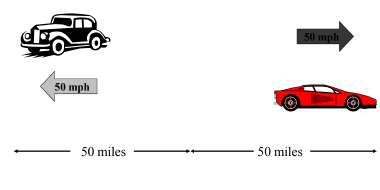
Ready, Set, Go!



Each car's speedometer reads **50 mph**

Relative to the road!

One hour later…



Relative Velocity

- So each car is moving at 50 mph
  – relative to the road
- But they are moving at 100 mph
  – relative to each other
- One hour later they will be 100 miles apart!
  – Their Relative Velocity is 100 mph!

Trick Question?

- What is your velocity right now?
  – The answer depends upon your point of view
- You are at rest, so your velocity is zero
  – with respect to the room
- Your velocity is about 67,000 mph
  – with respect to the Sun
- Which is the "right" answer?

Relative Velocity

- The "right" answer to the question…

How fast are you going?

- …is "relative to what?"
- The answer depends upon your point of view!

Absolute versus Relative

- To fully understand the Theory of Relativity
  - you ***must*** understand these two concepts!
- In Physics, we measure or calculate many quantities
  - Position, Velocity, Acceleration, Time
  - Mass, Momentum, Force
  - Kinetic Energy, Potential Energy
- Do all observers get the same result?

19

Absolute versus Relative

- If a quantity is **ABSOLUTE**
  - ***all*** observers agree on its value
  - Its measured value does ***not*** depend upon the relative velocity between observer and event
- Also called an "Invariant" quantity

20

Absolute versus Relative

- If a quantity is **RELATIVE**
  - ***all*** observers do ***not*** agree on its value
  - Its measured value does depend upon the relative velocity between observer and event
- Also called a "Variant" quantity

21

Galilean-Newtonian Relativity

- Relativity is the answer to this question:

  What is the true velocity of the Earth relative to absolute space?

- First we must answer another question:

  What is "absolute space"?

22

Frames of Reference

- Frame of Reference
  - a 3-dimensional object used to describe motion
  - A kind of map of 3-D Space
  - It is a mathematical device
    - Remember the equant, eccentric, etc…
- Motion is measured
  - relative to a particular Frame of Reference
- Usually we are at rest
  - relative to our own Frame of Reference

23

Frames of Reference

- Each Frame has a Coordinate System
  - A measuring device with numbers that is attached to the Frame of Reference
  - Defines an "origin" – where the zero point is!
- We can measure the location of any event
  - by determining its three coordinates
  - Coordinates ⇔ where it is located in Space

24

Frames of Reference

- To measure an object's motion…
  - relative to a Frame of Reference
- …we specify how its coordinates change
  - as time goes by

Motion ⇒ change in Position

Measure Motion ⇒ change in Coordinates

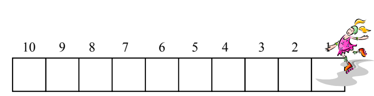
25

Frames of Reference

- Example: How fast can I cross a room?
- Reference Frame: Room
  - We measure my motion relative to the room
- Coordinate System: Floor tiles
  - We use the tiles to make the measurements
  - Origin: start of the first tile

26

Ready, Set, Go!



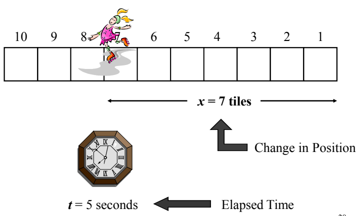
Initial Position ➡ ***x* = 0 tiles**

Let's start at the origin!

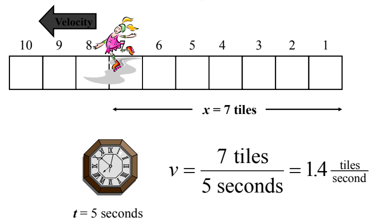
Initial Time ➡ *t* = 0 seconds

27

Five seconds later…



$$\text{Velocity} = \frac{\text{Distance Traveled}}{\text{Elapsed Time}}$$



Frames of Reference

- My Velocity is described completely
  - in terms of the Frame of Reference
- The result would be different
  - in terms of a different Frame of Reference
  - or with respect to a different observer
- Because Velocity is ***<u>RELATIVE</u>***!
  - A variant quantity

Frames of Reference

- Back to our question…
- Absolute Space
  - The Frame of Reference that is ***at rest*** relative to all other Frames of Reference
- Every observer would ***always*** agree on any
  - measurement made relative to Absolute Space

Frames of Reference

- There are two kinds of Reference Frames
- Inertial Reference Frames
  - Move at a constant velocity
  - Constant speed and direction
    - The Earth is a good ***approximation***
- Non-inertial Reference Frames
  - Move at a changing velocity
  - Also called Accelerated Reference Frames

Relativity

- The Theory of Relativity
  - Describes how observers view an event from different Frames of Reference
- By “different Frames of Reference”
  - we mean Frames of Reference with different Relative Velocities to the event

Absolute versus Relative

- An ***ABSOLUTE*** quantity
  - has the ***same*** value in ***all*** Inertial Reference Frames
    - Example: the speed of light
- A ***RELATIVE*** quantity
  - has a different value in different Inertial Reference Frames
    - Example: an object’s velocity

Relativity

- Velocity is a ***RELATIVE*** quantity
  - Your velocity relative to an event obviously depends on your velocity relative to that event
- So the value we measure depends
  - upon what we use as a reference
- Recall our two cars:
  - 50 mph relative to road, 100 mph relative to each other

Relativity

- Since Velocity is relative, then…

Momentum: mv
Kinetic Energy: $\frac{1}{2}mv^2$
Potential Energy: $E - KE$

- …are relative too. So?

Example

- Two kids are playing catch
  - in the back of a pickup truck.
- They gently toss a ball back and forth…

  They can throw a ball about 5 mph

  …while the truck drives at 100 mph.
- Do not try this experiment at home.
  - It only gets worse… ☺

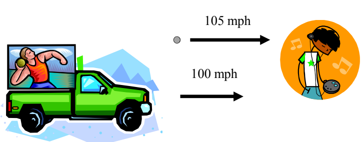
Example

- One of the kids gets carried away
  - and throws the ball out of the truck.
- This happens as the truck passes
  - a pedestrian waiting to cross the street, and the ball strikes the pedestrian in the head!
- How fast is the ball moving when it hits?

Example

- To the people in the truck,
  - the ball is moving at 5 mph.
  - Its Velocity is 5 mph ***relative to the truck***.
- To a person on the sidewalk,
  - The ball is moving at 105 mph.
  - Its Velocity is 105 mph ***relative to the sidewalk***.
  - Ouch!

Somebody call 911!!



Example

- In the truck frame of reference,
  - the ball has a ***small*** Velocity
  - and a ***small*** Kinetic Energy
- In the sidewalk frame of reference
  - the ball has a ***huge*** Velocity
  - and a ***huge*** Kinetic Energy

Facts versus Laws

- The Facts are Relative
  - Different values for Velocity, Kinetic Energy
- But the Laws are Absolute
  - Newton’s Laws valid in both frames
  - Energy is Conserved in both frames
- All observers agree: Energy was conserved
  - They just don’t agree on how much was conserved!

Galilean-Newtonian Relativity

- Galilean-Newtonian Relativity
  - Describes which quantities are Absolute
  - according to Newton’s Laws
- Including the Laws themselves
  - Newton’s Laws are Invariant
  - in all Inertial Reference Frames

Absolute Quantities in Newtonian Physics

- Length
- Time
- Mass
- Force
- Acceleration
- Laws of Mechanics

- All observers always agree on the value of these quantities
- Stationary observers

and

- Moving observers

Relative Quantities in Newtonian Physics

- Velocity
- Momentum
- Kinetic Energy
- Potential Energy
- Position

- Measured values of these quantities will be different
- For observers in different frames of reference

Galileo

- Gave the first sensible answer to our question about Absolute Motion
- He said Mechanical Experiments
  - ***cannot*** detect Absolute Motion
- There is ***no way*** to detect Absolute Motion
  - by doing a ***Mechanical*** Experiment

Galileo

- Recall our demonstration about falling balls
  - A Mechanical experiment
- Do the experiment in the lab
  - Both land at the same time (≈ ½ second)
- Do the experiment in an airplane
  - At an altitude of 7 miles above the ground
  - Moving 500 mph relative to the ground

Galileo

- I get the exact same result in the plane
  - They take the same time to land as in the lab
  - They still land simultaneously
- The results must be the same
  - otherwise I could tell from the experiment that I was moving

Principle of Relativity

- According to Galileo
  - The Laws of Mechanics are not changed by ***inertial*** motion
  - There is ***no way*** to detect inertial motion by doing a ***Mechanical*** Experiment
  - You cannot detect inertial motion unless you look out the window
    - See a different reference frame!

Principle of Relativity

- Inertial Motion ⇒ constant Velocity
- We cannot "feel" Inertial Motion
- We only feel the Accelerations
  - The changes in Velocity
    - Example: Only feel the bumps and turbulence

To review:

- Relative Velocity
  - Speed of one observer as measured by another
- The Theory of Relativity
  - Describes how different observers with different relative velocities view an event
- A theory about motion, space and time

- Reference Frame
  - A 3-dimensional object used to describe motion
  - A kind of map of 3-D Space
- Inertial Reference Frames
  - "Inertial" means constant velocity
  - Constant speed in a straight line
  - No accelerations!
- There is ***no way*** to detect inertial motion by doing a Mechanical Experiment

Absolute versus Relative

- ABSOLUTE

  Measured value does ***not*** depend on relative speed

  All observers get the same result

- RELATIVE

  Measured value does depend on the relative speed

  Different observers…

  different relative speeds with respect to the event

  …get different results

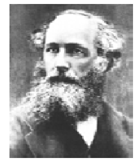
- The "Facts are Relative"
  - ***Different*** observers, ***different*** measured values
- The "Law is Absolute"
  - ***All*** observers agree that Energy is conserved.
- However, a new field of study was emerging to challenge these concepts…
  - Mid 1800's

Electromagnetism

- Galileo's Principle of Relativity
  - "Mechanical experiments" cannot detect Inertial Motion
- When Maxwell developed his theory
  - of Electromagnetism, it raised a possibility…
- Can Electrical or Magnetic experiments detect Inertial Motion?

James Clerk Maxwell (1831-1879)

- Born in Edinburgh, Scotland
- Brilliant but shy Scotsman
- Studied Math, Astronomy, Chemistry, Electricity/Magnetism
- Died at age 48 of abdominal cancer



James Clerk Maxwell

James Clerk Maxwell

- Published his first paper when 15 years old
  - Math paper on ovals
- Graduated from Trinity College (England) in 1854
  - Degree in Mathematics
  - Mostly self-taught though

James Clerk Maxwell

- Mathematically proved the rings of Saturn had to be small particles (not solid rings) in order to be in a stable orbit
  - Confirmed by Voyager I spacecraft in March 1979.
- Helped formulate
  - the Kinetic Molecular Theory

James Clerk Maxwell

- Most important work (in 1873)
  - 4 equations linking Electricity and Magnetism
    - New field called Electromagnetism (E&M or EM)
    - Called Maxwell's Equations today
    - They prove that light is an E&M wave!
  - One of the greatest mathematical achievements of 19th Century Physics!

Electromagnetism

- Maxwell's theory explains
  - both Electricity and Magnetism
    - A combined (unified) theory
      - More on this in a later chapter…
- Before Maxwell, E&M
  - were considered separate, distinct phenomena
- Maxwell showed they are related
  - Gave a unified theory of E&M

Electric Charge

- Static Electricity
  - That "shock" you get from a rug
  - Holds a balloon to a wall
- Caused by the transfer of Electric Charge
  - from one object to another
- Electric charge cannot be created or destroyed!
  - Another of those conservation laws…

Electric Charge

- Electric Charge is conserved!
- Every known process conserves charge
  - Total amount of Charge never varies
  - A violation has ***never*** been observed
- Charge cannot be created or destroyed
  - Charge can only be transferred

Electric Charge

- There are two kinds of Electric Charge
  - Named by Benjamin Franklin

Positive Charge ⊕ carried by Protons

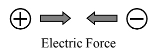
Negative Charge ⊖ carried by Electrons

- Note: Electrons are very light
  - so they are ***much*** easier to move than Protons
  - Proton mass ~ 2000 x electron mass

Electric Charge

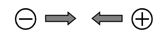
Like charges REPEL

Opposite charges ATTRACT



What holds a balloon to the wall?

- The balloon starts out "Neutral"
  - Equal amounts of Positive and Negative charge
- Rub the balloon on your hair
  - Transfers electrons from Balloon to Hair
  - Balloon is now positively charged ⊕
- Hold balloon against the wall
  - Negative charges in wall attract positive Balloon



Electric Fields

- How do Electric Charges "feel" each other?
  - A charge "here" can feel an electric force from another charge "there"
- How is the Electric Force transmitted?
- By the Electric Field
  - A property of Electric Charges
  - The Field is "associated" with a Charge

Electric Fields

- Every Electric Charge
  - creates an Electric Field which exerts
  - an Electric Force on other Electric Charges
- Every Electric Charge
  - is influenced by the Electric Field
  - created by other Electric Charges

Electric Fields

- Electric Force on a static Electric Charge

$$F = q\,E$$

Force (F) — **Electric Charge** (q) — **Electric Field** (E)

Electric Fields

- The Electric Field is a vector
- Magnitude "how much"
  - Stronger Field ⇒ larger Force
- Direction "which way"
  - Points the way a positive charge would move
  - Away from ⊕ Toward ⊖

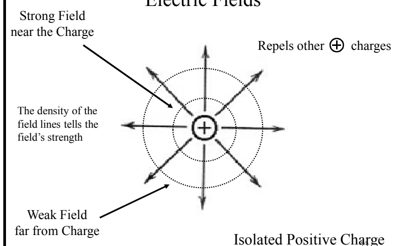
Electric Fields

- The total Electric Field
  - is the vector sum of all the Electric Fields
  - of all the Electric Charges present
- The total Electric Field depends on
  - Geometry: how the charges are arranged
  - Kinds of Charge: Positive or Negative

Electric Fields

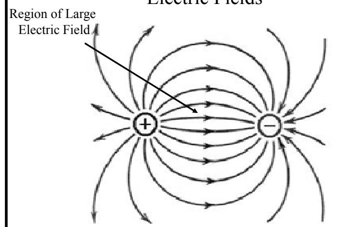
- We can draw the Electric Field
  - using Arrows
- Arrows tell us the magnitude
  - Closer together ⇒ stronger Field
- Arrows tell us the direction
  - Point the way a positive charge would move

Electric Fields



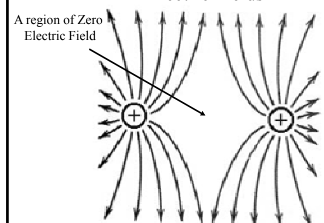
Isolated Positive Charge

Electric Fields



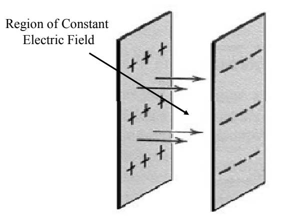
Dipole: equal ⊕ and ⊖ Charges

Electric Fields



Two equal ⊕Charges

Electric Fields



Sheets of equal ⊕ and ⊖ Charges

Electric Fields

- Electric Fields are a useful way
  - to calculate the total Forces exerted
  - by a collection of Electric Charges
- Electric Fields are a property of ***static*** Charges
  - Static ⇒ not moving
- What happens when they are moving?

Magnetic Fields

- Moving Electric Charges constitute
  - an Electric Current
- Electric Currents are measured in Amps
  - An electrical unit you may know
- Every known Magnetic effect is due to
  Electric Currents -- moving Electric Charges!

Magnetic Fields

- Electric Currents ***create*** Magnetic Fields
- Bar Magnets
  - Comprised of small individual currents
  - Electrons moving in Atoms
- Every Atom is a small Magnet
  - Permanent Bar Magnet ⇒ Atoms lined up

Magnetic Poles

- There are two kinds of Magnetic Poles
  - Magnetic version of Electric Charges

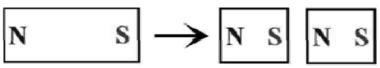
North Poles **N** South Poles S

- Note: there is an important difference
  - Magnetic Poles ***always*** come in pairs!

Magnetic Poles

No Individual N and S "monopoles"

Magnetic Poles

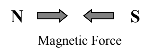


Two smaller N-S pairs

Magnetic Poles

Like Poles REPEL

Opposite Poles ATTRACT



Magnetic Fields

- Every moving Electric Charge
  - creates a Magnetic Field which exerts
  - a Magnetic Force on other moving Charges
- Every moving Electric Charge
  - is influenced by the Magnetic Field
  - created by other moving Charges

Magnetic Fields

- Magnetic Force on a moving Electric Charge

$$F = q\,v\,B$$

Force **Electric Charge** **Velocity** **Magnetic Field**

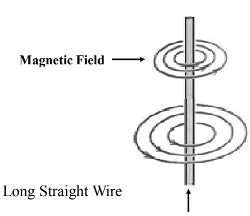
Magnetic Fields

- The Force on a moving Electric Charge
  - depends on the relative Velocity
  - between the Charge and the Magnet
- So a "moving" Magnet exerts a Force
  - on a "stationary" Electric Charge
    - And vice-versa…
- The Magnetic Force is ***RELATIVE***!

Magnetic Fields

- The Magnetic Field is a vector
- Magnitude "how much"
  - Stronger Field $\Rightarrow$ larger Force
- Direction "which way"
  - Points the way a North monopole would move
  - Away from **N**, Toward **S**

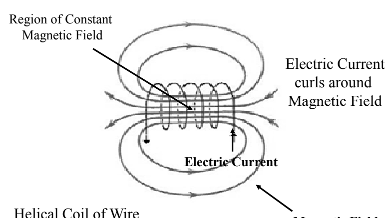
Magnetic Fields



Magnetic Field curls around Electric Current

Long Straight Wire

Magnetic Fields

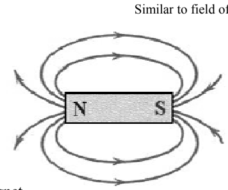


Electric Current curls around Magnetic Field

Helical Coil of Wire

Magnetic Fields

Similar to field of Helical Wire



Bar Magnet

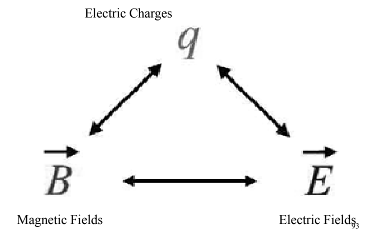
Magnetic and Electric Interactions

- Maxwell unified E&M
  - Showed Electricity and Magnetism are related
- There are relationships among
  - Electric Charges
  - Electric Fields
  - Magnetic Fields

Magnetic and Electric Interaction

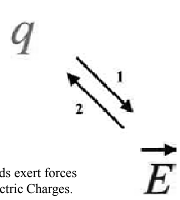
- They are all interrelated!
- Start with a stationary Electric Charge
- Apply an Electric Field
  - Exerts an Electric Force on Charge
  - So it accelerates ⇒ it moves! ***F = ma***
- Now we have a moving Electric Charge
  - which creates a Magnetic Field

Relationships among *q*, *E*, *B*



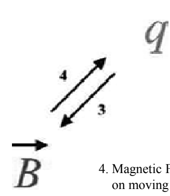
Relationships among *q*, *E*, *B*

1. Static Electric Charges create Electric Fields.



2. Electric Fields exert forces on static Electric Charges.

Relationships among *q*, *E*, *B*



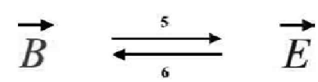
3. Moving Electric Charges create Magnetic Fields.

4. Magnetic Fields exert forces on moving Electric Charges.

Relationships among *q*, *E*, *B*

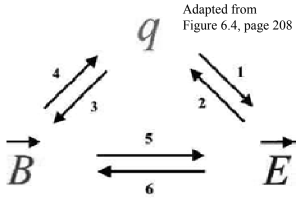
5. Changing Magnetic Fields create Electric Fields .

6. Changing Electric Fields create Magnetic Fields.



Relationships among *q*, *E*, *B*

Adapted from Figure 6.4, page 208



Relationships among *q*, *E*, *B*

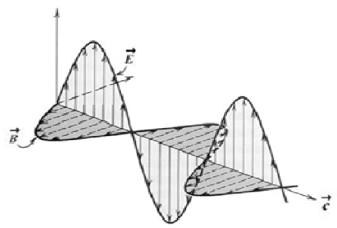
1. Electric Charges create Electric Fields
2. Electric Fields exert Electric Forces
3. Moving Charges create Magnetic Fields
4. Magnetic Fields exert Magnetic Forces
5. Changing Mag.Field creates an El.Field
6. Changing El.Field creates an Mag.Field

Light

- The final piece to our puzzle…
- In his theory of E&M, Maxwell proved
  - Light is a wave of changing E and B fields
- He even predicted the speed of light

$$c = 186{,}000\,\frac{\text{miles}}{\text{sec}}$$
$$= 670\text{ Million}\,\frac{\text{miles}}{\text{hour}}$$

Light



Light

- Light is an electromagnetic wave
  - Oscillating Electric & Magnetic Fields
  - Travels through space at the Speed of Light
- Many experiments showed
  - the wave nature of Light
- This raised a new question:
  - What is waving?

Light

- Most Waves need a medium
  - Sound waves need Air
  - Ocean waves need Water
- A Wave is a disturbance in the medium
- Light can travel through a vacuum
  - There is nothing to disturb in empty space
  - So there is nothing "waving"
  - So what is being disturbed????

Light

- So Physicists invented the "Ether"
  - Light is a disturbance in the Ether
- The Ether is ***very*** strange stuff…
  - Fills all of space
  - Massless, yet very stiff (Light is Fast!)
    - Wave velocity is proportional to medium stiffness
  - Does not affect the motion of objects
  - At rest relative to Absolute Space

Problems

- Since the Ether was "at rest"
  - Relative to Newton's Absolute Space
- Detecting the Ether offered a chance
  - to define an Absolute Frame of Reference
- Using E&M offered a chance to evade
  - Galileo's Principle of Relativity

More Problems

- According to Galileo-Newtonian relativity
  - ***All*** Forces are ***INVARIANT***
- This contradicts Maxwell!
  - Magnetic Force is ***RELATIVE***: $F = q\,v\,B$
  - Depends on Frame of Reference
  - Depends on Relative Velocity!

Velocity

More Problems

- This could be used to violate
  - Galileo's Principle of Relativity
- Measure the Force on a moving Charge
  - In two different Frames of Reference
  - The Lab (at rest relative to Earth)
  - A Car (moving relative to Earth)
- Compare results
  - Gives information on the velocity of the Earth!

Special Relativity

The situation around 1900 was this:

- No experimental evidence for the ether
  - None at all!
- Relative nature of the Magnetic Force
  - on a moving Electric Charge
  - violates Galilean-Newtonian Relativity!

The Problem

No experimental evidence for the ether!

- The experimental apparatus could detect
  - an effect 40 times smaller than the theory predicted
- Yet it detected nothing, zero, nada, zilch, zip
  - A "null result"
  - We still detect nothing even today!

Albert Michelson (1852 – 1931)

- Born in Strzelno, Poland
- Came to U.S. in 1855 at age 3

Albert Michelson

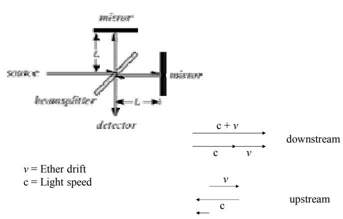
Albert Michelson (1852 – 1931)

- Graduated from U.S. Naval Academy @ 21
  - Stayed on for 4 years as a science instructor
  - Measured the speed of light so well that his value was the standard for the next 30 years!
    - Won the Nobel Prize in 1907
- Was a Professor of Physics at CWRU (1883)
  - Met Chemistry Prof Edward Morley there
- First Chair of the new Physics Dept at the University of Chicago.

Michelson-Morley Experiment

- Conducted for the 1st time in Germany
  - While serving as a Naval Attaché prior to WWI
- Repeated multiple times in Cleveland
  - Over a 25 year span
  - All with negative results
    - No ether ever detected!

Michelson-Morley Experiment



The Problem

Relative nature of the Magnetic Force

- Maxwell's successful theory of E&M…
  - Predicted the value for the Speed of Light
  - Explained all Electromagnetic phenomena
- …contradicted Galilean-Newtonian relativity
  - Which claimed all Forces are ABSOLUTE!

The Solution

- There were many scientists
  - Working on these problems
  - Some were ***very*** close to a breakthrough
- Many were ready for a new theory
  - And accepted the new one quickly
  - Even though it was revolutionary!
- But only one solved the problems…

Albert Einstein (1879-1955)

- Recently voted top
  - Physicist
  - Scientist
  - Person
    - He was a generally nice guy!
    - Unlike others we have seen…
- Of the 20th century
- Born Ulm, Germany

Albert Einstein

Albert Einstein

- Showed no particular intellectual promise
- A somewhat "typical" student
- Did very well in what interested him
  - Math and Science
- Did badly in most others
  - And dropped out of high school

Albert Einstein

- After leaving high school
  - Bummed around in Italy for a while
  - To avoid compulsory German military service
    - Renounced his German citizenship in 1896
- Entered college in 1895 in Switzerland
  - Had to cram for the entrance exam
  - Barely passed the non-science parts

Albert Einstein

- Not a particularly good college student
  - Disliked regimented style
  - Skipped classes often to read Physics
- Caused an explosion in a lab
  - He was a horrible experimentalist!
  - Good thing he became a theorist!
- Graduated only with the help of a friend
  - who shared his class notes

Albert Einstein

- Graduated in 1900
- Tried to get an academic position
  - No letters of recommendation
  - Told he'll "never amount to anything"
- Not a Swiss citizen, because he was a Jew
  - Eventually gained citizenship in 1901
- No connections ⇒ No academic job!

Albert Einstein

- Accepted a job in 1901
  - Junior official at the Swiss Patent Office for 8 years
- Worked on Physics in his spare time
  - Kept a notebook in his desk drawer
- No academic connections
  - Just him and his wonderful brain
  - Performing "thought experiments"

Thought Experiments

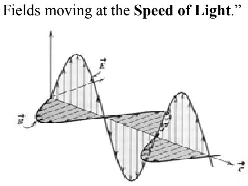
- The Physics version of "what if…"
- Imagine a physical situation
  - Apply the laws of physics
  - In a logical and consistent manner
  - Analyze what happens
- Special Relativity was the result
  - Of such thought experiments

Albert Einstein

- Sometime during his "drop out" year
  - When he was only 16
- Einstein first asked himself this:
  "What would happen if I was moving at the speed of light."
- Later in college he changed it slightly:
  "What would a light ray look like to an observer moving at the speed of light?"

Light

- Recall what Maxwell said about Light
  "A wave of changing **Electric** and **Magnetic** Fields moving at the **Speed of Light**."



Light

- This is called a "traveling wave"
  - A wave that travels from one place to another
- Consider a simple analogy
  - A wave moving down a taut rope
- Snap one end of the rope
  - A single wave travels along the rope

Light

- A "stationary" observer
  - Sees a moving wave
- An observer moving with the wave
  - In the same direction with the same speed
  - Sees the wave just standing there
- This is called a "standing wave"

127

Light

- So, to our moving observer
  - moving at the Speed of Light
- The Light wave would be
  "A standing wave of changing **Electric** and **Magnetic** Fields"
- But Standing Waves are ***NOT*** allowed
  - in Maxwell's E&M theory!

128

Maxwell and the Speed of Light

In Theory (believed by most to be correct),

- The only speed allowed for Light
  - is ***the*** Speed of Light: $c = 186{,}000\,\frac{\text{miles}}{\text{sec}}$
- There is no allowance for the Speed of Light
  - Relative to an inertial observer
  - It was an Absolute quantity!
- And Einstein noticed another problem…
  - While riding on the train to work

129

More Problems: The Speed of Light

- Measure the Speed of Light

On a moving Train	$c + v$
Subtract Maxwell's value	$-c$
Determine Inertial motion	v

- Violates Galilean relativity
  - Detect motion without looking outside

130

The Solution

- The Special Theory of Relativity
  - Published in 1905 by Einstein
- A big part of his "miracle year"
  - Published 5 papers and got his Ph.D. in 1905
    - Received the Nobel Prize in 1921
- Only two such years in history of Physics
  - Newton's year in 1666
  - Einstein's year in 1905

131

Albert Einstein

- All five were landmark papers
- One on the Photoelectric Effect:
  - quantum theory of light
  - Nobel Prize material
- Two on Brownian Motion
  - proved the existence of molecules
- Two on Special Relativity
  - Our current topic

132

The Two Postulates

- Einstein resolved all these problems
- By making two postulates
  - A Postulate is an ***assumption***
- He knew that if the postulates were right
  - then all the problems are solved

133

The Two Postulates

- His was a theoretical explanation
  - "On the Electrodynamics of Moving Bodies"
- Both postulates have since been confirmed
  - experimentally and conceptually
- Einstein simply recognized
  - "the way it should be and must be"
  - Knew they were correct even without an experiment!

134

The First Postulate

1. "The Laws of Physics are ***INVARIANT*** in all ***inertial*** reference frames."

- The Laws of Physics are ***ABSOLUTE***.

This postulate is not difficult to accept!

135

The First Postulate

- This is an upgrade of Galileo's statement

  Laws of Mechanics → Laws of Physics

- Now there is ***no way*** to determine Inertial Motion without looking outside
  - Not just no mechanical experiment
  - But no experiment at all!

The First Postulate

- Since the Laws of Physics are ***ABSOLUTE***
- We can not determine Absolute Motion
  - by any experiment
- All Inertial Reference Frames
  - are ***equally*** valid
- So ***all*** Forces are ***RELATIVE***!

The Second Postulate

2. "The Speed of Light is ***INVARIANT*** in all ***inertial*** reference frames."

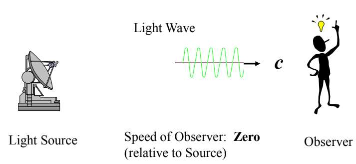
- The Speed of Light is ***ABSOLUTE***.

This one gets a little strange if you really think about it, which we will…

The Second Postulate

- Eliminates all the Speed of Light loopholes
  - which violated the Principle of Relativity
- But this is new and different!
  - The Speed of Light is ***ABSOLUTE***
- The Speed of Light is independent
  - of the motion of the observer

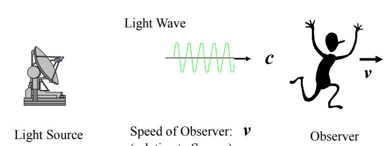
The Second Postulate



Speed of Observer: **Zero**
(relative to Source)

Speed of Light: ***c***
(measured by Observer)

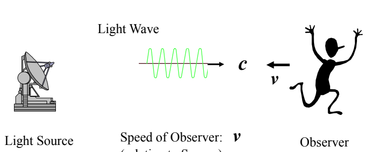
The Second Postulate



Speed of Observer: ***v***
(relative to Source)

Speed of Light: ***c***
(measured by Observer)

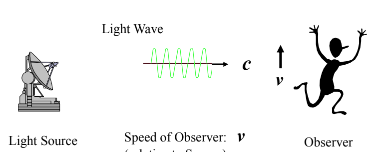
The Second Postulate



Speed of Observer: ***v***
(relative to Source)

Speed of Light: ***c***
(measured by Observer)

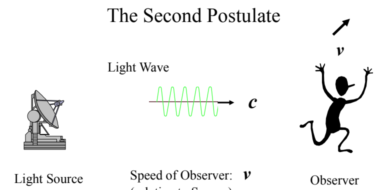
The Second Postulate



Speed of Observer: ***v***
(relative to Source)

Speed of Light: ***c***
(measured by Observer)

The Second Postulate

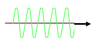


Speed of Observer: ***v***
(relative to Source)

Speed of Light: ***c***
(measured by Observer)

The Second Postulate

Light Wave



c

Light Source

Speed of Observer: **any** (relative to Source)

Speed of Light: c (measured by Observer)

Observer

“Moving in any direction at any constant speed”

The Second Postulate

- No matter what the relative speed…
  - between the Light Source and the Observer
- …the observer always measures the same value for the Speed of Light: $c = 186{,}000 \frac{\text{miles}}{\text{sec}}$
- The Speed of Light is ***ABSOLUTE***!!!
- This has been experimentally proven true
  - many, many times

The Second Postulate

- Explains the failure of all attempts to detect the Ether
  - Used variations in the Speed of Light
  - Due to the motion of the Earth
- If the Speed of Light is ***ABSOLUTE***
  - there is no way to detect the Ether
  - It is a useless concept in Physics
  - Its existence cannot be determined! ☑

Special Relativity

- With pure genius, Einstein had “fixed” it!
  - He concluded the Ether concept was garbage
    - Completely unnecessary!
- But there are other consequences
  - of his revolutionary new postulates
- The rest of the theory…
  - and this chapter
- …are about those consequences!

To review:

- Trouble with Light
  - No experimental evidence for Ether
  - Speed-of-Light “standing wave” not allowed
  - Measure Speed of Light while moving
    - Detect Inertial Motion
    - Violates Principle of Galilean-Newtonian Relativity
- Relative nature of Magnetic Force
  - Violates Principle of Relativity
  - Contradicts Newton

- The Solution: Einstein’s 2 Postulates
- Laws of Physics are ***INVARIANT***
  - There is ***no way*** to detect inertial motion by doing ***any*** experiment
- Speed of Light is ***INVARIANT***
  - All inertial observers measure the Speed of Light to be $c = 186{,}000 \frac{\text{miles}}{\text{sec}}$
  - This value is independent of the relative speed between the Observer and the Light Source

Special Relativity

- Einstein’s Two Postulates
  - had many surprising consequences
  - Redefined the meaning of some basic concepts
- We’ll need new concepts of Space and Time
  - The Space interval between two events
  - The Time interval between two events

Special Relativity

- The “Special” in Special Relativity
  - Refers to the fact that it refers only to ***Inertial Reference Frames***
- Special Relativity applies to
  - motion at constant velocity only!
  - No Accelerations!

Four Consequences

- Four consequences of the Postulates
  1. Space and Time Intervals
  2. The Addition of Velocities
  3. Inertia
  4. Energy
- Plus a bonus story…
- Now, things get tricky…

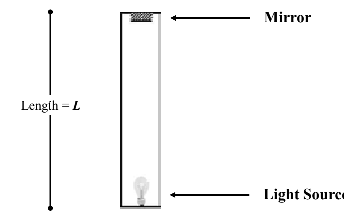
1. Space and Time

- Space and Time are abstract concepts
  - We need a simple definition.
- Einstein's definitions:
  - Space is what a meter stick measures.
  - Time is what a clock measures.
- These practical definitions are
  - based on physical measurements and
  - the Light that carries the information

A Light Clock

- Let's start with the Time Interval
  - between two events as seen in two different Inertial Reference Frames
- Our two events: "Tick" and "tock"!
- We'll use a Light Clock
  - measure the Time Interval between two events
  - using the Speed of Light

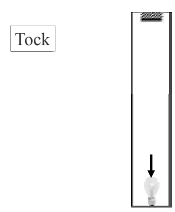
A Light Clock



A Light Clock

- Light source emits one flash of Light
- The Light reflects off the mirror
  - That's a "Tick"
- Then Light returns to the source
  - That's a "Tock"

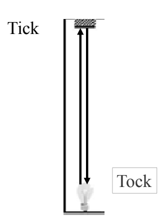
A Light Clock



The Clock Frame

- First we'll look at the Time Interval…
  - Between "Tick" and "Tock"
- …in the ***Clock Frame***:
- The Inertial Reference Frame
  - that is at rest relative to the clock.
- We and the Clock are in the same Frame
  - No relative velocity between us!

The Clock Frame



The Clock Frame

- In the Clock Frame
- The Clock is at the same place
  - when the "Tick" and "Tock" happen
- This Time Interval is called the Proper Time
  - The Time Interval measured in the reference frame where the Clock is in the same place

Space and Time

- Basic Physics review for Inertial Motion
  - Motion at constant velocity

$$\text{Time} = \frac{\text{Distance}}{\text{Speed}}$$

- Drive 100 miles at 50 miles per hour…
  - The trip takes 2 hours

The Clock Frame

- For our Light Clock
  - in the Clock Frame
- The Distance traveled is twice the Length
  - Back and forth
- The Speed is the Speed of Light
  - Light is doing the traveling

The Clock Frame

Time Interval (In the Clock Frame)

Total distance traveled

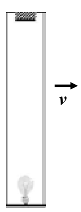
$$\Delta t_0 = \frac{2L}{c}$$

Speed of Light

The Lab Frame

- Now we'll look at the Time Interval
  - between the same two events
- …in the ***Lab Frame***:
- The Inertial Reference Frame
  - in which the clock is moving.
- We are sitting in the Lab
  - The Clock has velocity ***v*** relative us!

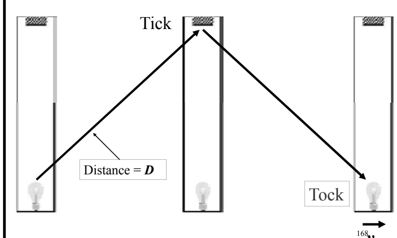
The Lab Frame



The Lab Frame

- When the Light hits the mirror
  - the Clock has moved to a different place
- The Light follows a different path
  - than it does in the Clock Frame
- In the Lab Frame
  - the Light has a longer path to travel

The Lab Frame



The Lab Frame

- In the Lab Frame
- The Clock is ***not*** at the same place
  - when "tick" and "tock" happen
- During the Time between the two events
  - the Clock has moved

Space and Time

- Now recall the 2nd Postulate
  - The Speed of Light is ABSOLUTE
- The Light's speed between "Tick" and "Tock"
  - is the same in both Frames
- That's what ABSOLUTE means!
  - Same value in ALL Inertial Reference Frames

The Lab Frame

Time Interval (In the Lab Frame)

Total distance traveled

$$\Delta t = \frac{2D}{c}$$

The Speed of Light

Space and Time

- In the Lab Frame
  - the Light travels a longer distance: $D > L$
  - at the ***same*** speed: ***c***
- Time Interval is ***Longer*** in the Lab Frame
  - Longer distance at the same speed!
    - The clock is running ***slower*** in the Lab!
- This is a direct result of the 2nd Postulate!
  - The Speed of Light is ABSOLUTE!

Time Dilation

- This is called Time Dilation
  - Dilate means "to become larger"
- The Time Interval in the Lab Frame…
  - between the same two events
  - The same "Tick" and "Tock"
- …is ***larger*** than that in the Clock Frame!

Moving Clocks Run Slow!

- This has nothing to do with our Clock
  - It is after all a rather strange clock
- This is a property of TIME
  - Not a property of Clocks
- The Clock just measures TIME

Time Dilation

- This applies to biological clocks too!
  - Such as reproducing bacteria
- Humans have many built-in clocks
  - Daily, monthly, yearly cycles
  - The aging process
- Time Intervals are ***RELATIVE***!

Time Dilation

The ***faster*** you move through Space,

the ***slower*** you move through Time!

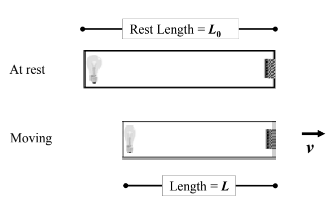
Space and Time

- Now let's look at the Space Interval
  - between two events as seen in two different Inertial Reference Frames
- Same two events: "Tick" and "Tock"!
- We'll still use the Light Clock
  - Measure the Space Interval between two events
  - Using the Speed of Light

Space and Time

- Now we'll lay our Light Clock on its side
- So it is moving in the direction
  - that is parallel to its Length
  - Before it was moving perpendicularly
- The analysis is similar to the Time Interval
  - We'll skip the details… ☺

A Light Clock



Length Contraction

- This is called Length Contraction
  - Contract means "to reduce in size"
- The Space Interval
  - between the same two events
  - The same "Tick" and "Tock"
- …is ***shorter*** for the moving Clock

Length Contraction

- If the object is a meter stick
  - its Rest Length is 1 meter
- Moving at 60% of the Speed of Light
  - its velocity is $v = (3/5)c$
- We would measure its Length to be $^4/_5$ meter
  - Only 80% of its Rest Length!

Moving Objects Are Shorter!

- They are shorter
  - ***along*** the direction of the motion
  - so their height is not affected at all!
- This is a property of SPACE
  - Not a property of objects
- The object just occupies the SPACE
- Space Intervals are ***RELATIVE***!

Length Contraction

The ***faster*** you move through Space,

the ***less*** Space you occupy!

(along the direction of motion only)

Space and Time

- Both of these effects are a direct result
  - of the 2nd Postulate
- Remember what "speed" means

$$\text{Speed of Light} = \frac{\text{Distance Traveled by Light}}{\text{Elapsed Time}} = \frac{\text{Space Interval}}{\text{Time Interval}}$$

Space and Time

- Both intervals change so that their ratio
  - The Speed of Light
- Remains INVARIANT
- Space and Time are interrelated
  - Both are part of one entity called Space-Time
- We live in a 4-dimensional Universe!
  - 3-D Space + 1-D Time = 4-D Space-Time

Space and Time

- The concepts of Space and Time…
  - Space interval between two events
  - Time interval between two events
- …are no longer separate!
  - Space-Time interval between two events

Space-Time

- Einstein showed the Space-Time Interval
  - between two events
- Is INVARIANT!
  - All observers agree on the Space-Time Interval Between two events
- This too is a direct result of the 2nd Postulate
  - The Speed of Light is ABSOLUTE

Space-Time

Space-Time Interval

$$\Delta s = \sqrt{c^2 T^2 - L^2}$$

The Speed of Light

Time Interval

Space Interval

2. Addition of Velocities

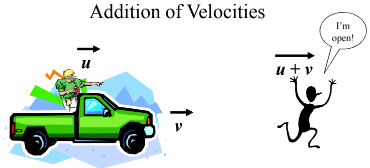
- How does the speed of an object…
  - in one Inertial Frame of Reference
- …transform into another Inertial Frame?
- By the Addition of Velocities
  - Remember the kids playing catch in the truck?
- Let's assume this time that you (a pedestrian) are playing catch with someone in the back of the truck.

Addition of Velocities

- According to Isaac Newton
  - If ***u*** is the speed of the ball relative to the truck
  - If ***v*** is the speed of the truck relative to you
- Then the speed of the ball relative to you is

$$u + v$$

Addition of Velocities



v is the speed of the truck relative to you

u is the speed of the ball relative to the truck

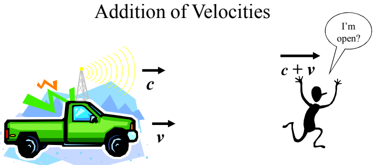
u* + *v is the speed of the ball relative to you

Addition of Velocities

- Now suppose we replace our thrower
  - with a Light Source
- According to Newton
  - If ***v*** is the speed of the truck relative to you
  - If ***c*** is the Speed of the light relative to the truck
- Then the speed of light relative to you is

$$c + v$$

Addition of Velocities



v is the speed of the truck relative to you

c is the speed of light relative to the truck

c* + *v is the speed of light relative to you

Addition of Velocities

- This violates the 2nd Postulate!!
  - You get a different result when you measure the Speed of Light
- Suppose the truck is very fast
  - Very, very fast
  - Its speed is ½ ***c***: half the speed of Light
- Then you measure $^3/_2$ ***c*** as Light Speed
  - Bigger than "***c***"

Addition of Velocities

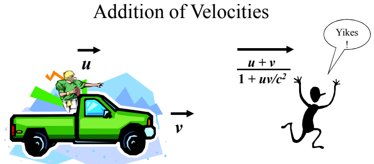
- Space and Time are RELATIVE
- We need a rule for adding velocities that
  - includes the different rate of Time and the different size of Space for the two different Reference Frames
- Einstein provides us with such a rule
  - Of course… It's his theory, it's his solution!

Addition of Velocities

- According to Einstein
  - If ***u*** is the speed of the ball relative to the truck
  - If ***v*** is the speed of the truck relative to you
- Then the speed of the ball relative to you is

$$\frac{u + v}{1 + \frac{uv}{c^2}}$$

Addition of Velocities



v is the speed of the truck relative to you

u is the speed of the ball relative to the truck

$\frac{u + v}{1 + uv/c^2}$ is the speed of the ball relative to you

Addition of Velocities

- Why don't we notice this different rule?
- There is an extra term in Einstein's rule: $\frac{uv}{c^2}$
  - It is very small at everyday speeds
- The "c^2" is a huge number: $\approx 10^{17}$ m²/s²

$$1 + \frac{uv}{c^2} = 1 + \text{a tiny number}$$

Addition of Velocities

u	***v***	Newton	Einstein
60 mph	30 mph	90 mph	90 mph
186 mps	18.6 mps	204.6 mps	204.59998 mps
0.6***c***	0.3***c***	0.9***c***	0.763***c***
0.5***c***	0.5***c***	***c***	0.800***c***
0.75***c***	0.75***c***	1.5***c***	0.960***c***
0.9***c***	0.6***c***	1.5***c***	0.974***c***
c	0.5***c***	1.5***c***	***c***
c	***c***	2***c***	***c***

Addition of Velocities

- The effects of Special Relativity
  - are noticeable ***only*** at very high speeds
- Even at 186 miles per second ($^{1}/_{1000}$ ***c***)
  - Newton and Einstein are very close
- The human speed record: $^{1}/_{27000}$ ***c***
  - The Apollo astronauts returning from the moon
    - 6.89 miles/sec = 24,800 mph
- There seems to be an upper limit on speed…
  - A "cosmic speed limit"

Addition of Velocities

- So what about our moving Light source?
- According to Einstein:

$$\frac{u+v}{1+\frac{uv}{c^2}} = \frac{c+\frac{1}{2}c}{1+\frac{(c)\left(\frac{1}{2}c\right)}{c^2}} = \frac{\frac{3}{2}c}{\frac{3}{2}} = c$$

- The 2nd Postulate holds!

Addition of Velocities

- Even if the truck is moving at Light Speed
- According to Einstein:

$$\frac{u+v}{1+\frac{uv}{c^2}} = \frac{c+c}{1+\frac{(c)(c)}{c^2}} = \frac{2c}{2} = c$$

- The 2nd Postulate still holds!

3. Newton's Laws and Inertia

- The Speed of Light is a natural speed limit
  - No object's speed can ever exceed
  - or ***even*** equal the Speed of Light
- It is a consequence of the 2nd Postulate
- But there is ***no*** speed limit in Newton's Laws

Newton's Laws

- Recall Newton's 2nd Law

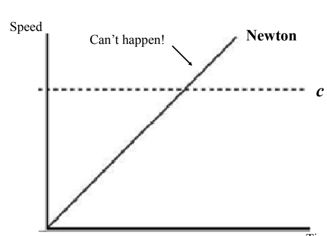
$$F = ma \quad \Leftrightarrow \quad a = \frac{F}{m}$$

- Relates cause and effect
  - Cause: Force
  - Effect: Acceleration (changes in motion)

Newton's Laws

- Apply a constant Force
  - produce a constant Acceleration
- According to Newton…
- If you push long and hard enough
  - your speed will exceed the Speed of Light
- For an acceleration of one "g" (9.80 m/s^2)
  - it takes about a year to get to Light Speed

Newton's Laws



Newton's Laws

- This is ***not*** allowed in Special Relativity
- But even Einstein can't change
  - how hard you can push
  - or how long you can push
- So how can he limit the speed of the object?
  - Where does the cosmic speed limit come from?
- So what does happen??

Newton's Laws

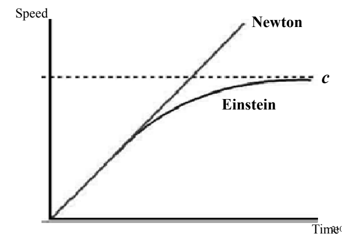
- According to Einstein
  - Acceleration is RELATIVE
    - it's based on a change in velocity after all
- As the speed increases
  - the acceleration must decrease
  - So the Object's Inertia must increase
    - Inertia is an opposition to a change in motion
- Inertia is the object's resistance
  - to Changes in its motion
  - and is determined by its Mass

Newton's Laws

- Mass is RELATIVE!
- As the object's speed increases
  - so does its Mass
- So for the same amount of Force $a = \frac{F}{m}$
  - there is less Acceleration

Moving objects have more Mass!

Newton's Laws



Newton's Laws

- The faster the object is moving
  - the more Mass it has
- The increase in Mass
  - produces smaller and smaller Accelerations
  - The speed is always less than Speed of Light
- Mass is RELATIVE

4. Energy

- Under Newton's Laws
  - the Kinetic Energy is $\frac{1}{2}mv^2$
  - Mass is ABSOLUTE
- Einstein showed that Mass is RELATIVE
  - More velocity $\Rightarrow$ more Mass
  - Even more Kinetic Energy

Energy

- Einstein also showed that

$$E = mc^2$$

- ***Mass is a form of Energy***
  - All Mass is equivalent to Energy
- This is a conversion formula
  - Mass $\leftrightarrow$ Energy

Energy

- One big difference between…
  - Newton and Einstein
- According to Newton
  - an object at rest has no Energy
- According to Einstein
  - even at rest, an object has Energy
- A ***LOT*** of Energy…

Energy

Speed of Light squared

$$E_0 = m_0 c^2$$

Rest Energy

Rest Mass

Energy

- The "c^2" is a huge number: $\approx 10^{17}$ m²/s²
- So a small amount of Mass
  - can be converted to a ***huge*** amount of Energy
- One kilogram of Mass (about 2.2 pounds)
  - completely converted to Energy
  - would run the entire U.S. for 9 hours

Energy

- Unfortunately (The Big IF!)
  - there is only one way known
  - to completely convert Mass to Energy
- Combining Matter and Antimatter
  - Just like on Star Trek
  - Not yet feasible technologically or economically
  - Antimatter is expensive to make, hard to handle

The Relativistic Factor: γ

- All of these new relativistic effects
  - are extremely small for everyday velocities
- There is a way to calculate how small
  - The Relativistic Factor: γ (gamma)

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The Relativistic Factor: γ

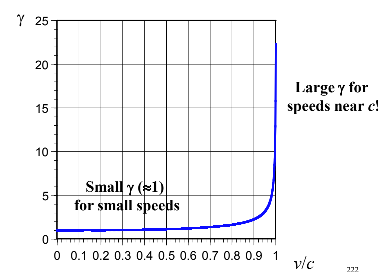
- The bigger the Relativistic Factor
  - the more important Relativity is
- For speeds small compared to Light Speed
  - we have **$\gamma \approx 1$**
- For speeds large compared to Light Speed
  - we have larger and larger **γ**

The Relativistic Factor: γ

- At a speed of $^1/_{10}$ ***c***, we have $\gamma = 1.005$
  - about 67 million miles per hour
- The predictions of Newton and Einstein
  - are only different by ½ percent
  - About 1 part in 200
- So if Newton says the answer is 200
  - Einstein says it is 201

The Relativistic Factor: γ

- At the human speed record: $^1/_{27000}$ ***c***
  - about 25000 miles per hour = 0.000037*c*
  - $\gamma = 1.0000000007$
- The predictions of Newton and Einstein
  - are different by only 1 part in a Billion!
  - Too small to notice without experimentation
- Can be measured with atomic clocks though



The Tale of the Traveling Twin

- Let's do our own thought experiment…
- Suppose we have two twin astronauts
  - Each is 30 years old at the start of the trip
  - One travels to a some star and returns
  - The other stays on the Earth
- When they are reunited
  - which twin is older?

The Tale of the Traveling Twin

- Let Twin A be the Space Traveler
  - So Reference Frame A is her point of view
- Then Twin B is the Mission Controller
  - Reference Frame B is the Earth's point of view
- Let's see what Special Relativity has to say

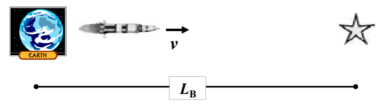
The Tale of the Traveling Twin

- Let's go to the star Vega
  - Distance: 25 light years (in Frame B)
- Let's travel at a speed of ***v*** = 0.999***c***
  - 99.9% of the Speed of Light
- At this speed we have
  - Relativistic Factor: $\gamma = 22$
- We expect Relativity to be important here

A Light Year

- A Light Year
  - The distance Light travels in one year
  - It is a unit of ***Distance***, not Time!
- Approximately 6 trillion miles
  - Or 6 million million miles
- So it takes the Light from Vega
  - 25 years to reach us here on Earth

Frame of Reference B



$$t_B = \frac{2L_B}{v}$$

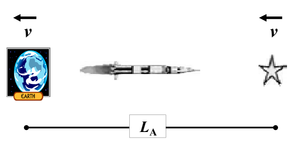
Frame of Reference B

- As measured by clocks on Earth
- This trip takes a time of

$$t_B = \frac{2L_B}{v} = 50\,\text{years}, \tfrac{1}{2}\,\text{month}$$

- Twin B is 50 years, ½ month older
  - So he is 80 years, ½ month old!

Frame of Reference A



$$t_A = \frac{2L_A}{v}$$

Frame of Reference A

- As measured by clocks on the Ship
- This trip takes a time of

$$t_A = \frac{2L_A}{v} = 2\,\text{years}, 3\,\text{months}$$

- Twin A is 2 years, 3 months older
  - So she is 32 years, 3 months old!

The Tale of the Traveling Twin

- Twin A sees Earth and Vega moving
  - so the distance between them is contracted
  - In her Frame of Reference
- They are closer in her frame: $L_A < L_B$
- So the trip takes less time in her frame
  - Same relative speed, shorter distance

The Tale of the Traveling Twin

- By traveling at a very fast speed
  - very near the Speed of Light
- Traveler A slowed her rate of time
- Moving fast through Space
  - Moving Slowly through Time

The Tale of the Traveling Twin

- This effect is sometimes called
  - The Twin Paradox
  - Paradox: "something that seems to contradict or oppose common sense"
- Why?

The Tale of the Traveling Twin

- Twin B sees Twin A move off and return
  - So Twin A's clocks run slowly
  - Twin A ends up younger
- Twin A sees Twin B move off and return
  - So Twin B's clocks run slowly
  - Twin B ends up younger
- Is each point of view is equally valid?

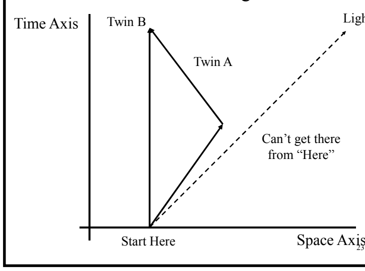
The Tale of the Traveling Twin

- No!
- Special Relativity says
  - All ***Inertial Reference Frames*** are equally valid
- Twin A uses two Inertial Frames
  - One "out" and one coming back
  - She turns around
  - ***So there were Forces and Accelerations***
    - No longer inertial reference frames!!

Minkowski Diagrams

- Also called "Space-Time Diagrams"
- A graph of Time versus Distance
  - Time is plotted on the vertical axis
  - Space is plotted in the horizontal axis
- Let's look at our two Twins

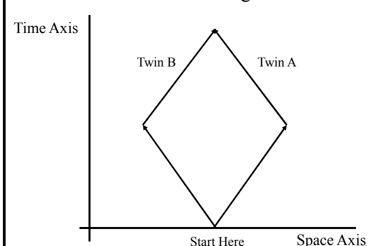
Minkowski Diagrams



Minkowski Diagrams

- Twin B stays at the same place
  - Only "moves" through Time
- Twin A changes location in Space
  - And also "moves" through Time
  - We see that see used two Inertial Frames!
- She will be younger!
- Let's look at some different trips…

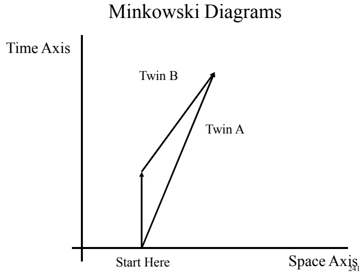
Minkowski Diagrams



Minkowski Diagrams

- Both leave at the same time
- Travel in opposite directions
- They both stop at the same Time
- Where they turn around and return home
- Both will be at the same age upon return

Minkowski Diagrams



Minkowski Diagrams

- Twin A leaves first
- Twin B stays home for a while, leaves later
- Travels faster and catches up to Twin A
- Meet at the same place at the same Time
- Twin B will be younger
  - Can prove this after much much math!

Summary of Special Relativity

- Moving Clocks run slower
  - Time Dilation
- Moving Objects are Shorter
  - Length Contraction
- Space, Time, and Mass are RELATIVE
  - Space-Time is ABSOLUTE

Beyond the Special Theory of Relativity

- The Special Theory of Relativity only covers the “special” case
  - of inertial reference frames
    - non-accelerated reference frames
- It gives the correct equations for transformations
  - between two reference frames moving at constant velocities with respect to each other

Beyond the Special Theory of Relativity

- Einstein wanted equations which were much more general than these special ones
  - so he devised a “general” theory to cover ***all*** reference frames, inertial ***and*** non-inertial.
- This theory is called the General Theory of Relativity and is ***MUCH*** more difficult mathematically.
  - Took 10 years of work to develop this new theory (published in 1916).

The General Theory of Relativity

- Called GenRel for short
- He started with an observation that both Newton’s 2nd Law and his Universal Gravitation Law both contained the same quantity – the object’s mass
  - ***Inertial mass*** in the former $F = m a$
  - ***Gravitational mass*** in the latter $F = G\frac{m_1 m_2}{r^2}$

The General Theory of Relativity

- Since these were two ***separate laws***, the masses did not necessarily need to be the same
- Precision experiments were carried out which ***proved*** the two masses were in fact the same
  - Einstein thought that this was ***not*** coincidental and that the acceleration in the 2nd law was related to the gravitational acceleration in the gravitational law.

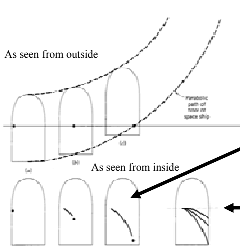
The General Theory of Relativity

- Proposed his Equivalence Postulate
  - It is impossible to distinguish a ***gravitational force*** from an equivalent ***acceleration induced force***
  - If you were standing in a space ship moving with an acceleration of g, then you would feel the same force as if you were standing on the Earth’s surface
    - You couldn’t tell the difference!

The General Theory of Relativity

- A force is being ***simulated*** by an acceleration
- Any effect which could be described by an accelerated reference frame
  - could also be described as a gravitational effect

The General Theory of Relativity



Gravity is being ***simulated*** by the spaceship’s acceleration

Path of a ball thrown horizontally on the Earth’s surface!

For different horizontal speeds

The General Theory of Relativity

- In an accelerated reference frame, even a beam of light would be bent
- This led Einstein to conclude that a gravitational field would alter (bend) the path of a beam of light!

The General Theory of Relativity

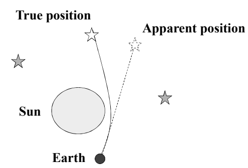
- Einstein interpreted the bending of the light as representing a ***curvature of space*** itself
  - Since the motion of the ship occurs in curved space, gravity was just an effect induced by moving through this curved space.
- Large concentrations of mass (stars, planets) curve the space around them
  - Any motion through this space causes an acceleration due to the curvature which we feel as gravity
    - Just as you “feel” a force pushing you outward as you round a curve in your car

The General Theory of Relativity

- The General Theory is much more than this; I’ve just scratched the surface
- The General Theory has been tested many times and has always been found correct!

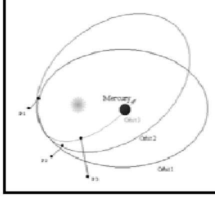
The General Theory of Relativity

- A star’s light is bent around the Sun as seen during an eclipse (in 1919).



The General Theory of Relativity

- The precession of the planet Mercury’s orbit can only be completely explained by the General Theory.



The gravitational pull of the other eight planets can only account for 93% of the precession.

The relativistic effect of the Sun curving the space near Mercury exactly accounts for the remaining 7%!

The General Theory of Relativity

- General Relativity says that the properties of space
  - are dependent on gravitational forces and the presence of matter
- It also says the properties of space-time are determined by light rays
  - Electromagnetic waves

The General Theory of Relativity

- Einstein believed these effects were related
- He spent the rest of his life trying to “unify” them into one overall theory
- The effort continues today to discover this single ***unified-field theory***
  - More on this in Chapter 9

Albert Einstein

12/31/1999