"Examinations are formidable even to the best prepared, for the greatest fool may ask more than the wisest man can answer."

Charles Caleb Colton, English writer (1780-1832)

"The examination system, and the fact that instruction is treated mainly as a training for a livelihood, leads the young to regard knowledge from a purely utilitarian point of view as the road to money, not as the gateway to wisdom."

Bertrand Russell, Welsh mathematician and philosopher (1872-1970)

"I was thrown out of college for cheating on the metaphysics exam; I looked into the soul of the boy sitting next to me."

Woody Allen, American actor & director (1935-)

Current Assignments ...

For the few next weeks:

- Prepare for the final exam!

Writing Assignment #2

- Due 11:00 AM, Thursday, April 4
- Final late-penalty deadline: 11:00 AM, April 11
- Will be marked available to pick up from your TA after April 22

Homework #5

- Due 11:00 AM, Friday, April 5
- Final late-penalty deadline: 11:00 AM, April 12
- Will be marked and available to pick up from your TA after April 15

My office hours:

- 3-4 Tuesdays & Thursdays, but NOT April 9

UNIVERSITY OF TORONTO

Course evaluations for Arts & Science students are now open. Please complete your evaluations – your feedback matters only if you provide it!

See: uoft.me/courseevaluations for more information.

Course Evaluation Window: March 24th – April 9th

PHY100 Marking Scheme

10%	Tutorial Attendance & Quizzes (best 10 of 11)
20%	Homework Assignments
10%	Writing Assignment 1
20%	Writing Assignment 2
40%	Final Exam

Note 1: Please check your grades on Blackboard before the exam and email me and your TA if you find any errors.

Note 2: If you missed a deadline for a valid documented reason, make sure that you have informed me and your TA, and that I have a paper copy of the document, along with details of the assignment or deadline missed.

PHY100 Final Exam

9:00 AM - 12:00 PM, Thursday, April 25

Location: BN2S

Large Gymnasium, South End, Benson Building, 320 Huron Street (south of Harbord Street), Second Floor

General Comments

- No examination aids are allowed.
  - → No calculators, no aid sheets.
- You should have no communication device (phone, pager, etc.) within your reach or field of vision during the test.
- Be ready to think; get a good night's sleep the night before.

Bring:

- Your student card.
- Pencils and/or pens and an eraser.

Exam Format

- 10 short answer questions worth 8 marks each
  - → Each question has two parts, (a) and (b).
  - → Similar to textbook end-of-chapter review questions and conceptual exercises.
  - → For each, provide a short answer. It need not be more than a few words and numbers, or a few sentences, but should explain your reasoning.
  - → Marks will be given for your explanations as well as for final answers.
- Two essay questions worth 10 marks each
  - → For each, write a 2 or 3 paragraph (one-page single-spaced maximum for each) essay.

12 questions in 180 minutes = 15 minutes/question

Material Covered

- All material from Lectures 1 through 24
- This includes
  - → Lecture notes - slides, blackboard, demos, websites included in slides (only as aids)
  - → All assigned sections from the textbook, whether they were discussed in class or not
  - → Supplementary "Notes on Chaos"
- The test does NOT include
  - → "Additional links that may be of interest" listed on the websites for each lecture
  - → Textbook sections not listed in the syllabus

Suggestions for Studying

Review the following:

- All the material from the lectures, particularly the slides and blackboard notes
- All assigned textbook sections & Chaos Notes
- All the homework problems
- All the suggested conceptual exercises
- All problems discussed in the tutorials
- Relevant end-of-chapter review questions

Syllabus - Assigned Readings

Lecture 1	§ 1.1, 1.6, 1.8, 3.1, 3.2	Lecture 13	§ 10.1 - 10.4
Lecture 2	§ 3.2 - 3.6	Lecture 14	§ 10.4 - 10.5
Lecture 3	§ 4.1 - 4.3	Lecture 15	§ 10.6 - 10.7
Lecture 4	§ 4.4, 4.5, 5.1	Lecture 16	§ 10.8
Lecture 5	§ 5.2, 5.5, 5.6, 2.6	Lecture 17	§ 11.1 - 11.2
Lecture 6	Chaos Notes	Lecture 18	§ 11.2 - 11.7
Lecture 7	§ 6.1 - 6.6	Lecture 19	Chapter 12
Lecture 8	§ 8.1, 8.2, 8.3, 8.5, 8.6	Lecture 20	§ 12.5, 12.6, 13.1
Lecture 9	§ 8.6, 9.1, 9.2	Lecture 21	§ 13.2 - 13.6
Lecture 10	§ 9.3 - 9.7	Lecture 22	§ 13.6, 13.7, 14.1, 14.2
Lecture 11	§ 9.8	Lecture 23	§ 14.3,14.4, 15.1 - 15.4
Lecture 12	§ 9.9	Lecture 24	Review

Why Study Science?

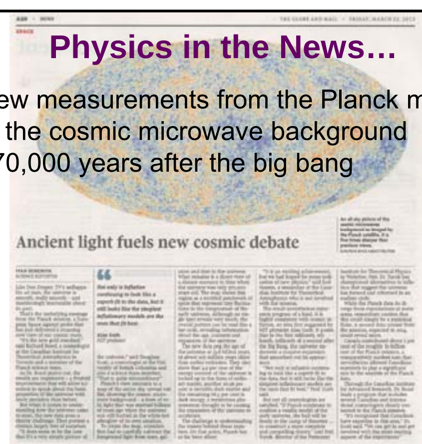
- Ma-Kellams C, Blascovich J (2013) Does "Science" Make You Moral? The Effects of Priming Science on Moral Judgments and Behavior. PLoS ONE 8(3): e57989. doi:10.1371/journal.pone.0057989 (http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0057989)
- *"Taken together, the present results provide support for the idea that the study of science itself–independent of the specific conclusions reached by scientific inquiries–holds normative implications and leads to moral outcomes."*
- *"These findings suggest the same scientific ethos that serves to guide empirical inquiries also facilitates the enforcement of moral norms more broadly."*

Be better, with science

"Want to be a better person? Spend more time thinking about science," says Pacific Standard magazine. "That's the implication of newly published research, which finds people who study science – or even are momentarily exposed to the idea of scientific research – are more likely to condemn unethical behaviour, and more inclined to help others. 'Thinking about science leads individuals to endorse more stringent moral norms,' report psychologist Christine Ma-Kellams of Harvard University and Jim Blascovich of the University of California, Santa Barbara. Their research is published in the online journal PLoS One."

Globe & Mail, March 22, 2013

Physics in the News…



- New measurements from the Planck mission of the cosmic microwave background 370,000 years after the big bang

Physics in the News…

- Quantum computing
- Mike Lazaridis's new quantum leap, The Globe and Mail, March 19, 2013
- *In an interview Wednesday, Mr. Lazaridis detailed a brand-new, $100-million venture capital fund that he will run with Mr. Fregin. Called Quantum Valley Investments, it is an initiative that pools some of the two wealthy men's money behind a vision to make Waterloo the centre of entirely new industries focused on the immense but largely untapped power of quantum computing."*
- *"Mr. Lazaridis, … says he and Mr. Fregin have gradually come to the conclusion that commercially viable spin off technologies are beginning to emerging from scientists' quest to create a fully functioning quantum computer – which he estimates is still at least 10 years away from fruition.*

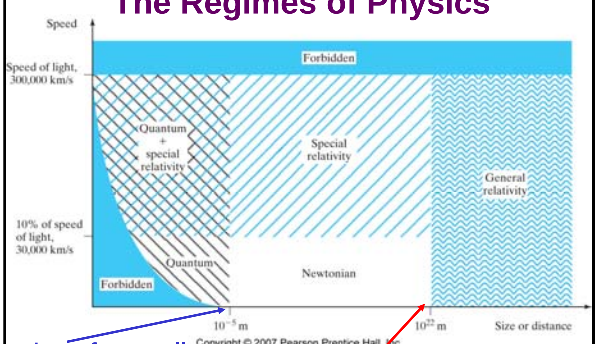
http://www.theglobeandmail.com/technology/tech-news/mike-lazaridiss-new-quantum-leap/article9071663/

Physics in the News…

- New measurements from the Alpha Magnetic Spectrometer (AMS) on the International Space Station may provide evidence of dark matter

- See the video at http://www.theglobeandmail.com/technology/technology-video/video-has-nasa-made-a-breakthrough-with-dark-matter-discovery/article10752633/

The Regimes of Physics



size of a small dust particle

10 x size of our galaxy

Law of Inertia = Newton's First Law

A body subject to no external forces will:

1) stay at rest if it was at rest to begin with

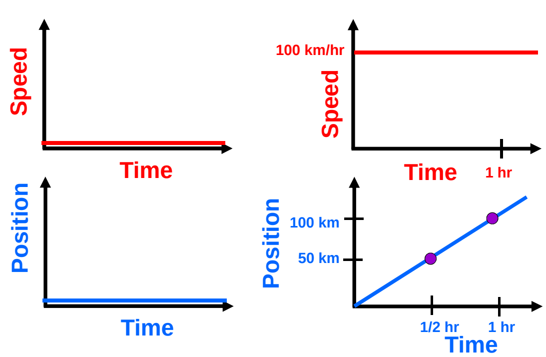
2) keep moving in a straight line at constant speed if it was moving to begin with.

In other words, all bodies have inertia.

This tells us that an undisturbed object will keep moving with a constant velocity.

If an object's velocity (= speed + direction) is changing, it is accelerating.

Using Graphs to Describe Motion



Newton's Law of Motion = Newton's Second Law

a* = net force / *m

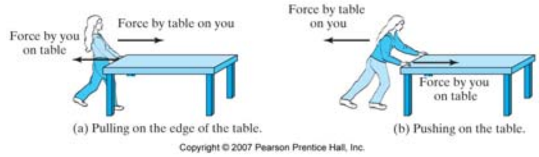
Where

- the net force is the sum or difference of all the forces acting on mass m.
- the acceleration is in the direction of the net force.

The Law of Force Pairs = Newton's Third Law

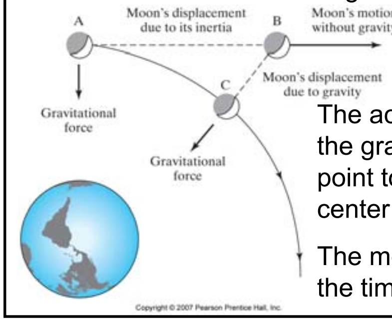
For every action, there is an equal and opposite reaction.

OR The forces of two bodies on each other are always equal in magnitude and opposite in direction.



Objects in Orbit

direction of the moon's acceleration
= direction of its change in velocity



The acceleration and the gravitational force point towards the center of Earth.

The moon is falling all the time.

Newton's Law of Gravity

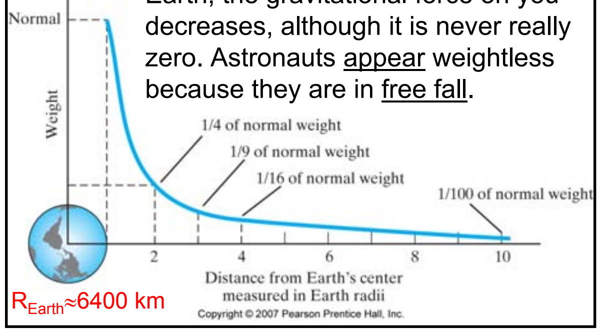
$$F_{gravity} = G\, m_1 \times m_2 / d^2$$

"The gravitational force between two masses is proportional to the product of the masses and inversely proportional to the square of the distance between their centers."

with m in kilograms, d in meters, F in newtons, and G = 6.7×10^{-11} N m^2 / kg^2
= universal gravitational constant

Weight vs. Distance from Earth

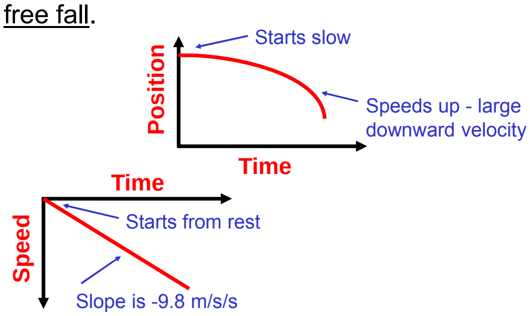
As you move away from the center of Earth, the gravitational force on you decreases, although it is never really zero. Astronauts appear weightless because they are in free fall.



$R_{Earth} \approx 6400$ km

Weightlessness on Earth

Any object only acted upon by gravity is in free fall.

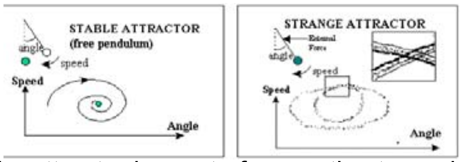


Properties of Chaotic Systems

- Deterministic in a mathematical sense (not random)
- Sensitive to initial conditions
- Unpredictable and unrepeatable
- Nonlinear
- Transition to chaos is preceded by infinite levels of bifurcation - the logistic map
- Fractional dimensionality

e.g., the butterfly effect, three-body problem, water wheel, population biology

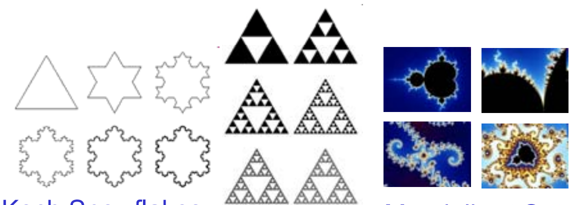
Attractors



- An attractor is a set of properties toward which a system tends to evolve, regardless of the initial conditions of the system.
  - → Can be a point, a curve, or a fractal structure.
- A strange attractor exhibits a chaotic approach to its final set of properties.
  - → Example: the Lorenz attractor

Fractals

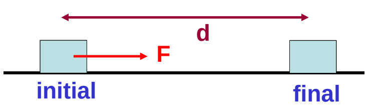
- Fractal = "fractional dimension"
- A fractal is self-similar - it resembles itself on all scales.



Koch Snowflakes Sierpinski Triangles Mandelbrot Set

Energy and Work

- A system has energy if it has the ability to do work.
- Work is done whenever an object is pushed or pulled through a distance. There must be both force and motion in the same direction.

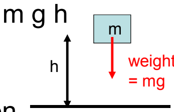


work = force × distance = F d

Two Forms of Energy

Gravitational energy

- = energy an object has at its highest point
- = work done = force (weight) x height
- = weight x height = (m g) x h = m g h

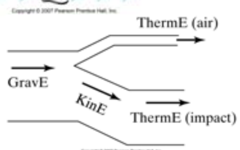


Kinetic energy

- = energy associated with motion
- = ½ times the mass times the square of the speed (derived from Newton's laws)
- = ½ m v^2 or = ½ m s^2

The Law of Conservation of Energy

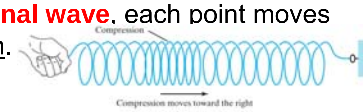
Energy cannot be created or destroyed. Energy can be transformed (changed from one form to another), and it can be transferred (moved from one place to another), but the total amount always stays the same.



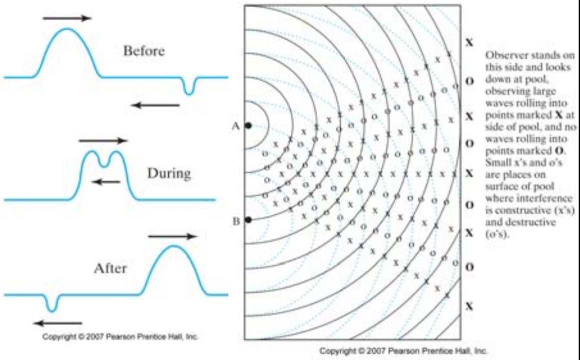
Waves

- A wave is a disturbance that travels through a medium in such a way that energy travels through the medium but matter does not.
- In a **transverse wave**, each point moves up and down.

- In a **longitudinal wave**, each point moves back and forth.

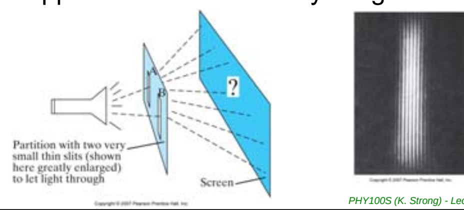


Wave Interference in 1 and 2 D



Young's Double Slit Experiment

- First performed by Thomas Young in 1801.
- Goal was to answer the question of whether light was made of particles or of waves.
- The resulting interference pattern supported the wave theory of light.

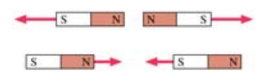


The Electric Force

- Electrically charged objects exert forces on each other.
- Objects may have positive or negative charge.
- Like charges repel each other.
- Unlike charges attract each other.
- The electric force between two charged objects decreases with distance.

The Magnetic Force

- Magnetic forces are similar to electric forces:
  - → Like poles repel
  - → Unlike poles attract



- Charged objects that are moving exert and feel an additional force beyond the electric force that exists when they are at rest.
  - → The magnetic force
- All magnetic forces are caused by the motion of charged objects.

Forces at a Distance: Fields

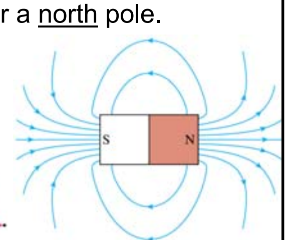
- A field transmits a force:
  - → It is a property of space.
  - → It requires a source, e.g., Earth, charge, magnet
  - → An object placed in a field experiences a force.
- Examples
  - → Gravitational field - exists in a region of space where an object would feel a gravitational force if it were placed there.
  - → Electromagnetic field - exists in a region of space where a charged object would feel an electromagnetic force if it were placed there.
  - → An electric field will exert a force on a charge.
  - → A magnetic field will exert a force on a moving charge.

Visualizing Fields

- Field lines show direction the force would be.
- They point in the direction the force would be on a positive charge or a north pole.

Field lines for a positive charge

Field lines for a negative charge



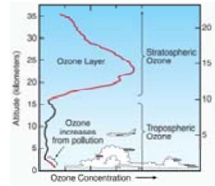
Field lines for a bar magnet

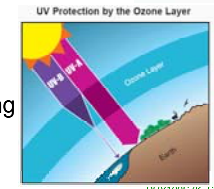
Faraday's Law

- When a wire loop is placed in the vicinity of a magnet and when either the loop or the magnet is moved, an electric current is created within the loop for as long as the motion continues. Stated in terms of fields:
  A changing magnetic field creates an electric field.
- This principle is used in modern electric power generators.
  → Electricity is generated by the rotating of a shaft wrapped in wires located in a magnetic field.

Atmospheric Ozone

- Ozone absorbs solar UV-B radiation (280-315 nm)
- This warms the stratosphere (~10-50 km)
- Ozone is also a greenhouse gas, absorbing IR radiation and heating the troposphere (0-10 km)





WMO Ozone Assessment 2006

Stratospheric Ozone - Chemistry

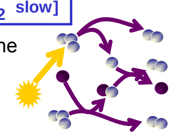
How is ozone created and destroyed?

(1) **Chapman Cycle (1930)** - oxygen-only reactions

- **Odd oxygen production:**
  $O_2 + h\nu \longrightarrow O + O$
  $O + O_2 \xrightarrow{M} O_3$
- **Odd oxygen destruction:**
  $O_3 + h\nu \longrightarrow O_2 + O$
  $O + O_3 \longrightarrow 2\,O_2$
  [$O + O \xrightarrow{M} O_2$ slow]

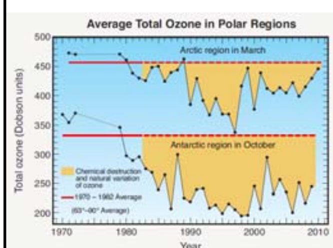
(2) **Catalytic Cycles (1970s)** - destroy ozone

$X + O_3 \rightarrow XO + O_2$
$XO + O \rightarrow X + O_2$
$O + O_3 \rightarrow 2\,O_2$

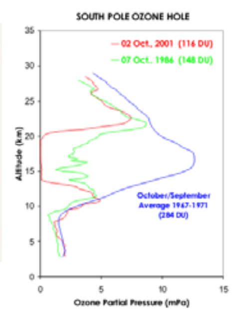


- where reactive species X (= H, OH, NO, Cl, Br) is regenerated

Polar Total Ozone Depletion



WMO Ozone Assessment 2010



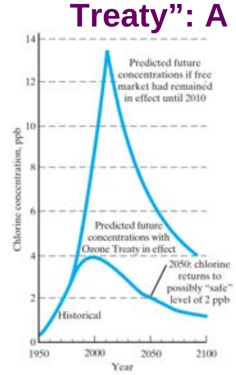
NOAA CMDL http://www.cmdl.noaa.gov/ozwv/ozsondes/spo/index.html

Polar Ozone Depletion - Processes

(1) Formation of the winter polar vortex (band of westerly winds)
→ *isolates cold dark air over the polar regions*
(2) Low temperatures in the vortex, T<195 K
→ *polar stratospheric clouds (PSCs) form (HNO_3, H_2O, H_2SO_4)*
(3) Dehydration and denitrification
→ *remove water vapour and nitrogen oxides which would otherwise react with and neutralize chlorine*
(4) Release of CFCs, mixing, and transport to the polar regions
→ *enhanced levels of chlorine and other halogen species*
(5) Heterogeneous reactions on the PSCs
→ *convert inactive chlorine (HCl, $ClONO_2$) to reactive Cl_2*
(6) Sunlight returns in the spring
→ *UV radiation breaks Cl_2 apart to form Cl*
(7) Catalytic chlorine cycles
→ *destroy ozone, while recycling Cl*

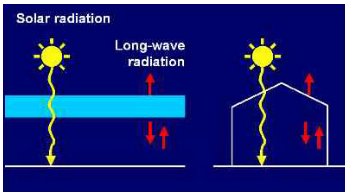
This continues until the Sun causes a dynamical breakdown of the winter vortex and PSCs evaporate.

The Impact of the "Ozone Treaty": A Simplified View



The actual chlorine concentration in the stratosphere, compared with a prediction of what it would have been if there had been no treaty until 2010.

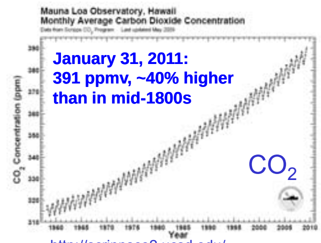
The Greenhouse Effect



Greenhouse Gases
- Water vapour (H_2O)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Ozone (O_3)
- Halocarbons

- Earth's temperature as seen from space (really the temperature of the upper atmosphere) is about -19°C.
- The average surface temperature is about 14°C.
- The 33°C difference is due to Earth's blanket of greenhouse gases; without them, the surface would also be about -19°C.

The "Keeling Curve"



Charles David Keeling began collecting data at Mauna Loa, at 3400 m elevation, in March, 1958.

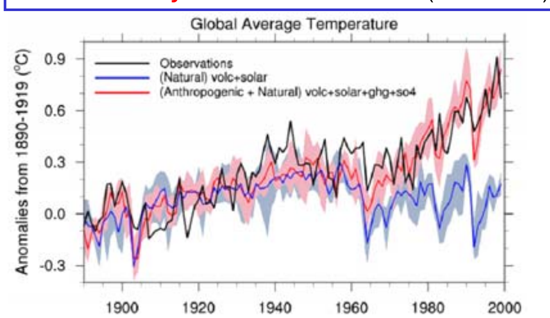
The Mauna Loa atmospheric CO_2 concentration measurements constitute the longest, continuous record of atmospheric CO_2 available in the world.

http://scrippsco2.ucsd.edu/
http://www.mlo.noaa.gov/programs/coop/scripps/co2/co2.html

Observed Fact: The CO_2 (and CH_4, N_2O,…) content of the Earth's atmosphere is steadily increasing due to the burning of fossil fuels which releases the trapped carbon into the atmosphere.

Surface Temperature Trends

IPCC 2007: **100-year** linear trend is **0.74°C** (1906–2005).



From presentation by Rick Anthes, UCAR Meeting, Boulder, CO, 7 October 2003
NCAR Ensemble Simulations

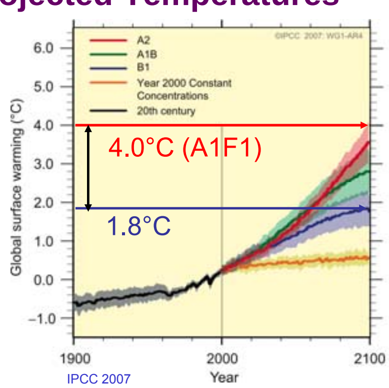
Some Key Climate Concepts

- A change in the net radiative energy due to changes in forcing agents is called a radiative forcing (W m^{-2}).
  - → Positive radiative forcings warm the Earth's surface
  - → Negative radiative forcings cool the Earth's surface
- The climate sensitivity parameter λ (not wavelength here!) is defined as the global mean surface temperature response ΔT_s to the radiative forcing ΔF: $\Delta T_s = \lambda \, \Delta F$.
  - → In 1-D models, λ is about 0.3 K / (Wm^{-2}).
- The global warming potential is a measure of the relative radiative effect of 1 kg of a given greenhouse gas compared to CO_2 over a chosen time period.

IPCC Projected Temperatures

Multi-model global averages of surface warming, relative to 1980-1999. Shading indicates the range of individual model annual averages (±1 standard deviation).

Four steps in model projections:
→ GHG emissions
→ atmospheric concentrations
→ radiative forcing
→ temperatures.



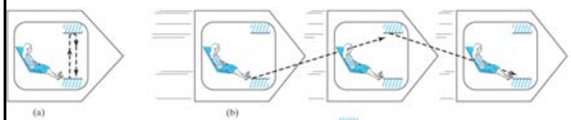
IPCC 2007
Figure SPM.5

The Special Theory of Relativity

The laws of physics are the same in all non-accelerating reference frames.

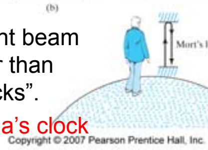
- Includes all laws of physics including mechanics and electromagnetism.
- Combines the principle of relativity and the constancy of the speed of light.
  - → "Special" because it is valid only for the special case of non-accelerating reference frames.
  - → The General Theory of Relativity deals with accelerating reference frames.

Velma Flies Past Mort



He sees her light beam traveling farther than his between "ticks".

Mort sees Velma's clock run slow.



She sees his light beam traveling farther than hers between "ticks".

Velma sees Mort's clock run slow.

Time is relative.
Rule: Moving clocks run slow.

Time Dilation

Time T measured by a clock moving at speed v is slow, or "dilated" compared to the time T_o measured by a stationary clock:

$$T = \frac{T_o}{\sqrt{(1 - v^2/c^2)}} = \gamma T_o$$

so $T > T_o$

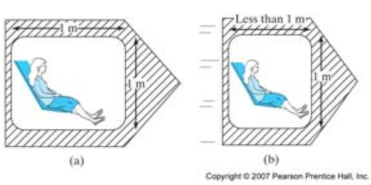
Time dilation allows time travel, but only into the future, e.g., the twin "paradox".

Length Contraction

No matter how we measure length, we find the same result: lengths in the direction of motion are contracted.

$$L = L_o\sqrt{(1 - v^2/c^2)} = L_o/\gamma < L_o$$

so $L < L_o$



measured by Velma   measured by Mort

where
L_o = object's rest length,
L = object's length when moving at v

The Relativity of Mass

- If the same force yields a smaller acceleration, the mass must be larger.
- Therefore, mass is also relative.
  - → Moving masses appear heavier than those at rest.
- We call the mass of an object in its own reference frame (not moving) its rest mass.
  - → This is a constant for any particular object.

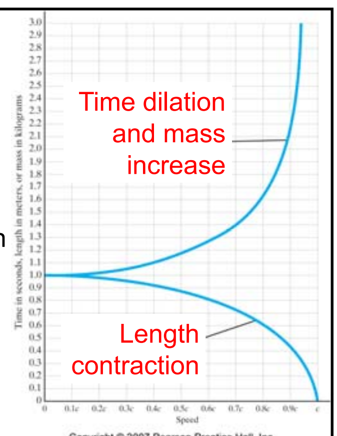
$$m = \frac{m_o}{\sqrt{(1 - v^2/c^2)}} = \gamma m_o$$

so $m > m_o$

m_o = object's rest mass,
m = object's mass when moving at v

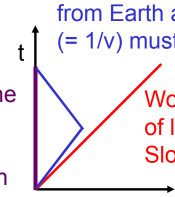
This diagram shows time dilation, mass increase, and length contraction as the speed approaches the speed of light:

- duration of 1 sec on a moving clock
- length of a moving meter stick
- mass of a moving standard kilogram



Space-Time Diagrams

- Provide a visual illustration of the path of an object through space and time - its worldline
- Plot distance on x-axis and time on y-axis



Space-time diagram for the twin "paradox"

The Principle of Mass-Energy Equivalence: $E = mc^2$

Energy has mass; that is, energy has inertia.

And mass has energy - the ability to do work.

All objects have rest energy: $E_o = m_o c^2$
where m_o is the rest mass.

This is true even if the object is stationary.

If the object is moving at speed v, then the total energy = rest energy + kinetic energy:

$$E = mc^2 = \gamma m_o c^2 = m_o c^2 + K.$$

"$E=mc^2$" either means $E=m_o c^2$ for an object at rest, or $E=\gamma m_o c^2$ when the object is moving.

In which of the following processes does the system's <u>total mass</u> change?

(A) An automobile speeds up

(B) A rubber ball is squeezed

(C) The total mass changes in both of the above processes

(D) The total mass changed in neither of the above processes.

An increase in energy causes an increase in total mass ($m = E/c^2$). Both A and B increase the total energy (kinetic and elastic) of the system, and so increase the mass.

In which of the following processes does the system's <u>rest mass</u> change?

(A) An automobile speeds up

(B) A rubber ball is squeezed

(C) The total mass changes in both of the above processes

(D) The total mass changed in neither of the above processes.

The rest mass of the automobile is unchanged. The rubber ball is at rest, but its energy increases (work is done), so its rest mass increases: $E = \cancel{m}c^2 = \gamma m_o c^2 = \cancel{m_o}c^2 + K$

The Equivalence Principle

- The <u>General</u> Theory of Relativity applies to accelerating systems.
- Einstein's Equivalence Principle is the foundation of General Relativity.

No experiment performed inside a closed room can tell you whether you are at rest in the presence of gravity or accelerating in the absence of gravity.

Gravity Bends Light

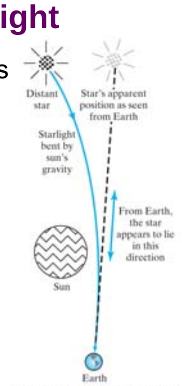
- Light beams are the definitions of straight lines; how can they bend?

Einstein's answer:

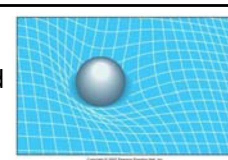
- <u>Gravity warps space</u>, so the light is still taking the shortest distance between two points.

Evidence:

- Stars behind the sun can be seen during a solar eclipse.

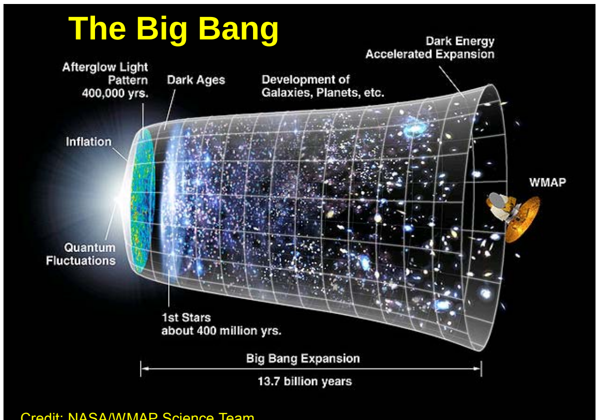


Spacetime



- Special Relativity showed us that space and time are closely connected.
- Thus warping of space also warps time.
  - → Time goes slower in strong gravitational fields.
- Space and time are bent by masses.
  - → There is a bending in the three space dimensions plus in the time dimension.
- <u>Spacetime</u> = these four dimensions.
- "Spacetime tells matter how to move; matter tells spacetime how to curve." John Wheeler

The Big Bang



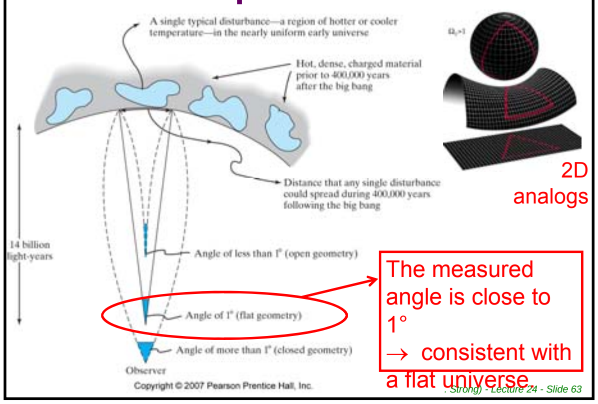
Credit: NASA/WMAP Science Team
http://map.gsfc.nasa.gov/m_ig/060915/CMB_Timeline300.jpg

The Expanding Universe

- The big bang was not really an explosion.
- It created space and time.
- The expanding universe continues to create spacetime.
- It is not expanding into anything.

The expanding surface of a balloon is a 2D analog of 3D space.

Which Shape Is the Universe?



The measured angle is close to 1°
→ consistent with a flat universe.

What is the Universe Made Of?

- protons, neutrons, electrons (form atoms)
- neutrinos
- black holes - regions of spacetime from which nothing can escape, even light
- **dark matter**
  - → does not interact with EM radiation
  - → can be detected due to its gravitational effects
    - galaxies can be "weighed" by measuring (1) the motions of stars and gas, (2) how they distort light coming from other galaxies (gravitational lensing)
    - the mass of the galaxies is ~10 times larger than that associated with stars, gas and dust
  - → comprises most of the mass of the universe

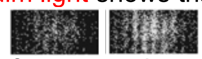
Dark Energy

- The expansion of the universe is apparently accelerating.
  - → Observations of exploding supernovas show that the most distant galaxies are too far away to be explained without acceleration.
- This energy that is slowly pushing the universe apart is called dark energy.
- When the mass of the dark energy and dark matter is added to the luminous and non-luminous matter, the result is just enough for the universe to be flat.

The Quantum Idea

- Quantization is the idea that certain properties can only take on certain values.
- Quantum physics describes the nature and behavior of matter and radiation, particularly at smallest scales.

Double slit experiment with dim light shows that

- Light is a quantized wave. 
- It consists of little packets of energy - photons
- It is the quantized EM field that comes through the slits and interferes at the screen.

The Quantum Theory of Radiation

- All electromagnetic fields are quantized.
- When carrying radiation of frequency f, the energy of the EM field must be a multiple of the energy increment **E = hf**.
- h = 6.6 x 10^{-34} J/Hz is Planck's constant.
- The energy of a single photon is E = hf.
- Photons travel at lightspeed (have no mass) and carry energy.
- An EM wave is still a wave - but it can only lose energy in units of photons.

Matter Waves and Fields

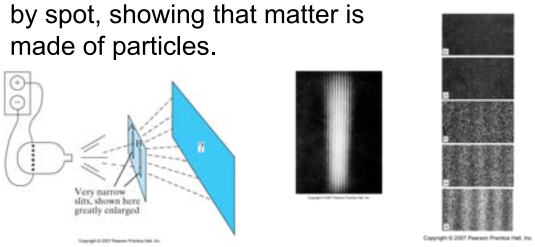
- Everything is made of radiation and matter.
  - → Radiation has particle-like qualities.
  - → Matter has wave-like properties → matter waves → new type of field called a matter field .
- The wavelength of any mass m is:

$$\lambda = h / m v$$

- Like EM fields, matter fields are quantized.
  - → e.g., the matter field for electrons is allowed to have enough energy for 0, 1, 2, ... electrons
  - → Electrons (and other particles) exist because matter fields are quantized in just these energy increments.

Electron Double Slit Experiment

- The result is an wave interference pattern, like that produced by photons.
- The interference pattern also builds up spot by spot, showing that matter is made of particles.

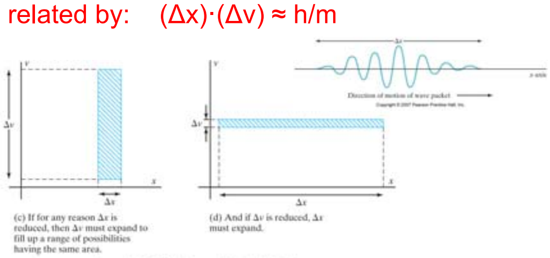


Key Ideas of Quantum Physics

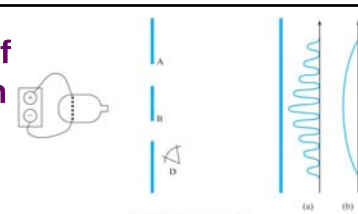
- Quantization of the EM field
- Existence of the matter field
- Quantization of the matter field
- Quantum nonlocality - collapse of the quantized EM or matter field to an uncertain small point of interaction
- Quantum uncertainty - impossible to predict the location of any individual electron impact, but the overall pattern is well defined
- Probabilities defined by Schroedinger Eq'n

The Uncertainty Principle

The position and velocity of every material particle are uncertain. Although either uncertainty can take on any value, the two are related by: $(\Delta x)\cdot(\Delta v) \approx h/m$

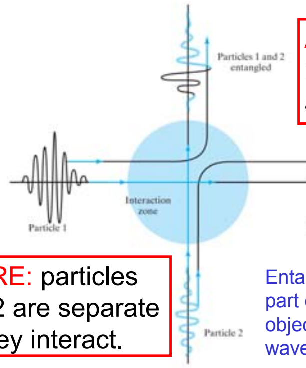


The Effect of Observation



- We cannot determine which slit the electron goes through without interacting with the electron,
- If we insist that the electron must go through one slit or the other by looking for it, all we get is a single-slit pattern.
- Double-slit interference pattern only appears if the electron's matter wave can pass through both slits.

Quantum Entanglement



AFTER they interact, they are entangled.

BEFORE: particles 1 and 2 are separate until they interact.

Entangled particles are part of a single quantum object: a two-particle wave packet.

The Nonlocality Principle

Quantum theory predicts that entangled particles exhibit behavior that can be explained only by the existence of real nonlocal (that is, instantaneous and distant) correlations between the particles.

That is, a physical change in one particle, such as might be caused by a measurement made on that particle, causes instantaneous physical changes in all other particles that are entangled with that particle, no matter how far away those other particles may be.

Can two microscopic [or quantum] particles be entangled even when they are exerting no forces on each other?

(A) Yes, because they can still communicate with each other by means of EM radiation.

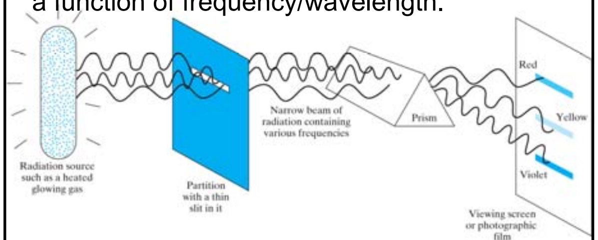
(B) Yes, they could be entangled but so far apart as to exert no significant forces on each other.

(C) No, because entanglement occurs only by means of the electromagnetic force and the other fundamental forces.

(D) No, because in order for a particle to be trapped in the field of another particle, it must feel the second particle's force field.

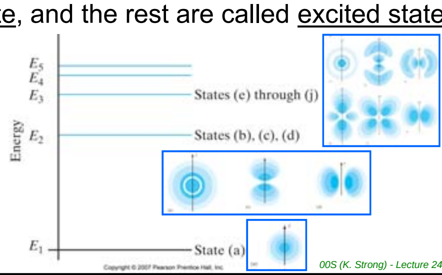
Atomic Spectra

A spectrum = the set of frequencies/ wavelengths emitted by (or absorbed from) the source of the radiation. Or the intensity as a function of frequency/wavelength.

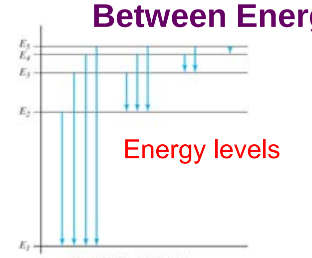


Energy Level Diagrams

- Each quantum state is a standing wave with a specific frequency and a specific energy.
- The lowest energy level is called the ground state, and the rest are called excited states.

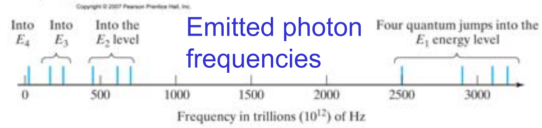


Quantum Jumps = Transitions Between Energy Levels



Energy levels

Emitted/absorbed photon has energy $hf = E_{\text{high-energy state}} - E_{\text{low-energy state}}$



Emitted photon frequencies

Four Fundamental Forces

- The strong nuclear force, holds the nucleus together.
  - → It acts over distances of about 10^{-15} m, attracting protons and neutrons.
- There is one other force, called the weak nuclear force, which is responsible for some forms of radioactive decay.
- Four fundamental forces – gravity, electro-magnetism, strong and weak nuclear forces.
  - → Responsible for the structure of our universe.
  - → Every other force can be reduced to one of these four.

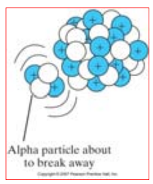
Atomic and Mass Numbers

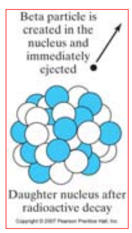
Mass number Atomic number	Chemical symbol

- Atomic number = the number of protons (also = number of orbital electrons)
  - → This determines the element of the atom.
- The number of neutrons determines the isotope of the element.
- Mass number = the total number of protons plus neutrons.
  - → An isotope is labeled by its atomic number and its mass number.

Radioactive Decay

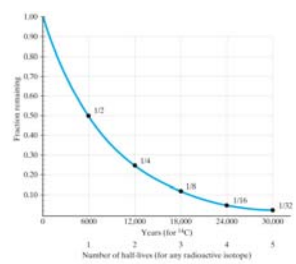
- **Alpha decay:** nucleus emits an alpha particle = $^4_2$He nucleus = 2 protons + 2 neutrons.
- **Beta decay:** nucleus emits a beta particle = an electron (although no electrons in nucleus!)
- **Gamma decay:** nucleus emits a photon as it returns to its ground state; often follows alpha and beta decay.





Half-Life: The Universal Decay Curve

- As with other quantum processes, the time when any particular nucleus will decay cannot be predicted.
- Nuclear decay rates are described by the half-life = the time it takes for half the remaining nuclei to decay.
- Applies to a large number of nuclei.

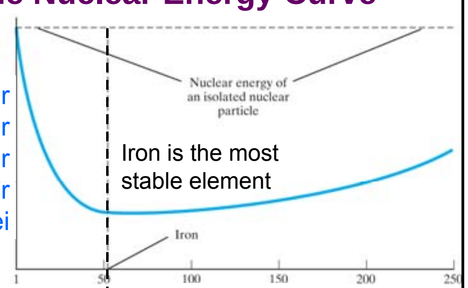


Nuclear Fission and Fusion

- Nuclear fission is the splitting of a single nucleus to make two smaller nuclei.
  - → Example: $^2_1$H (deuterium) + energy → n + p
  - → This requires lots of energy because they are held together by the strong nuclear force.
- Nuclear fusion is the uniting of two small nuclei to make a single larger nucleus.
  - → Example: n + p → $^2_1$H (deuterium) + energy
  - → Nuclear energy is released.
  - → The energy transformation is Nuclear E → Thermal E + Radiation E

The Nuclear Energy Curve

Nuclear energy per nuclear particle for all nuclei



Mass number

Lighter elements can generate energy by **fusion**

Heavier elements can generate energy by **fission**

"What we become depends on what we read after all of the professors have finished with us. The greatest university of all is a collection of books."

Thomas Carlyle,
Scottish author & historian (1795 - 1881)

Good Luck!