DAY 1

Summary of Topics Covered in Today's Lecture

Gravitational and Electromagnetic Forces

Four fundamental forces have been identified in nature. Two of these forces, the *strong nuclear force* and the *weak nuclear force*, do not extend beyond the nucleus of the atom. Because these forces have such limited range, we cannot observe them in the world around us -- they are involved in the working of atomic nuclei, and that is all.

The other two fundamental forces of nature -- the *gravitational force* and the *electromagnetic force* -- govern the world we see and observe on a regular basis. Both of these forces can act over long distances. Both are "action-at-a-distance" forces, meaning they act without some obvious means of transmitting the force (for example, the gravitational force between the Sun and the Earth holds the Earth in orbit around the Sun without some sort of rope or cable connecting the two together).

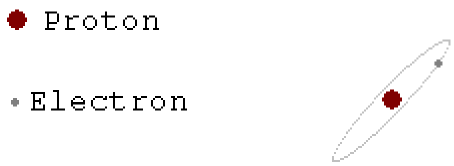
Gravity is a force between particles that depend on the particles' gravitational mass (this is not the same as inertial mass, the mass used in Newton's 2nd Law of Motion: $\Sigma F = ma$). We experience the gravitational force when we notice our own weight or another object's weight. While gravitational forces act between all objects, the force of gravity is typically very weak. Only the Earth has enough gravitational mass to produce gravitational forces that we regularly notice.

Electromagnetism is a force between particles that depends on the particles' electrical charge. We experience electrical forces when we notice "static cling", or when our hair is standing up due to "static". The electromagnetic force is fairly strong, so we can notice it even when there is not a large amount of charge present. Electromagnetism also is what holds atoms together, and therefore is what produces the strength the rope or cable or bone or concrete has. Thus most contact forces, such as that that occurs between your knuckles and a door when you knock on it, are electromagnetic. So are tension forces in strings or compression forces in bones. In fact, with the exception of your weight, every force you've ever experienced has probably been electromagnetic.

Electric Charge & Gravitational Mass

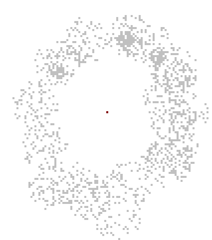
Gravitational mass and electric charge are fundamental physical properties, and fundamental physical properties can be difficult to explain. It can be very difficult to answer questions such as "What is time?" or "What is mass?" or "What is charge?" or "What is distance?" Therefore, we will discuss mass and charge in reference to a concept that we have all encountered before -- the Hydrogen atom.

A Hydrogen atom consists of a proton and an electron, two "sub-atomic" particles that, along with the neutron, are the basic building blocks of atoms. In illustrations Hydrogen atoms are usually depicted with the electron circling the proton:



Hydrogen Atom

Of course, the diagram at left is not an accurate portrayal of a Hydrogen atom. In a Hydrogen atom the proton is vanishingly small, and the electron surrounds the proton in a sort of diffuse cloud. This might be a better sketch of a Hydrogen atom:

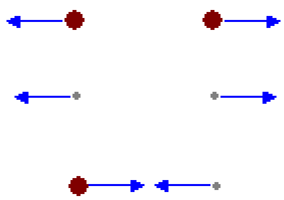


Hydrogen Atom

So, keeping in mind that we are talking about abstractions to some extent, let's compare the mass and charge characteristics of the proton and the electron:

	Gravitational Mass (m)	**Electrical Charge (q)**
Proton	1.0 u	+ 1.0 e
Electron	< 0.0006 u	- 1.0 e
1 u = 1.66 x 10^{-27} kg = 1 "atomic mass unit" Gravitational Mass is usually indicated by the variable m. Charge is usually indicated by the variable q.		

The proton and electron have equal size charges, but the charges are of differing types. There are two types of charge -- which are called positive and negative. The words "positive" and "negative" are holdovers from the days of Ben Franklin, when things like static cling were thought to be due to an excess or deficit of a colorless, odorless, massless, tasteless electrical "fluid". The "electricity is a fluid" theory has long since been abandoned, but the terms are still around. The electrical force between like charges is always repulsive; the electrical force between unlike charges is attractive. This is the *Law of Charges*.



The charge on a proton or electron is called *e*. In normal matter charge cannot occur in quantities of less than +1*e* or -1*e*. You can have

$q = 5e$
$q = -15e$
$q = 5557e$

but you cannot have

$q = 0.5e$
$q = -12.2e$
$q = 5557.89e$

Thus ***charge is quantized;*** it comes in discrete quantities. An *e* is a very small quantity of charge. The unit of charge normally used in physics is the *Coulomb (C)*, and

$1\ C = 6.241 \times 10^{18}\ e$

Most of our electrical devices use charge by the Coulomb. For example, 50 C of charge flow through a 100 Watt light bulb every minute. So *e* is a very small quantum, but it is important to recognize that, small or not, charge is quantized.

While the charges of a proton and an electron are similar in size, the sizes of their gravitational masses differ wildly. However, while the masses differ in size, they are alike in type. In fact there is only one type of gravitational mass, and the gravitational force is always attractive.

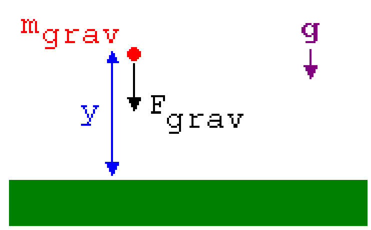
As far as we know, **mass is not quantized.** The atomic mass unit (u) is just a unit based on the approximate size of a proton (actually, it is based on the size of a Carbon atom, and a proton has mass of 1.00728 u). It is not the equivalent of *e* for mass.

Gravitational Field

The gravitational force acts by means of a gravitational field that is created by mass-having objects. Near the surface of the Earth this gravitational field is constant and uniform, is directed downward, and has a strength of 9.8 N/kg or 2.203 lb/kg. Expressed as a vector, the gravitational field strength at Earth's surface is

$$\mathbf{g} = 9.8 \text{ N/kg} = 2.203 \text{ lb/kg (directed down)}$$

An object in this field feels a gravitational force of



$$\mathbf{F_{grav}} = m_{grav}\,\mathbf{g}$$

This is what we called "weight" in Physics I, the only difference is that we just called the mass "mass" in Physics I rather than "gravitational mass". From Physics I, we remember that if an object of mass m_{grav} is at a height of y relative to a reference point on the Earth's surface, the gravitational potential energy of that object is given by

$$PE_{grav} = m_{grav}\, g\, y$$

If the mass is released, it undergoes free-fall. The only force acting on it is gravity. Newton's 2nd Law of Motion says the acceleration of the object depends on the force acting on it and its inertia (what we've always called mass, but what we now will call inertial mass):

$$\Sigma \mathbf{F} = m_{inertial}\ \mathbf{a}$$

Since the only force acting on the mass is gravity, we can use Newton's 2nd law to calculate the object's free-fall acceleration:

$$\mathbf{F_{grav}} = m_{inertial}\ \mathbf{a}$$

$$m_{grav}\ \mathbf{g} = m_{inertial}\ \mathbf{a}$$

$$\mathbf{a} = (m_{grav}/m_{inertial})\ \mathbf{g}$$

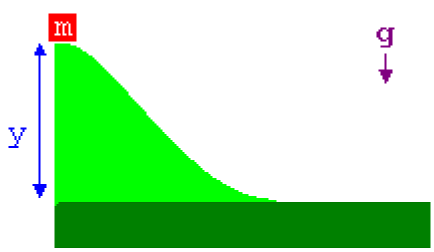
It turns out that gravitational mass and inertial mass are identical, so the acceleration of a fee-falling object is

$$\mathbf{a} = (m/m)\ \mathbf{g}$$

$$\mathbf{a} = \mathbf{g} = 9.8\ \text{N/kg} = 9.8\ \text{m/s}^2$$

However, it is important to realize that, prior to Einstein's development of the theory of General Relativity, there was no reason to expect that gravitational and inertial masses would have to be the same. After all, gravity and Newton's 2nd Law of motion seem to be two different concepts, just like electricity and Newton's 2nd Law of motion seem to be two different concepts. Charge (which we could call "electrical mass", perhaps) and inertial mass are not the same, so why was gravitational mass and inertial mass the same? We'll discuss why when we cover the Theory of Relativity.

Gravitational Potential



Imagine that a box of mass m sits atop a low-friction ramp of height y as shown in the picture. The box has gravitational potential energy of PE = mgy relative to the ground. If the box slides down the ramp, that potential energy will turn into kinetic energy (low friction means little of the potential energy will be turned into heat energy). However, while the box has potential energy, we can define a concept that applies to the location of the box. This is the concept of "gravitational potential", and is defined as

$$U_{grav} = PE/m = mgy/m = gy$$

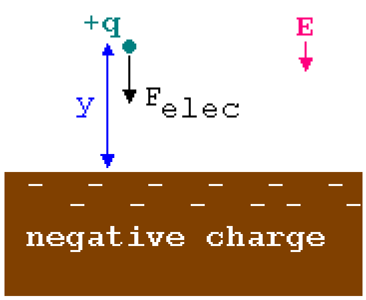
The units of gravitational potential are J/kg. Note that while the box has gravitational potential energy, the top of the ramp has gravitational potential. Any mass placed in that location will have potential energy.

$$PE = U_{grav}\ m$$

Electric Field & Potential

Like gravity, the electrical force acts by means of an electric field that is created by charge-having objects. In a constant, uniform electric field, an object with charge q in this field feels an electrical force of

$$\mathbf{F}_{elec} = q\ \mathbf{E}$$



This is mathematically identical to the gravitational field force. In fact, an electrical situation analogous to a mass near the Earth's surface would be a positive charge near the surface of a very large negative charge. If the charge in this figure were released, it would accelerate downward in an electrical free-fall.

The only force acting on it is electricity. Newton's 2^{nd} Law of Motion says the acceleration of the object depends on the force acting on it and its inertia (what we've always called mass, but what we now will again call inertial mass):

$$\Sigma\mathbf{F} = m_{inertial}\ \mathbf{a}$$

Since the only force acting on the mass is electricity, we can use Newton's 2^{nd} law to calculate the object's free-fall acceleration:

$$\mathbf{F}_{elec} = m_{inertial}\ \mathbf{a}$$

$$q\ \mathbf{E} = m_{inertial}\ \mathbf{a}$$

$\mathbf{a} = (q/m_{inertial})\ \mathbf{E}$

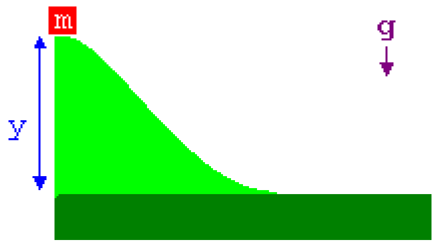
But since inertial and gravitational mass turn out to indistinquishable from each other, we'll drop the "inertial" subscript.

$\mathbf{a} = (q/m)\ \mathbf{E}$

By analogy to gravity, we can identify an Electrical Potential Energy and an Electrical Potential:

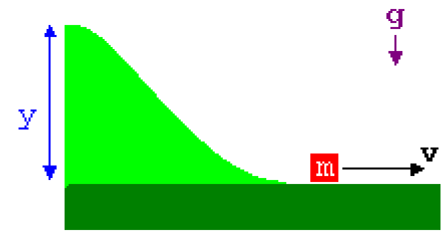
	Gravitation Force (Gravity)	Electrical Force (Electricity)
Mass/charge	m (units of kg)	q (units of C)
Field	$\mathbf{g}$ (units of N/kg)	$\mathbf{E}$ (units of N/C)
Force	$\mathbf{F_{grav}} = m_{grav}\ \mathbf{g}$ (units of N)	$\mathbf{F_{elec}} = q\ \mathbf{E}$ (units of N)
Potential Energy	$PE_{grav} = m_{grav}\ g\ y$ (units of J)	$PE_{elec} = q\ E\ y$ (units of J)
Potential	$U_{grav} = PE_{grav}/m$ $U_{grav} = g\ y$ (units of J/kg)	$U_{elec} = PE_{elec}/q$ $U_{elec} = E\ y$ (units of J/C)
Units: kg -- kilograms C -- Coulombs N -- Newtons J – Joules		

The units for electrical potential (J/C) are also known as *Volts* (V). 1 V = 1 J/C. Therefore electrical potential is also referred to as *Voltage*. These equations do not attempt to deal with whether energies or potentials are positive or negative; we will deal with that later.



Example Problem #1

In the figure the ramp is frictionless. Show that if the box is allowed to slide down the ramp, its speed when it reaches the bottom of the ramp (v) does not depend on its mass. Derive a formula for the speed in terms of gravitational potential. If the box's speed does not depend on mass, what is affected by mass?



Solution:

At the top of the ramp the box has gravitational PE.
The Law of Conservation of Energy says that when the box reaches the bottom of the ramp all that PE will be turned into Kinetic Energy (KE):

Energy at Top	=	Energy at Bottom
PE_{grav}	=	KE
$m\,g\,y$	=	$\frac{1}{2}\,m\,v^2$
$\cancel{m}\,U_{grav}$	=	$\frac{1}{2}\,\cancel{m}\,v^2$
v	=	$(2\,U_{grav})^{0.5}$

So my formula is $v = (2\,U_{grav})^{0.5}$

What is affected by the mass is not the box's speed, but it's energy. A more massive box will be packing more KE when it reaches the ground.