The Nature of the Physical World

1 Introduction

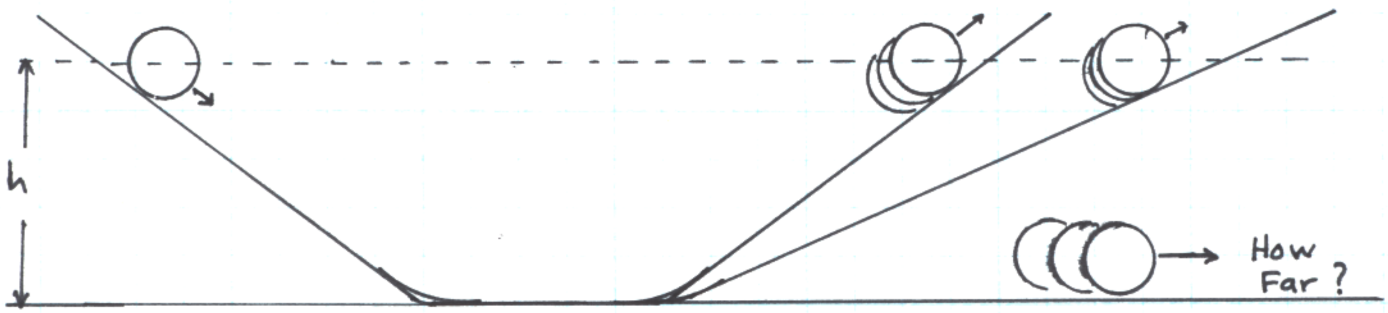
The word "Physics" derives from the Greek word "Phisis" ($\phi\sigma\iota\sigma$), which means "nature." I think the Chinese name for the subject "WU-LI"[物理], is somewhat more descriptive. Loosely translated. this means "how things work." The first character [物] means "things" and is used in such everyday words as "hardware" (metal "things") and garbage ("things" to throw away). The second character [理] means logic and is used in such ordinary words such as cooking (measuring "logic"). I like this word for Physics because it emphasizes the fact that we deal with the normal stuff that we see around us every day. Thus, although physicists study all sorts of extraordinary things like quarks and quasars, atoms and astronomy, etc., none of them has ever been to a quasar, or seen a quark or atom with his or her own eyes. What we know about these exotic things comes from applying the laws and experiences that we have accumulated from working with the ordinary, everyday materials that we *can* see and *can* touch, devising clever ways to use these things to make instruments that can sense those things that we can't see of feel with our own senses, and then applying lots of imagination. Frequently, the conclusions that are arrived at are very strange, counterintuitive and fascinating. We find that a few very simple principles have complex consequences. My intention in this class is to try to give you a flavor of the richness and beautiful subtlety of the subject and the awesome imagination of some of the great thinkers that developed it.

For example, people had seen stars in the heavens since the very begining of mankind. However, only after the invention of the telescope—made from ordinary glass and wood—were people able to see that, in fact, while in most cases the stars were points of light, there were some "stars" that appeared through a telescope as diffuse regions of light in the sky. Around 1755, Immanuel Kant, the famous German philosopher, speculated that these diffuse regions were giant clusters of stars. An idea that was not established until early in this century, when the American astronomer Edwin Hubble, using an extremely powerful (2.5 m in diameter) telescope at the Mount Wilson Observatory in California, was able to distinguish the individual stars in these diffuse regions, which we now call galaxies.

Similarly, no one has ever seen an atom with their naked eye. The ancient Greeks speculated that matter was composed of atoms, but had no real evidence. The atomic picture that we have today developed as a result of the careful categorization of the various elements that people found in nature and the systematic study of the characteristics of light emitted from various hot gases and from the Sun. Subatomic particles (such as electrons) have never been seen directly, their existence was first inferred from looking at the flashes of light that they produced when they hit a phosphorescent screen. The fact that we can extrapolate what we learn from our own limited senses to such enormous extremes is a true miracle of mankind. The nature of this extrapolation is the subject of this class.

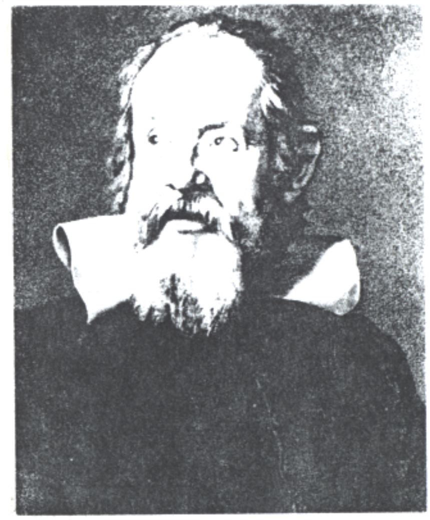
1.1 Laws of Nature: an early example

As a concrete example of this activity, we will try to reproduce what went into one of the first cases where a general law of nature was inferred from careful observations of rather everyday phenomena. This was a set of observations first made by the father of modern science, the Italian genius Galileo Galilei (1564-1642). Galilei did an experiment where he let a ball roll down an incline from some vertical height h, and measured how far it rolled up a connected incline whose angle relative to the horizontal could be varied.



If the track on the left was perfectly horizontal, the ball would travel forever and still not reach its original height.

What Galilei noticed was that as the angle of the second incline was made smaller, the ball would travel further. In fact, what Galilei realized after working with this system of inclined tracks was that the ball always traveled as far as it took to get back to the same vertical height (h) from which it started.



Galileo Galilei

Now a person of ordinary intellect would have been satisfied with this as a general principle that applied to balls rolling down inclined planes. Galilei, being a genius, had much deeper insights. He imagined what would happen if the second incline was exactly horizontal. In that case, the ball would have to travel an *infinite* distance and still not get back to the original height. Thus (if we didn't have any friction, and could make the track long enough, and perfect enough) the ball would continue forever! This was a totally new idea. No one before had considered that something could move forever without something pushing it along. (Planets were kept moving by lots of angels who were continuously flapping their wings.) This idea was reexpressed by Isaac Newton (1642-1727) as the Law of Inertia (or Newton's first law). In Newton's words (translated from Latin)

> *Every body perseveres in its state of rest, or of uniform motion in a straight line, unless it is so compelled to change that state by forces impressed thereon.*

Note that this law makes no mention of balls rolling down inclined planes at all. Moreover, we now know that this law is very general: it applies to the smallest subatomic particles as well as to enormous galaxies billions of light years away. Galilei and Newton knew nothing of galaxies nor of atoms. Thanks to the imagination of these exceptional people, observations and measurements made on a rather prosaic piece of equipment gave enormous insights into "how things work."

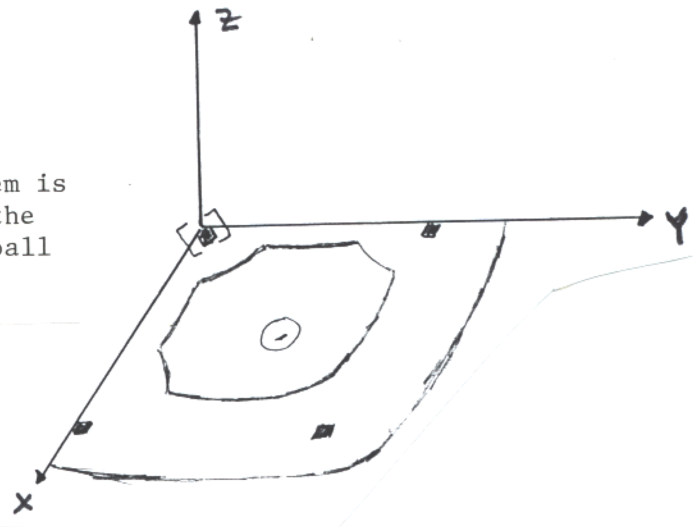
1.2 Measurement

In order to understand the laws of physics and how to apply them to various situations, it is necessary to make quantitative descriptions of what is going on. As we will see, only by precise and detailed studies applied in many different situations can general laws of Physics be deduced. Often, the crucial element in an important discovery comes from the observation of rather small discrepancies in very precise measurements. Thus, an important element of physics is the development of a precise system of measurement. Although in this class we will not go into very much detail about how measurements are made, we must be aware of some of the basic items that would be necessary if we were really going to make these measurements: i.e., coordinate systems and units.

AS SMART AS HE WAS, ALBERT EINSTEIN COULD NOT FIGURE OUT HOW TO HANDLE THOSE TRICKY BOUNCES AT THIRD BASE.

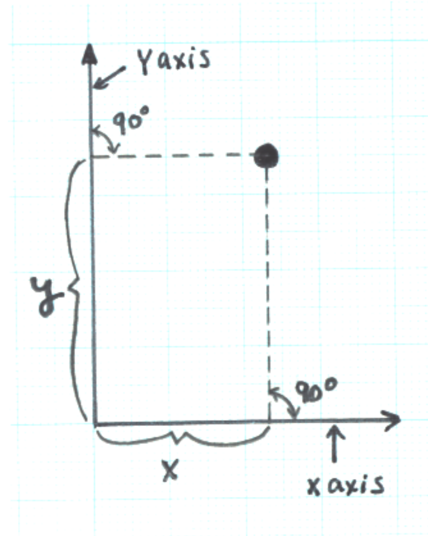
1.2.1 Coordinate Systems

Suppose, for example, we want to study the motion of baseballs that are being batted by a baseball player. To do this with any degree of precision, we must be able to specify the position of the ball at any time. To make measurements, we always need some reference points: i.e. places to put the end of our ruler or to hook the end of our tape measure. These reference points comprise what we call a *coordinate system.* Although there are many possible ways to define coordinate systems, the most common one is the so-called cartesian system, named after the French mathematician René Descartes (1596-1650). Here, we specify three mutually perpendicular directions (called axes) and specify the position of the ball relative to them. The position and orientation of the axes is arbitrary and is usually taken to be whatever seems to be most convenient. For our example, it is simplest to put the origin of the three axes at home plate, have one axis (let's call this the "x-axis") directed along the first-base line toward right field, another (the "y-axis") directed along the third-base line toward left field, and the third axis (the "z-axis") pointed straight up in the air.



A Cartesian coordinate system is well suited for describing the positions and motions of a ball used in a baseball game.

We can completely specify the position of any object by noting its z-coordinate, which is its vertical height above the ground, and its x- and y-coordinates. For these, imagine that the field is covered with a piece of graph paper (as in the figure below). Then the y-coordinate is the number of graph-paper lines that you cross in going from the x-axis (where $y = 0$) to the object—the y-coordinate is the number of graph-paper lines you cross in going from the y-axis (where $x = 0$) to the object. Of course, the field is not really covered with graph paper; what we really do for the y-coordinate is to measure the perpendicular distance from the object to the first-base line (x-axis) using a tape measure or something like that—the x-coordinate is the perpendicular distance from the object to the third-base line (y-axis). If either x or y is negative, the object is in foul territory; if z is negative, the ball is under the ground or in a hole. This coordinate system can be used to specify the position of any object in the stadium (or anyplace else, for that matter), such as a hot-dog saleman, a beer spigot at the concession stand, the Moon, the Sun, the center of our galaxy, etc., etc. etc.



The location of any point in a plane surface is specified by its x- and y-coordinates.

The coordinate system is for our convenience; we can locate it anywhere, and point the axes anyway we like. For example, if we choose to put the origin of the three axes (the point where $x = 0$, $y = 0$, and $z = 0$) at our seat in section 17, row 27, seat 46, we are free to do so. In that case, although the measured values of x, y, and z will be different, that won't effect the outcome of the game, or any incident in the game. If we use either coordinate system to determine the speed of the pitcher's fast ball or the total distance that the ball traveled after it is hit, we get the same result. The actual motion of the object is not effected by the choice of location of the coordinate system, only the numbers that we use to describe it are different.

This latter, rather simple and apparently obvious statement is, in fact, quite profound. We will come across it often when we discuss the very basic views of nature held by physicists. Here I simply state it and trust that it is so obvious to you that you'll accept it as true.

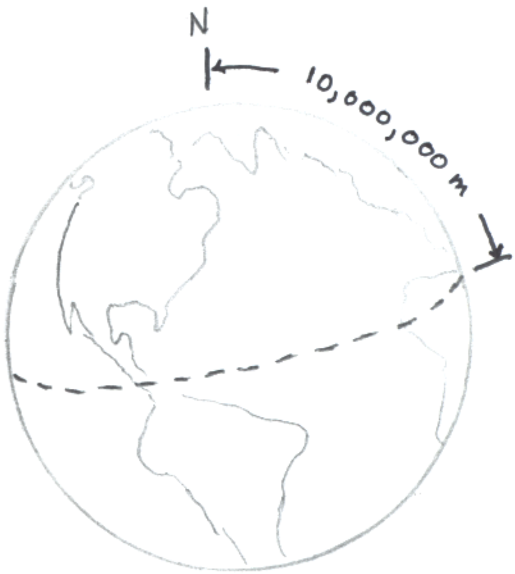
> *The motion of an object and the laws of nature that govern it are not effected by the location or orientation of the coordinate system used to de-*

scribe it.

One of the amazing things about physics is that this simple and seemingly obvious rule has enormous consequences. Its validity had to be established experimentally.

1.2.2 Units

To specify the coordinates of an object, say a baseball, we need a way of expressing our results. For example, to measure the x coodinate of the object alluded to in the previous section, we can pace of the distance between it and the third-base line (the y-axis). This is acceptable, but is of limited usefulness, because everyone has a different size foot, and, thus, our coordinates would depend upon who did the measuring. In the old days there was a simple way around this problem: everyone used the length of the King's foot as a standard. The King would place his foot on a stick and the Royal Measurer would mark off the front and back and then saw off the stick at the position of the marks. Then, the Royal Divider would put marks at 1/2, 1/4,..., etc., of its length, providing a ruler. The Royal Instrument Company would then make accurate copies of this and sell them to the kingdom's linoleum and carpet emporia, tailors and dress makers, and the like. Everyone in the kingdom could use these rulers for their measurements and get consistent results—until the King died, at which time the old rulers were obsolete and new rulers, based on the length of the new King's (or Queen's) foot had to be produced.



The meter was initially defined to be 1/10,000,000th of the distance between the Equator and the North Pole.

This system went out for good when, during the French Revolution, the Frenchmen (and Frenchwomen!) did away with their King, and, thus, needed a more democratic ruler, or unit of length (an inadvertant pun). What they did was to divide the distance from the North Pole to the Equator (via Paris, of course) into 10,000,000 equal parts. This was defined to be the standard of length and was called the "meter," which is roughly 40 inches long. They took a special metal bar and put two fine scratches on the bar that were 1 meter apart, and the distance between the scratches was defined to be the standard unit of length, and all rulers were made in reference to this standard bar. The meter is the unit of measure that we will use in this class, although these days the bar with scratches on it is not a precise enough reference for our high-tech society. Now the meter (still the same length as the Frenchmen's meter) is defined by atomic means.

In this class we will always use meter-based units for length, or the *Metric system.* For shorter distances we will use *centi*meters (1 cm = 1/100th of a meter) and *milli*meters (1 mm = 1/1000th of a meter). For longer distances, we will use *kilo*meters (1 km = 1000 meters). You may be more familiar with the "English" system of measurements, which uses inches, feet, yards, and miles. Although this is a perfectly good system of measurements to use, it is not very popular outside of the U.S., and is hardly ever used for scientific quantities. Thus, the English system is not very convenient for a class like this, and we will use metric units for everything (although now and then I may note what something is in English units to give you a better idea of the magnitude of what we're talking about). Below I have made a short table comparing metric units with English units.

Metric	Example	English
1 mm	thickness of a dime	0.04 in
1 cm	radius of a penny	0.4 in
1 m	nose-to-finger distance	39.4 in
1 km	2.5 Laps on the stadium track	5/8 mi

1.3 Exponential thinking

Consider this sheet of paper. It has dimensions of 22 cm by 28 cm and an area of $22 \times 28\ cm^2 = 616\ cm^2$. Now suppose I cut it in half, I end up with two 22 by 14 cm sheets, each with an area of 308 cm^2. Now suppose I keep cutting the remaining sheet of paper in half, every time I cut, the area goes down by a half, so after twelve cuts, the paper is very small—its area is

$$\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times\frac{1}{2}\times 616 cm^2 = (\frac{1}{2})^{12}\times 616\ cm^2 = \frac{616 cm^2}{4096} = 0.15 cm^2.$$

With just 12 cuts, which only takes about a minute, the area of the paper is reduced by a factor of about $\frac{1}{4000}$ (to be exact, a factor of $\frac{1}{4096}$). If I could cut the paper 60 times, i.e. repeat the above exercise five times (which would take only about five minutes if my fingers were small enough), I would have

By cutting a piece of paper in half 12 times, I reduce its area by a factor of 4096.

a piece of paper that was $\frac{1}{1,000,000,000,000,000,000}$ times the size of this sheet, which is about the size of a single atom.

Imagine that we reverse the process and somehow keep increasing this sheet of paper over and over again by a factor of 2. After 10 times, I'd have a sheet of paper with an area that is

$$2\times2\times2\times2\times2\times2\times2\times2\times2\times2\times616cm^2 = 2^{10}\times616cm^2 = 1024\times616cm^2 \simeq 630,000cm^2,$$

an area that is approximately the size of our lecture hall. (The symbol $\simeq$ means approximately equal.) If I doubled its size 80 times, I would have a sheet of paper with an area of $1,200,000,000,000,000,000,000,000$ times the size of this sheet of paper, which is about the area enclosed by the Earth's orbit around the Sun.

Sample Problem

During this semester you are expected to endure more than 15 weeks of physics lectures. Suppose that as an incentive to get through the semester, you decide to reward yourself with an increasing number of glasses of beer each weekend: after the 1$^{\text{st}}$ week you allow yourself one beer ($1 = 2^0$), after the 2$^{\text{nd}}$ week two beers ($2 = 2^1$), the 3$^{\text{rd}}$ week four beers ($4 = 2^2$), etc. How many beers will you be entitled to after the 15$^{\text{th}}$ week?

Answer:
Continuing the above reasoning, we see that after the 15$^{\text{th}}$ week, you will be entitled to 2^{14} beers. To see how many this is, enter 2 into your calculator, push the x^y button, then enter 14 and push the = button. My calculator tells me that you will be entitled to 16,384 glasses of beer!

Now in physics, we frequently deal with things much smaller than atoms and larger than the Solar System. However, small numbers like $\frac{1}{1,000,000,000,000,000,000}$ are difficult to imagine, much less keep track of or deal with; the same can be said for such enormous numbers like $1,200,000,000,000,000,000,000,000$.

However, to get the number $\frac{1}{1{,}000{,}000{,}000{,}000{,}000{,}000}$, we multiplied $\frac{1}{2}$ by itself 60 times—60 is not such a difficult number to deal with; and to get $1,200,000,000,000,000,000,000,000$ we multipled 2 by itself 80 times—80 is not so difficult to deal with either. Thus, when dealing with very small or very large numbers it is much easier to think in terms of the exponent, rather than the number itself—this is called *exponential thinking*.

1.4 Powers of 10

Usually, since we work with a decimal-based number system, we do not deal with powers of 2 or $\frac{1}{2}$, and instead use powers of 10 ar $\frac{1}{10}$. Nevertheless, the logic is the same and only slightly more difficult to imagine than the examples based on powers of 2 and $\frac{1}{2}$ given above.

1.4.1 Big things

To illustrate the application of exponential thinking to powers of 10, I've made a little chart of sizes and distances that you may have to consider during this semester. (In my chart, the symbol $\sim$ means "roughly equal," and implies somewhat less precision than the $\simeq$ symbol.)

From my nose to my finger	~1.0 m
From the front to the back of PSB 217	~10 m
From PSB to Puck's Alley	~1000 m
From Manoa to Haleiwa	~50,000 m
Radius of the Earth	6,370,000 m
From the Earth to the Moon	386,000,000 m
From the Earth to the Sun	~150,000,000,000 m
From Earth to the Next Star (Alpha-Centauri)	~40,000,000,000,000,000 m

Here we are only up to the next star, and I'm already running out of room to write down all of the zeroes that I need, I'll really be in trouble if I start worrying about *really* big distances, such as the distance to the edge of the

Universe. Clearly it would be useful to have a simpler, yet systematic way of dealing with such large numbers. We do this by thinking exponentially and keeping track of "powers of 10."

To see how this works, consider the following:

$$10^0 = 1$$

$$10^1 = 10$$

$$10^2 = 10 \times 10 = 100$$

$$10^3 = 10 \times 10 \times 10 = 1,000$$

$$10^4 = 10 \times 10 \times 10 \times 10 = 10,000$$

$$10^5 = 10 \times 10 \times 10 \times 10 \times 10 = 100,000$$

$$10^6 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 1,000,000$$

etc.

These guys need to learn about powers of 10 notation.

For these numbers, the number of zeroes equals the number of times we have to multiply by 10, i.e., it is the exponent of 10. Thus, for example,

$$1km = 1000m = 10^3 m,$$

$$5km = 5 \times 1km = 5 \times 10^3 m,$$

and the radius of the Earth is

$$6,370,000m = 6.370 \times 1,000,000m = 6.37 \times 10^6 m.$$

To express an ungainly large number in power of 10 notation, the "power of 10" is just the number of places that you have shifted the decimal place to the left:

$$5000. = 5. \times 10^3 \quad \text{i.e., 3 shifts to the left} \rightarrow \text{3 powers of 10.}$$

The distance to Alpha-Centauri (the star that is closest to the Sun) is then

$$40,000,000,000,000,000.m = 4. \times 10^{16} m \quad \text{16 shifts} \rightarrow \text{16 powers of 10.}$$

This notation makes it particularly easy to multiply two large numbers. Just remember the rule

$$10^a \times 10^b = 10^{(a+b)}$$

i.e., when you multiple two numbers, just add the exponents. For example

$$5,000 \times 6,370,000 = 5 \times 10^3 \times 6.37 \times 10^6 = 5 \times 6.37 \times 10^3 \times 10^6$$

$$= 31.8 \times 10^{(3+6)} = 31.8 \times 10^9 = 3.18 \times 10^{10}.$$

Here, in the last step I shifted the decimal point 1 place to the left and compensated by adding 1 to the power of 10.

1.4.2 Little things

Below I list the sizes of various small things we might want to discuss.

Radius of a Penny	$\sim \frac{1}{100}$ m = 0.01 m
Thickness of a Dime	$\sim \frac{1}{1000}$ m = 0.001 m
Radius of a Human Hair	~0.000075 m
"Diameter" of a red blood cell	~0.00000002 m
Radius of a Hydrogen Atom	~0.00000000006 m
Radius of a Hydrogen Atom's Nucleus	~0.000000000000001 m

To deal with numbers less than 1, we first note that

$$0.1 = \frac{1}{10} = 10^{-1}$$

$$0.01 = \frac{1}{100} = \frac{1}{10} \times \frac{1}{10} = \frac{1}{10^2} = 10^{-2}$$

$$0.001 = \frac{1}{1000} = \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} = \frac{1}{10^3} = 10^{-3}$$

etc.

For numbers less than 1, the power of 10 is negative and equal to the number of shifts that you make to the right. For example,

$$0.0005 = \frac{5}{10,000} = \frac{5}{10^4} = 5 \times 10^{-4}$$

or, more simply

$$0.0005 = 5 \times 10^{-4} \quad 4 \text{ shifts} \rightarrow \text{power of } 10 = -4$$

For multiplying, the same rule holds, just add exponents. But here you have to be careful of the signs.

$$5,000. \times 0.0005 = 5. \times 10^3 \times 5. \times 10^{-4} = 5. \times 5. \times 10^3 \times 10^{-4}$$

$$= 25 \times 10^{(3-4)} = 25 \times 10^{-1} = 2.5$$

Although I will not use very sophisticated mathematics during this class, the nature of the things that we will discuss is such that the use of powers-of-10 notation is unavoidable. Please practice this and develop some degree of familiarity with it. It is an important skill that will serve you well even outside of your physics class.

(It is my experience that even the most "non-mathematical" person has rather good quantitative skills whenever money is involved. Thus, if you are not comfortable with a certain calculation, put dollar signs in front of one of the numbers and then proceed. At the end erase the dollar signs.)

Sample Problem

The U.S. Federal deficit is about 5 trillion dollars (= $\$5 \times 10^{12}$) and the population of the U.S. is about 250 million ($250 \times 10^6 = 2.5 \times 10^8$) people. What is the amount of debt per person?

Answer:
Simply divide the amount of the debt by the number of people.

$$\frac{\$5 \times 10^{12}}{2.5 \times 10^8} = \frac{\$5}{2.5} \times 10^{(12-8)} = \frac{\$5}{2.5} \times 10^{+4}$$

$$= \$2.0 \times 10^4 = \$20,000/\text{person},$$

the price of a pretty nice new car.

I can do this on my calculator as follows:

- enter 5
- push the $\times$ button,
- enter 12
- push the 10^x button
- push the $=$ button

- push the $\div$ button
- enter 2.5
- push the $=$ button
- push the $\div$ button
- enter 8
- push the 10^x button
- push the $=$ button.

(Your calculator may be a little different.)