Part 1: Introduction to Physics and Units of Measurement

University Physics V1 (Openstax): Chapter 1
Physics for Engineers & Scientists (Giancoli): Chapter 1

Physics from ancient Greek meaning "knowledge of nature"

- Physics is the most fundamental branch of science.
- **Physics is the study of the behavior and structure of matter , including**
  - Its motion through time and space, and
  - Related concepts such as energy, momentum, and forces.
- Major areas of study in physics include:
  - Classical Physics (thru 1900)
    - Classical Mechanics
    - Thermodynamics
    - Electromagnetics
  - Modern Physics
    - Relativity (Special and General)
    - Quantum Mechanics

Physical Quantities have 3 parts

- Number
- Units
- Uncertainty

When you ask someone their age and they respond, "21" we know that they mean 20.5 ± 0.5 years.

Fundamental Quantities in Mechanics

- Time (T)
  - The standard SI unit for time is the second (s)
  - A second is defined to be "9,192,631,770 periods of the radiation of a cesium-133 atom."
- Length (L)
  - The standard SI unit for length is the meter (m)
  - The meter is defined to be "the distance travelled by light in through a vacuum in 1/299,792,456 s" (fixes c = 299,792,456 m/s)
- Mass (M)
  - The standard SI unit for mass is the kilogram (kg)
    ...NOT the gram (g) as is commonly used in other sciences such as chemistry
  - The kilogram was defined to be the mass of "the International Prototype Kilogram" or "IPK", a platinum-iridium cylinder kept at the "International Bureau of Weights and Measures" near Paris.
    - 40 copies were made and distributed to countries around the world.
    - Every kilogram mass is a copy of one of these copies
    - As contaminants could coat the kilogram's surface, they made the masses into cylinders, which have less surface area to acquire dust and debris.
    - The mass is stored in filtered laboratory air at constant temperature and pressure in an environmentally monitored safe in the lower vault. Three independently controlled keys are required to open the vault.
    - To clean it skilled technicians rub the cylinders with chamois leather dipped in alcohol.

- As the IPK has been found to vary in mass over time, a new definition based on Planck's constant was adopted on May 20, 2019. The kilogram has been redefined as the mass equivalent to the energy of 1.4755214×10^{40} photons at the frequency of the cesium atomic clock.

These quantities may be combined into new quantities (derived quantities).
For example, density is defined as mass per volume, and the standard units for density would be kg/m^3.

Units

- Units are carried through calculations much like an algebraic variable (x or y).
  - 7.1 cm + 5.2 cm = 12.3 cm
  - 5.0 m × 3.0 m = 15 m^2
  - 8.40 m ÷ 2.0 s = 4.2 m/s
- Numbers can only be summed when the units match.
  - If the units are for the same quantity (length, time, mass, etc), then they can be converted to same unit and then summed.
  - For example, You can't add 1.21 m + 48 cm
  - You can, however, convert 1.21 m to 121 cm, and then add 121 cm + 48 cm = 169 cm.

How to convert units will be explained later.

You can detect algebraic errors made when performing calculations by keeping the units with the numbers.

yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto	h	10^{2}
deca	da	10^{1}
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

Metric Multipliers (Prefixes)

- When dealing with very large or very small numbers, it is common to use scientific notation.
- A further simplification is to use Metric prefixes and multipliers.
- Metric multipliers (prefixes) take the place of the power of ten and are placed directly in front of the units (becoming a part of the units).
  - 1,210,000,000 Watts = 1.21×10^9 W = 1.21 GW
    "*1.21 gigawatts*"
  - 0.0357 meters = 3.57×10^{-2} m = 3.57 cm
    "*3.57 centimeters*"
  - 1050 g = 1.05×10^3 g = 1.05 kg ("*kilograms*")

The letter used for "micro" is the Greek letter "mu" (μ).

Unit Conversion

- To convert from one set of units to another, simply multiply by "1".
- First, find a conversion that compares the unit you have with the units you want (or a series of conversions if needed). For example
  - 1 year = 365.25 days
  - 1 day = 24 hours
  - 1 hour = 60 minutes
  - 1 minute = 60 seconds
  - 1 mile = 1609 m
  - 1 ft = 0.3048 m
  - 1 inch = 2.54 cm
- Writing a conversion as a ratio gives you "1" (1 day/24 hours = 1)

Examples

The Gateway Arch in St. Louis is 630 feet tall. How tall is it in meters?

$$(630\ ft)\left\{\frac{0.3048\ m}{1\ ft}\right\} = 192\ m$$

How many seconds are there in a year?

$$(1\ year)\left\{\frac{365.25\ days}{1\ year}\right\}\left\{\frac{24\ hours}{1\ day}\right\}\left\{\frac{60\ min}{1\ hour}\right\}\left\{\frac{60\ s}{1\ min}\right\} = 31{,}557{,}600\ s$$

The speed of light is 3.00×10^8 m/s. What is its speed in km/s?

$$\left(3.00\times10^8\ \frac{\mathrm{m}}{\mathrm{s}}\right)\left\{\frac{1\ km}{10^3\ m}\right\} = 3.00\times10^5\ \frac{\mathrm{km}}{\mathrm{s}}$$

A car is moving at 65 mph. How fast is that in m/s?

$$\left(65\ \frac{miles}{hour}\right)\left\{\frac{1609\ m}{1\ mile}\right\}\left\{\frac{1\ hours}{60\ min}\right\}\left\{\frac{1\ min}{60\ sec}\right\} = 29.05\ \frac{m}{s}$$

Dimensional Analysis

- All the equations in physics are dimensionally consistent (i.e. the units work)
- This can be checked by doing dimensional analysis
    - Replace each quantity (both number and unit) with the letter representing the fundamental quantity ("L" for lengths, "T" for time, and "M" for mass).
    - Simplify and combine

Example (with unit conversions): x = 20ft + (25mph)(150s) + (5m/s^2)(2.5 min)^2

- Are the dimensions consistent? → Dimensional Analysis

$$\begin{array}{lcl} x\ (\text{in meters}) & = & 20\text{ft} + (25\text{mph})(150\text{s}) + (5\text{m/s}^2)(2.5\ \text{min})^2 \\ L & = & L + \left(\frac{L}{T}\right)(T) + \left(\frac{L}{T^2}\right)(T)^2 \\ L & = & L + L + L \end{array}$$

As lengths add up to give length, the equation is dimensionally consistent.

- Convert units
    - $(20\ ft)\left\{\frac{0.3048\ m}{1\ ft}\right\} = 6.096\ m$
    - $(25\ mph)\left\{\frac{29.05\ m/s}{65\ mph}\right\} = 11.173\ m/s$
    - $(2.5\ min)\left\{\frac{60\ s}{1\ min}\right\} = 150\ s$
- Do the math
    - $x = 6.096\ m + \left(11.173\frac{m}{s}\right)(150\ s) + \left(5\frac{m}{s^2}\right)(150\ s)^2$
    - $x = 6.096\ m + 1675.95\ m + 112{,}500\ m$
    - $x = 114{,}182.046\ m$

Uncertainty

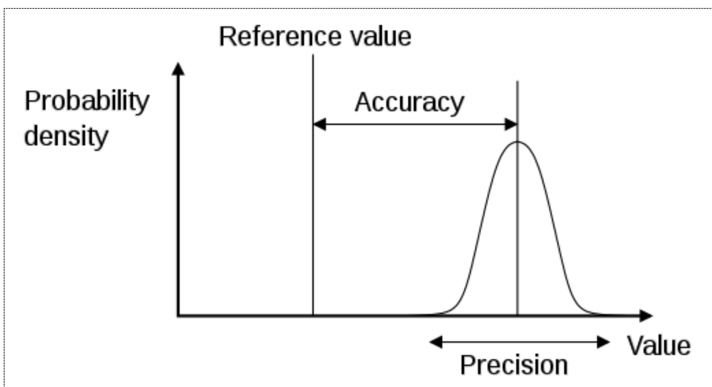
- No measurement is ever perfect. In many cases, this is due to limitations of equipment.
- The degree of uncertainty in a value can be as important as the value itself.

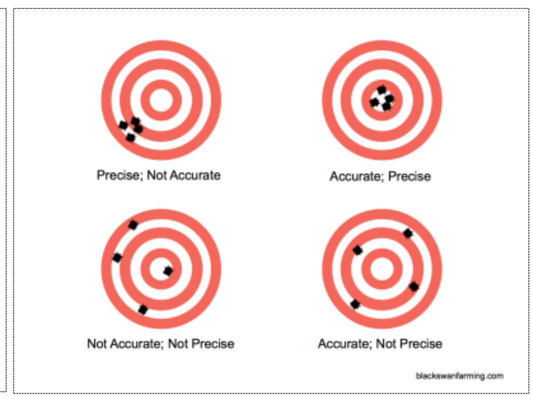
For example, when a police officer asks how fast you were going, telling him "I was going the speed limit give or take 1 mile per hour" is likely to be looked upon more favorably than "I was going the speed limit give or take twenty miles per hour."

- The majority of the material on uncertainties (including standard deviations, combining uncertainties, etc.) will be presented in the laboratory session associated with this course (where measurements are being made).

Accuracy vs. Precision

- Accuracy is a measure of how close the average value of measurements is to a reference value.
- Precision is a measure of how close the measurements are to each other.





Order of Magnitude Estimates

- Order of magnitude estimates are relatively quick and easy to do.
- Performing an order of magnitude estimate provides a check on calculator results (allowing you to catch errors).

In physics, "calculator operator error" happens much more frequently than you might imagine.

- To make an order of magnitude estimate, replace every number in a calculation with the nearest power of 10.
- As this tends to logarithmic in nature, rather than rounding up or down at 5, it is best to use a cutoff near the square root of 10 (3.16) *Hint: It's pretty easy to remember π, 3.14.*
- Powers of 10 are only good to 1 significant figure.

Example (Here's a calculation we did earlier): x = 20ft + (25mph)(150s) + (5m/s^2)(2.5 min)^2

- After unit conversions we found: $x = 6.096\,m + \left(11.173\,\frac{m}{s}\right)(150\,s) + \left(5\,\frac{m}{s^2}\right)(150\,s)^2$
- Let's do an order of magnitude estimate!
  - $6.096\,m \Rightarrow$ 10 m
  - 11.173 m/s $\Rightarrow$ 10 m/s

- 150 s $\Rightarrow$ 100 s
- 5 m/s^2 $\Rightarrow$ 10 m/s^2
- $x = 10\,m + \left(10\,\frac{m}{s}\right)(100\,s) + \left(10\,\frac{m}{s^2}\right)(100\,s)^2$
- $x = 10\,m + 1000\,m + 100{,}000\,m$
- $x = 100{,}000\,m$

- Let's note significant figures: $x = 6.096\,m + \left(11.173\,\frac{m}{s}\right)(150\,s) + \left(5\,\frac{m}{s^2}\right)(150\,s)^2 = 114{,}182.046\,m$
- Do the math: $x = 6.096\,m + 1675.95\,m + 112{,}500\,m = 114{,}182.046\,m$
- So the answer (to the correct number of significant figures) is 100,000 m.

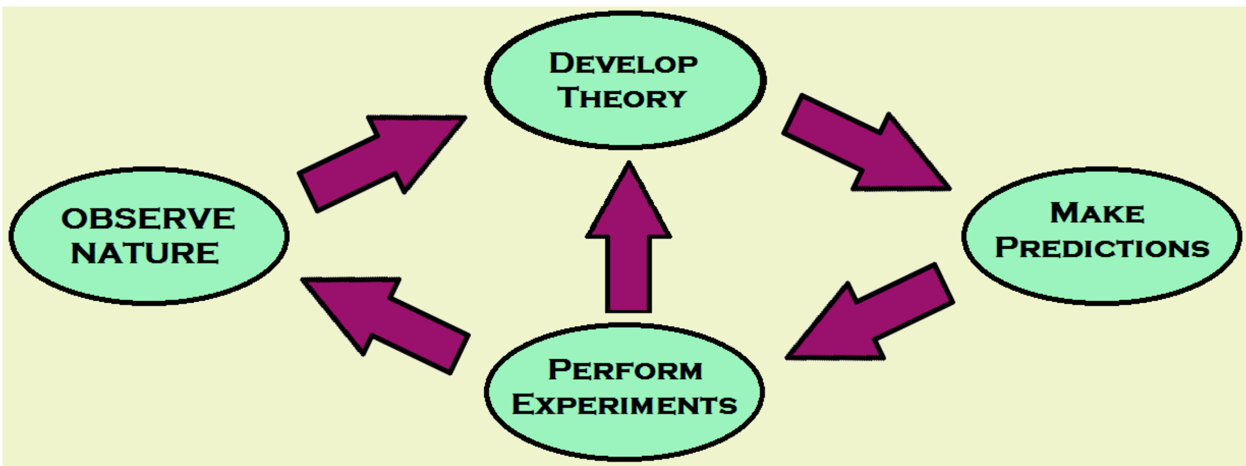
the order of magnitude estimate combined with the knowledge that the last and largest term was only good to one significant figure is sufficient to determine that the first two terms are negligible. We only had to calculate the last term!

Extraneous Note: Enrico Fermi, a Nobel laureate physicist, was a master of making approximations. By accounting for and combining the errors of his approximations he was able to rapidly make extremely accurate calculations using only his mind (without the benefit of a calculator nor even paper and pencil). This is known as "The Fermi Method."

Part 1: Supplemental Material

The Scientific Method

- The Goal of Science is Prediction.
    - The unknown is dangerous (unpredictable)
    - Allows us to make rare events happen (engineering)
- The Scientific Method is a combination of:
    - Logic (ancient Greeks)
    - Experimentation (alchemists)



- Scientific Methodology
    - Observe Nature (i.e. look for patterns)
    - Develop Theories
        - Theories must fit all observations (where applicable)
        - Theories must make testable predictions
    - Make Predictions
        - Predictions must differ from existing theories.
    - Perform experiments (test predictions)
        - These experiments must be repeatable
        - Experimental results may confirm the theory (in which case experimentation continues)
        - If results don't confirm the theory, they may be reconciled. This requires:
            - Something unaccounted for in the experiment affected the results, and
            - When this is accounted for the theory works.
        - One experimental result that can't be reconciled disproves a theory, then either:
            - The theory is modified to account for these results (if possible), or
            - The theory is discarded and a new theory is sought.
        - The more experimentation that a theory survives, the more likely it is to be valid (over some range of conditions). Theories can NEVER be definitively proven.

Significant Figures

- In class (outside of the lab) we will use Significant Figures ("Sig Figs") to account for uncertainty.
  - Digits that are reliably known are "significant figures". Digits that aren't reliable are "insignificant".
  - Numbers are written differently depending upon which digits are significant.
    - Trailing zeros with no decimal point are insignificant
      - "80" $\Rightarrow$ 1 significant figure (the zero is insignificant)
      - "80." $\Rightarrow$ 2 significant figures (the zero is significant)
    - Zeroes to the right of the decimal point are significant ONLY when they follow a non-zero digit.
      - "80.0" $\Rightarrow$ 3 significant figures (the zeroes are insignificant)
      - "80.00" $\Rightarrow$ 4 significant figures (the zeroes are significant)
      - "0.0080" $\Rightarrow$ 2 significant figures (the last zero is significant)
    - In scientific notation, only significant digits are shown
      - "8.0×10^2" $\Rightarrow$ 2 significant figures (the zero is significant)

    "8.0×10^2" is the only way to write "800" with 2 significant figures.

  - Some numbers are considered exact (having an infinite number of significant figures).
    - For example, if I were to count how many students were in a classroom (or any other number known to be an integer) that number would be exact.

  If you have 41 tomatoes, then "41" is exact and has an infinite number of sig figs.

  - The inherent uncertainty is ± 5 in the place beyond your last significant digit.
    - "80" $\Rightarrow$ 80 ± 5 (anything between 75 and 85 not including 85)
    - "80." $\Rightarrow$ 80 ± 0.5 (anything between 79.5 and 80.5 not including 80.5)
    - "80.0" $\Rightarrow$ 80 ± 0.05 (anything between 79.95 and 80.05 not including 80.05)
    - "0.0080" $\Rightarrow$ 0.008 ± 0.00005 (anything between 0.00795 and 0.00805 not including 0.00805)
    - "8.000×10^2" $\Rightarrow$ 800 ± 0.05 (anything between 799.95 and 800.05 not including 800.05)

Examples

"230" $\Rightarrow$ 2 significant figures (the zero is insignificant)
$\Rightarrow$ The uncertainty is ± 5 (anything between 225 and 235 not including 235)

"230.02 $\Rightarrow$ 5 significant figures (both zeroes are significant)
$\Rightarrow$ The uncertainty is ± 0.005 (anything between 230.015 and 230.025 not including 230.025)

"2.3×10^3" $\Rightarrow$ 2 significant figures (both digits are significant)
$\Rightarrow$ The uncertainty is ± 50 (anything between 2250 and 2350 not including 2350)

"0.03020" $\Rightarrow$ 4 significant figures (the first two zeroes are not significant)
$\Rightarrow$ The uncertainty is ± 0.000005 (anything between 0.030195 and 0.030205 not including 0.030205)

Combining Significant Figures

- All digits are kept throughout all calculations. Insignificant figures are only removed when reporting results (at the very end).
- When the highest-placed insignificant digit is 5 or greater, add one to the last significant digit (i.e. round up). If the highest-placed insignificant digit is less than 5, don't change the last significant digit (i.e. round down).
- When adding or subtracting, a digit in the sum or difference (answer) is significant if the same place (ones, tens, etc.) is significant in every added or subtracted term.
- When multiplying or dividing, the number of significant digits in the product or quotient (answer) is the same as the smallest number of significant figures digit in any term .

Examples:

$2.31 + 4.1 = 6.4\underline{1} \Rightarrow 6.4$ *While 2.31 is good to the hundredths place, 4.1 is only good to the tenth's place. Thus the sum is only good to the tenth's place.*

$4.31 - 2.1 = 2.2\underline{1} \Rightarrow 2.2$ *While 2.31 is good to the hundredths place, 4.1 is only good to the tenth's place. Thus the difference is only good to the tenth's place.*

$4.755 + 60.76 + 0.02 = 65.53\underline{5} \Rightarrow 65.54$ *Each term is good to the hundredths place, but every term isn't good to the thousandths place. Since the thousandths place is a 5, round up.*

$1000 + 100 + 10 + 1 = 1\underline{111} \Rightarrow 1000$ *Because the ones place, the tens place, and the hundreds place are all insignificant in the first term, the answer is only good to the thousands place.*

$2.31 \times 4.1 = 9.4\underline{71} \Rightarrow 9.5$ *4.1 is only good to two significant figures. Thus, the product is only good to two significant figures. The seven (greater than 5) is rounded up.*

$475.5 \div 60.76 = 7.82587228\ldots \Rightarrow 7.826$ *Each term is good to four significant figures. Therefore the product is good to four significant figures. Round up the 8.*

$(7.14 + 3.3) \times 4.05 = (10.4\underline{4}) \times 4.05 = 42.282 \Rightarrow 42.3$

Because the hundredths place in 3.3 is NOT significant, the hundredths place in 10.44 is not significant. As 10.4 and 4.05 are both good to three significant figures so is their product. While the last 4 in "10.4<u>4</u>" is not significant, it remains in the calculation until the end. Dropping it leads to the answer "42.1, which is incorrect.

Disturbing Sig Fig Exercise: $3 \times 5 = ?$ $3 \times 7 = ?$ $3 \times 8 = ?$

Remember, "20" means anything between 15 and 25, and "200" means anything from 150 to 250.

Significant Figures of Conversion Factors

- Some conversion factors are considered exact (i.e. having infinite number of sig figs)
  - 1 day = 24 hours
  - 1 minute = 60 seconds
  - 1 hour = 60 minutes
- In other conversion factors, the 1 on one side is considered exact, while the significant figures of the other term are determined normally.
  - Using "1 mile = 1609 m" as a conversion factor would only be good to 4 sig figs.

Exercises

You are expected to know how to convert units and use the appropriate number of significant figures. However, on tests we will treat all the values given as exact and simplify the answer to 3 significant figures (rounding the fourth significant figure of 5 or greater upwards and anything less than 5 downwards). Also remember that ExpertTA, the homework service, does not use significant figures unless specified in the problem. ExpertTA calculates the answer exactly and checks that your answer is within a few percent. Using significant figures on your homework could cause you to get problems wrong.

1. How many seconds are there in a 30-day month?

2. Convert 256 inches into meters. Use the correct number of significant figures.

3. Convert 180 km into miles. Use the correct number of significant figures.

4. A ship is moving at 25 knots. How fast is it moving in mph? Use the correct number of significant figures.

5. A Box is 45 cm long, 25 cm wide, and 15 cm tall. Determine the volume of the box in liters. Use the correct number of significant figures.

6. You have 4 jugs that each hold 1.00 gallons and two bottles that each hold 2 liters of fluids. Determine the combined volume of fluid they can hold. Use the correct number of significant figures.

   While we are at it, let's check to see if you make same rather common calculator errors. Just punch these last ones into your calculator to see if you get the right answers.

7. Divide 12.56 by 2π

8. Divide 5.00×10^{-9} by 4

9. Divide 15×10^{8} by 2.5×10^{4}

Exercise Solutions

1. How many seconds are there in a 30-day month?

$$(30\ days)\left(\frac{24\ hours}{1\ day}\right)\left(\frac{60\ min}{1\ hour}\right)\left(\frac{60\ s}{1\ min}\right) = 2{,}592{,}000\ seconds$$

2. Convert 256 inches into meters. Use the correct number of significant figures.

   Using "1 in = 2.54 cm" from the formula sheet and "1 cm = 10^{-2}m",

$$(256\ in)\left(\frac{2.54\ cm}{1\ in}\right)\left(\frac{10^{-2}\ m}{1\ cm}\right) = 6.50\ m$$ {*Not 6.5024 as answer is only good to 3 sig figs*}

   There are many ways you could have done this. For example. you could also have used "12 in = 1 ft" and "1 m = 3.281 ft".

3. Convert 180 km into miles. Use the correct number of significant figures.

$$(180\ km)\left(\frac{1\ m}{1.609\ km}\right) = 110\ miles$$ {Not 111.87 as answer is only good to 2 sig figs}

4. A ship is moving at 25 knots. How fast is it moving in mph? Use the correct number of significant figures.

$$(25\ knots)\left(\frac{0.5144\frac{m}{s}}{1\ knot}\right)\left(\frac{60\ s}{1\ min}\right)\left(\frac{60\ min}{1\ hour}\right)\left(\frac{1\ km}{1000\ m}\right)\left(\frac{1\ mile}{1.609\ km}\right) = 29\ mph$$ {2 sig figs}

5. A Box is 45 cm long, 25 cm wide, and 15 cm tall. Determine the volume of the box in liters (L). Use the correct number of significant figures.

$$V = (45\ cm)(25\ cm)(15\ cm)\left(\frac{1\ m}{100\ cm}\right)^3\left(\frac{1\ L}{10^{-3}\ m}\right) = 17\ L$$ {good to 2 sig figs}

   Remember that when converting areas of volumes you will need to convert each dimension. In this case, cm^3 means a cm×cm×cm, and all 3 need to be converted to meters.

6. You have 4 jugs that each hold 1.00 gallons and two bottles that each hold 2 liters of fluids. Determine the combined volume of fluid they can hold. Use the correct number of significant figures.

$$(4.00\ gal)\left(\frac{3.785\ L}{1\ gal}\right) + 2\ L = 15.1\ L + 2\ L = 17\ L$$

   {2 L is only good to the 1's place. Any digits past that are not significant.}

7. Divide 12.56 by 2π

$$\left(\frac{12.56}{2\pi}\right) = 1.999$$

If you entered "12.56/2π" into your calculator, you got 19.729*, which is wrong. Your calculator follows the order of operation, which gives no preference to multiplication and division. They are done in order. Consequently,*

$$12.56/2\pi = \frac{12.56}{2} \times \pi = 19.729$$

Instead try "12.56/(2π)" or "12.56/2/π" which will both give the correct answer.

8. Divide 5.00×10^{-9} by 4

$$\left(\frac{5.00 \times 10^{-9}}{4}\right) = 1.25 \times 10^{-9}$$

*If you got "*0.000000001*", then the likely cause is that your calculator truncated your answer because of the display setting. I'd recommend leaving the display setting as there are other ways to handle this. You could (1) multiply your answer by* 10^9*, revealing the extra digits that are off your screen, or (2) calculate the value again but calculate the powers of 10 separately. In this case that would look like this:*

$$\left(\frac{5.00}{4}\right) = 1.25 \text{ with a } 10^{-9} \text{ off to the side.}$$

9. Divide 15×10^8 by 2.5×10^4

$$\left(\frac{15 \times 10^8}{2.5 \times 10^4}\right) = 6 \times 10^4$$

If you got "6×10^{12}*", then the likely cause is that you got caught by the order of operations again.*

$$15 \times 10^8/2.5 \times 10^8 = \frac{15 \times 10^8}{2.5} \times 10^8$$

Instead try putting parentheses around your denominator. "$15\times10^8/(2.5\times10^4)$" will get you the right answer. You would also get the right answer if you use the "EE" button on your calculator. When you enter "1", then "5", then "EE", and then "8", your calculator will display "15E8", which is all treated as one number by your calculator rather than two numbers, "15" and "10^8" that are being multiplied together.