INTRODUCTION
How To Make A Good Grade In A Lab Course Without Really Trying

A laboratory course may seem to involve a lot of work for too few credits. However, remembering the following points may help:

A. A laboratory course supplements the lecture course and helps the students grasp the basic concepts of the subject.

B. A laboratory course teaches the students to be systematic and organized.

C. A laboratory course helps the students realize the distinction between 'exact' theoretical concepts and limitations of 'physical reality' of experimental work.

A Few Simple Rules:

1. Learn the basic theory of the experiment, working of the various pieces of equipment used in the experiment and the procedure of the experiment. Read the experiment, become familiar with the data sheet and answer the pre-lab questionnaire before coming to the laboratory.

2. In the laboratory, follow the steps of the procedure as described in the laboratory manual and record the observations as they appear in the data sheet. The readings should be recorded correct to the least count of the instruments. In general, if estimation is to be done, it should be done correct to half of the value of the smallest division on the scale of the measuring device. Units must be entered where necessary.

3. It is a good practice to make a copy of the data sheet in the note book, perform the calculations and then transfer the data onto the data sheet. Use scientific notation where necessary and avoid non-significant figures.

4. Prepare the laboratory report as soon as possible and submit the report on time.

Physical Quantities and Units:

Scientific work involves dealing with physical quantities - quantities that can be measured. Examples of physical quantities are length, mass, time, velocity, force, momentum, energy, etc. Of these, length, mass and time are the fundamental physical quantities. Other physical quantities can be expressed as suitable combinations of length, mass and time. For example, the velocity of a glider can be obtained by measuring its displacement in a given time interval.

Systems of Units:

System	Length	Mass	Time
MKS system	meter (m)	kilogram (kg)	second (s or sec)
cgs system	centimeter (cm)	gram (g or gm)	second (s)
British system or FPS system	foot (ft)	pound (lb)*	second (s)

* In fact, pound is a unit of force. However, in everyday life, it is used as unit of mass, that is , quantity of matter whose weight is 1 pound. The proper unit of mass in FPS system is a slug, which is the mass in which the force of 1 pound produces an acceleration of 1 ft/s^2. 1 slug is equal to 14.59 kg.

The units must be consistent in all calculations.

The units of some physical quantities are presented in the following table:

Physical quantity	cgs unit	MKS unit	Definition
Volume	cm^3	m^3	volume = length x width x height
Density	gm/cm^3	kg/m^3	density = mass/volume
Velocity	cm/s	m/s	velocity = displacement/time
Acceleration	cm/s^2	m/s^2	acceleration = velocity/time
Momentum	gm.cm/s	kg.m/s	momentum = mass x velocity
Force*	dyne	newton	force = mass x acceleration
Energy	erg	joule	energy = work = force x displacement

* Sometimes, force is measured in gm-wt (gram-weight) which is the force of gravity of the earth on a mass of 1 gram.

In a given laboratory experiment, all data should be obtained and recorded either in MKS or cgs units.

Scientific Notation:

Very large and very small numbers are handled more conveniently in scientific notation. Thus numbers like 2570, 14300 and 0.00056 should be written as 2.57×10^3, 1.43×10^4 and 5.6×10^{-4}, respectively. As a rule, numbers larger than 1000 and smaller than 0.001 should be expressed in scientific notation.

Significant figures:

In a number, all nonzero digits and the zeros that are not used to define the position of the decimal point are significant. This is illustrated in the following table.

Number	Number of significant figures
1.27	3
420	2
420.	3
0.023	2
0.0403	3

Rules for determining the number of significant figures in the result:

(i) Conventionally, at most one more decimal digit can be retained than the certainty of the result.

(ii) In addition and subtraction, the sum or difference has significant figures only in the decimal places where the original numbers have significant figures. Thus

$$
\begin{array}{ccc}
6.843 & 500 & 600. \\
+\ 0.002 & -\ 4 & +\ 7 \\
\hline
6.845 & 500 & 607
\end{array}
$$

(iii) In multiplication and division, the result can not have more significant figures than the least accurately known numbers. Thus

$$2.4 \times 5.8 = 14; \quad 2.413 \times 5.8 = 14; \quad \frac{44}{7} = 6; \quad \frac{44}{7.1} = 6.2.$$

In intermediate steps of calculation, generally, an extra significant figure is carried.

Error Analysis: Standard Deviation and Standard Error:

Errors are part of physical reality. In most cases, an error-free result may be obtained accidentally due to cancellation of errors or due to negligence. Some errors are accountable such as errors caused due to inaccurate graduation of a scale. Other errors are unaccountable. These are random errors, mistakes in reading the scale and recording of values, etc.

To avoid mistakes, it is a good practice to take at least 2 readings independently, even though only one reading is to entered in the data sheet. If any reading is substantially different from the other readings, it should be discarded or replaced, if necessary.

If only a few (about 3) readings are taken, the probable error can be considered to be equal to the least count of the instrument (the smallest value of a physical quantity that can be measured by the instrument). Thus the length of a cylinder, obtained with a meter stick, will have a probable error of 0.1 cm, if the scale is graduated in mm. Such a reading can be recorded as 12.3 ± 0.1 cm, if the average of the readings of the length of the cylinder is 12.3 cm.

If a number of readings (about 6) are taken, standard deviation and standard error can be used.

Standard Deviation:
Let n readings x_1, x_2, x_3, . . . x_n be taken. Their arithmetic mean (average) is $\bar{x}$ is defined as

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ . \ . \ . \ x_n}{n} \ .$$

Standard deviation is defined as

$$\sigma = \sqrt{\frac{\left(x_1 - \bar{x}\right)^2 + \left(x_2 - \bar{x}\right)^2 + \left(x_3 - \bar{x}\right)^2 + \ . \ . \ . \ \left(x_n - \bar{x}\right)^2}{n}} \ .$$

Finally, the standard error of the mean is defined as

$$\sigma_m = \frac{\sigma}{\sqrt{n-1}} \ .$$

An Example:

Two students, A and B, measure the length of an object with a meter stick and obtain the following values:

Number	Student A's data		Student B's data	
	x, length (cm)	$x - \bar{x}$	x, length (cm)	$x - \bar{x}$
1	31.4	-0.07	31.5	0.03
2	31.5	0.03	31.7	0.23
3	31.5	0.03	31.3	-0.17
4	31.4	-0.07	31.9	0.43
5	31.5	0.03	31.1	-0.37
6	31.5	0.03	31.2	-0.27
7	31.5	0.03	31.6	0.13
8	31.4	-0.07	31.5	0.03
9	31.5	0.03	31.3	-0.17
10	31.5	0.03	31.6	0.13

Results	Student A's data	Student B's data
Mean $\bar{x}$	31.47 cm	31.47 cm
σ	0.046 cm	0.232 cm
σ_m	0.015 cm	0.078 cm
Probable percent error*	0.05 %	0.25 %

* Taking probable error equal to σ_m.

Note that although the mean value in both sets of data is 31.47 cm, the standard deviation and standard error in the first set are smaller than those in the second set. Thus the first set of data is better than the second set.

Percent Errors:

$$\text{Probable percent error} = \frac{\text{Probable error}}{\text{Experimental value}} \times 100 \%.$$

If the standard value of the physical quantity is known, the percent error can be calculated by the formula

$$\text{Percent error} = \frac{(\text{Experimental value - standard value})}{\text{Standard value}} \times 100 \%.$$

Propagation of Errors:

The final experimental value of a physical quantity is obtained by a series of steps of calculations. Thus errors in the experimental data lead to errors in the final result. The following rules are applied to determine the probable error in the result:

(i) In addition and subtraction, the probable error in the result is the sum of the absolute values of the probable errors in the individual quantities which are used in the addition or subtraction. For example,

17.9 ± 0.2   (probable % error = 1.1 %)   14.8 ± 0.5   (probable % error = 3.4 %)
+ 24.3 ± 0.1   (probable % error = 0.4 %)   - 7.9 ± 0.2   (probable % error = 2.5 %)
_____   _____

42.2 ± 0.3 (probable % error = 0.7%)   6.9 ± 0.7   (probable % error = 10 %)

Note that in subtraction, the probable percent error in the result is considerably larger than the probable percent error in the individual quantities.

(ii) In multiplication and division, the probable percent error in the result is equal to the sum of the probable percent errors in the individual quantities. For example, consider the following data:
Length of a cylinder, $\ell = 5.4 \pm 0.1$ cm

(probable percent error = 2%)

Radius of the cylinder, r = 1.24 ± 0.05 cm

(probable percent error = 4%)

Volume of the cylinder,

$V = \pi r^2 \ell = \pi \times 1.24^2 \times 5.4$ cm^3

= 26.07154 cm (as given by the calculator

Probable percent error in V = probable percent error in ℓ

+ 2x(probable percent error in r)

= 2 + 2x4 % = 10%

Here r appears as r^2 in the formula for V. Thus the probable percent error in r has to be added twice in obtaining the probable percent error in V.

Note that the probable percent error in volume V is 10%. Thus the probable error in V is 2.6 cm^3. Accordingly, the volume should be reported as 26 cm^3 or at most 26.2 cm^3. All other digits given by the calculator are not significant.

Further remember that quantities like r in the above example, which are small and are raised to higher powers in the calculations must be measured more accurately.

Examples of Propagation of Errors:
The following examples illustrate propagation of errors:

Error in the sum of two numbers:
Let x = 17.9 ± 0.2 and y = 24.3 ± 0.1.
Maximum value of x + y = (17.9 + 0.2) + (24.3 + 0.1) = 42.2 + 0.3
Minimum value of x + y = (17.9 - 0.2) + (24.3 - 0.1) = 42.2 - 0.3
Thus the error in the sum = sum of the absolute values of errors
$$= 0.2 + 0.1 = 0.3.$$

Error in the difference of two numbers:
Let p = 14.8 ± 0.5 and q = 7.9 ± 0.2.
Maximum value of p - q = (14.8 + 0.5) - (7.9 - 0.2) = 6.9 + 0.7
Minimum value of p - q = (14.8 - 0.5) - (7.9 + 0.2) = 6.9 - 0.7
Thus the error in the difference = sum of the absolute values of
errors in p and q
$$= 0.5 + 0.2 = 0.7$$

Errors in the results of multiplication and division:
Let x = 5.4 ± 0.2 (% error = 3.7 %) and y = 3.0 ± 0.1 (% error = 3.3 %).
Value of the product xy = 5.4 x 3.0 = 16.2.
Maximum value of xy = (5.4 + 0.2)(3.0 + 0.1) = 17.36 = 16.2 + 1.16.
Percent error in the maximum value of xy = 7.2 %.
Minimum value of xy = (5.4 - 0.2)(3.0 - 0.1) = 15.08 = 16.2 - 1.12.
Percent error in the minimum value of xy = 6.9 %.

Value of $\dfrac{x}{y} = \dfrac{5.4}{3.0} = 1.8.$

Maximum value of $\dfrac{x}{y} = \dfrac{5.4 + 0.2}{3.0 - 0.1} = 1.93 = 1.8 + 0.13.$

Percent error = 7.2 %

Minimum value of $\dfrac{x}{y} = \dfrac{5.4 - 0.2}{3.0 + 0.1} = 1.68 = 1.8 - 0.12.$

Percent error = 6.7 %

Note that in each case, the percent error in the result is nearly equal to the sum of the percent errors in x and y.

GRAPH - An Example

Given the data:

t (sec)	0	5	8	12	17
v (cm/sec)	17	22	26	31	38

We note that t is the independent variable. Thus t should be plotted along the x-axis, and v, along the y-axis.

Suppose the graph paper has 70 divisions along the x-axis and 100 divisions along the y-axis. (Remember that this is just an example.)

First, we choose (x_0, y_0), where x_0 is the minimum value of t to be represented and y_0 is the minimum value of v to be represented. In the present example, $x_0 = 0$ and $y_0 = 17$ cm/sec, but for convenience, we will choose $y_0 = 10$ cm/sec.

The maximum values of t and v are 17 sec and 38 cm/sec, respectively.

Thus, along the x-axis, (17 - 0) sec are to be represented by 70 divisions.

Or 1 sec can be represented by 70/17 = 4.11 divisions.

For convenience, we will represent 1 sec by 4 divisions.

Along the y-axis, (38 - 10) cm/sec are to be represented by 100 divisions.

Or 1 cm/sec can be represented by 100/28 = 3.57 divisions.

For convenience, we shall represent 1 cm/sec by 3 divisions.

Now we form the following table:

t (sec)	v (cm/sec)	$x = t - x_0$ sec	$y = v - v_0$ cm/sec	4*x divisions	3*y divisions
0	17	0	7	0	21
5	22	5	12	20	36
8	26	8	16	32	48
12	31	12	21	48	63
17	38	17	28	68	84

Now plot the graph as follows:

1. Mark the origin. Mark a few equidistant points along the x- and y-axes.
2. Write the physical quantities and the units along the x- and y-axes.
3. Plot the points by using the values in the last two columns of the above table.
4. Draw the 'best' curve such that it passes through as many points as possible, and, nearly as many points are above the curve as below it.

$$\text{slope} = \frac{(v_2 - v_1)}{(t_2 - t_1)}$$