

How to write a laboratory report for PHYS 122L

The following is a collection of directions on how to write a lab report, what it should contain, what is important and what can be kept to the minimum, etc. Read it carefully before starting to write your first lab report and re-read it after one or two lab reports, when you begin to develop some experience. Also study the sample lab report and the comments made between the sections there.

You always write a paper to a specific audience. In this case, assume that the reader is a student from another university who took a physics lab on a comparable level, but never performed this particular experiment. She has general knowledge of the subject, but knows nothing about the details of the particular lab. The report must be a self-contained document that is understandable in itself. No additional source should be required for broad understanding, even though consulting the references (e.g. the Lab Pack) may be necessary to figure out some details.

Use an easily legible, but not oversized font. Cambria or Times, 12-dot size are good, similar fonts are also acceptable. The report must be well organized and written in proper English. It must be a pleasant read, a text, not a bulleted list of facts.

Title and heading

Use the same title as the title in the Lab Pack. In the heading, include your name, your partner's name, and the date of the measurement.

Abstract

Most scientific papers include an abstract. The abstract is a self-contained document that is not a section of the main text. It is a summary of what is contained in the paper, thus it may not present any new information.

The purpose of the abstract is to give a broad idea about the context of the paper, often to help the reader decide whether to read the paper in its entirety. Usually the abstract is available freely on the web site of a journal and it is also reproduced in compilations. Many readers will only read the abstract, while others will decide to get the full paper based on the abstract. Therefore the quality of the abstract is essential.

The abstract is typically 100-150 words long. Shorter is OK, if there is little to say; longer abstracts get skipped. A good abstract should summarize the:

- objective,
- experimental method,
- most important findings,
- any important general remark on the significance of the work,

all that in about 100 words. Condensing the information and selecting the most important points is the key to writing a good abstract. Typically the abstract contains no literature summary, unless it is essential to understand the objective. It is also short on experimental details and data evaluation, unless there is something new and important about the methods.

Purpose of the experiment

You must always begin with a short – one or two sentences – statement of the purpose of the experiment. This can be similar to the text in the laboratory guide, but it should not be a word-by-word copy.

Theoretical principles

There is little new in this section, thus keep it short. But state the most important principles involved and the equations that are needed for the data evaluation. Make references to the Lab Pack and your textbook or other sources instead of going into too much detail. This section should not be longer than half a page.

If you use material from the Lab Pack, the lecture slides, or any other source, make a clear reference. Using a source without proper reference is plagiarism, in other words stealing of intellectual property.

Do not place equations into the text; they must always be on separate lines, numbered to make later references easy. Do not use “calculator format.” $13\text{E}-2$ is unacceptable, use 13×10^{-2} instead.

Experimental procedure

It is important to give a concise but complete description of what you did in your experiment. This should not be a step-by-step regurgitation of the lab-guide procedures but a carefully written summary of what you did. References to the Lab Pack are OK. More detail is required, if you deviated from or improved on the prescribed procedure. Note that some attention is being paid to the uncertainty of the measured results. It is not necessary to include sketches in this section, unless it is needed to show your unique way of doing the measurement.

Separate theory from procedure in a reasonable way. Do not jump back and forth between fundamental equations and technical details.

Experimental data

Present your raw data in this section. Use tables rather than hiding data in the text. Every table must have a number and a caption. The caption is an extended title; it should not contain further data or any long description. Include units and instrumental limit error.

Data analysis and discussion of results

This is the longest section of your report, where you use the directly measured quantities to derive the quantities of interest. Too much numerical detail may break the flow of this section. In order to keep the report readable, you can present the details, such as spreadsheets for fitting, in an appendix. Yet, the main document should contain enough detail to keep it understandable on its own. It is a balancing act, but a very important one. Make sure to cross-reference the main text and the appendix: write “details in Appendix X” in the text, while in the appendix the final results that are used in the text must be boxed and a reference to the location in the text must be made. This can be done in pencil on a printout of the spreadsheet or some similar simple, fast, but clear way.

Error evaluation is part of this section also. It is very important – and correspondingly a large portion of your grade. An otherwise perfect lab report without proper error evaluation gets a marginal C. Do not risk it. It is tedious but important. If the error evaluation is too long, do it in an appendix. But make sure the source of the values in the text come from an identifiable source.

Use plots to present your results and evaluate desired quantities as needed. Make sure that your plots look good: Font sizes should be similar to the fonts of the text; symbols clear but not oversized, proper axes, axis titles with units, labels, etc. Every figure must have a number and a caption. The text refers to the figures by their numbers.

The Lab Pack directions to some experiments contain a few questions to guide your thinking. Those are not rhetorical questions; answer them as part of your discussion.

Conclusions

This is probably the most important section of your report. It is here where you discuss the meaning of your results. Compare your results with expected values from theory or other measurements. It is here that you describe potential error sources and what to do about them. Be as specific as possible. Generic statements like “the disagreement is probably due to experimental error” are worth nothing.

Appendixes

This is the place for spreadsheets for error evaluation, fitting, details of error propagation, etc. The appendix need not contain well-edited text. Instead, it is a place for details and number crunching. Make sure that it is easy to identify the items in the appendix. Indicate what is happening and where the results are used in the text. Include a printout of your spreadsheets and the formulas, used in error propagation (such as the necessary partial derivatives.)

Rubric

Grades will be assigned according to the rubric posted in Blackboard, used with some flexibility as required by the diverse style of the experiments.

The following section relates to a fictitious experiment in PHYS122L. It consists of the lab directions and the corresponding laboratory report. It is shorter than the “real” experiments, but has the same components. It should be used as a sample for your own lab reports. Text in black is part of the report. The sections in gray (like this paragraph) are comments on the expectations.

Measurement X

Spheres Rolling down an Inclined Plane: Measuring Moment of Inertia

This section simulates the kind of description given for each measurement in this Lab Pack. It gives guidance to your work in the lab as well as to the evaluation and interpretation for the lab report.

Purpose of the experiment

- Use simple kinematics to determine the acceleration of a ball rolling down an inclined plane.
- Use the dynamics of rotational motion combined with the conservation of energy to deduce the moment of inertia of hollow and solid balls.

Theoretical background

Consider a ball rolling down an inclined plane with zero initial velocity, as shown on Figure 1 below.

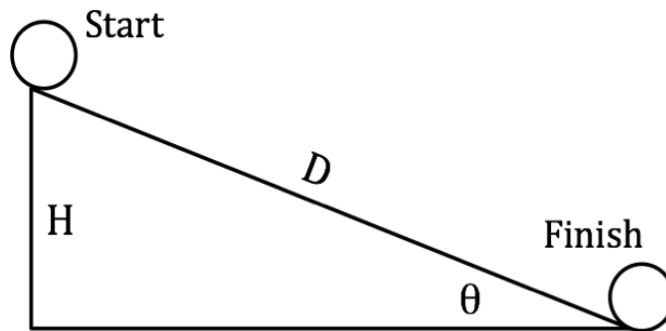


Fig. 1. Ball rolling down an inclined plane

If the ball rolls without slipping, the angular velocity of its rotation relates directly to the velocity of its translational motion,

$$v = \omega * r \quad (1)$$

thus the conservation of mechanical energy gives

$$mgH = \frac{1}{2}mv_f^2 + \frac{1}{2}I\omega_f^2 = \frac{1}{2}mv_f^2 + \frac{1}{2}(\beta mr^2)\left(\frac{v_f}{r}\right)^2 = \frac{1}{2}mv_f^2(1 + \beta). \quad (2)$$

Here we included the fact that the moment of inertia of a symmetrical rolling object can always be written as

$$I = \beta mr^2. \quad (3)$$

We also know that the maximum height of the inclined plane can be calculated using trigonometry as

$$H = D \sin(\theta). \quad (4)$$

Combining Eqs. (2) and (4), the final velocity of the ball at the bottom of the incline is

$$v_f^2 = \frac{2gD \sin(\theta)}{1 + \beta}. \quad (5)$$

The ball rolls with constant velocity motion, thus the kinematic relationship

$$v_f^2 = 2aD \quad (6)$$

applies. If we combine Eqs. (5) and (6), $2D$ drops out and the acceleration is obtained as

$$a = \frac{g \sin(\theta)}{1 + \beta} \Rightarrow \beta = \frac{g \sin(\theta)}{a} - 1 \quad (7)$$

Thus β can be calculated if a is known for a given value of θ . The acceleration can be determined by measuring the time it takes to roll down the entire length of the inclined plane

$$a = 2D/t^2 \quad (8)$$

Experimental procedure

Two photogates are set up in such a way that the first one starts the timer right after letting the ball move and the second one stops the timer when the ball reaches the bottom of the inclined plane.

Make sure that the two photogates are connected to the LabPro interface and the USB output of the LabPro is connected to the MAC. Turn on the power to the LabPro. Then click on the “Timer” icon to start the software. A simulated digital stopwatch should appear on the screen.

Solid ball

Measure the mass and the radius of the solid ball. According to the theory, you will not need these data. Nevertheless, they may come in handy for estimating possible errors, such as air resistance. Also measure the length of the inclined plane; it is the same as the distance between the photogates.

Set the angle of the inclined plane to 15° and roll down the solid ball five times. Measure the time it takes to reach the bottom of the incline.

Repeat for 30° and for 45° .

Calculate the acceleration and then the value of β for the solid ball for each angle. Determine the error of your results.

Hollow ball

Repeat the same procedure with the hollow ball.

Compare your results with the theoretically accepted values. Do they agree? Which ball has the larger β value and why?

Consider possible systematic errors and how to identify them and – if necessary – eliminate them or correct for them.

PHYS122L Laboratory Report**Moment of Inertia of Solid and Hollow Spheres****Student Name: Joe Smith****Lab partner: Jane Weaver****Lab Section: Tuesday****Abstract**

The moment of inertia of hollow and solid spheres was studied by measuring the travel times of two balls down an incline plane of known length as a function of angle. The results confirm the theoretical values of $\frac{2}{5} mR^2$ and $\frac{2}{3} mR^2$ within the approximately 10% experimental error. For a good quality measurement it is important to measure the angle of the inclined plane accurately and to make sure that the angle is not too high so that the balls roll without slipping.

This abstract is 84 words long. Notice that it is very condensed, yet states two important conclusions on the angle of the inclined plane and its accuracy.

Purpose of the experiment

The main goal of this experiment is to study the difference between the moments of inertia of solid and hollow spheres. In particular, solid spheres are supposed to have lower moment of inertia than hollow spheres with the same mass and radius. The comparison will be accomplished by determining the ratio I/Mr^2 for the various spheres.

You must always begin with a succinct statement of the purpose of the experiment. This can be similar to the text in the laboratory guide, but it should not be a word-by-word copy. Instead, a statement in your own words is required. After having done the experiment, you may wish to state its purpose differently anyway, based on your own experience.

An important principle for writing the report: It should be a self-contained document, understandable for a person who has general knowledge of the subject, but knows nothing about the details of the particular lab (like a student from another university who took a physics lab on a comparable level, but never did this particular experiment.) The report must describe what you did, why you did it, what you found, and what it all means.

Theoretical principles

When a sphere rolls down an inclined plane, it travels with constant acceleration motion. As described in the Lab Pack, the acceleration relates to the length of the incline and the time it takes to travel the distance D according to Eq. (8):

$$a = 2D/t^2. \quad (1)$$

The dynamics of the motion can be described using conservation of energy and basic kinematics as described in the Lab Pack. Alternatively, one could use Newton's second law and the corresponding fundamental equation of rotation. Either way

$$a = \frac{g \sin(\theta)}{1 + \beta} \quad (2)$$

is obtained (Eq. (7) of the Lab Pack.) Here β is the coefficient in the definition of the moment of inertia. The moment of inertia of any round object is proportional to the mass of the object and the square of its radius, thus it makes sense to write it as

$$I = \beta mr^2, \quad (3)$$

as given by Lab Pack Eq. (3). For a solid sphere $\beta = 2/5$ and for a hollow sphere $\beta = 2/3$ (see e.g. Young and Freedman, Introductory Physics, 13th ed. p. 291.)

Experimental procedure:

Solid and hollow steel spheres were rolled down an inclined plane, and the acceleration of each was measured by recording the time it took for a sphere to roll the distance D . The timing was done using light beams and photogates to “start” and “stop” a digital timer that is part of the LabPro data acquisition interface that feeds data to a laptop. The acceleration, a , was calculated for each attempt using Eq. (1), then the value of β was calculated by rearranging Eq. (2)

$$\beta = \frac{g \sin \theta}{a} - 1. \quad (4)$$

The procedure was repeated for three values of the angle of inclination of the plane, θ , namely 15° , 30° , and 45° . The time measurement was repeated five times for each angle for both the hollow and the solid sphere to determine the random error of the results.

Notice that the theoretical description is separated from the experimental details. Both are compact, as the Lab Pack contains all the details. But these sections are necessary to make the report understandable for a reader who is not familiar with the measurement and the instructions in the Lab Pack. References are plentiful.

It is important to give a concise but complete description of what you did in your experiment. This should not be a step-by-step regurgitation of the lab guide procedures but a carefully thought out *after-the-experiment* summary of what you did. Note that some attention is being paid to the uncertainty of the measured results.

It is not necessary to include sketches in this section. In fact, you should avoid sketches, if at all possible. You could directly copy a figure from an existing source, but then your action may be considered plagiarism; a reference to the source will do instead. (The reproduction of entire figures requires written permission from the copyright holder in real publishing.) Or you may draw your own sketch, but it is very time consuming. Do it only if you need to show some missed detail or a change of the arrangement and it is impossible to do it clearly without a figure. Of course, you will include graphs of your own data.

Experimental data

A precise value of the length of the inclined plane is critical as it shows up in every calculation. Our best value is

$$D = 0.800 \pm 0.002 \text{ m.}$$

The error reflects ILE in reading the meter stick.

Solid sphere

The mass and the radius of the sphere were measured for possible later use, although they are not directly needed for the evaluation. The measured values are:

$m = 0.0365 \pm 0.0003 \text{ kg}$ (The uncertainty reflects the ILE of the scale.)

$R = 0.01034 \pm 0.0008 \text{ m}$ (The uncertainty is derived by adding the standard deviation of the mean for five measurements, and the ILE in quadrature.)

The error from just reading the scale of a meter stick is only about 0.0005 m, but additional error originates from difficulties with locating exact position of the ball. Use common sense when judging errors; do not feel bound by rigid rules.

Follow the rules for significant figures. The errors are given to one sig. fig. and the value to the same decimal place as the error. You have to carry more significant figures for intermediate values to avoid the accumulation of rounding error. But round the error to only one sig. fig. for the final results (two figures in rare cases.)

Units must always be included. The stated units refer to both the value and the error, thus in principle they should be in parenthesis, like $(0.00365 \pm 0.0003) \text{ kg}$. Yet, we usually drop the parenthesis to make the report more readable; it does not cause any confusion.

The time taken by the ball to roll down the inclined plane is listed for every measurement in Table 1.

Table 1. Rolling times for the solid sphere at various inclinations

Trial #	$\theta = 15^\circ \pm 1^\circ$	$\theta = 30^\circ \pm 1^\circ$	$\theta = 45^\circ \pm 1^\circ$
1	0.922 sec	0.675 sec	0.575 sec
2	0.936 sec	0.683 sec	0.569 sec
3	0.945 sec	0.669 sec	0.563 sec
4	0.951 sec	0.671 sec	0.569 sec
5	0.948 sec	0.681 sec	0.549 sec

Note: Uncertainty in angle θ is based on ILE of protractor used to measure angle and uncertainty in finding the “level” position for the table on which the plane rests. The ILE for the time measurements is 0.0005 sec.

Note that the error of every measured quantity is given, either in the table or in a note.

Hollow sphere

$m = 0.012 \pm 0.002$ kg (The uncertainty reflect ILE in scale.)

$R = 0.01034 \pm 0.0008$ m (The uncertainty comes from the standard deviation of five measurements, plus ILE added in quadrature.)

The time taken by the hollow ball to roll down the inclined plane is listed for every measurement in Table 2.

Table 2. Rolling times for the hollow sphere at various inclinations

Trial #	$\theta = 15^\circ \pm 1^\circ$	$\theta = 30^\circ \pm 1^\circ$	$\theta = 45^\circ \pm 1^\circ$
1	0.995 sec	0.744 sec	0.621 sec
2	0.991 sec	0.730 sec	0.619 sec
3	0.987 sec	0.739 sec	0.623 sec
4	0.994 sec	0.751 sec	0.633 sec
5	0.985 sec	0.742 sec	0.609 sec

Note: Uncertainties are estimated as in Table 1.

Data must always be displayed in *tabular* form. Items that have only one value (m , R , D) are listed above the table, on separate lines. *Never* hide the result of a measurement in the middle of text.

Data analysis and discussion of results

The acceleration of the balls was determined using Eq. (1). First the average of the five roll-times was calculated and the error of the average was determined as the standard deviation of the mean plus the ILE added in quadrature. Then a_{avg} was obtained and its uncertainty was computed by propagating the uncertainties in t_{avg} and D ; this was done using relative errors.

The results for the six cases are given in Table 3. (See Appendix A for details.)

In this case the ILE is significantly smaller than the standard deviation and does not contribute much to the total error. However, this may not be always the case.

Notice that we calculated the best estimate and error of the primary measured quantities (time, radius) then used the theory of the situation and error propagation to get the acceleration and its error. Sometimes, especially if more than one quantity is measured as part of each attempt and their values may be correlated, one might calculate the desired quantity for each attempt separately and do the averaging only at the end.

Table 3. Average rolling times and accelerations for all six cases examined

	t_{avg} (s)	a_{avg} (m/s ²)
Solid sphere at 15°	0.9404 ± 0.0053	1.809 ± 0.021
Solid sphere at 30°	0.6758 ± 0.0028	3.503 ± 0.031
Solid sphere at 45°	0.5650 ± 0.0045	5.012 ± 0.081
Hollow sphere at 15°	0.9904 ± 0.0021	1.6312 ± 0.0081
Hollow sphere at 30°	0.7412 ± 0.0035	2.912 ± 0.029
Hollow sphere at 45°	0.6210 ± 0.0039	4.149 ± 0.053

As these are intermediate results, I kept one extra significant figure to avoid the accumulation of rounding errors. There will be only one sig. fig. kept in the final results.

Finally, the value of β is calculated for each of the six cases according to Eq. (4). The details of the calculation are given in Appendix B. For each of the six cases, β and σ_β were determined.

I recommend using a spreadsheet to perform these calculations. Please, attach a printout of your work. If you choose to do the calculation by hand, provide sample calculations to show that you really did the work. If you use a different software, provide sufficient information to allow evaluation of your work.

Table 4. Results for β

Case	θ (deg.)	Error from a	Error from θ	β
Solid sphere	15	0.01619	0.0913	0.4 ± 0.1
Solid sphere	30	0.01211	0.0423	0.40 ± 0.05
Solid sphere	45	0.02229	0.0241	0.41 ± 0.04
Hollow sphere	15	0.00765	0.1013	0.56 ± 0.11
Hollow sphere	30	0.01644	0.0509	0.68 ± 0.06
Hollow sphere	45	0.02139	0.0292	0.67 ± 0.04

A value of 9.8 m/s^2 was used for g with no associated uncertainty. As g varies less than 0.05 ms^{-2} over the earth (about 0.5% relative error), this contribution to the uncertainty is unimportant.

You have to convert the angle to radians, the error is $1^\circ = 0.017 \text{ rad}$. I left the error written out to two sig. figs. in one case to avoid substantial rounding up.

As mentioned in the theoretical section, the expected value for β is $2/5 = 0.4$ for solid spheres and $2/3 \sim 0.67$ for hollow spheres. The hollow sphere has the larger value as a larger fraction of its mass is far from the axis of rotation. (The moment of inertia of a

mass element is proportional to the square of its distance from the axis.) Our results agree with these values and with each other within experimental error.

Notice that the mass and the radius of the ball do not appear in Eq. (3). It is good to have them for the record, e.g. if a size-dependent effect comes up as a possible source of systematic error, but the result for β does not depend on them.

Inspection of the results leads to several observations:

The values of β are different for the hollow sphere and the solid sphere. Both agree with the expected values – 0.4 for solid sphere, 0.67 for hollow sphere – well within experimental error.

The errors are quite large. The columns showing the contributions from the errors of the acceleration and of the angle indicate that the primary error source is the angle measurement. Rolling the ball a larger number of times, refining time or distance measurement, getting the best possible value for g would not help much. In order to get better results, measuring the angle of the inclined plane more accurately is the most crucial step by far.

The error from the angle measurement is the least serious at the largest angle, suggesting that increasing the angle may be beneficial. But one must be careful, as the ball may not roll without sliding at much higher angles. It would be of interest to do the measurement as a function of angle for more angles, up to angles where the balls are certainly sliding, and see how the beginning of sliding appears in the data.

The mass and radius of the ball are indifferent. Nevertheless, doing the measurement with smaller and larger, lighter and heavier balls might uncover systematic errors, such as the possible role of air resistance.

Notice that there are interesting suggestions on how to improve this measurement, possible systematic errors, etc. This is a very important part of the report and a significant portion of your grade.

This measurement did not lend itself to meaningful plots. Dependence on the angle of the plane would be of interest, but the error is too large to give any meaningful result. In general, plots – especially linear ones – can show trends or information that are much more difficult to “see” by looking at data in a table. You should always include plots in your report. In many cases you are directly instructed to do so by the description of the measurement.

Conclusions

The basic objective of the experiment was achieved: all six measurements were within one standard deviation of the expected values, confirming both the theory and the execution and evaluation of the measurement.

In retrospect, I have put too little emphasis on measuring the angle of the inclined plane as accurately as possible. A more accurate protractor or measuring horizontal and vertical distances rather than the angle directly could be beneficial. Reducing the uncertainty of the angle would have affected the error of beta substantially, possibly allowing for more detailed evaluation.

This is an important section of your report whether or not you have obtained good results. Give convincing arguments on why the experiment did or did not work and how it could work better. You should *never* be in a position to have to write a statement like this: “This experiment was not successful because I forgot to take data at such and such...” or “...because I did not realize that we did not have the ... connected in the proper way”. These kinds of statements can be avoided if you do one thing that most students neglect to do while they are in the lab: Do not just take all your data and then leave. Do some preliminary calculations in the lab to see if your data is giving you the expected results and to make sure that you have all the data necessary *before* you leave the lab. (You can leave the error analysis for later).

Appendixes

Appendix A: Sample spreadsheet for the calculation of the acceleration and its error

The results from this spreadsheet (columns Acceleration and Sig a) are used in Table 3.

D and Sig_D	0.8	0.002	Eta_D	0.0025		
Time	Sig_T	Eta_T	Acceleratio	Eta_a	Sig_a	
0.9404	0.0053	0.0056359	1.80923400	0.01154571	0.02088889	
0.6758	0.0028	0.00414323	3.50335064	0.00865538	0.03032284	
0.565	0.0045	0.00796460	5.01213877	0.01612419	0.08081668	
0.9904	0.0021	0.00212035	1.63116809	0.00492276	0.00802985	
0.7412	0.0035	0.00472207	2.91238752	0.00976943	0.02845238	
0.621	0.0039	0.00628019	4.14893644	0.01280676	0.05313446	

Appendix B: Sample spreadsheet for the calculation of beta and its error

The value of β is calculated for each of the six cases according to Eq. (4).

As there is a sine function in the equation, the uncertainty of β had to be computed by using the general equation for error propagation:

$$\sigma_{\beta} = \sqrt{\left(\frac{\partial\beta}{\partial a}\sigma_a\right)^2 + \left(\frac{\partial\beta}{\partial\theta}\sigma_{\theta}\right)^2}.$$

Based on the expression for β in Eq. (4),

$$\frac{\partial\beta}{\partial a} = \frac{-g \sin\theta}{a^2} \quad \text{and} \quad \frac{\partial\beta}{\partial\theta} = \frac{g \cos\theta}{a}.$$

These calculations are performed in the spreadsheet below. The results in the columns with bold heading are used in Table 4.

g= 9.8

Th et a	Sig _Th eta	Theta	Sig_T heta	a	sig_a	Beta	dBeta/ da	dBeta/ dTheta	from a	from Theta	Sig_Beta
15	1	0.262	0.017	1.80 9	0.021	0.402	0.775	5.232	0.0162	0.091	0.093
30	1	0.524	0.017	3.50 3	0.030	0.399	0.399	2.423	0.0121	0.042	0.044
45	1	0.785	0.017	5.01 2	0.081	0.383	0.276	1.383	0.0223	0.024	0.033
15	1	0.262	0.017	1.63 1	0.008	0.555	0.953	5.803	0.0077	0.101	0.102
30	1	0.524	0.017	2.91 2	0.028	0.682	0.578	2.914	0.0164	0.051	0.053
45	1	0.785	0.017	4.14 9	0.053	0.670	0.403	1.670	0.0214	0.029	0.036

These tables were generated by pasting Excel files into the document. They are not particularly neat. Nevertheless, do not spend too much time on reformatting. You need to submit the spreadsheet to document your work, but your grade is determined by the report itself.

Comments for possible extra points – or for the end-of-semester student lecture. I do not normally expect this depth of working in a lab report.

1. Air resistance may be a source of systematic error. Is it? Let's estimate the air resistance when the ball is moving with the fastest speed.

According to our data, the largest acceleration is about 5 m/s^2 , exhibited by the solid ball. On the 0.8 m length of the track, it gives a maximum speed of

$$v = \sqrt{2aD} = \sqrt{2 * 5 * 0.8} \frac{\text{m}}{\text{s}} \approx 2.83 \frac{\text{m}}{\text{s}}.$$

The radius is about 0.01 m , the density of air is 1.2 kg/m^3 . The drag force depends on the geometry and I do not know how it works out for the rolling ball. But for a first order-of-magnitude estimate, calculating the drag force on a ball falling far from any object is sufficient. We try to improve on this estimate later, if it is necessary. For a sphere moving in a uniform medium the shape factor is $C = 0.4$. The drag force on the ball is

$$F_d = \frac{1}{2} v^2 \rho C (r^2 \pi) = \frac{1}{2} \left(2.83 \frac{\text{m}}{\text{s}} \right)^2 1.2 \frac{\text{kg}}{\text{m}^3} 0.4 \left[(0.01 \text{ m})^2 \pi \right] \approx 0.0006 \text{ N}.$$

The weight of the ball is $mg = 0.358 \text{ N}$. Thus the drag force is never larger than a small fraction, actually 0.17% , of the weight of the ball. The different geometry may change the drag force somewhat, but it is certainly too small to have a noticeable effect on the results.

2. Fitting a straight line is always a useful tool in data evaluation, thus let's see if a straight-line fit is a possible way to evaluate the data in this case. Equation (2) can be manipulated into the form

$$g \sin(\theta) = a(1 + \beta),$$

thus if we plot $y = g \sin(\theta)$ as a function of a , the slope should give $1 + \beta$. The results for solid spheres are plot on that scale in Fig. 1. The slope from the Excel's fit is 1.39 , corresponding to $\beta = 0.39 \sim 0.4$. The intercept was set to zero.

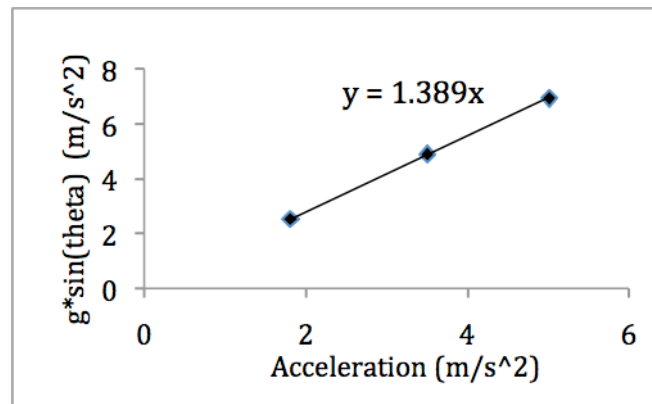


Fig. 1 Linearized plot for the solid ball experiment (see text)

Although nothing new was obtained from this plot for the present case, it would be very useful if we took data at many more angles and increased the angle until the ball began to skid. The point where ideal rolling would turn to a skidding roll would be recognized as the point where the points begin to deviate from the straight line, as the starting equation no longer applies in that case. In fact, the acceleration for a given angle is larger than anticipated from the skid-free theory.

Notice that I simply used the trend line feature of Excel to fit the data points. That is OK in a comment that goes far beyond the expected work, but not if it is part of the main data evaluation. Excel does not provide the error of the slope, thus it is not sufficient for our typical data evaluation tasks.