*Journal of Science Education and Technology, Vol. 11, No. 3, September 2002 (© 2002)*

# What Do We Expect From Students' Physics Laboratory Experiments?

**Ricardo Trumper**[1,2]

We want physics specialized high school and college students to think like physicists, and this involves an understanding of the scientific methods of inquiry and the ability to use these methods in their own investigations. In order to do that, students have to be made aware that no experimental result has any physical meaning unless an estimate of the uncertainty or precision is assigned to it. In this paper, we describe two simple experiments in which high school and college students measure physical constants, and make an easy analysis of their experimental data by applying the tools offered by microcomputers.

**KEY WORDS:** experimental uncertainties; spreadsheet analysis; measurement of refractive index; verification of Coulomb's Law.



## INTRODUCTION

Access to laboratories and experiences of inquiry have long been recognized as important aspects of school and college science. Most of the curricula developed in the 1960s and 1970s were designed to make laboratory experiences the core of the science learning process (Shulman and Tamir, 1973). Science in the laboratory was intended to provide experience in the manipulation of instruments and materials, which was also thought to help students in the development of their conceptual understanding.

It is hard to imagine learning to do science, or learning about science in general, without doing laboratory or fieldwork. Since experimentation underlies all scientific knowledge and understanding, laboratories are wonderful settings for teaching and learning science.

It is widely agreed that high school and college science education should provide science (chemistry, biology, or physics) specialized students with an understanding, at an appropriate level, of the scientific account of the natural world and of the processes of scientific inquiry (Black, 1993). As Lubben and Millar (1996) claim, "the two are related: understanding . . . some of the facts, concepts, laws and theories of accepted science involves an appreciation of the ways in which such knowledge came to be established and of our warrants for accepting it as valid." As a result, practical laboratory work is widely used as a teaching strategy and is also seen as crucial in developing an understanding of the procedures of scientific inquiry.

Let us consider for a moment what it would mean to develop students' understanding of scientific methods of inquiry and their ability to use these methods in their own investigations. According to Millar (1998),

> we would be aiming, through our teaching, to help students become more "expert" in selecting productive questions to investigate, designing suitable experiments to collect data which bear on these questions, making a planned series of observations or measurements with due attention to accuracy, validity and reliability, analyzing and interpreting these data to reach a conclusion which is supported by the data, and being able to evaluate the quality of the support which their evidence gives to their conclusion.

[1]Faculty of Science and Science Education, Haifa University, Israel.
[2]To whom correspondence should be addressed at Kibbutz Hahoterim, Doar Na Hof Hacarmel 30870, Israel; e-mail: rtrumper@research.haifa.ac.il



1059-0145/02/0900-0221/0 © 2002 Plenum Publishing Corporation

## DEFINING APPROPRIATE TERMS IN THE ANALYSIS OF EXPERIMENTAL DATA

In order to deal with experimental data in a proper way, we must define precisely the different terms we use in the estimation of their accuracy. In this paper we choose basically Thomsen's terminology (Thomsen, 1997), that is, we define

1. *resolution* of an instrument as "the fineness of detail revealed by the measuring instrument,"
2. *precision* or *uncertainty* of a series of measurements as "a measure of the agreement among the repetitive determinations," which is "usually quantified as the standard deviation of the measured values." (For a simple illustration of the relationship between statistics and measurement, see Kagan, 1989.) The precision or uncertainty of a series of measurements depends on how well we can overcome random errors, that is, the fluctuations in observations that yield results that differ between repeated measurements, and
3. *accuracy* of a measurement (or its average) as "its relation to a 'true,' 'nominal,' 'agreed upon,' or 'accepted' value," which "is often expressed as a deviation or percent deviation from the known value."

It is also important to take into account Roberts' assertion (Roberts, 1983) that "when an experimenter determines the range of likely values for a quantity, he or she determines a *best estimate* for it, along with an *experimental uncertainty*," that is the precision of the measurements. In a physics experiment we do not determine "true" values, but ranges within which true values probably lie.

The question that students should be encouraged to ask regularly is how well they trust the number they obtained in their measurement. Quantitatively, the degree of trust is expressed by the resolution of the instrument used in an individual measurement, and by the precision obtained in a series of measurements (its standard deviation).

No single measurement can be better than the instrumental limitations, that is, there are always scale errors that represent the highest resolution possible with a given instrument; for instance a meter stick graduated in millimeter marks has a resolution of about 0.5 mm. If we can do repeated measurements of a quantity (for example the free-fall time of a body dropped from a given height), we can improve the precision of the measurement by calculating its best estimate ($t_{\text{best}}$) and its uncertainty or absolute experimental error ($\delta t$). In many cases in which we make calculations that include multiplication or division of measured quantities, we use the fractional error, for example, $\delta t/t_{\text{best}}$.

Unfortunately, some authors (Johnston and Schroeer, 1992; Robinson, 1991; Thomsen, 1997) still guide students to perform what they call "error analysis," that is, to calculate the percent error of their measurement according to the expression:

$$\%\ \text{Error} = |\text{Measured value} - \text{Accepted value}| \times 100/\text{Accepted value}$$

where the "'measured value' is the student's experimental value, which is expected to be different from the accepted value (otherwise, why would we need to calculate the error?) and in some way 'incorrect'" (Deacon, 1992). This may be the reason that students so often come to the conclusion that physics, while it purports to be an exact science, never actually works in practice, or at least not for them. Thus, the old and unsuccessful phrase "If it doesn't work, it's physics" (T. D. M., 1973), may lead students "to decide, at best, that labs are a waste of time, and at worst, that physics makes no sense" (Roberts, 1983).

We want physics specialized high school and college students to think like physicists, and this involves an understanding of the scientific methods of inquiry and the ability to use these methods in their own investigations. In order to do that, students have to be made aware that no experimental result has any physical meaning unless an estimate of the uncertainty or precision is assigned to it. In the following sections, we describe two simple experiments in which high school and college students measure physical constants, and make an easy analysis of their experimental data by applying the tools offered by microcomputers.

## SNELL'S LAW: MEASURING THE INDEX OF REFRACTION FOR ACRYLIC

The equipment needed for the experiment includes an optics bench, a ray table and base, a slit plate, a cylindrical lens, a light source, a component holder, and a slit mask, like those provided by the Pasco[3] Introductory Optics System (see Fig. 1).

[3]Pasco Scientific, P.O. Box 619011, 10101 Foothills Boulevard, Roseville, California (www.pasco.com).

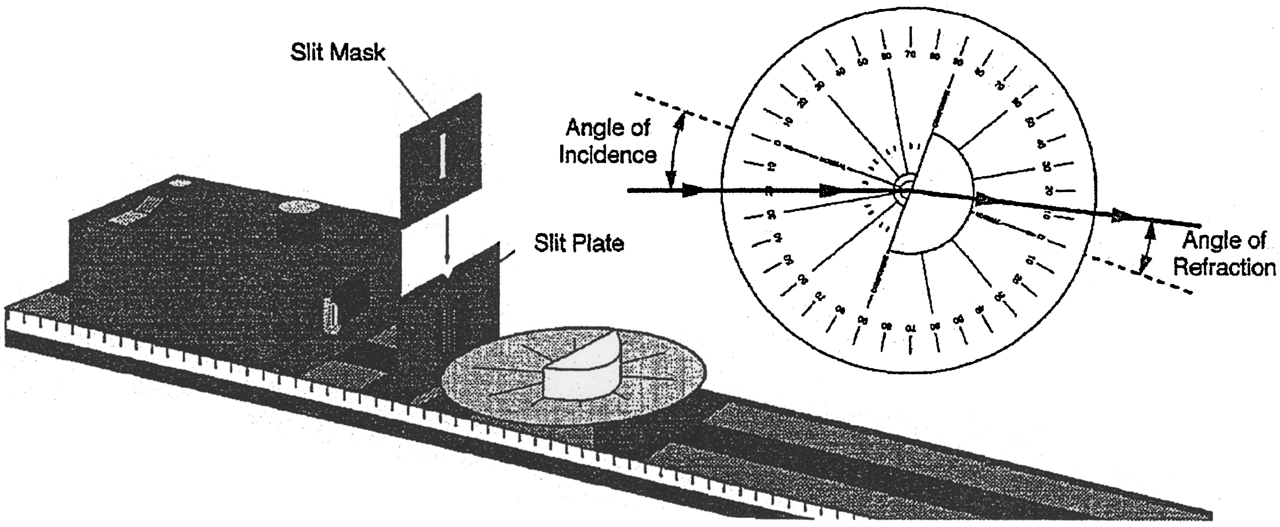


**Fig. 1.** Equipment setup for Snell's Law experiment.

The students set up the equipment and adjusted the components so that a single ray of light passes directly through the center of the ray table degree scale, and they aligned the flat surface of the cylindrical lens with the line labeled "component." To measure how the angle of refraction of the ray of light depends on its angle of incidence they rotated the ray table and observed the refracted ray for various angles of incidence, from both sides of the normal. Then they introduced these data in Columns A (angle of incidence) and B (average angle of refraction) of a Microsoft Excel spreadsheet (see Fig. 2).

According to Snell's Law

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{1}$$

where $n_1$ and $n_2$ are the indices of refraction of the two media through which the light is passing, and $\theta_1$ and $\theta_2$ are the angles of incidence and refraction, respectively (see Fig. 1).

In order to check the experimental results, students calculated the sine of both angles, put them in Columns C and D, respectively, and plotted a graph with its corresponding best-fit line (see Fig. 3).

As expected they got a straight line, whose slope has to be the inverse value of the index of refraction of the acrylic, assuming that the index of refraction for air is equal to 1. That is,

$$\sin(\theta_2) = \left(\frac{1}{n_2}\right) \sin(\theta_1) \tag{2}$$

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Angle of incidence | Angle of refraction | sin (incident | sin (refracted | | |
| 2 | (degrees) | (degrees) | angle) | angle) | Slope | Refraction |
| 3 | 0 | 0 | 0.000 | 0.000 | | index |
| 4 | 10 | 6.5 | 0.174 | 0.113 | 0.65 | 1.53 |
| 5 | 20 | 13 | 0.342 | 0.225 | 0.66 | 1.51 |
| 6 | 30 | 19.5 | 0.500 | 0.334 | 0.69 | 1.45 |
| 7 | 40 | 25.5 | 0.643 | 0.431 | 0.68 | 1.48 |
| 8 | 50 | 31 | 0.766 | 0.515 | 0.69 | 1.46 |
| 9 | 60 | 35.5 | 0.866 | 0.581 | 0.66 | 1.52 |
| 10 | 70 | 39.5 | 0.940 | 0.636 | 0.75 | 1.33 |
| 11 | 80 | 42 | 0.985 | 0.669 | 0.73 | 1.36 |
| 12 | | | | | | |
| 13 | | | | | Best estimate: | 1.46 |
| 14 | | | | | Precision: | 0.07 |

**Fig. 2.** The spreadsheet showing the results of the Snell's Law experiment, the needed calculations and data analysis.

P1: GVG/LOV P2: GXD
Journal of Science Education and Technology pp520-jost-375355 May 13, 2002 14:25 Style file version Oct. 23, 2000



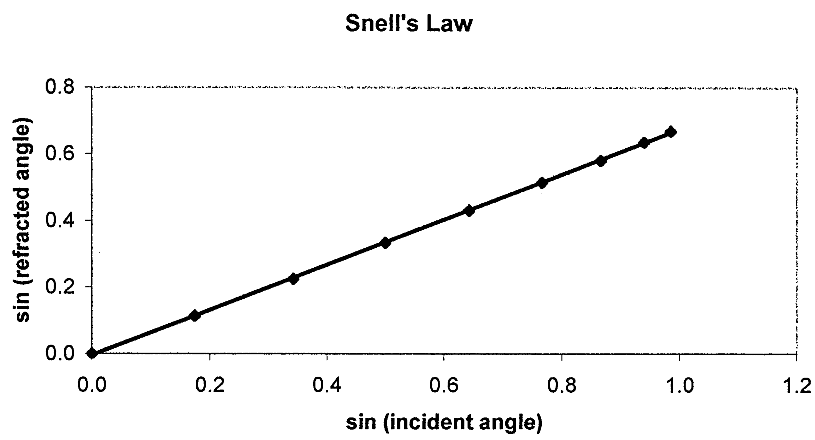


**Fig. 3.** Graph of the measured sinus of the refracted angle as a function of the sinus of the incident angle.

Students calculated the slope of the straight line in Column E and the corresponding values of the index of refraction of acrylic in Column F (see Fig. 2). Its best estimate [AVERAGE(F4:F11)] was calculated in Cell F13, and the precision of the measurements [STDEV(F4:F11)] was calculated in Cell F14.

Since the "accepted" value of the index of refraction of acrylic is 1.5, we can see that it lies within the range determined by the best estimate and the precision of students' measurement. The remaining question is how well students may trust in the number they obtained in their measurement, that is, what is the percentage precision they obtained. In this case we got about 5% (0.07/1.46), a very well justified precision if we take into account that the highest resolution of the instrument used is $1^\circ$ ($0.5^\circ$ for the light ray width and $0.5^\circ$ for the fineness of detail of the ray table), that is, a resolution that varies from 1.5 to 12.5% for the measured angles.

## COULOMB'S LAW: MEASURING COULOMB'S CONSTANT

The equipment needed for the experiment is the Pasco Model ES-9070 Coulomb Balance, a delicate torsion balance that can be used to investigate the force between charged objects (see Fig. 4). A conductive sphere is mounted on a rod, counterbalanced, and suspended from a thin torsion wire. An identical sphere is mounted on a slide assembly so it can be positioned at various distances from the suspended sphere. To perform the experiment, both spheres are charged with a stable kilovolt power supply, and the sphere on the slide assembly is placed at fixed distances from the equilibrium position of the suspended sphere. The electrostatic force between the spheres causes the torsion wire to twist. The student then twisted the torsion wire to bring the balance back to its equilibrium position. The angle through which the torsion wire must be twisted to reestablish equilibrium is directly proportional to the electrostatic force between the spheres.

All the variables of the Coulomb relationship ($F = Kq_1q_2/R^2$) can be varied and measured. In this experiment students verified the inverse square law, while keeping charges constant, and measured Coulomb's constant K.

In the first part of the experiment, students set up the Coulomb Balance as shown in Fig. 4. They set the torsion dial to $0^\circ$ and zeroed the torsion balance by rotating the bottom torsion wire retainer until the pendulum assembly was at its zero displacement position as indicated by the index marks.

With the spheres at maximum separation they charged both to a potential of 6 kV, using a charging probe that includes a 20 MΩ resistor for safety reasons. Then they put the sliding sphere at a position of 20 cm (distance between the center of spheres), and adjusted the torsion knob as necessary to balance the forces and bring the pendulum back to the zero position. They repeated this measurement three times and recorded the distance $R$ and the average angle $\theta_{avg}$. They did the same procedure for various distances between the spheres and introduced the data

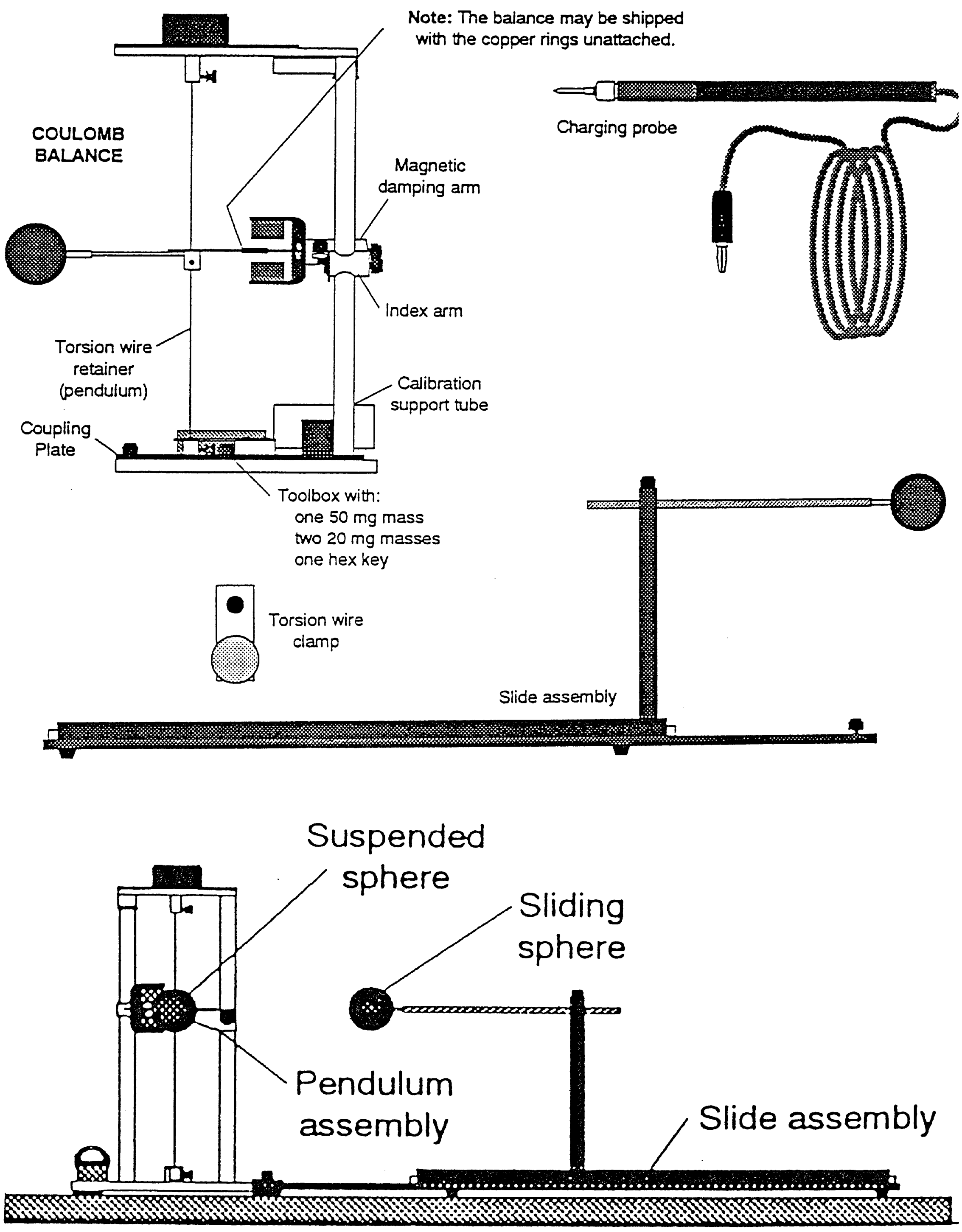


**Fig. 4.** The Coulomb Balance setup for the experiment.

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | R (m) | 1/R^2 (1/m^2) | Teta(avg) | F (N) | Slope | |
| 2 | 0.20 | 25.00 | 13.5 | 3.74E-05 | | K |
| 3 | 0.16 | 39.06 | 40.0 | 1.11E-04 | 5.22E-06 | 8.12E+09 |
| 4 | 0.14 | 51.02 | 64.0 | 1.77E-04 | 5.56E-06 | 8.65E+09 |
| 5 | 0.12 | 69.44 | 94.5 | 2.62E-04 | 4.59E-06 | 7.14E+09 |
| 6 | 0.10 | 100.00 | 161.5 | 4.48E-04 | 6.08E-06 | 9.45E+09 |
| 7 | 0.09 | 123.46 | 201.5 | 5.58E-04 | 4.73E-06 | 7.35E+09 |
| 8 | 0.08 | 156.25 | 275.0 | 7.62E-04 | 6.21E-06 | 9.66E+09 |
| 9 | 0.07 | 204.08 | 351.0 | 9.73E-04 | 4.40E-06 | 6.85E+09 |
| 10 | 0.06 | 277.78 | 451.5 | 1.25E-03 | 3.78E-06 | 5.88E+09 |
| 11 | 0.05 | 400.00 | 635.0 | 1.76E-03 | 4.16E-06 | 6.47E+09 |
| 12 | | | | | | |
| 13 | | | | | Best estimate: | 7.73E+09 |
| 14 | | | | | Precision: | 1.32E+09 |
| 15 | | | | | | |
| 16 | | | | | | |

**Fig. 5.** The spreadsheet showing the results of the Coulomb's Law experiment, the needed calculations and data analysis.

in Columns A and C of a spreadsheet (see Fig. 5). Students calculated the inverse square of the distance and introduced it in Column B.

In the second part of the experiment, students measured the torsion constant of the torsion wire ($k_{tor}$), in order to enable them to convert their torsion angles into measurements of force. To accomplish that they turned the torsion balance on its side, supporting it with the lateral support bar, as shown in Fig. 6.

They zeroed the torsion balance by rotating the torsion dial until the index marks were aligned, and recorded the angle of the degree plate. They placed a 20 mg mass on the center line of the conductive sphere, turned the degree knob as required to bring the index marks back into alignment and read the torsion angle on the degree scale. They repeated this measurement for various masses and introduced the data in Columns A and B in a separated sheet of the spreadsheet (see Fig. 7).

Finally they calculated the weight of each mass (Column C in Fig. 7) and plotted a graph of the exerted force as a function of the angle (see Fig. 8) in order to corroborate the proportionality of these two variables. The proportion constant ($k_{tor}$), that is the slope of the straight line, was calculated in Column D (see Fig. 7). Its best estimate [AVERAGE(D3:D6)] was calculated in Cell D8, and the precision of the measurements [STDEV(D3:D6)] was calculated in Cell D9, obtaining a percentage precision of about 8.5% ($2.35 \times 10^{-7}/2.77 \times 10^{-6}$).

Having the best estimate of the torsion constant, students turned back to the first sheet in the spreadsheet, calculated the forces corresponding to the different measured angles, introduced the data in Column D (see Fig. 5), and plotted a graph of the force as a function of the inverse square of the distance between the center of the spheres with its corresponding best-fit line (see Fig. 9).

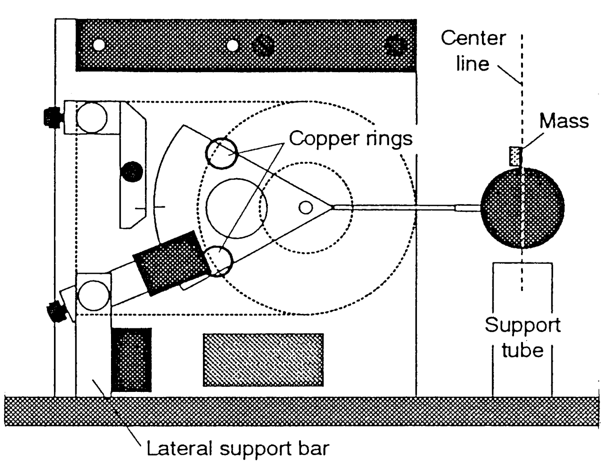


**Fig. 6.** Setup for calibrating the torsion balance and measuring the torsion constant.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | Teta | m (mg) | F (N) | |
| 2 | 35.5 | 0 | 0 | K-tor (N/degree) |
| 3 | 105.5 | 20 | 0.000196 | 2.80E-06 |
| 4 | 170.5 | 40 | 0.000392 | 3.02E-06 |
| 5 | 210.5 | 50 | 0.00049 | 2.45E-06 |
| 6 | 280 | 70 | 0.000686 | 2.82E-06 |
| 7 | | | | |
| 8 | | | Best estimate: | 2.77E-06 |
| 9 | | | Precision: | 2.35E-07 |
| 10 | | | | |

**Fig. 7.** The spreadsheet showing the results of the torsion constant measurement, the needed calculations and data analysis.

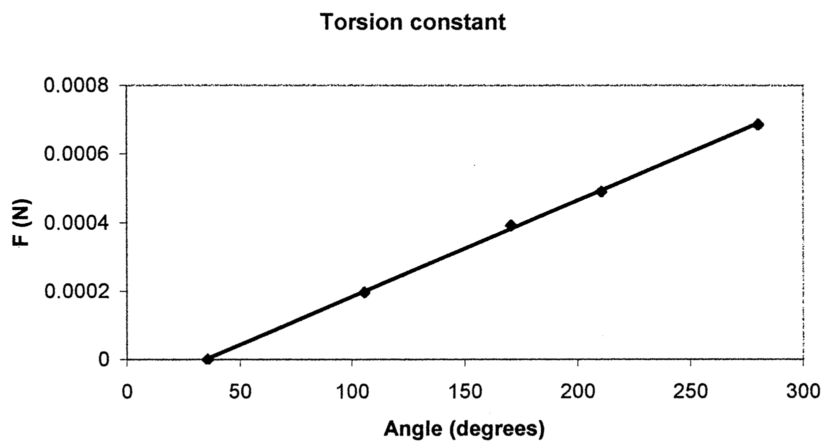


**Fig. 8.** Graph showing the linear relation between the force exerted to the Coulomb Balance and the torsion angle.

As expected they got a well approximated straight line, whose slope has to be Coulomb's constant times the squared value of the charge. That is,

$$F = (Kq^2)\,\frac{1}{R^2} \tag{3}$$

Students calculated the slope of the straight line in Column E and the corresponding values of Coulomb's constant in Column F (see Fig. 5), taking into account that $q = 4\pi\varepsilon_0 aV$ (where $\varepsilon_0 = 8.85 \times 10{-}12$ F/m, $a =$ 3.8 cm—the radius of the sphere, and $V = 6$ kV). Its best estimate [AVERAGE(F3:F11)] was calculated in Cell F13, and the precision of the measurements [STDEV(F3:F11)] was calculated in Cell F14.

Since the "accepted" value of Coulomb's constant is $9 \times 10^9$ N m$^2$/C$^2$, we can see that it lies within the range determined by the best estimate and the precision of students' measurement. The remaining question is how well students may trust in the number they obtained in their measurement, that is, what is the percentage precision they obtained. In this case we got about 17% ($1.32 \times 10^9/7.73 \times 10^9$), a very well justified precision if we take into account the highest resolution of the different instruments used.

- 0.5° for the resolution of the degree plate, that is, a percentage resolution that varies from 0.04 to 2.2% for the measured angles.
- 0.05 cm for the resolution of the slide ruler, that is, a percentage resolution that varies from 0.25 to 1% for the measured distances.

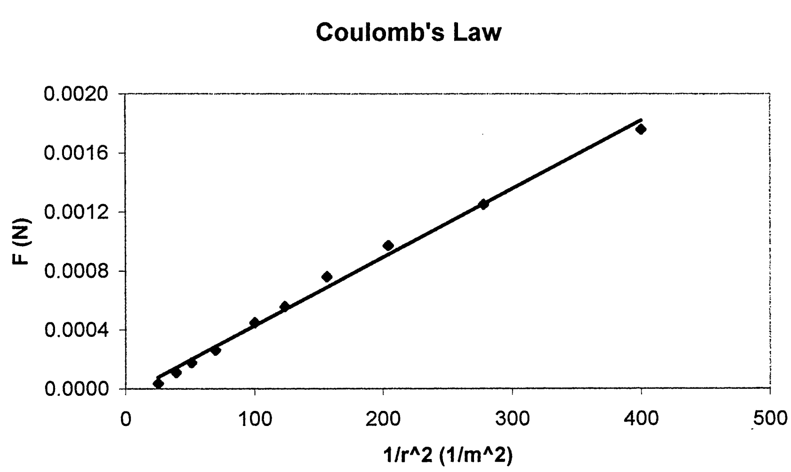


**Fig. 9.** Graph of the electrostatic force exerted by two identical charges as a function of the inverse square distance between them.

– 0.1 kV for the resolution of the power supply voltmeter, that is, a percentage resolution of 1.7%.
– The former measured precision of the torsion constant, 8.5%.
– An inestimable eye precision in the alignment measurement of the index marks.

Besides that, one can see in Columns E and F of Fig. 5 that there is a deviation from the inverse square relationship at short distances because of the fact that the charged spheres are not simply point charges.

## REFERENCES

Black, P. (1993). The purposes of science education. In Hull, R. (Ed.), *ASE Secondary Science Teachers' Handbook*, Simon and Schuster, London, p. 6.

Deacon, C. (1992). Error analysis in the introductory physics laboratory. *The Physics Teacher* 30: 368–370.

Johnston, B., and Schroeer, J. (1992). Take-home experiments for large lecture classes. *The Physics Teacher* 30: 94–95.

Kagan, D. (1989). A brief experiment to illustrate the relationship between statistics and measurement. *The Physics Teacher* 27: 44–45.

Lubben, F., and Millar, R. (1996). Children's ideas about the reliability of experimental data. *International Journal of Science Education* 18: 955–968.

Millar, R. (1998). Students' understanding of the procedures of scientific inquiry. In Tiberghien, A., Jossem, E., and Barojas, J. (Eds.), *Connecting Research in Physics Education With Teacher Education* [Online]. Retrieved June 5, 1998, from http://www.physics.ohio-state.edu/~jossem/ICPE/BOOKS.html

Roberts, D. (1983). Errors, discrepancies, and the nature of physics. *The Physics Teacher* 21: 155–160.

Robinson, P. (1991). *Laboratory Manual With Computer Activities*, Addison-Wesley, Reading, MA, p. 218.

Shulman, L., and Tamir, P. (1973). Research on teaching in the natural sciences. In Travers, R. (Ed.), *Second Handbook of Research in Teaching*, Rand McNally, Chicago, IL, pp. 1098–1148.

T. D. M. (1973). Etcetera. *The Physics Teacher* 11: 191.

Thomsen, V. (1997). Precision and the terminology of measurement. *The Physics Teacher* 35: 15–17.

**Au: Kindly provide "T.D.M" in full**