Philosophy of "Experimentation"

The purpose of an experiment is to study or verify a principle of Physics learned in a lecture course, by actually making it work in the laboratory. Such *hands-on* experience not only enhances our faith in those and other principles, but also leads us to a better understanding and a better grasp of the subject matter.

The role of an experiment doesn't end here. It trains and prepares us for *experimentation*; i.e. learning and developing techniques for performing experiments. A *theory* deals with ideal situations (environment, tools and materials) but in a real physical world, no environment is ideal and no tools or materials are perfect. This causes embarrassment as we cannot actually do things that we had anticipated doing, on the basis of a theory. The limitations, shortcomings and the handicaps, we meet with in a real world, may discourage us in the beginning; but then we learn to live with them. Many a times we use scientific ingenuity and end up with intelligent ways and means to bypass these limitations and achieve our goal.

Experimentation then goes one step further. It enables one to discover some new aspects of the subject matter that were opaque to the theory. Then it is the responsibility of the theory to catch up and justify the experimental findings. In one way, experimentation has the upper hand: if something is found experimentally, then it is a *fact* which *has* to be true. If this fact was not supported by the theory then it is the theory that must be abandoned or modified. Theory, on the other hand, has the upper hand in the sense that it has the capability of *predicting* experimental results and, as such, guides one to the experiments. Theory and experimentation thus team up and work together to *evolve* science. This is *research*.

Even though research or elaborate experimentation is not the purpose of this course, we do intend to work on parallel lines. We would like our students to be aware of the limitations that face us on a laboratory table. We will then apprise the students of the ways and means to bypass or overcome them in order to achieve the goals; preserving, at the same time, a high standard of accuracy, dependability and repeatability for whatever we do. The experimentation will be, to some extent, research or design oriented. This mode of performing experiments has been adopted not because we want to prepare our students for research at this stage, but because this is the *only* way experiments should be done at *any* level or stage.

The limitations, as mentioned above, may be divided into two categories. The first is concerned with the limit of what one can do and cannot do in a laboratory. This may be (a) due to lack of resources; for example, we may not have access to a good quality apparatus that we would need for a certain measurement with the desired level of accuracy (b) due to physical inability of doing something; for example we may not be able to apply an ideally (or mathematically) uniform force *manually* for a finite length of time; or we may not be able to switch on and off a stop watch to synchronize with the start and stop of an event.

The second is concerned with an *inherent inability* of a laboratory apparatus to make a measurement. This has nothing to do with the quality of the apparatus or the capabilities of a worker to use the apparatus. We shall illustrate this point by considering several different situations to emphasize its importance.

(1) Inability to *make* a measurement. Let us suppose that we want to measure the angle of transmission of a ray of light in a solid transparent material such as glass. It is customary to use

glass in the form of a slab or a prism. The angle of transmission lies *inside* the glass slab (or prism). Now it is inherently impossible to place an angle measuring device *inside* the glass specimen! As we cannot place the device inside the glass, we cannot measure the angle of transmission and a direct verification of the law of transmission of light is seemingly impossible.

(2) Inability to make a *true* measurement. A good example here is that of a voltmeter. A voltmeter no matter how sophisticated, when used to measure a voltage, becomes a part of the circuit and some current, no matter how tiny, flows through it. The voltmeter ends up using some electrical energy. This energy is part of the energy that the voltmeter was entrusted to measure. The measured energy, therefore, is less than the actual energy. Thus a voltmeter measurement can never be 100% accurate. It is *inherently* impossible. Modern day digital multimeters are no exception, even though the departure from the *true* value is minimal. Try measuring a voltage on two different scales; the measured values would be different!

(3) Inability to make a measurement for reasons of self destruction. It is inherently impossible to measure *resultant* vectors in the laboratory. Let us suppose that several tension forces have been set up on a force table, using cords (with attached suspended masses). The cords are tied to a ring which serves as the object on which the said tension forces are acting. Now, it is inherently impossible to determine the resultant of these forces! The reason is that the resultant force imparts acceleration to the ring and the ring begins to move immediately. An infinitesimal movement of the ring causes the directions of all constituent forces to change, thereby destroying the resultant. By imparting acceleration, the *resultant* vector destroyed itself! A new resultant takes over, only to self-destruct itself, a moment later. This is why no one ever ventures to find a *resultant* vector on a force table, in the laboratory.

(4) Inability to make a measurement for reasons of *invisibility* to the laboratory apparatus. Consider a diverging lens. The image formed by a diverging lens is virtual. Since a virtual image cannot be placed on a screen, it is *invisible* to the measuring apparatus. Obviously, a measurement of the *image distance* cannot be made and hence it is impossible to use the lens equation to determine its focal length.

The theory or the text book, however, is least concerned with these, so-called limitations, shortcomings and handicaps. It uses the familiar expression, *let* θ_r *be the angle of transmission in glass;* and the angle *inside* this solid transparent medium is deemed to have been measured as θ_r with infinite accuracy; or *let the voltage across* R *be* V_1 *volts* and then it is very conveniently assumed that this voltage has been determined with infinite accuracy and that V_1 is the exact result of this infinitely accurate measurement! Or *let the resultant force be* F_{net}; and for sure we have a precise knowledge of F_{net}. The list goes on and on.

One finds that there is a significant and apparently insurmountable difference between *theory* and *experiment* or between a *text book* and a *laboratory table*. If the two have to go hand in hand to evolve science, as mentioned above, one must find ways and means to change the insurmountable to the surmountable or find ways and means to bridge the gap between them. Finding such ways and means is *experimentation*.

Experimentation is thus simply a transition from the *text book* to the *laboratory table.* The techniques of experimentation reflect upon the continued and unending struggle (for supremacy) between theory and experiment. These techniques are based on scientific ingenuity, the use of the tools provided to us by *mathematics*, deeper insight into the subject matter, logic, and common sense. (Interestingly enough, these are also the criteria for developing a theory!) Some interesting and bizarre examples of these techniques may not be out of place here. (1) Consider the diverging lens that refuses to make a real image. A deeper look at mathematics, however; tells us that we can *force* the diverging lens to produce a real image by feeding it a suitable *negative* object-distance. Once the image is real, there are no longer any problems. (2) Take the case of the angle of transmission (refraction) inside a solid medium such as glass. It is obviously impossible to measure angles *inside* glass. Now, we *know* that a transparent material is of finite size and hence comes with two interfaces. A deeper look into the theory of reflection/transmission tells us that it is possible to render the second interface a non-interface by invoking the principle of *normal incidence*. This permits us to measure the angle of transmission inside the glass, *outside* the glass. Measuring an angle outside the glass is, of course, no problem. (3) Determination of the *resultant* force is achieved by *freezing* the *resultant.* All constituent forces remain in their original form and the resultant does not self-destruct itself. (4) As an examples of overcoming shortcomings of a different type, consider applying an ideally uniform force manually, which is an impractical proposition. The way out is to use a falling mass which must pull on an object with mathematically uniform force.

This discussion brings us next to some other vitally important aspects of scientifically valid experimentation. First and foremost is the *degree of accuracy* of the results i.e. a consideration of the overall error in an experiment. Apart from the relative merits of a measuring device, an experiments should be developed in such a way that the overall error of measurements is at its minimum. Each measurement has its own margin of error. Some measurements have large errors, others have less. The overall error is estimated by suitably combining all constituent errors. Obviously, the less the number of measurements, the less number of errors will have to be combined. An experiment should, therefore, be designed in such a way that a *minimum* number of parameters are required to be measured on the laboratory table.

The next very important aspect is *repeatability.* Suppose the result of a particular measurement is 13.57 units. One would expect that any number of subsequent repeated measurement will also yield the value:13.57 units. This is wishful thinking. An inherent characteristic of physical measurements is that if one repeats an experimental measurement, the new value will most likely be different from the first. The difference, in general, is small. Repeated several times, one would end up with a small interval of values for that particular measurement. Statistical analysis is then required to find the *mean* of that interval. This *mean* is then taken as the *experimentally determined* value or the *result* of the said measurement. The limits of the interval determine the *spread* of the result. If the spread is large (or wide), the measurement is said to have yielded a less dependable result and our confidence level in the experiment is low. If, on the other hand, the spread is narrow, the level of confidence will be high. This is a rather involved procedure for finding a dependable result of a measurement, but it cannot be simplified due to the irrepeatability of a lab measurement.

In an effort to somewhat simplify the above procedure, an ingenious technique has been developed which replaces the above procedure. It is the *graphical technique*. One plays around with the theoretical expression using mathematical methods (and ingenuity, common sense, etc.) and renders the expression comparable to the equation of a straight line: $y = mx + b$ or that of a quadratic equation. A comparison not only dictates the terms of the experiment but also spells out the procedure for extracting the result from the graph. One selects a number of values of the independent parameter and measures the corresponding values of the dependent parameter experimentally. The *best-fit* straight line represents the statistical mean, and the slope or the intercepts on the axes yield results of the experiment. It is very important to keep in mind that the purpose of these experimentally determined pairs of values is to enable one to construct the best-fit straight line. Once such a line is drawn, the said pairs of values become redundant and must not be used later (to find the slope; for example). One then selects two new points on the line (as far apart as conveniently possible) and calculates the slope and the intercepts, as required. The technique provides us with a dependable *mean* or the *result* of the experiment but it does not tell us a whole lot about the *spread* or the *confidence level*. Visual judgement provides one with a qualitative assessment of spread; which may be enough at the elementary level of experimentation. The use of a computer to plot the graph does provide us with a measure of the spread because it calculates the r^2 value.

The final episode of this discussion concerns the attitude of a student toward the experiment. The result of an experiment has a lot to do with the attitude. One approach to experiments is based on the spirit of learning while another is based on passing the course. This shows up in the results and an instructor can always find out the level of effort put in the table work by a student.

The experiments described in this manual are based on the philosophy discussed above. A *Setting Up* section is included in each experiment, with the purpose of highlighting the limitations. A mathematical analysis is then presented to show how these shortcomings are bypassed, and in what manner the objectives of the experiment are achieved. The emphasis is on (a) reducing the number of parameters, to be measured in the laboratory, to a minimum, and (b) reshaping a theoretical expression so that it becomes comparable to the equation of a straight line or that of a quadratic equation. This enables us to use the technique of plotting graphs.

Finally, not all experiments will be found to be *bugged* with shortcomings, but the ones that are, will probably be more challenging and hence, more interesting.

Experimentation