International Conference on Physics Teacher Education Beyond 2000, Select Contributions. R. Pinto and S. Surinach (Editors), 319-324, Elsevier (Ansterdam)

DEVELOPING A RESEARCH-BASED LABORATORY CURRICULUM FOR COLLEGE PHYSICS

Pratibha Jolly*, Vishnu B. Bhatia* and Mallika Verma[o]

*Department of Physics, University of Delhi, Delhi 110 007, India
[o]Miranda House, University of Delhi, Delhi 110 007, India

ABSTRACT

We recently launched a pilot study to systematically identify elements of procedural and conceptual knowledge that play a critical role in science experiments. The research instruments consist of specially designed laboratory activity sheets imbedding careful sequence of concept-questions, instructional-cues and experimental-tasks. The rubric used for evaluating students' performance and quality of data collected in a simple laboratory task is presented. Data shows deficient knowledge of procedural concepts; students do not use their understanding of physics to decide the values and range of measurement variables or check the validity of results. However, the overall validity of a hypothesis is judged using theoretical expectations rather than the data collected. Based on these findings, a three-step model of laboratory learning is proposed. At level one, students answer a pre-laboratory questionnaire on design of the experiment and procedures to be adopted. Then they perform the laboratory task taking crucial decisions about data collection. Level two aims to facilitate transition from novice to expert behavior. Here students assess their data and undertake simple bridging exercises designed to enhance procedural understanding and experimental skill. Level three tests the expertise gained. As an example, a laboratory tutorial based on this model is described for a specific task.

1. INTRODUCTION

In recent years, a great deal of effort has been directed towards gauging efficacy of teaching practices and identifying common misconceptions and learning difficulties that prevail in the various domain areas of physics theory. However, surprisingly little research has been carried out, particularly at the tertiary level, to identify understandings that underpin laboratory performance [1, 2]. Inasmuch as experiments, demonstrations and hands-on activities play a pivotal role in the learning of physics, there is an urgent need to extend the methods of physics education research to learning in the laboratory. We have recently launched a pilot study to systematically explore undergraduate physics students' understanding of

1. aim of the laboratory task and design of experiment;
2. variables of measurement and their character;
3. concepts of reliability and validity of data; and
4. how empirical evidence is used to test hypothesis;

The formulation of the problem as above has been influenced by the seminal work done by earlier researchers who have explored these aspects in younger children [3-6].

Laboratory tasks involve many parameters and it is usually not possible to study the affect of any of these in isolation. Suitable control experiments, leave aside complete learning environments, are difficult to design. To make a beginning, we tested two universal conjectures. First, when students are given a well-defined experimental task with complete instructions on how to acquire, handle and interpret data, they are usually able to execute the algorithm satisfactorily. On the same well-defined task, performance deteriorates when critical decisions such as what the range of variables should be and how many observations should be taken, are left to the student. Further, if the same task is worded differently or embedded in an unfamiliar context, the difficulty level increases manifold. Competence and transfer of learning are not assured. Second, when students are given an open-ended investigation without first executing a well-defined sample task, their performance is extremely deficient. Left to their own resources, students often face additional difficulties in evoking appropriate concepts to design the setup, identifying variables of the problem, establishing procedures for measurement and making sense of the data they gather.

These tenets, verified through several classroom investigations [7], have helped us in designing research instruments which incorporate an optimum sequence of instructions, cues and sample tasks alongside the research questions that seek data on select aspects of conceptual and procedural knowledge. The results of these investigations are being used to design a comprehensive research-based laboratory curriculum for use at the tertiary level. In this paper, we describe one of the research instruments and suggest a rubric for evaluating the quality of students' data. Finally, we propose a model of laboratory instruction and exemplify it through an Interactive Laboratory Tutorial that could be used to enhance students' concepts of procedure.

2. RESEARCH METHODOLOGY

2.1 Design of Research Instrument

A deliberate attempt has been made to probe students' understandings operative in contexts with which the students are familiar and which qualify in their perspective as scientific investigations. The research instrument described herein pertains to a block of activities titled "Test a Hypothesis." The unit contains five different activities. In each case, the problem required the student to determine the relation between two physical quantities. Specifically, they investigated the

a. time it takes a coin to fall from different heights;

b. horizontal distance traversed by a ball launched from different heights with a fixed velocity;
c. change in the resistance of a light detecting resistor with intensity of light;
d. change in current in a torch bulb as the voltage is varied;
e. change in level of water flowing out of a burette with time.

For each activity, the students were required to work through

I. A Pre-laboratory Questionnaire. This was a paper-and-pencil instrument that probed students' ideas about

- design of experiment; what apparatus would be required and how it would be used.
- procedure for data collection; what physical quantities would be measured, how many sets of observations would be taken and how the raw data would be tabulated.
- procedure for analysis; how the data would be analyzed, for graphical analysis what would be plotted on the X- and Y-axes and what would be the sketch of the curve.
- physics of the problem; this entailed posing few conceptual questions about the underlying principles and seeking the mathematical relation between the measured quantities.

II. A Laboratory Activity Sheet. This embedded the laboratory task within a carefully worked out sequence of exposition and questions. Instructions delineated details about

- design of experiment; how the setup was to be used.
- procedure for data collection; how observations were to be taken and tabulated in data sheets with labeled columns provided for the purpose.
- hypothesis to check; this entailed describing briefly the physics of the problem and the essential steps in deriving the mathematical relationship between the two physical variables.
- procedure for graphical analysis; what related quantities to calculate, how to tabulate derived quantities in columns provided in the given data sheets, and what to plot on the X- and the Y-axes.

Parameters crucial for successful completion of the task, however, were not spelt out. What the students had to do included

- deciding the values and range of measured quantities;
- deciding the number of repeats of measurement;
- calculating derived quantities from raw data;
- choosing an appropriate scale and plotting data points;
- drawing an appropriate curve through the data points;
- interpreting the result by looking at the graph drawn;
- inferring the validity of the given hypothesis;
- calculating a physical parameter of interest from the data or the slope of the graph; and
- specifying their level of confidence in the data and errors of measurement

These subtasks define the students' skill as an experimenter and adjudge how well the whole task is ultimately executed.

2.2 Data Collection

The Laboratory Questionnaire and the Activity Sheets were administered to students in the II year of the B.Sc. Physics Honors course in one of the prestigious colleges of Delhi University. The small population of 14 students facilitated in-depth analysis of data. Bits and pieces had however, been tested earlier with sample sizes extending from 100 to 300 students. The study was carried out at the end of the formal academic session just after a traditional laboratory examination. Thus it is safe to presume that the students were highly focussed and prepared for the task.

2.3 Criteria for Analysis

Student's answers to the concept probes were analyzed empirically. An attempt was also made to identify aspects of formal laboratory instruction that could have influenced a particular answer. For the laboratory task, the students' data was minutely scrutinized and evaluated in accordance to a specially constructed criteria list that looked at the students'

- choice of minimum and maximum value of the physical quantity taken as the independent variable x;
- choice of interval dx between consecutive values of x;
- number of sets of observations and number of repeats;
- scatter in repeated values of the physical quantity taken as the dependent variable y;
- overlap between the set of repeats for the variable y corresponding to consecutive values of the variable x;
- choice of scale for plotting the graph between x and y;
- correctness of the plotted points;
- graphical scatter of the plotted data points about a hypothetical curve;
- correctness of the curve fitted through the data points;
- method of determining the slope and its value;
- calculation of a physical quantity or parameter from the value of the slope;
- reporting of the result; and
- reporting of the errors of measurement.

Further, the entire class data was one, compared to check the consistency in the group performance and two, compared against the data we had taken ourselves on identical setups.

3. ANALYSIS AND DISCUSSION

We report herein the results of only one activity in the unit. In this, the students were given a one rupee coin and asked to determine the relation between the height (y) and the time of free fall (t) and find the value of acceleration due to gravity (g). Of the five tasks, this activity posed the least cognitive challenge. Hence it is appropriate for bringing forth how in a well understood task, the reliability and validity of students' data affect graphical analysis and the ability to test the validity of a hypothesis.

3.1 Conceptions About Design Of Experiment

The pre-laboratory questionnaire asked the students to describe the complete procedure for making the necessary measurements. All the students stated they would drop the coin from different heights, record the time using a stopwatch and tabulate these two quantities. All except one student also said they would plot a graph to determine the relationship between y and t. However, there were surprising variations in students' thinking about important details.

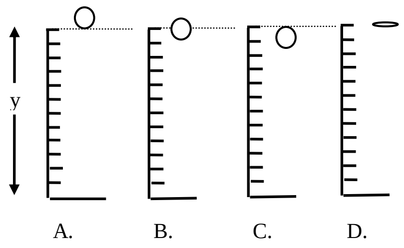

Figure 1: Students were asked the most appropriate way of placing the coin before it is dropped from a height *y*.

Height from which coin should be dropped. Asked to suggest the values of height, half the students chose the range of *y* as 20 to 120 cm. Five students suggested values varying from 1 to 3 m while one student wanted to drop the coin from 10 m. Only one student stated that she would choose the heights after some trial. The students who planned to drop the coin from 20 cm had not considered how accurately the time of fall could be measured using an ordinary digital stopwatch. Likewise, the student who planned to drop the coin from ten meters had not thought of how from that height she would ascertain the exact moment when the coin would hit the ground. She also did not ponder over how air friction and air currents would affect the fall.

Method of placing the coin. We asked the students to choose which of the four different ways of placing the coin at its rest mark shown in Figure 1 was the most appropriate. Ten students opted for placing the coin face down as shown in (d) while three students chose the edge down configuration (a). One student chose to align the middle of the coin with the marker as in (b). These answers reflect that while the majority of students understand how the height should be measured to avoid an offset error, they are oblivious of the fact that a coin dropped face down is likely to wobble more than a coin dropped edge down. Asked explicitly if the way the coin is dropped would change the time of fall, the student's opinion was divided almost equally (Table 1).

Theoretical Relation between height and time of fall. Study of freely falling objects is one of the first episodes covered in any course in Newtonian mechanics. However, when asked to give the time it would take for a coin to fall from a height of 1 m, only nine students gave the correct answer of $t = \sqrt{2/g}$. The remaining students quoted a variety of unacceptable formulae. When we checked if the student's believed the time of fall depended on the mass of the coin, the common belief that heavier objects fall faster was much in evidence (Table 2). No explanation of this thinking was forthcoming.

Table 1: Students' prediction about the time of fall for coin dropped edge down and face down being different.

Response Category	No. of Students
Yes: Coin dropped edge down is faster	4
Yes: Coin dropped edge down is slower	2
Yes: No further elaboration	2
No: No further elaboration	5
No response	1

Table 2: Student's response to which of the three given coins (Rupee 5, Rupee 1 and Paise fifty) would fall first. Coins are listed in the order of decreasing weight.

Response Category	No. of Students
All coins will take the same time	6
Rupee 5 coin will fall faster	6
Fifty paise coin will fall faster	2

Predicting the Graphical Relation. To check if the students understood how the data could be analyzed graphically to discover the relation between *y* and *t*, we first asked what they would plot along the X- and the Y-axes. The responses are summarized in Table 3.

Table 3: Students' choice of independent and dependent variables for graphical representation of data

Quantities Plotted along X- and Y-axes	No. of students
(X, Y): (y, t)	9
(X, Y): (t, y)	4
(X, Y): (t, y^2)	1

The response shows the inability of many students to correctly identify the independent and the dependent variable. This data belies the presumption that students have sufficient drill and practice in traditional laboratory to realize that the independent variable is generally plotted along the X-axis.

Next we asked students to sketch what they expected the graph describing the relationship to look like. A blank space with two unlabeled axes was provided for the purpose. Of the nine students who knew the correct formula, only four students could draw an acceptable graphical representation. All of them took time along the X-axis; three sketched the (t, y) curve as a parabola while one drew (t^2, y) as a straight line. The observation that the students are more comfortable taking time along the X-axis has been found in other contexts as well. The sketches of the remaining students merely confirmed another well established research finding that students have a major problem in translating a formula into a graph.

3. 2 Quality of Laboratory Performance

After completing pre-laboratory questionnaire, the students proceeded to actually carry out the experiment. To ensure that the exercise was carried out under fairly controlled conditions, the Activity Sheet clearly spelt out the procedure step by step and showed students how the coin was to be placed. A measuring tape was stuck on the wall to facilitate measurement of height. The bottom of the tape was at 1 m from the ground to cue a reasonable starting value. The students were expected to take note of this offset in recording the height. Table 4 summarizes the quality of student's data along the dimensions listed in the checklist given in section 2.

Table 4: Making sense of student's observations/ results.

Aspect of Data and Response Category	#
A. Recording height from which coin is dropped	
Apparently correct	11
Apparently Incorrect	3
B. Recording time of free fall	
Apparently correct	5
Wide variations in fall time	7
Apparently incorrect	2
C. Choice of range of *y*	
From 120 cm to 300 cm	9
From 70 cm to 150 cm	2
From 20 cm to 50 cm	3
D. Number of heights chosen	
4 to 5	10
6 to 10	4
E. Choice of interval *dy*	
5 to 10 cm	6
20 to 25 cm	7
50 cm	1
F. Number of repeats taken for time of fall	
10	1
2 to 3	4
One	9
G. Scatter in data about a hypothetical straight line	
Hardly any scatter	6
Reasonably small scatter	5
Unacceptably large scatter	3
H. Fitting a curve (X, Y): ($\sqrt{y}$,*t*)	
Fits straight line: apparently best visual fit	7
Fits a straight line: not the best visual fit	2
Fits a parabola: apparently best visual fit	4
Fits a complicated curve through all points	1
I. Value of intercept	
Nonzero	14
J. Calculation of slope	
Correct calculation from the straight line drawn	5
Incorrect calculation from the straight line drawn	3
Using mirror to calculate slope of the curve drawn	3
Not calculated	3
K. Reported value of '*g*'	
Less that 15 cm s^{-2}	3
Between 150 and 400 cm s^{-2}	4
Between 600 and 800 cm s^{-2}	2
Between 900 and 1030 cm s^{-2}	4
Not calculated	1
L. Reported value of % error	
Less than 5%	3
Between 10% and 30%	6
Greater than 50%	4
Not calculated	1
M. Concluding data supports hypothesis $t = \sqrt{2y/g}$	
Yes: Hypothesis is valid	12
No: Hypothesis is not valid	1
No response	1

<u>Measurement of height and time of fall.</u> While most of the students were able to measure the heights chosen correctly, the time data of more than half the class showed wide variations and unexpected values. In the pre-activity question, students had said they would repeat the measurement of time at each height; eleven suggested up to 5 repeats while three suggested taking 15 to 25 repeats. Of these, one student had this to say: " … four times with each side (heads/tails) facing N, S, E, W in turns so as to eliminate errors due to air current variations." This is an interesting comment that reflects the vividness with which surface features of a problem motivate students to visualize how they will execute a task. However, despite intentions, in actual practice, more than half the class took only one measurement of time for each height.

<u>Inferring the validity of the hypothesis.</u> The students were asked to compute $\sqrt{y}$ and plot *t* with respect to $\sqrt{y}$. The quality of measured data was gauged by looking at these ($\sqrt{y}$,*t*) plots. The data of eleven students showed reasonably small scatter about a hypothetical straight line. However, only nine students drew a straight line while 4 students drew a parabolic curve. One student drew a complicated curve passing through all her data points. None of these curves could be extrapolated to pass through the origin.

The activity required the students to look at the nature of the ($\sqrt{y}$, *t*) curve and state if the observations supported the hypothesis $t = \sqrt{2y/g}$. Despite the fact that only nine students drew a straight line through the data points, as many as twelve students claimed the validity of the hypothesis. Then they proceeded to calculate the "slope" of the curve drawn and thence the value of *g*. Three of the students who had drawn nonlinear curves used a mirror to evaluate the slope at some arbitrary point on the curve and used this value to compute *g*! These students did not ponder on why they had obtained a nonlinear curve but allowed that picture to trigger memory of how slope of a nonlinear curve is obtained. The transfer of a procedure recommended to them in other contexts where nonlinear curves appear (such as the experiment to determine Stefan's Constant), allowed them to proceed further in their slated task despite its inappropriateness in the present situation.

<u>Reporting the value of g and percentage error.</u> Using the value of the slope – however computed – students reported values of *g* ranging from 4.58 cm s^{-2} to 1029.4 cm s^{-2} (the significant figures are as reported by students). However, the percent error from the accepted value of 980 cm s^{-2} were all less than 60%. These values, however, cannot be taken at the face value; in most cases the calculations hide gross errors. Of the four students who reported *g* between 900 and 1030 cm s^{-2}, one had obtained a nonlinear curve and found the slope at an arbitrary point; another had made a numerical error in calculating slope; two had erroneous values of height ranging from 0 to 40 cm and thus meaningless data from the outset. All the three students who obtained extremely low values of *g*, took quantities with mismatched units while computing the percent error. To exemplify, one student reported

Calculated value of *g* = 11.8 cm s^{-2}
Expected value of *g* = 9.8 m s^{-2}
% error = (9.8-11.8)*100/9.8 = 20.408%

It would appear that obtaining a value close to 9.8 made the students oblivious to the fact that only quantities with similar units can be compared; it is meaningless to compute percentage error when the observed value differs from the accepted value by two orders of magnitude.

Evaluating the "Goodness" of Raw Data. The above findings lead to the unfortunate conclusion that not one student had performed the experiment satisfactorily to the end. Discomforted by this thought, we undertook to evaluate the worth of the data collected by each student. First we compared the values of time with what we had ourselves measured. Then, we used the method of least squares to draw the best curve through the student's data points ($\sqrt{y}$,t). Finally, where applicable, we calculated the value of g the student would have reported had she used the correct procedure for evaluating it. Since none of the students had taken care to set the intercept at zero, we also checked how forcing the intercept to zero would affect the correlation in data and the value of g.

Observations taken by only three students survived the scrutiny. Table 5a summarizes the characteristics of their raw data. They are amongst the few that have an appropriate choice for the range of y, the interval dy. The higher than expected values of time are because of the very few repeats.

Table 5a: Select students' measured data. S identifies the data taken by students and R by the researchers.

ID	Range of y (cm)			Range of t (s)		Heights chosen	Rep-eats
	Min	Max	dy	Min	Max		
S1	150	250	50	0.55	0.78	5	3
S2	150	225	25	0.53	0.79	4	10
S3	150	250	25	0.59	0.84	5	3
R	150	250	25	0.54	0.71	5	25

Table 5b gives the parameters of the best fit and the value of g calculated therefrom. Second row in each cluster shows how the slope and value of g would change when the intercept is set to zero. In each case, forcing the ($\sqrt{y}$,t) straight line through the origin improves the value of g but also decreases the correlation. The data shows the extent to which bad graphical analysis can influence results. Only one student's observations yield a value of g with about 5% error. Ironically, left to her own devices, this student produced a value of ~ 5 cm s^{-2}.

Table 5b: Results of rigorous analysis of data carried out by researchers to evaluate quality of observations. R identifies data taken by the researchers.

ID	Using Linear Least Square Fit				Quoted value of g cm s^{-2}
	Slope	Inter-cept	Corr-elation	g cm s^{-2}	
S1	0.06 0.05	-0.20 0	0.98 0.95	550 929	4.9
S2	0.09 0.05	-0.53 0	0.96 0.87	253 791	945
S3	0.06 0.05	-0.16 0	0.95 0.94	498 737	385.8
R	0.045	0	0.99	1000	1000

3.3 Summary

On the face of it, the experimental task is simple and involves straightforward measurement of a static distance and timing of an event. However, successful performance hinges on recognizing that the time of fall is less than one second for heights under 5 m. At very small heights, the reaction time is comparable to the time of fall and in the first instance, one would not expect to get accurate values. On the other hand, larger the height, more are the effects due to air friction and air currents. The challenge then is to choose optimum values of y to reduce both, the errors of measurement and errors due to undesirable effects. Since one expects a large scatter in data, to get reliable and valid results, it is extremely important to take several repeat measurements of time for each height and be able to recognize and discard anomalous data before taking an average. Further, to avoid overlapping measurements of time, consecutive heights have to be spaced by an appropriately large interval. It is meaningful to undertake graphical analysis and draw an inference only when the data passes this benchmark.

Our study shows that students do not use their theoretical understanding of physics to choose the values and range of measurement variables or check the validity of results they obtain. Nevertheless, they have great faith in the intuitive procedures they adopt and the correctness of their measurements. However, when it comes to judging the overall validity of a hypothesis, they take recourse to their theoretical expectations rather than the evidence provided by their data.

4. MODEL FOR LABORATORY INSTRUCTION

One of the objectives of laboratory training is to help the student outgrow novice performance and develop what is accepted as experimental expertise. This is not so much a matter of giving more hands-on experience to hone skills in manipulating equipment as of creating a minds-on environment to promote conceptual learning about procedures [8]. As evidenced by data, such learning does not occur naturally in a traditional laboratory. Before appropriate procedural concepts can take root, it is important to

- elicit deficiencies in performance;
- explicitly confront students with quality of their data assessed using an objective set of criterions;
- provide experiences that explicate the causes responsible for poor quality of data; and finally
- suggest alternative mechanisms, procedural and conceptual, for enhancing performance.

Analogous steps have been found to be successful in engendering conceptual change in the learning of theoretical concepts; we believe these steps would also provide a paradigm for learning in the laboratory.

4.1 Laboratory Tutorial

We have used the above model of laboratory instruction to construct teaching units that pertain to various procedural concepts. The implementation is at three levels. At each level, the specially designed worksheets integrate concept probes with hands-on activities.

Level 1: Eliciting Novice Performance.

(i) *Pre-laboratory Questionnaire*: This includes questions to elicit students' understanding about design of experiment, concepts of procedure and the physics of the problem.

(ii) *Laboratory Activity*: The worksheet provides the theoretical background and a guided exposure to the laboratory task. Inasmuch as many critical decisions about data collection are left to the student, the activity provides an opportunity for spontaneous play with the measurement process. Learning by hit and trial is a crucial in situations that are little understood.

Level 2: Facilitating Transition.

(iii) *Data Assessment*: The instrument helps the student to subdivide the whole task into subtasks and assess each step using a pertinent set of criterions. By comparing her data with that of an imaginary experimenter, the student is sensitized to deficiencies in her performance.

(iv) *Bridging Exercises*: The worksheet consists of a careful sequence of concept and data probes. Simple hands-on exercises and thought experiments provide analogous learning for each subtask and help the student make informed choices about the measurement parameters.

Level 3: Generating Expertise.

(v) *Laboratory Activity*: With negligible guidance, the new worksheet seeks a fresh hands-on performance on either the same task, suitably enhanced and extended, or a related application. The assessment of this activity determines the gain in learning and the success of the instructional process. Depending on individual requirement, the student may be required to cycle through the earlier steps in this process at her own pace.

It is in order to add that assessing the quality of data requires a certain degree of statistical rigor. To go beyond qualitative understandings, it is essential to introduce students to computer-based tools for data analysis at an appropriate point in the instruction sequence. At the tertiary level, this could be mandatory. Obviously, this new dimension brings its own pedagogic challenge.

Example

For the coin activity, the level one instruction is provided by the questionnaire and the Laboratory Activity Sheet described in section 2 as the research instruments.

At level 2, students' data assessment sheets employ the rubric evoked in Table 4. The bridging tutorial consists of two clusters. The first motivates the concept of reaction time through a story line. The students are asked to attempt to stop a digital stopwatch when it reads 10 s and record the data for 50 trials; explain the reasons for the scatter in values; decide what to report as a result; and, repeat the process for time values of 1 s and 0.5 s. They are encouraged to examine the relative accuracy of the results in the three cases and plot the histogram to develop a visual comprehension of the nature of the spread in data and answer why taking repeats of a measurement is necessary. Data taken by different students is compared and then the entire class data is clubbed to see what happens to the distribution and the result. The challenge is to reduce the errors due to reaction time as far as possible; this drill is useful in helping students be more agile.

The second set of questions ask students to examine data sets such as

S1: (0.58, 0.65, 0.55, 0.54, 0.53, 0.65, 0.57, 0.56, 0.54, 0.53)

S2: (0.55, 0.52, 0.58, 0.58, 0.62, 0.53, 0.54, 0.54, 0.51, 0.53).

Students have to state what they would report as the result. Through similar questions, they learn how to handle anomalous data points; compare the quality of data taken by different observers; differentiate between gross errors, systematic errors and random errors; and explore the notions of precision and accuracy of data in the context of the given task. Exercises used for enhancing procedural concepts invoked in graphical representation of data are not discussed herein but are adapted from the unit on graphing.

At level 3, students are asked to work in groups of four and challenged to determine g accurate to within, say, 2% and state the conditions necessary for reducing error. A natural extension to the group activity is clubbing the data of the entire class and discovering how this changes the distribution and the average value of the fall time for each height [9]. This sequence of instructional steps provides useful learning about the inherent limitation of the measurement process and methods for reducing the errors of measurement.

5. EVALUATION

While the various concept and data probes have been tested individually, we are in the process of testing the complete block in a classroom situation. Meanwhile, it would perhaps suffice to say that the student response to this form of instruction has been extremely enthusiastic. According to students, it is hands-on and minds-on.

6. REFERENCES

1. M. Sere, R. Journeaux and C. Larcher, Learning the statistical analysis of measurement errors, *Int. J. Sci. Educ.*, 15(4), pp. 427-438, 1993.
2. S. Allie, A. Buffler, L. Kaunda, B. Campbell and F. Lubben, First-year physics students' perceptions of the quality of experimental measurements, *Int. J. Sci. Educ*., 20(4), pp.447-459, 1998.
3. R. Millar, F. Lubben, R. Gott and S. Duggan, Investigating in the school science laboratory: Conceptual and procedural knowledge and their influence on performance, *Research Papers in Education*, 9(2), pp. 207-248, 1994.
4. R. Millar, R. Gott, F. Lubben and S. Duggan, Children's performance of investigative tasks in science: A framework for considering progression in M. Hughes (ed.), *Progression in Learning*, pp. 82-108, Multilingual Matters Ltd. Clevedon, 1996.
5. F. Lubben and R. Millar, Children's ideas about the relaiability of experimental data, *Int. J. Sci. Educ*., 18(8), pp. 955-968, 1996.
6. S. Duggan, P. Jhonson and R. Gott, A critical point in investigative work: Defining variables, *J. Res. In Sc. Teach*., 33(5), pp. 461-474, 1996.
7. P. Jolly and V. B. Bhatia, Developing a research-based laboratory curriculum for college physics in A. A. Tajuddin et al (eds.), *Proceedings of ASPEN conference: University Physics Education for the 21st century*, ASPEN, Malaysia, 65-73, 1997.
8. F. Reif and M. St. John, *Am. J. Phys*., 47(11), 950-957, 1979.
9. R. Ehlrich and M. L. Hutchinson, Random and systematic errors in timing the fall of a coin, *The Physics Teacher*, 32(1), pp. 51-53, 1994.