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A Course in Modern Physics for Colombia

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A modern physics course oriented to the specific educational needs of the Colombian student is discussed. Emphasizing independent thinking and original work, the course reinforces the efforts of the student through a strong correlation between the homework, the lectures, and a laboratory, which takes the form of a research project. Flexibility and a relatively inexpensive laboratory make it ideal for many Latin American universities.

The problems one encounters in teaching physics in Colombia have been recognized for a number of years and can be easily generalized to almost every country in Latin America.[1] These problems are sufficiently widespread, reaching not only across international lines but throughout all the levels of the educational system, that they constitute a serious barrier to any educational reform. In what follows, we describe an attempt to meet some of these problems with a modern physics course that orients itself toward the specific weaknesses of the student and the educational system. We begin with a specific statement of the problems with which we are concerned, followed by a general discussion of how a physics course might handle such problems, and finally an analysis of the actual course, as given, and the results of the method.

I. GENERAL CONSIDERATIONS

A. Educational Problems Encountered in Colombia

The major troubles that the majority of Latin American students have when they approach any science course stem from two fundamental traits acquired in their educational past: learning by memorization and the belief in the supremacy of the teacher. The former necessarily leads to inability to do independent thinking, because education is viewed as something to be accepted, not analyzed. Laboratories are limited to verification, if given at all. This, in turn, leads to a serious lack of organizational ability; in the organization of something simple, like data in a notebook, as well as in organizing reasonable processes of thought for problem solving.

The latter part of the student's past tends to make him unconvinced of the value of his own work and ideas, because the teacher has all the answers and there is nothing left to say. This develops into a reluctance to offer anything to the course on an individual basis. Thus, we find a tendency for the student to do almost all of his work in groups, largely eliminating the evaluation of the individual (and therefore individual help) from everything except examinations.

We might summarize the basic problems of the student in terms of (1) lack of organizational ability extending to all thought processes and modes of expression and (2) the inability or reluctance for independent thinking and individual expression. We assume, then, these to be universal faults that may differ from student to student, depending on the quality of his past education. This being so, we consider the *primary* educational objective of the modern physics course, discussed below, as follows: to give the student the abilities he lacks, as stated above. It is important to note that this objective is stated in terms of changes that should occur in the student by the end of the course, rather than in terms of a list of topics that the professor will cover in class.

B. How a Physics Course Might Help Solve these Problems

The course, structured in terms of the goals given above, must then use the subject matter as the base from which the primary objectives are met, putting the objective of increasing the student's store of knowledge of the physical world on a secondary, though certainly not unimportant, level. The course discussed here has tried to confront directly the problems involved in a three-step process, each step representing one of the fundamental components of a physics course: homework problems, the laboratory, and the theory (lectures).

The first working contact the students have with the course is through the homework problems. The type of homework given in the first few weeks of class seems to be important both to the attitude of the students and to their preparation for the thought processes involved in the laboratory discussed below. For this reason, care must be given to the design and selection of problems. The homework has the task of permitting a first attempt to think on one's own, in terms of a relatively simple physical situation. In order to lead the student slowly from, perhaps, never having analyzed an experimental situation up to the working conditions of the laboratory, the homework is composed in terms of (1) experimental situations and their value in science; (2) simple representation of experimental variables and changes in representation when, say three variables (two variables and one parameter) are used; (3) interpretation of results expressed in graphical form; and (4) the experimental process as it relates to the formation of hypotheses. Examples are presented in Sec. II. A.

The laboratory is where the ideas introduced in the homework are brought to life in an experimental situation. The laboratory, as envisioned here, does not emphasize experimentation in physics so much as the student's *own* experimentation with the processes of creative thinking, keeping in line with our primary objective. Of course, the actual experimentation and working with heretofore theoretical ideas cannot help but improve appreciation and understanding.

The laboratory has been organized into six basic parts, as suggested in the following: (1) the breakdown of a problem concerning the study of a physical situation into its significant variables, into functions of these variables that can be measured and graphed, and into parameters effecting any two-variable relationship; (2) distinguishing experimental variables from derived ones, thereby permitting a first step in the design of actual experiments that study the various relationships that have been selected; (3) selection and design of satisfactory apparatus, taking into account physical and cost limitations; (4) experimentation; (5) representation of the results that lead to a meaningful interpretation of the data and conclusions; and (6) final interpretation of the results, consisting in an attempt to explain the phenomenon studied in terms of the theory, with emphasis on individual thinking and originality.

Finally, we consider the lecture part of the course. The lectures, in reality, play a minor role in the realization of our stated goals, but, since the laboratory and the homework make no sense without them, we must try to see what purpose this part of the course has. In order to follow up the trend in the homework and laboratory, the lecturers should try presenting the subject in terms of problems or questions, giving experimental evidence to support them and then resolving the two in terms of a theoretical explanation or the formation of hypotheses. This is particularly easy in modern physics, in which every text presents a list of some of the key experiments that in some way have caused the theory to be modified.

Thus, the course may present itself in terms of a model-problem-solving situation akin to the type of problems the student is working, which may give him a more thorough background in this kind of analysis. The problem, of course, is that the student is not doing it, the professor is, and we have the same situation as before. The conclusion is that the theory cannot be treated effectively without corresponding parts of the course that involve student participation and that emphasize the fundamental points of the theory, under the circumstances found in Latin America. Its purpose is to give the necessary theoretical background, and to provide the factual resources that the student may draw upon to base his "own" interpretation of the laboratory work.

II. MODERN PHYSICS COURSE GIVEN AT UNIVERSIDAD JAVERIANA

A. Homework Problems

We have already discussed how the homework problems might meet the objectives of the course by preparing the student for the laboratory and initiating certain types of thought processes. In the actual case, this was done in such a way as to introduce certain topics before they were seen in the lectures, to give the student a chance to analyze the situation for himself.

There were also many standard-type problems given throughout the semester. These were necessary because the techniques of calculation, for example, when one is working with different units of energy or order of magnitude estimates, are invaluable to meaningful work in the lab-

Table I. The structure of and relation between the theory, laboratory, and homework of the modern physics course given at the Universidad Javeriana.

Principal topics covered in the lectures	Major steps in the development of the laboratory	Homework problems	Week
The Universe and relativity			1
	Study of general steps involved in a research project	Set I	2
Ideal gas and Maxwell distribution, structure of nuclear atom	Basic theory of the solid state		3, 4
Quantum experiments, x rays, de Broglie waves, uncertainty principle, Bohr atom			5
	Study of photoconductivity and electroluminescence experimentally, in order to introduce the phenomena	Set II	6
Wave equation, potential wells and barriers, selection rules, and atomic transitions	Study in groups of significant variables and relations that might lead to meaningful experiments about electroluminescence in diodes		7
	Study in groups to select and design apparatus to carry out the experiments discussed the week before		8
Application of basic quantum theory to atomic structure	Preparation and construction of the experimental equipment and planning of procedure for experimental work		9
	Experimentation, taking of data		10
Molecular binding and spectra			11
Application of basic quantum theory to the solid state			12
	Discussion of results, interpretation, relation to theory	Set III	13, 14
Nuclei and elementary particles, philosophical implications of modern physics	Defense of laboratory report as the oral final exam		15

oratory. These are not discussed, since they can be found in any text on the subject. We are most interested in those problem sets (marked I, II, and III in Table I) that deviated from the norm, in order to meet our objectives.

Problem set I consisted of an explanation of the procedure of an experiment in which x rays are emitted from a metal plate in a vacuum tube, the emission occurring when a beam of electrons strike the metal. Also given were two graphs: one showed the intensity of the emitted x rays as a function of their wavelength for one type of target material and for three different values of the accelerating potential in the electron tube; the other graph used the same axes but showed the curves for three different metals with the same acceleration potential.

The students were asked to examine the curves and describe them. In this way, they began to distinguish the variables as having physical meaning and to learn about the different ways an experimental situation can be represented. This type of problem has been suggested, up to this degree of difficulty, for use with nonmajors in more elementary courses.[2] It can easily be extended to the consideration of the "why" of certain details of the experiments, rather than the simple observation of their existence.

Thus, after the student had made these observations, he was given a brief explanation, in terms of classical physics, of what should happen when an electron strikes the target plate. He was then asked how the results differed from this explanation and whether there were other experiments he might do to study the problem in more detail. Finally, given the supposition that the radiation could be emitted in the form of photons whose energy was inversely proportional to the wavelength, they were led to a derivation of the cutoff wavelength at the lower end of the spectrum (a property that most had observed in the first part of the problem).

In this way, they were beginning to interpret the experiment in terms of the theory, approaching the analysis in the organized way indicated by the questions. The answers received were a clear indication of their lack of ability for this type of analysis, whereas the latter homework, which involved straight calculations, even though difficult, had much better results.

Problem set II was given in the form of a quiz in the laboratory during the sixth week of class. The experiment presented consisted of two circuits: one contained a battery, an ammeter, and a semiconductor crystal, while the other contained a semiconductor diode with battery and ammeter. The characteristic of each device was plotted with incident light intensity as a parameter. For the single crystal, there were straight lines passing through the origin of the current versus voltage plot, whose slope increased with increasing light intensity directed at the crystal. For the diode, we saw reversed-bias current increasing with increasing intensity of the incident light (see Fig. 1). The questions asked were (1) to explain why the light produced the effects observed, using the elementary band theory of solids and the theory of the p–n junctions the students had seen in the laboratory; (2) to explain why the crystal gave, more or less, a straight-line characteristic; (3) to explain why light seemed to effect only the diode with reverse bias; and (4) to draw the graphs of current vs intensity for several values of bias voltage as a parameter.

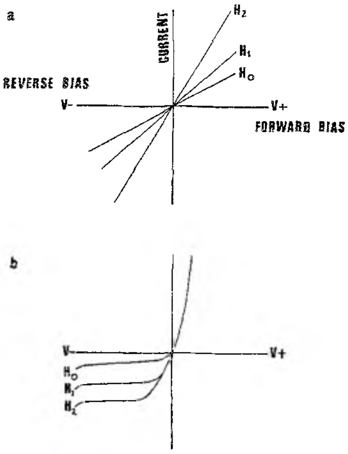

FIG. 1. Experimental data given to accompany a laboratory exam. The characteristic in graph **a** is that of a photoconducting crystal, where there is an incident light of intensity $H_2 > H_1 > H_0$. Graph **b** is the characteristic of a photoconducting diode under the same conditions. Current and voltage are in arbitrary units.

Although, once again, the actual results of the test were not outstanding, the same ideas and techniques could be immediately applied and reinforced in the next few laboratory sessions, as discussed in the next section. At this point, as we will see, the laboratory took over the job of carrying out the objectives.

Problem set III, given near the end of the course, was no more than reading an article from the literature on electroluminescence.[3] This was done during the study of the solid state in the lectures. The reason it is mentioned is that it is a practice not often followed, and it served to introduce some ideas about the practical limitations involved in building an efficient solid-state light source. Most important, learning that the *thing* they were studying was not going to obey any known formula, and the fact that their interpretations could be as valid as any others, tended to create a great deal of interest. The students used the article given, at their own request, as a very effective reference in the theoretical interpretation of the results of their experiments.

B. Laboratory

The most important part of the course, in terms of the actual carrying out of the objectives, and the part that received the most interest from the students, was the laboratory. It is substantially the same as one given to freshmen recently in the United States,[4] the major modifications being a more advanced treatment of the subject matter and more time spent on the analysis of the experiment. The development of the laboratory can be seen from Table I.

Table II. Experiments proposed and performed by the students, in order to study the properties of a light-emitting diode.

Experimental variables	Apparatus and procedure
Light intensity as a function of the resistance of the photoconducting solid used as a photocell	Resistance of the photocell was measured with a VTVM as a function of the distance between it and a light bulb
Intensity of the light emitted by the diode as a function of the applied direct current, alternating current, and frequency of the alternating current	With the diode in series with a resistor and power supply, the current in the circuit can be measured across the resistor with a VTVM, while the photocell is enclosed in a black container with the diode and its resistance is read by a second VTVM as a function of the current and frequency in the diode circuit—this set of data can be converted into current vs intensity, using the calibration of the photocell from the first experiment
The characteristic of the diode (current vs applied voltage) in darkness and with incident light	With the diode in series with a resistor and a power supply, the direct-current characteristic can be measured. Incident light was supplied by holding a light bulb near the diode
Characteristic of the diode at various temperatures	This was done by enclosing the diode in an aluminum box with a hole to permit entry of wires and thermometers. The box was emersed in ice, then heated on a hot plate, while the characteristic was measured as before
The emission spectrum of the diode, a direct current with constant voltage	This was measured with a standard PSSC spectroscope calibrated with the hydrogen red line
The emission spectrum as a function of direct current, alternating current, and frequency of alternating current	Done by applying the different currents across the diode and looking at the changes in the spectrum with the spectroscope
Polarization of the emitted light	Done with polaroid filters looking at the light from different angles

The laboratory starts off orienting itself towards being a research project. It begins with a talk about research and what it means, putting emphasis on the creativity of the scientist within the bounds of the scientific method and giving a few examples of the procedure used in current research, using some experiments on cosmic rays (which had been discussed the first day of class) taken from the literature. Then follows a three-lecture introduction to a given branch of physical knowledge, in this case, the solid state.

This field was chosen for several reasons. One was the composition of the students, about two thirds electrical engineering students and the rest, education majors. The more or less thorough study of some solid-state electrical properties was oriented toward the technical needs of the engineering majors, although both groups benefited from the general techniques of analysis employed. Another reason is the relatively current work being done in this area. There are few texts that contain detailed information about the topic studied (electroluminescence), so not only has the student to rely more on his own resources, but doing something recent provides him with a stimulus no textbook experiment could give. The final reason for choosing this field of investigation is the relatively easy and inexpensive experiments that can be done whose theoretical interpretations are not obvious, and which need a basic understanding of quantum-mechanical behavior.

The laboratory continues with the students being given several common-junction diodes, a light-emitting diode, and a photocell made from a photoconducting solid. The behavior of the common diode and the photocell had been studied in the laboratory lectures and quiz (see Sec. II.A). Students were asked to measure the characteristic of each element, and they soon noticed the differences between them. They had seen how incident light might increase the current in a crystal or a diode, but the problem now was, how could a current produce light?

During the next few laboratory sessions, they worked in groups to decide what kinds of experiments they would have to do in order to understand the situation better. They were asking questions about how the diode might emit the light, but it is important that the teacher supply sufficient (but not too much) guidance, so that they learn to ask the "right" questions.

These questions then must be expressed in terms of certain experimental variables, for example, intensity of the emitted light, current through the diode, temperature, spectrum of the emitted light, etc. These variables were then related to each other and, as such, became the experiments: "How does the intensity of emission depend on the current through the diode?" or "Does the frequency of emission depend upon the applied current?" In Table II, there is a complete list of the experiments proposed and done by the students.

Also in Table II can be found the experimental technique that they decided to use to implement each step. They built what they needed that was not standard laboratory equipment, for example, several aluminum boxes for experiments at different temperatures and several large and small boxes of black construction paper and tape, in order to carry out certain experiments in complete darkness.

Following the experimental work were two periods of analysis and interpretation of results. Here, the data had to be organized in such a way that a meaningful interpretation was made possible in applying the theory of the diode and luminescence in solids, then being discussed in class.

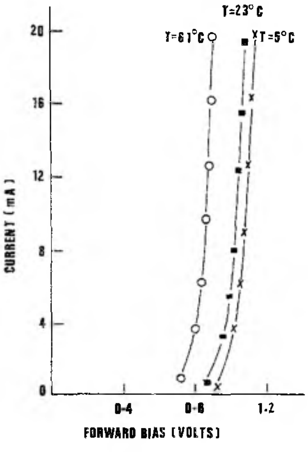

Fig. 2. Typical characteristics for the General Electric SSL-1 diode, as measured by the students at three different case temperatures.

It must be emphasized here that this type of assimilation is particularly demanding for any student, and, given the newness of the experience for these students, it is even more so. It is, therefore, of fundamental importance that all of the student's work—homework, lectures, laboratory—during this period be limited to the study of one topic (in this case, the interpretation of certain solid-state phenomena), in order to give him sufficient opportunity to think about the problem, and, as mentioned before, to reinforce his understanding and his newly acquired abilities. Thus, we see in Table I the simultaneous presentation of this phase of the laboratory with the theoretical presentation in the lectures and the view of how a similar experiment was interpreted in an actual research situation using problem set III.

Even with this, there are still many problems for the students to overcome. The important thing is that they, themselves, devise feasible explanations for what they have observed. Nevertheless, teacher participation, up to a point, is strongly recommended. This participation should take the form of helping students to reorganize their thought processes, reasking some old questions in new terms, or restating the problem, rather than giving any kind of hint about the theoretical explanation. Since this is the part of the course that ultimately determines the success or failure of our objectives, we must be careful to keep building upon the enthusiasm of the student.

Consider the example shown in Fig. 2. The experiment was to measure the characteristic of the diode at different temperatures. All that was observed was that the curve preserved the same form but moved to the left for increasing temperatures and they were not able to interpret what that might mean. It was suggested that they consider one of the values of bias voltage and find out what happened to the current as the temperature increased (reasking the question). Then they were asked to use the results of the intensity as a function of current experiment, to decide how the intensity of emission might behave as temperature increased, and to design a new experiment that would verify the conclusion directly (restating the problem). Not only did they understand the experimental results better, but they saw that there were other experiments that could have been done, and that what they had done was not unique or complete, in any sense.

C. Lectures

As mentioned in the last section, the lectures were designed to give a relatively detailed account of solid-state theory near the end of the semester, just at the time when the students were beginning to analyze their results. The lectures also provided reinforcement near the beginning of the course in weeks five and six (see Table I) before the different experimental methods began to be studied in the laboratory. This was in the form of a discussion of the photoelectric effect, the Compton effect, x-ray emission, etc., presented in terms of an experimental situation similar to that which they would encounter in the laboratory. This part of the lectures logically followed up the methods developed in problem set I.

Thus, we have a strong correlation between the lectures, the laboratory, and the homework near the beginning of and the end of the course, as opposed to having a laboratory largely independent of the lectures in terms of the relation between the experiments being done and the topics being presented in class at that time. This correlation is necessary to the fulfillment of our educational objectives, but it also has a sort of psychological necessity, because the students are much more impressionable during the first few weeks, when everything is new, and near the end of the course, when they are able to see some of the results of their work, than they are near the middle of the course. During that time, they are mostly concerned with learning the new vocabulary and ideas associated with modern physics and are spending most of their time acquiring the tools that will be necessary to carry out the laboratory work. The principal topics covered in the lectures are listed in Table I.

CONCLUSIONS

How the student reacted to the course was judged through talks with him at various times during the semester and, also, by the use of written evaluations. There seemed to be a unanimous approval of the method, but for several different reasons. Many liked the course because it increased their understanding of diodes and solid-state phenomena. Others were particularly impressed with the fact that they could use their own resources in the laboratory in order to carry out a more or less complete study of a physical process. Most were enthused with the fact that the phenomenon studied was of recent interest, and then felt that they were actually doing serious research.

The success of the course was due to the fact that we decided to orient it to the specific needs of the students. Giving them the opportunity to think originally and providing the proper stimulus and reinforcement to enable them to do so effectively enough to arrive at some conclusions was as satisfying to them as to the teacher, who faced a similar challenge, in that the procedure of the course was flexible and he had to learn to follow the students, instead of the students following him.

The course offered ample opportunity for its self-evaluation and for the evaluation of the students during the discussion sessions in weeks seven, eight, and nine. In addition, the oral final exam for the laboratory left no doubt that the students had achieved a substantial amount of ability in thinking independently and critically and in organizing thoughts, when compared to the results of the problem sets I and II. They were able to analyze results and new problems presented to them, create new experiments, and discuss their limitations during the exam. Their laboratory reports show considerable evidence of their having developed along the lines of the objectives laid down at the beginning of this article.

A few suggestions for future courses became evident, also, in talking with the students. One is that the particular phenomenon studied should be changed every semester, or the laboratory will lose its originality as results pass among the students. This is especially difficult in Latin America, where the laboratories are not well enough equipped, in most circumstances, to provide more than very simple apparatus to the student investigators. Also, the effect studied should meet the requirements of applicability discussed in Sec. II.B. Some effects with similar properties can, nevertheless, be easily studied, and they adapt well to this curriculum, for example, a photodiode or phototransistor, a tunnel diode, or the Ramauer–Townsend effect, to name a few that will be used in future courses at this university.

These all have the property that the theoretical interpretation is based upon relatively simple wave-mechanical ideas, but the effect, in practice, is complicated by physical limitations or technology, like the role of impurities in semiconductor processes, dissipation of energy through heat, etc. Most of these effects can be readily observed with the most basic of equipment.

To give an example, using the PSSC spectroscope with its plastic diffraction grating, we could observe that the part of the spectrum with lower energies was brighter than the rest. This gave a good indication that, in the diode, the probability for a radiative recombination was greater by means of some type of recombination center in the forbidden gap than by direct recombination of the electron–hole pair across the gap. The width of the emission band also leads to speculations about broadening through lattice vibrations.

Another improvement, perhaps of more fundamental importance than the one discussed above, concerns the nature of the homework problems. It has been suggested[5] that physicists begin stockpiling well-written problems on specific subjects. We could extend this one step further and try to write problems that aim at certain educational objectives, whether for physics majors or nonmajors. This course needs more problems like sets I and II to give not only a basis for other work, as these did, but to develop skills more fully during the whole course, each time at a higher level of sophistication and including practice with the necessary calculational techniques. This could take the place of all other homework, but we must make sure it is well correlated to the lectures at all times. To do this well, we have to ask much more detailed questions about the relations between the homework, the laboratory, and the theory, and about how each depends upon the objectives of the course, than have been discussed here.

A final question that arises is at what time during the student's career he should see such a course. Clearly, if we give a course by this method to a freshman, we can develop some of the abovementioned skills early enough so that he may be able to take more advantage of his education. The problem is that (at least in Colombia) it is not likely that the student has had a high-school physics course, or else, he has had a poor one, so that the resources he has to call upon in order to devise variables and design experiments are very few. It is more likely, at least at the present time in this country, that he will benefit and appreciate such a course better after having seen a good bit of general physics and done some of the basic experiments with circuits, mechanics, and heat. The necessity of this type of "elementary" work in a college course cannot be underestimated when the student has not done anything like it before.

It is clear that the type of course described here requires a great deal of planning so that all of its parts hold together, but, from the results we have seen here, it is hoped that more work will be done along these lines to improve the quality of the education and, hence, of the student. Considering the general poorness of primary and secondary education in Latin America, the universities that train teachers are the logical places to begin such a reform.

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