Millikan Lecture 1994: Understanding and teaching important scientific thought processes

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I. INTRODUCTION

Physics is an intellectually demanding discipline and many students have difficulties learning to deal with it. Further, our instruction is often far less effective than we realize. Indeed, recent investigations have revealed that many students, even when getting good grades, emerge from their basic physics courses with significant scientific misconceptions, with prescientific notions, with poor problem-solving skills, and with an inability to apply what they ostensibly learned.[1–4] In short, students' acquired physics knowledge is often largely nominal rather than functional.

This situation leads one to ask: Why is this so, and what might be done about it? More specifically, it has led me to address the following two basic questions: (a) Can one understand better the underlying thought processes required to deal with a science like physics? (b) How can such an understanding be used to design more effective instruction?

These are the questions which have been the focus of my work during the last several years and which I want to discuss in the following pages.

A. Formulation of the instructional problem

Instruction is a problem that requires one to transform a system S (called the student) from an initial state S_i to a desired final state S_f where S can do things which S could not do initially. This transformation process can schematically be expressed in the form

$$S_i \to S_f. \qquad (1)$$

Although this may seem like a cold-blooded physicist's way of formulating the instructional problem, it is certainly *not* dehumanizing. On the contrary! Rather than dealing primarily with physics subject matter or curriculum, it focuses central attention on the human student S trying to deal with physics.

More important, the formulation (1) of the instructional problem makes apparent that a systematic approach to instruction needs to address the following issues.

(1) Analysis of desired performance (S_f). (a) One needs to specify clearly the desired final student abilities and observable performance. (b) On a more theoretical level, one needs to understand the underlying cognitive mechanisms (knowledge and thought processes) required to achieve these abilities.

(2) Analysis of the initial student (S_i). (a) One needs to describe adequately the characteristics and performance of students coming to instruction. (b) On a more theoretical level, one needs to identify what they know and how they think.

(3) Useful comparisons. A good analysis of desired performance (i.e., of S_f) allows several useful comparisons: (a) A comparison with actual expert performers. (This can suggest improved models of good performance, can help reveal "tacit knowledge" of which experts are unaware, and may sometimes disclose that experts are far from perfect.) (b) A comparison with novice students. (This can reveal anticipated learning difficulties and identify more precisely what needs to be taught.) (c) A comparison with prevailing methods of instruction. (This can reveal the deficiencies of such instruction, e.g., important skills that are never explicitly taught.)

(4) Design of instruction (the transformation process $\to$). (a) One needs to design an effective learning process whereby the student can acquire the knowledge and thinking skills required to achieve the desired final performance. (b) Finally, one needs to implement this design in practical settings.

The preceding approach to instruction is centrally based on an adequate understanding of the thought processes leading to the desired performance. The basic premise is that one cannot teach physics effectively without an adequate understanding of the thought processes needed in this field (no more than one can teach someone how to play good chess without an adequate understanding of the thought processes needed to play that game).

B. Outline of important issues

Let me then follow the preceding instructional approach to identify some of the specific issues important to the teaching of physics.

Instructional goals. The choice of instructional goals is a matter of judgment and depends also on the particular student audience. However, my central goal has been to help students acquire a modest amount of basic knowledge which they can *flexibly use*. There are at least two reasons why such flexible usability seems centrally important. (a) The goal of science is not the accumulation of various facts, but the ability to use a small amount of basic knowledge to predict or explain many diverse phenomena. (b) Students will have to function in a complex and rapidly changing technological world where they will profit little from knowledge that is rotely memorized or poorly understood. Any acquired physics knowledge will be useful to them only if it allows them to cope flexibly with any future courses or tasks encountered by them.

Abilities facilitating flexible usability. What kinds of thought processes are required to ensure that scientific knowledge can be flexibly used? My work suggests that the cognitive abilities summarized in Fig. 1 are of particular importance. These include the basic abilities required to interpret properly scientific concepts and principles, to describe knowledge effectively, and to organize it effectively. These are necessary prerequisites for more general problem-solving abilities, including the abilities to analyze problems, to construct their solutions, and to check these solutions.

Overview of this paper. In the following pages, I shall examine more closely each of the preceding abilities, pointing out why each of these is important and more complex than one might naively believe. In each case, consideration of the instructional problem $S_i \to S_f$ will lead me to do the following: (a) Indicate some common inadequacies of students' initial abilities. (b) Analyze the thought processes re-