# APPLYING COGNITIVE SCIENCE TO EDUCATION

## Thinking and Learning in Scientific and Other Complex Domains

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# Preface

## FOSTERING A MORE SCIENTIFIC APPROACH TO EDUCATION

***Unmet educational needs*** Since many people in our technological world need to acquire a knowledge of scientific subjects, numerous science courses are taught in high schools, colleges, universities, and professional schools. However, students often find it difficult to deal with the learning required in mathematics, physics, chemistry, biology, engineering, or similar such subjects. Furthermore, several investigations (such as Halloun and Hestenes, 1985) have revealed that students frequently emerge from such courses with significant misconceptions, with fragmented knowledge that they cannot reliably use, and without the problem-solving abilities needed to apply their acquired scientific knowledge.

***Recent attempts to improve science education*** A greater awareness of such educational deficiencies has motivated some scientists to become more interested in improving science education and in applying a more scientific approach to such educational efforts. For example, physics education research has recently become a respected subfield of physics pursued in several universities. Indeed, some physics departments now offer Ph.D. degrees to physics students who are interested in pursuing careers in physics education. Furthermore, the *Physical Review* (the primary professional journal of American physicists) recently started a special online section of the journal devoted to research in physics education (PER, 2005).

Increasing interest in improving science instruction is also reflected in some recent scientific publications. For example, a guest editorial in the *American Journal of Physics* advocated more systematic efforts to foster physics education research (Heron and Meltzer, 2005). Similarly, eleven scientists from different fields recently published a joint article in *Science* (the journal of the American Association for the Advancement of Science) in which they call for more scientific approaches to teaching (Handelsman et al., 2004).

***Limitations of such improvement efforts*** Attempts by university scientists to improve science education are certainly welcome and address important needs. But are these attempts sufficient—and to what extent are they really scientific? Most of them have tried to devise more effective teaching methods or to deal with students' scientific misconceptions. However, these attempts are unlike those used by scientists in their own scientific fields, where they aim to identify underlying mechanisms (processes and structures) responsible for observable phenomena and to achieve desired goals by building on an understanding of such mechanisms.

In science education the primary interest is not focused on the science itself, but on *students* who are trying to learn scientific knowledge and thinking. A truly scientific approach to education would thus need to strive for a better understanding of the underlying human thought processes and knowledge required for good performance in particular scientific domains. Such an approach would then deliberately exploit an understanding of these underlying mechanisms to help students learn.

***Challenges of a genuinely scientific approach to science education*** The thinking needed for scientific work is often considerably more complex than that commonly required in everyday life. A fundamental difficulty is that science is largely an *artificial* domain—that is, one deliberately devised by special people ("scientists") who pursue the explicit goal of inventing knowledge where a few basic principles enable the prediction and explanation of many observable phenomena. Hence science is significantly different from the domain of everyday life where knowledge and thinking have historically evolved more naturalistically without the deliberate pursuit of any explicit goal.

Einstein was certainly correct when he wrote "the whole of science is nothing more than a refinement of everyday thinking" (Einstein, 1954, 290). However, this statement can be misleading because the refinement has been deliberately pursued for several centuries by some of the best minds in each generation. Hence the resulting refinement has been substantial and has resulted in scientific knowledge and thought processes that are often significantly different from those prevalent in everyday life. These differences need to be clearly understood since they can cause major difficulties for students' learning of science.

College or university science instructors are usually knowledgeable about their scientific discipline, but have ordinarily not studied psychological or educational issues. Thus they approach their educational activities largely on the basis of common sense, intuition, and personal experience. For example, they commonly teach in the way that they themselves have been taught—and try predominantly to transmit knowledge about important scientific facts and methods. They rarely think much about the underlying thought and learning processes that students need in order to use such factual knowledge and methods effectively. Furthermore, extensive experience in their scientific fields has led instructors to acquire knowledge that has become largely *tacit* (outside the range of their conscious awareness). Unless this important knowledge is elucidated, it is never explicitly communicated to students.

## GOALS OF THE BOOK

This book aims to present a coherent introduction to some of the *cognitive* issues (issues concerning knowledge, thinking, and learning) that are important in scientific and other complex domains. In particular, I was motivated by the belief that a better understanding of the underlying knowledge and thinking useful in such domains can help to improve instruction and significantly facilitate students' learning.

The book's point of view is that of an *applied* cognitive science that is not as deeply theoretical as "pure" cognitive science, but is centrally interested in a level of analysis that is well suited for the design of practical applications (such as education or human-computer interaction). This level of analysis transcends the more empirical approach of most practitioners (such as teachers or textbook writers). An applied cognitive science thus strives to exploit insights identified by pure cognitive science (in the same way as the applied science of medicine exploits insights obtained by human biology).

As usual, there is a mutually beneficial interaction between pure and applied sciences. A pure science provides insights about underlying mechanisms and may suggest practical applications. Conversely, an applied science provides excellent opportunities for testing theoretical ideas and often reveals new phenomena that merit deeper investigation.

While I was a physics professor teaching at the University of California, my perception of the previously mentioned educational problems caused me, some thirty-five years ago, to shift my interests from research in physics to research dealing with the cognitive and educational issues involved in scientific domains. The present book is an outgrowth of my interests in these issues.

## DESCRIPTION OF THE BOOK

The book attempts to present a coherent and readily accessible introduction to thinking, learning, and teaching in scientific domains (or in similar complex domains such as mathematics, engineering, or expository writing). The level of targeted complexity is that needed by high-school or college students, and is also a prerequisite for more demanding intellectual performance.

I have attempted to be judiciously selective by focusing on issues that I deemed most important and by trying to provide a framework that could help to explore other cognitive issues relevant to education.

In particular, the book examines the following questions: What kinds of knowledge and thought processes are needed for good performance? What are some of the difficulties faced by students, used to everyday thinking, when they need to deal with scientific domains? What instructional methods can help students to learn the kinds of knowledge and thinking skills required in such domains? How can such methods be implemented to provide practical instruction for many diverse students? The table of contents provides an outline of the topics explored to answer these questions.

***Intended audience for the book*** The following kinds of people may potentially be interested in the preceding questions: (1) Instructors (at high schools, colleges, universities, or professional schools) who are teaching scientific, mathematical, or similar demanding subjects. (2) College or university students studying such subjects and interested in improving their learning. (3) Students preparing for careers in teaching or educational research. (4) Authors of textbooks or other instructional materials. (5) Persons interested in cognitive processes or education. (6) People not motivated by specific professional concerns, but interested in ways of achieving good intellectual performance.

My own experience includes dealings with all such people. For example, I have for many years taught physics to undergraduate students and have authored several physics textbooks. I have also published research papers in cognitive-science journals—and taught courses on instructional design to graduate students preparing for careers in teaching or educational research. (I have even discussed cognitive issues in some courses for senior citizens and retirees.)

***Attention to practical educational implications*** While examining various cognitive issues, the book repeatedly points out their practical educational implications for learning, teaching, and instructional design.

***Scope of the book*** The following pages deal predominantly with knowledge and thinking skills of the kind needed for science or mathematics courses in high schools or colleges. Such knowledge and thinking skills are only moderately complex and might seem simple to some people. But they are essential prerequisites for more highly demanding intellectual performance. Deficiencies in such basic knowledge and thinking skills are also responsible for many students' difficulties or failures in science courses. Furthermore, the teaching of such knowledge and thinking skills is often inadequate.

***Simplicity and comprehensibility*** Although I have attempted to be fairly analytic, I have tried *not* to be excessively theoretical so that the ideas discussed here might be readily accessible to most teachers and to people unfamiliar with cognitive issues. In particular, I have tried to follow the advice, attributed to Einstein, that "everything should be made as simple as possible, but not simpler" (Calaprice, 2000, 314–315). Thus I have aimed to present a reasonably coherent framework of basic ideas, to illustrate abstract notions with homely examples, to avoid jargon, and to shun tedious prose where many words convey few significant ideas.

***Form of presentation*** The book emphasizes that effective knowledge and learning require as much attention to form (description and organization) as to content. To practice what I preach, I have tried to implement the following guidelines. (1) Explicate clearly the organization of the book since this makes it easier to assimilate, review, and retain the relevant information. (Thus I have used major titles to highlight the global structure of the book, and have used local titles to indicate the content of particular paragraphs.) (2) Emphasize central ideas by displaying subordinate comments or examples in a distinct smaller font. (This can help a reader to acquire a hierarchical knowledge organization where a few major ideas subsume more detailed information.) (3) Convey the same information in multiple forms of description (e.g., both words and pictures) since some particular forms may make it easier to perceive some relationships or to perform some tasks.

Since the book is largely intended for people who work or teach in scientific or technical domains, its style may perhaps be more similar to that of a book in the physical sciences than that of a typical book in education or psychology.

***Kinds of examples*** The illustrative examples used in the book often deal with basic physics or mathematics. There are good reasons for this (besides the fact that these subjects are familiar to me). (1) These subjects are prototypical of successful sciences, are commonly encountered by students early in their college careers, are prerequisites for many other courses (in physics, chemistry, biology, or engineering), and cause students difficulties that are similar to those encountered in more advanced science courses. (2) The chosen examples are likely to be comprehensible to most readers since these are probably familiar with elementary physics or mathematics. (3) The thought processes in physics or mathematics are complex, but the criteria of good performance are very clear. This is why even psychologists, who are not especially interested in these fields, have done substantial cognitive and educational research in these.

## CONCLUDING REMARK

When I wrote my first book some forty years ago (Reif, 1965), I concluded the preface with the words "an author never finishes a book, he merely abandons it." This statement still seems equally applicable today. I realize that much in this book could be improved, that I may have failed to attain some of my intended goals, and that further revisions might result in a better product if my life expectancy were less limited. I can only hope that the book may (despite its deficiencies) be useful to some people—and may perhaps stimulate some others to do better.

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