# APPLYING COGNITIVE SCIENCE TO EDUCATION

## Thinking and Learning in Scientific and Other Complex Domains

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A Bradford Book
The MIT Press
Cambridge, Massachusetts
London, England

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This book was set in Stone Serif and Stone Sans on 3B2 by Asco Typesetters, Hong Kong and was printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

Reif, F. (Frederick), 1927–
Applying cognitive science to education : thinking and learning in scientific and other complex domains / Frederick Reif.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-262-18263-8 (hardcover : alk. paper) 1. Cognitive learning. 2. Learning, Psychology of. 3. Cognitive science. 4. Education. I. Title.
LB1060.R423 2007
372.15′2—dc22 2007006486

10 9 8 7 6 5 4 3 2 1

# 1 Performance, Learning, and Teaching

## 1.1 THINKING ABOUT THINKING

We spend most of our waking hours engaged in thinking, but rarely think much about thinking. Indeed, we are ordinarily not consciously aware of the thinking and knowledge that we commonly use. For example, we may speak our native language correctly, yet be unable to specify its underlying grammatical rules.

However, we may need to think more deeply about thinking when we want to engage in tasks that are more complex than those encountered in daily life. In particular, it is important to think more explicitly about the knowledge and thought processes needed for work in scientific domains, especially if one is interested in achieving good performance or in teaching students the skills and knowledge required for scientific work.

Einstein pointed out the need for a better understanding of human thought processes when he wrote

> *The whole of science is nothing more than a refinement of everyday thinking. It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the concepts of his own specific field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking.* (Einstein, 1954, 290)

These words apply even more to the nature of *scientific* thinking since this has become increasingly complex as a result of refinements extending over several centuries of scientific progress.

***Central question*** Such an interest in human *cognition* (in thought and learning processes and associated kinds of knowledge) leads naturally to the following question of primary concern in this book: *What kinds of knowledge and thought processes are needed for good performance in scientific or similar complex domains—and what instructional methods*

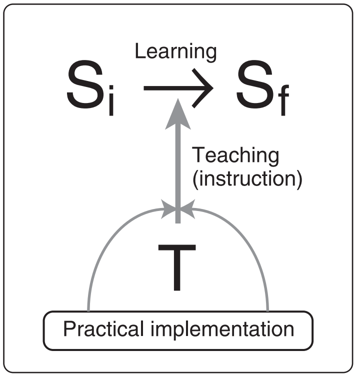


**Figure 1.1**
Learning and teaching.

*can be devised to facilitate students' learning of such knowledge and thinking?*

The following pages attempt to answer this general question because it is centrally important for all educational efforts in scientific or similar demanding fields.

## 1.2 BASIC ISSUES

The preceding general question about performance in complex domains requires a consideration of the following basic issues (schematically summarized in figure 1.1).

***Initial performance*** What do we know about a student $S$ (or other specified person) in an initial state $S_i$ *before* the occurrence of new learning? For example, what kinds of things does $S$ then do or is $S$ able to do? What kinds of underlying knowledge and thought processes lead to this performance?

***Final performance*** What do we know about a student $S$ in the final state $S_f$ *after* the occurrence of some learning? For example, what kinds of things does $S$ then do or is $S$ able to do? What kinds of underlying knowledge and thought processes lead to this final performance?

***Learning and teaching*** *Learning* is the process (indicated by the horizontal arrow in figure 1.1) whereby a student $S$ is changed from an initial state $S_i$ to a final state $S_f$ where the student can do things that the student could not do initially. Learning is thus an important transformation process that we would like to understand in greater detail.

*Teaching* (or *instruction*) is deliberate assistance provided to facilitate learning. (In figure 1.1 such teaching is indicated by the vertical gray arrow pointing to the learning process.)

Note that learning can also occur spontaneously *without* the aid of any deliberate assistance. (For example, most children learn their native language without any deliberate intervention, merely by being immersed in an environment where this language is spoken.) Conversely, teaching can occur *without* any learning (a situation unfortunately all too familiar in many classrooms).

The letter *T* in figure 1.1 indicates a *teacher* (tutor or instructor) who does the teaching. It may also denote a more complex teaching system consisting of a human teacher who may be supplemented by computers, books, and other teaching aids. Teaching can also be accomplished without an *external* human teacher if the learning is deliberately assisted by the student himself or herself. (In such *self-teaching* the student must also play the role of teacher by deliberately deciding what to read, what and when to practice, when to review, and so forth.)

***Practical instructional implementation*** There is a significant difference between instruction provided to an individual student by a good teacher and practical instruction whereby many diverse students can be effectively taught by various teachers in realistic situations. Hence we may also need to be concerned with issues involved in practical instructional implementation.

## 1.3 IMPORTANCE OF THESE ISSUES

***Applicability to the design of any complex system*** The basic issues mentioned in the preceding section are not only relevant when trying to achieve good human performance, but are generally important when trying to design or construct any complex functional system *S* (such as an airplane or a computer).

For example, in any such case one must deal with the following four basic issues: (1) One must know the components of the desired final system $S_f$ and how these components interact to produce the desired functioning. (For example, one must know the needed components of an airplane and how these function to produce well-controlled flight).

(2) One must know the initial system $S_i$ (for instance, the initially available components that might be assembled into an airplane). (3) One must know the processes by which this initial system can actually be transformed into the desired final system (such as the processes by which the initial components can be assembled into a functional airplane). (4) Finally, the construction of a few airplanes by excellent engineers and mechanics is far from sufficient to lead to the practical implementation of an airline transportation system like *United Airlines*.

***Medical analogy*** Medicine is somewhat analogous to education since it too deals with human beings. Thus figure 1.1 (illustrating an educational process) is also applicable to medicine, which is centrally interested in the transformation of a person, from an initial state $S_i$ where the person is sick, to a desired final state $S_f$ where the person is in good health. Accordingly, medicine is concerned with the following four central issues: (1) A thorough understanding of the desired final state of good health (achieved by well-functioning anatomy, physiology, and biochemistry). (2) An understanding of possible initial states corresponding to various illnesses and their underlying causes. (3) A knowledge of the kinds of therapies that can help to cure sick persons so as to transform them into healthier ones. (4) The practical implementation of a health-care delivery system that can manufacture suitable drugs, provide sufficient hospitals and well-trained doctors, ensure patients' access to such medical facilities, and so on.

Note that each of the preceding issues is quite complex. Medical students spend many years trying to learn about the first three issues, and our society is desperately struggling with the problem of creating an adequate health-care delivery system. If they are seriously addressed, the corresponding educational issues (illustrated in figure 1.1) cannot be expected to be much simpler.

***Importance of each issue*** The following example illustrates, in a simple and amusing case, that each of the basic issues listed in section 1.2 (and indicated in figure 1.1) is important, even in a seemingly trivial learning task. Each one requires even greater attention in more complex situations involving human learning or teaching.

#### A simple example: Learning to pronounce *R*

When I came to the United States from Austria at the age of 14, I was faced with the need to learn English. Although I found the learning task fairly simple, my main difficulty was English pronunciation. I gradually managed to learn most

English sounds, but could not learn how to pronounce the sound corresponding to the letter R. Instead, I produced the guttural R with which I was familiar from my native German tongue.

***Lack of spontaneous learning*** Although I was highly motivated to learn the proper pronunciation of this sound, and could hear people around me pronounce it correctly all the time, I was *not* able to learn it despite my best efforts.

I could hear that my pronunciation of the R-sound was wrong and believed that I sounded much like a caricature of Adolf Hitler. But even though I felt embarrassed by my faulty pronunciation and was highly motivated to do better, I could not learn to improve my performance. This example illustrates the following general lesson: *Although high motivation may help learning, it may not be sufficient.*

Every day I was surrounded by people who spoke good English, and was constantly exposed to examples of good pronunciations of the English R. But months of such exposure did not help me. This example illustrates a second general lesson: *Although exposure to examples of good performance may help learning, it may not be sufficient.*

***Clarification of initial inadequacies*** When I was in high school, an English teacher tried to help me learn the proper pronunciation of R. She first clarified my initial state $S_i$ by pointing out that I was inappropriately trying to pronounce R by using my throat and that this was wrong. Thus I now knew what *not* to do. *But this did not help me to know what I actually should do.*

***Explanation of good performance*** How would *you* explain how to pronounce the letter R? If you are like most native English speakers, you can properly pronounce this sound, but probably cannot explain how you do this. For example, you might need to pronounce this sound, carefully observe what you are doing, and then try to describe your observations. (Your knowledge of the proper pronunciation is thus a good example of *tacit* knowledge—that is, of knowledge that you have without any conscious awareness).

My English teacher did, however, provide me with the following explanation of the desired final performance: I should *not* use my throat, but merely hold my tongue close to the roof of my palate (without touching it) and then blow a gentle steam of air over my tongue.

I tried to do this. *But despite repeated attempts, no correct sound emerged from my mouth.*

***Suggestion of a learning process*** Two more years elapsed without any progress on my part. The mere specifications of my initial state $S_i$ of poor performance, and of the desired final state $S_f$ of good performance, had been totally inadequate to help me learn since I did not know the process whereby I could go from my initial state to the desired final state.

By then I had entered college, where an English teacher suggested a helpful process. She advised that, when speaking, I should simply substitute the letter D for the letter R. (For example, instead of saying *rose*, I should say *doze*.) She also explained the rationale for doing this. When producing the sound for D, I could not possibly use my throat. Furthermore, my tongue would then be approximately in the right position (touching the roof of my palate, instead of being slightly away from it). I should then gradually, by successive approximations, be able to move my tongue further from my palate and thus obtain the proper English sound for R. *This seemed like very good advice.*

***Implementation problems*** But I had difficulty in implementing this advice because the teacher had not considered the practical difficulties that I might have in following her suggestions. Could I, a busy college student struggling with many intellectually demanding courses, spare the time to engage in much deliberate pronunciation practice? And would it not be embarrassing for me in daily life to say *dead* when I meant *red*, to say *ditch* when I meant *rich*, or to ask a waiter for *dice* when I meant *rice*? The net result was that I did not engage in much practice—and that my awful pronunciation persisted.

But a few months later I was drafted into the United States Army and found myself in basic training in a Florida camp, surrounded by other soldiers almost exclusively from the South. Their Southern accent prevented me from understanding almost anything they said, and they probably could not understand anything that I said. Thus it occurred to me that it did not matter what I would say in this environment—so that I *could* comfortably substitute the letter D for the letter R. *After no more than one week, I thus learned how to pronounce an English R, a feat that I had not managed to accomplish in the preceding four years!*

***Lessons from this example*** The preceding example illustrates, in a very simple case, the importance of all the four previously mentioned issues (which are even more important in more complex situations). Thus it is not sufficient to understand the desired kind of performance or a student's initial performance before instruction. It may not even be sufficient to understand the learning and teaching process by which the student may attain the desired final performance—unless one also thinks about practically realistic ways of implementing the instruction.

## 1.4 STRUCTURE OF THE BOOK

This first portion of the book consists of one more introductory chapter (chapter 2) dealing with intellectual performance. After that, the book is divided into the following four further parts, each dealing successively with one of the four basic issues mentioned in section 1.2.

***Part II, Good Performance*** This longest part (chapters 3 through 15) identifies some essential characteristics of good intellectual performance (the kind of final performance ordinarily desired as a result of learning). To examine the kinds of knowledge and thinking enabling such good performance, it discusses important types of knowledge, how this knowledge can be specified and properly interpreted, how it can be usefully described and organized, how it can be flexibly applied by making judicious decisions and solving various problems, and how all such processes can be carried out effectively and efficiently.

This part of the book is centrally concerned with ways of achieving good performance, but also points out relevant educational implications. Thus it indicates what proficient performers do, what inexperienced students often do, what deficiencies exist in prevailing instructional approaches, and what improved instructional methods are suggested by an examination of relevant cognitive issues.

***Part III, Prior Knowledge*** This part (chapters 16 and 17) examines the knowledge and thinking that are common in everyday life and prevalent among students before they try to learn about an unfamiliar scientific domain. It identifies some of the significant differences between the cognitive frameworks of science and of everyday life, points out how these differences lead to naive notions differing from more sophisticated scientific conceptions, and how these differences can cause appreciable learning difficulties.

***Part IV, Learning and Teaching*** This part (chapters 18 through 21) focuses on the development of instruction that facilitates learning. Thus it discusses how to design an effective learning process—and how then to devise teaching methods that can provide the guidance, support, and feedback needed to ensure that students engage in effective learning.

***Part V, Implementing Practical Instruction*** This last part (chapters 22 through 24) discusses how the preceding teaching methods can be extended to implement practical instruction for large numbers of diverse students. Lastly, this part ends by mentioning some unmet educational challenges that could be addressed with significant beneficial results.