

*Scientific Literacy as a Goal in a
High - Technology Society*

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There is a great concern in our society today, reminiscent of the post-Sputnik era, about education in science, technology, and mathematics. The concern is both about the adequacy of our supply of competent professionals trained in science and technology and the scientific “literacy” of The Celebrated Mensch in the Street, T. C. Mits.¹ Innumerable national committees and commissions, on one of which I served recently, have been appointed to examine these problems, and to recommend the actions that are required to give science and mathematics their proper place in the scheme of education. School districts across the land are reexamining their science and mathematics curricula, the competence of their teachers of these subjects, and the access of their students to microcomputers.

In my remarks here, I should like to address just one segment of the whole problem of education in science, mathematics, and technology, in particular, the concern with T. C. Mits, who does not intend to become a scientist or an engineer, but who looks forward to a long life in a high-technology society. What does Mits really need to know about scientific and technical subjects? What are the possibilities of Mits learning what he or she needs to know? I will begin with an overview of these two questions and then proceed to elaborate several aspects of them that seem to require more thorough exploration.

¹T. C. Mits was the hero of the popular books on science and mathematics written some years ago by Lillian Lieber, the best-known of which was *The Education of T. C. Mits* (New York: The Galois Institute Press, 1942). I have borrowed Mr. Mits for my purposes here, altering slightly the translation of the acronym. Since a Mensch may be either a Herr or a Frau, I interpret the initial in T. C. Mits’ surname in this sexless fashion.

THE NEED TO KNOW

One more discussion in general terms of the goals of education is unlikely to contribute very much to the mass of wisdom and foolishness that has already been uttered on this subject. Hence, I will not strive for novelty, but simply set forth in commonplace terms the usual taxonomy of educational objectives for T. C. Mits. In my version of that taxonomy, we should consider the needs of Mits for knowledge and skills for survival in the everyday world, the needs for knowledge and skills to which so-called liberal education is directed, and, finally, Mits' needs for adequately discharging the obligations of citizenship.

EDUCATION FOR EVERYDAY LIVING

The Mits family lives surrounded by the usual assemblage of high-tech and low-tech artifacts, although it has not yet acquired a personal computer. An investigator could follow the family through its everyday life, taking note of its interactions with these artifacts and the scientific and technical knowledge it applies in using them. Such an investigation would result in one of two conclusions, depending on the definition of "scientific and technical knowledge that was used."

When Mr. Mits cooks the family dinner (his chore on Thursdays and Saturdays), he must know how to light the stove and how to operate the can opener (which is manual, not electric). The scientific law that governs the stove is that if he turns counterclockwise the valve marked "left front," the left front burner will ignite. He must know this and many other scientific laws and facts of a similar kind. Mits and his wife are considering acquiring a new computer-controlled stove. Then they will have to assimilate additional scientific knowledge, that is, how to program such a device.

But these pieces of information and skill appear to be radically unrelated to what is usually taught in courses on physics or chemistry. In such courses, the Mitses would learn that certain inflam-

mable gasses ignite in the presence of oxygen and combine with that oxygen to form a new compound. They might also learn that water vaporizes when heated to 100 degrees Celsius. None of that knowledge, or the much deeper knowledge they would acquire about atoms and chemical bonds and the like would really be called on very often — if ever — as they went about their everyday tasks.

Sometimes we express the distinction I am making as a difference between knowing how to work something and knowing how and why it works. Clearly, the T. C. Mits family needs to know *how to work* many artifacts, some of them quite complex and even high-tech. The repairmen they summon periodically must know *how these artifacts work*, so that they can put them into proper operating condition, or at least identify the defective modules that must be replaced. But only the designers of the artifacts and the scientists who study the natural laws employed in them feel obligated to know *why they work*.

If knowledge of how to work things is taken as the criterion of scientific and technical literacy, then the people of our society are fabulously literate — almost all of them. For better or worse, ninety-five per cent of the adults among us are licensed to operate complex and lethal motor vehicles. Yet little if any of this knowledge and skill, except perhaps the skill of reading traffic signs, is acquired through formal education. You will immediately confront me with the counterexample of driver education courses. I will respond by questioning whether such courses serve any essential educational purpose, since generations of drivers, including my own, learned without them.

Moreover, it is an interesting question, whose answer is not at all obvious, whether those of us who are trained in science or engineering are any more skillful in handling artifacts than is the T. C. Mits family. Are engineers especially good automobile drivers? And are their diets more nutritious than those of persons who majored in English literature?

However, I really do not want to engage in a discussion as to whether courses in driver education, nutrition, and personal hygiene should be taught in the schools. The point is that if there is some illiteracy in these matters, it is not irremediable. And in any event, it is not this ignorance that we have in mind when we talk about scientific illiteracy.

The conclusion we reach is that scientific literacy is neither a necessary nor a sufficient condition for our everyday interactions with our artifacts. We can dismiss this aspect of the education of T. C. Mits and family from our consideration.

LIBERAL EDUCATION

Since I do not anticipate much success in defining either the term “liberal education” or the goals that such education is intended to reach, I will not even attempt a rigorous characterization. Instead, I shall try to establish some outer and inner limits of what liberal education might encompass, with the hope that such vague indications may satisfy our needs for definition.

In particular, I should like to avoid puzzling over whether liberal education is supposed to be useful or not. Utility itself is a slippery concept. In the framework of traditional Christianity, education is useful if it contributes to the salvation of the soul and not very useful otherwise. Alternative pictures of the human condition lead to other definitions of utility.

In the writing on liberal education there does seem to be some consensus that it has to do with the cultivation of the “whole person,” and that such cultivation may be expected to have (beneficial) consequences for the fullness of life and the level of morality that life attains. The concerns of liberal education, as usually defined, tend to be speciescentric. The human condition, including both the existential problem that every person faces and the problems of interaction among human beings, has a central place in these concerns — a humanistic concern complementing or replacing the theological concerns that I mentioned previously.

The relation of human beings to their natural environment has played, historically, a much smaller role in conceptions of liberal education. This, of course, was the complaint of C. P. Snow in his “Two Cultures” argument, and I share Snow’s views on this matter.² Let me explain briefly why I think his views are correct.

The phrase “natural philosophy” symbolizes the relation that has long been perceived between the questions that human beings ask about their own existence and some of the basic questions of the natural sciences. In fact, the connection is so close that the four fields of greatest excitement in basic science today are also the fields that are most relevant to questions about the meaning of life: What is matter? What is the origin and fate of the cosmos? What is life? What is mind?

1. *What is matter?* The pursuit of this question is the task of particle physics, armed with ever more powerful accelerators. I suppose that there are few who believe that the quest can ever lead to final answers, but the interminability of the effort does not dull the imperative urge to continue the search into deeper and deeper recesses of the world of elementary particles.

2. *What is the origin and fate of the cosmos?* Answering this question, closely related to the first one, is the task today of astrophysics, armed with space vehicles, radio telescopes, and the sharp tools of mathematical physics. Here, too, the finality of answers is elusive.

3. *What is life?* Here the powerful methods of contemporary molecular biology lead us ever closer to a reduction, at least an “in principle” reduction, of the laws governing living organisms to the laws of chemistry and physics.

4. *What is mind?* Jurisdiction over this question has only in recent times been transferred from the domain of philosophy to that of cognitive science, which now has available the modern computer as a powerful tool of investigation, indispensable for both simulation of mind and formalization of theories about it.

² C. P. Snow, *The Two Cultures and the Scientific Revolution* (Cambridge: Cambridge University Press, 1959).

Particle physics, astrophysics, molecular biology, and cognitive science provide us today with our creation myths, to replace those pre-scientific ones that no longer satisfy us. And we feel a profound need for these creation myths in contemplating our place in the universe and the nature of the human condition. Whatever may have been the case five hundred years ago, there can be no question today that science is an essential component of liberal education. Snow was quite right in questioning whether one who did not understand the Second Law of Thermodynamics could think the thoughts of an educated person.

There is more to humanism than the question of mankind's relation to nature, or even the existential question. To the list of central questions, we must add, at least:

5. *How do we know about the external world?* The epistemological question, closely associated with the nature of mind, is also, today, a central focus of inquiry in cognitive science.

6. *What is the relation of motivation and emotion to thought?* Psychology must encompass the wanting and feeling person as well as the thinking person.

7. *How do human beings relate to each other?* To which we may wish to add: "and how should they?"

This is neither intended to be an exhaustive list of Big Questions nor an assertion of priorities. Rather, it is a *minimal* list of questions that are centrally relevant to liberal education and that can be addressed seriously only with the help of scientific knowledge. One might suppose this conclusion to be uncontroversial, but it is not. It is slightly paradoxical that, among the sciences, the claim of the social and behavioral sciences for an important role in liberal education is sometimes questioned even more vociferously than the claim of the physical and biological sciences. In fact, if the latter sciences did not sometimes have mathematical content and were not generally "hard" (in the pedagogical meaning of that term), it is likely that all of the opposition to science in the liberal arts curriculum would be focused on the social sciences.

The paradox is really not so hard to understand. For the social sciences and the humanities are direct competitors in their claims to special possession of the wisdom that is relevant to at least the last three of the questions I have listed. "Does one learn more about human nature by reading Shakespeare or a psychology textbook?" The reader's answer to the question will disclose which culture commands his loyalty. Having raised the question, I intend to leave it open. In a recent lecture, I have made some brief suggestions about how to approach an answer.³ For the moment, I would be satisfied if we could agree that the human condition can be illuminated by literature, by history, by philosophy, by the arts, and by the social and behavioral sciences as well. (If I have left out your favorite subject, I shall be glad to add it to the list.)

In the preceding paragraphs, I have sketched out the claims of science, both natural and social, to relevance for many of the topics which have always had an important place in the liberal curriculum. But the concerns that have been addressed so far do not by any means cover all of the goals that have usually been proposed for liberal education. I should like now to turn to the goal of preparing students for the responsibilities of citizenship.

EDUCATION FOR CITIZENSHIP

If people do not need scientific knowledge to drive their cars or cook their meals, do they need it to cast their ballots wisely, or to write intelligent letters to their legislators? That there is an enormous technical component in the assessment of many or most public policy questions today is obvious. The consequences of setting automobile emission standards tighter or looser than they now are depend on the chemical processes in internal combustion engines, the chemistry of the atmosphere (with a little meteorol-

³ *Reason in Human Affairs* (Palo Alto: Stanford University Press, 1983), pp. 29-34.

ogy mixed in), human physiological responses to contaminants in air, and the social and economic costs of illness and death. All of these matters are subjects of scientific inquiry, some in the physical sciences, others in the biological sciences, and still others in the social sciences.

Even policy issues that do not seem as obviously “technical” as this one are heavily impregnated with questions of fact, the answers to which are likely to be determined reliably only on the basis of scientific inquiry. One of the central and perennial issues in societies throughout history has been to arrive at an appropriate balance between providing incentives to socially productive effort and preserving some measure of equality in the distribution of the social product among families and individuals. Our view of this balance will depend very strongly on whether we think that we can provide effective incentives without accepting substantial inequality. In our time we have seen two immense nations, the Russian and the Chinese, try to fashion a New Man who would give his best efforts in production without differential reward. Most of us, perhaps including most of the people in those nations, are unimpressed with the success of the experiments. But the shifting economic policies we see pursued in these and other countries are perhaps far less a reflection of shifting values than of shifting beliefs and expectations about the laws of human behavior. Social science is as relevant to the question as ethics.

We must not be hasty in concluding, from this and the many similar examples we could adduce, that T. C. Mits needs to know a great deal of science in order to be a responsible citizen. The important thing is not that *Mits* be able to supply the correct factual premises for making these decisions, but that the correct premises be supplied, somehow, by the political process. If we could hire experts to give us the facts, just as we hire doctors and auto mechanics to deal with the technical facts of everyday life, we could spare ourselves a technical education as a condition for citizenship. In this respect the citizenship argument for scientific

literacy is a less compelling argument than the arguments of the last section which rested on human needs for philosophical understanding of their world.

I will return in a later section of my remarks to the educational requirements for citizenship. We cannot reach a conclusion on this matter until we inquire into the feasibility of attaining widespread scientific literacy, and until we have examined possible alternative political arrangements that would eliminate or reduce the need for it. I will take up the topic of feasibility after I have commented on one other matter: the incompatibility that is sometimes supposed to exist between liberal and vocational, or liberal and useful, education.

LIBERAL VERSUS VOCATIONAL

Historically, resistance to the replacement of traditional by scientific subjects in the curriculum has been based on the idea that scientific and technical knowledge, as contrasted with liberal knowledge, is *merely* useful. Of course, the argument cannot be intended quite literally; the contrast cannot be between useful and useless, but between those things that are useful only to “practical” ends and those that are useful to more fundamental and important ones.

The argument rests on a premise that needs to be questioned. That premise is that scientific subjects are (ought to be?) mainly taught to produce and develop skills, while liberal subjects are taught to produce understanding. Understanding is a requirement for the liberally educated person; skill is not.

Of course, postulating an incompatibility between skill and understanding is nonsense — for more than one reason. First, it is improbable that any but the narrowest skill can be imparted without imparting some measure of understanding. In most circumstances, learning “why” greatly facilitates learning “how to,” and facilitates, also, retaining what one learns. If the skill involves a highly repetitive action, performed in an unchanging way

from one week to the next, then understanding may contribute little to the quality of the performance. But in a constantly changing environment, skill must be modified continually and transferred to new situations. And there is ample evidence that skill without understanding of underlying principles simply does not transfer.

This is hardly a novel argument. It has been used for decades, if not centuries, to distinguish between the education appropriate to “technicians” (skills without understanding) and “professionals” (understanding with some skill). Today we would probably insist that the technician, too, will not long retain useful skills without an understanding that is sufficient to adapt them to continually changing applications.

A second objection to contrasting skill with understanding is that almost all genuine understanding contains a large component of skill. To understand a foreign language (an accomplishment traditionally within the scope of liberal education) means acquiring the skills of reading, writing, speaking, and listening to it, or some subset of these. To understand literature means acquiring the skills of extracting meanings from prose, of extracting ideas from it, of comparing and contrasting ideas, of attending to the beauty of language, of assessing and judging character, of forming mental images, and many others.

A liberal subject, taught effectively, teaches skills. And a vocational subject, taught fundamentally, teaches understanding. The fact that there are skills based on science, technology, and mathematics says nothing about the relevance of these subjects to liberal education, or the understanding that can be acquired by studying them.

THE FEASIBILITY OF PRODUCING SCIENTIFIC LITERACY

Necessity is alleged to be the mother of invention, but no human necessity has yet produced a gravity shield. It may be questioned on the same ground whether the importance of scien-

tific literacy to a society, or to the individuals in it, is a sufficient cause to produce that literacy or even to guarantee its possibility. There may be no way from here to there.

C. P. Snow observed, correctly, that in our society some measure of literacy in language, literature, and the arts is expected of every “educated” person, but that even an elementary literacy in science and mathematics beyond arithmetic (perhaps we should say, beyond addition and subtraction) is not. The “educated” person is also expected to be able to discuss public affairs and to exhibit a certain amount of information about them, but his discussion of them need not be informed by any systematic training in the social sciences. These are the asymmetries between humanistic and scientific education that Snow deplors in his “Two Cultures” essay.

Presumably this could all be changed, if we thought it wrong, simply by changing the curriculum of primary, secondary, and college education to require of everyone a larger measure of scientific study. But can it be changed? Snow points to a second interesting social phenomenon. Not only are many people innocent of scientific knowledge, and not only are they unembarrassed about admitting this deficiency, but they are often heard to proclaim, “I never was able to understand math [or physics, or organic chemistry, or economics].”

Now if a society’s attitudes toward education changed, so would these habits of speech. People would become private know-nothings instead of proclaiming publicly their ignorance of science and mathematics. But the worrisome possibility is that perhaps they are telling the truth; that they *could not* learn these subjects even in the face of strong social pressures to do so.

A SCIENCE–MATHEMATICS BUMP ?

The Two Hemispheres. The hypothesis is rather popular nowadays that there are two distinct kinds of intelligence: the analytic intelligence of scientific and technical thinking, supposed

to be localized in the left hemisphere of the brain (at least in right-handed people), and the intuitive, creative intelligence of non-technical thinking, which is supposed to be localized in the right hemisphere.

There is of course solid physiological evidence for some specialization of function between the two hemispheres of the brain, and, for that matter, among various subregions within each hemisphere. There is also evidence, however, of considerable relocatability of function in response to brain damage, particularly early brain damage. But brain location is largely irrelevant to the question of whether there are two quite autonomous and qualitatively different forms of thought. To say that the hemispheres are specialized is like saying that the engine of an automobile is usually in the front, while the differential is commonly in the rear. This is true of most automobiles, but it in no way implies that there are two ways in which an automobile can operate, one with the engine and one with the differential.

The important question, then, is whether or not humans (some humans) are capable of two distinct modes of thought, each carried out with a different mechanism. The fact of brain specialization may facilitate experimentation that will help answer the question, but it is not, in itself, at the heart of it. How strong is the evidence, then, for these two autonomous modes of thought? It is mainly negative.

The right hemisphere is supposed to be the principal site for visual and auditory recognition and imagery processes, but the left hemisphere is distinctly the site of most linguistic processes and linguistic knowledge, both syntactic and lexical. The pitch of a pure tone appears to be recognized by the right hemisphere, but as soon as harmony enters the picture, the left hemisphere, with its syntactic capabilities, comes into play. Thus, it would appear that the musical experience is an experience of the whole person, and not of some special holistic process ensconced in the right hemisphere. In fact, there is no solid evidence, known to me, that

any single important human cognitive function can be carried out by the right hemisphere without the participation of the left. Specifically, there is no evidence that some people make “right brain” intuitive decisions, while others make “left brain” analytic decisions. The facts of hemispheric localization are much more mundane and prosaic than the romances that have been woven out of them.

Analytic and Intuitive Thought. What, then, about the common subjective experience that we attain some of our ideas and conclusions suddenly and intuitively, while others are attained on the basis of sustained conscious effort and analysis? The mass of evidence for such a distinction cannot be denied, even if it could be shown conclusively that it has nothing to do with hemispheric specialization. What is important is how the difference is to be *interpreted*; in particular, what is important is to arrive at a clear scientific explanation for the process that we call intuition.

The defining conditions for intuition have already been mentioned. A problem is posed: e.g., a patient describes symptoms to a physician. Without any apparent effort, and almost immediately, the physician says, “You have chicken pox.” A prudent physician will ask some further questions, make additional observations, and perhaps call for some tests before regarding the diagnosis as final. But the remarkable fact, the one that confirms our belief in the reality of intuition, is that the skillful physician’s first judgment, arrived at within a minute, is usually right.

Sometimes, as in certain celebrated occasions in the annals of science — Poincart boarding the bus at Coutances, Kekult staring into the fire — the successful intuition is an answer to a question that has long been pursued, without success, and that has temporarily been laid aside. Except for these circumstances of preparation and “incubation,” the phenomenological signs of intuition are just like those of the more prosaic and frequent occasions of professional practice. The central phenomenon is that the expert can often know without conscious sustained thought.

When it is stated in this way, the frequency with which experts exhibit intuition should occasion little surprise — no more surprise than that Mits can usually recognize his wife instantly (i.e., within a second or so) when she approaches him on the street, even if he is not expecting to see her there. Not only does he recognize her, but all sorts of information about her, stored in memory during the course of a long marriage, becomes available to him. The capacity for intuitions is the capacity for recognizing familiar situations, old acquaintances, on the basis of perceptual cues that present themselves, and for evoking from memory information that one has stored about the recognized situations. The intuitive brain is simply the expert brain, and intuitions occur no less frequently in the practice of the sciences and technical professions than they do in the arts and humanities.

If we describe thought that requires more than intuition, and that is conscious and sustained, as “analytic” thought, then we would expect to find greater or lesser amounts of analytic thought admixed with greater or lesser amounts of intuition in all kinds of intellectual performances. But we should be surprised to find any considerable sequence of expert thinking that was not liberally sprinkled with intuitions. Moreover, such evidence as we have of creative thinking in the sciences and the arts indicates that analytic and intuitive thinking go on side by side in both. If there is a “mathematics bump” in the brain, or a “literature bump,” or any other, it appears unlikely that its presence or absence is much associated with a preference for intuitive or analytic thinking, or a differential capacity for the one or the other.

Math and Science Aptitude. Dismissing the analytic–intuitive dichotomy, however, does not dispose of the question of whether there may be a substantial number of people who, though exhibiting high levels of intelligence on tests of verbal ability, are yet unable to acquire skills in science, and especially science requiring the use of mathematics. The fact that there are demonstrably

many people who do fail in science and mathematics, and who find courses in these subjects exceedingly painful and impenetrable, does not prove the point one way or another. There is always the alternative explanation of motivation, of the primary school teacher who successfully immunized students against ever enjoying mathematics or succeeding in it. Perhaps what we are dealing with is not a cognitive inadequacy but trauma. That is certainly a tenable hypothesis, but we should not be too quick to embrace it until we have a much deeper factual understanding of the situation than we now have.

One curious fact, though it is a fact supported only by anecdotal evidence, is that for persons with high verbal aptitude but low mathematical aptitude, their difficulties with mathematics are most acute when they face tasks that require translation between verbal and mathematical representations of information. Middle school algebra teachers report, for example, that most students of good general ability master the mechanics of manipulating algebraic expressions. The moment of truth — the moment that separates those who will continue in science and mathematics from those who will leave the arena as soon as they are permitted to — arrives when the students are confronted with their first algebra story problems, problems stated in natural language that has to be translated into the language of equations. One might naively suppose that this would be precisely the part of the algebra course in which students of high verbal ability would shine. If the anecdotes are reliable, it is not.

In setting goals of scientific and mathematical literacy, it would seem to be of utmost importance to understand the nature of the difficulties I have just described and the prospects for alleviating them. To acquire that understanding, we have to analyze deeply the processes that are involved in performing such tasks as solving algebra word problems or physics problems. Some of the research in cognitive psychology of the past several decades

has already given us important hints as to what these processes are.⁴ Let me use an analogy to explain what has been learned.

A skilled translator putting a French text into English does not make a direct syntactical-cum-lexical translation from the source language to the target. Moreover, mechanical translation schemes that attempt to do just that have been uniformly disappointing and unsuccessful. What the expert translator does is to extract the meaning from the French text, transposing it into some kind of internal “semantic” representation, and only then rendering that semantic representation into English in the same way that English prose is generated from internal thoughts. Observation of students who have difficulties with word problems in algebra and physics has frequently revealed that they are unsuccessful in translating the natural language of the problem description into an adequate semantic representation. Their difficulties appear to center less upon the mathematical symbolism than on creating a mental representation to which that symbolism can be applied.

On the basis of any evidence of which I am aware, it is simply unknown whether and by what means these difficulties can be overcome. I do not even know what probabilities to assign to the possibilities. To the extent that math-blindness and science-blindness are incorrigible, we shall have to limit our goals of universal literacy. The consequences could be serious, for we could be continuing to exclude a portion of the population from a feeling of full participation in the affairs of our high-technology society. That feeling of exclusion is not uncommonly accompanied by alienation from the society, or at least hostility toward its technologies and a feeling of helplessness about them. Both are significantly present in our own and other high-technology societies today.

⁴ See J. Larkin, J. McDermott, D. P. Simon, and H. A. Simon, “Expert and novice performance in solving physics problems,” *Science* 208 (1980), pp. 1335–42, and references cited there.

It seems highly unlikely that unsusceptibility to science and mathematics education is an all-or-none matter. Hence, there is no reason to postpone our efforts to raise the general level of literacy until such time as we have accurate knowledge of the limits. Activities aimed at raising literacy and efforts aimed at understanding the difficulties encountered along the way can go hand in hand.

To the extent that we regard scientific literacy to be an important goal for a high-technology society, or for any society, we need to assign a correspondingly high priority to research aimed at gaining a deeper understanding of the nature of the internal representations that are effective in solving problems in domains like physics and chemistry, the nature of the individual differences in aptitude for constructing such representations from problem descriptions, and the means for improving those aptitudes, particularly among those in whom they are weak. Until we have such an understanding, and preferably also an understanding of what methods are effective for improving this skill, it will be hard to define realistic social goals for literacy.

We need this understanding not only for the students of science, but for the teachers as well. There is much concern today as to whether all or most of the teachers responsible for science instruction in the schools, particularly at the elementary level, themselves have the depth of understanding of science and mathematics that is needed for effective instruction in these subjects.

COMPUTER LITERACY

In recent discussion of school curricula, the topic of computer literacy has assumed an even greater prominence than literacy in science and mathematics. We need to ask just what the connection is between these two kinds of literacy, for it is not at all obvious. We may be interested in providing students with the skills necessary in using a computer, in helping them to understand mathematics by using the computer as an instructional device, or

in using the computer as a tool for instruction in science. These are different things.

In their ability to assume an active role in interaction with their users, computers are unlike any of our previous artifacts. Domestic animals are the closest analogy, and they cannot speak. The level of sophistication that can be reached in human interaction with computers has little or nothing to do with the hardware but depends instead on programming. And since our experience with computers is very limited — only a generation, and that devoted mainly to number-crunching — we have hardly begun to realize the potential of computers as active partners in an educational process.

Because of the limits on human imagination in dealing with novel complexities, the first generation of computer-aided instruction systems has (with some notable exceptions) largely been limited to using the computer as a substitute for a programmed textbook, providing massive opportunity for drill and practice. Drill and practice programs have a useful place in instruction, but they are not at all what CAI will mean in the future. As research in artificial intelligence advances, we will find ways to provide computers with more and more of the capabilities of an intelligent human tutor, and perhaps other capabilities as well. At what point and to what extent we will be able to afford to use these capabilities for instruction on a large scale is harder to foresee. And we must continue to give equal attention to the ways open to us, with or without computers, for raising the competence of our human teaching force.

Computers Teaching Computing. Let me turn now to the various applications of computers to instruction in computation. Computer literacy in the narrowest sense is the easiest to comprehend. The main precondition for automobile “literacy” in our society was the widespread availability of automobiles. In the same way, the wide availability of computers is the necessary, and almost sufficient, condition for computer literacy. “Literacy” in

its narrowest sense means the ability to use computers in simple applications like arithmetic calculation and word processing. These can be taught and learned as rather narrow skills and with little or no understanding of the computer hardware or software that implements them.

I suppose that by computer literacy we usually mean, or should mean, somewhat more than this. The most ambitious attempt to use the computer to teach basic concepts of computation — in particular, to lead users to an understanding of the fundamental notion of *procedure* — has been the activity associated with the programming language LOGO. The efforts of Seymour Papert and his associates to apply LOGO to education from the earliest levels have been as imaginative as the language itself. However, we do not yet have systematic evaluations of the educational impact of LOGO on students. We do not know what is learned, how effectively it is learned, or what individual differences may be expected in the response to systems of this kind. Nevertheless, I think a good case can be made for LOGO-like approaches to computer literacy in contrast to standard instruction in programming in languages like BASIC or FORTRAN.

The goal is to make the computer, for T. C. Mits, a less mysterious and magical object than it has been; to provide all or most of us with some insight into how it is able to do all kinds of things that resemble the things that we humans can do by thinking. And if that insight can be provided, it will carry with it a considerable insight into how the human mind works, penetrating that mystery also.

Computers Teaching Science. So much for the “egocentric” use of computers to teach about themselves. They also offer much promise, although a promise largely unrealized, to contribute to the teaching of mathematics and science. We can already catch a few glimpses of the directions that such instruction may take. For twenty-five years, a number of graduate schools of business have been using computerized business games to give students the ex-

perience of making decisions in realistic manufacturing, marketing, and financial environments. For nearly the same length of time, some students in chemistry, genetics, and psychology (and perhaps many other subjects) have been provided with data banks that allow them to plan, run, and interpret simulated experiments. As graphic display devices have become more widely available, computerized displays have been applied to teaching about various kinds of dynamic systems, giving students an opportunity to visualize the changes in dynamic behavior that result from altering system parameters. Students in history and sociology courses have been provided with data banks that allow them to test empirically some of the theses they find asserted in their textbooks. Programs that diagnose student errors, and work interactively with the student to remove them, are under development for subjects ranging from arithmetic and electronics to writing.

We can look forward to at least a generation of rapid exploration of these potential applications of the computer to education, and at the end of that generation (and possibly long before) the label CAI will have a radically changed meaning. What is less certain is whether the computer has any special contribution to make to the problem discussed in the previous section: whether it can help reduce the number of people who are immune to instruction in scientific mathematical subjects. I hesitate to make a prediction, one way or the other.

A CLOSER LOOK AT SCIENCE AND CITIZENSHIP

I have already introduced the topic of the needs of scientific education for effective citizenship and raised the question whether access to experts could substitute for literacy. I should now like to turn the question around: Would literacy be an adequate substitute for access to experts? Let me take as a difficult example the policy decisions we have to make in our society about energy sources.

Every discussion of energy policy today encompasses not only the questions of exhaustibility of resources but also the vexing issues of environmental effects of using one source of energy or another. Petroleum, nuclear energy, coal, biomass, gasified coal, and solar energy are all claimants for a major role in the supply of our energy. Understanding each of these sources and its environmental implications involves a formidable body of physics, chemistry, meteorology, geology, physiology, and perhaps other sciences as well.

We are concerned with the disposal of slow-decaying nuclear wastes. What do we know about the capacities of deep-lying salt deposits for containing such wastes in the long run? Some of our fuel sources produce immense quantities of carbon dioxide, which is vented to the atmosphere. What is the magnitude of the greenhouse effect, and what is the time scale within which we need to be concerned about it? What are the economics and ergonomics of the production of biomass for fuel? Can we obtain it without consuming more energy for fertilizer and cultivation than we harvest for fuel? What are the prospects for storing large enough amounts of solar energy to tide over periods of nighttime and overcast? What are the prospects of achieving economical energy production from nuclear fusion, and what kinds of wastes will be produced from fusion processes? What are the prospects and costs of extracting the sulfur oxides that produce acid rain from the stack gasses of coal plants?

This is just a sample of the questions that can be asked about energy policy. No matter how great our enthusiasm for educating the Mits family in science and technology, it is unlikely that they will ever feel confident in their abilities to handle these questions without expert help. And where are the experts? Even if the Mitses can find experts to answer *each* of these questions (a matter to which I will return in a moment), they are highly unlikely to encounter many who can answer *all* of them. Even if they can get answers, how are they to put them all together?

CAN WE LEAVE IT TO THE EXPERTS ?

By an expert on some topic, we mean someone who knows all that is known about it and can reason correctly about that knowledge. What is known, however, may not be enough to answer the Mitses' questions, or ours. Today, it is generally agreed among atmospheric scientists that an increase in carbon dioxide in the atmosphere will cause a warming of the earth's climate. Less than fifteen years ago, I heard several of the country's principal experts discuss this topic. They all agreed that carbon dioxide in the atmosphere had three, additive, effects upon temperature. One was the greenhouse effect, and I have forgotten the nature of the other two. The greenhouse effect had a positive sign (more CO₂, higher temperature), while the other two had negative signs (more CO₂, lower temperatures). However, understanding of the processes was not then complete enough to determine whether the positive or negative signs dominated. That was the most expert opinion available, but it was cold comfort to anyone responsible for recommending policy. Today we are better off. It seems to be agreed that the positive term dominates. But experts can still disagree widely as to the magnitude of the effect.

We may be tempted to dismiss this problem as irrelevant to scientific literacy. If we human beings, collectively, do not have the knowledge we need, no training in science or mathematics, and no lack of it, will remedy the situation. But if the Mitses and their friends are to use the experts wisely, they should have some capacity to judge when the experts really know and when they are guessing. A measure of scientific literacy might be exceedingly useful in assessing the degree of certainty of the scientific conclusions presented to them.

Expert advice has to be evaluated not only with respect to its certainty, but also with respect to possible biases of the experts. We are accustomed to making allowance for bias arising out of pecuniary interest, and frequently we require our experts to disclose any conflicts of financial interests they may have. We are

increasingly aware of, but perhaps not yet fully sophisticated about, biases that arise from human bounded rationality. The human mind, even the brightest human mind, can only embrace a very small part of all human knowledge, and can attend at one time to only a tiny fraction of even this small part. One way it deals with these limitations is to limit the goals with which it is concerned and confine its attention to a subset of all the causal connections in the situations it is considering. And in this process of narrowing, the part on which attention focuses becomes more interesting, more important, and somehow more valuable. Hence, several years of immersion in research or development on the X energy source is highly likely to produce a deep conviction in the researcher or engineer that X is a highly desirable source of energy, that continuing research and development will certainly soon assure its technical feasibility and bring it within our means, and that its deleterious environmental effects, if any, can be reduced to acceptable proportions.

In an area of science or technology where human knowledge is relatively complete (if there are any such), we could presumably predict what an expert would tell us if we ourselves possessed the expert body of knowledge. In most areas of real complexity, like the energy technologies I have mentioned, different scientists, all expert and reasonable, could tell us quite different things. The most useful information about them, if we want to predict what they will tell us, is information about their professional histories, their identifications and commitments. If we want a favorable view of nuclear energy, we go to Edward Teller and not to Barry Commoner.

To make this observation is not to accuse these experts, or any others, of venality or mendacity. It is simply to affirm the well-known phenomenon that human rationality is severely bounded, and that identifications with particular goals, particular subject matters, particular people and groups of people, and particular regions of space and time provide some of the important bounda-

ries that allow us to simplify problems to manageable (if unrealistic) proportions. Commitment to nuclear power or to energy from biomass arises from the same psychological sources, derives from the same psychological mechanisms, as commitment to American (or Chinese, or Russian) supremacy in science and technology. They are all corollaries to the proposition that what we know well we value and seek to perfect.

INSTITUTIONALIZING EXPERTISE

The recognition that experts operate with uncertainties that are sometimes immense and identify with partial viewpoints that are inescapably blinding leads to a variety of proposals for improving the quality of expert advice by institutionalizing the process of providing it. The National Research Council and its governing organizations, the National Academy of Sciences and the National Academy of Engineering, provide an example of such institutionalization. The function of the National Research Council is to provide expert advice, on request, to the organs of the national government, executive and legislative. A variety of mechanisms are built into the structure to guarantee the highest attainable levels of expertness and objectivity. Membership in the governing bodies is determined by a rigorous process that is supposed to weigh only scientific and technical eminence, and which probably comes about as close to this goal as human imperfections in motive and judgment allow. Membership is for life, eliminating one form of external pressure. A large part of the membership, especially of the NAS, is based in universities, which are generally perceived as more closely identified with the public interest — or at least less identified with special interests — than are most other employing institutions.

The governing group of the NAS-NAE-NRC complex selects ad hoc committees to examine the specific questions that are put before it. The selection process takes into account both expertness and the need to balance interests and prior identifications, where

these are known or can be guessed. Nominees are expected to disclose conflicts of interest that might bias their judgments.

There is fairly wide agreement among persons familiar with the operation of these institutions that they perform a useful and sometimes important function, and that they are not perfect. Cries of conflict of interest have sometimes accompanied the publication of reports on controversial topics, but that is to be expected—and may even occasionally have some validity. But the most severe limitations of this use of experts are limitations of scientific and technical knowledge. On some occasions, a committee has given advice that, from hindsight, was poor. On other occasions, a committee has given advice that seemed to some to be wishy-washy, (Senator Muskie once complained that scientists were “two-handed.” On the one hand, they said “yes,” on the other hand, “no.” In the face of uncertainties and gaps in knowledge, others might describe the same behavior as “even-handed.”) When these things have occurred, I believe that they can most often be attributed to genuine inadequacies in the scientific knowledge available for answering the questions posed.

Earlier, I mentioned auto emission standards as an example of a policy question that called for extensive knowledge of science and technology. Since I once chaired an NAS committee that offered advice on this topic (to Senator Muskie!), I might say a few more words about it. In principle, the problem had a clear conceptual structure. The chain of causality ran from automobiles to chemical reactions in the atmosphere, to the air we breathe, to human health. The greatest conceptual difficulty lay in balancing costs and benefits, which clearly involved (implicitly or explicitly) assigning values to life and health that could be compared with resource costs. Any economist, and many noneconomists, could write down the equations that would formalize this conception and seek an optimal answer by equating partial derivatives, the coefficients that represented the effects of policy changes and their costs or values.

But the practical difficulty that faced the committee in reaching conclusions and recommendations lay in quite a different direction. How were we to find the actual numbers to assign to these coefficients? We had available to us the nation's experts on automobile engineering, atmospheric chemistry, cost-benefit analysis, and the health effects of toxic substances in air. Almost none of them (except the engineers) felt confident or even comfortable in providing quantitative estimates of the strengths of the causal connections that they studied. The health experts, for example, were willing to hazard judgments about the minimum concentrations of certain substances that would have toxic effects. They were most uncomfortable when asked how much these health effects would increase as the concentrations increased. Yet the latter judgments, not the former, provided the relevant parameter for the decision that had to be made.

What can you say of recommendations arrived at under these circumstances? For the committee did make recommendations. You can say, I believe, that the scientific evidence that the committee reviewed placed limits, very broad limits to be sure, on the range of conclusions and recommendations that was scientifically acceptable. You can say that the recommendations finally agreed upon by the committee were such as reasonable people, with a good understanding of the evidence, could have adopted. Whether this degree of certainty is sufficient to deal adequately with the questions that face our society is uncertain. That it is as much certainty as we are able to attain is quite evident.

EXPERTS AND T. C. MITS

Experts are used in our society through a large variety of institutional arrangements and channels, of which the NAS-NAE-NRC structure is only one example, albeit perhaps the most prominent one. Whatever the arrangements, the problems that are encountered in using them are very similar to those that I have illustrated in my example. In light of these problems, we clearly

will not wish to depend on the experts alone. What additional procedures are available? In particular, what role can the Mits family play in the process?

Courts and legislatures give us models of deliberation that are alternatives to the expert process that I have described. Both of these alternatives share a couple of properties: they do not rely on experts to make the final decision, although they may call on them for assistance; and they both assume that the relevant interests will be represented in the process — to that extent, they are adversary proceedings. Both are attuned to bounded rationality and to conflict of interest. Rashomon is no stranger to them.

Even the rank layman can be informed by listening carefully to experts presenting conflicting analyses. I have observed a federal district judge hearing testimony, in a patent suit, about the physical processes that cause the arc to extinguish when an electric switch is opened. At the end of the week, he appeared to be wiser and better informed than he was at the beginning. As far as I know, he was innocent of formal training in physics, but cross-examination can be a powerful method for eliciting truth. And there would seem to be good reason to believe that Judge Mits or Attorney Mits could ask sharper and more penetrating questions about scientific and technical disputes if she had a modicum of scientific understanding of the matter at hand than if she were wholly ignorant of it.

This is the strong case for teaching science for citizenship. It is illusory to suppose that such instruction can produce expertise, even over a tiny range of the questions that face courts, legislatures, and consumers today. But it is not illusory to think that the Mits family can become more effective questioners and cross-examiners than they would be without such training.

If this is to be a primary goal of science for the citizen, we can ask what content of the science curriculum is most suitable for attaining it. At the outset, we can dismiss any great concern for subject-matter coverage, for we are not trying to produce experts;

we are trying to produce questioners and adjudicators. Since we can cover only an infinitesimal part of the subject matter that is potentially relevant, there is no part that we *must* cover. Far more important than subject matter is the method of science: the nature of scientific evidence, the ways in which that evidence is obtained, and the ways in which it can be interpreted. Of course, methodology is sterile when taught in abstraction. What needs to be taught are specific bodies of science — sampled from the whole domain — viewed and examined as instances of the application of scientific method. It is far less important what particular examples are chosen than how they are explored.

One advantage of this approach to scientific literacy is that it brings about a convergence between the goals of liberal education and the goals of producing a literate citizenry. A second advantage is that it affords some opportunity to avoid the worst difficulties of possibly incorrigible illiteracy that I addressed in the last section. Incorrigibility seems to center on subjects with a mathematical, or at least a formal, structure. We need not organize the whole curriculum around such subjects, although it would be unfortunate to avoid them altogether (allowing the “science requirement” to be satisfied by a course in anthropology or geology).

In proposing this emphasis on the methods of science, I do not believe that I am proposing a “science for poets” approach. The potential cross-examiner or questioner needs to know some science, not just something *about* science. Specifically, it is unlikely that any considerable appreciation of the scientific process or of the weight to be placed on scientific conclusions is to be gained without a student’s going through that process and striving to reach such conclusions. If in the course of achieving this objective some scientific content is also learned, as it surely will be, so much the better.

KNOWING OURSELVES : THE SOCIAL SCIENCES

“We have met the enemy and they is us.” It is all too easy to locate the problems that face our species in the physical world

that surrounds us. Their real locus is in ourselves. And one of the conditions that complicates our efforts to deal with our problems is ignorance of ourselves. Scientific literacy cannot be limited to understanding of the external world; it must encompass literacy in the sciences of man.

It may be credible to equate knowledge with power, but surely not with virtue. There is no certainty that if the Mitses understand the economy better, or the ways their brains work, or the psychological and sociological roots of racial prejudice, that they will behave in more benign ways. But there is reasonable certainty that if they continue in ignorance of these matters, they will create many problems for themselves and others. For this reason, I must give a prominent place to the social sciences in the curriculum for scientific literacy.

In teaching the social sciences, as in teaching the physical and biological sciences, coverage is not the issue. It is neither possible nor desirable for its own sake. What needs to be taught is something about the tools we have available for inquiring objectively about ourselves, as individuals and as members of families, organizations, economies, and polities. What need to be taught, also, are ways of challenging and testing the received wisdom, the proverbs about human behavior that pass in everyday discussion as explanations of human phenomena.

What we can teach goes no further than what we know. I am not one of those who think we know little, scientifically, about human behavior. The fact that economists cannot predict next year's production or fine-tune the economy does not mean that they do not have a considerable understanding of how a complex economy operates and a great deal of consensus — comparable, let us say, to consensus among meteorologists or geologists. In our century, psychologists, sociologists, political scientists, and many others have gone far to establish a basic understanding of human individual and social behavior.

The quality of the teaching of the social sciences in the primary and secondary schools is a scandal that no one denies. No young person with a zest and aptitude for science is likely to be attracted to those subjects by what he learns of them before he reaches college, or is likely even to perceive them as subjects to which the scientific method applies. Recruitment to the social sciences has been too much a story of born-again scientists, converted from their initial commitment to physics or chemistry or biology. If one of the goals of scientific literacy is to expose youth to the whole range of opportunities for careers of intellectual challenge and excitement, then that goal is poorly served by contemporary education in the social sciences.

And now I will reveal my own biases and identifications. I believe that answering the question of “What is mind ?” is one of the most exciting and important directions of scientific inquiry today. I believe that this direction, usually labeled cognitive science, will make an important contribution to the definition of scientific literacy and to the discovery of the most effective means for working toward it — and perhaps also toward delimiting the boundaries of the attainable. In building a curriculum for scientific literacy, it will be important to sample cognitive science as one of its components, as well as computer science, upon which research in cognition now so heavily relies.

CONCLUSION

In my paper, I have presented the reasons why it is important, in our kind of society, for T. C. Mits to have more than a little acquaintance with science, technology, and mathematics, quite independently of his or her vocational needs. I have argued that these subjects are an essential part of liberal education and of education for citizenship.

With respect to citizenship education, the essential skill is the ability to manage the experts — to gain the advantages of their expertise without becoming dependent upon them or vulnerable to

their biases and identifications. But it is illusory to suppose that this skill can be developed purely by training in the forensic arts, or in other subjects that are independent of science. For their adequate development, members of society require no little knowledge of science, and especially a genuine understanding of scientific method, grounded in concrete experience with that method.

In liberal education it is even less feasible to skirt the sciences and mathematics; for these subjects address directly and profoundly the questions of our place in the world that are most central to the goals of liberal learning.

The more importance we attach to universal education in the sciences, the more important it becomes to establish realistic and realizable goals. But we have only a slight understanding of the magnitude and origins of individual differences in the ability to assimilate scientific and mathematical skills and knowledge. And we have less understanding of the methods that will be effective in dealing with the illiteracy of those who evidence, or claim, or even boast of, incorrigibility. Gaining that understanding must be assigned high priority among the research goals of cognitive science.

And finally, all of the arguments for the essentiality of education in the sciences apply as strongly to the social and behavioral sciences as they do to the physical and biological sciences. It is as important that we understand ourselves as that we understand the matter of which we are made and the universe in which we live. At the present time, we do almost nothing at the pre-university level to satisfy T. C. Mits' need to understand psychological and social processes and structures. Meeting that need must be added to the agenda of science education.