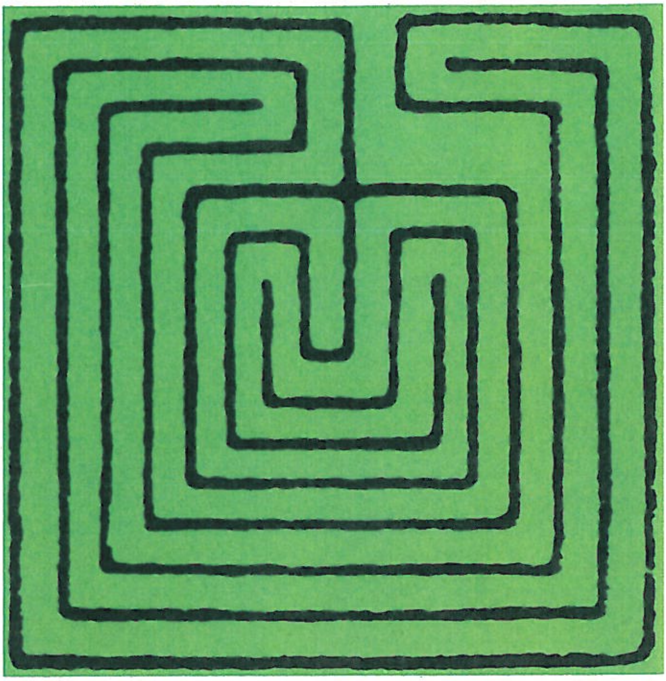
DÆDALUS

JOURNAL OF THE AMERICAN
ACADEMY OF ARTS AND SCIENCES



SCIENTIFIC LITERACY

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SPRING 1983 $5.00

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Spring 1983

Issued as VOLUME 112, NUMBER 2, of the Proceedings of the American Academy of Arts and Sciences

Contents

David Hawkins

Nature Closely Observed

THERE IS A MARVELOUS CONTINUITY between the worlds of children's experience and the adult worlds of the arts, of the sciences and mathematics, of conduct and social life. This continuity is one of cumulative learning. Learning, in this educationally important sense of the word, is always in principle spontaneous. Man, said old Korzybski, is a time-binding animal. We store experience, well or badly, as the squirrel stores nuts. Not for a coming winter, though in a winter time the store may save us. But learning is also always, in some degree, *induced*. In this essay I wish to use both these words, in a sense as technical terms. For *spontaneous*, I go back to the Latin *sponte*, of one's own accord, and still later to an Indo-European root *spon*, which is one of that vast collection of words derived from the weavers' art, to spin.[1] In the hand of the spinner, the spindle is given an initial twist, but it continues for a time spontaneously, of its own accord or, as we may prefer to say, its own spin energy. Children only learn well of their own accord. In this case, we need not wind them up to start the process; nature does that. But in another sense, the learning they engage in can be induced; they can be led into association with matter that matches their readiness to assimilate and to make much of that which counts and that they might otherwise never gain access to. Induced learning is still, for children, spontaneous, if they are led, not dragged. When children are only dragged, they learn to cope with a curriculum of intimidation. To teach, then, is to have the authority of the guide, of one who shows the way. To teach is not to drag, though some element of the imperative mood is always latent in teaching; the guide who shows the way is never merely permissive. When children have been brought into some fresh territory for exploration, and find in it some joy and satisfaction, they forgive the hand that sometimes had to push their noses into such milk. But mostly, the hand is not needed; trust can take its place. And an attentive guide is open to questioning, to the suggestion of alternative routes.[2]

So what anthropologists call the transmission of culture is not at all the sort of telegraphic imprinting that the word itself suggests, but rather an enormously complex and problematic concept. At its best, the continuity between generations means that babies can grow up to be inventive women and men; children who have been excited by learning can later become adults who infect new children with that same excitement, supporting their entry into the great world, maintaining and advancing the qualities of life, of all that which over hundreds of millennia has increasingly set us apart from our sheer animal existence.

But there is also a dreadful continuity between the limitations and failures of one generation and those it visits upon the next. Under deprivation or duress continued too long, children are not able to find those affirmative choices that would enhance their lives. As they enter the streams of adult life, they often must take with them their miseries, their accommodations to failure, even to brutality. They then may themselves sow dragon's teeth, a crop their own children will in turn harvest and replant, sometimes in even greater measure.

Such connections, educative and miseducative, are powerful; they are the counterpart for cultural evolution—including the rise and fall of cultures and civilizations—of all the genetic transmissions and changes that evolutionary biologists are concerned about in the history of terrestrial life. As a product of that biological evolution, we are predisposed to care for the young for some major fraction of their whole lives, to bring them up and to educate them over the long years of infancy and childhood. Disposed in their turn to assimilate what the adult world can offer them, children may assimilate and respin its strands and reweave its wefts of competence and creativity. They may also, in self-defense, emulate its self-destructive capacities. If our best and most insightful nursery schoolteachers could be transformed by some magic into anthropologists and historians, I think they would look for a different sort of evidence than historians have mainly offered to explain the rise and fall of cultures and civilizations: they would look to the transmission of cultures and of the zeal to learn, or to the failures of education thus broadly defined. The task would not be an easy one; the detailed processes of culture transmission have long been practiced but seldom much noticed or recorded; the exercise of sheer habit can go for long unquestioned.

I have spoken about the extremes of the process, the best and the worst. More frequent than either, of course, is a pattern of partial education to which we have become too well accustomed.

In the total ambience of children's lives, then, there exists always some educative potential of which the school is only one component. The other components of this potential for education or miseducation—family life, peer association, and the big world they increasingly respond to—are in many ways more powerful than schooling. Schools are, after all, only an institutional invention, and in the long sweep of history, a recent and still very uneven one. But even today, children of the well educated often likewise emerge as well educated, along pathways that owe less to their formal education than might appear. Teachers are prone to claim more in this regard than is really justified. On the other hand, where the out-of-school potential is low, school can be a vital alternative. This is often true for those from generally meager backgrounds; and where the educative potential of some major part of society is in fact low, then what can be learned in school can become a saving grace, ameliorating the dreadful continuity. In saying this, I do not wish to minimize those informal extensions of formal education, intended for adults and children alike, represented in our day by film and television and by museums. As extensions of schooling, they can enrich the ambience, at least for some.

I have begun with these rather wide-ranging remarks because I wish to discuss an educational domain in which the spontaneous potential of even our otherwise well-educated classes is on balance quite low: mathematics and the sciences. We are all acquainted with the extraordinary history of rapid social change that, over three or four centuries, has been coupled with the evolution of the special subculture of science. This subculture of science has owed its vigor, as a necessary condition, to its ability to reproduce itself on a scale that has steadily increased. This increase is in numbers, in detailed knowledge reduced to order, and in specialization. Thus an important part of the history of science has been the recruitment of the young. To this end, science has long since invaded the universities, and now in some manner can dominate them. Its influence is far less in the secondary schools, and almost negligible in the first six or eight years of schooling. Along the way, however, and perhaps as a necessity of rapid growth, the scientific subculture has developed such cumulatively special ways of learning, of reorganizing, and of communicating as to constitute increasing barriers to entry. The required preparation of neophytes has become more and more extensive and elaborate, and there is finally a threat of their sheer depletion. The well is not dry, but the needed talent level has been steadily lowered. Some of us have come first to a new concern for earlier and wider science education because of this threatened depletion, a threat to the continued prosperity of our craft. The wells of available talent must now somehow be refilled and maintained by earlier and wider and more effective science education. Such is the narrow view. The institutional statecraft of science has for a long time taken too much for granted, beginning its educational efforts too little, too late, and with too little attention to quality.

There is a wider view, however, concerned less immediately with recruitment than with the welfare of a society that on the average has so low a diffuse out-of-school potential for science education, but that depends crucially upon the institutions of science and upon their increasing symbiosis with industry, with medicine and agriculture, with government and with the military. Our aim in teaching basic science should be to prepare all youngsters for eventual participation in the democratic discussion and reordering of ends; the narrowing, even the failure to broaden basic science education, creates scientific and technological oligarchies, while the rest of us tend to become incompetent for democratic rule, to become—in the language of Toynbee—a cultural proletariat.

Both these honorable views, which have become very familiar to us, are clearly not incompatible. If the range of scientific literacy is widened, the diffuse educative potential increases, and the level in the wells of talent will also rise. Twenty years ago we argued—or at least competed for educational funds—in terms of the ordering of priorities as between upper-level professional science education and lower-level science for the citizen. Now, I think, this sort of debate seems rather stale and innocuous. We need both equally, each for the other.

But there is a third, a still wider view, growing out of good works that have often been attempted but not widely credited or understood. There are beginnings of it in the traditions of enlightenment; surely not, however, much reduced to widespread practice, and perhaps least so among the official austerities of present-day formal education. I think it is a view necessary to the empowerment of the narrower views I have summarized, but it has more important justifications as well. I shall elucidate it, as best I can, from the educational lives of children and of those who teach them. It is most accessible there.

In this wider view of science education, the central aim is to contribute, quite generally, to the improvement of *all* education. As such education should prove successful, it would of course contribute to enlarging the pools of potential scientific talent and enhance the qualities of intelligent citizenship. But such aims are thin gruel; they lack the kind of informational richness we need to guide our efforts. They may indeed only lead us today—in a new round of concern—to intensify conventional efforts already marked for failure. I propose to start instead with some account of what I believe to be our most successful experience. I cannot document it on any but a small scale, out of the experience of good teachers I have had the luck to know. It also fits a certain good theoretical mold, however, which supports it and which I shall try to sketch.

In singling out our present-day inadequacies for teaching science and math, and then in proposing a direction for remedy, I may seem to risk a false assumption: that all else is well in our early education practice. It is a risk made all the more obvious by the widespread talk of the deterioration of schooling, usually in the areas of reading, writing, and computational skill. But there is the opposite risk, that we fail to recognize the ways in which children's early involvements with the substance of science and math can open gates for them, into all the domains of knowledge and enjoyment. I shall try to compensate for the first risk by doing what I can to avoid the second.

As a first step, a basic assumption: to lead children into domains of science and math can presuppose less, by way of any prior richness in their educative backgrounds, than is needed for other essential parts of a school's curriculum. History, for example, or literature, even reading and writing, can come easily to children whose family and social background provides them, early and steadily, with surroundings where such matters are valued as part of daily life. For those who lack that sort of background, these interests can be relatively inaccessible. There are exceptions, of course; but when we look closely there, among the children of poverty, we seem to find only rare, special circumstances that have opened the doors for them into the worlds of the written word, of the arts and humanities. The sheer fact of poverty does not always exclude those drops of nectar in the sieve that can heighten children's taste for poetry, for fantasy, for storytelling, and so for the written word. Nevertheless, such engrossing interests presuppose an early richness of experience and of experience reflected upon, which the life of poverty can seldom afford.

If we follow this line of thought, we are led to the conclusion that there is more of the basic background experience for mathematics and science in the life of every child than for most other subjects in the early curriculum. These are the daily phenomena of nature that surround us constantly, early and late, and about which we all accumulate a central store of experience—of light and dark and color, of heat and cold, of motion and rest, of forms of matter and of life. In a trial course of geometry, the *Gruppo Scuola e Università* in Rome, for example, introduced planes, lines, and points by slicing a potato at right angles once, twice, thrice.

But this conclusion seems in violent contradiction with the everyday wisdom of curriculum designers and of most teachers. Math and science are reputedly the most difficult subjects to teach. As a result, science is taught hardly at all, while math is reserved for the early hours of the day when children are, it is supposed, least fatigued. If this belief is correct—and it is surely based on massive experience of a kind—then something is very wrong with my line of argument, which implies that of all the traditional subjects in the curriculum, math and science should in principle be the most accessible to children from a wide range of backgrounds. But I prefer to take refuge from evidence of this sort. There is an old joke: "Don't confuse me with the facts!" I think the facts are there, but they are wrongly taken. Early math and science are on balance so badly understood and taught that the failures we know so well lie with the style of teaching and hardly at all with the children. School failures are typically regarded as children's failures, rather than failures of the school itself. There is very little evidence readily available to decide between my own belief and that which usually prevails; we have many would-be child doctors, but too few school doctors. Against a mainstream of opinion that I reject, I reaffirm my argument: the kind of experiential background in children's lives before schooling begins, or along the way, is more uniformly adequate to math and science than to most other school subjects. The poverty or riches of social background matter less here in the early years than in other school subjects. Math and science should therefore be the great equalizers, whether they are now seen to be or not.

I have said that in our elementary schools, science is seldom taught at all, while math is reserved for the early hours of the day. But that is inaccurate. I should have said that neither subject is taught, for the most part, at all. What is called school mathematics is not mathematics, or is barely so. The lives of children in elementary school are dominated during "math" periods by assignments that are only called arithmetic. A tiny bit is called geometry, but most of that bit dwells on the mere names of things unloved, such as triangles, squares, pentagons, and the like. Most of what is taught is called arithmetic, and children learn, soberly, to add, subtract, multiply, divide. They also may learn some bewildering rote algorithms about fractions, how to add or subtract, even multiply or divide them. They learn, in a fashion, to handle negatives or decimals. And this modest goal takes six or eight years of dubious battle; a thousand or two hours, central hours, of children's days for 10 or 20 percent of their lives.

The ancient Greeks made a distinction in their language between what they called *arithmetic* and what they called *logistic*. Arithmetic was the investigation of the world of numbers; logistic was a set of rules, to be memorized, for doing rote sums, differences, products, quotients. Arithmetic was a kind of science, always fresh and open to endless investigation. Logistic was a dull art, needed for bookkeeping and other such practices, which you could learn by rote. If you understood something of arithmetic, you could easily master the rules of logistic; if you forgot those rules, you could reinvent them. What we mainly try to teach in all those early years of schooling is logistic, not arithmetic. We drag, not lead, and the efficiency of learning is scandalously low. Of course, it is not all one way. In order to pursue arithmetical investigations and the many practical uses to which some can be put, it is useful to deal easily with sums or quotients. In some purely formal order of development, the rules come first.

But, in the order of optimal understanding, the intuitive grasp can often run far ahead of the computations necessary for completely reliable answers to questions that a budding curiosity has raised. We put poker chips together on the table in the patterns of triangles or squares, and find that these patterns can grow larger and larger, yet preserve their shape. It can be an invitation for counting, for tabulating, for seeing relations of sum and product and quotient. We begin to see a pattern of number growth in the patterns of shape; we predict and perhaps confirm; we find nice relationships between the visual world of geometric form and the step-by-step logical world of number. These are small examples of the vast array of relationships that cross-connect two very important domains within all our experience—number and form—which early schooling, if it treats them at all, too often treats in isolation. It is a simple and shocking example of this separation that, to most elementary schoolteachers in the courses I teach, the adjective *square,* when applied to numbers, has no perceived relation to the same adjective applied to shapes. Even triangular numbers, not to mention pentagons, cubes, or tetragons, are then a complete surprise, as are other classes of number shapes.

Many investigations into the connections between number and form are quite accessible to children and bring new understanding. Along with the many practical uses of math that can engage children (carpentry, sewing, weaving, classroom bookkeeping, mapping, and measuring), the genuinely mathematical investigations can motivate the acquisition of computational skill, of logistic. This skill is—or should be—subordinate to real math, and when subordinated, can be learned more easily. In all of this, one can live and work in the style—often the very content—of the ancient Greeks before Euclid. In the three centuries before his works appeared, there were many little and some big mathematical discoveries made. Those early mathematicians, and many still later, used the letters of the alphabet for numerals and the abacus for computations, and drew shapes in smooth sand. The language they used was just the ordinary Greek; there was no elaborate shorthand symbolic notation such as we associate with present-day mathematics and force too early upon our children. But from such everyday beginnings, the ancients began to develop some powerful ideas and important questions, the beginnings of our own tradition. Children guided can do that, too.

A classroom in which this sort of real mathematics is pursued becomes a math lab—I call it the Laboratory of Archimedes—and by an easy extension, it can also become a science lab, with much of the simple apparatus for investigating physical phenomena (heat and light, sound and motion), and with space for various growing plants and sometimes resident or transient animals. And since all important matters that transpire in such a classroom must be related to what one finds in books, there must be a good library corner. Good things must also be reported on, with texts and posters. (A "nonreader" will learn to use them if they contribute to learning, and will learn to write if there is fresh excitement to communicate.) In its contrast with most classrooms we have seen, it may sound forbidding, but it is in fact the opposite. It is most inviting.

I recall, with amusement still, a class in North Wales, in which a group of ten-year-olds put old Galileo to the test. A children's science book had told the too-simple story of the unequal weights dropped from the Leaning Tower of Pisa, and had rather primly missed the whole point of it by insisting that the heavier weight would fall a bit faster. Those children devised a beautiful experiment that would have warmed the heart of Galileo himself; it was, in fact, one used first by Galileo's elder contemporary, Stevin of Brussels. They managed a tall ladder from which the two weights could be dropped onto a bit of galvanized iron. The ear (better than the eye) could recognize small differences in the time at which two weights, dropped together, would hit the tin. These Welsh children were treading sacred ground. Most agreed with what they were told was Galileo, and explained away the very small differences they heard; two held out against this conclusion. Their teacher and I agreed that there was no need for us to straighten the whole thing out, at least that day. In his training, he said, he had been told that one should never leave children with wrong conclusions. But he thought children would never hold too strongly to conclusions of their own devising. The danger was that they might uncritically accept the errors that adults so often uncritically impose.

A central argument against the style of science and math education I am suggesting here is that there is no time for it; no time, they say, to reinvent the wheel. I cannot resist a first reply, which is that not everything is known, as yet, about the wheel, either the mathematics of it or the physics. I am thinking of the long and beautiful history, in mathematics and physics, of the circular functions, of the Fourier transformations that use them so elegantly, of the complex domain and the infinite scheme of the roots of unity. I am thinking also of the world of modern physics, in which one may learn to think of rotations that go twice around before getting back to the starting point. Today's children will do well *not* to close their minds prematurely on the subject of wheels.

Past experience must indeed be somehow summarized, must in some way be put in soluble capsules; it cannot be relived in its totality. If we had to relive all past errors and discoveries, it would be a commitment to absurdity. A part—indeed a major part—of the structuring of our minds must come from instruction. But this obvious statement leads much too easily to notions that are, I believe, radically false. *In*struction by a teacher fails without a matching *con*struction by the learner, induction without spontaneity, words without things. The lecture or the textbook passage that succeeds is one that meets an apperception well prepared. When we merely surrender to the textbook, we surrender to defeat.

What is essential, then, is that children should *often* be instructed, but they should *seldom* be instructed before they are prepared to engage, to criticize, and test at least some small part of what they are being taught. But how does a teacher, knowing such essentials, manage it all? Here, I think, we are most likely to fail. Good teaching is above all a preparation for the unforeseen, for the lovely things that can happen when one has faith that they will happen. When children are optimally involved, they bring to their interpretations of fresh experience a marvelous diversity of understandings from their own past; from what they have recurrently observed and put together and from what they have assimilated from adult associations, all mixed together in ways that are individually diverse but that have a common style. The teachers' job is not to fill some empty places in their minds with new knowledge. The human mind is never empty, though parts of it are often filled without those kinds of large-scale interconnections and reductions-to-order that education should seek to further. The teachers' job is, or should be, to help children sort and rectify. The great teaching art is that of observing and listening, of searching for clues, and of then providing that which may steady and further a budding curiosity, or failing, may lead to further clues. It is as profoundly inductive, in its own way, as children's own learning should be. Teachers, in their own differently ordered minds, can often convict children of error, when in fact, the children's statements are right answers to questions different from those the teachers thought they had asked.

Just here lies the central answer to the critics who impatiently say we have no time to reinvent the wheel, and the right critique of that kind of didacticism to which their thinking tends then to regress. Spoken or written language, isolated from all immediate connection with what it seeks to convey, has little power to excite those resonances in children's minds that can call forth their full powers to retrieve the understandings they already possess and that they can potentially link together in fresh connections and analogies. I quote here a passage from Henry James, used by Frances Hawkins in a broader context, that of a classroom atmosphere in which children of diverse interests and talents can learn well. I use it for the related, but narrower, purpose of suggesting the way in which closely observed natural phenomena can excite early curiosity and understanding. "Small children have many more perceptions than they have terms to translate them; their vision is at any moment much richer, their apprehension even constantly stronger, than their prompt, their at all producible, vocabulary."[3]

To this elegant statement I would only add a converse. The early-evolved filing systems of children's minds, their resources of memory and analogy and generalization, are often far more readily summoned up by fresh input from activity and observation than by any of those thin verbal streams that well-meaning teachers so often direct at them. What is not within the range of their "at all producible vocabulary" is also not readily excited by a teacher, however produced. The linkage between the closely observed and the thoughtfully stated can only develop well in an informal dialectic, in which what is said, is said in the context of what is seen, and what is seen, is seen in the context of what is said, contexts linked in daily intercourse. If the classroom is bare of the materials and phenomena discussed, this linkage is destroyed. When they are present, the communication between children and teachers can acquire a second and third dimension, indeed an *n*th, which the linear sequence of spoken or written signs can never wholly replace. The phenomena observed in classroom laboratories or field trips become symbols of themselves, so to speak, literal parts of discourse; the talk about them is enriched and informed. Children's grasp of them can be expressed in many ways, in talk, but also in dance sometimes, or painting; the words themselves, of children or teachers, can then be relieved of a freight that alone they cannot bear.

Let me illustrate. The textbook says that heat flows from hot to cold, or that light travels in straight lines, or that the earth goes about the sun; the teacher tries to elucidate, with questions and answers, with drawings, and through other means. But failure is often imminent. In each case, the intended communication is blocked, more often than not, by a radical mismatch between the presuppositions of the book or the teacher and those of the child. What the book and the teacher obedient to it try to communicate often presupposes (but fails to induce) a radical reorganization, in each case, of some commonsense category of experience. If our early grasp of motion is itself all *geo*graphical, then the earth itself surely does not *go*. If our early understanding of light is in contrast with darkness, light may *shine* but not *travel*. Heat may melt the ice or warm the hands, but it is not a flowing kind of thing, a fluid. In all such cases, one must, I think, demand an efficient division of labor between the spontaneous investigations of children and the planning and participation of teachers. When we try to describe the kinds of teaching that contribute successfully to children's reorganization of such big ideas as the earth's motion and the nature of heat and light, we find that the sheer amounts of time involved—time for induction—are large compared to what is usually allotted to them, but also, that the growth of scientific understanding is then overall more rapid. When children can bring their own resources and spontaneous motivation to such learnings, their ability to break fresh ground can be enhanced beyond the range of any of the usual measures.

As for the kinds of phenomena to be brought together with the children and the teacher, there is a rich array, lying on the edge of everyday experience, that children can closely observe. For the beginning study of optics, we can easily provide a wide variety that bring illuminations and shadows center stage. Children (as well as many adults) have a vast background acquaintance; but they have seldom put the lamp, the object, and its shadow in that simple projective relation that has been there all along. It is a bit of geometry that has seldom been closely observed. With lamps and mirrors and pinholes for those strange inverted images, the geometrical abstraction of the light ray is within the reach and grasp of children, though it often takes a great diversity of examples, and some real time, to become compelling. A single classroom demonstration will often miss the point. Taken out of doors, there are new dimensions opened up, among them the daytime astronomy of the sun's motion and the most elegant of all sundials, the classroom terrestrial globe, flooded with sunlight, with its axis pointing to the North Star, and Our Town just on top. We cannot bring the solar system into the classroom, and mechanical models are confusing, because their introduction presupposes the very analogy they are supposed to show. But two string pendulums, hanging near each other, provide a diversity of phenomena that are among the closest terrestrial counterparts of planetary motions. With heavy weights and ceiling or doorway suspensions, their motions are only slowly lost, and they share the style of the heavenly motions, of Newton's sacred laws. Closely observed, they bring to the fore in children's minds a frame of thought very different from the common sense that Galileo and Newton had to overcome in establishing the laws of motion. But again, the phenomenal diversity needed is large, and the times to be spent with such things, in classroom or out, must be generously allotted.

I could spell out a similar story for children's abilities to investigate the phenomena of heat and cold, and for much of the rest of quite elementary science. Most of what we can thus teach—may I please still use the word?—has the same quality: it is a quality of playfulness and enjoyment in some of the rich worlds of phenomena that early schooling can provide.

Let me now speak of the very different ambience in which the biological sciences have evolved. Added to the Laboratory of Archimedes, plants and animals import one essential element, which Ronald Colton has repeatedly emphasized: respect for life. The term at first suggests only a detached moral commitment, one alien to the usual amoral stereotypes of science. But looked at closely, the obligations of maintenance are both profoundly moral and, so, instructive. The style of biology, unlike that of the physical sciences, begins with the conditions of maintenance that, over some billions of years, nature herself has supplied. To the usual biological and aesthetic sterility of the classroom, teacher and children must manage to add the necessities of plant and animal maintenance, and must do so with a degree of commitment that is absolute; otherwise they die. Seedlings will grow in the dark, but not for long. What else is needed? Small animals will flourish under conditions that we must try to investigate, and be provided, to that end, with rich environments and choices of food, not just the bland commercial pellets (which will do for a start). Even colonies of bacteria and molds require some conditions of maintenance and care. And finally, again, the field trips are a widening exposure—to the diversities of life, to the ecological web (again, a metaphor from the weaver's art), the flows of matter and energy that sustain us all, the interweaving of context and content without which none of the sciences of life—even molecular biology—would have any proper subject matter; it would have ceased to exist.

Several years ago Frances Hawkins and Ronald Colton offered a course for teachers called "Animals in the Classroom." It was a fascinating enterprise, a trial run of a large subject, one that brought together a great deal of past experience which both had had. The range of animals maintained, or at least investigated, in the course was large, from guinea pigs to hydras. The latter lived in shallow dishes, and managed a living from another species, brine shrimp. The guinea pigs were benignly vegetarian, consuming lettuce and carrots from supermarket sources but, more educatively, the grass that was grown on their premises: seeds of wheat and rye and barley grown in their own territory, a large open steamer trunk of vintage 1910, filled with potting soil and peat moss, with rocks and logs and growing plants. They could have left their Eden, but they never did. There had been other ventures of this sort, such as a large and beautiful cage, in a Head Start classroom, for small mice, odor-free when the soil under their feet had the right bacteria and the living area per mouse was large enough. Out of this collaboration, between two teachers who shared a deep understanding of the worlds of children and of other living things, there grew an analogy of proportions: only a good classroom, a good world for children, could sustain and care for a good world within it for small animals. Otherwise there would be only a surface interest, then indifference and neglect.

It is just here, I believe, that one can see the ways in which a good early education at the roots of science and math can nurture the concern for human affairs generally, for the arts and humanities. What I began to describe as the Laboratory of Archimedes has now grown, as it must, into a small human world linked in many ways to the large world of nature, but also to that of human affairs. Out of doors, in the schoolyard and beyond, is an environment rich in subject matter, man-made and natural, open to investigation. The town has a history, accessible from many starting points. Once, that I know of, the search began with a map of children's routes to school, then broadened to its valley and river, an older route to the sea.[4] It could as well begin with a map of ancestry, where each was born, then the birthplaces of parents and even grandparents. And the library corner can hold, for a time, good children's literature of history, of fiction and fantasy, as well as sober science, all sources for the enlargement of acquaintance and imagination. Craft work with yarn and clay and other materials is often relegated to spare time, but can be brought center stage through its relations to history and technology, to the stuffs and arts of everyday life, as well as to science and mathematics.

In all such children's work, guided by thoughtful and responsive teachers, there is a spirit of play. The adult conception of play is usually a stereotypic one: enjoyable activity devoted to no single or sober or serious end, and often disparaged for that reason. I think this definition of play is in fact a good one, but the disparagement is unwarranted. Children's play, closely observed and then steadied and extended by adult provisioning, represents a powerful organizer of their growing experience and, at the same time, a synoptic expression of it; it is an expression that is the precursor of all the established arts, wider in its range and never lost among those who grow creatively into the traditions that those arts represent.[5] But it is also the matrix out of which is born the capacity for the very definition of sober and serious ends, and the capacity to reconstruct them in the course of a worthy life. It is the unifying sphere in which all the major capacities of the mind are brought together in some potentially fruitful relation. In the *Critique of Judgment,* Immanuel Kant[6] defined the aesthetic domain by reference to what he called "the free play of understanding and imagination," unfettered by the strict disciplines of cognition or the commitments of conduct. The bachelor sage of Königsberg never explicitly included childhood within the range of his critical philosophy (as Rousseau tried later to do), but his analysis of the role of the arts required a conception of *play* that could have led him there.

I trust that my sketch of a classroom-laboratory-library-atelier is not taken to be giving some temporal priority to math and science, as though it would be expanded stepwise to include the other components only later in the game. There have been many good teachers whose work included nothing of math and science, at least nothing so called or so recognized. There have always been, and must remain, many pathways into the wider worlds of education suited to the special talents of teachers and of children. Good teachers differ more among themselves, and from themselves year by year, than do those who offer a meager fare. The universals of good teaching are invariants across a wide range of surface diversity. Bad teaching is more uniform and more easily described and condemned, and in recent times, we have had a spate of that sort of protest literature.

My argument for the importance of early math and science involves, then, only two logical steps. The first is the recognition that the doorways into these disciplines from the predisciplinary world of childhood are more widely accessible than others. The second is that in creating a school environment in which some of these doors are opened, teachers can evolve a penumbra and a style of inquiry that opens many other doors as well. To create such an atmosphere it is necessary—though by no means sufficient—to stock that classroom with diverse materials that exemplify or generate a wide range of natural phenomena in order to legitimate and invite children's curiosity. Printed paper, mass produced, is cheap and thin, and in its proper subordinate place, essential. It can never transmit more than a small—if necessary—part for the equations of understanding, even for adults. Yet if you conduct a census of materials in most of our classrooms (empty, on a Saturday morning), you find little else.

The classroom paper I despair of is not that of children's literature, too rarely present. Nor is it the vehicle of their written stories and journals, their early engagement with the disciplines of poetry and prose. If a classroom has two doors to a hallway, it should have a third, at least, a "lion door"—so a young friend once called it. The well-husbanded library corner, linked to the writing tablet and to a teacher-critic prepared to applaud and to question, can become a lion door. If nature closely observed can first extend children's "at all producible vocabulary," then the written language itself, closely observed and well used, can in turn extend the range of their perceptions. These extensions can reach in all the directions of experience, not least the scientific. And among the scientific extensions, not least is that of size and scale and complexity, which we represent, in shorthand, by the formal written code of the powers of ten. The dough of puff pastry is buttered, folded over, and rolled out repeatedly. Seven foldings make a flaky pastry. How many powers of two (or ten) to reach the thickness of an atom?

There is, then, an added, third step to my argument, which I venture to make in closing it. This step is one that bears on the need for fresh blood in the sciences and for a more informed citizenry, but which also extends the definition of those needs. On the one hand, the evolution of science since the sixteenth and seventeenth centuries has transformed our working relations with nature and has brought us, as a single biological species, to dominate—but also to destablize—the whole of our planetary world. We can learn to love it as a potential Second Garden or, by the turn of the screw, destroy it, and with it, ourselves. The love cannot come as a belated afterthought; it must begin in our early years with the onset of knowledge and wonder, of nature closely observed, observed first in detail and later conceived in powerful generality. Such love has always been a motivating force in scientific investigation, but it can get short-circuited in the pursuit of clever technologies, or is tolerated, in the halls of industry, as a useful eccentricity.

Yet the whole development of science, however motivated, has transformed for us any acceptable understanding of man's place in nature, and thus the framework within which we can adequately form or conceive our own ends and means. In these three or four centuries, our knowledge of the natural world has been extended upward and downward, in the scale of sizes, from the atoms to the cosmos. Begun in speculation, it was vivified by the microscope and telescope, radical extensions of our senses. The first major poet of this extension, awed and frightened by its implications, was Blaise Pascal, contemporary of Newton and of Leeuwenhoek. Pascal was a mathematician and physicist, abreast of, and contributing to, all those early developments of science. He was also one of profound ethical and religious commitment, who saw that nature, in its vastness, could no longer be regarded as only a set of theatre props for the medieval Christian domestic struggle of good and evil. Another contemporary, Baruch Spinoza, was equally involved in, and affected by, the new world of science. Christian and Jew, both faced with the vision of infinite nature, concluded that man's whole dignity lies in the power of thought: the thinking reed can achieve some comprehension of the power of nature and of man's place. Pascal dramatized the uniqueness of man, while Spinoza sought to understand it as a mode of nature's own self-comprehension. But both acknowledged the new vision of science as a turning point for ethics and for religion.

Today we can add a new dimension to that vision that fills it out and makes its import still more compelling. To the vast scale of size we can add the scale of historical time, a scale unknown and hardly guessed in the seventeenth century. In size we are almost half-way between the greatest thing we know and the smallest, as Pascal announced. More precisely, we are twenty-five powers of ten above the smallest things we know, and sixteen powers of ten below the largest.[7] In time, the scale is almost as great, from the briefest possible subatomic events to the duration of the cosmos in its now-estimated history. The duration of our own human least awareness is some twenty powers of ten above the subatomic minimum, while that of a human generation goes up by about nine further powers of ten. The duration of our species is about a hundred thousand of these generations, five powers of ten. For the duration of terrestrial life as a whole, we must multiply again by a thousand, the third power. On this scale, the earth itself, and then the whole cosmos, is less than ten times older, a single power of ten. If our dignity lies in the power of thought, as Pascal said, it is matched by a dignity of age; we and all our cousins in the terrestrial living world, though middling on the scale of sizes, are almost as ancient as the cosmos itself.

To have a sense for all these numbers, and the rich scientific story from which they are distilled, will surely suffice us not at all in baking bread or in coping with the destruction of our farmlands or the pollution of city slums. It will not of itself avert the peril of nuclear war, that terrifying stepchild of scientific advance. Nevertheless, we need that story as a framework for understanding, a framework that allows us first to acknowledge the issues that face us today, and then to work to understand and meet them. What we desperately need are the powers to cultivate the imagination far beyond the limits of everyday parochial life, and these surely include a sense for the many powers of ten. Our parish, our pueblo, our shamba—the neighborhood of each of us—has grown by many such powers, in space and in history, whether we know it or not. We need six powers of ten to understand the difference between a chemical explosive and a nuclear bomb; that is something even our great leaders, and the constituencies that elect them, have not yet adequately grasped. We need several powers of ten to frame the difference, in our imaginations, between our own years—six or ten or sixty—and those of the rocks we scramble over on a field trip or holiday. Again, it is six powers of ten to go from the perimeter of our school grounds to the distance to the moon, and a few more to span the distance to the sun. And so it goes, for the distance to the nearest star, then to Andromeda, and finally to the edges of the early universe. So it goes also to the distant past, in which we can see that all living things under the sun are cousins and all men are brothers.

As a final step, I wish to acknowledge a second sort of argument against much that I have said and against the optimism implicit in it. It is an argument that will rise most cogently in the minds of those wise in the ways of our present-day schools, and I must acknowledge it fully. I began with an emphasis on the continuity of culture, whether marvelous or dreadful or only drearily predictable, a continuity that is unavoidable in all our educative associations—and the schools are no exception. This argument is very simple: the educative potential of our schools is not high enough, and will not foreseeably rise high enough, to warrant any implicit optimism. To have such good education, except here and there and almost by chance, implies the existence of teachers who are themselves the products *of* that very education; while in fact the teachers we mainly produce are poorly educated. They are poorly educated with respect to subject matter, first of all. They are poorly educated with respect to the patterns of human development and the arts that foster it. And they are enchained within a school bureaucracy that has not learned to treat them as professionals in need of professional support and capable of a fully professional independence and accountability. They are treated rather as civil servants of a low grade, and the treatment is all too often self-confirming. In short, there is no way visible in which the antecedents of what we need can be matched to the consequents of what we have. So goes the argument of the critics.

Two decades ago, indeed, many of those who sought to improve our education in science and math were given to a false optimism, based on the belief that the curriculum reforms then fashionable would be so potent that their effects would somehow bypass the inadequate education of teachers. This was an unjustifiable arrogance, and time has shown it to be so. The good consequences of those efforts lay mainly in those cases where teachers themselves became deeply involved in the reforms and showed us how to reduce them to practice. Help from the outside is of no avail unless, and in the measure that, it contributes to the growth and stature of the teachers, and they in turn contribute. That should be held to, I believe, as a firm axiom. We should judge all new proposals by it, whether for texts or guides or computer modules.

The continuity, then, is unavoidable, as is a certain pessimism concerning the probability of significant reforms. The optimism that many of us feel, the sense of romance about the potentialities of early education, is an optimism of the possible, not one of somehow calculable probabilities. But, I respond, possibility can be robust. Those of us who have been fortunate enough to sniff out and find the good classrooms, variations on the sorts of themes I have been suggesting, have indeed found them, though rarely enough—have found them, reduced to practice and thriving, guided by quite bona fide mortals, overworked but happy in their craft. And here, too, there is continuity. Almost always in the background or foreground of these teachers there is some strong educative influence, some professional support that they have assimilated and modified, perhaps extended. No one person invented the wheel or the telescope or the internal combustion engine. They have been evolved, step by step, without any violation of continuity. And so can good education, though it is far more complex. The Law of Continuity is no warrant for fatalism.

In the biological world, there is a kind of theorem about the emergence of new types and new species: they do not arise by sudden or massive modification of older and dominant species, but appear, rather, because some genetic variety, initially rare, manages to grow at a rate faster than others around it when a new ecological niche appears that favors it. That is why evolution is not predictable; it works through the amplification of initially rare varieties that early go unnoticed. Good ideas have that kind of history, too, and so we often see it only in retrospect. I should hope that we begin to think of the improvement of education in just these terms. If good patterns of work with young children can be recognized early, while they are—

as indeed they are—still rare and all too easily lost, we can hope to create for them some systems of protection, of support, and of growth. Since they are rare, the initial investment is moderate, and it can grow with the success it increasingly demonstrates. In our own search for the good sorts of early educational patterns, we have found them very unevenly distributed. Where they have been thickest on the ground, we have found such systems of professional support and encouragement, working high above the average level of what is called in-service education or staff development, usually a perfunctory service with marginal budgets that can be most easily lopped off in hard times. To say this is not an expression of pessimism, but of outrage.

The continuing education and professional growth of our teachers is of course not the only way of modifying the loop of continuity from teacher inadequately educated to children poorly taught. There are others, especially those affecting the pre-service education of teachers. Here it is customary to blame the schools of education, themselves inadequately provided for serious professional training. They are, to be sure, responsible for some part of the failure. But a large part of the blame should be laid at the feet of our undergraduate arts and sciences colleges, which fail conspicuously to provide rich fare for future teachers of the young. Such students especially need what all college students could profit from, a wide and liberal exposure to the riches of genuinely elementary subject matter. This kind of provisioning is typically sacrificed to a pattern that leads as quickly as possible to advanced subject matter of sorts that have little relevance to the teaching of the young. With honorable exceptions here and there, mathematics and science are especially subject to this criticism. Future teachers are typically required to complete one or two courses, of which the content is regarded as so elementary as to be beneath the dignity of college lecturers; still formal in style, they are thin in content. Often those who teach such courses are themselves unfamiliar with the elementary riches of their own subject matter, and a typical course in the number system, or in remedial algebra, has little relevance to the needs or to the intellectual capacities—often substantial—of students bound for careers as teachers of the young. Knowing nothing of its enticements they have often been turned off by such subject matter, and we do very little indeed to meet the challenge. Again the treatment we provide is self-confirming: if they were any good, it is said, they would go into some more prestigious vocation.

The same pattern is visible in the sciences, with the same honorable but all-too-rare exceptions: Physics is taught mainly for future physicists, chemistry for those who might, with one chance in forty, become chemists, biology for future biologists, and so on. The upward draft, what physicists should recognize as an academic chimney effect, is very powerful, and not easily counteracted by the efforts of those few who have insisted on a wider view of their own professional commitments.

In all early education, then, the part played by the teacher is central and critical. It can be ameliorated by the enrichment of several kinds of support now on the whole very poorly provided, but only in the measure of its contribution to teachers' own continuing professional education, their growth of skill and insight, their morale. I believe we should accept this proposition as central and critical to the theory of early education. It can be derived from wide ranges of evidence; in the formulation of theory, it should be treated as an incontrovertible starting point. I have called it an axiom. In the history of mathematics, the word *axiom* came to mean an unquestionable truth, from which others could be derived. Later it was bled of that meaning and stood only for some arbitrary logical starting point, a hypothesis whose contradictory could also be a starting point for some alternative logical theory. The original meaning of the word is, I think, more useful than either of these. In that meaning, an axiom is a proposition most highly valued (ἀξίωμα, a thing valued), and thus the last to be questioned in any further investigation.

When the central importance of the teacher is accepted as axiomatic, it provides a strong criterion in judging any proposed educational reforms. Thus curriculum development that robs teachers of opportunities for developing their own curricula, imaginatively matched to their children and their circumstances, should be weighed as negligible or negative. The sort of curriculum development that contributes to teachers' own critical and inventive powers should be supported; that which purports to replace their powers of invention with a dismal array of daily guides geared to dull texts and readers, and those endless workbooks that destroy all zeal for reading or expression—those should be destroyed. No ban against book burning should protect them.

In the hands of children and under their inventive guidance, the classroom computer can add more than one dimension to a teacher's repertoire—as a glorified scratch pad for extending children's powers, as an *n*-dimensional kind of book, and as a sheer (though for some, powerfully addictive) delight in fun and games, sometimes educationally worthy. In its cheapest and now best-advertised programs, it robs the teacher of vital initiatives, and if our axiom is seriously meant, should be condemned. This does not exclude all routine uses, such as foreign language practice, review of some imaginative arithmetic and geometry of the Pythagorean genre, or as a challenge to skill in estimation of numbers very large and very small. But because the computer is literally infinite in its potentialities, it can create the illusion that it is the real world, safely confined by the keyboard or even, in expensive versions, the light pencil. Einstein said that God is subtle but not malicious. We should add that commercial programmers are seldom malicious but never, in principle, divinely subtle. They are never even as subtle as teachers who know their particular children and guide them well. I quoted earlier the theorem that well-cared-for animals are possible only in a well-cared-for classroom. In the same spirit it should be added that a computer in the classroom can be well used only if there are other enticements there that will fully compete with its attractions. Much of its perceived addictiveness is only an escape from boredom. We should be thankful that there are such escapes, but there should be many more. The stuff for which computers can be well used, seldom discussed, is an abstract from the close observation of natural and human affairs; otherwise, they give us only another turn of the screw.

But there are other and more powerful conclusions from our axiom, and the chief of these is that teachers should by all means endlessly educate themselves in the substance of their craft and be well-trained in its practice. The substance is to be found in the wide range of elementary subject matter accessible to children, from which teachers can, over the years, evolve increasing and impressive repertoires. The practice contributes as it is reflected upon and collegially examined, alone and with others, in the context of professional curiosity about human learning and development. And all of this—I repeat—implies levels of professional support, pre-service and in-service, that we are as yet very far from providing.

The cadres who can support such growth are, then, the key. They may not now be numerous, but they are more numerous than our present readiness to enlist and honor them will admit. It is an encouraging fact that in recent years their ranks have been filled by increasing numbers who have come from such disciplines as mathematics or physics, willing to learn about children and about teaching them, and who believe that their own professions should be expanded to include such commitments. There are also many successful teachers who can be persuaded to spend some time, at least, in others' classrooms. Coming from varied backgrounds and able to learn from each other, such cadres can over time become a powerful agency of improvement in early schooling. Working through the colleges of education, they can guide beginners to good classrooms for serious apprenticeship. Working in the schools themselves, they can give personal support to teachers who seek it. Through workshops and seminars, they can bring to the schools something of the atmosphere of a learned society, the nourishment and morale of professional work and talk.

The secret of this whole process is a working association that is essentially personal, mainly one to one or to a few. As in the classroom for children, books and pamphlets and research reports can help, but only as supplements. Teaching as an art can be reduced to practice primarily with the help of others already skilled in it. Unfortunately, our schools of education have retreated more and more to a world remote from classrooms of the young, and those who spend much time there in violation of this tendency are typically less honored than those who publish many little papers. Even fewer and less honored departmentally are those who regularly visit from departments of math or physics, history or literature, though it might teach them more about college students. We have evolved an academic pecking order in which such ventures are vaguely demeaning. We might all learn more if we reversed it or at least gave serious support to interesting deviations from it. Even our public school systems are guilty, in the main, of a similar retreat. Principals used to be selected as principal teachers, the most skilled and successful, able to help those who worked under them. If the selection was not always wise, the criterion was. Supervisors and consultants and specialists have always been available in principle, though in times of tightened budgets, their ranks have mostly been depleted—unless their work has shifted to a more bureaucratic role invisible to the teachers they should be available to. Yet all of the professional support I have been speaking of is little more than a percent or so of the budgets from which they are now so frequently excised. Such budgets, of course, are not decisive, only necessary. What counts is the quality of professional support we offer to our now-neglected teachers, and that is where all of our discussion, of early math and science, and of all else in the curriculum, should come to a final and practical focus.

To start with the best we already know, toward a new species of early education, is to start small, putting the most effort where we find the greatest readiness for growth. This is unfortunately not a precept that fits our current fashionable notions of cost-effectiveness. To trim quantity to quality is often regarded as elitist, but it is not—not if it aims at growth. Some of our colleagues in these efforts, here and abroad, have deliberately sought out promising beginnings where the going is hardest, in the schools of city slums or regions of rural poverty. The work is harder there, but success is more conspicuous. That is surely not elitist. On the other hand, cost-effectiveness will usually be measured by some average changes (in test scores and the like), and in the early stages these will be buried in the numbers, the tyranny of the arithmetic mean. From this point of view, a long-term commitment of the sort we all might otherwise support is hard to justify. From small beginnings, the growth, in early stages, will always be buried in the sea of statistical noise. What can accrue over some years of growth is another matter, and that seems to require an act of faith, as indeed it does. Growth can follow the exponential curve for a good time at least, and before long will overtake all that begin large and, of necessity, are mediocre. And if faith cannot be justified by short-term statistics, it is all the more important that it be supported by knowledge. I have urged that we possess this support, that it lies in the axiom of the centrality of our teachers' own professional and human needs, now poorly met.

ENDNOTES

[1]See Edwin Herbert Lewis, "What a Linguistic Contextualist Thinks of Philosophy," *Outlook* no. 20, Summer 1976 (Boulder, Colorado).

[2]David Hawkins, "What it Means to Teach," *Teachers' College Record*. Teachers' College, Columbia University, New York, Spring 1973.

[3]*What Maisie Knew* (New York: Penguin Books, 1974), p. 7. Frances Hawkins's discussion is in "The Eye of the Beholder," in *Special Education and Development: Perspectives on Young Children with Special Needs,* edited by S. Meisels (Baltimore: University Park Press, 1980).

[4]A classic account of such work in physical and human geography is Lucy Sprague Mitchell, *Young Geographers* (New York: John Day, 1934).

[5]See Michael Armstrong, *Closely Observed Children* (Richmond, Surrey, England: Chamelion Press, 1980). See also a fine new translation of *Tolstoy on Education,* selected and edited by Alan Pinch and Michael Armstrong (East Brunswick, New Jersey: Associated University Presses, 1982).

[6]Immanuel Kant, *Critique of Judgment* (New York: 1952). See also John Dewey's *Art as Experience* (New York: 1934). Dewey is more Kantian here than he was willing to acknowledge.

[7] These powers of ten are from *Powers of Ten*, by Philip and Phylis Morrison and The Office of Charles and Ray Eames (New York: Scientific American Library, 1982). The book is based on a film of Charles Eames of the same title, which in turn was inspired by an earlier small book, *for children*, by a Dutch schoolteacher, Kees Boeke, *Cosmic View: The Universe in Forty Jumps*.