

The Children's Machine



RETHINKING SCHOOL IN THE
AGE OF THE COMPUTER



Seymour Papert



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Instructionism versus Constructionism

I have tried to stay for as long as I could with a style one could loosely describe as concrete. The time has come to switch, although only for the space of one chapter, to a slightly more academic and abstract style so as to allow comparisons and interchange with other points of view. In doing so I shall also work at sharpening and formalizing (which does not necessarily mean improving) mathetic ideas that I have introduced up to now mainly by way of stories.

My preference for a concrete way of writing is not simply a literary tactic for saying what I could have expressed in more abstract language. Rather, it is a case of making the medium the message. A central theme of my message is that a prevailing tendency to overvalue abstract reasoning is a major obstacle to progress in education. One of several possible formulations of my view of how learning might become very different is that this will come about through an epistemological reversion to more concrete ways of knowing—a reversal of the traditional idea that intellectual progress consists of moving from the concrete to the abstract. Moreover, I see the need for the reversal not only in the content of what is learned but also in the discourse of the educators. Using

a concrete mode of expression myself allows me to show as well as say what I mean by this, and contributes to a richer sense of what makes concrete thinking powerful. However, it is not surprising that the concept most in need of a more abstract formulation is "concreteness" itself.

In the discourse of education, the word *concrete* is often used in its everyday sense. When teachers talk about using concrete materials to support learning the idea of numbers, one easily understands that this embraces such methods as using wooden blocks to form number patterns. But the word has also acquired more specialized meanings, of which the most prominent is closely associated with Jean Piaget's famous (or, in some circles, infamous) theory of stages. Unfortunately the two kinds of use are often confounded: It is easy to fall into the trap of reading Piaget as if the word had its ordinary meaning, and the fallacy is supported by the many books written in a patronizing tone on the lines of "Piaget made easy" for teachers. In fact, Piaget is doing something more complex and much more interesting when he describes the thinking of children of elementary school age as "concrete." This is as much a technical term as the physicists' use of the word *force* or psychiatrists' use of the word *depression*—in all these cases meanings will be misunderstood unless one realizes that the words get a special twist from theories that often go against the grain of common sense. Piaget's concept of "concrete intelligence" gets its meaning from a theoretical perspective that emerged slowly, and not always consistently, in the course of an enormously productive lifelong enterprise of research. We shall have to disentangle this very insightful concept from certain more problematic aspects of Piaget's theoretical constructions, in particular his notion of "stage." The opposition of educational philosophies that forms the title of the chapter provides a good context for pinning down what "concrete intelligence" means in Piaget's theoretical framework.

The suffix *-ism* is a marker of the abstract and its presence in the title reflects my shift in intellectual style. The word *instructionism*

is intended to mean something rather different from *pedagogy*, or the art of teaching. It is to be read on a more ideological or programmatic level as expressing the belief that the route to better learning must be the improvement of instruction—if School is less than perfect, why then, you know what to do: Teach better. Constructionism is one of a family of educational philosophies that denies this “obvious truth.” It does not call in question the value of instruction as such. That would be silly: Even the statement (endorsed if not originated by Piaget) that every act of teaching deprives the child of an opportunity for discovery is not a categorical imperative against teaching, but a paradoxically expressed reminder to keep it in check. The constructionist attitude to teaching is not at all dismissive because it is minimalist—the goal is to teach in such a way as to produce the most learning for the least teaching. Of course, this cannot be achieved simply by reducing the quantity of teaching while leaving everything else unchanged. The principal other necessary change parallels an African proverb: If a man is hungry you can give him a fish, but it is better to give him a line and teach him to catch fish himself.

Traditional education codifies what it thinks citizens need to know and sets out to feed children this “fish.” Constructionism is built on the assumption that children will do best by finding (“fishing”) for themselves the specific knowledge they need; organized or informal education can help most by making sure they are supported morally, psychologically, materially, and intellectually in their efforts. The kind of knowledge children most need is the knowledge that will help them get more knowledge. This is why we need to develop mathematics. Of course, in addition to knowledge about fishing, it is as well to have good fishing lines, which is why we need computers, and to know the location of rich waters, which is why we need to develop a large range of mathematically rich activities or “microworlds.”

Take mathematics once more, to see the general issue in its most extreme form. It is obvious that as a society we in the United States (and most places in the world) are mathematical under-

achievers. It is also obvious that instruction in mathematics is on the average rather poor. But it does not follow that the only route to better performance is the improvement of instruction. Another route goes via offering children truly interesting microworlds in which they can *use* mathematics as Brian did, or *think about* it as Debbie did, or *play* with it as Dawn did. If children really want to learn something, and have the opportunity to learn it in use, they do so even if the teaching is poor. For example, many learn difficult video games with no professional teaching at all! Others use Nintendo's system of telephone hot lines or read magazines on strategies for games to find the kind of advice for video games that they would get from a teacher if this were a school subject. Moreover, since one reason for poor instruction is that nobody likes to teach reluctant children, the constructionist route will make teaching better as well as less necessary, thus achieving the best of both worlds.

Debbie provides a good example of a little of the right instruction going a long way. Instruction in programming the computer and thinking about how to develop a complex project was like teaching her to catch fish. With these skills she could build her software and transform her thinking about fractions. She learned something very different from what she was taught. This is very different from something that used to be called *process learning*. In the 1960s, at the same time as the New Math movement reached its peak, it was fashionable to say that it was more important to teach "the process of scientific thinking" than any particular scientific content. The significant difference is that scientific process divorced from content is very abstract. The programming skills Debbie learned were even more down-to-earth and concrete in every possible sense than the knowledge about fractions she acquired by using them.

Debbie's success in the test on knowledge of fractions goes against the instructionist idea that the unique way to improve a student's knowledge about topic *X* is to teach about *X*. Anyone who has doubts about the prevalence of this idea would do well

to read Ivan Illich's *Deschooling Society*, again in the spirit of seeing an idea starkly through its extreme form. Illich eloquently states his case that the principal lesson School teaches is the need to be taught. School's teaching creates a dependence on School and a superstitious addiction to belief in its methods. But while School's self-serving lesson has pervaded world culture, what is most remarkable is that we all have personal experience and personal knowledge that go against it. On some level we know that if we become really involved with an area of knowledge, we learn it—with or without School, and in any case without the paraphernalia of curriculum and tests and segregation by age groups that School takes as axiomatic. We also know that if we do not become involved with the area of knowledge, we'll have trouble learning it with or without School's methods. In the context of a School-dominated society, the most important principle of mathematics may be the incitement to revolt against accepted wisdom that comes from knowing you can learn without being taught and often learn best when taught least.

Kitchen math points up the same moral; it shows that a large number of people have learned to do something mathematical without instruction—and even despite having been taught to do something else. Indeed, it may even suggest that there is no real crisis in education after all, since people with a will do find a way to learn what they need!

Of course, this complacent suggestion is not serious. Pointing to the use of mathematical methods that were somehow developed without being taught cannot justify educational complacency: Kitchen math and the like are wonderful demonstrations of people's mathetic capacity, but they are extremely limited. The conclusion to be drawn is not that people manage anyway and so do not need help, but rather that this informal learning points to a rich form of natural learning that goes against the grain of School's methods and needs a different kind of support. The question for educators is whether we can work with this natural learning process rather than against it—and to do this we need to

know more about what the process is. What kind of learning lies behind kitchen math knowledge, and how can we foster and extend it?

These questions move us to the second pole of "instructionism versus constructionism." The poor reflection on School is a minor aspect of what one can see in kitchen math. The major aspect is not the failure of School but the success of the people who had developed their own methods for solving such problems—not what School failed to convey to them but what they constructed for themselves.

The metaphors of conveying and constructing are the pervasive themes of a larger and more variegated educational movement within which I situate constructionism and underscore this by the wordplay in its name. For many educators and all cognitive psychologists, my word will evoke the term *constructivism*, whose contemporary educational use is most commonly referred back to Piaget's doctrine that knowledge simply cannot be "transmitted" or "conveyed ready made" to another person. Even when you seem to be successfully transmitting information by telling it, if you could see the brain processes at work you would observe that your interlocutor is "reconstructing" a personal version of the information you think you are "conveying." *Constructionism* also has the connotation of "construction set," starting with sets in the literal sense, such as Lego, and extending to include programming languages considered as "sets" from which programs can be made, and kitchens as "sets" with which not only cakes but recipes and forms of mathematics-in-use are constructed. One of my central mathetic tenets is that the construction that takes place "in the head" often happens especially felicitously when it is supported by construction of a more public sort "in the world"—a sand castle or a cake, a Lego house or a corporation, a computer program, a poem, or a theory of the universe. Part of what I mean by "in the world" is that the product can be shown, discussed, examined, probed, and admired. It is out there.

Thus, constructionism, my personal reconstruction of construc-

tivism, has as its main feature the fact that it looks more closely than other educational *-isms* at the idea of mental construction. It attaches special importance to the role of constructions in the world as a support for those in the head, thereby becoming less of a purely mentalist doctrine. It also takes the idea of constructing in the head more seriously by recognizing more than one kind of construction (some of them as far removed from simple building as cultivating a garden), and by asking questions about the methods and the materials used. How can one become an expert at constructing knowledge? What skills are required? And are these skills the same for different kinds of knowledge?

The name *mathetics* gives such questions the recognition needed to be taken seriously. To begin answering them I shall discuss and adapt somewhat to present purposes the ideas of two thinkers, Jean Piaget and Claude Lévi-Strauss, who went as far as anyone in identifying large pockets of knowledge that are not learned in School's way and do not conform to School's idea of what proper knowing is. My purpose in discussing both of these authors here is to derive from them a technical sense of the notion of concreteness that will allow me to say that the important mathetic skill is that of constructing concrete knowledge. Later on I use this insight for another formulation of what is wrong with School—that its perverse commitment to moving as quickly as possible from the concrete to the abstract results in spending minimal time where the most important work is to be done.

In his 1966 book *The Savage Mind* (whose French title, *La pensée sauvage*, should be read with an awareness that in French wildflowers are called *fleurs sauvages*), Lévi-Strauss adopts the untranslatable French word *bricolage* to refer to how “primitive” societies conduct “a science of the concrete.” He sees this as different from the “analytic science” of his own colleagues in a way that parallels the difference between kitchen math and school math. School math, like the ideology, though not necessarily the practice, of modern science, is based on the ideal of generality—the single, universally correct method that will work for all

problems and for all people. *Bricolage* is a metaphor for the ways of the old-fashioned traveling tinker, the jack-of-all-trades who knocks on the door offering to fix whatever is broken. Faced with a job, the tinker rummages in his bag of assorted tools to find one that will fit the problem at hand and, if one tool does not work for the job, simply tries another without ever being upset in the slightest by the lack of generality.

The basic tenets of *bricolage* as a methodology for intellectual activity are: Use what you've got, improvise, make do. And for the true *bricoleur* the tools in the bag will have been selected over a long time by a process determined by more than pragmatic utility. These mental tools will be as well worn and comfortable as the physical tools of the traveling tinker; they will give a sense of the familiar, of being at ease with oneself; they will be what Illich calls "convivial" and I called "syntonic" in *Mindstorms*. Here I use the concept of *bricolage* to serve as a source of ideas and models for improving the skill of making—and fixing and improving—mental constructions. I maintain that it is possible to work systematically toward becoming a better *bricoleur*, and offer this as an example of developing mathetic skill. One sees the spirit of the true *bricoleur* most directly in the story of Ricky's ingenuity (and delight) in using Lego parts for purposes that were never imagined by their makers: a wheel as a shoe, a motor as a vibrator. One also sees in this use of Lego-Logo a microworld strongly conducive to the skills of *bricolage*. And I see it in my experience with plants.

Kitchen math provides a clear demonstration of *bricolage* in its seamless connection with a surrounding ongoing activity that provides the tinker's bag of tricks and tools. The opposite of *bricolage* would be to leave the "cooking microworld" for a "math world," to work the fractions problem using a calculator or, more likely in this case, mental arithmetic. But the practitioner of kitchen math, as a good *bricoleur*, does not stop cooking and turn to math; on the contrary, the mathematical manipulations of ingredients would be indistinguishable to an outside observer from the culinary manipulations. Thus kitchen math ex-

hibits the quality of connectedness, of continuity, that I have presented several times as so powerfully conducive to learning. This embeddedness sharply illuminates the relationship between the mathetic question of instructionism versus constructionism and the epistemological question of analytic science versus *bricolage*. Analytic principles such as multiplying $1\frac{1}{2}$ by $\frac{2}{3}$ are routinely taught through direct instruction in math. But the close association of kitchen math with the kitchen suggests that it is not natural, even if it is possible, to "teach" mathematical (or any other kind of) *bricolage* as a separate subject. The natural context for learning would be through participation in other activities than the math itself.

A comparison between Debbie and kitchen math brings out the special role of the computer in doing this. I have no doubt at all that increased skill and confidence would come to many people if they engaged in more respectful and thoughtful talk about their learning processes in cooking, gardening, home maintenance, games, and participation in sports whether as player or spectator. None of this absolutely requires computers. What we see in experiences like those of Debbie or Maria or Brian is how the computer simply, but very significantly, enlarges the range of opportunities to engage as a *bricoleur* or *bricoleuse* in activities with scientific and mathematical content.

The phases of Debbie's experience show an expanding extension of engagement and competence through a *bricoleurish* type of appropriation. In the first phase we see her engaged in a familiar activity minimally transformed by being done on the computer. She writes poems using the computer as little more than a word processor. Then she decorates her poems much as she might decorate a paper page. It is only when she is thoroughly comfortable with doing this that she begins to do anything interesting with fractions. Then we see her engaged in activities that are concerned with fractions; but in the same way as kitchen math is not separate from cooking, these activities are not distinguishable in form from the poetry work. And it is precisely this continuation

of the familiar into the new that brings her breakthrough to connecting fractions with "everything."

This praise for the concrete is not to be confused with a strategy of using it as a stepping-stone to the abstract. That would leave the abstract ensconced as the ultimate form of knowing. I want to say something more controversial and more subtle in helping to demote abstract thinking from being seen as "the real stuff" of the working of the mind. More often, if not always in the last analysis, concrete thinking is more deserving of this description, and abstract principles serve in the role of tools that serve, like many others, to enhance concrete thinking. For the confirmed *bricoleur*, formal methods are on tap, not on top. In the kitchen, formal multiplication of $1\frac{1}{2}$ by $\frac{2}{3}$ is a perfectly acceptable method, no worse, but no better, than improvisations with spatulas and measuring cups.

Statements like this have brought down on my head accusations of "logic bashing." But the issue is really one of balance. I am a mathematician and know firsthand the marvels of abstract reasoning. I know its pleasures as well as its power. I also know how stultifying it can be if it is used indiscriminately. Our intellectual culture has traditionally been so dominated by the identification of good thinking with abstract thinking that the achievement of balance requires constantly being on the lookout for ways to reevaluate the concrete, one might say, as an epistemological analog of affirmative action. It also requires being on the lookout for insidious forms of abstractness that may not be recognized as such by those who use them. For example, styles of programming that are often imposed as if they were simply "the right way" express a strong value judgment between the abstract and the concrete ways of doing things.

In her book *The Second Self*, Sherry Turkle describes styles of programming used by children who were given sufficient access to computers and a sufficient sense of freedom in developing a personal style:

Jeff is the author of one of the first space-shuttle programs. He does it, as he does most other things, by making a plan. There will be a rocket, boosters, a trip through the stars, a landing. He conceives the program globally; then he breaks it up into manageable pieces. "I wrote out the parts on a big piece of cardboard. I saw the whole thing in my mind just in one night, and I couldn't wait to come to school to make it work." Computer scientists will recognize this global "top-down," "divide-and-conquer" strategy as "good programming style." And we all recognize in Jeff someone who conforms to our stereotype of a "computer person" or an engineer—someone who would be good with machines, good at science, someone organized, who approaches the world of things with confidence and sure intent, with the determination to make it work.

Kevin is a very different sort of child. Where Jeff is precise in all of his actions, Kevin is dreamy and impressionistic. Where Jeff tends to try to impose his ideas on other children, Kevin's warmth, easygoing nature, and interest in others make him popular. Meetings with Kevin were often interrupted by his being called out to rehearse for a school play. The play was *Cinderella*, and he had been given the role of Prince Charming. . . .

Kevin too is making a space scene. But the way he goes about it is not at all like Jeff's approach. Jeff doesn't care too much about the detail of the form of his rocket ship; what is important is getting a complex system to work together as a whole. But Kevin cares more about the aesthetics of the graphics. He spends a lot of time on the shape of his rocket. He abandons his original idea but continues to "doodle" with the scratchpad shape-maker. He works without plan, experimenting, throwing different shapes onto the screen. He frequently stands back to inspect his work, looking at it from different angles, finally settling on a red shape against a black night—a streamlined, futuristic design. He is excited and calls over two friends. One admires the red on the black. The other says that the red shape "looks like fire." Jeff happens to pass Kevin's machine on the way to lunch and automatically checks out its screen, since he is always looking for new tricks to add to his tool kit for building

programs. He shrugs. "That's been done." Nothing new there, nothing technically different, just a red blob. . . .

By the next day Kevin has a rocket with red fire at the bottom. "Now I guess I should make it move . . . moving and wings . . . it should have moving and wings." The wings turn out to be easy, just some more experimenting with the scratchpad. But he is less certain about how to get the moving right. Kevin knows how to write programs, but his programs emerge, he is not concerned with imposing his will on the machine. He is concerned primarily with creating exciting visual effects and allows himself to be led by the effects he produces.

The supervaluation of the abstract blocks progress in education in mutually reinforcing ways in practice and in theory. In the practice of education the emphasis on abstract-formal knowledge is a direct impediment to learning—and since some children, for reasons related to personality, culture, gender, and politics, are harmed more than others, it is also a source of serious discrimination if not downright oppression. Kevin is lucky to be in an environment where he is allowed to work in his own style. In many schools he would be under pressure to do things "properly," and even if his way of working were tolerated, there might be a snide sense that this is because he is "artistic," said with a tone that implies he is not a serious academic student. For example, in interviews reported in a paper written jointly with me, Turkle was told by a female student that the pressure to follow Jeff's kind of "hard" style was so great and so contrary to her sense of herself that she "decided to become someone else" in order to survive a compulsory course. Others in a similar situation simply dropped out.

Furthermore, the supervaluation of abstract thinking vitiates discussion of educational issues. The reason is that educators who advocate imposing abstract ways of thinking on students almost always practice what they preach—as I tried to do in adopting a concrete style of writing—but with very different effects.

A simple example is seen in the formulation of research questions. In front of me is a stack of learned papers, filled with numbers, tables, and statistical formulas, with titles such as "An Assessment of the Effect of the Computer on Learning." Their authors would be indignant at the suggestion that their work is "abstract." They would surely say that the shoe is on the other foot: They have produced "concrete numerical data," in marked contrast with my "abstract anecdotal philosophizing." But however concrete their data, any statistical question about "the effect" of "the computer" is irretrievably abstract. This is because all such questions depend on the use of what is often called "scientific method," in the form of experiments designed to study the effect of one factor which is varied while taking great pains to keep everything else the same. The method may be perfectly appropriate for determining the effect of a drug on a disease: When researchers try to compare patients who have had the drug with those who have not, they go to great pains to be sure that nothing else is different. But nothing could be more absurd than an experiment in which computers are placed in a classroom where nothing else is changed. The entire point of all the examples I have given is that the computers serve best when they allow *everything* to change.

The point of abstract thinking is to isolate—to abstract—a pure essential factor from the details of a concrete reality. In some sciences this has been done with marvelous results. For example, Sir Isaac Newton was able to understand the motions of the earth and the moon around the sun by representing each of these complex bodies by a concretely absurd "abstraction"—by treating each body as a particle with its entire mass concentrated at one point he could apply his equations of motion. Although it has been the dream of many psychologists to possess a similar science of learning, so far nothing of the sort has been produced. I believe that this is because the idea of a "science" in this sense simply does not apply here, but even if I am wrong, while we are waiting for the Newton of education to be born, different modes of under-

standing are needed. Specifically, in my view we need a methodology that will allow us to stay close to concrete situations.

Not long ago this suggestion would have been seen as inconsistent with the very idea of the scientific method. However, in the past few decades anthropologists have been more diligent than Lévi-Strauss was in examining the actual behavior of scientists in their laboratories with the same rigor as he applied to examining the ways of distant villages. Bruno Latour, one of the leading figures in this movement, finds that the theoretical line between the science of the concrete and analytic science is blurry and frequently transgressed by ways of thinking and acting that are closer to what Lévi-Strauss describes as *pensée sauvage* than to "analytic science." The concept of the highly rigorous and formal scientific method that most of us have been taught in school is really an ideology proclaimed in books, taught in schools, and argued by philosophers, but widely ignored in the actual practice of science. For Latour, Lévi-Strauss's "'grand dichotomy' with its self-righteous certainty should be replaced by many uncertain and unexpected divides."

Such observations have come from many other sources—including feminist scholars, who have argued that traditional science is strongly androcentric, and Sherry Turkle and myself, who have observed that some of the best professional programmers work in a style more like Kevin than like Jeff. These data must be taken seriously by educators, and they have multiple implications for thinking about School.

The simplest and most immediate observation, from an instructionist point of view, is the need to offer children a more modern image of the nature of science. The point here is not simply bringing the content of school science up to date, which is being done even if too slowly, but giving children a better sense of the nature of scientific activity, a goal that does not easily fit into School and is therefore almost entirely neglected. It is important to bring about these changes in science education both for the high-minded reason of respect for truth in education and, espe-

cially, for the mundane reason that the image traditionally presented repels students who would be attracted to the life of science if they only knew what it was really like, and to scientific thinking if they only knew how much it was like their own.

From a constructionist point of view there is a deeper implication, which I introduce by reopening the discussion of some important observations of children by Jean Piaget and his colleagues. Essentially, Piaget had made the same observation as Lévi-Strauss, except that where the anthropologist had looked at *la pensée sauvage* in distant societies, Piaget looked at *la pensée sauvage* close to home, in children. What they both saw was thinking that differed from “our” norms and yet had a degree of inner coherence that forbade dismissing it as simply erroneous. Both saw their findings as an important discovery of an unsuspected way of thinking; both gave what they saw a name, each using the word *concrete*—in one case as “the science of the concrete” and in the other as “the stage of concrete operations.” Both set out to investigate the workings of concrete thinking paralleling the investigation of laws of abstract thought that had been studied since ancient Greek times. Both gave us valuable insights into the workings of a nonabstract way of thinking. And both had the same blind spot. They failed to recognize that the concrete thinking they had discovered was not confined to the underdeveloped—neither to Lévi-Strauss’s “undeveloped” societies nor to Piaget’s not yet “developed” children. Children do it, people in Pacific and African villages do it, and so do the most sophisticated people in Paris or Geneva.

Moreover, and this is what is of the most central importance, the sophisticates do not resort to “concrete thinking” only in their preliminary gropings toward solving a problem or when they are operating as novices outside their areas of expertise. As I noted in citing Latour, features of what Lévi-Strauss and Piaget identify as “concrete” are present at the core of important and sophisticated intellectual enterprises. It is hard to give examples without too wide a digression into a technical discussion of a particular

science. Feminist scholars who want to make a similar point in arguing that the supervaluation of the abstract is androcentric are fond of citing Evelyn Fox Keller's biography of the Nobel Prize-winning biologist Barbara McClintock. Keller's account gives an important role to an incident that is easily citable in nontechnical language: McClintock has become as well known for saying that she studied plants by getting to know them as individuals and cells by getting inside them than for the important genetic discoveries she made. The image of McClintock shrinking into the cell has a vividness that conveys a certain sense of an anti-abstract approach, but to appreciate the point in more than a superficial way, you should read Keller's book or look for new additions to the burgeoning field of criticism of traditional epistemology.

It might be more accurate to describe the blind spot I attributed to Piaget and Lévi-Strauss as "resistance," in the sense that Freud uses when he explains reluctance to accept his theories as a manifestation of what the theory predicts—a repression of the unacceptable aggressive or sexual content of the unconscious. In Piaget's case the unacceptable is the possibility that good thinking might not conform to the standards that have been set up by generations of epistemologists. The repression consists of accepting the existence and effectiveness of such thinking but relegating it to children. Readers who have battled with Piaget's writing might even go a step further with me in speculating that Piaget is protecting himself from acknowledging that his own thinking has more of the *bricoleur* than of the formal and analytic standards of the dominant epistemology. But whatever the ultimate reason, the fact is that Piaget hid the light of his best discovery under the bushel of his theory of stages.

In outline, Piaget's theory presents intellectual development as divided into three great epochs, which (by coincidence or otherwise) approximately match three major periods in the timetable of life as seen by School. The first epoch, called the "sensorimotor stage," is roughly the same as the preschool period. This is a period of prelogic in which children respond to their immediate

situation. The second epoch, which Piaget calls the stage of “concrete operations,” is roughly coextensive with the elementary-school years. This is a period of concrete logic in which thought goes far beyond the immediate situation but still does not work through the operation of universal principles. Instead, its methods are still tied to specific situations, like those of an expert at kitchen math who is incapable of handling a pencil-and-paper test on fractions. And finally there is the “formal stage,” which covers high school—and the rest of life. Now at last thought is driven, and disciplined, by principles of logic, by deduction, by induction, and by the principle of developing theories by the test of empirical verification and refutation.

This neat picture of successive stages has aroused such strong positive and negative reactions that the ensuing debates have obscured Piaget’s really important contribution: His description of different ways of knowing is far more important than quibbling about whether they neatly follow one another chronologically. And what is especially important is the description of the nature and the development of the middle stage of concrete operations. This is the task to which he devoted the greater part of his mature life and the topic of all but a handful of the more than one hundred books he wrote about how children think in a staggering range of domains, including logic, number, space, time, motion, life, causality, machines, games, dreams.

Piaget’s descriptions of thousands of conversations with children fit well with Lévi-Strauss’s image of the *bricoleur*. The child will bring to bear on a situation a way of thinking about it that might be very different from what is used in a seemingly logically equivalent problem. Where Piaget has something very different to add is in his focus on change over periods of years. For example, he has conversations with children as young as four about situations involving number.

The best-known examples are the so-called conservation experiments. In one of these, children whose ages vary from four to seven are shown a row of egg cups, each containing an egg, and

are asked whether there are more eggs or more egg cups. The typical response at all ages is "no" or "the same." The eggs are then removed from the egg cups and spread out in a long row while the egg cups are brought together in a tight cluster, all in full view of the child. The same question is posed. This has been done often enough, and under sufficiently varied conditions, to justify asserting with confidence that virtually all children of four or five will say "more eggs." They will defend this position under extensive cross-questioning and even when pressure is placed on them to change their minds, for example, by being told that three other children all said there were not more eggs, or by being asked to count the eggs and the egg cups. Most children will resist falling in line with the others, and one neatly commented after counting: "They count the same but it's more eggs." Thus the first remarkable observation from the experiment is that these children seem to hold a view contrary to something that is absolutely obvious to any adult—indeed, so obvious that nobody seems to have noticed before Piaget that children did not share our self-evident truth. The point is not simply that the children do not know the adult answer to the question and flounder in ignorance; the point is that they firmly and consistently give a different answer.

A sensible objection that casts light on what is really being learned is that the children are more likely to have misunderstood the question than to hold the bizarre "nonconservationist" opinion: They think they are being asked about the space occupied and not about the number. In one sense the objection must be true. If the children really understood the question as we do, they would answer as we do. But the objection deepens rather than trivializes Piaget's experiment. There may indeed be a misunderstanding, but it is not a "mere verbal misunderstanding." It reflects something deep about the child's mental world. If one suspected an adult of such misunderstanding, one would say, "No, I mean number, not space." However, saying this to a four-year-old will serve no purpose, for the child does not know how to make the distinction. Number is what you see on "Sesame Street," and space

is where you sit. Neither is relevant to the distinction about eggs and egg cups. The possibility of the misunderstanding shows the state of development of this area of a child's knowledge. The work being done in the concrete period is that of gradually growing the relevant mental entities and giving them connections so that such distinctions become meaningful. When you or I see six eggs, the sixness is as much part of what we see as the whiteness or the shapes of the individual objects. As with Debbie, for us number (like fractions) is something we "put on" everything. But we must "have" it before we can do so, and it seems that for a sensorimotor child it is either not there or, like the early Debbie's fractions, too rigidly anchored to be manipulated. Following this thought, I see phenomena that Piaget ascribes to the stage of concrete operations as models for how fractions developed for Debbie or how "floweriness" and "familyness" (in the botanical sense) developed for me. In this view the educational implications of Piaget's ideas are reversed. Most of his followers in education set out to hasten (or at least consolidate) the passage of the child beyond concrete operations. My strategy is to strengthen and perpetuate the typical concrete process even at my age. Rather than pushing children to think like adults, we might do better to remember that they are great learners and to try harder to be more like them. While formal thinking may be able to do much that is beyond the scope of concrete methods, the concrete processes have their own power.

It is impossible not to feel frustrated in thinking about the nature of concrete knowledge by the advantages enjoyed by the traditional epistemology. Its unit of knowledge is a clearly demarcated entity—a proposition—and there is a well-developed, widely accepted language in which to talk about it. Part of the gap one encounters in developing any alternative epistemology is the result of time: Starting fresh, we are essentially at a disadvantage. Part of the gap is very likely to be permanent, for an epistemology predicated on pluralism and on connection between domains is bound to be less clear-cut, more complex.

A third kind of gap, which is of a more subtle nature, is the

relationship of knowledge to media. The traditional epistemology is based on the proposition, so closely linked to the medium of text—written and especially printed. *Bricolage* and concrete thinking always existed but were marginalized in scholarly contexts by the privileged position of text. As we move into the computer age and new and more dynamic media emerge, this will change. Although it might be futile to outguess such radical departures in ways of dealing with knowledge, it will be interesting to keep the question in mind as we turn now to look more directly at some aspects of the history of computers in relation to epistemology and learning.