# MINDSTORMS

## Children, Computers, and Powerful Ideas

SECOND EDITION

**SEYMOUR PAPERT**

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## Preface

# The Gears of My Childhood

BEFORE I WAS two years old I had developed an intense involvement with automobiles. The names of car parts made up a very substantial portion of my vocabulary: I was particularly proud of knowing about the parts of the transmission system, the gearbox, and most especially the differential. It was, of course, many years later before I understood how gears work; but once I did, playing with gears became a favorite pastime. I loved rotating circular objects against one another in gearlike motions and, naturally, my first "erector set" project was a crude gear system.

I became adept at turning wheels in my head and at making chains of cause and effect: "This one turns this way so that must turn that way so . . ." I found particular pleasure in such systems as the differential gear, which does not follow a simple linear chain of causality since the motion in the transmission shaft can be distributed in many different ways to the two wheels depending on what resistance they encounter. I remember quite vividly my excitement at discovering that a system could be lawful and completely comprehensible without being rigidly deterministic.

[ believe that working with differentials did more for my mathematical development than anything I was taught in elementary school. Gears, serving as models, carried many otherwise abstract ideas into my head. I clearly remember two examples from school math. I saw multiplication tables as gears, and my first brush with equations in two variables (e.g., 3x + 4y = 10) immediately evoked the differential. By the time I had made a mental gear model of the relation between x and y, figuring how many teeth each gear needed, the equation had become a comfortable friend.

Many years later when I read Piaget this incident served me as a model for his notion of assimilation, except I was immediately struck by the fact that his discussion does not do full justice to his own idea. He talks almost entirely about cognitive aspects of assimilation. But there is also an affective component. Assimilating equations to gears certainly is a powerful way to bring old knowledge to bear on a new object. But it does more as well. I am sure that such assimilations helped to endow mathematics, for me, with a positive affective tone that can be traced back to my infantile experiences with cars. I believe Piaget really agrees. As I came to know him personally I understood that his neglect of the affective comes more from a modest sense that little is known about it than from an arrogant sense of its irrelevance. But let me return to my childhood.

One day I was surprised to discover that some adults-even *most* adults-did not understand or even care about the magic of the gears. I no longer think much about gears, but I have never turned away from the questions that started with that discovery: Flow could what was so simple for me be incomprehensible to other people'? My proud father suggested "being clever" as an explanation. But I was painfully aware that some people who could not understand the differential could easily do things I found much more difficult. Slowly I began to formulate what I ,till consider the fundamental fact about learning: Anything is easy if you can assimilate it to your collection of models. If you can 't, anything can be painfully difficult. Here too I was developing a way of thinking that would be resonant with Piaget's. *The understanding of learning must be genetic.* It must refer to the genesis of knowledge. What an individual can learn, and how he Iearns it, depends on what models he has available. This raises, recursively, the question of how he learned these models. Thus the laws of learning" must be about how intellectual structures grow out of one another and about how, in the process, they acquire both logical and emotional form.

This book is an exercise in an applied genetic epistemology expanded beyond Piaget's cognitive emphasis to include a concern with the affective. It develops a new perspective for education research focused on creating the conditions under which intellectual models will take root. For the last two decades this is what I have been trying to do. And in doing so I find myself frequently reminded of several aspects of my encounter with the differential gear. First, I remember that no one told me to learn about differential gears. Second, I remember that there was feel*ing,* love, as well as understanding in my relationship with gears. Third, I remember that my first encounter with them was in my second year. If any "scientific" educational psychologist had tried to "measure" the effects of this encounter, he would probably have failed. It had profound consequences but, I conjecture, only very many years later. A "pre- and post-" test at age two would have missed them.

Piaget's work gave me a new framework for looking at the gears of my childhood. The gear can be used to illustrate many powerful "advanced" mathematical ideas, such as groups or relative motion. But it does more than this. As well as connecting with the formal knowledge of mathematics, it also connects with the "body knowledge," the sensormotor schemata of a child. You can *be* the gear, you can understand how it turns by projecting yourself into its place and turning with it. It is this double relationship- both abstract and sensory---that gives the gear the power to carry powerful mathematics into the mind. In a terminology I shall develop in later chapters, the gear acts here as a *transitional object.*

A modern-day Montessori might propose, if convinced by my story, to create a gear set for children. Thus every child might have the experience I had. But to hope for this would be to miss the essence of the story. I *fell in love with the gears.* This is something that cannot be reduced to purely "cognitive" terms. Something very personal happened, and one cannot assume that it would be repeated for other children in exactly the same form. My thesis could be summarized as: What the gears cannot do the computer might. The computer is the Proteus of machines. Its essence is its universality, its power to simulate. Because it can take on a thousand forms and can serve a thousand functions, it can appeal to a thousand tastes. This book is the result of my own attempts over the past decade to turn computers into instruments flexible enough so that many children can each create for themselves something like what the gears were for me.

Introduction

# Computers for Children

JUST A FEW YEARS AGO people thought of computers as expensive and exotic devices. Their commercial and industrial uses affected ordinary people, but hardly anyone expected computers to become part of day-to-day life. This view has changed dramatically and rapidly as the public has come to accept the reality of the personal computer, small and inexpensive enough to take its place in every living room or even in every breast pocket. The appearance of the first rather primitive machines in this class was enough to catch the imagination of journalists and produce a rash of speculative articles about life in the computerrich world to come. The main subject of these articles was what people will be able to do with their computers. Most writers emphasized using computers for games, entertainment, income tax, electronic mail, shopping, and banking. A few talked about the computer as a teaching machine.

This book too poses the question of what will be done with personal computers, but in a very different way. I shall be talking about how computers may affect the way people think and learn. I begin to characterize my perspective by noting a distinction between two ways computers might enhance thinking and change patterns of access to knowledge.

Instrumental uses of the computer to help people think have been dramatized in science fiction. For example, as millions of "Star Trek" fans know, the starship *Enterprise* has a computer that gives rapid and accurate answers to complex questions posed to it. But no attempt is made in "Star Trek" to suggest that the human characters aboard think in ways very different from the manner in which people in the twentieth century think. Contact with the computer has not, as far as we are allowed to see in these episodes, changed how these people think about themselves or how they approach problems. In this book I discuss ways in which the computer presence could contribute to mental processes not only instrumentally but in more essential, conceptual ways, influencing how people think even when they are far removed from physical contact with a computer (just as the gears shaped my understanding of algebra although they were not physically present in the math class). It is about an end to the culture that makes science and technology alien to the vast majority of people. Many cultural barriers impede children from making scientific knowledge their own. Among these barriers the most visible are the physically brutal effects of deprivation and isolation. Other barriers are more political. Many children who grow up in our cities are surrounded by the artifacts of science but have good reason to see them as belonging to "the others"; in many cases they are perceived as belonging to the social enemy. Still other obstacles are more abstract, though ultimately of the same nature. Most branches of the most sophisticated modern culture of Europe and the United States are so deeply "mathophobic" that many privileged children are as effectively (if more gently) kept from appropriating science as their own. In my vision, spaceage objects, in the form of small computers, will cross these cultural barriers to enter the private worlds of children everywhere. They will do so not as mere physical objects. This book is about how computers can be carriers of powerful ideas and of the seeds of cultural change, how they can help people form new relationships with knowledge that cut across the traditional lines separating humanities from sciences and knowledge of the self from both of these. It is about using computers to challenge current beliefs about who can understand what and at what age. It is about using computers to question standard assumptions in developmental psychology and in the psychology of aptitudes and attitudes. It is about whether personal computers and the cultures in which they are used will continue to be the creatures of "engineers" alone or whether we can construct intellectual environments in which people who today think of themselves as "humanists" will feel part of, not alienated from, the process of constructing computational cultures.

But there is a world of difference between what computers can do and what society will choose to do with them. Society has many ways to resist fundamental and threatening change. Thus, this book is about facing choices that are ultimately political. It looks at some of the forces of change and of reaction to those forces that are called into play as the computer presence begins to enter the politically charged world of education.

Much of the book is devoted to building up images of the role of the computer very different from current stereotypes. All of us, professionals as well as laymen, must consciously break the habits we bring to thinking about the computer. Computation is in its infancy. It is hard to think about computers of the future without projecting onto them the properties and the limitations of those we think we know today. And nowhere is this more true than in imagining how computers can enter the world of education. It is not true to say that the image of a child's relationship with a computer I shall develop here goes far beyond what is common in today's schools. My image does not go beyond: It goes in the opposite direction.

In many schools today, the phrase "computeraided instruction" means making the computer teach the child. One might say the *computer is being used to program* the child. In my vision, *the child programs the computer* and, in doing so, both acquires a sense of mastery over a piece of the most modern and powerful technology and establishes an intimate contact with some of the deepest ideas from science, from mathematics, and from the art of intellectual model building.

I shall describe learning paths that have led hundreds of children to becoming quite sophisticated programmers. Once programming is seen in the proper perspective, there is nothing very surprising about the fact that this should happen. Programming a computer means nothing more or less than communicating to it in a language that it and the human user can both "understand." And learning languages is one of the things children do best. Every normal child learns to talk. Why then should a child not learn to "talk" to a computer?

There are many reasons why someone might expect it to be difficult. For example, although babies learn to speak their native language with spectacular ease, most children have great difficulty learning foreign languages in schools and, indeed, often learn the written version of their own language none too successfully. Isn't learning a computer language more like the difficult process of learning a foreign written language than the easy one of learning to speak one's own language? And isn't the problem further compounded by all the difficulties most people encounter learning mathematics?

Two fundamental ideas run through this book. The first is that it is possible to design computers so that learning to communicate with them can be a natural process, more like learning French by living in France than like trying to learn it through the unnatural process of American foreign language instruction in classrooms. Second, learning to communicate with a computer may change the way other learning takes place. The computer can be a mathematics speaking and an alphabetic speaking entity. We are learning how to make computers with which children love to communicate. When this communication occurs, children learn mathematics as a living language. Moreover, mathematical communication and alphabetic communication are thereby both transformed from the alien and therefore difficult things they are for most children into natural and therefore easy ones. The idea of "talking mathematics" to a computer can be generalized to a view of learning mathematics in "Mathland"; that is to say, in a context which is to learning mathematics what living in France is to learning French.

In this book the Mathland metaphor will be used to question deeply engrained assumptions about human abilities. It is generally assumed that children cannot learn formal geometry until well into their school years and that most cannot learn it too well even then. But we can quickly see that these assumptions are based on extremely weak evidence by asking analogous questions about the ability of children to learn French. If we had to base our opinions on observation of how poorly children learned French in American schools, we would have to conclude that most people were incapable of mastering it. But we know that all normal children would learn it very easily if they lived in France. My conjecture is that much of what we now see as too "formal" or "too mathematical" will be learned just as easily when children grow up in the computerrich world of the very near future.

I use the examination of our relationship with mathematics as a thematic example of how technological and social processes interact in the construction of ideas about human capacities. And mathematical examples will also help to describe a theory of how learning works and of how it goes wrong.

I take from Jean Piaget a model of children as builders of their own intellectual structures. Children seem to be innately gifted learners, acquiring long before they go to school a vast quantity of knowledge by a process I call "Piagetian learning," or "learning without being taught." For example, children learn to speak, learn the intuitive geometry needed to get around in space, and learn enough of logic and rhetorics to get around parents all this without being "taught." We must ask why some learning takes place so early and spontaneously while some is delayed many years or does not happen at all without deliberately imposed formal instruction.

If we really look at the "child as builder" we are on our way to an answer. All builders need materials to build with. Where I am at variance with Piaget is in the role I attribute to the surrounding cultures as a source of these materials. In some cases the culture supplies them in abundance, thus facilitating constructive Piagetian learning. For example, the fact that so many important things (knives and forks, mothers and fathers, shoes and socks) come in pairs is a "material" for the construction of an intuitive sense of number. But in many cases where Piaget would explain the slower development of a particular concept by its greater complexity or formality, I see the critical factor as the relative poverty of the culture in those materials that would make the concept simple and concrete. In yet other cases the culture may provide materials but lock their use. In the case of formal mathematics, there is both a shortage of formal materials and a cultural block as well. The mathophobia endemic in contemporary culture blocks many people from learning anything they recognize as "math," although they may have no trouble with mathematical knowledge they do not perceive as such.

We shall see again and again that the consequences of mathophobia go far beyond obstructing the learning of mathematics and science. They interact with other endemic "cultural toxins," for example, with popular theories of aptitudes, to contaminate peoples' images of themselves as learners. Difficulty with school math is often the first step of an invasive intellectual process that leads us all to define ourselves as bundles of aptitudes and ineptitudes, as being "mathematical" or "not mathematical," "artistic" or "not artistic," "musical" or "not musical," "profound" or "superficial," "intelligent" or "dumb." Thus deficiency becomes identity and learning is transformed from the early child's free exploration of the world to a chore beset by insecurities and self imposed restrictions.

Two major themes that children can learn to use computers in a masterful way, and that learning to use computers can change the way they learn everything else have shaped my research agenda on computers and education. Over the past ten years I have had the good fortune to work with a group of colleagues and students at MIT (the LOGO' group in the Artificial Intelligence Laboratory) to create environments in which children can learn to communicate with computers. The metaphor of imitating the way the child learns to talk has been constantly with us in this work and has led to a vision of education and of education research very different from the traditional ones. For people in the teaching professions, the word "education" tends to evoke "teaching," particularly classroom teaching. The goal of education research tends therefore to be focused on how to improve classroom teaching. But if, as I have stressed here, the model of successful learning is the way a child learns to talk, a process that takes place without deliberate and organized teaching, the goal set is very different. I see the classroom as an artificial and inefficient learning environment that society has been forced to invent because its informal environments fail in certain essential learning domains, such as writing or grammar or school math. I believe that the computer presence will enable us to so modify the learning environment outside the classrooms that much if not all the knowledge schools presently try to teach with such pain and expense and such limited success will be learned, as the child learns to talk, painlessly, successfully, and without organized instruction. This obviously implies that schools as we know them today will have no place in the future. But it is an open question whether they will adapt by transforming themselves into something new or wither away and be replaced.

Although technology will play an essential role in the realization of my vision of the future of education, my central focus is not on the machine but on the mind, and particularly on the way in which intellectual movements and cultures define themselves and grow. Indeed, the role I give to the computer is that of a carrier of cultural "germs" or "seeds" whose intellectual products will not need technological support once they take root in an actively growing mind. Many if not all the children who grow up with a love and aptitude for mathematics owe this feeling, at least in part, to the fact that they happened to acquire "germs" of the "math culture" from adults, who, one might say, knew how to speak mathematics, even if only in the way that Moliere had M. Jourdain speak prose without knowing it. These "mathspeaking" adults do not necessarily know how to solve equations; rather, they are marked by a turn of mind that shows up in the logic of their arguments and in the fact that for them to play is often to play with such things as puzzles, puns, and paradoxes. Those children who prove recalcitrant to math and science education include many whose environments happened to be relatively poor in mathspeaking adults. Such children come to school lacking elements necessary for the easy learning of school math. School has been unable to supply these missing elements, and, by forcing the children into learning situations doomed in advance, it generates powerful negative feelings about mathematics and perhaps about learning in general. Thus is set up a vicious self perpetuating cycle. For these same children will one day be parents and will not only fail to pass on mathematical germs but will almost certainly infect their children with the opposing and intellectually destructive germs of mathophobia.

Fortunately it is sufficient to break the self perpetuating cycle at one point for it to remain broken forever. I shall show how computers might enable us to do this, thereby breaking the vicious cycle without creating a dependence on machines. My discussion differs from most arguments about "nature versus nurture" in two ways. I shall be much more specific both about what kinds of nurturance are needed for intellectual growth and about what can be done to create such nurturance in the home as well as in the wider social context.

Thus this book is really about how a culture, a way of thinking, an idea comes to inhabit a young mind. I am suspicious of thinking about such problems too abstractly, and I shall write here with particular restricted focus. I shall in fact concentrate on those ways of thinking that I know best. I begin by looking at what I know about my own development. I do this in all humility, without any implication that what I have become is what everyone should become. But I think that the best way to understand learning is first to understand specific, wellchosen cases and then to worry afterward about how to generalize from this understanding. You can't think seriously about thinking without thinking about thinking about something. And the something I know best how to think about is mathematics. When in this book I write of mathematics, I do not think of myself as writing for an audience of mathematicians interested in mathematical thinking for its own sake. My interest is in universal issues of how people think and how they learn to think.

When I trace how I came to be a mathematician, I see much that was idiosyncratic, much that could not be duplicated as part of a generalized vision of education reform. And I certainly don't think that we would want everyone to become a mathematician. But I think that the kind of pleasure I take in mathematics should be part of a general vision of what education should be about. If we can grasp the essence of one person's experiences, we may be able to replicate its consequences in other ways, and in particular this consequence of finding beauty in abstract things. And so I shall be writing quite a bit about mathematics. I give my apologies to readers who hate mathematics, but I couple that apology with an offer to help them learn to like it a little betteror at least to change their image of what "speaking mathematics" can be all about.

In the Foreword of this book I described how gears helped mathematical ideas to enter my life. Several qualities contributed to their effectiveness. First, they were part of my natural "landscape," embedded in the culture around me. This made it possible for me to find them myself and relate to them in my own fashion. Second, gears were part of the world of adults around me and through them f could relate to these people. Third, I could use my body to think about the gears. I could feel how gears turn by imagining my body turning. This made it possible for me to draw on my "body knowledge" to think about gear systems. And finally, because, in a very real sense, the relationship between gears contains a great deal of mathematical information, I could use the gears to think about formal systems. I have described the way in which the gears served as an "object-to-think-with." I made them that for myself in my own development as a mathematician. The gears have also served me as .m object-to-think-with in my work as an educational researcher. ,My goal has been the design of other objects that children can make theirs for themselves and in their own ways. Much of this hook will describe my path through this kind of research. I begin by describing one example of a constructed computational "object-to-think-with." This is the "Turtle."

The central role of the Turtle in this book should not be taken to mean that I propose it as a panacea for all educational problems. I see it as a valuable educational object, but its principal role here is ’o serve as a model for other objects, yet to be invented. My interest is in the process of invention of "objects-to-think-with," objects in which there is an intersection of cultural presence, embedded knowledge, and the possibility for personal identification.

The Turtle is a computer-controlled cybernetic animal. It exists within the cognitive minicultures of the "LOGO environment," LOGO being the computer language in which communication with ’he Turtle takes place. The Turtle serves no other purpose than of being good to program and good to think with. Some Turtles are abstract objects that live on computer screens. Others, like the floor Turtles shown in the frontispiece are physical objects that can )e picked up like any mechanical toy. A first encounter often begins by showing the child how a Turtle can be made to move by typing commands at a keyboard. FORWARD 100 makes the Turtle move in a straight line a distance of 100 Turtle steps of about a millimeter each. Typing RIGHT 90 causes the Turtle to pivot in place through 90 degrees. Typing PENDOWN causes the Turtle to lower a pen so as to leave a visible trace of its path while PENUP instructs it to raise the pen. Of course the child needs to explore a great deal before gaining mastery of what the numbers mean. But the task is engaging enough to carry most children through this learning process.

The idea of programming is introduced through the metaphor of teaching the Turtle a new word. This is simply done, and children often begin their programming experience by programming the Turtle to respond to new commands invented by the child such as SQUARE or TRIANGLE or SQ or TRI or whatever the child wishes, by drawing the appropriate shapes. New commands once defined can be used to define others. For example just as the house in Figure 1 is built out of a triangle and a square, the program for drawing it is built out of the commands for drawing a square and a triangle. Figure 1 shows four steps in the evolution of this program. From these simple drawings the young programmer can go on in many different directions. Some work on more complex drawings, either figural or abstract. Some abandon the use of the Turtle as a drawing instrument and learn to use its touch sensors to program it to seek out or avoid objects.' Later children learn that the computer can be programmed to make music as well as move Turtles and combine the two activities by programming Turtles to dance. Or they can move on from floor Turtles to "screen Turtles," which they program to draw moving pictures in bright colors. The examples are infinitely varied, but in each the child is learning how to exercise control over an exceptionally rich and sophisticated "microworld."

Readers who have never seen an interactive computer display might find it hard to imagine where this can lead. As a mental exercise they might like to imagine an electronic sketchpad, a computer graphics display of the not-too-distant future. This is a television screen that can display moving pictures in color. You can also "draw" on it, giving it instructions, perhaps by typing, perhaps by speaking, or perhaps by pointing with a wand. On request, a palette of colors could appear on the screen. You can choose a color by pointing at it with the wand. Until you change your choice, the wand draws in that color. Up to this point the distinction from traditional art materials may seem slight, but the distinction becomes very real when you begin to think about editing the drawing. You can "talk to your drawing" in computer language. You can "tell" it to replace this color with that. Or set a drawing in motion. Or make two copies and set them in counter-rotating motion. Or replace the color palette with a sound palette and "draw" a piece of music. You can file your work in computer memory and retrieve it at your pleasure, or have it delivered into the memory of any of the many millions of other computers linked to the central communication network for the pleasure of your friends.

That all this would be fun needs no argument. But it is more than fun. Very powerful kinds of learning are taking place. Children working with an electronic sketchpad are learning a language for talking about shapes and fluxes of shapes, about velocities and rates of change, about processes and procedures. They are learning to speak mathematics, and acquiring a new image of themselves as mathematicians.

In my description of children working with Turtles, I implied that children can learn to program. For some readers this might be tantamount to the suspension of disbelief required when we enter a theater to watch a play. For them programming is a complex and marketable skill acquired by some mathematically gifted adults. But my experience is very different. I have seen hundreds of elementary school children learn very easily to program, and evidence is accumulating to indicate that much younger children could do so us well. The children in these studies are not exceptional, or rather, they are exceptional in every conceivable way. Some of the children were highly successful in school, some were diagnosed as emotioniIly or cognitively disabled. Some of the children were so severely Afflicted by cerebral palsy that they had never purposefully manipulated physical objects. Some of them had expressed their talents in n "mathematical" forms, some in "verbal" forms, and some in arc tistically "visual" or in "musical" forms.

Of course these children did not achieve a fluency in programming that came close to matching their use of spoken language. If we take the Mathland metaphor seriously, their computer experience was more like learning French by spending a week or two on vacation in France than like living there. But like children who have spent a vacation with foreignspeaking cousins, they were clearly on their way to "speaking computer."

When I have thought about what these studies mean I am left with two clear impressions. First, that all children will, under the right conditions, acquire a proficiency with programming that will make it one of their more advanced intellectual accomplishments. Second, that the "right conditions" are very different from the kind of access to computers that is now becoming established as the norm in schools. The conditions necessary for the kind of relationships with a computer that I will be writing about in this book require more and freer access to the computer than educational planners currently anticipate. And they require a kind of computer language and a learning environment around that language very different from those the schools are now providing. They even require a kind of computer rather different from those that the schools are currently buying.

It will take most of this book for me to convey some sense of the choices among computers, computer languages, and more generally, among computer cultures, that influence how well children will learn from working with computation and what benefits they will get from doing so. But the question of the *economic* feasibility of free access to computers for every child can be dealt with immediately. In doing so I hope to remove any doubts readers may have about the "economic realism" of the "vision of education" I have been talking about.

My vision of a new kind of learning environment demands free contact between children and computers. This could happen because the child's family buys one or a child's friends have one. For purposes of discussion here (and to extend our discussion to all social groups) let us assume that it happens because schools give every one of their students his or her own powerful personal computer. Most "practical" people (including parents, teachers, school principals, and foundation administrators) react to this idea in much the same way: "Even if computers could have all the effects you talk about, it would still be impossible to put your ideas into action. Where would the money come from'?"

What these people are saying needs to be faced squarely. They are wrong. Let's consider the cohort of children who will enter kindergarten in the year 1987, the "Class of 2000," and let's do some arithmetic. The direct public cost of schooling a child for thirteen years, from kindergarten through twelfth grade is over $20,000 today (and for the class of 2000, it may be closer to $30,000). A conservatively high estimate of the cost of supplying each of these children with a personal computer with enough power for it to serve the kinds of educational ends described in this book, and of upgrading, repairing, and replacing it when necessary would be about $I,000 per student, distributed over thirteen years in school. Thus, "computer costs" for the class of 2,000 would represent only about 5 percent of the total public expenditure on education, and this would be the case even if nothing else in the structure of educational costs changed because of the computer presence. But in fact computers in education stand a good chance of making other aspects of education cheaper. Schools might be able to reduce their cycle from thirteen years to twelve years; they might be able to take advantage of the greater autonomy the computer gives students and increase the sire of classes by one or two students without decreasing the personal attention each student is given. Either of these two moves would "recuperate" the computer cost.

My goal is not educational economies: It is not to use computation to shave a year off the time a child spends in an otherwise unchanged school or to push an extra child into an elementary school classroom. The point of this little exercise in educational "budget balancing" is to do something to the state of mind of my readers as they turn to the first chapter of this book. l have described myself as an educational utopian not because I have projected a future of education in which children are surrounded by high technology, but because I believe that certain uses of very powerful computational technology and computational ideas can provide children with new possibilities for learning, thinking, and growing emotionally as well as cognitively. In the chapters that follow I shall try to give you some idea of these possibilities, many of which are dependent on a computerrich future, a future where a computer will be a significant part of every child's life. But I want my readers to be very clear that what is "utopian" in my vision and in this book is a particular way of using computers, of forging new relationships between computers and people that the computer will be there to be used is simply a conservative premise.

## Chapter 5

# Microworlds: Incubators for Knowledge

I HAVE DEFINED mathetics as being to learning as heuristics is to problem solving: Principles of mathetics are ideas that illuminate and facilitate the process of learning. In this chapter we focus on two important mathetic principles that are part of most people's common-sense knowledge about what to do when confronted with a new gadget, a new dance step, a new idea, or a new word. First, relate what is new and to be learned to something you already know. Second, take what is new and make it your own: Make something new with it, play with it, build with it. So for example, to learn a new word, we first look for a familiar "root" and then practice by using the word in a sentence of our own construction.

We find this two-step dictum about how to learn in popular, common-sense theories of learning: The procedure described for learning a new word has been given to generations of elementary schoolchildren by generations of parents and teachers. And it also corresponds to the strategies used in the earliest processes of learning. Piaget has studied the spontaneous learning of children and found both steps at work-the child absorbs the new into the old in a process that Piaget calls assimilation, and the child constructs his knowledge in the course of actively working with it.

But there are often roadblocks in the process. New knowledge Often contradicts the old, and effective learning requires strategies to deal with such conflict. Sometimes the conflicting pieces of knowledge can be reconciled, sometimes one or the other must be abandoned, and sometimes the two can both be "kept around" if safely maintained in separate mental compartments. We shall look at these learning strategies by examining a particular case in which a formal theory of physics enters into sharp conflict with commonsense, intuitive ideas about physics.

One of the simplest of such conflicts is raised by the fundamental tenet of Newton's physics: A body in motion will, if left alone, continue to move forever at a constant speed and in a straight line. This principle of "perpetual motion" contradicts common experience and, indeed, older theories of physics such as Aristotle's.

Suppose we want to move a table. We apply a force, set the table in motion, and keep on applying the force until the table reaches the desired position. When we stop pushing, the table stops. To our superficial gaze, the table does not behave like a Newtonian object. If it did, textbooks tell us, one push would set it in motion forever and a counteracting force would be needed to stop it at the desired place.

This conflict of ideal theory and everyday observation is only one of several roadblocks to the learning of Newtonian physics. Others derive from difficulties in applying the two mathetic principles. According to the first, people who want to learn Newtonian physics should find ways to relate it to something they already know. But they may not possess any knowledge to which it can be effectively related. According to the second, a good strategy for learning would be to work with the Newtonian laws of motion, to use them in a personal and playful fashion. But this too is not so simple. One cannot do anything with Newton's laws unless one has some way to grab hold of them and some familiar material to which they can be applied.

The theme of this chapter is how computational ideas can serve as material for thinking about Newton's laws. The key idea has already been anticipated. We saw how formal geometry becomes more accessible when the Turtle instead of the point is taken as the building block. Here we do for Newton what we did for Euclid. Newton's laws are stated using the concept of "a particle," a mathematically abstract entity that is similar to a point in having no size but that does have some other properties besides position: It has *mass* and *velocity* or, if one prefers to merge these two, it has *momentum.* In this chapter we enlarge our concept of Turtle to include entities that behave like Newton's particles as well as those we have already met that resemble Euclid's points. These new Turtles, which we call Dynaturtles, are more dynamic in the sense that their state is taken to include two velocity components in addition to the two geometric components, position and heading, of the previously discussed geometry Turtles. And having more parts to the state leads to requiring a slightly richer command language: TURTLE TALK is extended to allow us to tell the Turtle to set itself moving with a given velocity. This richer TURTLE TALK immediately opens up many perspectives besides the understanding of physics. Dynaturtles can be put into patterns of motion for aesthetic, fanciful, or playful purposes in addition to simulating real or invented physical laws. The too narrowly focused physics teacher might see all this as a waste of time: The real job is to understand physics. But I wish to argue for a different philosophy of physics education. It is my belief that learning physics consists of bringing physics knowledge into contact with very diverse personal knowledge. And to do this we should allow the learner to construct and work with transitional systems that the physicist may refuse to recognize as physics.'

Most physics curricula are similar to the math curriculum in that they force the learner into dissociated learning patterns and defer the "interesting" material past the point where most students can remain motivated enough to learn it. The powerful ideas and the intellectual aesthetic of physics is lost in the perpetual learning of "prerequisites." The learning of Newtonian physics can be taken as an example of how mathetic strategies can become blocked and unblocked. We shall describe a new "learning path" to Newton that gets around the block: a computer-based interactive learning environment where the prerequisites are built into the system and where learners can become the active, constructing architects of their own learning.

Let us begin with a closer look at the problem of prerequisites. Someone who wanted to learn about aerodynamics might lose interest upon seeing the set of prerequisites including mechanics and hydrodynamics that follow an exciting course description in a college catalogue. If one wants to learn about Shakespeare, one finds no list of prerequisites. It seems fair to assume that a list of prerequisites is an expression of what educators believe to be a learning path into a domain of knowledge. The learning path into aerodynamics is mathematical, and, as we have seen in our culture, mathematical knowledge is bracketed, treated as "special"-spoken of only in special places reserved for such esoteric knowledge. The nonacademic learning environments of most children provide little impetus to that mathematical development. This means that schools and colleges must approach the knowledge of aerodynamics along exceedingly formal learning paths. The route into Shakespeare is no less complex, but its essential constitutive elements are part of our general culture: It is assumed that many people will be able to learn them informally. The physics microworld we shall develop, the physics analog of our computer-based Mathland, offers a Piagetian learning path into Newtonian laws of motion, a topic usually considered paradigmatic of the kind of knowledge that can only be reached by a long, formalized learning path. Newtonian thinking about motion is a complex and seemingly counterintuitive set of assumptions about the world. Historically, it was long to evolve. And in terms of individual development, the child's interaction with his environment leads him to a very different set of personal beliefs about motion, beliefs that in many ways are closer to Aristotle's than to Newton's. After all, the Aristotelian idea of motion corresponds to the most common situation in our experience. Students trying to develop Newtonian thinking about motion encounter three kinds of problems that a computer microworld could help solve. First, students have had almost no direct experience of pure Newtonian motion. Of course, they have had some. For example, when a car skids on an icy road it becomes a Newtonian object: It will, only too well, continue in its state of motion without outside help. But the driver is not in a state of mind to benefit from the learning experience. In the absence of *direct* and physical experiences of Newtonian motion, the schools are forced to give the student indirect and highly mathematical experiences of Newtonian objects. There movement is learned by manipulating equations rather than by manipulating the objects themselves. The experience, lacking immediacy, is slow to change the student's intuitions. And it itself requires other formal prerequisites. The student must first learn how to work with equations before using them to model a Newtonian world. The simplest way in which our computer microworld might help is by putting students in a simulated world where they have direct access to Newtonian motion. This can be done when they are young. It need not wait for their mastery of equations. Quite the contrary: Instead of making students wait for equations, it can motivate and facilitate their acquisition of equational skills by providing an intuitively well understood context for their use.

Direct experience with Newtonian motion is a valuable asset for the learning of Newtonian physics. But more is needed to understand it than an intuitive, seat-of-the-pants experience. The student needs the means to conceptualize and "capture" this world. Indeed, a central part of Newton's great contribution was the invention of a formalism, a mathematics suited to this end. He called it "fluxions"; present-day students call it "differential calculus." The Dynaturtle on the computer screen allows the beginner to play with Newtonian objects. The concept of the Dynaturtle allows the student to think about them. And programs governing the behavior of Dynaturtles provide a formalism in which we can capture our otherwise too fleeting thoughts. In doing so it bypasses the long route (arithmetic, algebra, trigonometry, calculus) into the formalism that has passed with only superficial modification from Newton's own writing to the modern textbook. And I believe it brings the student in closer touch with what Newton must have thought before he began writing equations.

The third prerequisite is somewhat more subtle. We shall soon look directly at statements of what is usually known as Newton's laws of motion. As we do, many readers will no doubt recall a sense of unease evoked by the phrase "law of motion." What kind of a thing is that? What other laws of motion are there besides Newton's? Few students can answer these questions when they first encounter Newton, and I believe that this goes far toward explaining the difficulty of physics for most learners. Students cannot make a thing their own without knowing what kind of a thing it is. Therefore, the third prerequisite is that we must find ways to facilitate the personal appropriation not only of Newtonian motion and the laws that describe it, but also of the general notion of laws that describe motion. We do this by designing a series of microworlds.

The Turtle World was a microworld, a "place," a "province of Mathland," where certain kinds of mathematical thinking could hatch and grow with particular ease. The microworld was an incubator. Now we shall design a microworld to serve as an incubator for Newtonian physics. The design of the microworld makes it a "growing place" for a specific species of powerful ideas or intellectual structures. So, we design microworlds that exemplify not only the "correct" Newtonian ideas, but many others as well: the historically and psychologically important Aristotelian ones, the more complex Einsteinian ones, and even a "generalized law-of-motion world" that acts as a framework for an infinite variety of laws of motion that individuals can invent for themselves. Thus learners can progress from Aristotle to Newton and even to Einstein via as many intermediate worlds as they wish. In the descriptions that follow, the mathetic obstacles to Newton are overcome: The prerequisites are rooted in personal knowledge and the learner is involved in a creative exploration of the idea and the variety of laws of motion.

Let us begin to describe the microworld by starting with Newton's three laws, stated here "formally" and in a form that readers do not have to understand in detail:

1. Every particle continues in a state of rest or motion with constant speed in a straight line unless compelled by a force to change that state.
2. The net unbalanced force (F) producing a change of motion is equal to the product of the mass (m) and the acceleration (a) of the particle: $F=ma$.
3. All forces arise from the interaction of particles, and whenever a particle acts on another there *is* an equal and opposite reaction on the first.

As we have noted, children's access to these laws is blocked by more than the recondite language used to state them. We analyze these roadblocks in order to infer design criteria for our microworld. A first block is that children do not know anything else like these laws. Before being receptive to Newton's laws of motion, they should know some other laws of motion. There must be a first example of laws of motion, but it certainly does not have to be as complex, subtle, and counterintuitive as Newton's laws. More sensible is to let the learner acquire the concept of laws of motion by working with a very simple and accessible instance of a law of motion. This will be the first design criterion for our microworld. The second block is that the laws, as stated, offer no footholds for learners who want to manipulate them. There is no use they can put them to outside of end-of-chapter schoolbook exercises. And so, a second design criterion for our microworlds is the possibility of activities, games, art, and so on, that make activity in the microworlds matter. A third block is the fact that the Newtonian laws use a number of concepts that are outside most people's experience, the concept of "state," for example. Our microworld will be designed so that all needed concepts can be defined within the experience of that world.

As in the case of the geometry Turtle, the physics Turtle is an interactive being that can be manipulated by the learner, providing an environment for active learning. But the learning is not "active" simply in the sense of interactive. Learners in a physics microworld are able to invent their own personal sets of assumptions about the microworld and its laws and are able to make them come true. They can shape the reality in which they will work for the day, they can modify it and build alternatives. This is an effective way to learn, paralleling the way in which each of us once did some of our most effective learning. Piaget has demonstrated that children learn fundamental mathematical ideas by first building their own, very much different (for example, preconservationist) mathematics. And children learn language by first learning their own ("baby-talk") dialects. So, when we think of microworlds as incubators for powerful ideas, we are trying to draw upon this effective strategy: We allow learners to learn the "official" physics by allowing them the freedom to invent many that will work in as many invented worlds.

Following Polya's principle of understanding the new by associating it with the old, let us reinterpret our microworld of Turtle geometry as a microworld of a special kind of physics. We recast the laws by which Turtles work in a form that parallels the Newtonian laws. This gives us the following "Turtle laws of motion." Of course, in a world with only one Turtle, the third law, which deals with the interaction among particles, will not have an analog.

1. Every Turtle remains in its state of rest until compelled by a TURTLE COMMAND to change that state.
2. a. The input to the command FORWARD is equal to the Turtle's change in the POSITION part of its state.
   b. The input to the command RIGHT TURN is equal to the Turtle's change of the HEADING part of its state.

What have we gained in our understanding of Newtonian physics by this exercise? How can students who know Turtle geometry (and can thus recognize its restatement in Turtle laws of motion) now look at Newton's laws? They are in a position to formulate in a qualitative and intuitive form the substance of Newton's first two laws by comparing them with something they already know. They know about states and state-change operators. In the Turtle world, there is a state-change operator for each of the two components of the state. The operator FORWARD changes the position. The operator TURN changes the heading. In physics, there is only one state-change operator, called *force*. The effect of force is to change velocity (or, more precisely, momentum). Position changes by itself.

These contrasts lead students to a qualitative understanding of Newton. Although there remains a gap between the Turtle laws and the Newtonian laws of motion, children can appreciate the second through an understanding of the first. Such children are already a big step ahead in learning physics. But we can do more to close the gap between Turtle and Newtonian worlds. We can design other Turtle microworlds in which the laws of motion move toward a closer approximation of the Newtonian situation.

To do this we create a class of Turtle microworlds that differs in the properties that constitute the state of the Turtle and in the operators that change these states. We have formally described the geometry Turtle by saying that its state consists of position and velocity and that its state-change operators act independently of these two components. But there is another way, perhaps a more powerful and intuitive way, to think about it. This is to see the Turtle as a being that "understands" certain kinds of communication and not others. So, the geometry Turtle understood the command to change its position while keeping its heading and to change its heading while keeping its position. In the same spirit, we could define a Newtonian Turtle as a being that can accept only one kind of order, one that will change its momentum. These kinds of description are in fact the ones we use in introducing children to microworlds. Now let us turn to two Turtle microworlds that can be said to lie between the geometry and Newtonian Turtles.

VELOCITY TURTLES

The state of a velocity Turtle is POSITION AND VELOCITY. Of course, since velocity is defined as a change in position, by definition the first component of this state is continuously changing (unless VELOCITY is zero). So, in order to control a velocity Turtle, we only have to tell it what velocity to adopt. We do this by one state-change operator, a command called SETVELOCITY.

ACCELERATION TURTLES

Another Turtle, intermediate between the geometry Turtle and the Turtle that could represent a Newtonian particle, is an acceleration Turtle. Here, too, the state of the Turtle is its position and velocity. But this time the Turtle cannot understand such a command as "Take on such-and-such a velocity". It can only take instructions of the form "Change your velocity by x, no matter what your velocity happens to be." This Turtle behaves like a Newtonian particle with an unchangeable mass.

Thus, the sequence of turtles-geometry Turtle to velocity Turtle to acceleration Turtle to Newtonian Turtle--constitutes a path into Newton that is resonant with our two mathetic principles. Each step builds on the one before in a clear and transparent way, satisfying the principle of prerequisites. As for our second mathetic principle-"use it, play with it"-the case is even more dramatic. Piaget showed us how the child constructs a preconservationist and then a conservationist world out of the materials (tactile, visual, and kinesthetic) in his environment. But until the advent of the computer, there were only very poor environmental materials for the construction of a Newtonian world. However, each of the microworlds we described can function as an explorable and manipulable environment.

In Turtle geometry, geometry was taught by way of computer graphics projects that produce effects like those shown in the designs illustrating this book. Each new idea in Turtle geometry opened new possibilities for action and could therefore be experienced as a source of personal power. With new commands such as SETVELOCITY and CHANGE VELOCITY, learners can set things in motion and produce designs of ever-changing shapes and sizes. They now have even more personal power and a sense of "owning" dynamics. They can do computer animation-there is a new, personal relationship to what they see on television or in a pinball gallery. The dynamic visual effects of a TV show, an animated cartoon, or a video game now encourage them to ask how they could make what they see. This is a different kind of question than the one students traditionally answer in their "science laboratory." [n the traditional laboratory pedagogy, the task posed to the children is to establish a given truth. At best, children learn that "this is the way the world works." In these dynamic Turtle microworlds, they come to a different kind of understanding---a feel for why the world works as it does. By trying many different laws of motion, children will find that the Newtonian ones are indeed the most economical and elegant for moving objects around.

All of the preceding discussion has dealt with Newton's first two laws What analogs to Newton's third law are possible in the world d' Turtles? The third law is only meaningful in a microworld of interactive entities-particles for Newton, Turtles for us. So let us assume a microworld with many Turtles that we shall call TURTLE 1, TURTLE 2, and so on. We can use TURTLE TALK to communicate with multiple Turtles if we give each of them a name. So we can use commands such as: TELL TURTLE 4 SETVELOCITY 20 (meaning "Tell Turtle number 4 to take on a velocity of 20).

Newton's third law expresses a model of the universe, a way to conceptualize the workings of physical reality as a self-perpetuating machine. In this vision of the universe, all actions are governed by particles exerting forces on one another, with no intervention by any outside agent. In order to model this in a Turtle microworld, we need many Turtles interacting with each other. Here we shall develop two models for thinking about interacting Turtles: linked Turtles and linked Dynaturtles.

In the first model we think of the Turtles as giving commands *to one another* rather than obeying commands from the outside. They are *linked Turtles.* Of course, Turtles can be linked in many ways. We can make Turtles that directly simulate Newtonian particles linked by simulated gravity. This is commonly done in LOGO laboratories, where topics usually considered difficult in college physics are translated into a form accessible to junior high school students. Such simulations can serve as a springboard from an elementary grasp of Newtonian mechanics to an understanding of the motion of planets and of the guidance of spacecraft. They do this by making working with the Newtonian principles an active and personally involving process. But to "own" the idea of interacting particlesor "linked Turtles"-the learner needs to do more. It is never enough to work within a given set of interactions. The learner needs to know more than one example of laws of interaction and should have experience inventing new ones. What are some other examples of linked Turtles?

A first is a microworld of linked Turtles called "mirror Turtles." We begin with a "mirror Turtle" microworld containing two Turtles linked by the rules: Whenever either is given a FORWARD (or BACK) command, the other does the same; whenever either is given a RIGHT TURN (or LEFT TURN) command, the other does the opposite. This means that if the two Turtles start off facing one another, any Turtle program will cause their trips to be rnirror images of one another's. Once the learner understands this principle, attractive Kaleidoscope designs can easily be made.

A second microworld of linked Turtles, and one that is closer to Newtonian physics, applies these mirror linkages to velocity Turtles. No static images printed on this page could convey the visual excitement of these dynamic kaleidoscopes in which brightly colored points of light dance in changing and rotating paths. The end product has the excitement of art, but the process of making it involves learning to think in terms of the actions and reactions of linked moving objects.

These linked Turtle microworlds consolidate the learner's experience of the three laws of motion. But we have asserted that multiple microworlds also provide a platform for understanding the *idea* of a law of motion. A student who has mastered the general concept of a law of motion has a new, powerful tool for problem solving. Let's illustrate with the Monkey Problem.

> A monkey and a rock are attached to opposite ends of a rope that is hung over a pulley. The monkey and the rock are of equal weight and balance one another. The monkey begins to climb the rope. What happens to the rock?

I have presented this problem to several hundred MIT students, all of whom had successfully passed rigorous and comprehensive introductory physics courses. Over three quarters of those who had not seen the problem before gave incorrect answers or were unable to decide how to go about solving it. Some thought the position of the rock would not be affected by the monkey's climbing because the monkey's mass is the same whether he is climbing or not; some thought that the rock would descend either because of a conservation of energy or because of an analogy with levers; some guessed it would go up, but did not know why. The problem is clearly "hard." But this does not mean that it is "complex." I suggest that its difficulty is explicable by the lack of something quite simple. When they approach the problem, students ask themselves: "Is this a conservation-of-energy' problem?" "Is this a 'lever-arm' prob lem?" and so on. They do not ask themselves: "Is this a 'law-of-motion' problem?" They do not think in terms of such a category. In the mental worlds of most students, the concepts of conservation, energy, lever-arm, and so on, have become tools to think with. They are powerful ideas that organize thinking and problem solving. For a student who has had experience in a "laws-of-motion" microworld this is true of "law of motion." Thus this student will not be blocked from asking the right question about the monkey problem. It is a law-of-motion problem, but a student who sees laws of motion only in terms of algebraic formulas will not even ask the question. For those who pose the question, the answer comes easily. And once one thinks of the monkey and the rock as linked objects, similar to the ones we worked with in the Turtle microworld, it is obvious that they must both undergo the same changes in state. Since they start with the same velocity, namely zero, they must therefore always have the same velocity. Thus, if one goes up, the other goes up at the same speed.'

We have presented microworlds as a response to a pedagogical problem that arises from the structure of knowledge: the problem of prerequisites. But microworlds are a response to another sort of problem as well, one that is not embedded in knowledge but in the individual. The problem has to do with finding a context for the construction of "wrong" (or, rather, "transitional") theories. All of us learn by constructing, exploring, and theory building, but most of the theory building on which we cut our teeth resulted in theories we would have to give up later. As preconservationist children, we learned how to build and use theories only because we were allowed to hold "deviant" views about quantities for many years. Children do not follow a learning path that goes from one "true position" to another, more advanced "true position." Their natural learning paths include "false theories" that teach as much about theory building as true ones. But in school false theories are no longer tolerated.

Our educational system rejects the "false theories" of children, thereby rejecting the way children really learn. And it also rejects discoveries that point to the importance of the false-theory learning path. Piaget has shown that children hold false theories as a necessary part of the process of learning to think. The unorthodox theories of young children are not deficiencies or cognitive gaps, they serve as ways of flexing cognitive muscles, of developing and working through the necessary skills needed for more orthodox theorizing. Educators distort Piaget's message by seeing his contribution as revealing that children hold false beliefs, which they, the educators, must overcome. This makes Piaget-in-the-schools a Piaget backward--backward because children are being force-fed "correct" theories before they are ready to invent them. And backward because Piaget's work puts into question the idea that the "correct" theory is superior as a learning strategy.

Some readers may have difficulty seeing the child's nonconservationist view of the world as a kind of theory building. Let's take another example. Piaget asked preschool children, "What makes the wind?" Very few said, "I don't know." Most children gave their own personal theories, such as, "The trees made the wind by waving their branches." This theory, although wrong, gives good evidence for highly developed skill in theory building. It can be tested against empirical fact. Indeed there is a strong correlation between the presence of wind and the waving of tree branches. And children can perform an experiment that makes their causal connection quite plausible. When they wave their hands near their faces, they make a very noticeable breeze. Children can imagine this effect multiplied when the waving object is not a small hand but a giant tree, and when not one but many giant trees are waving. So, the trees of a dense forest should be a truly powerful wind generator.

What do we say to a child who has made such a beautiful theory? "That's great thinking, Johnny, but the theory is wrong" constitutes a put-down that will convince most children that making one's own theories is futile. So, rather than stifling the children's creativity, the solution is to create an intellectual environment less dominated than the school's by the criteria of true and false.

We have seen that microworlds are such environments. Just as students who prefer to do their programming using Newtonian ( Turtles with third law interaction are making Newton their own, children making a spectacular spiral in a *non-Newtonian* microworld are no less firmly on the path toward understanding Newton.

Both are learning what it is like to work with variables, to think in terms of ratios of dissimilar qualities, to make appropriate approximations, and so on. They are learning mathematics and science in an environment where true or false and right or wrong are not the decisive criteria.

As in a good art class, the child is learning technical knowledge as a *means* to get to a creative and personally defined end. There will be a product. And the teacher as well as the child can be genuinely excited by it. In the arithmetic class the pleasure that the teacher shows at the child's achievement is genuine, but it is hard to imagine teacher and child sharing delight over a product. In the LOGO environment it happens often. The spiral made in the Turtle microworld is a new and exciting creation by the child--he may even have "invented" the way of linking Turtles on which it is based.

The teacher's genuine excitement about the product is communicated to children who know they are doing something consequential. And unlike in the arithmetic class, where they know that the sums they are doing are just exercises, here they can take their work seriously. If they have just produced a circle by commanding the Turtle to take a long series of short forward steps and small right turns, they are prepared to argue with a teacher that a circle is really a polygon. No one who has overheard such a discussion in fifth-grade LOGO classes walks away without being impressed by the idea that the truth or falsity of theory is secondary to what it contributes to learning.