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THE TURTLE'S LONG SLOW TRIP: MACRO-EDUCOLOGICAL PERSPECTIVES ON MICROWORLDS

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I: CONTEXT

In the literature on microworlds, the writing that is closest to the "macro-educological" intent of this essay is Celia Hoyles' (1993) *Microworlds/ Schoolworlds: The Transformation of an Innovation*. By loose analogy with the usage of the terms macro-economics and micro-economics my neologism recognizes as a field worthy of serious theoretical attention the study of phenomena such as microworlds on the level of the functioning of *the system of education* or, as I should rather say, *the learning environment*. I use the opposing term "micro-educological" to encompass the kind of work most of us who care about microworlds do most of the time; typically work focused on the learning process or on the invention and study of specific means of learning. These macro and micro domains are not intended to be exclusive; for example, I shall be looking at epistemological questions that straggle between them and serve as a basis for a unified approach, which differentiates what I have in mind from typical writing by sociologists and historians of education.

Hoyles is on macro-educological territory when she describes a systematic "trivializing" tendency in School's[1] adoption of the microworld idea. For example, the idea of a computational world rich enough for children to make mathematical discoveries is turned into a set of virtual manipulative materials to exercise mathematical manipulations taught in a traditional "instructionist" mode. On a general level, I join her intention to explain the phenomenon, as rooted in incompatibilities of fundamental cognitive values. Yet, I am less willing than she

[1] Papert uses capitalized "School" to refer to an abstraction to which individual schools conform to a lesser or greater extent —the editors.

is to explain School's transformation of microworlds into innocuous forms, by arguing that it does not "want" the critical, creative ways of thinking that people such as she and I have tried to foster through their use. There is some truth in this explanation; indeed, School's faddish adoption of the term "critical thinking skills" has itself been accompanied by a denaturing transformation of *that* idea not very different from what it has done to the microworlds idea. But I think there is also something deeper. I shall be developing here, as my candidate for principle factor another kind of reason, which on one hand goes deeper, and on another projects a more optimistic view of the future of microworlds. In fact, my essentially theoretical essay has an activist subtext intended to incite members of the microworld community to prepare for a shift of status from a peripheral to a central position in mainstream mathematics education. I shall be suggesting some lines of micro-educological research directed at developing and studying particular microworlds, but my choices will be framed by macro-educological consideration of strategies for making effective interventions. Thus, macro-ecological considerations play a role here that they are not explicitly given in Hoyles' paper: In addition to explaining the tendency to transform, I use them also to suggest strategies for reversing it and even in some cases *exploiting* it.

My personal way of thinking about the denaturing transformation is woven from three threads whose meaning will become clearer as we proceed through this article.

The first thread is a view of School as a system in dynamic equilibrium whose various components have co-evolved to fit harmoniously together.[2] Changing any single component creates dissonances and sets in motion re-equilibrating processes. *Significant change will have to be systemic change.*

The second thread draws out far-reaching consequences of recognizing the curriculum itself as a component of this co-evolution, rather than the outcome of rational consideration of social or personal needs. The content of the curriculum—not in its detail but in its essence—has been selected (in a Darwinian sense at least as much as by deliberate choice) to fit School's methodologies. The topics that have been selected for inclusion are exactly the topics that best match School's traditional methods; it is almost as if these had been selected specifically to be the areas where the use of microworlds has the least (which does not mean no) learning leverage. *Introducing the microworld idea in isolation from ideas about radically changing the content of the curriculum is a set-up for defeat.*[3]

My third thread recognizes that the media (e.g., oral, written, digital) used to represent and manipulate knowledge exert an overwhelming influence on its nature. All aspects of School—and not least the content of the curriculum—are

[2] Think of a system of rings connected by elastic bands under tension to one another and to a few fixed anchor points. Pull one out of place and it will jump back when released.

[3] For an elaboration of my view that we should consider eliminating most of the content of school mathematics, see Papert (1996).

determined to a high degree by the epistemological constraints of static—"paper and pencil"—representational media. The role of computer-based microworlds is at its most powerful as a prototypical methodology for the dynamic media made possible by digital technology. In a system pervaded by the epistemology of static media it is a foreign body waiting to be rejected by the defense mechanisms (one might say "immune reactions") characteristic of dynamically stabilized systems.

These sources of resistance would not bode well for the chances of healthier uses of microworlds entering school practice but for one fact: The shift from the predominance of paper-based media to a predominance of electronic-based media is taking place under the impulsion of societal forces that are quite independent of the system of education. For the first time in its history, School is subject to a paradigm-threatening force capable of escaping the cold hand of its bureaucracy, the entrenched positions of the academic education establishment and even the myopia of partisan politics. Sooner or later the new media will pervade schools as they are systematically pervading all knowledge work.

When I wrote Mindstorms (Papert, 1980) almost a quarter century ago, "later" was by far the more appropriate term: Although some critics seemed blind to this, I carefully avoided giving a date to the book's educational visions,[4] which were explicitly linked to a level of digital presence that we are only today approaching. Today it is no longer only visionaries who will choose "sooner." The media shift will come about soon enough to be within the time horizons of practical-minded education planners and all too soon in relation to the time needed to develop new ideas to take full advantage of it. One can even dare give dates: certainly within the decade, probably within five years, the idea of a personal computer for every student will be widely implemented and seen by all serious mainstream educators at least as a serious option.

My easy optimism about the media shift (as opposed to a more guarded optimism about its educational consequences discussed below) is influenced by insights gained from campaigning in the American state of Maine (where I live) in support of a proposal that every student should be provided with a portable, connected, personal computer. A macro-educological lesson learned from this experience has led me to replace opinions like "It can never happen; the system is too conservative" by more quantitative statements like "overcoming the system's resistance requires a well designed intervention based on appropriate developmental principles applied with sufficient energy over a period for which my best current estimate is approximately a year."[5] When the idea of a computer for each student in Maine surfaced politically early in 2000 in the form of

[4] The fact that anyone could have read that book as "promising" that deep changes in thinking would come from a few hours a week exposure to Logo is an interesting data point for macro-educological consideration.

[5] The successful adoption of the laptop idea in Maine will probably reduce this time. But not by much.

an initiative by State Governor Angus King, it was roundly opposed by the legislature, by editorial writers and by educational organizations. The hypothesis "it cannot happen" seemed obvious to all except a small group of "visionaries." Three months later the hypothesis seemed to be even more strongly confirmed: Despite hard campaigning not a single legislator had yet come out in support of the idea; newspaper editorials were still mostly antagonistic, the education community was split between negative and skeptical. Yet the hypothesis was false. Eighteen months later the state government signed a contract with Apple Computers to provide an iBook for every middle school student in the state.

Of course I do not equate handing out computers with deep educational change[6] and still less do I think that if deep change comes about it will necessarily go in directions that would please the kind of person who would be reading this paper.[7] I would be very pleasantly surprised if in the first year more than 10 percent of the seventh grade teachers in Maine make use of microworlds in a form that would not fall on the "SchoolWorlds" side of Hoyles' classification. The shift in technological infrastructure cannot do more than create better conditions for a reversal of the transformations she deplores. But the conditions it creates will be *immensely* better conditions; moreover a 10 percent change in the first year would be a significant start for a potentially exponential dynamic process whose time constant is necessarily much longer than a year.[8]

Some of these conditions are logistical: for example relieving the inhibiting effects of limited access to computers on the development of programming skills and of classroom walls on collaborative work across subject boundaries. But the deepest are cultural. There is a mounting cultural discordance created by the sluggish (or even negative) rate of change manifested by School in the midst of a society that is changing at an accelerating pace. I see the static media as a dike that prevents the pressure of new cultural forms from flooding School. A connected laptop in every student's desk, satchel, and bedroom will give greater opportunity to all the actors in the system who want to break out of its restrictions. The strategies I present here are crafted to help them do so; but while even ten years ago I saw my goal as promoting change in a resistant system I now see it as influencing the direction of an inevitable flood which could well go in directions that would wash away my—or any!—intellectual values.

[6] I think I can claim an impeccable record on this score (see Papert, 1980, 1987).

[7] While the Internet offers many children new intellectual horizons it also encourages in many a "grasshopper mentality" and involvement with influences they may not be equipped to handle critically or emotionally.

[8] Estimating the "half-life" of the "old ways" after the technological shift is an interesting project for research. My estimate, based on rough statistics on staff turnover and on how teachers change, is four or five years. Of course the actual number depends on how one measures, but I find that it is not very sensitive to choices.

A final point about my interpretation of the events in Maine: In the United States there is a saying "Where Maine goes, there goes the nation." Maine ranks low among the states on economic and population statistics. But it ranks high in spirit. The fact that it could make this decision is a straw in a wind that is blowing over the planet. One small country—Iceland—has already adopted the principal that every high school student must have a notebook-style computer. Several hundred schools in Australia and in the United States have implemented "the laptop option." Some large American school districts are seriously discussing doing so. In third world countries there is an emergent sense that the development of an inexpensive personal computer (which is certainly technically feasible) provides the only hope of closing the planetary knowledge gap. Maine's decision was not an isolated event: Even if new developments, perhaps the consequences of September 11, 2001 were to reverse the decision, it would remain significant as one among many indicators of a direction that can in any case be anticipated on general principles.

II: UNIFYING MACRO AND MICRO

Everyone who has tried to use microworlds as a basis for innovation in education must have been frustrated at some time by the fact that the concept is so prone to epistemological dilution: The language and a simulacrum of the idea are adopted but on closer examination one finds that the essential epistemological thrust has been pared down to a vanishingly small residue. To deepen understanding of the phenomenon, I begin by noting that it is not unique to microworlds. Tyack and Cuban's (mostly[9]) excellent book *Tinkering Towards Utopia* (1995) surveys 20th century American education reforms and offers an interpretation not unlike Hoyles' of their consistently disappointing results. Paraphrased slightly to fit her language they say: Reforms try to transform School but in the end School transforms the reform. Radical new ideas are "normalized" to fall in line with, or even bolster, School's old ways.

In a review of Tyack and Cuban, I (Papert, 1997) suggested that this process is strikingly similar in form and function to what Piaget[10] calls "assimilation." Here, I develop this manner of thinking about School's resistance to change—its "conservatism"—but with a greater emphasis on a positive aspect. Piaget uses the concept of assimilation to explain the "conservatism" manifested by children who

[9] The book egregiously misunderstands of the nature and roles of technology. At its lowest point it lumps together Edison's famous prediction about film replacing books with the most advanced uses of computers to make the "failure" of the first a source of doubt about the other. See my review (Papert, 1997).

[10] It has become fashionable to believe that "Piaget has been refuted" by research on the innate capabilities of babies. Indeed, much of what he believed was mistaken. But "epistemologie genetique" still offers the most powerful framework for thinking about children.

stick with certain ways of thinking despite "evidence" or even pedagogical pressure to the contrary. But in the end the children move on; assimilation eventually gives way to accommodation and in Piaget's view the temporary conservatism plays an essential role in preparing for the change. I believe that we are approaching a time when School is about to move on to a new stage of educational thinking. Perhaps the assimilative conservatism displayed by School in its transformation of microworlds and other innovations will one day be seen to have played the same necessary role in the development of this new stage. But historically necessary or not, the assimilative phenomenon is so powerful that without understanding it—*and using it*[11]—we are doomed to be forever frustrated in our attempts to intervene in the development of the system. It is quite paradoxical that education theorists who are committed in their thinking about children to a developmental approach give little or no serious theoretical attention to the developmental dynamics of the system of education itself. Their mode of bringing ideas to schools is closer to an instructionist than to a constructivist way of bringing ideas to children—and fails for the same reasons.

This perspective leads to a shift in focus in considering educational innovations. Traditionally, we look primarily at how the particular construct contributes to a student's learning when it is "properly used." Instead, I suggest looking not at its "proper use" but at its "likely use" and at how this will contribute to the development of the system. Concretely, the guiding questions should be the following. 1) What kinds of innovation are likely to be appropriated by the system? 2) Under what conditions will their *assimilated* forms enter into the formation of new structures capable of growing *in accordance with the system's own internal logic* into the kernel of a new equilibrium? The use of microworlds is a prime answer to the first question provided that attention is paid to the second, which in my view leads to breaking away from away from subservience to the existing mathematics curriculum. In fact, it suggests breaking out of the confines of what is usually defined as the province of "mathematics education." My projection into the near future of the image of "mathematics educator" at the elementary levels is not necessarily someone who "teaches math," but possibly someone who brings mathematical values and ways of thinking to the design of microworlds primarily seen as belonging to other domains. I see this process as reverting to the historical line of development of mathematics, whose first inchoate glimmers took the form of new ways to think about issues more typically like building pyramids or telling fortunes from the stars than like proving theorems or finding patterns in numbers. Pure mathematics as a separate activity emerged slowly with time. I have long argued that the real sense of constructivism requires us to recognize that School artificially and mistakenly reverses this order and that

[11] Think the "martial arts" technique of using the opponent's movement to strengthen one's own. Think "Trojan Horse."

reversing the reversal requires giving up the procedure of "teaching math" and then "applying it" or even of "teaching math by applying it to everyday problems." Examples in the next section will illustrate very different ways of thinking about fostering a process of emergence of mathematical ideas not only in the minds of students but also in the culture of School. It will also illustrate my proposal that constructivist methodologies be applied to fostering the development of School as much as of children. New ideas about mathematics education cannot be brought (injected) into School by a transmission process any more than they can be injected into the minds of students; being as constructivist in relation to the development of School as we want to be in relation to the development of children implies seeking conditions for a natural development of mathematics itself (mathematical ways of thinking, mathematical values, a mathematical aesthetic) in the world of School.

Consider an example.

III: DIFFERENTIAL CALCULUS IN THE ELEMENTARY SCHOOL?

Of course the idea is absurd if your image of differential mathematics is something like "D of x to the n is n times x to the n minus 1." But what is really fundamental to "the calculus" is a cluster of ideas that could be conceptualized in a context of computer presence and computer fluency in forms that will be not only accessible, but also truly useful to very young children. Here, I discuss only one of them and only just sufficiently to make the point of principle.[12] Consider the "turtle circle" concept. The classical turtle microworld is defined by a turtle, standard FORWARD, BACK, RIGHT, and LEFT commands and a suitable subset of Logo programming. The traditional way to make the turtle move in a circle is by repeating:

FORWARD <a little> RIGHT <a little>

Glossing over details, this captures a kernel of what would be expressed more formally by the idea that a curve can be represented—and *usefully* represented—as the limit of a concatenation of straight-line segments. Before discussing whether this is an appropriate idea for a very young child let us first agree that we are not discussing the formalism: It is of only superficial consequence whether the Logo commands are expressed by text or by hieroglyphs, whether the child pounds on a keyboard or manipulates a mouse. The more serious questions are about what makes this idea of a circle valuable.

What kind of criteria should be used to assess "value?" As a mathematician, I might see value in the fact that this child is in contact with an idea that played a key role in the development of mathematics. But while I might personally give some

[12] See the references for more discussion.

weight to this consideration, I am sure that that no primary school teacher would think that it is anywhere near a good enough reason. The conflict is significant. Indeed, the crux of the difficulty in designing the strategies for effective use of microworlds as carriers of mathematical ideas is exemplified by divergences between what would be meaningful to a mathematician and what would be meaningful to teacher with a typical teacher's background. Consider, for example, a range of ideas about the use of the Logo-based turtle microworld. I first proposed this as an entry point for otherwise inaccessible mathematical ideas; among them those that connect the turtle circle with differential mathematics. But very few (very, very few) of the many tens of thousands of teachers who have used this microworld in their classrooms think of it in this spirit. Most, in a classical example of the phenomenon discussed by Hoyles, use it as a "virtual manipulable" for the study of topics already in the curriculum, such as properties of the simplest polygons. The microworld is undoubtedly a good instrument for this purpose, but it is far from necessary and certainly does not open directly into radical educational change. I don't believe that this purpose would justify the trouble.

My own struggle to develop criteria that work on both sides, for me and for the teacher, has led to the program of elaborating an epistemology of "idea power" (Papert, 1996, 2000). Drawing turtle circles does not in itself rate high on my scale of idea power and I sympathize with teachers who do not see it as a rich activity and prefer polygons. But it comes closer when it is embedded in a larger set of activities most of which would not be counted as "math" in schools.

I have recently been very much engaged (when not campaigning!) in working with programmable physical robots—mostly but not necessarily constructed with modified versions of the LEGO "Mindstorms" materials though never programmed in LEGO's programming system. Consider the project of programming goal-seeking behavior such as going toward a light. A key idea in this is "thinking locally to obtain a global effect." This idea is expressed, for example, in the following advice: "Don't worry about the form of the path the robot will follow; think only of the differential of its direction—at each moment ask whether it would do better to turn a tiny bit left or a tiny bit right." Once understood this model of control of motion earns a high rating in the pragmatic dimensions of idea power by opening doors to a large range of interesting applications.

These applications obviously include other problems of guidance of physical vehicles. But what gives the idea a high rating in a more intellectual dimension of idea power is the diversity of its connections. Consider, for example, the turtle circle, the light-seeking vehicle and the family of "getting hotter, getting colder" games. On the surface these are quite unrelated situations. The ideas used to program them—for example, "think in tiny steps," "use feedback," and recursion—gain intellectual power from their convergence. They also gain power by connection to a rich range of scientific and social domains. For example, the behavior of many simple creatures is controlled in exactly the same way. It is as if nature discovered the same principles as a child might do in a microworld of goal-seeking artifacts. What a sense of personal empowerment can come from the thought of one-ness with nature as a problem-solver!

It is this connection to situations that are not obviously the same that serves best to incite reflection, and whether or not it is cast in language that is recognizable to the teacher as "math" this is quintessentially mathematical reflection. *It brings together phenomena by virtue of sharing the same formal structure.* But paradoxically *not* casting it in a language that is recognizably "math" might be exactly what makes it assimilable to the school culture in a form that retains its mathematical essence. Consider, for example, a science teacher for whom what is exciting about engagement with feedback is its connection with many biological situations such as the goal seeking behavior of simple creatures and homeostatic process such as the maintenance of body temperature (or, perhaps with more motivating power for some students, the maintenance of body weight.) In this teacher's mind, the idea of differential process is good *biological thinking* rather than *mathematics*. Insisting on seeing it in its mathematical guise is at best irrelevant, at worst likely to inhibit its appropriation.

What is suggested, by the example of the biology teacher, is that skill in designing microworlds is what will allow the lower school mathematics educator to be most effective in laying the foundation for mathematical thinking. This could mean becoming a "good biologist" (or physicist or whatever) and largely (note the word) reserving the presentation of pure mathematics for later years in the student's development.[13]

When I have made this kind of recommendation in the company of math educators, I have often been told that it is already being done: Most new presentations of mathematics take pains to show how each concept can be "used in the real world." But using biological application to *illustrate* a concept in the mathematics curriculum is diametrically opposed to what I am suggesting in at least two respects. Both flow from the question: Which comes first, is the biology there to elucidate a piece of math or is the math there to help in biology? The first, is about experiencing the role of mathematics as a body of knowledge to which one can turn when one has run into a real *personal* problem and this is more likely by far to happen when students are engrossed by a long term biological project in which they have a passionate interest for its own sake. The second, is about breaking out of the confines of the math curriculum: My example was not about illustrating or giving relevance to what is already in the curriculum but about creating situations where something new (in this case the cluster of differential concepts) might find meaning and take root in the school culture.

What I am suggesting as a model for thinking about mathematics in schools is close to the historical development of mathematics. Long before pure mathematics

[13] See Papert (1996) and especially my forthcoming publications for discussion of the idea that *mos*t of what we include in school mathematics serves no purpose at the age at which it is taught.

existed as a self-contained discipline whose methods could be applied to such domains as science or engineering or commerce, mathematical *ways of thinking* began to emerge in these domains. School has reversed this historical sequence in its teaching of mathematics not because educators foolishly misunderstood history but because they had little choice. For obvious practical reasons children could not go through such experiences as navigating the oceans, building pyramids, planning for floods, or predicting the stars in which mathematical thinking had its embryonic beginnings. Pencil-and-paper media do not allow immersion in any comparably generative domains. Computers do, especially in the form of microworlds. But, to be authentic the microworlds must genuinely belong to these domains and not "use" them to support the development of mathematics.

To round off my argument that domains such as biology might present mathematical concepts with an easier entry route into School, I must of course deal with the obvious question: why would the biology teachers not also trivialize the microworlds? Indeed they might. But several factors make it happen to a lesser degree.

First, they have less of an ideological block. In the world of mathematics "the differential calculus" has been categorized as something for "advanced students" at a later age. Second, these ideas can be useful to them in their daily work. On the other hand most teachers of elementary mathematics have no use whatsoever for any of the ideas I have mentioned in this section. The ideas don't help them do what they are expected to do. The ideas are not relevant to their curriculum. But the ideas are very relevant to the trends in biology toward paying more attention to ecological studies as well as to traditional topics such as the observational study of simple creatures.

Third, biology is richer in connections with the larger culture in which the children live.

Finally, as Piaget consistently reminded us, the biologist's maxim that ontology recapitulates phylogeny has at least a metaphorically suggestive analog here: Perhaps it is not only advisable but necessary for individual children to acquire knowledge by a process (ontology) that follows the evolution of knowledge on a historical scale (phylogeny.)

IV: PRECURSORS

In the previous section, I presented some ideas about strategies for helping a particular family of microworlds, closely related to my turtle, find a place in schools. In the next sections I develop a larger view of microworlds. Again, I take the Hoyles paper as a starting point and try to go further in the directions she has defined.

Hoyles tracks the microworld concept through a line of evolution which I recast in my own language and simplify slightly by reducing it to four successive phases (P1, P2, P3, P4) and the three transformations (T1, T2, T3) that mark the transitions from each phase to the next. P1 was developed in the mid-sixties at the MIT AI Lab (of which I was at the time co-director with Marvin Minsky) in our search for a theoretical foundation for Artificial Intelligence. It was influenced by educational concerns and especially by Piagetian theory but was not explicitly about education: The microworld idea was used for robots before it was used for children. The first transformation, T1, gave it an educational intention and began the search for examples of microworlds that would be better suited to children than those conceived for AI. For the first decade of its life, the transformed concept, P2, continued to live almost entirely at MIT in the Logo Lab, which had been set up within the AI Laboratory. There it developed into a keystone of a radical vision of education, which was exposed to a wider community of educators with the publication of Mindstorms in 1980. The coincidence of this publication and the first infusion of microcomputers into schools opened the way for T2 and P3.

P3 is closest to what I would guess to be the spirit of most of the essays in this volume. The P3 meaning of "microworld" was part of a vision in which "school as we have known it" will have disappeared. P3 turns "microworld" into a practical tool for innovation and research in contemporary schools. Hoyles uses as a specific example of a wide movement based in this sense of microworld the exceptionally productive academic community of researchers in mathematics educators known as LME[14]. The microworlds devised or studied by LME (as well as American research groups particularly at University at Buffalo, SUNY[15] and at MIT) were designed to retain from the Mindstorms vision such constructionist qualities as *exploratory, playful, personally meaningful rooted in "kid culture*" while coming close enough to the reality of school mathematics to permit adoption in a reformist rather than revolutionary spirit[16]. They did come closer, but evidently still not close enough to avoid the transformation T3 : P3 —> P4 which is signaled by Hoyles' title—*Microworlds/Schoolworlds*—and given the central place in her discussion of transformations. What is eventually adopted by schools (P4) has been stripped of the constructionist qualities valued by the innovative researchers and forced into a traditional instructionist mold. With this final transformation "microworld" becomes a mere exercise to illustrate or practice content taught in a typical curriculum-centered instructionist classroom.

The place where I most want to add to her account is in bringing out the extent to which T1 and T2 prepared the way for T3. This line of thinking is prefigured in the previous section where I argued that T2, by narrowing the use of computer-based microworlds in schools to applications within the existing mathematics

[14] E for education; M for mathematics; L ambiguously for Logo or Learnable.

[15] See, for example (Clements, Battista, & Sarama, 2001; Clements & Gullo, 1984; Clements & Sarama, 1996).

[16] In a more detailed study, I hope to give more macroeducological attention to the importance of a grassroots production of microworlds by classroom teachers which has collectively produced at least as much as the academic groups.

curriculum, exposed the microworld idea to the reductive T3. In this section I look further back in the evolution of the microworld idea to its earliest phase as a general theory of learning encompassing phenomena that existed long before computers or schools or mathematics. The discussion concludes in the following section with a bold thesis: Microworlds understood in this more general way play a central role in the home-style learning of early childhood; they have been partially displaced by school-style learning because of the limitations of pre-digital media; they will return to their natural place in the wake of new media.

I begin with a series of vignettes of microworld-like situations of a kind that influenced the first formulation of the idea. These are chosen also to highlight different aspects to emphasize the multi-dimensionality of the idea.

Microworld Vignette 1: Microworld as Simplified Reality

> Walking across an alpine field I see an interesting wildflower and look around for landmarks to help find it again: an old barn, a clump of pine trees. But returning the next day I am confused by other barns and clumps of trees. If only the world were simpler!

It is simpler for the bees that find their flowers without being confused by barns and pine trees. Their eyes don't see such things and so their world is simplified. One might say, adapting the jargon of this volume, that the bees live in a microworld determined by their sensory systems. Ethologists don't quite use the term microworld, but the guiding idea behind it is closely related to their important insights into how beings with simple nervous systems can handle the complexities of the world. Nature did for the honeybee one part of what educators try to do for humans when they create simpler worlds to get around the fact that the "naked real world" is just too darn complicated.

Readers with a taste for history might find it instructive to know that this kind of ethological consideration had a salient presence in the culture of the MIT Artificial Intelligence Lab in the nineteen sixties, at the time when the concept of "microworld" as a category for thinking about human learning began to emerge. Others will find the connection with ethology somewhat tenuous; however, what is not tenuous is a connection with a microworld-like interpretation of components of children's development that I refer to as "spontaneous microworlds," because they were not deliberately set up by educators with a pedagogical intent. For me, this connection is central to understanding microworlds as providing a basis for a more "natural" mode of learning than the school-style mode and contributes significantly to my anticipation of a central role for microworlds in schools.

Microworld Vignette 2:
Microworld as Mental Structure

> Five-year old is asked about a row of eggcups each containing an egg: "More eggs or more eggcups?" Answer; "No. Same." Eggs are removed and spread out. Eggcups are clustered together. Same question. New answer: "More eggs."

Now someone might be tempted to think this is a "simple misunderstanding" that could be cleared up by saying (in some age appropriate language) something like: "No, I meant numerically more, not spatially more." But in fact you can't do this. What giving the non-conservation answer tells us is that in this child's mental space the "number microworld" has not yet been delimited. Number has not been split off from a general idea of "moreness" and "quantity" that includes space occupied and geometric arrangement.

Besides being unorthodox Piagetian theory, this passage will strike many as unorthodox in its use of "microworld" to refer to something internal, something that exists in the mental structures—in the head—of the child rather than in the external world. This usage runs diametrically contrary to P4. But as one goes back in the line of evolution, it is has greater naturalness. In the days of P1 it was actually the primarily meaning. One of my goals here is to reinstate it, not instead of, but in addition to, the more physical meaning so that we would talk about external and internal instantiations of a microworld. The following vignettes show aspects of this double sense by looking at examples first from the lives of children and then from early work on AI. These are small steps leading to the cheeky suggestion that the creation of the number microworld in the sense I am giving this vignette might be prototypical of the kind of mental construction that is most central to developing mathematical thinking. The development of conservation of number is not about the properties of numbers: Lots of children who say there are more eggs than eggcups will concede, "they count the same . . . but there are more eggs." It is about developing a mental structure that will keep out considerations (like space occupied or color) that do not belong to the microworld. I see a close affinity with the difficulty beginning students notoriously have with Newtonian mechanics. The difficulty does not lie in understanding that something could move forever if there is no friction. That's easy. The real difficulty is adopting the mindset of keeping out of considerations anything that does not belong to this formal system, the mental set that in fact defines the idea of formal system.

Microworld Vignette 3:
Microworlds in Everyday Life.

> I take setting the dinner table (a place setting for each diner, a fork, two knives and a spoon for each place) and even dressing (e.g., 1-1 correspondence in foot—sock—shoe.) as simple cases of external microworlds related in content to the development of number in general and to internal number worlds.

These might not be the most creative microworlds—although for a toddler they are far more challenging and creative than they appear to an adult—but they have the advantage of authenticity and presence in many variants. They surely play a role in the child's development of numerical thinking.

It is not inconceivable that in a an evolution of societies an analog of Darwinian selection could have favored those whose social customs such as eating and dressing habits happened to support powerful cognitive capacities such as the sense of number. Such co-evolution is even more plausible in the development of toys and games for children. Although we obviously cannot assume that all features of life that support cognitive growth came into being for that purpose, we could take more seriously in the study of individual intellectual development the opportunities for serendipitous microworld genesis.

Microworld Vignette 4: Microworlds as Convivial tools

> In a foreword to Mindstorms I described an example from my own childhood and take the fact that this has been very widely quoted as evidence of a resonance with common personal experiences. The simple kernel of a complex story is that too early[17] in life for any but the vaguest memories, I became fascinated with gears, and especially with the differential gear of an automobile. What I do remember clearly is that before I went to school at age 7, gears had become a serious interest and that they served as entry points for numerous ideas. Some of these were quite general; for example, the idea that behind what one sees (in social and psychological domains as well as physical) there are interesting hidden mechanisms. Some were more specific. For example even today a relationship like z=x+y feels to me like a transmission shaft whose rotation (z) is distributed in varying proportions between the rotations (x and y) of two wheels.

Without entering into semantic discussions about whether "gears" constitute a microworld, I want to use my experience with them to identify an issue that comes up in less marginal cases. This is a distinction between two functions. In one function, the gears provided me with an opportunity to learn about other matters, for example fractions or functions of several variables, which once learned had no further connection with gears. In the second function, the gears would be incorporated into in mental models that might continue to be used throughout life[18]. This double function played a role in the (P1/AI) sense of microworlds I discuss in the next section and continues to be important for me in the design of

[17] I have a photograph of me with gears that I can date to early in my third year.

[18] I hope that in future publications I shall be able to offer stronger objective evidence for the importance of this function. In the meantime I rely on personal experiences for which I have strong "subjective evidence." Readers might note a relationship between this function and ideas that have been used in more or less related contexts: diSessa's "p-prims"; what Minsky calls "exploitation" in *Society of Mind*; and my term in Mindstorms "object to think with."

microworlds for learning: The intention of providing a stepping stone for a learner to attain something very different might diverge from the intention of providing a framework for building permanent mental representations.

V: BLOCKS WORLDS

My earliest recollection of the word "microworld" was in conversations with Marvin Minsky in the mid-sixties. Very soon constructing "worlds" had become a major meme in the intellectual world (so to speak) of the MIT AI Lab. In the following decade, such language became part of the growing computer culture's language. It is impossible, even if it were interesting, to determine the extent to which the meme spread or was independently reborn, because it is such a natural way to think about what one does with computers when one goes beyond manipulations of linear symbols. But in either case, the word "worlds" as generally used lacks the specific epistemological meaning as a form of knowledge carried by the constructs made in the AI Lab.

The simplest and most famous of these was the "Blocks World," which in some significant ways stood to the robots we were designing as many computer-based microworlds stand to human children. The ultimate goal of our research was to learn how to build entities capable of dealing intelligently with the full world in which humans operate. An important theoretical choice was between two directions. We could try to build a robot that would cope with the full complexity of the world encountered by a human child. Like a baby, the robot would begin by coping poorly, indeed very poorly, and gradually improve. The Blocks World exemplifies the other direction: Designing a simplified world with which a robot could cope in a masterful way at a very early stage of development. A typical Blocks World (there were several versions) provided a surface on which could be placed physical blocks of varying shapes, sizes and colors. A typical task for a robot in this world would be: Put the small red block on top of the big blue block. To do this, the robot might have to recognize that the only small red block was at the bottom of a pile of other blocks, which would first have to be removed as would other blocks that obstructed the top surface of the blue block.

A second, and epistemologically deeper, concept of simplified worlds comes from contrasting two interpretations of what the performance of the robot in the Blocks Worlds might mean for the larger AI enterprise of constructing a robot with general intelligence. The view of AI that was prevalent in the early sixties would have liked to see the performance of such a robot in the specific world as an instantiation of very high level, essentially abstract and very general, computational structures. For example, the most elegant and intellectually cleanest version of this approach is seen in Newell and Simon's early idea that the robot's actions could be generated by a General Problem Solver (GPS) conceived as a powerful, highly recursive engine for working with goals and subgoals in general. The same GPS, in principle even the same computer cycles, would operate in choosing the next move in a chess game: At that level it "knows nothing" about whether it is dealing with blocks or pawns.

The opposite theoretical view tends to minimize (or even deny) general intelligence in favor of very specific knowledge. The general robot would use different, specialized computational processes in different situations. For example it might have within itself an "internal blocks world" together with a large number of similar specialized structures. Some of the tension between these points of view would later spill over from AI to the then still embryonic field of "cognitive science" which would grow strong in the seventies and powerfully influence educational thinking in the eighties. For the ideas I am exploring here, the most relevant spill-over is seen in the interplay between the search for very general "high order" forms of knowledge and the widely held view that "expert knowledge" is "domain specific" while novices rely on general methods.

Two potential contributions of the microworlds idea to this interplay have not entered the mainstream of cognitive theory: The idea that what is specific can often be represented as a "world" (illustrated by Vignette 2) and the idea that "abstract" knowledge can be re-conceptualized as a particular way of using concrete knowledge (illustrated by vignette 4).

VI: A THREE STAGE THEORY OF THE DEVELOPMENT OF LEARNING

The transfer of these ideas to support a transformative vision of school is best understood in the framework of the developmental model that has guided my own thinking, a model I can present here only in a grossly over-simplified form. This model also helps to identify the areas of learning that best fit with mainstream cognitive theory and those in which the microworlds idea has the most to contribute.[19] It is formulated as three stages, with the caveat that the word must be taken in a loose sense that allows blurry boundaries and considerable overlap. Stage 1 covers the period of universally successful learning that begins with the newborn. It is characterized by direct exploration of the immediate environment. It is essentially exploratory, self-directed, experiential, and non-verbal. Classical cognitive theory with its emphasis on symbolic language-like representations of knowledge has to struggle to fit this kind of "home-style" learning. Microworlds in the senses suggested by vignettes #2 and #3 play a large, if not dominant, role.

Stage 2 is characterized by the acquisition of mediated knowledge—questions and answers, stories, and pictures. The opening to this stage comes about as a direct result of successful stage 1 learning. As the child's understanding of the world develops, so do interests that go increasingly beyond the possibilities of direct

[19] The idea was first articulated as "three phases" in my book *The Connected Family* (Longstreet Press, 1995) *but* was already implicit in Mindstorms. What is presented here is a highly schematic summary treatment.

exploration of an immediate environment. The pursuit of these interests requires learning that is more verbal in its epistemological structure and more strongly other-directed in its acquisition. These characteristics reach their apogee in school. Epistemologically, this stage is favorable to mainstream cognitive theory and unfavorable to the use of microworlds either in practice or as a theoretical model.

As stage 1 development leads into stage 2, so stage 2 leads to the acquisition of skills that will, in principle, allow the individual to revert to a self-directed exploratory mode of intellectual work. In particular, reading and related research skills offer an extended immediacy: the library (and later the laboratory or the studio) becomes a world that can be explored by older individuals as young children explored their immediate surroundings. Thus stage 3 is opened. We see its presence in research institutes, in the boardrooms of creative companies, in artists' studios. Like stage 1, it is dominated by self-directed largely exploratory work. Unlike stage 1, it is open-endedly extensible. But the transition is precarious and eliminates the majority of children who either never reach the third stage or arrive there handicapped by grave psychic scars.

In this perspective the essential contribution of the development of new media is to allow a smoother, less precarious transition from the first stage to the third. Or perhaps one could say that it eliminates the stage transition altogether by blurring out the sharp boundary between an immediate world that a child can see, touch and feel, and everything that is far away in time and space. This account is too abridged for such distinctions to matter. What is important here is a view of traditional School as primarily structured by the needs and limitations of stage 2 learning. Access to online information (which in principle does not have to be text-based) and to richer microworlds could avoid the child's forced dependence on adults[20] to provide knowledge and bypass the need to go through the long process of mastery of reading/research skills before reaching the promised land of intellectually exciting areas of work.

It was obvious from the beginning that the creation of a model of school that would allow this path of development would not be an easy task. In the 1960s when these ideas began to form the technology itself was barely adequate. But we knew that better and less expensive technology would come. What would take resolve as well as time would be developing sources of information and microworlds that would enable children to appropriate powerful and exciting ideas. The work on Logo, turtles, and related ideas was begun in the spirit of a first step on a long journey. The final section of this essay gives some insights into why the turtle seemed, and still seems, to be a good choice not only for its own value but also as a carrier of the more general ideas.

[20]For an early discussion of problematic aspects of too great a degree of independence see my paper, "Redefining Childhood: The Computer Presence as an Experiment in Developmental Psychology," presented at the proceedings of the 8th World Computer Congress: IFIP Congress, Tokyo, Japan and Melbourne, Australia, in October, 1980; also available on www.papert.org.

VII: THE TURTLE'S TRIP

Microworld Vignette 5: Getting to Know You

> A child is introduced to the turtle with an invitation to "get to know it . . . find out what it can do."

The discussion of microworlds in Mindstorms[21] is framed by rejecting as incomplete the dichotomy reflected in "knowing that and knowing how" or "facts and skills." When I say "I know Boston" or "I know my wife" I am saying something that does not fit either side of the dichotomous classification. These statements refer to forms of knowledge that are central to everyday life. They also have a place in the conduct of science reflected in language like "getting to know an idea" and "exploring an area of knowledge." Yet they are not at all recognized in the official epistemology of school math or science and have very little place in the current paradigms of cognitive science.

Of the many roles of microworlds recognized in Mindstorms the one given the greatest weight is remedying this deficiency in a manner illustrated by four features of the turtle. The first is the possibility of getting to know the turtle by using what might be the most powerful known heuristic: relate the unknown to something you already know and giving it a special affective force by choosing yourself as the something. (The use of the turtle in Mindstorms is closely associated with the idea of "body-syntonic" representations of knowledge encouraged by a technique called "playing turtle" which consists of bringing a problem cast as turtle geometry out of the computer screen onto the floor and putting yourself in place of the turtle.) The second feature is the turtle's embodiment of one of the key ideas in applied mathematics: by getting to know the turtle you are closer to getting to know its conceptual "friends." The third is about what the turtle can do for you once you do get to know it[22]; unlike school math it can be used to produce graphics, to support the creation of videogames and, especially, to gain entry into other equally powerful ideas. And the fourth is that a child can grasp all four features both on a level of use and on a level of meta-use: beyond solving any specific geometric problem the technique of "playing turtle" can be used to give a child an explicit understanding of such concepts as heuristic and theorem.

Microworld Vignette 6: Scary Intimacy

> A teacher has heard the kind of talk of the previous paragraphs but prefers to teach knowledge as facts and skills rather than through identification with a computational object. It keeps her body out of it and she certainly doesn't

[21] Papert (1980, Chapter 6).

[22] My colleague and ex-student David Cavallo (MIT Ph.D. Thesis, 2000) likes to refer to the three aspects as the roots, the shoots and the fruits of the work.

> think that an eight-year old would could understand or be interested in talk about "heuristics." That's not stuff to talk to a kid about.
>
> So after the child has drawn a triangle and a square and put them together to make a house everyone wonders whether it was worth it.

The point of these last two vignettes is not specifically about turtles but about microworlds in general. The first illustrates a presentation as a big idea. The second illustrates a teacher who is diffident because she has not believed that it is a big enough idea to get over her reticence. The two together make me add another facet to the explanation of the tendency to epistemological dilution. Reticence. Unless the microworld ideas are presented and accepted as big ideas they are not worth the trouble and will be trivialized. They cannot exist at an intermediate level! Of course, if they are presented as big ideas many, indeed most, educators will reject them as too challenging. From a macro-educological systemic point of view a question for study is whether there is a level at which a formulation sufficiently powerful to have an effect will be accepted by a number of educators great enough to have an effect. This strategic consideration is related to my comment that the transformation T2 that made radical ideas fit more comfortably into the established culture of School mathematics also prepared the way for its neutralization.

There are many other reasons-in addition to paternal indulgence-for choosing the Turtle as my prime example to concretize the themes of this essay. It has a venerable historical status: I think it certainly safe to say that the Turtle was the first computer-based microworld deliberately conceived with a pedagogical intent and very probably safe to say that it has an unequalled track record in terms of use and intellectual content. It is also provides the best example of dilution: while the turtle has been very widely taken up—at least twenty and possibly a hundred million children have had some contact with it—this has almost always been in a form that falls far short of its potential, and intended, intellectual content. But the considerations that felt strongest came from speculation about a sense in which the turtle has remained quite singular. In *Mindstorms* my presentation of the Turtle was immediately qualified by a statement that "its principal role here is to serve as a model for other objects yet to be invented." I meant that seriously, and even expected that the publication of the book would incite others to invent these objects. Invention there has been, but almost entirely of other turtles and other ways of using them. Abelson and diSessa have turtles crawling on a variety of surfaces, Reggini has them flying through space, Resnick and Wilensky have them moving in crowds. But these are all still turtles. I do not know of any other computer-based mathematical object created for a learning-related microworld that has a track record approaching the turtle's.

Why this is so is itself a question that deserves some attention. Quite possibly the answer is quite trivial. Perhaps the failure is simply blindness on my part to inventions have actually been made. Or perhaps it simply reflects the small number of researchers so far engaged in this kind of work. But there may be a deeper epistemological reason connected with some unique characteristic of the turtle. Consider for example the following simplified hypothesis relating the arrival of the computer to a critical turning point a couple of centuries earlier in the history of mathematics. It is not unreasonable to see Newton at a transition point between mathematics of static and mathematics of dynamic objects. But although the differential calculus provided a formalism for movement it had to use the static medium of written formal expressions. This made for a high threshold of entry into the new ideas. Microworlds of dynamic screen objects lower the threshold by providing a formalism that is closer to the spirit of the mathematical ideas themselves. It also happens to be closer to intuitive thinking that is shared by non-mathematicians and, most relevantly here, by children. Hence the turtle stumbled into a special niche determined by an intersection of three lines of development: the historical development in mathematics represented by Newton and Leibniz, the modern development in expressive media represented by the computer, and the psycho-epistemological development of the individual child.

If this model has truth, the slow pace of the turtle's progress into the school world may only reflect the sluggish transition of School to the new media. In a famous story the other kind of turtle, usually known in this context by its British name, wins the race after being left behind by the hare. Perhaps ours will too.

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