1. Computers and Exploratory Learning: Setting the Scene

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Love is a better teacher than duty.
—Albert Einstein

Exploratory learning names a family of approaches to education that share principles like the following:

- Learners can take substantial control of their own learning. We should cultivate them as responsible intellectual agents.
- Knowledge is rich and multidimensional. There is no need to follow narrow, prescribed paths to enlightenment.
- In a similar way, learners are diverse. There is no need to christen any one intellectual style or short list of achievements as preferred.
- In an appropriately designed physical and cultural context, learning can often, if not always, feel easy and natural.

These general directions are scarcely modern inventions. The most casual reader of Dewey, for example, will find a strong family resemblance to these principles in his philosophical writings. However, there are two more distinctly modern trends that have brought exploratory learning from a visionary's chimera (which it surely has been regarded by many) closer to the mainstream. First, constructivism has emerged as a strong scientific orientation and political force. As a scientific orientation, the gradual construction of new knowledge out of old on the basis of the learner's own interpretive powers now has endless support in research studies. Politically, constructivism has clearly spilled over into, for example, the current mathematics reform movement. Problem solving and even a move toward projects-based learning are sanctioned at the highest levels not only in academia but in "real-world" professional circles such as framework documents that guide development of textbooks and curricula for many U.S. states.

The second modern impetus toward exploratory learning is the emergence of computers as a genuinely practical basis for revised instructional forms. Advocates of exploratory learning seem finally to have a medium adaptable enough to alter the balance of power between, on the one side, blind conservatism and the tyranny of "covering the established curriculum" and, on the other side, enticing new exploratory learning modes. The seminal image is, perhaps, Papert's mathland wherein children learn mathematics gradually and naturally as the computer-implemented principles of manipulation for achieving effects they value and understand.

But computer-based exploratory learning is not yet the steamroller it might be. Scientifically, there are still knotty problems that need attention. Foremost, perhaps, we still don't adequately understand the relationships among material environments (like computer microworlds), the activities they support and the knowledge represented in the environments or emergent from the activities. Technically, there are still emotional internescine wars between advocates of open, general systems (computational media) and systems that are open in a narrower sense, tools focused on topics like, for example, geometric constructions. Politically, educational reform and computer-based learning are still a somewhat divided coalition. For example, computers continue to be all too frequently marginalized into vocational ("learning programming") or enrichment slots and kept out of significant roles in core educational curricula. Computers are addenda in reform documents, and, worse, many of the best constructivist reformers and teachers view them as "something else" rather than key instruments to their ends.

This volume has been brought together to display the state of the art in computers and exploratory learning. We want to portray progress and limitations:

a) in current technology: systems like Boxer, Cabri, Logo, and StarLogo
b) in the scientific understanding of the principles of learning and knowledge development in exploratory systems
c) in principles of systems and learning activity design
d) in understanding the social, cultural and institutional processes related to widespread use (or non-use) of computers in exploratory modes.

The Plan for the Book

Our strategy for introducing and synthesizing these issues is a little unusual. First, in this Introduction, we try to present a view of the issues as they emerged in discussions at the workshop that led to this volume. We are attempting to capture a bit of the spontaneity and spirit of a lively community, represented in microcosm by the participants in the conference, not just an erudite list of ideas and accomplishments. We do this, in part, by quoting participants' contributions extensively to carry the burden of a tour of issues.

Second, we "commissioned" three thematic chapters with a slightly broader charge than the rest of the contributions. Each of the thematic chapters concentrates on one layer of issues: Theme I, epistemology (theories of knowledge) and systems design; Theme II, psychological, pedagogical and educational issues; Theme III, broader social and cultural issues, especially those that affect how designed artifacts are reconstructed in broad appropriation. The trick for these chapters is to achieve some breadth and "coverage" without sacrificing the coherence of a story line and the sparkle of detail. The other contributions of workshop participants were divided, admittedly somewhat arbitrarily, among these thematic divisions.

Now, let us turn directly to computers and exploratory learning as experienced "from the floor" of the workshop.

Theme I: The Map and the Territory—Knowledge and the World

> *...the problem session was for us a window on the ways people here may conceptualize the same problem...the way the conceptualizations were very different from one person to another person, and...[how] the ways of conceptualizing the same problems were shaped by the tool, by the software these people use.*
>
> *People look like their dogs. (laughter)*

The workshop that led to this volume highlighted the design of computational media to support exploratory learning. A computational medium is a broadly useful system which is exemplified at the present time by *Boxer* (a system designed to integrate text, hypertext, interactive/dynamic graphics capabilities and programming) and the new family of *Logos* (for example ***StarLogo*** which has more than 65,000 turtles operating in parallel—currently implemented on a Connection Machine and simulated on a high-end Macintosh). A major theme, which surfaced several times throughout the workshop, centered on differences of approach between scientists within the Boxer/Logo community on the one hand, and those with expertise in specific exploratory systems tuned towards a particular mathematical/scientific knowledge domain.

A remarkable feature of the workshop as a whole was the feeling of community among the group; there were shared goals and approaches and many common assumptions which were barely articulated:

> *There really was a lot of diversity in the group, although...I really felt there was a lot of commonality. One thing that brought it home to me was that when I looked at the list of all the NATO workshops, there were a lot that had sort of similar phrases about computers and learning in the title, but my sense was that...in most of those I would feel like an outsider, and here I didn't at all. I thought there were some things that were assumed that we didn't have to talk about. [At] a lot of those [NATO] meetings...the talk is about using the systems to model the student. Clearly that's not a major theme here. So things that are missing also help define what a community is. Another aspect, there was a certain sort of playfulness in trying things out and making of things, which is also absent from a lot of other communities. So even though people take very different approaches—and it's very interesting that people take different approaches—they all had a certain sort of playfulness and a sort of tinkering around and trying out things....Building things is something also that was in common. And then even just the fact that there were different approaches but everyone was very open to different approaches: There wasn't so much of 'no that's not the way things should be done in school.'*

This aspect of playfulness and experimentation was a major factor contributing to the success of the hands-on evening sessions where participants were invited to solve some nontrivial mathematical problems using a variety of systems. Participants used at least the following: Cabri, Boxer, StarLogo, a spreadsheet, Logo, Geomland and paper and pencil. Perhaps we should view this exploratory atmosphere as something of a model for the kinds of systems we were discussing and designing. One of the problems became known as Henri's Problem (in honor of Henri Picciotto who had suggested it). It is reproduced below as it generated considerable discussion and is mentioned in several chapters of this volume (in particular, the chapters by Sendov and the Labordes):

Henri's Problem

Consider any triangle, ABC. From what points in the plane does the triangle 'look isosceles'? That is, suppose you are at point P, and from your position point B appears between A and C. Then if angle APB equals angle BPC (the subtended angles are equal), we shall say the triangle 'looks isosceles.'

More generally, if any of
(angle APB equals angle BPC), or
(angle BPC equals angle CPA), or
(angle CPA equals angle APB)
then the triangle 'looks isosceles.'

Explore the set of points in the plane from which a triangle looks isosceles.

A second problem had to do with maximizing a subtended angle subject to a constraint. (See "the Rugby Problem" in Resnick's chapter.) Although this also seemed like a geometry problem, perhaps optimally solved with Cabri, the most interesting solutions came from StarLogo, a spreadsheet and the classic technology of paper and pencil! The third problem had to do with understanding the subtle idiosyncrasies of several implemented dice, originally in Boxer. This last did not seem to travel well to other systems, in some cases for obvious reasons.

We shared the strikingly different approaches taken to the problems and discussed how these contrasting strategies were shaped by the different media. This discussion was not only fascinating in itself but also raised profound epistemological and conceptual questions. Two of these surfaced repeatedly: Does it make sense to refer to the knowledge "contained in" or "required by" the problems if solution paths are so various and so dependent on the medium at the solver's disposal? If not (and a consensus clearly emerged in support of this position), what is the relationship between specific tools or technologies and the kind of thinking that may develop as a result of interactions with these tools?

The second question is related to the structuring by the technologies of the knowledge itself:

What was striking for me in this meeting was how often people used the word 'window'...or the word 'lenses,' and for me it was an opportunity to have a window on differences. The software is an opportunity to have a window on knowledge and for me it was also very interesting to see that at the beginning of the meeting, geometry was disgusting, you know? (laughter) It was boring. How can you work on geometry? Why do you work on geometry? It's a very special interest, and maybe France was viewed as a strange country. And because of Cabri or because of other kinds of software, geometry becomes a more interesting subject....In the problem session it was very interesting to see how people were involved even in geometrical problems and how people could see how geometry can be a way of modeling problems, not only coming from geometry itself, but coming from other domains.

So that is a window on knowledge. And another window, and Celia stressed the point very much, is a window on the student. The software is a window on the learning processes, on the solving processes of the student.

The interdependence between technology and knowledge was best illustrated by a number of virtuoso performances with which the workshop was interspersed:

I guess the most striking thing about the workshop for me has been sort of seeing computational media and the masters perform—it's so rare for me to see someone who really understands the medium, show[ing] what it means [for it] to be a computational medium—they think through it.

A possible drawback of learning to "think through" a particular computational medium was noted by more than one participant, in the sense that changing viewpoints and changing computational environments might be difficult...even impossible!

...we wanted people to try the problems with a different medium....I think we failed completely. Now perhaps this is a matter of time scale, but it perhaps might be something more significant. It's familiarity with the software and knowing your way around it, but I think it's even more significant than that...you do begin to see the world through the software.

Essentially this points to the cognitive implications of using computer tools. If *we* at the workshop had problems in flexibility, then it would almost certainly be an issue for our students:

...if it was very difficult for us to change the tool, can you imagine how it can be difficult for students to change their environment, to move from one environment to another? So it means that, I think it's also a point which needs to be discussed and analyzed....A lot of you stress the idea of multiple linked representations, but [that] is not so simple to organize.

That is one way of looking at the difficulty. But there are emotional issues too. We would not expect a pianist to feel comfortable performing with a cello—or even with a different piano:

One thing that I experienced for myself is I tried really hard—I watched these Cabri folks while they were doing one of the problems...but I experienced, as probably the Cabri experts [did], just this emotional pull I have to do this in Boxer. It's just, that it's a piece of my life....I suppose I could explain it sort of logically, but it's a piece of my expressive repertoire....I believe this is encoded emotionally.

Another influence on our choice of approach to any problem is our prior experience and personal history in relation to the challenge set:

I felt a very strong difference between Henri's problem and the rugby problem... I didn't want to go near a computer to solve that problem [rugby]. I had an idea; I sat down and it worked. I solved it to my satisfaction, I didn't feel I needed any technology...Henri's problem was very different. My first instinct was to start writing tools to think about it.

Pencil and paper—not to mention the congealed outcome of several millennia of mathematical and scientific history (including calculus, algebra and many less material "ways of thinking")—constitute a technology. We should not be surprised at the comment above, but, in contrast, it is a ubiquitous idea that "new" technology might *replace* existing forms, rather than being shaped by existing cultures (and, reciprocally reshaping those cultures as it does so).

The comment quoted above refers to the role of "tools," and it is here that we delineate one of the crucial distinctions between exploratory and non-exploratory environments. The kind of "tools" which might be constructed within a medium like Boxer, or Logo (or, in the more limited domain of geometry, Cabri) form part of a culture—what it means to express ideas within that environment. From the pedagogical point of view, there is an interesting complication: Sometimes tools tuned for solving a given problem come to serve a broader pedagogical purpose—they can evolve into microworlds useful for the exploration of the general domain within which the original problem was embedded.

Sometimes you discover that there's a finite set of tools that can be sufficiently refined so that you really have an interesting activity structure. And sometimes that just doesn't happen. The tools are very specific and don't have powerful activity connected to them.

Note the idea of activity structures here. There is no talk of representation (of what?), rather of the student constructing their own meanings and expressions within a structure of activities which the microworld is designed—more or less well—to offer. This approach seems to stand in contrast to the more fashionable "multiple linked representation" approach:

I think people have gotten into this camp of multiply linked representations. Now that's the solution, 'we don't need one, we need multiple and they need to be linked'....I would add another perspective on this whole problem, which is presenting our work in terms of...giving students materials and time and freedom to develop their own representations. So a more generative view of representations [is] as things in part that are constructed by the kids and *may be thrown away. Now are these competing strategies, are they strategies for different things, or can you say one's better in one circumstance and one in the other? How do these relate to internal knowledge structure?*

There is a deeper issue at work here, concerning the degree of coherence between the intention of the designer and the point of view of the learner. The designer's intentions and understanding of the domain may be embedded in the system, but clearly the learner brings his/her own set of understandings and knowledge to the learning environment. Thus there is always a tension or gap between these two perspectives.

If you are watching a child interacting with a system that's been designed for someone, from what perspective should you be trying to understand what's going on? With respect to the designer? From the perspective of the child? In what ways are they different, in what ways might they be the same, and so forth?...There's some kind of healthy tension between the designer's epistemology and the child's epistemology, and hopefully you could use that as some sort of lever.

So what is knowledge and how does it relate to tools? A catch phrase introduced at the beginning of the conference was: "the map is not the territory," the idea that a computational model of a natural phenomenon or system is not the same as that which is being modeled.

It really is true, that maybe the map isn't the territory, but the map certainly alters the territory in many ways. And there are lots of examples of this. I think kids know now about the real numbers differently than they did when I was in school, for example, because of the kind of extensive use of calculators. I grew up thinking that the square root of 2 was some number you multiply by itself to get 2. They think of it much more as an algorithm for getting closer and closer and closer to this thing, they can press keys to get a decimal approximation to any degree of accuracy. We were talking last night a bit about how the way you think about plants has changed from the time we were in school to now. When I was in school I thought that the leaf on a tree was something that was just completely out of the range of mathematical description....It was just so unusual that none of the mathematical models could apply to it. And now you really look at trees differently. You think of these algorithmic structures that you studied in Logo. And in some sense that's really changed trees.

Of course, such claims and discussions raise deep and complex philosophical and epistemological questions. The first of our three thematic chapters, diSessa's on Epistemology and Systems Design, develops some of these. We conclude this section, with one observation which points to the complexities involved:

Whenever I hear the map is not the territory, I insist that the territory is not the territory...It's so easy to be naive realists in this world and say, well, there's our construction of the world and then there's the world. It really is a fundamentally important point that the world in every respect is a construction also....Another slogan that I have for myself as a measure of profound educational change—and this is just a slogan which is expressing *the same thing that you said [in the quote above]—is 'reexperiencing the world.' That is my measure of whether I've changed myself or somebody else: when a tree is not the same tree as it was before, or when the sun is just not the same sun as it was before I took my astronomy course.*

Theme II: Curricula and Computers

I think the early days of discussions of things like direct manipulation tended to focus on domains like digital logic where there was a very clean mapping, or thought to be a clean mapping, between the items of the domain and...[the software]. But for some domains like function machines it becomes problematic how to make a visual representation of an object.

Two hot issues for debate which surfaced throughout the workshop were:

- What are the trade-offs between, on the one hand, the generality, flexibility and consistency of interface of computational media, and, on the other hand, the focused exploration of a knowledge domain offered by the fine-tuned systems?
- What are the advantages/disadvantages and the implications for learning of text-based programming as opposed to direct manipulation?

It is clear that the questions above center on both epistemological and psychological aspects of the problem of design. A direct manipulation advocate at the workshop claimed no one had ever learned from writing a program. Programming advocates invoked multiple representations arguments and needled their direct manipulation counterparts about how they could distinguish between (advocated) "macros" and (disavowed) programs. At one point a debate arose about whether it was possible for a crash or program bug to be epistemological in the sense of showing the programmer a limitation in the form of knowledge he/she assumed.

Beyond psychological and epistemological issues, a cultural perspective raises new questions. If the problem of design boiled down to creating a "clean mapping" between system and knowledge to be learned, it would be hard enough. In practice it is harder: Software is embedded in curricula, curricula are embedded in school practices and cultures.

The interaction between these issues and questions of design is complex. Consider the following—on the relation between specific purpose versus general purpose systems:

We tended to think that was less of an issue—there's really less division between those two apparent camps—than might be thought in the sense that one could easily, well not easily, but one could imagine building a general purpose substrate of the form of Boxer or a language substrate into which many different more or less special purpose applications are built...it seems like that's been gone over many times, at least I don't feel that there's any [essential difference] between those two positions.

That feeling summed up many of the participants' feelings, although the relative merits of a language or "point and click" method of interaction continued to give rise to heated discussion. Yet the same issue in the context of inserting a system into the educational milieu raises new problems, as will be discussed by Hoyles in the second of our thematic chapters. First, the specificity of a system plays a crucial role in determining the ways in which it is culturally constructed. One such example is provided by the Logo/Boxer style of general purpose systems "versus" that offered by Cabri and other dynamic geometry systems. The universal acclaim with which dynamic geometry systems have been met owes much to the direct applicability—in the language of curriculum theorists, "curricular fit"—which Cabri appears to have in common with traditional Euclidean geometry, at least in countries which still include geometry in their mathematics curricula.

For a fine-tuned system such as Cabri, one difficulty appears to be resolved: the location of a niche which the software is supposed to fill. Hoyles shows, however, that even this issue is more complex than it might at first seem. And Noss, in the third thematic chapter, contrasts that position with that of Logo or Boxer, where the question is as much how to create such niches as it is to locate existing ones.

Discussion centered, too, on the question of *subversion.* One participant noted that some exploratory computer environments may be more easily accepted within traditional school environments, because they fit within familiar curricular and subject matter boundaries. However, they may still be "subversive" in their potential to redraw the boundaries of instruction and learning, though perhaps less radically than general purpose computational media such as Boxer:

> *...in which way are we subversive in the positive sense? The comparison was made between Cabri and Boxer where, on the surface, potentially Cabri is less subversive because it ties into geometry, which is a generally recognized subject to be taught. It is well matched to an existing approach, so at first it may be not as subversive. However, it may be a more powerful means to be indirectly subversive in the sense that you get into a culture, but then by being in it, you can change it. Whereas if you have a directly subversive environment where you say, 'I want to do things fundamentally new,' it's much more difficult to get into the culture. And so systems like Logo originally, or Boxer now, may be slightly more directly subversive and met with a lot of resistance because many people did not see...a meaning to what they were doing.*

Just how this idea of subversion plays itself out, or how it can be used as a lever, is discussed by Hoyles. What was repeatedly emphasized, however, was the need to reconsider the notion of "child" or "learner" as an undifferentiated category: a homogenous grouping with common goals, interests and aspirations. First is the question of audience. It is tempting—and prevalent—to attempt to design for the majority; indeed it seems many presume that an encounter with a system will produce some outcome for all. This is, of course, an underlying assumption of schooling: that it is "good" for all. In fact, exploratory learning environments may have some claim to just the opposite, to be designed for relatively rare occurrences.

> *I have a phrase that I keep in mind about this, I think of designing for rare events. I think rare events can be extraordinarily important, and you cannot count on rare events because they're rare, but it is possible to accidentally design against them...what I mean by rare events are personally, deeply-meaningful and important in somebody's life, and that doesn't have anything to do [directly] with mathematics or physics or art, for that matter, or any of those standard things.*

There are three points here. First, that deeply meaningful events cannot be an everyday occurrence, and that—by implication—it may be worth sacrificing breadth for depth:

> *I would almost be suspicious of software that every child liked or that every child had the same response to....That borders on the intellectual equivalent of Muzak. What I'd rather have, in fact, is some software which might really profoundly capture the imagination of a few kids as opposed to the sort of mild acquiescence of all.*

Second, there is the difficulty of avoiding designing out rare events by accident. One may assume that the London subway was not deliberately designed to exclude disabled people—despite their relative "rarity" in comparison with the population—but exclude them it does. We may similarly assume that the designers of ubiquitous and bland "instructional software" do not deliberately seek to exclude rare insights, but such insights are generally excluded by a variety of forces which converge to support the production of software which is both innocuous and instantly accessible. The Muzak analogy is apt.

The third consequence concerns assessment.

> *If you're talking about evaluation and assessment, I think you have to ask who wants to know what about what in what context. For example, if you're trying to persuade a group of people whose only thought is what will this guarantee for every child, you're caught. And the discussion so far seems to me to emphasize the difference between what is possible and what is guaranteed. Nothing is guaranteed. That's my particular position. You can't guarantee anything; you can only talk about what is possible. But when you're dealing with a community whose whole rhetoric is in terms of what is guaranteed, you have to acknowledge that and either provide something that they recognize or work on changing their perspective.*

This is an important issue, pointing to the way in which people can appropriate technologies, as opposed to technologies guaranteeing an outcome. But it also raises a question concerning support for those teaching and learning with such technologies. Of course, guarantees don't exist; but they are thought to exist. And in this context, the "simpler" the better; the less exploratory (more focused, better "fitting") the more likely it *seems* that guarantees can be given.

Thus traditional modes of assessment are likely to devalue or entirely miss effects of working with such exploratory environments, since such methods typically focus on changes in performance that can be measured across groups of children over brief spans of time. It is much more difficult to assess subtle or long-term changes in the thinking of the learner, or to characterize profound but rare learning events. The systems we were discussing were designed to support just this kind of deep, but perhaps rare learning, which might not be susceptible to traditional modes of evaluation.

We refer the reader to Hoyles' thematic chapter on many of these issues.

Theme III: Cultures and "Commodification"

The focus on the influence of the learning culture raised in Hoyles' paper was taken up in the group discussion. More than one participant noted that a focus on the technological artifact itself was insufficient; that the way the artifacts are used in the learning culture around them was crucially influential.

> *It's all about humans making use of things, not about devices guaranteeing that humans will do something.*
>
> *Spreading a culture means you spread the use, philosophy, successful examples behind the artifact. This may not be as easy as just sending a disk.*

How does school shape the meanings carried with a system? One aspect is the feelings and expectations of the students themselves.

> *There are systematic issues here, right? As I grew up, I was sure that school was a place where I was not allowed to do anything that I liked; that was completely clear to me....Teachers tried to be helpful, to bring my outside interests in, and I was told I could do my science work, my electronic work in school, and it simply didn't work because of the time scheduling....That reinforced my impression that school was not a place where I could do anything that was interesting to me.*

Another aspect of this "schoolish epistemology"—as diSessa put it—is the effect of partitioning knowledge into artificial pieces. Here the computer may have some particular role in breaking down these divisions.

> *How can your computer environment help to give this feeling that there is the unity of knowledge?....I...would be in favor of producing people who feel that they have several dimensions in their life, and they can talk about history or art, being also mathematicians at the same time, in some way giving more importance to formal things and to modeling of complex phenomena and transferring physical phenomena to biological phenomena and so on. This would be an ideal school.*

Third is the issue of *time*.

If you think of the issue as reshaping the technologies available for people to express themselves, not only mathematically, but artistically, aesthetically, and a...number of ways, that's a useful way to view it. It has an implication, which you may say is a rather pessimistic one, which is that the time scale must be long. Reshaping the technology of the way we express ourselves in mathematics and artistically and all the rest of it—musically maybe—these are long scale things....Just like Uri was saying, you interview kids and it turns out that something interesting happened nine years before, but they wouldn't have known it at the time.

Schooling and its assessment also imposes a time scale on learning which may not provide reliable outcome data. These short time scales compound the pressures which emanate from what Noss, in the third of our thematic papers calls the *commodification* of systems.

I'll tell you one other story. I won't tell names, but there is a well-known researcher, A, who worked with another well-known researcher, B, on a project in computers in education, in mathematics education....This project resulted in very large gains in mathematics competence among the student population, and researcher A, however, who was subordinate to B, said that none of the kids ever wanted to see a computer ever again in their lives after that.

Noss's project is to better understand how these and other aspects of educational change are mediated by the educational system itself, and its relation to broader levels of society. Such understanding seems to benefit from the import of currents and ideas only marginally aligned with questions of system design and educational change. Nevertheless, the value of this interdisciplinary dimension was recognized as an emergent theme of the meeting:

New ideas very frequently come from outside of the official discipline that's in charge of the territory. I feel that the diversity of perspectives—epistemological, psychological, learning, whatever—that this community is likely to bring to bear on systems design is a special strength of it for the purposes that essentially all of us have....That is, to involve a very broad range of kinds of people to help their [own] intellectual lives with technology.