Powerful Ideas or Paradoxical Effects: Educational Computing in a Department of Physics

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Project Athena at MIT

The Massachusetts Institute of Technology has been known for its contributions to computer science for over forty years. MIT scientists were central in the early development of cybernetics; its graduates founded computer companies that made Boston's Route 128 an internationally recognized center of research and development. In the 1960s and the 1970s, it was clear that there was a challenge that MIT had not yet faced. This was the use of computers to do MIT's own job: The use of computers for education. In 1983, MIT tried to meet this challenge by embarking on "Project Athena," a large-scale experiment in the use of computers in the undergraduate curriculum.[1] At MIT, something like this could never be small: Athena was built around a $50 million gift of equipment from two large computer manufacturers: International Business Machines and Digital Equipment Corporation.

The vision of what Athena should be grew out of priorities that had developed over many years within the School of Engineering.[2] They were above all about technical excellence. In the eyes of the engineering faculty it was time for MIT to take a leadership position in the field of educational computing. To do so, it must establish a new, graphically sophisticated computer service utility. At its heart would be a network, a "system of pipes." The engineers thought of the system as the necessary condition for innovations in educational software, developed by MIT faculty, which would necessarily follow once the technology was in place. There would be "a thousand flowers." And

MIT being MIT, with its entrepreneurial, even "Darwinian" spirit, it was expected that these flowers would not simply bloom, they would compete, and the best would thrive. The vision was technology-centered: the offer of state-of-the-art equipment coupled with financial resources was all that would be required for the faculty to create a computer revolution in undergraduate education.

The School of Engineering tried to raise money to make this vision a reality within their School. When IBM and Digital made their very large offers, the MIT administration decided to accept, but insisted that the resources be spread throughout the Institute. In an undertaking on this scale. It was not acceptable for there to be "haves and have-nots".

It was thus that the vision of educational computing drawn up by and for the School of Engineering became an outline for all of MIT. Its first priority was a direct descendent of the "system of pipes": the creation of a "coherent network" so that a student's one-time investment in learning the system would provide access to the full range of Institute-developed educational software. Since it was the faculty who were to write the software and this required money, Gerald Wilson, the Dean of the School of Engineering, made a commitment to raise an additional $20 million to support faculty proposals.

The presence of money to spend set up a logic of its own. You couldn't just give it away. You couldn't give it to departments because they didn't yet understand the system. The core group of engineering faculty who served as the principal architects of Athena turned to the model they knew best, a federal system along the lines of the National Science Foundation. There would be requests for proposals, peer review, dispositions, and a central administration.

Faculty committees within each school were set up to review proposals which had to conform to constraints deemed necessary for "system coherency." There were constraints on computer language: four were allowed, with the notable absence of BASIC, the language in which most currently available educational software was written and Logo, a language at the center of a long tradition of MIT research in computers, education, and learning epistemology. There were constraints on the operating system: it had to be UNIX, although MS-DOS and the Apple Macintosh systems were on their way to becoming the common coin of rapidly and spontaneously growing MIT personal computer cultures. And there were constraints on style of educational innovation: it had to be "courseware," preferably for large lecture courses, although many faculty members were interested in very different ways of bringing computers into their teaching. Some wanted to provide students with computer tools for writing literary annotation, musical composition, bibliographies, and historical data bases. Some wanted to provide resources for thesis research or for UROP, the popular undergraduate independent research program. All of these fell outside Athena's purview, as did the use of existing educational programs that were not written in an approved language or for the approved operating system.

From the point of view of those at the center of Athena, none of these rules were "really" constraints. They were simply technical requirements for keeping the system uniform and pointed toward future developments in computing. And the image of the "10,000 flowers" reinforced thei notion that Athena was about freedom and decentralization. But many of the faculty saw things differently. The Athena project had been negotiated and finalized without any formal consultation with the faculty as a whole. Most faculty members felt peripheral, and from their perspective, Athena was highly centralized and controlling: "They are going to tie us to mainframes...They are going to give us terminals. They are going to tie us to a system which they know is the only one to use."

Outside the School of Engineering and a pocket of enthusiasm within the School of Architecture and Planning, Athena seemed an uninvited guest. And particularly for the School of Science, Athena brought the added irritation of engineers telling scientists what to do.

A technology-centered approach to change brings with it certain well-known vulnerabilities. From a practical point of view, putting technology at the center of planning means a vulnerability to the potential for technology failure, and indeed, in the case of the Athena project, technology did not go MIT's way. IBM and Digital Equipment promised many things in good faith and in good faith they couldn't deliver on many of them. Systems development was late, shipments were delayed, it was hard to plan in an orderly way. Technology-centered thinking simplifies context, opening a window for decisive action, for example, the very launching of Athena. But this simplification in the service of action brings another vulnerability. The simplification usually underestimates the weight of history and culture. And with the massive introduction of computers into undergraduate education, MIT was seeking -- without fully realizing it -- to create a new computer culture. Computers extend the power of people's minds; they affect how people think and work. Experiences with computers were bound to become entangled with the social systems and intellectual styles of and regulations impinged. Professor Martin Deutsch spoke of the physicists' "instinctive negative reaction to anything that smells at all like something that will regulate or control our activities, because basically our success, when it comes, comes from the fact that we disregard such things."

Deutsch was not alone; as a group the Physics faculty was put off by Athena's style. In addition, many came to Athena with their own ideas, and some of them quite negative, about the place of computers in science education.

For the past twenty-five years, computers have been an essential element in physics research because of the need to process large amounts of data. FORTRAN became the language of choice and was deeply embedded in the physics culture. Thus, most physicists' ideas about computers grew out of experiences in a particular and very limited kind of computer culture: the data processing culture.

Although in recent years, the speed and interactivity of personal, dedicated computers provided possibilities in data collection and analysis that have little to do with the "number crunching" of the FORTRAN culture, its domination was background to a general reticence about computers among physicists. At MIT, this reticence was magnified by the fact that a number of distinguished members of the Physics Department saw computers as a possible detriment to serious physics. Victor Weisskopf, longtime chairman of the department, now Professor Emeritus, feels that the computer distances physicists from the steps between problem and solution. When colleagues would show him their computer print-outs, he was fond of saying, "When you show me that result, the computer understands the answer, but I don't think _you_ understand the answer." Herman Feshbach followed Weisskopf as chairman. With Philip Morison, another influential MIT physicist, Feshbach wrote a classic two volume work on methods of mathematical physics which made an implicit statement about a hierarchy of methods. One of their colleagues summarizes its message: "If you are really gifted at solving problems in mathematical physics, you might have as a corollary that somebody who has to resort to a computer to solve problems is not as clever as somebody who can solve them with mathematical techniques."

But only a small subset of real world physics problems are solvable by purely mathematical, analytical techniques. Most require experimentation, where you do trials, evaluate forces, and fit data to a curve. Not only does the computer make such numerical solutions easier, but in a practical sense, it makes many of them possible for the first time. Professor Anthony French whose interest in science education goes back to the time of his collaboration with Zacharias, stresses that the computer puts students, even beginning students, in touch with a physics that they would otherwise only be able to read about.

> The chief difficulty of teaching elementary physics is that it tends to be presented as a set of absolute truths. Students don't see the things that go outside these oversimplified models; they are simply not things you can handle in simple terms. But the computer makes that possible.

Although he acknowledges that computers undermine certain oversimplifications, like many of his colleagues, French also believes they may have the opposite effect: to mask reality by substituting simulation for direct experience. "In general, students come here innocent of any particular acquaintance with the real world, the physical world. . . . So, if there is anything at all that can be achieved by direct experience, I would want to go for that rather than for the substitute." Computers encourage "substitutes" by making simulation too easy.

The theme of the computer's "dual effects," to mask and reveal nature, ran through the feelings physicists' brought to Athena. Computers are good when they make it clear that the world is characterized by irregularities which demand a respect for measurement and its limitations. Computers are bad when they interfere with the most direct experience of the world. Physicists stress that it is always better to get your hands dirty. If simulation becomes too easy, students will turn away from the messy reality to which they owe a first allegiance. In this context, simulation is only acceptable when there is nothing else to work with.

As a science, physics is a kind of religion. Senior physicists "believe," students believe as well. In the MIT department, student sentiment about computers is striking in the degree to which it mirrors faculty attitudes. Like their professors, students talk of the new possibilities in numerical solutions and the dangers of reality "substitutes." Like their professors, they fear that computers mask as well as reveal nature. One says, "Using computers as a black box isn't right. For scientists who are interested in understanding phenomena and theorizing, it's important to know what a program is doing. You can't just use them to measure everything." For another, computers speed things up too much: "When you plot data with the computer, you just see it go 'ZUK' and there it is."

In Physics, involvement with Project Athena was limited to a small group of faculty, functioning in a departmental setting that in balance was hostile to their efforts. Interviews with participating faculty put a set of issues (ranging from scientific epistemology to institutional process) into sharp relief. I now turn to three of these:

styles of scientific work, particularly as they emerge in the laboratory, the scientist's relationship with the real, and the management of education innovation.

Styles of Computing and Styles of Science

For Martin Deutsch, Athena's centralization, terminal rooms, and list of "acceptable" languages harkened back to an old way of doing things, the way of doing things that predated the advent of the personal computer. Deutsch discovered computers in the 1960s with the PDP-1. For a few years he devoted himself to that machine, writing programs in machine language, getting involved in its internal architecture, "having a good time." Then for ten years he had nothing to do with computers until he met the Apple 2E: "I bought a 2E and I said, 'That's going to change my life." And it did. "For the first time in my life, I could write."

Deutsch does not write or solve physics problems by making a plan and following it through top to bottom. He prefers to assemble the elements and "sculpt" a solution. The combination of this sculpting style of work and a perfectionistic nature had always made writing painful to the point of near impossibility. Deutsch found it too linear a process for his associative style. The computer presented a new opportunity.

> A person like me can never write anything. By the time I had five sentences down, I'd start correcting them. And by the time I'm through correcting them, I've lost the train of thought. So I used to do things like use a tape recorder, put it at the far end of the room, hang up the microphone, walk over to the other end of the room so I couldn't get to the machine in time to stop it, you see, and start talking. Because once you have a draft, you can work on it. And of course, the word processor solves all that. You can just put it in any old way and then start working on it.

Deutsch uses the sculpting style, a concrete "playing with" the materials at hand in writing, physics, and computer programming. His way of working illustrates that despite widespread stereotypes about computers encouraging or even enforcing one style of use (a "top-down" structured, planned, and structured style) computers become partners in a far wider variety of intellectual styles. Indeed, the computer facilitates a style of work which, like Deutsch's, deals with the world of formal systems through the use of objects rather than the rules of logic to think with.[4]

I call the use of "objects to think with," bricolage, after Levi-Strauss who used the idea of bricolage to contrast the analytic method of Western science with a non-Western science of the concrete.[5] The bricoleur scientist does not move abstractly and hierarchically from axiom to theorem to corollary. Bricoleur scientists construct theories by arranging and rearranging, by negotiating and renegotiating with a set of well known concrete materials.

While hierarchy and abstraction show up in how structured programmers use a "planner's aesthetic," bricoleur programmers, like Levi-Strauss' bricoleur scientists, rely on negotiation and rearrangement of their materials. The bricoleur resembles the painter who stands back between brushstrokes, looks at the canvas, and only from this contemplation, decides what to do next. Bricoleurs use a mastery of associations and interactions. Unlike the planner, where mistakes are missteps, theirs is a navigation of mid-course corrections. Like a paradigmatic bricoleur, Deutsch admits that he "never reads the literature first. I first try to solve the problem."

Unlike many of his colleagues, whose experiences with computers had been limited to batch processing and FORTRAN, Deutsch's background led him to see them as personal tools that enter the researcher's intellectual space. He had used them to get into a new relationship with words and saw little reason why they couldn't be used to get into a new relationship with scientific data. But this would not follow from the old model of using computers where you feed data in and use a FORTRAN program to get it out.

For Deutsch, the most valuable instrument in the laboratory is his Swiss army knife, a simple, understandable, and all-purpose tool. He has generalized his ideas about what makes the knife a good tool to what makes a good computer. Other people want to use the most up-to-date tools. Deutsch wants to use the most transparent ones.[6] In the realm of computers, this translates into a preference for general purpose computers which allow you to "look under the hood." Without transparency, Deutsch claims you lose a sense of your material and how it is being transformed by your technology. And when you lose a sense of the "intermediate steps," "you are an engineer, not a scientist."

When Deutsch approached his colleagues about using personal computers as intellectual tools in physics, he felt misunderstood: "They didn't know what I was talking about." "Everybody knew what a computer was. It was in a computer center where you submit your stuff in the evening and pick it up the next day." And I said, 'Look, this is really going to change. We're really going to have new things.'" Deutsch created an ad hoc committee on computers within the Physics Department, to "stir the pot," to create an awareness of the new possibilities.

It was at this point that Athena announced its resources. Deutsch thought its ideas about networks interesting, but impractical in the short run and in the long run off the main point of what computers could do for education. More exciting was an opportunity to bring computers into students' lives as direct, personal, and transparent tools. Deutsch's idea was simple: introduce personal computers into the physics laboratory required of all majors in their junior year: make computers the Swiss army knives for the Junior Laboratory.

Deutsch begins with the assumption that the most dangerous thing in a laboratory is a "black box" -- an incompletely understood piece of equipment or procedure. Ideally, each "apparatus should be simple enough so that the student can open it and see what's inside." For practical reasons, students can't design their instruments for themselves, but they should be able to feel that they could have. Deutsch's educational philosophy is based on his learning style: it emphasizes intellectual environment.

As Deutsch sees it, his lifelong battle against the black box is a "rear-guard action" because, "as techniques become established, they naturally become black boxes." But "it's worth fighting at every stage, because wherever you are there is a lot to be learned if you keep the box open that you will surely miss if you close it." Deutsch made the computer a new weapon in his battle by writing data collection and analysis programs that he tried to make transparent to their users. One such program was for the Stern-Gerlach experiment on space quantization.

When an electron travels around an atomic nucleus, a magnetic field is set up. Classical physics predicts that if influenced by another magnetic field, the orientation of the electron will be deflected. One expects a continuum of deflections depending on the strength of the external magnetic field and the magnetic momentum of the atom itself. But quantum physics predicts only two positions; the Stern-Gerlach experiment demonstrates this space quantization. A beam of silver atoms is passed through a that the experience of using the computer to analyze data was surprisingly powerful. Some went so far as to say that it enabled them to have a different relationship with physics.

For example, one recalls how before the computer, access to the data in an experiment in resonance fluorescence was through Polaroid photographs taken of the oscilloscope.

> Before you could only get a qualitative understanding. There was less data on the photo than you have on the computer. Now, you can get an exact fit of the data to the function and see the deviations and how much of it doesn't fit an exact curve. Seeing that the data fits in spite of the variations is part of the allure of physics.

Deutsch was struck by how the computer enabled laboratory physics to "come alive for his students." Speaking of how they were able to manipulate data in the resonance fluorescence experiment, Deutsch commented: "A student can take thousands of curves, and develop a feeling for the data. Before the computer, nobody did that because it was too much work. Now you can ask a question, and say, 'Let's try it.'"

At the same time that Deutsch was seeing experiments "come alive" in the Junior Physics Laboratory, something similar was happening in the Department of Chemistry. The comparison is important because whereas Deutsch had anticipated powerful effects from a powerful machine, in Chemistry, preconceptions were quite the reverse. There, the faculty did not begin with assumptions about the computer's power, but about its triviality. They hoped that laboratory software would help students move more quickly through experiments in order to have more time to explore, the "really important stuff" through mathematical insights that would come only "when students sit down with book, a pencil, and paper." There was no question that students in the Advanced Chemistry

Laboratory appreciated the computer's ability to speed up calculations, but they said it did something else as well. It changed their experience of chemistry because they could get to know data in a new way.

In chemistry as in physics, computers allowed a subject as abstract as quantum mechanics to be directly experienced through a hands-on exercise. The computer made students feel closer to underlying processes, opening science up to intuition. It gave a window onto theory through impressionistic glimpses of physical phenomena. Some students used this more concrete and dynamic point of contact as a supplement to traditional mathematical understanding. But among other students, particularly those I have called bricoleurs, there was a sense of really understanding for the first time.

Computers offer a great deal to bricoleurs. When they program, the machine offers the computational object. Belonging to both the world of ideas and things, computational objects offer physical access to formal systems.[7] And when bricoleurs use software, the computer makes it possible to manipulate the abstract as though it were concrete. In the scientific laboratory, the tool that so many feared would force an alienation from the real had a paradoxical effect -- it brought students closer to data because they were able to get their hands "dirty" playing with them.

The Computer and the Real

Problems of Error.

Like his colleague Martin Deutsch, Professor of Physics Robert Hulsizer was interested in educational computing for many years before Athena began. When Athena got underway, Hulsizer submitted a proposal for a major "rethinking" of the physics curriculum in light of what computers could offer. His

Here, as in the Junior Laboratory, the computer is being used for its "paradoxical effect": a tool usually associated with rules and precision is being used to bring students closer to the messiness and irregularity of the real world. One student in the Freshman Seminar says, "When you have to consider these forces that otherwise you ignore in dealing with plain [analytical] theory, it changes things radically. You really try to make the connection between theory and data. It's not someone else's experience. You have to make it work for yourself."

Like Anthony French, who acknowledged that computers provide access to an otherwise inaccessible reality, Ledoux also fears they mask it. For years, MIT faculty have complained that students have a deteriorating ability to deal with scale and that computers are partly to blame. The slide rule, goes the received wisdom, demanded that its user specify the placement of the decimal point in order to put down an answer; the calculator makes no such demand. Ledoux feels that students "have gotten lazy; they don't want to do things by hand and they don't want to include units in their calculations."

A return to the slide rule is not practical, but Ledoux believes that students should be forced to do "back-of-the-envelope calculations." There, he said, "you need to understand the scale you are working in, the units you are using, the number of significant digits that make sense." He points out that in the realm of understanding error, failure to learn while at MIT can translate into "a space shuttle blowing up" later. He sees the faculty's job as being "mind police," making sure that students do understand.

> In any model you have to state error. It's an unpopular but fundamental topic. I think it is something in which MIT education is very deficient. . . I've never heard a student say, "I took a course in error analysis." I've

> never seen that. . . There may be some in applied math, but for physical measurements, you have to learn it through a lab. So we try to provide that service. We're ideologues in this; we're preachers.

Martin Deutsch tries to be such a "preacher." His Junior Laboratory programs will not accept a data point without the specification of an error factor. If students insist, Deutsch will show them how to remove this feature. But to do so, "they have to take affirmative action. The default is always to put an error in." Ledoux and Meyer use graphics programming in a similar spirit: "When students plot points for the first time, they literally understand what the physical screen is, what the graphics screen is, and how to actually put points on the screen," says Ledoux. "So, if a curve drawn on the screen and theoretical curve don't look the same, students are in a position to investigate the screen's resolution. If the two things overlap, they may differ at the tenth of a pixel level, which you can't see." And yet, this tenth of a pixel level may be critical. It may be the margin of error that makes all the difference.

Simulating the Invisible Physics. The same physicists who don't like "demonstrations" in science speak of "learning Newton's laws by playing baseball" and acknowledge that there is no such direct access to quantum physics and special relativity. When presented with a film that demonstrated wave packers propagating as a function of time and fragmenting on collision, even the skeptical senior theorists were impressed. Anthony French describes their reaction as "amazed":

> You see this thing moving along and doing remarkable things. That's something the likes of which had never been seen. It is difficult to calculate that count without a computer. Seeing it as a moving picture is also wonderful. There's been published recently a handbook, a picture book of quantum mechanics which includes, among other things, some of these wave packet collision things, but to see them just static doesn't begin to give the effect of watching a screen and seeing these things actually happen.

Although not a member of the department, Edwin Taylor, another Zacharias collaborator, proposed an Athena project within it in the spirit of that film. He hoped to use the interactivity the computer makes possible to give an experience of actually living in the quantum world so that students could develop intuitions about it the way they develop intuitions about the world of classical physics, by manipulating its materials. Metaphorically speaking, they should be able to "play baseball" in it.

One of Taylor's programs simulates what it looks like to travel down a road at nearly the speed of light. Shapes are distorted; they twist and writhe. Objects change color and intensity. All of this can be described mathematically, but without the computer they cannot be experienced. Taylor shares his colleagues' reticence about "demonstrations," so his students are required to use his programmed worlds as utilities for problem solving.

Taylor uses the programs he developed in a subject he teaches on special relativity.[9] But in order to continue his funding, Athena asked for reassurance that the programs would ultimately be used in large introductory subjects. The Physics Department could not provide this reassurance and Taylor was denied further funds.

Within the Physics Department, the discussion about Taylor's programs turned into a forum for strong views about how "simulation" poses a threat to science. Physics faculty were vigorously opposed to anything that smacked of demonstration, calling it "the stuff of engineering education." (An engineer is satisfied with a simulation. A physicist wants to be in touch with the real.) The physicists saw canned programs, even as sophisticated as Taylor's, as threats, almost as viruses that could inject the scientific culture with engineering values.

Given his aesthetic of transparency, it is not surprising that Martin Deutsch's feelings about simulation are negative and impassioned. Deutsch feels that simulations always function as black boxes. As such, they run counter to his style: "I like physical objects that I touch, smell, bite into. . . . The idea of making a simulation. . . excuse me, but that's like masturbation." Deutsch characterizes his views as extreme, and characterizes Taylor's work as good -- but disliked the genre. Indeed, he laughingly accepts a characterization of it as a "good thing of the bad kind." Deutsch fears that students watch "as they would a movie" and come to believe that something will happen in the real world because they have seen it in the computer model.

The physicists accept that simulation may be a necessary evil since our everyday experience only puts us in touch with the world of classical physics. They are willing to accept a simulation when no "real world" experience could possibly be substituted, but when Taylor uses the computer to demonstrate something that could be done in a traditional laboratory setting, one sees the full force of his colleagues' feelings about keeping the computer in its place.

The following interchange between physicists John Negele and Robert Ledoux speaks eloquently to this issue. Negele describes how a physicist must come to grips with how light behaves both like a particle and like a wave.

> <u>Negele</u>: If you have a dike, and two little openings, the waves of water will propagate through those two little openings. They'll form little rings, which will then interfere with one another, and you'll see the results of these two wave fronts coming out, interfering with one another. That's a very clear wave front. If you think about shooting bullets through these two holes, you know the bullet goes through one or through the other. Now, you're being told as a student of quantum mechanics that sometimes you're supposed to think about light in one way and sometimes you're supposed to think about it the other way. And so a very important experiment comes to mind. You take this case of two slits and decrease the level of illumination so you're very sure photons are only going through one at a

Committed to the idea of computers in education, Negele involved himself in Athena as early as he could, but felt that the key decisions had already been made by an inner circle of engineers. "They created a huge number of committees and I was a real sap, and it took me about a year to figure out what these committees were about. These committees were to give the impression of involving faculty. But there was no substance. Nearly every major decision had already been taken."

For example, while he was serving as a member of a technical issues committee, the Athena restrictions on computer languages and operating system were brought up for discussion. Negele insisted that the restrictions were not "technical issues," but a form of censorship and inappropriate for a university. "It was as though they were saying, 'these are the approved books and these other ones have too much secular humanism in them or whatever.'"

> If my department chairman told me what book I must use to teach a course, I would hand in my resignation. As a professor of physics, I believe I am the person who can make the best judgement as to what textbooks to use when I teach a course. Now who are these people at Project Athena? And who do they think they are that they should tell me what languages I'm allowed to use to teach a course and what languages I'm not allowed to use?

Negele says that the result of his objections was that he was asked to "cool it." He was made to understand, that this question, for better or worse, was closed.

In fact, Athena would later soften its language restrictions, ironically because of technical difficulties and increasing pressure to get things running; the "policy-in-practice" about faculty salaries was not Institute-wide, but a provisional decision on the part of the allocations committee in the School of Science.[10] It, too, would change. But this relaxation of the rules was several years in coming. Certainly, in Physics, the rules about salary, computer languages and operating system contributed to an environment openly hostile to Athena. As Negele sees it, they led his colleagues to a basic assumption that "Athena is something they don't want to hear about. They think it's such a stupid, ridiculous, terrible mistake. They aren't even going to waste their time talking about it."

In the end, MIT faculty (in Physics and elsewhere) usually found a way to use the languages they preferred, but there was a cost: lost time, wasted energy, and the widespread sentiment that to make an Athena project work, you had to circumvent Athena. For example, physics faculty were convinced that since the purpose of the Freshman Seminar was not to teach a new programming language but numerical problem solving, they wanted its students to program in the familiar and Athena-disapproved BASIC. After their sustained protests, Athena grudgingly agreed to support an IBM version of BASIC. But the physicists wanted "Quick BASIC, Microsoft Version 2," arguing that it was more suited to their educational purposes. (Ledoux says, "We would have been fools" not to use it.) The Physics Department purchased its own Quick BASIC, but this means that Ledoux and Meyer have to keep track of the software, update and maintain it. Ledoux says, "It takes manpower to do something that Athena doesn't support, "It is a manpower that Athena doesn't provide.

Alan Lazarus, Chairman of the Physics Department's Education Committee comments that in the event, Athena's concession about BASIC served to intensify rather than abate the faculty's hostility: "We finally got them [Athena] to agree that it was okay but then they disowned us. They said, 'Here are the terminals, but don't expect us to keep them up to date, or put new operating systems in them. You're on your own. This put people off rather severely."

There was a great resistance to using Athena machines for senior theses.

> They were supposed to be used for large courses. That was crazy. At that time, there was nothing of intellectual substance that had been developed for large courses, but yet there was a whole generation of students coming up with senior theses and UROP [undergraduate independent research] projects.

Negele has similar feelings about Athena's position on word processing. To him, word processing is a common sense application that saves students time, and for some, seems to increase quality of writing. But Athena wanted to break new technological ground, and originally would not support word processing because it was too mundane. Only when surveys of how students actually used Athena showed that despite official discouragement, over 80% of all use was for wordprocessing, did the system relent, for example, by providing more printers.[11]

As things turned out, Athena projects in the Physics Department would have proceeded more smoothly if the emphasis had not been on the hi-tech equipment and if faculty could have simply used off-the-shelf computers.[12] Indeed, Edwin Taylor fights to use only the "bottom end" of Athena equipment because he wants to develop software that can be used at other universities. But Athena created a climate in which using currently available technology was read as a sign of failure. Faculty felt like "second class citizens" if their innovations were not technical, but purely educational.

When Negele evaluates the Athena experience as a whole, he notes that no textbooks have been produced and the majority of proposals, although "nice," "don't blaze the way." "They don't put MIT in a position of intellectual leadership in a way that I would like to see." Negele admits that he "finds it more fun to move into a new field where I'm the first person to do something than to move into a mature field where the cream has already been skimmed off by others." He believes that MIT shares his intellectual temperament, his preference for the new. From his point of view, even if Athena policy could be reversed, it is too late for MIT to get what it wants in educational computing. "The timing is no longer right because other places have seized the lead."

Negele believes that the straightforward acknowledgement of a missed opportunity would be a first step towards doing things better. But not surprisingly, his ideas about doing things better are firmly opposed to where Athena began. In brief, he thinks one should "abolish all those silly rules." Indeed, one might look at the "Negele Plan" as a suggestion that MIT switch to what he has understood as the "Cal Tech Plan": identify faculty members who are willing to experiment, put a machine in their office, give them one to take home, give them a semester or a year off to work, and tell them that they own their product. In other words, give faculty incentives that will make it worth their while to be taken away from their major research. In addition, decentralize funding decisions ("A chairman knows his faculty") and don't "penalize" MIT students for taking Athena courses. Cal Tech required students to take courses that used educational computing, while at MIT, Athena courses are electives and with rare exceptions, electives are doomed to low enrollments.

MIT students "optimize" their time by taking required courses and a few graduate courses. THe system works against the success of programs such as Athena. Although thirty-five sophomores signed a petition asking Negele to teach computational physics, only ten of them were able to fit this elective into their schedules because the Physics Department had just added a new required subject for majors. Negele suggests that subjects which use educational computing be made requirements for graduation.

"Students could choose among what was available -- the Architecture students might tend to go one way, the Physics students another. But as students "made one or more natural couplings," faculty who had put in the time and effort would know that there was a clientele for their work.

Views from the Center and from the Periphery

Athena reflected stresses and strengths that characterize MIT as a whole. In doing so it raised issues that must be addressed not only in the context of computing, but in other areas of educational innovation as well.

For example, the Athena experience in Physics made it clear that to foster innovation, junior faculty must be given greater incentives for participation. Martin Deutsch commented that he was free to join in because as an older and very senior member of the department he could come to it "without ambition."

> I don't have to write two papers a year, three papers a year, I don't have to write any papers a year if I don't feel like it. It's easy for me ... in a funny way, and that goes into many things. It's easier when you're sort of pulled out a little bit, out of the struggle.

In the Physics Department, major Athena commitments were made by people marginal to the department such as Taylor, by "elder statesmen," such as Deutsch and Hulsizer who could "afford to play," and by younger faculty such as Ledoux and Mayer who were recruited. "Elder statesmen" and "marginals" are naturally limited in their ability to effect lasting change and younger faculty will "cycle out" of their assigned roles. Not only is educational computing marginal to their research problems, but they can't afford to make it more central. The incentive system will ultimately "punish" them if they remain involved for too long.

Project Athena won a new visibility for educational computing at MIT, but that doesn't translate into promotion and tenure within a discipline. One solution is for senior faculty to take the initiative in educational innovation. Another is to hang the incentive system so that it is rewarded with promotion and tenure. What does not work is the Athena solution where it was assumed that a serious experiment in education could be done as an "exercise for the left hand," something for faculty to do on the side. This model had two negative effects: it denied the difficulty of the task, thus further devaluing educational research, and it allowed the incentive system to remain unquestioned and unmodified.

Finally, the Athena experience raised the issue of the balance between center and periphery in "managing" innovation. I noted that from the perspective of the "center," the project gave enormous freedom within necessary technical restrictions. Long-term planners did not want MIT divided into incompatible computing "empires" that would force students to learn multiple systems as they passed from course to course, discipline to discipline. And from the perspective of the center, a funded Athena proposal provided money and freedom to work undisturbed. But things looked different from the periphery. Professor Lazarus, speaking of the development of the Freshman Seminar, made it clear that "working undisturbed" felt like "no feedback."

> Athena seemed not to care what we did with the terminals or what we had developed. Nobody came around and said, "What have you guys done, show us, give us a demonstration." We have invited people over, but nobody, as far as I know, came. We mentioned this to the people at Athena and they said, "We have no provision for that sort of thing." It was clearly "Here they are, good-bye." It was not the king of mutual working together it should have been.

In the laboratory, computers relieved the tedium of data collection, plotting, and analysis. Quick calculations enabled students to implement though experiments which gave theory a concrete, visual, and more intuitive dimension. For some, these new possibilities were a supplement to traditional mathematical understandings. For others, they seemed to offer a new and privileged path of access to science. It may be a path of access that opens science to a different kind of learner.

In the Freshman Seminar, numerical problem solving with the computer presented a challenge to the traditional "textbook physics," skewed towards those problems that can be solved analytically. As such experiences become widespread, there may be change in what is considered "high" or prestigious physics, a position currently occupied by the "pure" (i.e. mathematical) approach.

In both classroom and laboratory the computer brought students closer to the "real" by forcing a new consideration of error and the limitations of measurement. With the computer, students were better equipped to handle uneven and anomalous data. This was always a problem for students who were meeting theory for the first time, and needed "clean" data to see how it embodied theory. Before the computer entered the Laboratory, if a students' one round of an experiment yielded only anomalous data, the student could not bring his or her experimental result in relation to theory, but would have to rely on prepackaged data. Now it is possible to generate a richer and more representative data set.

Edwin Taylor's relativity programs stimulated a sharp and ongoing debate about simulation and demonstration. What is the epistemic status of an interactive simulation? Is it unfair to reduce a microworld to the status of a simulation? These questions clearly require further study. At present, they tend to be debated philosophically; they need to be argued empirically.

As personal computers became an everyday part of the physics culture, something that Athena did not cause but contributed to, it was clear that different people made computers their own in their own ways, using different intellectual approaches, different points of contact with what the technology has to offer. Martin Deutsch used a "different" computer than John Negele. The physical machines may have been the same; the machines in the mind were not. The fact that computers invite their "personal appropriation" has important implications for education. It suggests that equal access to even the most basic elements of computation demands an epistemological pluralism, an acceptance of the validity and equality of multiple ways of knowing and thinking.

If students have an opportunity to sculpt a thinking environment that "fits," computers facilitate learning. If they do not, many feel left out, believing that they don't have the "kind of mind" that works well with computers. The irony is that it is often the bricoleurs who are made to feel the most "left out," and it is they whom the computer may be most able to help. The experience of Athena in the Physics Department made it clear that it is naive to launch experiments in educational computing that expect diversity in content but not in the form and feeling of computer use.

From the time that it was announced as an MIT-wide plan, Athena declared ambitious educational goals that ranged from pedagogy to epistemology, for example, "help[ing] students learn more creatively and fully" by developing "new conceptual and intuitive understanding."[13] But both for its architects and most of the faculty who submitted proposals, the real expectations were far more modest. This was summed up

Endnotes

1. This study of the Physics Department was part of a larger project on the educational impact of ATHENA. In Spring 1986, the Project ATHENA Study Group, an MIT faculty committee chaired by Professor Jean de Monchaux, Dean of the School of Architecture and Planning, mandated a study of the impact of Athena on teaching and learning. Four departments were chosen as case studies: Architecture and Planning, Chemistry, Civil Engineering, and Physics, with Sherry Turkle and Donald Schon as principal investigators. The field studies began in April 1986, were completed in Fall 1987, and were reported in Sherry Turkle, Donald Schon, Brenda Nielsen, M. Stella Orsini, and Wym Overmeer, "Project ATHENA at MIT," May 1988. This essay draws on a chapter I authored in that report, "ATHENA in Physics," and is based on field research by Brenda Nielsen (observations and interviews with faculty, conversations with students in the Junior Laboratory and Freshman Seminar) and on a roundtable discussion with department members which I held as "feedback" session after they read an early draft of this chapter. All persons quoted have had an opportunity to review their quotations.

2. Two important documents for tracing the developing vision of an ATHENA like activity are MIT, Report of the Ad Hoc Committee on Future Computational Needs and Resources, April 1979 (committee co-chairs: Weston Burton and Michael Dertouzos); and Joel Moses, Report on Computers and Education for the School of Engineering, October 1982. Other data on the growth of the ATHENA vision come from conversations with its central architects, among these Michael Dertouzos, Professor of Electrical Engineering and Director of the Laboratory of Computer Science, Robert Logher, Professor of Civil Engineering, Joel Moses, Professor of Electrical Engineering, and Gerald Wilson, Dean of the School of Engineering, which took place in the context of the larger study of ATHENA at MIT (see note 1).

3. This essay covers the project within the Department of Physics from the beginning of ATHENA until Fall 1987. It does not attempt to follow the actors and the development of their ideas beyond this point.

4. For a more explicit discussion of computer "style" and the issue of personal appropriation, see Sherry Turkle, The Second Self: Computers and the Human Spirit (New York: Simon and Schuster, 1984) and Sherry Turkle and Seymour Papert, "Epistemological Pluralism: Styles and Voices Within the Computer Culture," Signs, forthcoming.

5. Claude Levi-Strauss, The Savage Mind (Chicago: University of Chicago Press). Of course, Levi-Strauss was wrong in excluding bricolage from the practice of Western science. Many writers are starting to correct this. A most spirited polemical essay on this is Feyerabend, Against Method. Among numerous other texts, there is N.R. Hanson, Patterns of Discovery (Cambridge: Cambridge University Press, 1958) and in a less formal vein, Richard Feynman, Surely You Must Be Joking, Mr. Feynman (New York: Norton, 1985).

6. For an explicit discussion of the relationship between bricolage and a preference for transparent understanding, see Turkle and Papert, "Epistemological Pluralism."

7. On the computational object as "betwixt and between" in many senses, see Turkle, The Second Self, especially Chapters 1, 2, 3, and 6.

8. In our interviews with faculty, we found that many saw this as "Project ATHENA Policy," especially in the early years, interpreting in this light decisions by one or more of ATHENA's proposal committee and the rationale given for not funding proposals. ATHENA's Executive Committee, however, never officially adopted this policy which emerged, nevertheless, as what my colleague Donald Schon refers to as a "policy-in-use."

9. A word on terminology: At MIT, what most institutions refer to as "courses" are referred to as "subjects," as in "I am taking five subjects next semester."

10. See note 7.

11. From 1985, ATHENA commissioned surveys of student use, done by Karen Cohen, Principal Research Associate. They appeared as "Project ATHENA Impact Study Reports."

12. This was not the case in all departments. For example, in Chemistry, projects suffered because the most advanced equipment was late or never arrived. See Sherry Turkle and Brenda Nielsen, "Chemistry," in Turkle et.al. "Project ATHENA at MIT."

13. Project ATHENA, "Faculty/Student Projects," MIT Bulletin, March 1985.