EDUCATIONAL FUTURES

SHIFTING PARADIGM OF UNIVERSITIES & EDUCATION

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DESIGNING A UNIVERSITY FOR THE MILLENNIUM: A SANTA FE INSTITUTE PERSPECTIVE*

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Introduction

At the Fred Emery Memorial Conference, I was asked to examine the question of how can we utilize what we have learned and are learning at the Santa Fe Institute (SFI) to design a new university. This challenge has led me to consider the implications for university organization and curricula on the premise that a multidisciplinary inherently nonlinear complex adaptive systems perspective of the kind being developed at SFI offers a more useful starting point for educating students in the 21st century than does the simple single disciplinary linear model implicit in the Newtonian approach of the 19th century.

Such a change in perspective poses a number of questions for a university "designer." Among these are the following:
- What modifications in the standard model of discipline-based university education are required to prepare undergraduate and graduate students alike for the increasingly interconnected and interdependent world of the 21st century?
- What is the balance to be sought between transmitting the essential tools of a given discipline and conveying to students the fact that, increasingly, research on the most important problems of the 21st century requires that we go outside the boundaries of existing disciplines?
- What is the appropriate balance between courses which fall within a given discipline or department and courses which encompass two or more disciplines?
- To what extent should a university which aspires to a transdisciplinary approach be designed around departmental fiefdoms?

In preparing my response to these and related questions, I used Internet to ask SFI colleagues to join me in arriving at a perspective which is built on the interactive wisdom of the SFI community. A number responded, and their responses are incorporated in the remarks which follow.

I begin with a brief history and overview of the Santa Fe Institute seen from the perspective of one of its founding fathers since during its early years I served, at various times, as its Vice-President, Chairman of the Board of Trustees, Cochair of the Science Board, and Cochair of the Science Steering Committee. Following an SFI-inspired examination of universities as a collection of interacting communities, I then present some specific proposals concerning students, faculty, courses and curricula, departments, and the role of centers in an "SFI-inspired" university.

The Santa Fe Institute: From Emerging Syntheses to Complex Adaptive Systems

The Institute's founders recognized as early as 1982 that science was undergoing a paradigm shift. For the first part of the 20th century, the focus in science had been on problems which were posed by experiments carried on within the laboratory and which could be solved within a single discipline. Increasingly in the early 1980s, the best and the brightest were turning their attention to problems which did not fall within a single discipline, problems whose solutions required *emerging syntheses* involving an active collaboration between scientists trained in a number of different disciplines.

After sponsoring two successful workshops on emerging syntheses (Pines, 1985) at which topics ranging from protein folding to the origins of warfare were discussed, the Santa Fe Institute began functioning as an independent institution in 1984. As a visiting research institute with no permanent staff, it sponsored: exploratory workshops, research networks, theme years, summer school, and outreach programs.

All of these activities involved bringing together scientists from different disciplines to discuss problems of common interest. Early on it became clear that scientists from disparate disciplines (e.g., theoretical physics and economics) were genuinely interested in working together. Nurturing these nascent collaborations required both understanding and bridging language and cultural differences, a process which requires both patience and time. For example, in our first workshop on economics, the theoretical physicists discovered that their economist counterparts were superb mathematicians, while the economists were surprised by the willingness of the physicists to use numerical simulations on a computer to explore the consequences of a given model. We found that, for the most part, it was the scientists who had been very successful within their original discipline who were willing to take the risks involved in working outside those disciplines.

We pursued a rather broad research agenda, based on topics suggested initially by members of our Board of Trustees and by the outside research community, and subsequently by our Science Board, an advisory committee of some fifty scientists selected for their intellectual breadth and depth as well as their interest in the transdisciplinary approach being developed at the Institute. Among the topics examined in depth by scientists participating in workshops or research networks were: theoretical immunology; the economy as an evolving complex system; artificial life; computers and DNA; molecular evolution on rugged landscapes, that is, proteins, RNA, and the immune system; the evolution of human languages; time series prediction; and understanding complexity in the prehistoric Southwest.

As the SFI research agenda developed, it became evident that the problems being studied were most often those posed by nature or society (not those posed by a scientist in the laboratory), and a candidate integrating framework for the systems being studied emerged: *complex adaptive systems*. Complex adaptive systems are composed of large numbers of interacting variables, parts, or agents, interrelated in an essential way. They cannot be analyzed by decomposition into simple independent parts or subsystems. This collection of interacting agents typically respond in nonlinear fashion to one another or changes in their external environment. The systems are

dynamic, not static. The dynamics may take several forms (e.g., deterministic or stochastic) and may involve multiple time scales (e.g., responding versus learning). Understanding complex adaptive systems thus requires new techniques and concepts for analysis, going beyond or merging the traditional approaches of dynamical systems, statistical mechanics, population biology, economic theory, and so on. Much of the work is necessarily done by computer studies and simulation.

In the course of a workshop devoted to an examination of complex adaptive systems as an integrating framework for the SFI research agenda (Cowan, & Pines, 1994), we arrived at a somewhat more specific definition: Complex adaptive systems can be regarded as a collection of information-gathering entities (agents) which (a) respond to the environment, (b) respond to one another, (c) segregate information from random noise, (d) compress regularities into a model, and (e) modify their internal characteristics—that is, adapt to improve their performance of desired tasks.

Typically, complex adaptive systems (a) possess intrinsic nonlinearities which can lead to either negative or positive feedback, (b) display emergent (self-organized) behavior, (c) are unusually sensitive to initial conditions ("frozen accidents"), and (d) are rarely capable of finding an optimal state; instead, get "stuck" in local minima which are often "history" dependent. Finally, intervention in the affairs or behavior of a complex adaptive system often gives rise to unexpected consequences.

Some examples of complex adaptive systems include complex adaptive matter—strongly correlated "hard" matter (high temperature superconductors), soft matter (polymers, gels, soaps etc.), and biological matter (proteins, RNA, DNA etc.); animals/humans in isolation; the immune system in animals and humans; the brain; ecological systems; humans in interaction: the family, the state, the global economy, organizations; and *universities*, to which I now turn.

Universities as Complex Adaptive Systems

As shown in Figure 1, universities may be viewed as a collection of interacting communities each of which functions as a complex adaptive system. Within each community, we encounter multiple interactions and levels of organization. For example, in the "standard model" of a contemporary

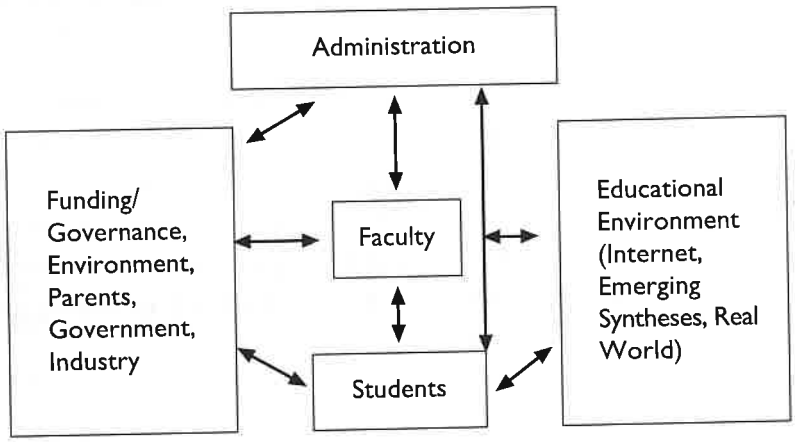

FIGURE 1: A top-down, faculty-centered, view of the university

university, the faculty is a collection of weakly interacting academic disciplines, while the interaction between faculty and students occurs within a disciplinary context, tends to be one-way, and is generally confined to the classroom. However, as John Seely Brown (Brown, & Duguid, 1995) has emphasized, the core competency of the university is not transferring knowledge, but creating it.

Creating knowledge is, in a real sense, a shared responsibility of faculty and students. It is, therefore, instructive to invert the top-down, faculty-centered view expressed in Figure 1, and consider instead the student-based complex adaptive learning community, depicted in Figure 2. Here it is evident that students are coupled to teachers, other students, the real world, and eventual employers. Note that all couplings are two-way. It is evident that the success of a student depends on the significance of components shaping his or her education and the strength of his or her coupling to those components. Because students naturally cut across departmental lines and make novel connections, student feedback on teaching as well as the direction of research and the internal structure of the university can be especially valuable.

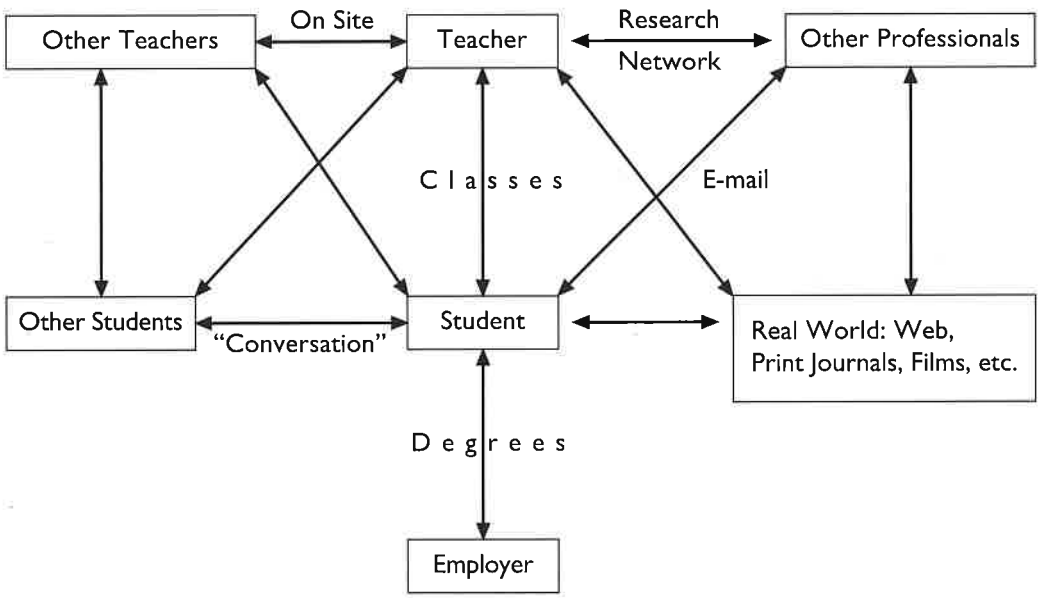

FIGURE 2: The university as a student-based complex adaptive learning community

Of course, learning itself is a complex adaptive system. Because learning is nonlinear (with positive or negative feedback), on-line assessment of progress is highly desirable. Learning can be reinforced electronically with course notes, problem sets, and/or term papers on the Web. However the Web is not a substitute for direct contact between teachers and students in courses or seminars, or between students and students outside the classroom. Moreover student-based interaction-feedback or "just-in-time" learning is playing an increasingly important role.

Some Modest Proposals

Faculty are the key to making any university design work. If we seek a new approach to learning, to creating knowledge, a new approach to faculty selection is also called for. Thus the criteria for faculty selection in a university which seeks to focus the attention of its students and faculty on the problems posed by nature and society must go beyond the usual criteria of demonstrated research and teaching excellence within a disciplinary context to take into account transdisciplinary interests and experience. In brief, we seek faculty who possess a demonstrated record of being innovative, integrative, and interactive, and, as shown in Figure 2, willing to be involved.

Courses and curricula can and should be different. Thus we can follow the suggestion of my SFI colleague, Richard Palmer, and mix traditional "bottom-up" layered learning (which builds up a broad base of competency before tackling topics at the frontier) with innovative "top-down" learning (which starts with a frontier topic and moves downward, picking up at each level the knowledge required to understand a frontier problem or solution). We can, moreover, mix single discipline courses, taught by one professor, with transdisciplinary courses, taught by a team of professors representing a number of different departments. Above all, it is important to be adaptive, to avoid predetermined curricula and predetermined courses, to encourage student input into course and curriculum development, and *always* to encourage students to learn from one another.

Faculty can and should emphasize in introductory survey courses (and beyond) that almost every system at the frontier of science today, as well as almost every problem posed by nature or society, is inherently nonlinear. Through examples, they can encourage students to regard themselves and the world in which they live as being both complex and adaptive, and so begin to learn to live with nonlinearity. However, in developing new approaches to teaching and learning, it is not necessary to "reinvent the wheel." Rather we can search Internet for documented examples of multidisciplinary approaches with complex systems elements which have been tried and have succeeded and build on these successes in educational research. Two examples brought to my attention by my SFI colleague, Michael Cohen, are the undergraduate information major at Carnegie Mellon and the graduate major at the School of Information at the University of Michigan. (On-line: See references.)

Quite generally, faculty and students should use Internet for what it does best: facilitating multiple conversations which can become an important part of the learning experience of both students and faculty. Set up a Web site for every course. By posting, updating, and correcting lecture notes on the course's Web site, students can share with each other, and with the lecturer, what has been learned and what has not. Such electronic lecture notes provide a written record of value to student and faculty alike and may, over time, be expanded into a lecture-note volume.

Faculty should also be encouraged to develop teaching techniques which incorporate complex systems ideas. An example has been suggested by my SFI colleague, John Miller. As he puts it:

> Ask your class a key question that involves recently discussed material. After each student works on answering the question, poll the class to see what kinds of answers people are coming up with. Next, allow the students to talk to their neighbors, to see whether a

> consensus about the right answer emerges. In such group work, students learn by acting as self-tutors, prompting each other about key ideas, etc. Again, poll the class. Next, allow the larger "neighbor" groups to talk to one another...And so on.

Miller notes that it is really amazing to watch, but you generally get a gradual consensus converging on the right answer from such deliberations, and, in the process, students pick up a lot of material: decentralized cognition leading to global learning...complexity at work.

Two more tips for teachers. First, in courses at every level, bring out the transdisciplinary approach to one field. An example is cited by my SFI colleague, Rajarshi Das: If lecturing on psychology, note that the neuroscience, cognitive science, computer science, evolution, physiology, and so on, play a major role in understanding the phenomena studied in psychology departments. Second, while encouraging students to use computers for modelling and simulation, bear in mind a lesson learned at SFI about modelling and simulation. Do not confuse the solution to a toy model (i.e., one in which the complexities of the real world are reduced to a small manageable set of interacting agents) with the solution to a real world problem.

I now turn to the role of departments in our redesigned university. In the standard model of a disciplined-based university, departments are inevitable, for how else could we organize the transmission of basic disciplinary skills or research on discipline-based problems? In the basic sciences and mathematics, that argument is also applicable to a transdisciplinary university since, until a student has acquired a number of basic disciplinary skills, he or she is not ready to move beyond that discipline. However in the social sciences, engineering, and the humanities, I would argue that while departments are inevitable, they need not be immutable, and that departments can and should be treated as dynamic entities which can both form and disband. Moreover, even though a department may maintain its name, in the best of today's research universities, the research interests of its members undergo continuous change as subfields form (and occasionally) disband.

Having put that forth, given our premise that the solutions to the most important problems of the 21st century will not be found within a single discipline department, it is equally important for the "new" university to establish problem-oriented entities, *centers*, which cut across departmental boundaries or, to put it more positively, make it possible to construct bridges between departments and disciplines. With their problem orientation, such centers can and will be the source of, or the inspiration for, courses and seminars which address the problems which nature and society pose for us, as distinct from those which address only discipline-based problems. Moreover centers provide a way of attracting (and keeping) faculty whose interests and experience go beyond a single discipline.

We can go further by establishing a center which is devoted to nurturing *pre-center* exploratory research on a broad range of transdisciplinary problems. Such a center might be run very much along the lines of the Santa Fe Institute with a budget sufficient to run an active program of exploratory workshops, research networks, and theme years involving scientists both within and without the university. It should have no permanent faculty; decisions concerning its scientific agenda should be taken by a science steering committee whose membership rotates.

As a research program initiated by this *center of centers* matures, the university could then consider spinning it off into a new (and more specialized) center which might over time become

a department. What I am proposing here is an evolutionary process: Not all center research problems will mature in this way, and it is essential that "sunset laws" or their equivalent be devised for center research programs so that this center of centers remains small, flexible, and innovative rather than becoming ossified into a school or college.

Concluding Remarks

In this brief paper, I have focused on the modern research university. I have argued that we should never forget John Seely Brown's thesis (Brown, & Duguid, 1995) that the core competency of the university is to create knowledge, not transfer it, that we should regard students as an *active* component of the learning community which is the university, and that in considering faculty, we should make explicit the fact that transdisciplinary potential and accomplishment represent significant criteria for appointment and promotion. The general guidelines for curricula design which I have proposed appear applicable as well to existing universities, and indeed a number of research universities are implementing them to a greater or lesser extent. Essentially all of these ideas are equally applicable to undergraduate institutions, but changes there may turn out to be even more difficult to bring about. What is clear is that as a university or college establishes centers and gives them power and influence, a certain amount of tension between departments and centers is to be expected. It is likely that those universities and colleges which work out mechanisms for successfully resolving those tensions will lead the way in the 21st century.

Let me conclude by encouraging students and faculty alike to take to heart and perhaps use as the university motto the words used by Robert Oppenheimer in 1946 to characterize theoretical physics, words equally applicable to the university at its best, "What we don't know, we teach one another."

Acknowledgements

It gives me pleasure to recall the many stimulating discussions about the design of a new university with my cofounders of the Santa Fe Institute, George Cowan, Stirling Colgate, Murray Gell-Mann, Nick Metropolis, and the late Herb Anderson, Peter Carruthers, and Dick Slansky, in the period leading up to the foundation of the Institute, discussions which have influenced my present views on university design. I should also like to thank my SFI colleagues, Michael Cohen, Rajarshi Das, John Miller, and Richard Palmer for the suggestions I have incorporated in this paper, Esther Dyson for bringing the paper by Brown and Duguid to my attention, and Catherine Pines for her helpful suggestions.

*Note

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