ENHANCED HUMAN-COMPUTER INTERFACES: A MULTIDISCIPLINARY APPROACH

A Report to the National Science Foundation

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1. MOTIVATION FOR THE WORKSHOP ON ENHANCED HUMAN-COMPUTER INTERFACES

One of the most significant emerging areas of computer science is the human-computer interface; that aspect of a given computer system which allows a person to interact with the system or program. It has been estimated that the human-computer interface of most significant programs or systems is about 48% of the entire system, and that about the same percentage of time is used in constructing the interface [Myers & Rossen, 1992]. In addition, the new technologies which enable virtual reality and other advanced forms of human-computer interfaces will greatly extend the role of the interface in new computer systems.

Computer systems with advanced Human-Computer Interfaces (HCI) will play a role in many applications. One of the most promising of these will be in systems for education. This is particularly important as our society is grappling to improve education, especially in the science and technology areas. By incorporating advanced HCI into educational computer systems, it will be possible to more vividly and concretely communicate with students. It will be possible to create "environments" in which students can learn and explore different concepts in science, and it will be possible to tune feedback to the individual student user. All these factors are needed as we face the challenge of creating a greater scientific literacy - and interest in scientific literacy - in our student population. Thus, there is strong motivation to explore the link between human-computer interface research and interactive learning environments.

The National Science Foundation workshop was motivated initially by the shared desire among the workshop co-chairs, the NSF sponsors, and the participants to explore new ways in which we could enhance human-computer interfaces, particularly with regard to creating systems to aid education. We were initially interested in how some aspects of cognitive psychology, particularly the psychology of individual differences, might beneficially influence human-computer interface design. We also thought there were some as-yet unrealized potentials to be explored in using connectionist (or neural-networks) based processing methods to enhance human-computer interfaces. Thus, at the genesis of the workshop plan, the initial question we formed was:

> Can we improve next-generation Human-Computer Interfaces (HCI); particularly with regard to how they differentially respond to different users and/or user types?

It was at this stage that program managers at the National Science Foundation were approached. Interactions with Drs. Paul Werbos, John Hestenes, Joseph Young, and later, Andrew Molnar, led to collaboration between Drs. Maren and Lesgold on developing the workshop concept. In order to focus the very broad question raised above, we decided to explore the relationship between the question raised above to the challenge of science education. This led us to the question which guided development of the workshop plan:

> "How can advances in connectionist (neural network) methods, combined with advances in cognitive psychology (particularly individual differences) be used to <u>enhance human-computer interfaces for improved science education?</u>"

This question is diagrammatically posed in Figure 1.

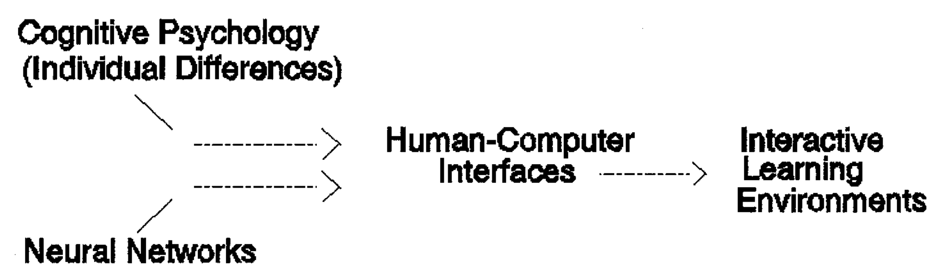

Figure 1. Initial view of possible interrelation among workshop topics, leading to enhanced human-computer interfaces for interactive learning environments.

To address this question, we formed a list of invited participants, whose areas of expertise (including that of the chairs) were in:

- o Human-Computer Interfaces (6 persons)
- o Interactive Learning Environments (6 persons)
- o Neural Networks (5 persons)
- o Individual Differences / Cognitive Psychology (4 persons).

Also, we invited two science fiction authors whose published books had featured virtual reality and other novel approaches to learning environments. A complete list of the workshop sponsors and participants is given in Appendix A.

During the course of our workshop planning and the workshop itself, we developed realizations which were different from those anticipated when we set the initial agenda. Although a "focus question" had been formed prior to the workshop, the actual workshop process (included pre- and post-workshop activities) enveloped a much wider range of issues. The questions which each of the participants asked, and the interactions among the participants, led to a set of "core issues" which became the actual workshop investigation. These in turn led to our formation of a "proto-agenda" for recommended research directions. We describe the questions raised by participants in their position papers in the next section, and the "core issues" which emerged during the actual workshop itself in the following section.

2. PRE-WORKSHOP: PLANNING AND POSITION PAPERS

This section describes in detail the plans and goals for the workshop, and then illustrates how different participants responded to the "focus question" of the workshop with issues raised in their position papers. Many of the issues raised in the position papers will be developed and presented as chapters in the edited book which will be another result of this workshop.

2.1 The Workshop Plan

One goal of this workshop was to set up cross-disciplinary dialogues on the posed question (and questions which devolved from it) with a view to forming a research proto-agenda to be submitted to the NSF in the form of this report. Other, supporting goals, were to share the outcome of this workshop with the scientific community through brief reports on this workshop presented at conferences or submitted to journals. We also planned to create an edited book based on the workshop. (The contract for this book, tentatively titled Enhanced Human-Computer Interfaces: A Multidisciplinary Approach, and edited by Maren and Lesgold, is being negotiated with Academic Press. We anticipate that the book will be published in Spring, 1993.)

In order to explore the long-range implications of a research agenda, we realized it was important to have participants from both industry and academia. In particular, we had industry representatives in such highly commercializable areas as neural networks and human-computer interfaces. Our final ratio was about 60% from academia and 40% from industry.

This workshop was unique in its cross-disciplinary breadth. This was reflected not only in the participants in this workshop, but in the NSF sponsorship. This workshop was sponsored by four different program managers, from four different directorates in the National Science Foundation. Each sponsor was instrumental and helpful in shaping the initial context of the workshop. These sponsors were:

- Dr. John Hestenes, Program Director, Interactive Systems Program, Computer and Information Science and Engineering Directorate

- Dr. Andrew Molnar, Program Director, Program Director, Application of Advanced Technology Program, Human Resources and Science Education Directorate o Dr. Paul Werbos, Program Director, Neuroengineering Program, Engineering Directorate

o Dr. Joseph Young, Program Director, Human Cognition and Perception Program, Integrated Biological and Neural Sciences Directorate

The two co-chairs for this workshop had backgrounds in neural networks (Alianna Maren) and interactive learning environments (Alan Lesgold).

One of the big challenges in facilitating this workshop was the cross-disciplinary nature of the inquiry. Participants from the same discipline knew each others' language, knew the issues that were considered important in that field, and knew the history of the development of those issues. They were often familiar with the work of the other participants from the same disciplinary group. In contrast, the researchers from one discipline were often not at all familiar with the language, work, or issues of the other three disciplines. To complete this challenge, the two science fiction writers were not familiar with the research processes in any of the four scientific areas.

In order to facilitate communication across these disciplinary barriers, we asked each participant to submit a position paper describing their approach to the question posed well before the dates of the workshop. These position papers were circulated to all participants.

The workshop itself was organized to facilitate dialogue. We alternated small-group discussions with reports of the group discussions to the whole group, intermixed with large group discussions. The first round of discussions was organized as four concurrent "within-discipline sessions." Participants were grouped by scientific discipline for these sessions. At the end of the session, each session leader reported from a "disciplinary perspective" on the problem posed.

All remaining discussions were organized into breakout groups, where the assignment of participants to a breakout group (the same group for the remainder of the workshop) was done to create the greatest possible juxtaposition of each of the four research areas, as well as balancing industry and academic perspectives. The workshop plan is summarized in Appendix B.

2.2 The Position Papers

Each of the workshop participants was asked to prepare a position paper in advance of the workshop. These papers were circulated among all the participants and sponsors some weeks before the workshop itself. The goal of these position papers was to encourage each participant to address the focus question of the workshop in his or her mind, and to share their perspective with other participants.

Brief excerpts from the position papers of the research participants, given in Appendix C, illustrate the issues and suggestions which participants made. They will be developed at greater length in the contributed chapters the participants are creating for an edited book resulting from this workshop. The visionary outlook offered by the two science fiction writers who participated in the workshop is extracted in Appendix D.

3. THE WORKSHOP: WHAT HAPPENED

It is greatly to the credit of all the participants that they were able to move beyond their disciplinary boundaries and grapple with the challenging cross-disciplinary issues brought up in light of the workshop focus question. For most participants, the workshop was both exhilarating and frustrating as we developed communication and shared perspectives. We commend the session chairs and break-out group chairs (noted in Appendix A) for their excellent work in guiding their groups and synthesizing the diverse points of view.

Two notable things happened during the workshop. One was that certain topics emerged with all the force of "strange attractors" in the continuing discussions. The second is that some cross-disciplinary dialogues were smooth and easy and readily identified common issues, and that other cross-disciplinary dialogues consistently manifested rough edges. Sometimes, the participants did not know how to talk with each other. More accurately expressed, they didn't know what to talk about with each other. We will posit that the interactions between the emergent topics and the most notable communications barriers in the workshop will provide the most fruitful - and even the most compelling - areas for research. These areas are discussed in Section 4.

The two topics which emerged as "strange attractors" were virtual reality and learner motivation. As the workshop progressed, it became evident that these were not topics in isolation, but rather that they manifested as icons or archetypes of a whole class of concerns. The fascination which almost everyone had with virtual reality and its promise for education was actually only the most highly charged focus of a overwhelming interest in the evolution of highly sensory-rich interactive human-computer environments. Similarly, the concern which many participants expressed regarding learner motivation as a key to facilitating learning was an encapsulation of many concerns about how we as a society hold the paired roles of learning and teaching.

Another topic - cognitive engineering - emerged as a context for the workshop. Throughout the workshop, the issue was not "Can we?" but rather "How can we?", as applied to creating effective interactive learning environments and other systems. This topic was a deep realization of both the potential of and the need for successful development of cognitive engineering practices.

The areas in which cross-disciplinary communications did - and did not - occur readily also are very suggestive of areas for further investigation. The communication link which was most easily established was between the interactive learning environment workers and the human-computer interface workers. A link which was difficult to establish was between those in the neural networks (connectionist) area and persons using symbolic-based systems development, such as interactive learning environments. Also, we collectively found it difficult to clearly ascertain the role of individual differences. The reason for this is that as the foci of interest emerged (cognitive engineering, high-density sensory-rich interactive environments, and motivation-based approach to learning), the concerns about individual differences per se became subsumed into the more general discussions of how to best create complete systems for human-computer interaction. Also, participants had different views regarding the importance of user modeling in human-computer interaction and interactive learning systems.

Some of the difficulties of communication arose because of the rapid state of progress in the disciplines represented. An example is the cognitive psychology of learning. The classic cognitive view, that people have (or can build) rich representations of tasks and then carry out those tasks by operating on those representations, was pretty well assimilated by participants from other disciplines. However, the cognitive learning people themselves included some who were seriously challenging the classic view. The "situated learning" camp sees interactions with the environment as the building blocks of knowledge and sees representations more as ways of talking about what one knows rather than what is stored in memory. They see acquiring knowledge as a "transaction with the situation" [Schon, 1987]. Work in artificial intelligence on the respective roles of well-indexed memory for cases (or situations) and abstracted knowledge also has moved beyond the classic view of experts making and then operating upon representations, again seeing learning as the acquisition of modes of interacting with the world rather than an ability to abstract from the world and then to process the abstraction. And, of course, the neural networks school of learning research holds positions that speak to this complex point. Sometimes, because of the rapid changes and increased complexity of cognitive viewpoints, non-cognitive learning people were surprised that points they were willing to concede were being challenged by those expected to insist upon them. Similar situations arose in other disciplinary areas as well.

There were several topics that emerged often within the context just described. These included situated or life-long learning, fidelity of representation in an interactive learning environment, and an orientation towards "design-based science" rather than "science-based design" for creating systems with which humans interact [Carroll, 1990]. With regard to life-long learning, Gerhard Fischer's position paper described the need: "Information overload, high functionality systems, and the rapid change of our world have created new problems and new challenges for education and training. New instructional approaches are needed to circumvent the unsolvable problems of coverage and obsolescence." This concern led one group to characterize learning more as construction of shared meaning than flow of information.

It led them to describe the problem for computation as less one of channeling information flow more efficiently, and more one of enabling social negotiation of meaning among collaborators. This problem represents a significant shift for the role of computers: from primary roles of word processing, data manipulation, and number crunching to a primary role of enabling communication and collaboration. This means that computer systems should create opportunities for people to become "legitimate peripheral participants" (in the sense of contributing from different locations to an ongoing process) [Lave & Wenger, 1989]. This is a distinction from a previous concept which treats people as consumers of information flows.

The concern with "design-based science" was brought up by several participants. Quoting Don Norman, "Science is too late, too sparse, and too costly" to serve as the basis for the abundance of decisions required in a design process. Particularly in human interfaces, science always lags technology. Toulmin's [1990] observations about the contrast between reflective action and rationalistic perspectives is helpful: Good design requires an orientation to the timely, the local, the particular, and the personal, whereas high science is more typically concerned with the absolute, the timeless, the universal, the general, and the objective. In a design-based science, the process should start from a strong base of data on actual instances of the kind of activity one would like to support. Selection and reflection over actual instances of learning and doing can provide exemplars, archetypes, and mock-ups that guide the design and evaluation process. As the design-evaluation loop iterates, patterns of activity will begin to emerge. As these patterns emerge, theories and methods from individual difference psychology, neural network research and cognitive research could help clarify the observations, present them concisely, and predict consequences. From these one might build towards conceptual models, and eventually reactive systems.

The workshop has led to publication of three reports [Maren 1992, 1991a&b], and to development of a book [Maren & Lesgold, expected 1993].

4. A PROTO-AGENDA OF RESEARCH ISSUES

The research proto-agenda which we outline in this section results from integration of reports submitted by session leaders and break-out group leaders regarding their group's insights and recommendations, along with elements from the position papers submitted prior to the workshop by all participants. Because the workshop brought up issues which were different than those originally anticipated, we have reevaluated the reports we received and the records we made of the workshop dialogues to be consistent with the emergent workshop foci.

We have identified three major areas for investigation, resulting from the two workshop foci (high-density sensory-rich HCI and learner-oriented interactive systems) and the emergent context of cognitive engineering. However, the areas we suggest for investigation lie in the relations between each of these areas, rather than within a single area itself.

4.1 Research Issues between Learner-Oriented Interactive Systems and Cognitive Engineering

4.1.1. Investigate relationship between cognitive load and learning

One of the most basic issues which we can effectively research over the next decade, and one which will have substantial impact on real system design, is the relationship between cognitive effort in working with a system and long-term learning. This can be restated as an investigation into the relationship between short-term performance cost (as a user invests more effort into managing the cognitive load of a system) and long-term performance benefit (as a user has developed a more complete or effective mental model or task mastery). Wickens [1992a] has described this issue in more detail.

At issue is the following: Certain features of interface design, like translating semantic intentions into arbitrary sequences of keypresses, are effortful and work to the detriment of learning. For example, as Sweller and his colleagues [1990] have noted, the resources invested into these operations compete with the resources necessary to acquire and store new knowledge. However, other features of the interface, which may be designed to reduce effort, may in fact eliminate learner task components whose effort demands are necessary for the learner to form new insights. For example, it may be effortful to understand the <u>relationship</u> between scientific phenomena expressed in several different formats (symbolic formula, semantic words, graphical, and "experiential") through virtual reality, yet this effort would seem to be a necessary investment before full understanding of the phenomenon is realized [Wickens, 1992a].

In sum, there are clearly some features that induce learning-irrelevant effort, and others that induce learning-relevant effort, but the continuum between these features is not well understood, nor are the appropriate techniques identified that will induce an unmotivated student to invest effort in the appropriate aspects of a computer-mediated learning environment.

This issue will become of greater concern as we develop interfaces with greater sensory richness (e.g. virtual realities). We need to identify combinations of sensory inputs, cognitive processes and cognitive load (which must often be inferred), and user actions which result in effective long-term learning and the ability to generalize and transfer the learned material to new situations.

4.1.2. Investigate how groups of individuals can interact effectively with performance support and learning tools

Most work is done by teams. This is partly a consequence of the informatic age. Simple and routine tasks are done by machines. People handle complexity, reconciliation of conflicting viewpoints (e.g., concurrent engineering discussions among designers, manufacturers, and crises. Yet, most schooling is centered upon individual activities that help people learn the skills needed to be replaceable human components for assembly lines and middle managers. Schools do not provide much opportunity for learning to function as part of a problem-solving group. At the same time, the particular human skills involved in shared problem solving are a major part of the human skill repertoire that remains valuable as machines take over routine information processing. Humans acting in groups can better deal with the inconsistencies and conflicts that are part of complex enterprises.

Technological support for group cognitive work is beginning to be developed, and much of this support can be extended to produce new tools for collaborative learning activity. We suggest the need for extended research on:

(a) the group cognitive characteristics of work in the informatic era,
(b) the knowledge and skill needed to engage in such work, and
(c) tools that can support simultaneously the exercise of group interactive skill and further acquisition of group-related basic cognitive capability.

4.1.3. Identify ways to increase the versatility of intelligent tools to meet different needs of users

Different users will have different needs when they interact with an intelligent system. Within the last few years, there has been a growing awareness within the cognitive learning community that interactive learning environments need to be designed to allow the interaction to meet these diverse user needs. This realization is a more mature approach than that associated with previous work in computer-aided learning. This is because most teaching systems (whether books, lectures, or interactive learning environments) attempt to establish what the learner is to learn; to dictate the terms of the experience. The prospect of using existent learner interests to motivate further learning is essentially a manipulation of the user in order to bring him or her into an established body of knowledge which some person(s) have determined to be the material which should be learned.

Practical experience with interactive learning environments such as Sherlock II has produced a reevaluation of the role of such tools. In the real world, not only do people start out at different levels of capability in a course, or with different motivations or interests, they also have differing (and authentic) needs. One person, who may be in charge of a function within a work group, needs to become very expert. Another person may need moderate expertise so he/she can fill in when the expert is on vacation. A third person may need an overview so he can discuss the needs of the job intelligently in administrative meetings.

While individualization with respect to student entering ability was the goal of the early intelligent tutoring system movement, we can see now that it may be even more significant to allow for individualization with respect to different user (student) goals and needs.

4.1.4. Need for a systematic basis for developing performance / learning support tools for different needs

The best tools are usable and modifiable at the job site. Research is needed to articulate ways of accomplishing participatory design more effectively and to produce tools to facilitate participation in design of learning environments by the people (students and teachers) who will be using those environments. For example, we need a set of performance support tools that can be adapted by local school systems to support a variety of teacher and student-led activities, ranging from targeted learning to student projects to self-assessment. There are two key requirements for such tools:

1. The tools must be readily modifiable by students and teachers to support learning and self-assessment activities that they choose and/or design.
2. The tools must be tested sufficiently to promote confidence among teachers, school leaders, and educational policy makers that using them pays off.

To get away from hand-crafting every individual system, we need tools that support development of interactive applications. IN the context of this workshop, we particularly need authoring tools to be used by educators to develop computer-based instruction for students. Much is known about producing good and bad instructional design. Now we must take this existing knowledge beyond the rather simplistic use of multimedia that it has, for more than a decade, employed, into a broader, more innovative uses of emerging new technologies and concepts.

A common misconception is that just having the right tools (here "tool" means authoring system) will guarantee a good <u>product</u>. But of extreme importance is the <u>process</u> by which that product is developed. In instructional applications, as in any interactive application, it is possible to use a good tool to produce a bad product, if the tool is not used in the context of an appropriate process. This process, especially how to evaluate the effectiveness and usability of resulting instructional applications, is a major open area of research. In fact, we often have the tail wagging the dog, when we attempt to build tools to support a process that is ill-defined and poorly understood. We must reverse our approach and focus on understanding the appropriate process for computer-based instructional applications. That, in turn, will help us produce more effective and usable products - not just in the educational world, but for interactive systems in any domain [Hix & Hartson, 1993].

4.1.5 <u>Research on Development of Simulations for Learning</u>

Realistic, and relatively concrete, simulations make complex phenomena more accessible to students and permit experimentation and exploration in virtual worlds that is either costly or impossible in real worlds. In the area of development of simulations for learning environments, participants made the following recommendations:

- Tools are needed for rapid development of simulations, especially dynamic modeling tools for several different system types (e.g. linear, nonlinear, qualitative, symbolic-logical).
- New paradigms and architectures for instructional simulations should be explored. To enable this, object-oriented tool kits are needed to support programming, simulation data bases, graphic user interfaces, and other components of reality-grounded learning.
- Work should be supported on advanced intelligent "agents" that embody extended versions of the primary roles now enacted in intelligent tutoring systems (e.g., coaching, assessment of student knowledge, "expert models," etc.).
- Work is needed on adaptation methods that allow simulation systems and other intelligent computer tools for learning to improve with experience, to incrementally incorporate the "collective wisdom" of experience with students.

4.2 Research Issues between Sensory-Rich Interactive Environments and Learner-Oriented Interactive Environments

Workshop participants addressed student modeling and realistic simulations as important components of learning environments.

4.2.1 Develop Adaptive Student-System Interaction Models

Participants addressed the problem of student modeling as the assessment of student capability by intelligent learning tools, both to guide instruction and to certify outcomes of learning. Current student modeling approaches have two problems [c.f. Lesgold, 1988; Lesgold, Bonar, & Ivill, 1989]. First, it is not possible to have a certainty about whether or not a particular piece of knowledge is present in a student. Human competence is characteristically redundant and unreliable. That is, a student may perform a procedure even if he or she doesn't really know how to do it. And, even after a student knows how to do something, he or she may fail to do it right due to temporary stress, fatigue, or distraction. So, student modeling, for us, is inherently probabilistic. A second problem is that microlevel detail may not be the only useful level for student modeling. Often, the choice of which problem to give or how much help to provide is based upon broader curricular goals than the learning of individual facts or rules.

The first task in student modeling, then, is to classify patterns of noisy performance, to discover the changes over time that occur in the many local variables we track. Often, this can be done with standard data aggregation techniques such as regression, but other techniques are also beginning to be considered [Mislevy, personal communication; Van Lehn, personal communication], such as Bayesian belief net architectures [cf. Pearl, 1988]. Another possibility is the use of competitive learning neural networks to discover patterning in the patterns of incomplete knowledge seen among students using intelligent learning systems. The second problem involves relationships between specific knowledge states of the learner and the efficacy of alternative teaching strategies. That is, we have complex patterns regarding the student's knowledge state, as indexed by a number of measures of details of the student's performance on learning tasks, and we have to decide which of a number of potential next task assignments is appropriate. Sometimes we are successful, and sometimes not. We would like to be more successful, so we need to find a way for a system to learn from experience. This, too, looks a lot like a neural network task. Use of neural network technology for student modeling within intelligent tutoring systems is a promising approach that merits further research.

Such a system will be one which can adaptively construct a set of relationships based on metrics which represents optimal "human-computer system" performance. These relationships between system "observables" (metrics on the user, environment, and interface configuration, as well as interaction descriptors between the human and the computer) and system "effectors" (the ways in which a system can adapt or change its interaction with the user or environment) form the basis for a system identification problem. When we can identify desired system performance metrics, we have the basis for creating a non-parametric model and control system useful for optimizing observable / effector relations.

Because we do not know in advance the nature of the relationships between the observables and the effectors of a system, we need a system which can adaptively construct a set of relationships using a metric which optimizes system performance. This type of task is more suited for connectionist approaches rather than symbolic or algorithmic ones. This is an area in which the neural networks community has already made significant advances, the most pertinent of which is the "Adaptive Critic" neural network systems. This system design arose from considerations of systems engineering, a fundamental problem in the engineering of complex systems [Werbos 1992a,b, 1990]. Adaptive Critic systems are currently in use for robotic motion control [Barto, 1992, Sutton et al., 1991] and are being developed for other applications.

Even though connectionist approaches such as Adaptive Critics offer a methodology for adapting HCI systems to the needs of individual users (or classes of users), there are major research issues which need to be addressed. These include investigations into optimal selection of:

o <u>System inputs</u> - What dynamic and static characteristics of the user, the environment, and the human-computer interface configuration form appropriate inputs into an Adaptive Critic monitor and control system? This is a research issue which can not be addressed at a simple level, because we anticipate that the "bandwidth" of information a human-computer interface can present to and access from a user will grow dramatically over the next two decades. We do not yet know how our measures of the information presented to and accessed from the user will scale relative to increases in the "bandwidth" of information channels. It will be critically important to develop useful measures of both the nature and the complexity of presented and accessed information.

o <u>System outputs</u> - What attributes or characteristics of an HCI can and should be adapted to different (classes of) users? This area invokes all the questions we have asked during the workshop regarding the usefulness of user / learner models. (See Section 4.1.3.)

o <u>System performance metrics</u> - What aspects of overall human / computer system performance do we want to emphasize by selecting certain performance metrics? As described in

Section 4.1.1, Wickens and colleagues have demonstrated that different human-computer interface system configurations can lead to optimal performance of different sorts. Thus, the desired nature of the desired performance needs to be carefully specified.

4.2.2 Investigate Use of Realistic Simulations as Parts of Learning Environments

We do not yet have a very rich knowledge base of principles of learning from realistic simulations. Observational studies of children using simulation tools for learning will be a necessary first step towards such a knowledge base. The following recommendations were made by different break-out groups:

- o A special area of needed work is on forms of simulation fidelity and their relationships to learning. When should reality be "scaled back" (and which aspects should be attenuated), because it distracts from learning-producing activity?
- o Work is also needed on processes and techniques of scientific discovery and the role that simulations can play in fostering development of scientific reasoning and discovery capability.
- o Work is needed on assessment methods that can be incorporated in learning environments that use high fidelity simulations. Techniques for summarizing the ways in which students interact with simulations and estimating student knowledge from those interactions are needed.
- o Research is also needed to establish optimal means for providing effective feedback about performance in complex virtual reality environments.

Virtual reality systems, which are important potential components of training systems in the future, will have complex issues of display configuration to handle, and these too might benefit from neural network representations for connections between properties of displays, properties of expertise, and properties of the student in the midst of learning. Different presentation modes are best suited to different learning situations. Audio presentation, for example, is of low bandwidth but highly eliciting of attention. Similarly, choosing to use photographs versus diagrams, separated simple graphs vs. complex integrated graphs, and static vs. animated illustrations of how things work are decisions that can benefit from being tuned to individual differences. Research on tuning of presentation formats to individual student needs is likely to pay off in improved teaching technology. What is not yet clear is whether tuning to global differences among people or tuning to knowledge and performance state within each individual will pay off the most. Overall, research is needed to establish when the tuning of interfaces to student individual differences is facilitative of learning. We recommend that work on neural networks and other schemes for adapting interfaces to individual differences consider both intra- and inter-individual differences.

As a final note on research in the cross-disciplinary link between high-density sensory-rich interactive environments and technologies for learning, we need to take into account some very strong social factors that influence how interactive learning environments will be experienced by users; especially by young users. Our children are growing up in a "quasi-virtual-reality" experience that comes about through playing Nintendo and similar computer-hosted games. These activities lead them to have expectations about the nature of human-computer interactions, which they will take with them into new experiences with an interactive learning environment. We should anticipate that these early experiences will affect their experiences with interactive learning environments, and consider this when we design human-computer interfaces for learning environments.

4.3 Research Issues between Cognitive Engineering and Signal-Rich Interactive Environments

In order to build effective next-generation human-computer interfaces, we need to address several challenging issues involving the connection between signal-based environments (such as used for information presentation and acquisition) and symbolic environments which encapsulate the "cognitive" or higher-level knowledge of a system. We need to know how to direct processing resources to aid this interaction. Finally, next-next-generation human-computer interfaces (in the year 2000 and beyond) will take advantage of biometric readings of their human users. These will include user characteristics already under investigation, such as eye-gaze and gesture detection, up through less commonly used biophysical parameters, such as EEG measurements.

4.3.1. Develop a Stronger Foundation for Signal-to-Symbol Information Representation

One of the most imperative challenges in developing the next generation of human-computer interfaces is to develop a strong basis for transitions between signal and symbol information representation. Both the signal level and the symbol level of representation are crucial; but a human-computer system operating with very dense information presentation / acquisition channels (e.g. combined visual, acoustic, kinesthetic, etc.) will need to have effective conversion methods. This area of investigation is inherently cross-disciplinary and is a significant research challenge.

Representing the level of knowledge and/or information has long been of great significance in artificial intelligence systems [Newell, 1981], and has been discussed in terms of human-computer interfaces [Rasmussen, 1983]. The relevance of this issue will increase dramatically as we build human-computer interface systems which have two-way human-computer interactions at the levels of signals, signs and symbols with wide-sensory-bandwidth human-computer interfaces.

To achieve effective signal, sign, and symbol representation and communication in an human-computer interface, we need to facilitate a relationship between signal-level processing methods (e.g. neural networks and adaptive systems) and symbol-based processing methods. This area has received some attention [Maren & Minsky, 1989], but needs to be developed further.

There are several subareas which contribute to the above challenge. These include, but are not limited to, developing methods to:

i) Integrate different and/or off-set timescales for presentation and acquisition of information,
ii) Self-organize pattern perception and representation across multiple spatial scales,
iii) Determine different (but related) hierarchies of data presentation in different submodalities of data / information acquisition and processing,
iv) Integrate information across different sensor modalities, and
v) Represent information at intermediate (e.g. "perceptual" or "organization") levels which can facilitate the signal-to-symbol information recoding.

We note that these issues are not limited to developing human-computer interface for interactive learning environments, but are important in other applications areas as well. We suggest that this work be sponsored under the National Science Foundation, though, to ensure development of generic technologies which can motivate the next class of commercializable human-computer interfaces.

4.3.2 Develop Theoretical and Experimental Foundation for Design of Multi-Modal Presentation of Information and Cues

We will need to expand the current work in human-computer interface design guidelines to encompass the greater richness and complexity afforded by next-generation human-computer interface systems. There is currently a great deal of work being done on developing consistent and effective user interfaces, and much attention is being given to specific interface environments, e.g. graphical user interfaces. As we move to being able to consistently present information using more than one medium (e.g. couplings of visual, auditory, and kinesthetic), we will need to investigate how information from these multiple sources should best be presented to different users.

Extensive work has been carried out on optimizing the format of information within a single modularity. However, surprisingly little research has examined the conditions in which redundancy gain, produced by information presentation across modularities does [Booher, 1975; Nugent, 1987], or does not [Oshima & Wickens, 1991] emerge, whether in a performance or an instructional context. While general findings are that redundancy gain occurs more often than not [Wickens, 1992b], theoretical models of the integration of information across sensory modalities must be developed [Yee, Hunt, & Pellegrino, 1992] to establish the circumstances when separate representations in sound, pictures, and words will lead to the greatest transfer of knowledge to the learner. Such work can also help establish whether identical (pure redundancy) is more useful than cross-modality redundancy (e.g. auditory-visual) or cross-format redundancy (e.g. verbal-spatial). In short, research must identify when "more" is useful, and when it is simply noise.

This issue is, in a sense, the reverse of the challenge described in the previous subsection; the initial information will often be symbolically embedded, and will need to be converted into symbols and/or signals which will be embedded into a perceptual environment. "Perceptual" factors such as relative size, intensity, and orientation of different information components will need to be adjusted. Such perceptual, as well as signal-level, considerations will become more complex when multiple channels for communication will be used.

4.3.3 Develop Methods to Measure and Direct User Attention

Even though next-generation human-computer interface systems will operate using more powerful and parallel systems than we currently use, we anticipate that generating and updating a very sensory-rich environment for the user will still be computationally demanding. It will also be a demanding processing challenge to process all the observations which can be made on a user. For multi-user systems, the processing requirements will be even greater. Thus, we need to develop methods to minimize computer processing. This can be done, in part, by developing a combined theoretical, experimental, and systems basis for measuring and directing user attention within a next-generation human-computer interface environment.

Methods to track user attention should include measures of both user characteristics (e.g. eye-gaze) as well as measures on the environment created and presented by the system. These latter should include measures of perceptual salience of the environment, the effect of change, and the effects of synchronous or coordinated change in multi-modal information presentations. Earlier work done on flight simulators may yield insights on performance measures that can be used to infer the skill of the user [Vrenls & Obermayer, 1985].

4.3.4 Investigate Influence of Previous Experience on User Adaptation to and Acceptance of New human-computer interface Systems

We need to take into account the realization that it will not necessarily be simpler to learn and use very sensory-rich human-computer interfaces than existing human-computer interfaces. It is likely that such new interfaces will in fact be more complex and subtle than existing ones. This will be particularly true if part of the human-computer interface includes adaptive learning or response to user-specific characteristics, such as eye-gaze movements or gestures. People will learn - directly or indirectly - that they influence an human-computer interface with these more subtle indicators, and will build up both a model of the human-computer interface and an interaction pattern based on their history of interaction with a particular system. This will lead to strong expectations and to proficiencies with certain interaction patterns. There will be a psychological component to this user-adaptation to an human-computer interface.

There is a system identification and control issue here related to those discussed in Section 4.2. In any closed loop, negative feedback system, there is the potential for instability if the error-detection and correction algorithm takes too long to proceed. This may well be the case if it takes some duration of time for an intelligent system to infer operator knowledge [Wickens, 1992b]. Research needs to be done on the timing considerations for a given adaptive system.

We know now that there are strong loyalties among people to different types of human-computer interfaces; for example, many PC users have strong preferences for IBM-type environments or for Mac-type environments. We can anticipate that as the complexity of human-computer interface options grows, different user groups will develop both skills and preferences for specific environments. It is also common knowledge that many people have a strong resistance to changing their patterns of interaction (in any area). We need to take into account the strong influence that users' previous experiences will have on their future inclinations and their adaptability to and acceptance of new environments.

4.3.5 Develop Basis for Use of Biometrics in Human-Computer Interfaces

The recommendations made up to now deal with human-computer systems which we expect to realize in the coming decade. Next-next-generation human-computer interfaces will operate on a more tightly coupled linkage between the human and the computer, creating a more intimately responsive system with performances which we anticipate being beyond the capabilities of either a computer system or a human alone. These systems will require rapid integration and response to biometric readings of the human. Some work in this area, e.g., that using eye-gaze detection and gesture recognition, is already well underway. Nevertheless, we anticipate that next-next-generation human-computer interfaces will use neurophysiologically-based information, such as that obtained from neuron bundle activity analysis or from macro or micro-EEG.

One area which has significant potential is the use of neural prostheses; or neurally-directed human-machine interactions. One avenue is the use of neural network devices to interact with a bundle of motor neurons; an area especially useful for prosthetic devices but which has long-term implications for teleoperation and other applications. Kovacs and colleagues have been developing methods for neural-network control of neurally-coupled prosthetic devices [Wan et al., 1990; Kovacs & Rosen, preprint]. This work, coupled with work being done by Carver Mead and colleagues in the development of artificial cochlea and retina, and work by Walter Freeman and colleagues [Eisenberg, Freeman, & Burke, 1989] in developing models of the olfactory system, pave the way for deeper linkages between human neurophysiology and man-made systems.

The possibility of neural prostheses is not limited to coupling neural network systems to the receptor points for biological sensing and motor control. We can also envision cortically-based neural prosthetic devices using measurements of EEG activity. There is still considerable question about the extent to which EEG information, particularly <u>E</u>voked <u>R</u>esponse <u>P</u>otentials (ERPs) can be a useful stimulus in a human-computer interface. However, Hudspeth [in press], in an experiment in which subjects viewed stimuli that had two attributes (one each of two color and two form possible presentations), found that the evoked response potentials obtained reliably classified the stimulus attributes. This work indicates that ERP observations can be used to identify abstract features in stimuli and respond to different features presented together in a single stimulus. These investigations have a long history of supporting distinctions between the different ERPS evoked by different stimuli. (See, e.g. [John & Morgades, 1969]). It is possible to extract useful information from specific components of ERPs, as is demonstrated by Donchin and colleagues (See, e.g., [Donchin & Fabiani, 1991; Donchin & Coles, 1988; Fabiani et al, 1987]).

There is work linking the effectiveness of human performance, or the effect of workload on performance, with EEG signals. Gevins et al. [1987] report that brain electrical patterns before accurate performance differ from the patterns before inaccurate performance. Trejo et al. [1990] correlates ERPs with task workload.

Efforts to create neural prostheses have been reported by Farwell and Donchin [1988], Hiraiwa et al. [1990], and others. These preliminary efforts show limited correct classification of ERPs; even using neural network pattern recognizers the classification is only about 70%. However, new methods of analysis, such as those developed by Hudspeth [in press], should lead to improved capabilities.

It is important to note that direct monitoring of brain cognitive activity is rapidly becoming simpler and non-invasive. For a very long time, available techniques were so broad and noisy that ties between evoked potential recording and educational tools were characteristically bogus. However, new approaches, in which slower indicators of metabolic change are used to calibrate speedy scalp surface recording schemes, are quickly making headway. This suggests that the set of microindicators upon which connectionist individual difference recognition schemes might operate could readily include simple direct indicators of brain activity patterns. An example of recent work in improved microelectrodes for both recording and stimulation of neural tissue has been reported by Kovacs et al. [1990]. A recent book [Agnew & McCreery, 1990] discusses advances in creating neural prosthetic devices.

In order to gain a better understanding of how, e.g., concept category activation relates to the underlying neural processes, it would be very helpful (and in the long run, crucial) to develop a combined formal and computational model of neurophysiological processes. This model should be able to link observed neurophysiological processes (such as observed via EEG at both the macro and micro levels) with cognitive processes, such as concept class formation and recall. It will be especially important to have a model of how neurophysiological processes relate to cognitive activity as we work to "scale up" interface devices for a large range of tasks.

In addition to modeling methods, we will also need to have better signal detection devices and also rapid, parallelized algorithms for signal processing and correlation. Such are already under development with many research groups across the country. Further, we can envision a need for neural-network integrable "bio-chips." Again, these are also under development. Work in this area should be sponsored, with the goal of creating systems which can both model and interpret human perceptual and cognitive activities using a variety of measures of neurophysiological processes.

4.4 Conclusions

In order to address the challenges outlined in the previous sub-section, it will be necessary to continue the dialogues begun during this workshop and encourage researchers to perform cross-disciplinary research. This will require a long-term effort and a substantial commitment to developing cross-disciplinary communication. The challenges are significant, but the benefits are substantial. These benefits can be experienced as the National Science Foundation continues to sponsor innovative and inter-disciplinary work such as that begun with this workshop and outlined in these recommendations.

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APPENDIX A:

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A MULTI-DISCIPLINARY APPROACH

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APPENDIX B:
WORKSHOP ORGANIZATION

APPENDIX C:
EXCERPTS FROM PARTICIPANT'S POSITION PAPERS

As described in the body of this report, the participants were drawn from four major research areas; Human-Computer Interfaces (HCI), Interactive Learning Environments (ILE), neural networks / connectionist methods, and cognitive psychology / studies of individual differences. The topics which came up in the position papers we received reflected certain orientations within each discipline. We group the position paper foci into five areas:

- o Theory-based design for HCI and ILE,
- o Use of neural network / connectionist systems to model individual differences,
- o Use of individual differences in HCI design,
- o Effective use of interactive learning environments in real-world educational settings, and
- o Use of virtual reality systems for education.

Theory-Based Design for Human-Computer Interfaces and Interactive Learning Environments:

"If a design is in any sense principled, its psychological design rationale is not simply a jumbled heap of myriad specific claims. Systematicity in claims can be provided by the design adhering to some theoretical vision." (John M. Carroll et al.)

"I suggest that we try to develop causal theories of learning, [specified to be] the mental representations, objects, and processes that the learner uses during any problem solving that leads to learning, and the representations, reasoning processes, goals, strategies, and actions tutors use to promote learning during problem solving." (David Littman)

"... it is in the behavioral domain that many interface developers, especially designers and evaluators, do their work. Thus, there is a need for behavioral techniques, coupled with supporting interactive tools, to give a user-centered focus to the interface development process." (Deborah Hix)

"... recent research in education from a socio-cognitive perspective is pointing to three necessary changes in the way we design software: (i) from delivery systems to conversation pieces, (ii) from control to communication, and (iii) from task analysis to participatory design. [As an example of the first change,] the design question changes from 'What representation do I want to implant in the student's mind?' to 'What conversation do I want students to have?'" [Jeremy Roschelle]

"We need a better understanding of what aspects of adaptive functionality are likely to cause difficulties for users. We need a better understanding of how to portray those aspects of the functionality. And to do this, we need a deep understanding of how various aspects of the portrayal of an interface influence the sorts of mental models which users form." (Tom Erickson)

Using Connectionist Approaches to Form User Models

"... computer-human interfacing draws on at least three key areas of psychology: personality theory, negotiation, and education. Current connectionist (or neural network) models fall short of being able to model these processes in a predictive manner. I believe, though, that the gap is not as wide as is commonly believed. Preliminary models relevant to all these areas have already been propounded, and a "toolkit" of network principles is already in place to build more refined models. Hence, within a few years, models along current lines are likely to provide useful suggestions in all these areas of psychology." (Daniel Levine)

"Information is the derivative of the relationships that exist among the patterns or distinctive features embedded in the communication between man and computer...So the missing element in the human-computer interface is an adaptive system that captures these features [of discovering underlying patterns]. Based on its interactions, the interface should concentrate on only the subset of the information that a user needs." [A. Sharif Heger]

"For adaptive instruction, it will be desirable to define and detect context in terms of the recent past history of the program state, rather than the current static state, and possibly in terms of projections of probable near term future program states. Temporal sequence classification, recognition, and prediction have received considerable attention in neural network research, with promising results. Such techniques should make it possible to determine program context in more meaningful temporal terms, to distinguish "familiar" (for the individual user) sequences of operations from "unfamiliar" sequences of operations, to predict likely next operations (future context), and to classify sequences of operations in terms of the likelihood of near term success or errors. This should facilitate the implementation of powerful context sensitive help/advice/instruction, as well as context sensitive adaptation/adjustment of interface dynamics and information display." [W. Thomas Miller]

Individual Differences and Human-Computer Interface Design

"Knowledge of the specific user population's cognitive characteristics and skills should assist the designer to tailor his user-interface and thus increase its likelihood of being successfully incorporated. Finally, another important but strongly neglected area is motivation. Issues of user motivation interacting with cognitive skills in the acquisition of skills is only now becoming an important research issue ..., but should be of relevance to the field of human-computer interaction when considering individual differences." (Helen Crawford)

"We need a language for describing individual difference features of particular human-computer interfaces. That is, the language used in cognitive psychology in general and individual difference psychology in particular is almost completely intra person; abilities, motivations, etc, reside inside person's heads. Similarly, the language used to describe the machine is almost all situation - outside the person. The person-situation interaction at the interface is the area of interest." (Richard Snow)

Effective Use of Interactive Learning Environments for Education

"The key to learning science is not the memorization of facts, it is the development of a way of thinking. Teaching students how scientists find out things is much harder than teaching students what scientists have found out... The problem comes when we want to teach methods of inquiry. When this is our goal our focus should be on the teacher, with the computer as an aid, rather than the other way around." (Earl Hunt)

"A major goal of the simulated environments [for education] is to provide a background that is alive and active for the understanding of complex ideas and concepts. While the simulation forms the backdrop, we must design pedagogical strategies that help illuminate the concepts in a wide range of subjects in as unobtrusive manner as possible. The emphasis is to encourage and foster participation so that the student feels as if the computer-based system is the laboratory that is very comprehensive and that encompasses a wide range of systems." [T. Govinderaj]

"Inquiry-based learning environments must support all of the authentic activities of scientists practicing their craft ... Learners, individually and in groups, must be engaged in modeling, arguing, and explaining. They should be able to develop knowledge of generic modelling concepts and techniques and have tools to help them design provisional explanatory models. These tools should help them reason using these provisional models in order to predict their behaviors under varying conditions. They should be able to test these predictions by designing experiments to test their hypotheses and running the experiments using standard simulation models." [John Frederikson]

[On the issue of adaptive versus adaptable systems] "... there is little evidence that user models have been a success in real systems ... therefore, focus on adaptable rather than adaptive systems [which] support end-user modifiability, tailorability, [and] human problem-domain communication. [On the issue of domain models versus user models] ... "do <u>not</u> focus on user models, because [they are] (1) intractable to implement, (2) there are no success models, and (3) they require explicit domain models as prerequisites. [Instead,] develop explicit domain models, because they (1) support human problem-domain knowledge, (2) eliminate the need to anticipate interactions, and (3) make the knowledge representation task more feasible." [Gerhard Fischer]

Virtual Reality for Education

"... one must be more cautious in assuming that all features of virtual reality ... that reduce the cognitive effort of interaction and may therefore improve performance, will necessarily be of benefit for long term retention of the information. This is particularly true to the extent that such features may eliminate effort-demanding cognitive transformations that are necessary to form mental links between different representations of the material to be learned, or if they eliminate effort demanding decisions of where and how to proceed through the virtual space... with [virtual reality], excessive realism and sensory experience, while 'natural,' can distract the learner from focusing attention on the key relations to be mastered... However, there is one component of [virtual reality], closed loop interaction, for which good evidence exists that it enhances learning. The irony here however is that from the point of view of effort and performance, interactive participation generally produces short term costs, which are then compensated by later gains in knowledge." [Chris Wickens]

"... we can ... imagine new uses for the capabilities that virtual reality provides. Among such speculative applications are ... [the] overlap of real and artificial experience. One approach, now in common practice, is to overlap computed data and information visually on the "normal" scene. This is done in aircraft through 'heads up' cockpit displays and through special glasses mounted to the pilot's helmet. It is also beginning to appear in automobiles and as an aid to maintenance personnel. In the future, we might overlap elements of an artificial world on our normal world for other purposes." [Gershon Weltman]

"Persons who have experienced the elementary artificial reality (AR) environments available today often report that AR ... rapidly produces the feeling of a real world... One of the implications of such reports is that it may be possible to use AR to manipulate and thereby study 'the sense of reality.'" [Dean Radin]

The two science fiction authors who participated in the workshop each had much to say in their position paper regarding virtual reality for education. Their visionary perspective and realistic concerns were very interesting, and indeed encapsulated the vision of where the technologies described here may lead us within a few decades. Their comments are reproduced, at greater length than those given above, in Appendix D.

APPENDIX D:
A VISION FOR THE FUTURE:
EXTRACTS FROM THE POSITION PAPERS OF C.J. CHERRYH AND JANE FANCHER, SCIENCE FICTION AUTHORS

C.J. Cherryh, author of Cyteen and Downbelow Station, as well as many other works of science fiction, writes:

"Indeed, 'gateways' of communication (oral, aural, oral/aural, tactile and various others) work differently for different individuals; and the most successful tactics for teaching illogical data involve immediate feedback -- like singing, chanting, achieving rhythm, unison, or even hearing one's own voice, so as to involve another circuit of the brain...

"... But I do think that feedback teaching, especially delivered on all sensory fronts, would be an immense practical aid for students of all levels: for the rapidly or widely cross-connecting student, keeping information coming at him at his own speed of reaction could be a great benefit: such students tend mentally to time-out during repetitions and during those time-outs, to miss important secondary information: hence the practiced teacher's habit of getting eye contact with everyone in the class before proceeding. A system that could accelerate or decelerate its pace to match student acceptance of information would be a boon; likewise one capable of veering off into side "rooms" containing related information [communicating that diversion to the human teacher would also be advisable, lest the student form a false connection]. A system capable of producing review for students who may have missed a key connection could save students who would otherwise be lost and identify problem areas for teacher intervention and help. The percept that one is in control of a system is particularly attractive to young students: hence, I think, the popularity of the computer.

"And a system capable of changing its display from verbal to tactile to audiovisual could solve the 'gateway' problem: as an example, faced with a student who couldn't learn a Latin declension from reading it on a blackboard, I asked him his chosen field: finding out that he was apprenticing to a plumber, a mechanical-visual-tactile field, I simply wrote the declension on paper, cut it up and asked him to assemble the pieces in the right order. He learned the declension in a couple of attempts, and I dare say, probably visualized it as an assembly problem -- which it is, in a perfectly valid way of looking at it.

"A program that can identify preferred 'gateways' and adjust its feedback characteristics to take advantage of the student's best approaches would help all those students who do not flourish under the traditional visual display and lecture method."

In a thoughtful vein, Jane Fancher, author of a soon-to-be-published novel which deals with virtual reality, offers commentary on the possible downside of virtual-reality-enhanced educational systems:

"If we expose children too early, and indoctrinate them too thoroughly -- i.e. if our teaching methods become too efficient -- don't we risk running ourselves into a perceptual dead-end? The temptation to get the kids trained early so they can keep up with the info-flow might not be as important as teaching them to analyze critically all they are told -- to cross-reference 'truths' and recognize limitations imposed by their world-view. If this skepticism underlies the VR [virtual reality] experience and its effective presentation of information, the individual should then be able, later in life and upon additional input, to adjust their perception of 'truth.'"

C.J. Cherryh writes in conclusion:

"Changes in technology produce social changes; and the more wide-reaching the technological change, the more profound the social change. This one [virtual reality] has the potential to change how we teach, how we learn, how we hire, how we train, how we view and create attitudes, how we employ, we tolerant we are of differences, the speed at which we are able to react, the way we entertain ourselves, and how much we trust human versus machine input and information. And it raises legal questions, such as: Is an intimately trained system a real property of the human who has been linked to it over a lifetime? ... Is it subject to laws governing estates? Does it have a monetary value? Does the buyer or inheritor have a right to enter and use it in a manner that may change its character?

"The whole working relationship with the machine is at issue here; and I do not think it too much to say that it is a coming of age for the machine and a potential redefinition of the individual."