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Colloquium Paper

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# Issues of imaging science for future consideration

ROBERT N. BECK

Center for Imaging Science, The University of Chicago, Chicago, IL 60637

**ABSTRACT Acceleration of the emergence of imaging science as a new discipline will require the development of new organizational structures to foster research and educational programs that integrate components of the traditional disciplines, all of which stand to benefit. However, the greatest impact of imaging science will likely be from computer-based general educational programs that present both visual and verbal materials utilizing software that is not only interactive but also analytic, diagnostic, and adaptive in response to individual students. Ultimately, this powerful learning paradigm will have profound effects on all aspects of our culture. Imaging science will not have emerged fully until the conceptual, organizational, educational, cultural, and ethical issues it raises have been addressed.**

In view of the importance of imaging tools and images to advances in many areas of research and education, it seems relevant to ask: What needs to be done to facilitate progress in imaging science? What resources will be required? What are the prospects for success? and What will be the impact on our culture of a fully emerged new discipline of imaging science?

## Facilitation of Research and Education in Imaging Science

Most important is the need for new organizational, administrative, and management structures that would facilitate multidisciplinary activities within our universities, which play a leadership role in defining new disciplines. These new structures would cut across the traditional disciplinary boundary lines of organization—specifically, the departmental and divisional lines. Currently, these boundaries tend to separate the individuals and small groups in the physical, biomedical, and social sciences and the visual arts that are engaged in research activities related to imaging science; these workers function in relative isolation and generally with limited resources that have been developed and are supported specifically for intradisciplinary research. As a consequence, there is much redundancy of effort that yields suboptimal results. This is probably true not only within our universities but also within the national laboratories and major industries, where similar boundaries exist, as well as within and among the federal funding agencies, which tend to be organized along the traditional disciplinary lines of universities.

Such boundaries impede progress, particularly in new disciplines such as imaging science, in which no one has been formally trained. To date, essentially all progress in imaging has been the result of efforts made by individuals trained in the traditional disciplines, who have a natural interest in improving the tools needed for their research, including the physical, conceptual, and methodological tools of imaging science. In short, an organizational structure is needed that will facilitate communication, cooperation, and collaboration among workers trained in mathematics, statistics, computer science, physics, engineering, biophysics, biopsychology, astronomy, geophysical science, materials science, the biomedical and radiological sciences, and the graphic arts, as all have important contributions to make to imaging science.

Clearly, the prospect of bringing all of these individuals and small groups together in a single facility would be highly disruptive and counterproductive, and it must be regarded as unthinkable. However, we must anticipate the future development of high-speed networks that would obviate the need for face-to-face interaction on a daily basis. Even if highly effective computer networks were available today to all individuals who were eager to collaborate, organizational impediments at the funding level would remain.

As an example based on experience, it is difficult to identify a federal funding agency to support research in any generic issue—e.g., image reconstruction—say, to develop a new method that would make use of both amplitude and phase information obtained from a very-large-array radiotelescope, an ultrasonic microscope, and/or a medical ultrasound system with a phased-array transducer. Prospects are further reduced if the proposal comes from a multidisciplinary team consisting of a radioastronomer at a national radiotelescope facility, a physicist in materials science at a national laboratory, a medical physicist at a university-based medical center, an electrical engineer/computer scientist with expertise in inverse problems at another university, and an expert in software development who is employed by a major manufacturer of medical imaging equipment. Even though such a proposal may be highly meritorious on scientific grounds, and may hold the promise of contributing significantly to advances in several fields of science and medicine, it does not fit comfortably into any existing funding category. As a consequence, funding agencies have great difficulty in dealing with such proposals.

In addition, organizational structures for developing, administering, and managing such proposals (if funded) currently do not exist. Moreover, such a proposal raises a number of issues regarding the commercialization of intellectual properties that might be developed by a multiinstitutional team with federal funding, not the least of which might be the appearance of conflict of interest. Such complex issues need to be addressed and workable solutions found. Although the experience in Japan (or other nations) may serve as an example of one approach, we need to find solutions that are based in our own unique and evolving culture.

To succeed, the organizational structures that are designed to facilitate the emergence of imaging science must not ignore or attempt to erase existing organizational boundaries, but rather must make them more clear, surmountable, and transparent. Moreover, these new structures must be sufficiently flexible to allow a natural evolution to occur that is respon-

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Abbreviation: CAI, computer-aided instruction.

sive to changing interests, activities, needs, and opportunities as this new discipline develops. In particular, it is important that the new organizational structures be seen accurately as facilitating the goals of the existing traditional disciplines, rather than as being disruptive or competitive. The resolution of these issues of territoriality will require open intra- and interinstitutional discussion in which goals, needs, and values are addressed, so that win–win strategies can be developed. More specifically, the creation of an organizational structure for research and education in imaging science within a university must be seen as an opportunity to expand the current resource boundaries for the benefit of all—that is, as an opportunity to raise additional new funds that could not be raised otherwise, to establish improved facilities for research and education, to enhance productivity within the traditional disciplines, to stimulate industry by facilitating the development of new products, and to add to the pool of highly trained individuals by developing the intellectual potential of women and minorities to participate in a new discipline that is not already oversubscribed.

Despite such clear opportunities, the establishment of effective new organizational structures that will facilitate the emergence of imaging science will require vision, creativity, determination, and courage at the highest levels of administration within universities, national laboratories, relevant foundations and industries, as well as state and federal funding agencies.

In summary, if our broad goals are to accelerate: the emergence of imaging science as an intellectual discipline that is broadly recognized, the development of new and improved imaging methods for numerous applications, and the transfer of new imaging science and technology from universities and national laboratories to industry, in order to stimulate the economy, then effective strategies might include (*i*) the development of postgraduate and graduate programs of education in imaging science *per se*, which might be organized around the generic issues of imaging science—i.e., around image-data acquisition, reconstruction, processing, distribution, display, analysis, and evaluation; (*ii*) the coordination of funding for research and education in imaging science within, and among, the federal agencies and foundations that currently support discipline-specific aspects of these activities (this might also be organized around the generic issues); and (*iii*) the enhancement of communication, cooperation, and collaboration within and among universities, national laboratories, industries, governmental agencies, and foundations.

Implementation of these structures and strategies will be accelerated by expansion and upgrading of High-Performance Computing and Communications systems, which has been identified already as one of the Grand Challenges of the FY 1992 U.S. Research and Development Program.

## Anticipated Impact of Imaging Science and Technology on Our Culture

Although the primary focus of this colloquium has been on imaging science in relation to research within the physical and biological sciences, and the rationale for developing educational programs in imaging science, it is important to call attention to the potential impact of imaging science on education in all fields, and at all levels. In particular, as public education in the U.S. is widely considered to be in crisis, I will close with a brief outline of thoughts focused on the future potential of imaging science and technology to deal with this critically important issue.

Most would agree that human vision provides our principal means for knowing about ourselves and the world around us and that language provides our principal means for communicating what we know to others. Historically, these means for knowing (through visual images) and for communicating (through words) have been separated. In part, this separation is due to the fact that it is much easier to record and to reproduce words than images. Every technological advance that has enabled us to bring together images and words—that is, to cause them to converge within a single medium—has had a major impact on our culture and on education. As examples, printing, motion pictures, and television have had an enormous impact. However, such media communicate visual and verbal information and knowledge to an audience that is essentially passive—hence, the difficulty of sustaining audience attention without resorting to the presentation of emotionally charged materials. This is particularly true of motion pictures and television, where the reader/viewer/listener not only has no control over the content of the presentation (beyond its selection) but also has no control over the rate or the sequence of materials presented. In large part, this may account for the popular appeal of video tape technology, which is now widely used for both entertainment and education. This technology incorporates features such as fast-forward, slow-motion, freeze-frame, and rewind that enable the viewer to be somewhat more selective of the content, rate, and sequence of presentation. These interactive features tend to sustain attention, which is well recognized as an important factor in learning. The principal limitation of video tape technology for educational purposes is serial access, which presents a major inconvenience when large amounts of data are stored. However, this limitation is largely overcome by video-disk technology, which provides rapid random access. A major advantage of such technologies is that the equipment required for presentation of materials (a standard television set, plus a video tape or disk drive) is already mass-produced and relatively inexpensive, and therefore widely distributed.

To the extent that video tape and disk technologies have been used in education, they have resulted in a significant shift away from language as the dominant mode of communication toward a more balanced use of both images (which promote insight) and words (which explain and enrich these insights). However, the optimal mixture of images and words that will maximize the learning rate and retention is undoubtedly highly variable among individuals. As a consequence, for use by individual students, there is a need for more flexible means for varying this mixture, as well as the rate and sequence of presentation, in order to maintain a high level of attention, interest, and motivation to learn.

One solution is to use full-featured computers that can present both images and words and that are inherently interactive. In addition, they do what you tell them to do—and they do it quickly, accurately, and reproducibly without complaint or fatigue. One might well imagine that such computers provide the ideal medium for education. However, until very recently, efforts to develop computer-aided instruction (CAI) programs that incorporate both high-quality images and words have met with only modest success, in part because of limitations of affordable hardware. (We would point out that images tax the capabilities of inexpensive computers. A single, high-resolution image may contain more than ten million bits of information, whereas a single printed page of text contains only a few thousand bits. To a significant degree, these hardware limitations also have limited the development of software of the sort that is needed for truly effective CAI programs.)

**Advances in Computer Hardware.** Very recent advances in computer science and technology have largely overcome the earlier limitations of affordable hardware of the sort required for dealing effectively with both images and words. As a result, we can expect to see an accelerated convergence of these means for knowing and for communicating within a common mode that is highly interactive—namely, the multimedia computer workstation. These devices enable the user to interact not only through the keyboard but also through other mechanical devices (e.g., the mouse, roller ball, joy stick, and drawing pad), as well as through voice commands, touch-screen displays, and hand signals. In addition, they provide rapid access to vast quantities of information stored on disks, and they produce responses not only through high-resolution color displays but also through sound and speech. These technological advances not only make interacting with computers easier for users with limited experience but also enrich the process of gaining experience by broadening the range and improving the quality of the visual and verbal materials that can be presented or produced.

Currently, the multimedia workstation is still relatively expensive; however, other technologies have been developed recently that will ultimately reduce the cost. Here we have in mind the development of high-speed networks, archival storage devices with vast capacity, as well as data-compression schemes that reduce the requirements for network speed and storage capacity. As a consequence, many of the information-handling capabilities that are currently built into the workstation will ultimately reside in a remote storage facility that serves numerous, inexpensive, multimedia terminals simultaneously over a high-speed network. It appears that technology of this sort will be ideally suited to the requirements of education, as it provides the basis for establishing *learning laboratories* in which the unique needs of many individual students can be served at the same time.

In short, it seems clear that the more intensive and flexible convergence of visual and verbal materials provided by this technology will have a profound impact on education. We must expect to see an ever-increasing number of learning laboratories based on such technology, as the potential for further development of CAI is now enormous. The central issue is how best to utilize this advanced hardware to develop innovative educational programs that address the broad range of interests, needs, abilities, and limitations of individuals in our heterogeneous population, particularly disadvantaged students who find it difficult or impossible to learn in the current classroom environment. A part of the answer lies in the development of comparably advanced software, which always lags behind the development of hardware.

**Need for Advanced Computer Software.** Software to facilitate learning is necessarily very sophisticated and complex, because learning *per se* is an intrinsically personal and private process that involves playful, exploratory, and experimental behavior and that succeeds frequently enough for us to maintain our interest and motivation to try new things and to make creative use of the available ideas, materials, and tools for learning.

To be most effective, educational programs will require incorporation not only of the sort of *interactive* software that is needed for such exploratory behavior but also *analytic, diagnostic*, and *adaptive* software, much of which is yet to be developed. The development of such software for the presentation of images and textual materials will require the combined expertise of first-rate programers, educators, psychologists, and computer and imaging scientists, as well as persons with specialized knowledge in particular fields of study.

In general, these educational programs might begin with a sequence of tests (without feedback), perhaps incorporating some of the features of computer games in order to sustain attention. These tests would be designed to assess the student's current level of intellectual development and readiness to learn, the current level of knowledge, skills, and strategies used for problem solving, as well as abilities to listen, speak, read, write, reason, and do arithmetic.

Based on this assessment, an appropriate level of material for study would be made accessible. User-friendly *interactive* software would enable the student to select general and specific topics of interest (within the course constraints), to select the mode, style, and sequence of presentation (i.e., the mixture of images, sound, and spoken and/or displayed words), to solve problem exercises, to answer questions and obtain immediate responses, to seek help, and, depending on his/her level of development, to conduct simulated experiments and explore the effects of varying parameter values, to plot and analyze results, to write or dictate reports, and to explore the historical, philosophical, cultural, and/or utilitarian aspects of the topic being studied.

The development of *analytic/diagnostic* software would permit the continual assessment of the student's current state of knowledge and skill, based on the continual monitoring of performance in terms of such factors as speed, accuracy, consistency, and pattern of his/her responses, as well as factors related to abilities to deal with and to learn from both visual and verbal materials. In addition, such software would provide an analysis of the types of errors made—errors due to limited knowledge of facts, or understanding of principles, concepts, strategies, and methods, and/or to difficulties in applying these to problems that require, for example, reasoning, formulation of equations, calculation, and interpretation of results. These errors might be related to the student's lack of readiness to learn, or to difficulties in reading, or in interpreting graphs and images, and they may be associated with problems of perception, cognition, and/or memory. In general, we must expect the result of this analysis to be somewhat different for each student, as each of us has a unique set of strengths and limitations that make it difficult to fit us into a limited number of meaningful diagnostic categories.

Without necessarily invoking overly simplistic diagnostic categories, *adaptive* software would continually make use of this multidimensional analysis of performance to adjust the content, style, sequence, and rate of presentation of new material to meet the unique interests, talents, limitations, and needs of each student; to prompt or constrain the student to review topics requiring further study; to provide suggestions and hints; and to encourage the student to explore relevant new material so as to maintain a high level of interest and motivation to learn.

These multimedia laboratories would facilitate learning by reducing one of the serious deterrents commonly found in the present classroom situation—namely, the virtual impossibility for overburdened teachers to attend to the interests, abilities, limitations, and special needs of every student. Perhaps more importantly, these laboratories would help to minimize the invidious comparisons that are commonly made solely on the basis of scores on standardized tests designed primarily for ease of grading. Such comparisons foster a sense of self-worth in only the highest-scoring student; to varying degrees, all others feel like losers. By working at his/her own rate, and with little awareness of what other students are doing (except that it is likely to be somewhat different), every student would feel the sense of accomplishment and self-worth that is essential for maintaining a high level of curiosity, interest, and motivation to learn.

To date, some of the most sophisticated software of this general type has been developed primarily for entertainment, rather than for educational purposes. For example, for computer games, in which our competitive tendencies are exploited to establish and sustain attention and motivation to win, and in which strategies for winning can be explored, certain aspects of performance can be analyzed and assessed, and the degree of difficulty can be preselected and/or altered adaptively in incremental steps that provide challenge, along with some hope of winning. These games frequently incorporate images and words as well as sounds, and frequently they are implemented by highly interactive means that do not require a keyboard. Although such games may facilitate the development of certain reasoning, coordination, and motor skills, they are generally not designed to convey significant knowledge and understanding—i.e., to educate.

On the other hand, a considerable amount of interactive, analytic, and adaptive software that incorporates visual and verbal material has been developed for elementary education and for individuals with learning disabilities—e.g., for courses in spelling, reading, typing, and arithmetic, in which attention is established and maintained by an appeal to our innate curiosity and motivation to learn, and by supportive responses. With state-of-the-art hardware, the potential for development of very advanced CAI programs is greatly increased.

While we believe this potential currently exists, we must point out that the development of all truly effective educational software (especially adaptive software) is a challenge of immense complexity and subtlety. It requires a deep understanding of numerous factors: the human developmental process and ways of assessing the readiness of individuals to learn; the best means of establishing and sustaining attention and motivation to learn at each stage of development; the topics students need to learn, and in what sequence and at what depth; how students learn through the use of both visual and verbal materials, and what specific materials and what mixture of these will accelerate learning and facilitate retention in individual students; how to assess the student's performance in meaningful terms; what incremental steps in the presentation of new materials will maintain the realistic level of challenge required to improve the performance of individual students; and what is the range of variation of their individual talents, skills, and limitations. As a consequence, it is not surprising that the development of educational programs employing such software is still in its infancy.

The effectiveness of educational software will be enhanced by a deeper understanding of these subtle and complex biopsychological aspects of learning, some of which overlap with the interests of imaging scientists who are currently working on a broad range of problems related to the production, management, and use of images to meet the needs of the traditional disciplines of science and medicine.

In particular, the effectiveness with which images are incorporated into educational programs will be enhanced by further development of the scientific and technical aspects of image processing and image compression, storage, retrieval, and transmission, and especially by a deeper understanding of strategies for image display (e.g., three-dimensional display of images of objects and dynamic processes incorporating methods for surface and volume rendering, depth coding, texture modeling, shading, perspective, and motion parallax), the response characteristics of the human visual system (e.g., the spatio-temporal response; spectral sensitivity; visual-attentional and perceptual biases; contrast, color, and depth perception; visual cognition and memory; visual masking; and visual illusions), as well as by further development of methods for assessment of observer performance in the use of images for educational purposes. These are among the topics that will be incorporated in curricula of graduate programs in imaging science in the future.

Clearly, the full development of the educational paradigm outlined above is an endless task that calls for continual revision as new hardware, materials, and insights into the learning process are developed. Nevertheless, it is not too early to make a beginning to develop the main features of this paradigm, perhaps by employing current, state-of-the-art, multimedia workstations connected to an archival storage facility via a high-speed network—hardware virtually identical to that needed for research and education in imaging science *per se*—with the view to porting these developments to more advanced, yet more cost-effective hardware in the future. Also, it is not too early to begin the more daunting task of developing the interactive, analytic, diagnostic, and adaptive software that is needed for implementation of this paradigm.

Ultimately, we must expect to see technologies developed that will make the entire spectrum of educational materials available to the general public, in homes as well as in learning laboratories. One effect of this will be to enable every individual to follow his/her curiosity and to learn with the help of a (virtual) private tutor. Will this eliminate the need for schools and teachers? Most emphatically, it will not!

**Role and Functions of Teachers in Learning Laboratories of the Future.** In the educational environment of the learning laboratory of the future, the role and functions of the teacher will differ substantially from those at present, and we must expect some teachers to feel threatened initially by the changes that will occur. However, with appropriate training, this situation will probably be transitory, as the new functions will be both exciting and personally rewarding. We anticipate the primary functions of teachers will be to provide feedback and suggestions to the multidisciplinary teams engaged in the development of improved course materials and teaching/learning tools; to lead discussions among small groups of students, with the goal of developing their skills in self-expression (the key to the development of self-esteem and interpersonal skills); to foster cooperation and collaboration through small-group, problem-solving exercises based on the course materials (the key to the development of social skills); to review the stored summary of the multidimensional analysis of each student's performance in order to assess the level of mastery, to identify special problems such as learning disabilities that are too complex or profound for the adaptive software to compensate, and to make appropriate referrals; to serve as mentors to individual students and to assist them in identifying appropriate career goals and opportunities for further education and training; and to provide encouragement and inspiration by conveying personal excitement about the subject matter and the value of a life style based on the never-ending process of learning.

These are very human functions that are not likely ever to be performed effectively by computers. Rather, we believe that the use of modern multimedia technologies for education will unburden teachers and allow them to devote their energies to the uniquely rewarding profession of teaching—of facilitating the learning of others in ways that only human beings can—with interest, concern, compassion, insight, and understanding.

**Social/Ethical Issues Raised by Powerful Tools for Education.** Finally, the very power of educational tools such as we have described—which could be used effectively by the scrupulous and the unscrupulous alike—requires that they be used thoughtfully and responsibly if the impact on our culture is to be constructive. We are all too familiar with the media use of emotionally charged images for manipulating public opinion and for persuading, rather than informing. When coupled with advanced software of the very sort needed for educational purposes, which would tailor the presentation of visual and verbal materials in a way that is conditioned by the response of each individual, the power to manipulate would be increased manyfold. As a consequence, issues concerning the ethical use of these tools need to be addressed, and the public made aware of the potential for their abuse.

Vulnerability to such manipulation, even of "well-educated" individuals, is currently very high. With the past and present concentration on verbal materials as virtually the sole medium for education, we have come to regard the "educated" person not only as one who has verbal knowledge of certain materials, but, more importantly, as one who can read or hear verbal presentations accurately, analyze them critically for content and style, and give an appropriate and insightful verbal response. Generally, we are not educated to deal comparably with visual presentations. Education in the future must be based on a recognition of the fact that both images and words may contain important information and provide means for knowing and for communicating what we know to others. However, even when they are not used rhetorically, each provides only incomplete and otherwise imperfect information, and each may therefore give false or misleading impressions. In short, both images and words may be regarded as limited, though complementary, means for education. In the future, formal education must prepare us to deal with both in an objective, insightful, critical, and ethical manner. How this can be accomplished is unquestionably the most important and challenging issue for future consideration.

## Conclusion

Imaging science will not have emerged as a separate new intellectual discipline until the conceptual, organizational, educational, cultural, and ethical issues it raises have been addressed. By suggesting and sponsoring this special colloquium, the National Academy of Sciences has taken a leadership role in initiating this process, which clearly must be continued.

On behalf of my colleagues Chin-Tu Chen, Oscar H. Kapp, Robert Rosner, and Steven K. Shevell, who participate in the Center for Imaging Science of The University of Chicago and Argonne National Laboratory, and who served as Co-Chairmen on the Program Committee, I wish to express our sincere gratitude to the Academy for providing this forum, to Albert V. Crewe for inviting us to organize the program, to the R·R· Donnelley & Sons Company, Polaroid Corporation, and Digital Equipment Corporation for their cosponsorship and financial support, and to Data Display Corporation for providing large-screen visual support.