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COMPUTERS AND THE FUTURE OF HUMAN CREATIVITY, (U)

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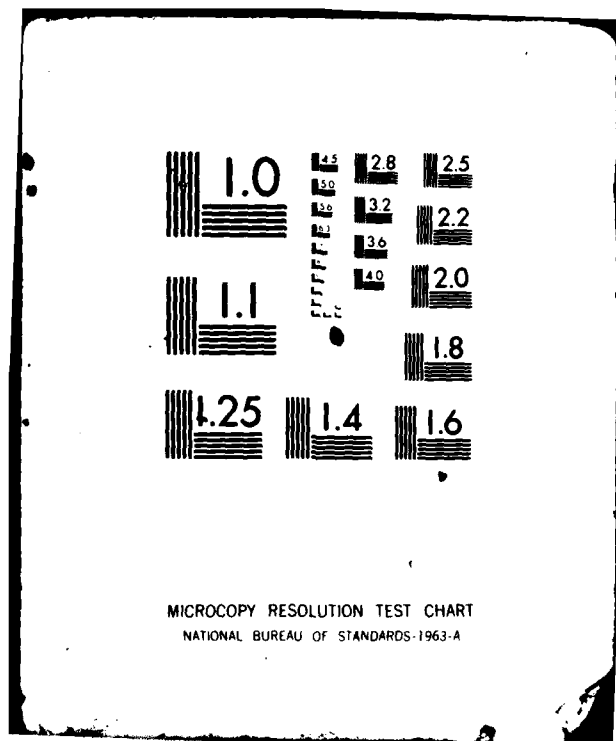
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COMPUTERS AND THE FUTURE OF
HUMAN CREATIVITY

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ABSTRACT

The effects of computer science on human society can be usefully viewed in the framework of scale change. A number of examples of scale change are considered, in design, mathematics, social organization, medicine and, most especially, in the modeling and perception of the complex biological and social world in which we live. The common feature in these examples is the computer's ability to allow humans to return to modes of thought which are crucial for both the psychological and historical origins of scientific and engineering activities, but which were deemphasized in the classical scientific paradigm due to limitations on information processing. The explicit appreciation of the scale changing power of the computer has important implications for computer science education and for its role in fully releasing the creative possibilities in the human-computer relationship.



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1. INTRODUCTION

How can computer science education be organized so that human beings can most creatively use the power which the computer makes available to them? This question is continually being addressed by educators and administrators in universities and other institutions responsible for supporting and benefiting from computer science activities.

Such a complex question could hardly be expected to have a simple answer. The immense computational power of modern computers has a social power which bears on this issue in a way which is insufficiently appreciated, the power to create changes in scale in areas as diverse as scientific investigation, artistic expression and social interaction. By scale change, we mean sufficient change in the relative amount of effort expended on the different components of an activity to fundamentally alter its character or its relation to other human activities. While it is not difficult to recognize that changes in scale created by the computer effect dramatic transformations in many features of human society, it is difficult to appreciate the changes which must occur in human beings in order for them to adapt to and benefit from the new world of possibilities which the computer offers them.

These scale changes are forcing paradigm changes on human beings. By paradigm change, we mean a change in a scheme or framework used as a reference point for evaluating experience.

The framework may be determined by a set of examples shared by the community. This definition is one of several used by the historian Kuhn in his studies of scientific revolutions such as the Copernican revolution or the change from the Newtonian conception of space and time to the relativistic one [1].

There has always been a natural human tendency to resist changes of such a fundamental nature, whether they involve the developments considered by historians of science or the developments currently being instituted by the computer. Since this resistance may lead to the neglect of those uses of the computer which have the greatest potential value to human beings, it is necessary to carefully examine the nature of the paradigm changes which are occurring, taking appropriate steps to insure that our educational practices facilitate rather than resist them.

The phrase "paradigm change" is in one respect misleading. The computer creates an indefinitely large and varied number of new ways of perceiving both the world and ourselves. While instituting many new paradigms, it is destroying the traditional methodological paradigms with which scholars, scientists, engineers and artists have worked for hundreds of years, but which inhibit the creative use of the computer.

The best way to examine the phenomenon of scale change is through examples. We consider several, in design, mathematics, social organization, medicine, and most especially, in the

modeling and perception of the complex world in which we live. We shall argue that scale changes created by the computer enable man to return to modes of thinking which in both a psychological and historical sense are "primitive", but which have been discarded, in some cases thousands of years ago, due to scale changes in human activities which could not at the time be matched by scale changes in information processing.

2. FOUR EXAMPLES OF SCALE CHANGE

2.1 THE PROCESS OF DESIGN. For several hundred years, man has relied on lines when designing structures and devices he wishes to build. The architect makes line drawings of the building he wishes to build while the machine designer makes two-dimensional blueprints, as does the carpenter, gardener and city planner. If one desires to work with three-dimensional models and the problem involves the design of a small building or an uncomplicated device, it is possible to model it with clay, experimenting with different versions of it in three dimensions. If, however, the design involves a complicated machine such as an automobile engine or a large building such as a hospital, it is basically impossible to experiment with it in three dimensions. Although possible to build a model, it is necessary to design it with lines, using illusory devices such as perspective to explore its three-dimensional structure. In order to experiment with it, one has to expend too much effort demolishing and rebuilding it.

With the advent of computers, it has become possible to return to a more primitive and intuitive mode of thinking. Using the computer, it is possible to model solid objects with combinations of a few primitive solids (such as cubes, spheres, cylinders and cones), then to experiment with different configurations and proportions of the models [2]. Such real space design techniques are now used in architecture and in the design of machinery.

Thousands of years ago, advances in technology separated man from a direct use of space in design, inaugurating an age of designing with abstraction. Today, a further advance of technology enables man to separate himself from the use of abstraction for design, reinaugurating an age of design through experiment with perceived three-dimensional models.

2.2 THE PRACTICE OF MATHEMATICS. For a thousand years, the major mathematical activities of human beings have been routine. Although we read about great creative mathematicians such as Archimedes, Newton, Gauss and Alkhwarizmi (after whom the word algorithm is named), most of the effort expended on mathematical activities has involved routine computations. Even Gauss expended years of labor calculating the motions of the planets. The possibilities for experimenting with mathematical structures have been limited to those which could be done by hand.

The most obvious capability of the computer is its ability

to perform routine computations, leaving the mathematical practitioner free to concentrate on the understanding of the mathematical process rather than the execution of its technique. More importantly, by sharpening the border between the creative and routine components of mathematics, the computer is redefining what can be considered bona fide mathematical work. What was previously considered work for mathematicians, e.g., difficult integrations or simplifications of complex algebraic expressions, is now work for computer programs. Writing the programs is creative; executing them, routine.

The paradigm change in mathematics is, however, much greater. The great mathematician Poincare thought that induction was the basis of mathematics, and one can reasonably assume that he meant experimentation with cases. The earliest mathematicians discovered the basic features of geometry and arithmetic through experimentation. Problems then became too difficult for experiment. With Euclid began the axiomatic method which eventually became the guiding paradigm.

As in the case of design, the computer plays the role of the great scale changer. The possibility of experimenting on mathematical structures with computers has opened problems for investigation previously un contemplated from an axiomatic point of view, thereby fundamentally altering the balance of power between investigation through experiment and investigation through formal analysis and proof. Yet the computer program which is used for such experimental exploration of the abstract

world is the ultimate of formal prescription and constructive proof.

It is worth illustrating this point with another historical example. Leibniz, co-inventor of the calculus, was perhaps the earliest writer to conceive of a symbolic language which could be used as a deductive calculus [3]. At the same time, he distinguished the process of generating the elements of a set from the process of determining whether an element is a member of that set. In modern parlance, this distinction corresponds to the distinction between recursive enumerability and recursiveness. Leibniz had the quaint idea that it would take about five years to solve all problems by deductive means using his logical symbolism. Although he had recognized the importance of questions which could only be answered through a generative process, he understandably failed to recognize that the power of computing as a means of exploring mathematical structures is greater than its power to prove theorems about these structures.

It is now known that even problems which are unsolvable in principle may be answered with a degree of confidence, depending on the amount of computation invested in them [4]. It is clear that the idea of proof confidence radically alters the concept of mathematical truth, eroding the traditionally sharp distinction between deductive and inductive methodologies. These concepts and distinctions are even more radically altered when the enumerative power of the computer as a means of mathematical experimentation is recognized. This previous lack of

computational power had forced mathematicians such as Leibniz to discard the experimental conception of mathematics in favor of a completely axiomatic and deductive one. The scale-changing power of the computer again returns us to a historically more primitive conception dominant in the time of Babylon and old Egypt and radically different from the present one. Leibniz's process of enumeration has been so amplified by the computer that it has fundamentally undermined the deductive paradigm it was originally conceived of as supporting.

2.3 THE SIZE OF SOCIETY. Originally human beings lived in small societies in which all members of the group had personal awareness of one another. As time passed and the population increased, the potential for knowing all members of one's social group or even all individuals with whom one had important interactions decreased. For some writers and social scientists, the alienation of the individual from those on whom he depends and from those who depend on him is the most pronounced feature of human society.

The usual view is that the computer increases the alienation of man from man. Although computers can increase the specialization of society, invade the privacy of the individual at will and erect barriers between individual and institution, they need not. Properly understood, the computer can be used to decrease the effective size of society by increasing the number and value of interpersonal contacts. If properly used, it can allow individuals a greater awareness of each other's needs and

a greater access to available resources. An instructor in a large, diverse institution can recognize and respond to the needs of his individual students. As a researcher, he can use the computer to identify other individuals with relevant interests or skills. Large libraries can be made effectively smaller with the use of more effective searching techniques while the computer can provide selective and effective channels of communication among individuals with common interests. In short, properly used the computer can change the scale of social interaction, recapturing some of the personal features which people value in simpler societies, while avoiding the constraints and parochialisms which undoubtedly gave many people the impetus or at least the desire to escape from these societies.

2.4 THE PRACTICE OF MEDICINE. Prior to this century, life support systems which could maintain catastrophically injured and critically impaired individuals were not available. With the development of industrial society, the number of catastrophic injuries from which an individual could survive but which would leave him in an impaired state has increased. In effect, the first consequence of scientific medicine and technology has been an increase in the number of handicapped individuals in society.

With the development of intelligent micro-processor based prosthetic devices, it is now possible and even economical for a paralyzed individual to use myoelectric signals to control effector devices or voice synthesizers to manipulate objects or

create artificial speech [5]. The scale-changing power of the computer is reversing the byproducts of scientific medicine and technology, returning us to a more primitive situation when all members of society were capable of full participation.

Previously, there has been a sharp distinction between man and the machine he creates. As machines become more intelligent, this distinction becomes less clear. Perhaps this scale change allows a return to a time when man viewed himself as a part of nature and coadapted to it.

3. MODELING THE EXTERNAL WORLD AND EXPERIMENTING WITH INTUITIONS

Very early in human history thinking about the world in which we live was informal. Formal tools such as classical mathematics were not available. Only natural, human languages such as Greek, Hebrew or Persian were available. Scholars and scientists used these powerful but informal languages as tools to describe the natural universe and social world and to explore the mental images they had created.

As time passed, scholars developed certain specialized instruments of analysis such as geometry, algebra and calculus. Not everything which can be described or contemplated with natural language can be contemplated conveniently with these formal tools. What can be described may be explored by precise means that go well beyond our intuitive, informal capability. As

a consequence, premathematical thinking about the world with the powerful tool of natural language gave rise to mathematical thinking about models of the world which could be formulated in a tractible mathematical framework. Although intuition did not cease being the source of these models, scientists attempted to the greatest possible extent to couple intuition with abstraction. The ability of the human being to perform many types of computations is so weak that an enormous amount of abstraction is necessary if one is to arrive at a humanly computable model.

Not all sciences went in this direction. In some cases, as in the historical disciplines, the required degree of abstraction simplified the reality too much to be worthwhile. In those cases, the advantages of the ability to compute were outweighed by the losses inherent in the initial abstractions. As a consequence, science has split into two parts. One part has practitioners who recognize only those phenomena which can be formulated in tractible mathematical frameworks. The second part deals with other phenomena and is still formulated in natural language. There are of course disciplines which use both descriptions. An example is economics, one part of which is mathematical and rigorously deductive, but unable to describe economic phenomena adequately. The very description of these refractory phenomena requires informal modes of thinking which rely on ordinary language.

The computer can again create a profound change of scale,

altering the balance of power between intuitive and formal thought and potentially introducing a greater unity into the bifurcated structure of science. By enormously amplifying man's power to compute, the computer has reduced the degree to which man must abstract the world around him in order to compute. Our symbiosis with the computer has so enhanced our formal capabilities that we are now free to utilize our natural powers of problem formulation more fully. The mathematically oriented sciences can enlarge the sphere of problems which they treat and the sphere of phenomena which they are willing to contemplate. They can experiment with ideas which were previously rejected on the grounds that they were incompatible with a formal analysis. The nonmathematical, natural language based sciences can use the medium of formal computer languages to formally express and compute with models which were previously outside the range of formal investigation.

In fact, computers are not being used as creatively as they could be for this purpose. Although all natural and social sciences now use the computer, in nearly all cases it is as a prosthetic to the traditional pre-computer methodologies. Many examples could be given. One is from ecosystem biology. Over fifty years ago, the mathematician Volterra formulated a simple differential equations model to describe the interactions of predator and prey in an ecosystem [6]. Today the computer is used by many investigators to find numerical solutions to these equations. These studies are using the computer as a prosthetic to a traditional model which was formulated to be analyzable, at

least to some extent, without the computer. Although a legitimate use of the computer, it is not a powerful one. We can formulate our understanding of the complex interactions in an ecosystem more completely and accurately by directly using the formal instrument of a computer language. That is, instead of mapping the reality into the formalisms of traditional mathematics, then using the computer to compute this map, we can map the reality directly, using the language instruments of computer science [7].

Contemplate for a moment the immense complexity of the genetic and physiological processes within organisms, the spatial and temporal dynamics of the environment, the interactions among organisms and between each organism and the environment, and the flow of mass between organisms and environment. Contemplate the statistical process of variation, the problem-solving behavior of organisms and the selective action of the environment. The investigator who refuses to admit the validity of computer languages as primary instruments of analysis foregoes any possibility of giving a holistic but formal description of such a system, or, more precisely, of formally expressing a holistic theory of it. Accepting such language instruments, we can use them to give formal expression to theories about reality which previously could only be formulated using the instrument of natural language. We can use the computer to calculate these rigorously formulated theories as easily and automatically as we use natural language to describe them. The problem reduces to one of translating from

the natural language description to the computer language description.

The difference between these computer models and pre-computer mathematical models is not that one is mathematical and the other is not. The difference is that the computer has redefined the term tractible. Traditionally, a tractible model implies an analytically solvable model. Significant simplifying assumptions are necessary about the complex interactions in the real world in order to make models which are analytically manageable. For dynamic models, the sine qua non assumption is that they are analytic, that is, that their local behavior can be used to derive all relevant information about their global behavior. One cannot reasonably call a model mathematical unless it is solvable - otherwise it is just symbology. The crucial point is that our scientific thinking need no longer be guided by the pre-computer criteria of tractibility. What was previously symbology is now bona fide mathematics. As in the examples of design, mathematics per se and social organization, the computer has introduced a change in scale which returns us to modes of thought which played an important role in the early stages of human history, but which were quenched by the advance of technology, in this case, by the advance of the analytical technology of classical mathematics.

In modeling the world, we argue that the most valuable role of the computer is as a prosthetic to the human thought process itself, not as a prosthetic to pre-computer methodologies. Yet

most natural and social science modeling is guided by pre-computer criteria. Some of it, especially in the biological and social sciences, is completely conceptual and informal. The reason, we believe, is that there are two ways of judging models and theories. One is aesthetic; the other, practical.

For the computer scientist, computer models may be aesthetically pleasing even if they have no utility. Exploring such models experimentally, using methods usually associated with experimental science, seems like a legitimate activity. For the pre-computer scientist, models formulated directly in terms of computer languages and the experimental models used to study them may seem aesthetically unpleasing and dubious even if they have enormous utility. The question involves the criteria to which we have become habituated over hundreds of years. The criteria which had to be fulfilled by a model to make it useful in the pre-computer stage of science have, after hundreds of years, become transformed into aesthetic criteria. These aesthetic criteria have been useful in guiding scientists in the direction of utilitarian models and theories. Now new classes of models are possible which are unaesthetic according to these traditional criteria, but which are clearly useful. With these models, we can investigate the consistency and implications of informal theories which guide our intuitions about ecological systems, business firms, whole economies and the thought process itself. It is the change in aesthetic criteria which is the painful but fruitful methodological paradigm shift which the computer is introducing into natural and social science.

Man's new power to formulate algorithmic models in the languages of the computer and to use the computer to explore these models has an interesting epistemological implication. Man's knowledge and procedure bases are limited by his biological evolution. There is a tendency, in some cases, even an urge, to perceive and analyze the world in terms of one, two or three categories. Thus, there are monistic philosophies which view all observable phenomena as a manifestation of a single underlying reality, dualistic philosophies such as Zoroastrianism which attempt to perceive the world in terms of two competing forces and triadic philosophies such as Hegel's dialectic. The computer is not inherently subject to the same limitations. We can program it so that it can perceive and analyze in terms of many more categories than any human being could. It is possible that with the computer we will reach a point where we can communicate useful models without understanding how these models work. Conceivably man's biologically and historically developed tastes are completely arbitrary as far as his understanding of the world is concerned. Conceivably there is a fortuitous and marvelous match between the structure of reality and the structure of his thought processes. More likely, there is a good match for some aspects of reality, a poor one for others. One new possibility created by the computer is that of obtaining a deeper appreciation of the relationship between the human mind and the external world, a problem of immense philosophical interest which until now could never have been the object of serious experimentation.

4. EDUCATION OF THE COMPUTER SCIENTIST

How do the possibilities which the computer has created bear on the education of the computer scientist and, equally important, on the computer education of the public at large? The chief problem with the computer remains communication with it. At first, communication involved the arduous formulation of algorithms in primitive codes which could be used to control the state of the machine. As time passed, higher level languages were developed in which the ideas of the programmer could more easily be expressed. The problems of compiling these languages into machine code became prominent. As more people began to use the computer, the problem of program management, essentially of operating systems, became prominent. As programs became more complex and as computation became less costly, the problem of writing readable, modifiable programs and of establishing the correctness of programs assumed greater importance. A great deal of emphasis in computer science education is rightfully placed on these and related issues, that is, on the issues involving the structure and use of the formal languages which we use to abstract reality for the machine.

The view of the computer as a scale changer which we have suggested in this paper points to another issue which should enter into computer science education more prominently than it does. The development of the computer has shifted the balance of effort involved in the formulation and solution of problems. The computer is a formal instrument, and our symbiosis with it has

extended the formal side of our linguistic capabilities. We argue that by so doing it should free our intuitive, creative capabilities, not only because it reduces routine work, but also because it opens new possibilities for the creative formalization and exploration of intuition. For classical scientists, the problem of calculating a solution was enormously time consuming, so the formulation had to be very careful. Only the very best scientists could successfully concern themselves with problem formulation. With the advent of modern computer systems, the problem of solving formulated problems has become much easier. Once a problem is formulated in a computer language, the computer automatically solves it. The problem of modeling reduced to one of problem formulation. The computer as a scale changer has effected a major shift in the faculties of thought which a scientist can most fruitfully cultivate. As computer languages and computer systems have developed to become more powerful and usable, they have shifted the return on the investment of scientific effort from the problem solving faculty to the faculty of problem formulation.

There is an interesting analogy to the structure of the brain itself. It is now believed that the right and left hemispheres of the brain specialize for different functions, just as the left and right hands do. Evidence indicates that one hemisphere specializes for linguistic and analytical tasks; the other, for intuitive, geometric and gestalt thinking. These specializations are not sharp, just as the different tasks performed by the left and right hands are not sharply delineated

into two classes of functions. It appears that the brain of a single individual is a symbiosis of two kinds of computing. The development of traditional mathematical techniques placed constraints on the intuitive modes of thinking which were the source of this technology. The development of computers provided such an enormous amplification of power of the linguistic, analytical side of the brain that it has created previously unknown opportunities for the intuitive, creative side.

One problem in computer education is to train the linguistic side in the proper use of formal computer languages, a difficult task even for individuals gifted in these linguistic, analytical capabilities. The mastery of these formal skills is necessary for communication with the computer even though it seems counterproductive to concentrate solely on their cultivation when the computer is so much more effective than any human in executing formal processes. Once this mastery is effected, these formal skills should be used creatively, that is, the student's intuitive, ideational capabilities to communicate useful things to the computer should be cultivated. Arriving at an algorithm or proof idea and formally formulating it in a computer program involve different, though interacting modes of thought. In our teaching of computer science, we have emphasized the linguistic side. Now, as we step into the age of the new possibilities opened by the computer, it is time to emphasize the use of these formal tools to express ideas and formulate problems.

This educational goal should be consciously incorporated into our computer science curricula at the earliest levels. It is, of course, already implicitly present. For example, the field of artificial intelligence has as its main problem the communication of a conception of the world to the computer. Nevertheless, in all but the most advanced parts of our educational programs in computer science, we place so much emphasis on the formal, linguistic side that the intuitive capabilities which guide program construction atrophy in many students before they reach the point where they can recultivate them. This situation can be altered. The two modes of thinking required for working effectively with the computer can be cultivated simultaneously, just as the learning of an artistic technique can be pursued simultaneously with the cultivation of artistic ideation by the student of creative arts. In this respect, the computer is a new medium, and computer science has an aspect of the creative arts which should be explicitly recognized at the beginning of our educational practice.

Viewed as a device which forces the programmer into inhumanly formal modes of thinking, the computer is alien, evoking hostility in those forced to deal with it. Viewed as a new medium of expression and as a way of harnessing our most personal human potentialities, it should evoke pleasure in those dealing with it. Viewed merely as a prosthetic to classical scientific methodologies, the use of the computer will always be viewed as an admission of failure to be sufficiently clever to avoid using it. Viewed as a prosthetic to the human thought

process itself, the computer can be viewed as one of the most effective means of thought. Accepted as a paradigm changer, the computer can serve to reveal new views of the world as meaningful for the evolution of human thought as those which arose during any period of scientific revolution.

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