4

From Control Systems to Knowledge Systems

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Historically, the human species has been dependent upon technology for survival. This dependency placed people in a control loop from which they learned that mechanical cause-and-effect models were useful as explanatory mechanisms. These models were selectively reinforced to the exclusion of other forms of explanation. As the human's role shifts from that of a controller to a supervisor, new forms of rationality are reinforced. This process is being facilitated by new information technologies that demassify images and allow the individual to construct a highly personal understanding of human beings and nature.

INTRODUCTION

Most engineering psychologists are not inclined to be philosophical. We may occasionally turn to musings when things go wrong in the laboratory or the field or when we finally run out of things to do. But, by and large, we prefer to stick to the practical and serious business of persons and machines and leave philosophizing to others. Division presidents, in particular, are expected to be serious. And serious means reporting research rather than wool gathering. Today, however, I have decided to gather wool about a topic that has long been of interest to me, namely, human knowledge and understanding, and how people acquire them.

Engineering psychology is rooted in technology. Without technology there would be no engineering psychology, and all of us here today would be off at some other convention. Historically, our discipline has centered upon the interaction of technology with human performance. By performance, we have usually meant the overt behavior or response that a person makes when using some system, machine, or device. We have called this human activity *control,* and much of our endeavor has centered on methods for measuring, modeling and optimizing the human's behavior as a controller. We have paid scant attention to how technology affects human thought.

This paper examines the human activities of controlling, knowing, and understanding as stages in human evolution. It considers these activities in relation to technology and shows how they have been shaped by it. It illustrates how the technology of the past has produced certain forms of thought and how the technology of the future is likely to change thought. Finally, it discusses what all of this may mean for future generations of engineering and applied experimental psychologists.

HUMAN SURVIVAL DEPENDS ON TECHNOLOGY

History can be told in terms of the history of the technologies that people have devised

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to ensure their survival and of the skills, rules, and knowledge that have been instrumental to the use of that technology.

The first human beings had no technological aids to survival. Most of their waking time and energy was devoted to surviving in a hostile environment. They had nothing with which to protect themselves but the raw materials about them. But they must have been able to observe, remember, and reason. Out of the cause-and-effect lessons of a harsh daily life, they learned the basic skills of survival. These simple skills were transmitted by imitation from person to person and from generation to generation. Human behavior during this most primitive period is most appropriately characterized as coping rather than control. Coping not only must have occupied many of the waking hours of early humans, it must also have fueled their thinking and their fears.

In time, the discovery that some materials worked better than others improved the chances of survival. A sharp rock was found to cut better than a round one. A pointed stick pierced leather more easily than a dull one. These muscle-powered artifacts made the human a manual controller. The axe, spear, and drill are examples of simple manual control systems. Later, devices that replaced or augmented muscle-power with an external power source, such as the bow, extended the human-tool control system. At about this time it can be said that human survival had become completely dependent upon technology. The human had become part of a manual control loop whose efficiency determined whether or not that person perished or lived. And efficiency depended not only on the devices and tools used for survival, but also on the skills learned and refined by its users.

As time passed, some quirk in genetic structure gave humans a larger and more efficiently organized cerebrum. This made possible the development of speech. Speech gave everything a name and permitted the world of natural objects and events to be differentiated from human-made objects and events. It allowed one person to designate to another the different tools used for hunting, fishing, and other survival strategies. Speech was found to be a better way than imitation to transmit the performance skills necessary to make effective use of technology. In time, these skills became codified into rules that increased the efficiency of tool use and further improved the chances of human survival.

Tribes with gifted tool designers and skilled users fared better than those without them. This meant that the more inventive clans with more advanced technology—especially those that inhabited mild climates—survived better than the less creative tribes in harsher environments. A culture competent at survival was able to spend less time in practicing survival skills and more time in other endeavors, such as the pursuit of knowledge for its own sake. The Egyptians were an example of a civilization in a benign climate and with an advanced technology that could devote time to philosophy, religion, literature, art, and music. The Eskimo and the Laplander could not. Thus under certain conditions, technology and climate allowed human thought to explore a new dimension—the understanding of humans and their universe. These explorations, however, were limited in scope and restricted to a few privileged individuals.

As technology became more elaborate, it created the need for measurement methods and concepts. Construction and trade required standard units of length, volume, and weight. For example, the cubit (the measurement from the elbow to the tip of the middle finger) came into general use throughout Egypt in the tenth century B.C. Larger units of linear measure were required to survey the land along the Nile after the annual flood waters receded. As the art of measurement became more sophisticated, the concrete rules of arithmetic and geometry developed for building, surveying, and trade became abstract. Once abstract, they could be applied to other measurement problems such as astronomy and weapons design. For example, the effective use of a Roman crossbow depended upon a knowledge of the concepts of distance, mass, and angle. Thus the concrete rules for using technology when augmented by knowledge became generalizable. The rules themselves were not generalizable, but the knowledge was. This generalized knowledge formed the basis for the development of scientific theories.

TECHNOLOGY SHAPES HUMAN THOUGHT

For most of human history, the rate of technological advance has been slow. Survival technology and skills changed little for thousands of years. However, in the 15th century, an intellectual renaissance took place that surpassed that of the Egyptians, Greeks, and Romans and rivaled the development of human speech as a step in human evolution. In quick succession a number of inventions left an indelible stamp on human thought that persists to this day. The mechanical clock and printing press are outstanding examples. The clock introduced the concept of precise time—time in hours and minutes, not in sunrises, sunsets, and seasons. Human life became organized about clock time. The concept of time has driven us ever since, appearing to move us inexorably from the past into the future. The printing press extended human memory and linearized human thought. Other inventions altered the human's role as a controller. The fly-ball governor of 1780 regulated engine speed so that people no longer had to perform that function on a continuous basis. Other inventions followed. One of the most significant was the Jacquard loom, which used a punched template to control textile design. Inventions such as these introduced the concept of a programmable machine capable of carrying out human plans and intentions.

Each of these technological inventions contained an assembly or linkage of interacting mechanical parts. The form of a linkage was a physical expression of a set of cause-and-effect relationships. Being visible, a machine produced, in the minds of those familiar with its structure and function, a mental model, image, or analog of the cause-and-effect process embodied in the machine. These models became useful for describing and explaining other phenomena and events. It is said that the mechanical clock led to the formulation of the theory of planetary movements. Mechanical analogs were easy to grasp, and quickly became assimilated as popularly held explanatory concepts. They provided models that could be used to explain the complex questions of nature and life that could not be readily understood as a result of direct observation. Machines had now taken on a theoretical significance. In time it was believed that the working of the mind itself would be explained by mechanical forces. Was it not Descartes who said that the soul was influenced by pressure upon the pineal gland?

Each new generation of technology was the genesis of a new, expanded, and more complete view of the world that had not existed before. Although technology had great explanatory power, it also constrained human thought and understanding. Physical and mechanical models discouraged other modes of explanation; they displaced magic and reshaped philosophy and theology.

How are we to account for the fact that machines have had such a profound effect on human thought? I believe the answer may be found in the simple principles of operant conditioning. In operant conditioning, consequences, in the form of reinforcements or rewards, occur as a result of human performance. Any stimulus in the environment that is present when an operant response is reinforced acquires control. Stimuli that occur frequently, and that do not change, acquire greater control than other less constant stimuli. Now it happens that all of the stimuli in the environment (human-made tools, implements, devices, and systems) represent the least variable set of stimuli. Other stimuli change in one or more dimensions almost continually. The amount of entropy in a machine is far less than in nature.

Technological devices reward their users by providing reinforcement that satisfies a need. Each device and gadget we use is analogous to a Skinner box. From the earliest age, we learn that sucking a bottle will bring milk; flipping a switch, light; turning a faucet, water; tuning a radio, music; and tuning a TV, images. The reinforcement function fulfilled by a given technology also extends to the skills, rules, and knowledge required to use it. Just as the responses associated with the operation of a device are reinforced, so too are the skills, rules, and knowledge that must accompany these responses. In this way, mental models derived from the use and understanding of technology are constantly rewarded and strengthened. They imprint on us a way of viewing the world. This perhaps has always been so.

When technology was primarily mechanical, mechanical models were used as explanatory concepts. As electricity came into use, current flow, resistance, and switching became useful explanatory concepts. With the introduction of the computer, the concepts of information storage, search, and retrieval have been added.

ANALOGS AS EXPLANATIONS

We need only consider our own discipline of psychology to discover that the origins of many of our theories and models come from physics and engineering. Descartes explained the reflexes of humans in terms of the functioning of a mechanical statue that moved as water was forced through pipes in its limbs. The Gestalt theory of perception was borrowed from electrical field theory. In engineering we have likened the human to an amplifier. Our account of human information processing comes from communication theory. We have used computer storage as an analog to describe human memory. Our physics and engineering envy has dominated our science so thoroughly that, until recently, we have refused to admit cognition as a legitimate object of study because we could find no physical analog to account for it. Penis envy never captured our attention as much as our envy of physics. The history of our profession is the history of the development of physical models of human behavior and of human thought.

Figure 1 summarizes the major points I have made so far. It shows that for much of human history we were manual controllers who used simple tools and implements for survival. During this period the intellectual content of the human species was derived from the rudimentary skills learned in the use of simple devices. With the development of speech, skills were codified into rules for the design, manufacture, and use of technology. As more complex technologies were devised, survival rules were generalized into knowledge that formed the basis for scientific theory. Scientific theory, in turn, became the creed and dogma of popular belief. Each new invention was accompanied by a parallel genesis in the structure of human thought: from simple to more complex skills, from simple to more complex rules, and from simple to more complex knowledge.

Looking to the future—and barring genocide or some natural cataclysm—human beings will continue to use technology to

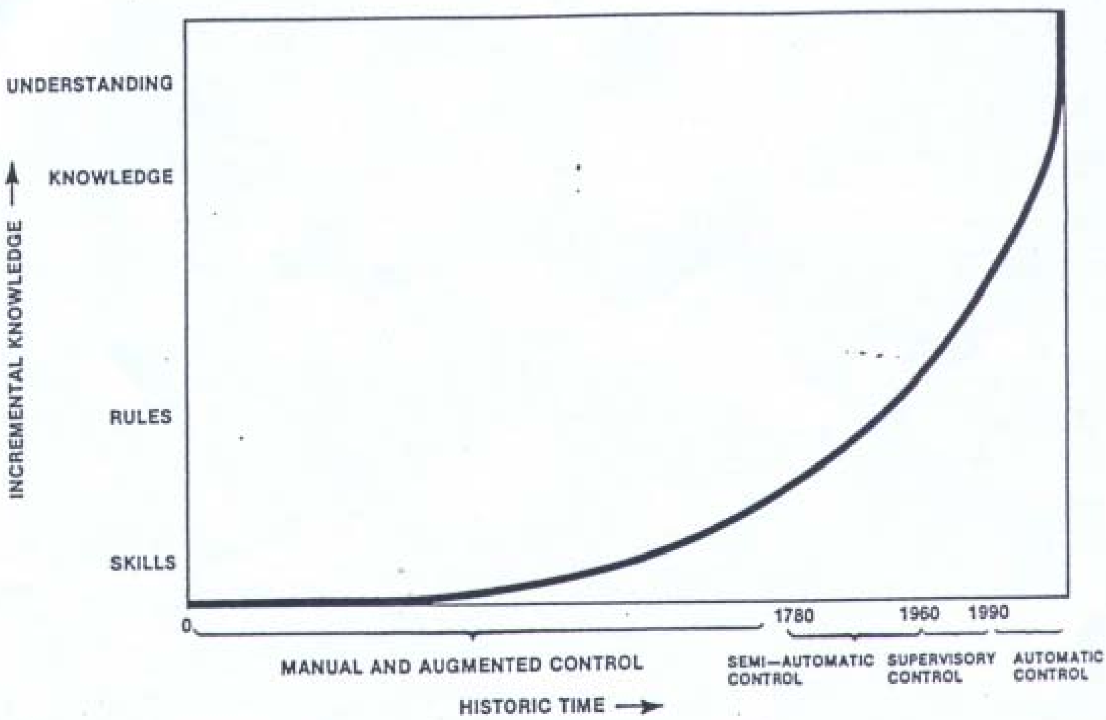

Figure 1. *Knowledge as it relates to technology.*

transform more and more of the resources of nature into human-made resources. And a time will come (it is already beginning to unfold before us) when people will be able to blueprint a world controlled largely by automation. In this new world of the future, the office and factory, the home and the hospital, the store and transportation, will be automatic. Robots will perform the control functions once performed by people. The human race will have become the instrument of its own evolution. This freedom from the necessity for humans to be in direct control of the machines necessary for their survival will create an opportunity for large numbers of individuals to experience the greatest adventure in human history—understanding. It will be an intellectual adventure, not a physical one. It will be an adventure in which new forms of information technology will become a vital force in human evolution that will cause a major restructuring of human life and thought.

THE INFORMATION BOMB

In the recent book, *The Third Wave*, Toffler (1980) said: "An information bomb is exploding in our midst, showering us with a shrapnel of images and drastically changing the way each of us perceives and acts. . . . In shifting from a technosphere to an infosphere we are transforming our own psyches."

Before the advent of mass media, children grew up in a slowly changing community and built up a model of reality out of images received from a limited number of sources. The teacher, the minister, and particularly the family, interpreted life and imparted the skills, rules, and knowledge of a simple world and its simple technology. Knowledge came largely from the speech and images learned from first-hand experience with other individuals and with artifacts. There was no radio and no television to provide different images and models of the world. Images were narrow in range, and the knowledge conveyed by them was limited.

Later (and in parallel with the growth of industrialization), books, newspapers, magazines, radio, and television multiplied the number of channels of information from which an individual formed models of reality. Information, like products, was mass produced. Certain images were so widely distributed and fixed into so many people's memories that they were transformed into icons. The images of the Hindenberg in flames, of Hitler and Stalin, of Roosevelt, and of the weapons of World War II dominated my youth. They recurred again and again in the newsreels; in *Life*, *Look*, and *Time*. Scientific knowledge was also mass-produced and digested. It appeared in *Reader's Digest* and *Scientific American*. Conventional wisdom held that most nearly all phenomena could be understood and explained by physical models and a science based on these models.

In the past decade, the number of information channels and the number of images available to us has continued to multiply. These new images reach us at a faster rate than ever before. They are temporary images. Polaroid snapshots, Xerox copies, paperback books, and disposable graphics appear and disappear. More ideas, beliefs, and explanations flood into consciousness, are developed, and then vanish. The mass-produced images of what we took to be reality and the explanations of reality have begun to crumble and fade. A subtle but startling change has begun to occur. The once powerful, monolithic mass media are being "demassified." Information is becoming more personalized. Cable television and video and audio cassettes provide us with a greater individual choice of images, models, analogs, and knowledge. Communication satellites shrink and warp the dimensions of time and space that once were measured in clock time and travel distance. We need not visit a place to know it. Video games teach children how to use television sets and computers in an interactive manner. We are becoming a generation of message senders as well as message receivers. We are learning to manipulate and control information rather than being controlled by it. We are learning to use information as humans once used technology as a means for acquiring understanding as well as a means for survival.

THE DEMASSIFICATION OF INFORMATION

The most significant of all of these changes in information technology is the personal computer. It allows me not only to selectively retrieve images, but also to create images of my own design. My visual frame of reference is no longer restricted to an 8-1/2 × 11 page; it has become a video window past which I can move, manipulate, create and examine graphics, diagrams, spread-sheets, and text. Instead of passively adopting a mental model of reality produced for me by others, I can invent and reinvent one of my own design.

This demassification of information will lead to greater individuality. It will explain why opinions on everything from science to religion will become less uniform. Consensus will shatter. And all of this will have a far-reaching effect on the way we think. Taken together, these changes in information technology will revolutionize our view of the world and our ability to sense and understand it.

As we become more familiar with the intelligent environment provided by the computer and computer networks, and learn to converse with them as we now do with people, we will use computers with the ease and naturalness with which we now drive a car or ride a bicycle. And they will help us to understand ourselves and the world in a way that has never before been possible. Computers can be expected to alter our view of causality, to heighten our awareness of the interrelatedness of things, and to permit us to synthesize meaningful wholes out of the disconnected sense data that surround us.

For the past 200 years, the study of nature at all levels has relied upon physical reductionism as a major explanatory concept. This approach has attempted to comprehend phenomena at one level in terms of concepts at a lower and presumably more fundamental level. It has been widely held that human thought and behavior can be explained by the activity of the nervous system. The nervous system was believed to be reducible to processes in the cell; the cell to be explained in terms of chemical processes; and chemical processes, in terms of atomic physics. Finally, atomic physics has been believed to be explainable by means of quantum mechanics. Each of these levels of explanation is physical. They are derived from a paradigm of nature and are causally driven, at least in part, by our heritage of mechanical analogs. Recently, however, an unusual thing has begun to happen. Many physicists now say that quantum mechanics cannot be understood without introducing cognition as a component of the system. Physicists in increasing numbers claim that until we understand cognition and intelligence we will never understand the human or the universe.

I do not wish to suggest by what I have said that physical science and physical models are invalid. Rather, I propose that there may be alternative models that are not only less constraining but also are as rational as the mechanical models of physical science. I believe that we may be able to devise these alternative models by our interactions with the intelligent environment created by networks of computers and information media. These networks will be able to tap nearly any data set of our choosing or devising. These data sets will not be limited to numerical and scientific data, but will include and integrate other representations of reality in the form of images, poetry, literature, history, and philosophy.

IMPLICATIONS FOR ENGINEERING PSYCHOLOGY

Throughout most of its brief history, engineering psychology has been concerned with the human as a component of closed-loop control systems. We have used engineering and physical models and concepts to account for human performance. It was not considered necessary to explore the cognitive process of the human controller. This approach was fitting and proper because it was responsive to the technology of the time and to the human's role in relation to it.

More recently, with the development of process control systems, engineering psychology has become concerned with the human as a supervisor and monitor of a process. This new technology has required us to develop concepts and models that express the cognitive content of these new process control tasks. We have had to become concerned with the operator's mental model or map of a system and its states. This approach has been fitting and proper because it is responsive to the human's role in relation to process control technology.

Even more recently, as computers and information systems have become almost a direct extension of the human brain, engineering psychologists have shifted attention from the human as a controller of technology to the role of the computer as an aid to human planning and decision making. Our concern is not with how humans can support a system, but how systems can be used to support humans.

The day is at hand when engineering psychologists will direct much of their attention to the problem of coupling machine intelligence with human intelligence. Their focus will be on educational systems and on knowledge systems. Their goal will be to promote human understanding. The object of their study will be what J. C. R. Licklider once called the "symbiosis of man and machine." The variables of interest will be the variables associated with the structure of the universe in relation to the structure of human cognition.

We can now only dimly perceive the types of questions that the applied study of human knowing and understanding will raise. Few of the methods available to us now appear to be suitable for answering these questions. For example, we now have a reasonably good method for the analysis of physical tasks; however, we do not have a method for the description or analysis of cognitive tasks. We must devise one.

In the future the engineering psychologist will need to understand how people aggregate the bits and pieces of images and data from different data sources into larger concepts. We will need to develop a method for evaluating and validating the data from information networks because the data in these networks will always be secondhand or surrogate data. And we will need to study the larger questions of the differences among information, knowledge, and understanding. These are but a few of the issues engineering psychology will face as it approaches its new frontier.

CONCLUSION

Throughout history human rationality has taken different forms. I have tried to show how one form of rationality has been derived from our relationship to technology and technological systems. This form of rationality has permitted us to survive, but it has constrained our ability to fully understand. I believe that future generations of engineering psychologists will help to develop the new systems that will permit humans to better understand themselves and their relationship to the world about them in a way that has never before been possible.

Alfred Lord Tennyson said:

Our little systems have their day;
They have their day and cease to be,
They are but broken lights of Thee;
And Thou, O Lord, are more than they.

Let knowledge grow from more to more;
But more of reverence in us dwell;
That mind and soul, according well,
May make one music as before.

REFERENCE

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