Technology and Human Progress: The Information Revolution

by Thomas E. Everhart

It is an honor to be asked to give this second annual Gould Distinguished Lecture on Technology and the Quality of Life. The lecture honors the accomplishments of Bill and Erlyn Gould, a husband and wife team it was my great good fortune to meet six years ago, when I became associated with the California Institute of Technology. Bill Gould has been a trustee of Caltech for fifteen years, and he and Erlyn have been strong supporters of that institution, although they reserved their strongest loyalty for this institution, the University of Utah, where they courted while they were students.

Bill and Erlyn's lives testified to their faith in God, and their love for each other, and for their family. While this love of family was implicit in their words and actions, it became explicit for me at the wonderful memorial service held on June 6, 1992, in Southern California for Erlyn shortly after her passing. The outpouring of love through words and music from essentially every one of their twenty-nine children and grandchildren was inspirational. Erlyn left a large family and many friends with wonderful, enriching memories of her loving interactions with them.

It is also a pleasure to present this lecture in conjunction with the J. Willard Marriott Library, because of my friendship and respect for his son, J. Willard Marriott, Jr. I know that succeeding generations of Marriotts have provided both affection and support for this institution.

The first lecture in this annual series was given by Bill Gould, and linked his love of the arts to his chosen field of service to society engineering. As you all know, Bill made major technical and societal contributions while leading a major electric utility, a company that served modern society's need for electrical power for factories, businesses, and homes. His lecture was a personal account of his life with Southern California Edison, where he rose to positions of leadership. By his decisions, he made Southern California Edison an innovative leader of electric utility companies.

The purpose of these lectures, as set forth by Bill in his inaugural lecture, is to provide a forum for examining how technology, creatively applied, can preserve and enhance the quality of life on earth. He meant not only the material quality of life, but the quality of life in every sense, including art, music, religion, science, engineering, medicine, and the constructive interaction of human beings with each other and with nature. This is an ambitious purpose.

Humans have many needs in our evolving society. Not only is power needed for factories, businesses, and homes, but these factories, businesses, and homes have to be constructed. They must be connected together with roads, and water and food are needed for nourishment of the people who work and live in them. Technology has played a key role in meeting these human needs.

Technology and Human Progress

Technology and human progress are bound together so tightly that technology dates human progress. We speak of the Stone Age that period of human history when tools were made of stone. That period evolved into the Bronze Age, then the Iron Age, again ages named for the material that was used for tools. As humans developed stronger materials, our knowledge of how to use them improved also. We learned how to build vessels that withstood higher pressures, and to make machines that could generate more power for useful work than the animals used previously. The horse was replaced by engines, but the unit of power is still derived from it automobile engines are still rated in horsepower. These new machines enabled one person to perform the work of many, and gave rise to the Industrial Revolution.

During the Industrial Revolution, humans grew more interdependent. No longer did a person or a family need to grow all their food from the soil or provide all their shelter from natural resources such as timber, sod, or stone. Rather, 'individuals learned more specialized trades, many of them dependent on the new machinery. As this trend toward specialization evolved, terms such as "mechanic"-or a person who could design or repair mechanisms acquired different prefixes such as auto mechanic or airplane mechanic. Recently, as electrical circuits have been used more frequently to control mechanical devices such as automobiles and airplanes more broadly trained individuals, or teams of specialists, have become necessary to design or repair increasingly complicated electro mechanical devices.

Mechanical design tools of the industrial age rulers, protractors, and compasses have given way to drafting tables, which in turn have been replaced by computer terminals. Semaphore flags were replaced by the telegraph, then the telephone and walkie-talkies for much more rapid two- way communication. For mail delivery, the pony express was replaced by the train, then the truck, and the airplane, and very recently, fax or electronic mail. All of these changes have required improvements in infrastructure, a point to which I shall return.

The examples of the last paragraph relate to the communication of information. For most of human existence, people have been satisfied to communicate orally face to face, and history was passed down orally, as well. Written communication developed gradually, for recording events, thoughts, and sending information over distances. The use of the printing press in relatively recent times (metal type was known in China and Korea in the thirteenth century, and Gutenberg invented moveable type in about 1440) enabled printed information to be distributed more widely and more economically. Virtually instantaneous mass communication, such as radio and more recently television, are phenomena of this century.

As people roamed farther from home, and eventually settled far from their families, the need for personal communication grew. As business enterprises became more widely distributed, the need for rapid, accurate business communication grew as well. Telegraph, then telephone, have helped, including recently the increasingly popular fax machine, but today much electronic information is digital, and in the future, most electronic communication will be between computers, with audio or visual output for humans. In short, the world is entering the Information Age; information technology is improving global efficiency, quickening communication, shrinking the world, changing, and often enhancing, our quality of life. How this has developed and is presently taking place is the subject of the rest of this lecture.

I shall try to show that technology enables all members of society to accomplish far more than we could without it. Technology is also tightly linked to progress in science, so that it is difficult to decide sometimes whether science is driving technology, or technology science. In fact, they are synergistic. Both enable advances to be made in the knowledge we have of both the natural universe and those portions of it that are man made.

Information technology also enables us to appreciate the arts. It allows us to amplify and record music and video images, so they may be heard or viewed at a more convenient time. Symphony concerts, once heard by only those who could obtain tickets for the performance, can now be enjoyed by millions at the time of the performance, or at the time and place of their choosing. Broadcast media has evolved from amplitude modulation (AM) to frequency modulation (FM). Recording media has evolved, from grooved plastic cylinders to disks and magnetic tapes. Initially large plastic discs that rotated at 78 rpm, they have evolved to slower rotations of 45 rpm and 33 rpm, and eventually to compact disks read by laser beams. Magnetic storage has also become more compact, and is used not only for audio and video, but also for digital storage for computer processing. Technology also enables four-color images to be printed in mass production, so they can be shared by millions simultaneously in Sunday magazines or the numerous catalogs we all receive.

A Personal Vignette

Before delving more deeply into the evolution of science and technology and how it effects us all, permit me an autobiographical aside to mention some examples of change that have happened in my lifetime. They may strike a responsive chord for some of you who can remember life before World War II. When I was a boy in Kansas City in the 1930s, bread was sold from horse-drawn wagons that came by our house, milk was delivered to the door, and radio was our source of news and entertainment in the home. Moving pictures were seen at a cinema, which we called a movie theater, in Kansas City. The term video was not part of a growing boy's vocabulary, the transistor had not been invented, and commercial television was a dream for the future. Long-distance transportation was generally by train, bus, or car; air transportation was in its infancy, using propeller-driven airplanes of the day. Highways were generally two narrow lanes, but cars were narrower, too.

While driving from the Midwest to New England in the early 1950s, I recall nothing similar to an interstate highway west of the Pennsylvania turnpike. Communication home was by letter. Long- distance telephone calls were so expensive they were used only for emergencies. Themes were typed on erasable bond, to make typing corrections less noticeable. Calculations were quickened by a mechanical device called a slide rule. During my final year in college, I chanced to see a special building set aside for research, in which large banks of electron tubes were connected together in a device that filled a very large room. The device was called an "electronic computer." It had less power than many personal computers in use in offices today!

My master's degree resulted from a cooperative plan between Hughes Aircraft Company and UCLA, in which Hughes provided me a job and educational expenses, and UCLA provided classes, and eventually, a degree. My research at Hughes was an education in itself as we attempted to understand, develop, and build useful broad-band microwave amplifiers and oscillators called traveling wave tubes. There I met young Ph.D. scientists and engineers. These men (they were all men in those days) were an inspiration to me. They were teachers, mentors, and role models. Their encouragement, like that of a few professors I had, made a great difference. Their examples of how to apply science and technology to make a useful device or process was seminal. They knew much more than I did, and inspired me to seek more advanced education. In October 1955 my wife and I found ourselves in Cambridge, England, where I was to study for a Ph.D. degree.

There is something inspiring about walking where others have walked, others who later became leaders of their fields. It is akin to the sense any disciple has in following in the footsteps of the master. You want to do well, to prove that you can, and to justify the faith people have had in you. Cambridge University is such an inspiring place. During three years in England, not only did we make many friends from all over the world, but I also learned a great deal about the scanning electron microscope.

While this is not a technical lecture, but rather one about how technology impacts society, some sense of what the scanning electron microscope does will enable you to understand my perspective on the information revolution. Conventional-transmission electron microscopes image electrons that have lost no energy in penetrating very thin samples. Their resolution in the mid-1950s was about three orders of magnitude better than a light microscope. The scanning electron microscope works on a television principle, and can produce an image from any signal that the electron beam produces by interacting with the object being scanned, even a rough, bulky, solid object that cannot be viewed in a transmission electron microscope. The scanning electron microscope's best resolution then was about one order of magnitude better than a light microscope, but it could produce images with a much greater visual depth, so that their information content was perhaps one hundred to one thousand times higher. My task was to determine how contrast was produced in the microscope, and my doctorate was awarded for a thesis on this topic.

Later, in collaboration with others, it was possible to image integrated circuits, and visualize these circuits both physically and electrically. (Parenthetically, the scanning electron microscope has helped visualize samples from biology, medicine, and many other fields of science and engineering, as well.) The scanning electron microscope has helped solve several important problems as integrated circuits have been developed over the past thirty years. It has speeded the development of the integrated circuit, led to the development of electron beam machines that make very fine masks necessary to produce integrated circuits, and in general, has been one of many techniques that have enabled the revolution in integrated circuits, and hence computers and communication, to take place so rapidly. It has been part of the infrastructure needed for the integrated circuit to be developed so rapidly.

The Evolution of Technology

Indeed, the invention of the integrated circuit by Jack Kilby and Robert Noyce, working separately and with rather different concepts, is clearly one of the great inventions of our age. The first Draper Prize of the National Academy of Engineering, the largest financial prize for engineering accomplishment, was awarded to these two men for this invention. However, their invention could not have taken place without the development of transistors that took place over the previous decade and a half. Similarly, the development of the integrated circuit to its present state could not have taken place without a myriad of techniques and instruments that were developed, or without the people who puzzled over problems of design, development, fabrication, packaging, and utilization. These problems ranged from mask design, registration, and optical imaging, to resist application, chemical etching, and metal evaporation, and from contamination elimination to diffusion of impurities in order to produce the expected device structure, and on and on.

Just as modern automobile transportation cannot function without modern highways, filling stations, skilled mechanics, and many other necessary items of infrastructure, nor can air transportation exist without airplanes, airports, and ground transportation to airports, etc., the integrated circuit industry could not exist without its infrastructure. This infrastructure includes suppliers of semiconductor wafers, suppliers of process equipment (for optical exposure of properly registered patterns, etching, diffusion, metal evaporation, circuit testing, and packaging, for example), the factories to make the integrated circuits, and the marketing and distribution complex.

The integrated circuit industry, now selling products valued at over $65 billion dollars per year, is fueling the computer revolution which enables us to process information words, equations, and data, as well as display graphs and images much more rapidly than before. Let me illustrate how remarkable this progress has been. When I was at Hughes in 1954, the computer we used for difficult problems rented for several thousand dollars per month. It was not "user friendly". Today, one can buy a personal computer over 1000 times more powerful for about $1000. The cost effectiveness has improved over ten million times ! Had the same improvement occurred in the development of the automobile, the good news is that mileage would be measured in thousands of miles per gallon, at speeds of thousands of miles per hour. The bad news is that the car providing this performance would only be about an inch or two long!

Not only has the integrated circuit reduced the cost of information processing, but it has also helped decrease the cost of information transmission, although not so dramatically. Taken together, the greater cost effectiveness of information processing and communication fuel the information revolution, and propel us into the Information Age.

Since the rapid accumulation, processing, and transmission of information has so many advantages, one is tempted to ask why this didn't happen earlier. The short answer is that the knowledge base was inadequate earlier. If this is true, how did the knowledge base become adequate? How did science and technology evolve to provide an adequate base? How did people learn what they needed to know, and become motivated to develop the devices and systems that allow us to communicate so much more information so much more rapidly today than we could even a half century ago? Did someone have a vision that computation and communication could become so accessible to everyone, and at such a reasonable price? Or did we achieve our present state of accessible computation and communication by a fortunate evolution?

The evolution of information technology is a fascinating story, which I should like to sketch from a rather personal perspective. It involves fundamental advances in science, developments in science and technology, and profound changes in the way in which engineering is taught and practiced. It is difficult to see how this development could have been so rapid without the federal government's investment in research that was stimulated by the second world war and our need for a strong defense. It is an ongoing process even today, involving considerable debate, and sometimes painful change.

Changes in Research in Science and Engineering

At the start of this century, many physicists thought they understood their field completely, and longed for new fields to conquer. Discoveries subsequent to 1900 such as the photoelectric effect, the wave nature of particles, the equivalence of mass and energy, and quantum mechanics have made possible tremendous strides in our understanding of nature, and these in turn have allowed us to apply this knowledge to the development of new devices, processes, and systems which can benefit mankind. The progress in physics was accompanied by great strides in chemistry and biology as well. The binding of atoms into molecules and crystals, the nature of the chemical bond, and a host of other principles have been understood, and analytic experimental techniques, then instruments, have been developed that speed our detailed understanding of chemistry. The development of new chemical compounds, techniques, and processes that have benefitted us all. Concurrently in biology, the new knowledge of physics and chemistry has led to an understanding of biological structure, such as the double-stranded helical structure of DNA, and the communication of electrical impulses along neurons. A fascinating story could be told using examples from these fields; nevertheless, I shall stay with physics and engineering because that is where my experience lies.

Before World War II, research was carried on by motivated people who wanted to discover the secrets of nature and were willing to make a career doing so. While a few corporations had research laboratories, much research was carried on in universities by faculty and a few graduate students who were similarly motivated. Much academic research was funded privately. Scientific research was not a high-paying field, and was not viewed as particularly important by society at large. It was satisfying to those who practiced it, and it helped keep them stimulated over a lifetime, and was stimulating to those they taught. During World War II, political leaders realized that academic scientists and engineers had knowledge that could benefit our nation in the emergency that threatened its existence. Groups were formed at MIT, Harvard, and Caltech, as well as other universities, and important contributions that influenced the outcome of the war were made by these scientists and engineers who were applying their knowledge to help the country. Many advances in electronics, radar, and aeronautics resulted. Perhaps the most famous contribution was the development of the atomic bomb, which associated in the public mind the words science *and power.* The urgency associated with the war also produced a sense of urgency in science, and gave new meaning to the words: *competition in science.*

When the war was over, the involved faculty returned to their universities, and resumed their careers. However, the teaching of at least some of them changed, leavened by the practical problems they had encountered during their wartime experience. I found this to be so in classes I took during the early 1950s, and as a result, I had a better idea of how certain principles I was learning could be applied, and what the significance of the application would be. On the national scene, Vannevar Bush wrote a report to President Truman: "Science, the Endless Frontier," and advocated continued support for scientific research by the federal government as a national strategy to promote strength in defense and a supply of well educated, technical people. Since then, the federal government has been a strong supporter of scientific research, and the sophistication of our technical achievements in defense, in space, in health care, and in many other areas show the wisdom of that support.

National laboratories have generally conducted research focused on defense and the development of atomic, then nuclear, weapons. Corporate laboratories have generally concentrated on research and development that would further corporate goals in the development of new products or processes that would enhance the corporation. Universities have conducted more fundamental, or basic research, than any other participant, and have educated increasing numbers of graduate students who have often joined national or corporate laboratories. Research funding at universities changed dramatically after World War II. In 1940, Caltech received no federal funds for research. Since 1950, almost one-half of the campus budget has come from federal research grants and contracts. Similar changes took place in other universities.

The Increased Pace of Change

The rate of change has accelerated during the past half century. Increased funding for research in science and engineering has speeded discoveries in both. Novel instrumentation has made new scientific experiments possible, and the rapid accumulation of data. Scientific and engineering advances have opened the doors for new and better products and processes. New mathematics, and especially the availability of highspeed computers, have enabled both science and engineering to become more quantitative, to be based more on analytic techniques and less on empirical knowledge, and to bring experiment and theory into closer agreement. Much of the art of engineering has been replaced with the science of engineering. Using models developed for computers, simulation of many processes and many experiments has become common. The teaching of engineering has become based more on principle and mathematics, and less on rule of thumb and empirical tables and curves. With better understanding has come better design and improved performance.

The new engineer is closer to the scientist of today than the engineer before World War II was to his scientific counterpart. However, there are still differences. While the background information that the engineer uses to design new devices, processes, or systems is much more mathematical, scientific, and analytical, today's engineer has to be concerned with the application of science to society in the larger sense. How will her product effect the environment? How will his process improve productivity, quality, efficiency? How will her device improve the system in which it will be used? How will his product be accepted by the customer? While some of this can be learned in college, some is best learned by experience, and much is attitudinal. In fact, there is much less difference between the education of a scientist and engineer than there is in their attitude and how the education will be used. Many practicing engineers have been educated in science, but are engineers because of their motivation, and how they choose to use their education.

There are many ways our society has benefitted from the Information Age. Information can be shared by many people virtually simultaneously. A travel agent can reserve a seat on a particular flight from Salt Lake City to San Francisco using an airline reservation data base from anywhere in the country. The ticket is printed out and delivered to the customer, who expects when he shows up at the airport that his reserved seat is waiting and he is generally not disappointed. The computer in which the reservation data base resides is part of the Information Age infrastructure. So are the telephone lines that connect our homes to the nation-wide telephone infrastructure, the cables that bring television into many homes, and the satellites that relay signals to distant parts of the globe. Telephone lines existed when I was growing up; computers, television cables, and satellites did not. But today telephones are used much more, especially for long-distance communication. The relative cost of long-distance calls has decreased dramatically, the quality and convenience has improved, and consequently, so have both business and personal communications.

Our finances have changed also. Years ago, people carried cash to pay for things they bought. Later, checks were used to pay for groceries at the store, and for other purchases. Credit cards then came into use, and can be used today to pay for gasoline at the pump at self-service gasoline stations, for meals at restaurants, for groceries, clothing, or virtually anything one wishes to buy. Cash can be had at automated teller machines by using a credit card or bank card. Paychecks can be deposited automatically to the employee's bank account. Although these changes have taken place slowly, the financial systems of the country have evolved, and transactions are generally quicker and more trouble free than they were years ago.

The Digital Computer

At the heart of these changes is the digital computer, and modern computers are hard to imagine without integrated circuits. As most of us know, the computer is a system of active and passive electronic elements that understand only yes or no, symbolically abbreviated "l" and "O". These elements perform logic operations on the "1s" and "0s", which is the computing. The electronic elements can also remember the instructions they need to perform these operations; the instructions are contained in the computer's memory. The instruction set, a sequence of operations, is the so-called software of the computer, while the electronic devices themselves, suitably connected, are termed the hardware. While the basic theory of computation has been understood for a considerable time, the hardware was too expensive, or too unreliable, for electronic computation to be really practical or useful until about the 1950s.

The very early computers used vacuum tubes as electronic devices. These tubes had a heated cathode, were about a centimeter in diameter and a few centimeters long. The wiring for each tube was attached by hand to a socket, and the tube was then plugged into the socket. The tube and other component reliability was such that a computer containing thousands of components might run reliably for a few hours, perhaps even a few days, but then a component failure would cause the system to fail (or crash). The heat generated by all the tubes had to be carried away, and the cooling systems added cost and complexity. These early systems were large, expensive, and unreliable. I'm told that just before IBM started to make computers, someone there estimated that ten computers would saturate the market. Such unreliable machines were "only of academic interest" ! Fortunately, academics saw computers as worthy of study and experimentation.

Mathematicians were interested because the software was highly mathematical, and electrical engineers were interested because the systems were electronic indeed, at the leading edge of electronics. Both saw the need for faster electronics that were smaller, cheaper, and more reliable, and both saw the need for more memory that could be accessed electronically and rapidly. Cost and size had to be minimized, while speed and friendliness toward humans needed to be maximized. Individuals in industry started to pursue these goals, and urged universities to educate students who could become involved.

Gradually, a group of people grew in universities whose main interest was the understanding, development, and utilization of the digital computer. Many of them wanted to be associated with others of like mind, and in some universities, departments of computer science were formed. Other faculty wanted to stay allied with their previous colleagues, and groups strong in computer research and development grew up in electrical engineering departments, and occasionally elsewhere. Many scientists and engineers started to use the digital computer to further their research, design, and teaching objectives. It also found increasing use in other parts of the university, particularly in business schools and in administration.

The science of computers is not a natural science. The natural scientist studies laws of nature that are immutable. Since computers are manmade, and change as designs change, computer science may be termed an "artificial science". Although principles underlie a particular computer, and some of these principles appear universal, others may change depending upon the computer design. Certain components may also seem unimportant at one time, and extremely important if they can be made so cheaply that they are used virtually universally. The read-only memory was hardly mentioned in early courses on computers, for example. However, when read-only memory became very inexpensive to make and found extensive use in computers, it was incorporated into the curriculum.

When transistors became fast enough to be useful in computers, it became obvious that because they had no need of cathode heaters, and because they were intrinsically small, they would be faster, cooler, cheaper, and better. In short, they would ultimately be much better suited as active computer elements than vacuum tubes. They were developed rapidly during the 1950s, and were used in other devices as well. I'm told that the first commercial use of a transistor was in telephone switching equipment in 1952. The most popular use was the hand-held transistor radio, which allowed music and news to be received wherever people wanted to be.

A limitation to computers in those days were the connections that had to be made by hand. As the computers became larger and more complicated, the number of transistors increased, and the number of connections increased also. It became increasingly difficult to connect the devices correctly, and even when this was done, the probability that a connection might fail over the life of the computer increased with the number of connections. A better way of making connections was called for, preferably one that could be done reliably in mass-production. At this time, the planar transistor was becoming popular, and Robert Noyce had the idea of combining several elements of a computer,, and the connections among them, using the same processes as were used in the manufacture of planar transistors. The integrated circuit as we know it was born.

The Integrated Circuit

Early integrated circuits had a few resistors and a single transistor, but these soon were replaced by circuits with several transistors. Each of the early circuits performed a Boolean function, and later circuits performed more complicated computer functions. The complexity of the circuits increased, and the designs became more complicated (and expensive), but because the manufacturing process could turn out many circuits in mass production, the cost per function decreased. Even though the manufacturing processes were complex, as the manufacturing cycle proceeded, the engineers supervising the processes learned how to increase the yield, or the fraction of good integrated circuits that were produced in each batch. As the yield increased, the cost per circuit decreased. This decrease over time was important and predictable; it was called the learning curve. It enabled the circuit manufacturer to either make more profit from circuits produced later in the manufacturing cycle, or to drop the circuit price and still make an acceptable profit. It had three important implications. First, it was a significant advantage to be first in the market place with a circuit of a given function, complexity, and performance. Second, continuous improvement of a particular manufacturing process was important, to proceed rapidly down the learning curve. Third, the development of new processes that could lead to smaller, faster devices as internal components of integrated circuits was also important. Both evolutionary improvements and revolutionary breakthroughs were important!

The integrated circuit was different than previous electronic circuits in that the elements were in closer proximity, and analytic models of the circuits required more sophisticated analyses. An integrated circuit engineer needed to know not only electrical circuit theory and design, but also solid state materials, especially semiconductors, how circuit components may interact if they are in close proximity in a material, how circuit patterns are transferred to a wafer, how the exposed wafer is processed, and how circuits are tested, packaged, and used. As the circuits became more complex, computer analyses became necessary in order to predict how elements, and assemblies of elements, would function. The industry needed people who understood all these complexities, and could design circuits and processes that would keep a given company on the leading edge. New courses were developed in universities, based on the research being done in the universities and in industry. These courses had to evolve rapidly, as the design and processing of integrated circuits changed rapidly.

It was my good fortune to be at the University of California at Berkeley from 1958 to 1978, and watch the development of the integrated circuit research in the Department of Electrical Engineering and Computer Sciences. This research started in the early 1960s, and was quite controversial at the time because most people thought that integrated circuit fabrication was too complicated to be performed in a university. The graduate students who initiated the laboratory learned all aspects of integrated circuit design and fabrication, and became some of the leaders of the industry. Their work also led to courses in integrated circuits, which were taught to generations of Berkeley students.

Other universities followed suit. Industry was eager to see students educated in this new field, and was supportive of keeping the laboratory running and up to date, donating equipment, advising on techniques, and helping in other ways. The students educated in the universities helped industry get off to a faster start than would have been possible otherwise, and when the students became engineers in industry, they formed a natural linkage back to the university, providing information and support that kept the university laboratories up to date. This synergism would not have been possible without federal support for the university research, which was a wise investment that kept the United States in a leadership role in perhaps the most important industry in the Information Age. Interestingly enough, many companies did not want to accept federal support for their leading edge integrated circuits and processes, because they deemed the intellectual property too valuable to share, and they believed the incumbent government procedures would slow them down in a very competitive industry in which speed was essential to maintain a lead.

Individuals have made a great difference in the advances of the integrated circuit, sometimes from very different perspectives. Often those who made the advances saw further into the future than their contemporaries, were willing to take the risks associated with being a pioneer, and worked hard to make their risky course successful. Among the industrial pioneers who come to mind are Bob Noyce and Gordon Moore at Fairchild Semiconductor, Jack Kilby and his colleagues at Texas Instruments, and Les Hogan and his colleagues at Motorola. While there were major developments at other corporations and by other individuals, I particularly remember these. As the silicon integrated-circuit developed, and semiconductor memory became competitive with the magnetic core memory used in most computers of the time, I particularly remember a lecture given by Les Hogan at a national conference. To make the point that semiconductor memory would become much cheaper than magnetic core memory, he threw handfuls of semiconductor memory chips to the audience, giving them away as free samples. Not too many years later, his prediction came true. Semiconductor memory has dominated for many years now.

Gordon Moore observed several years into the integrated circuit revolution that the number of active devices on an integrated circuit chip was doubling every year. This became known as

Moore's Law. Although empirical, it held true for almost two decades, and then the rate of increase declined somewhat, although it is still increasing exponentially. For those not mathematically inclined, a doubling every year corresponds to approximately a thousand times increase each decade, so if there were two active elements on a chip in 1961, there should be one million by 1981, and over one billion today. There are actually about twenty million active elements on commercially available memory chips today, and almost four million active elements on today's logic chips, which are somewhat more complicated and less regular. This is the most dramatic increase in complexity over time that I know of in the history of man-made devices, and it is still continuing! This rapid increase in complexity empowers the information revolution we are experiencing; it is a revolution fueled by the integrated circuit.

Moore identified three reasons why the number of active devices on integrated circuit chips was doubling each year and the integrated circuit power per unit cost was increasing. First, the devices themselves were becoming smaller and faster, so more devices could be fabricated per unit area of chip and more computation could be done per unit time. Second, the wafers were becoming larger, so more chips of a given complexity could be fabricated on each wafer, hence manufacturing became more efficient. Third, engineers were becoming more skillful in designing the circuits, so that more speed and complexity could be designed in each unit area. Each of these driving forces required a host of researchers and designers working in different corporations and universities to improve the circuit performance.

The increasing number of transistors per integrated circuit required a much higher emphasis on quality in design and processing. When transistors were discrete components, they could be individually tested, and those not meeting specification could be rejected. Transistors in integrated circuits are interconnected on the chip, and must correctly work together or the entire chip must be rejected. If only 99'% of discrete transistors functioned correctly, the yield was quite acceptable. If only 99% of the transistors on a one-million transistor integrated circuit function correctly, 10,000 transistors do not meet specification, and the chip must be rejected. Consequently, extreme care in designing, simulating, and processing modern integrated circuits is absolutely essential.

As integrated circuits became more powerful, many more people needed to know how to design them for custom applications, and have them fabricated in small batches. Many educational institutions wanted to give their students the opportunity to design integrated circuits as well, and test the student designs. However, the cost of fabrication facilities was too expensive for most individual institutions or small businesses to afford, and so the concept of a silicon foundry was born. Corporations could dedicate a portion of their unused capacity to fabricate circuits for university classes, for example. While designers for mass-produced circuits needed to pack devices as closely as possible to make their circuits competitive, custom designers could optimize by saving design time instead of silicon area. Design methods for large scale and very large scale integrated (VLSI) circuits were needed that would open such circuit design to many who were not experts. Carver Mead of Caltech and Lynn Conway, then at the Xerox Palo Alto Research Center devised, tested, and taught such methods. They then published a book entitled Introduction to VLSIsystems, which has taught many scientists and engineers how to design VLSI systems.

The complexity of integrated circuits is increasing still, and the amount of information that can be processed per unit time is also increasing. Computers are being designed which process information in parallel, rather than in series, so that increases in speed comparable to those found when a printing press is used rather than a typewriter may be obtained. New sensors are being developed that transform information from mechanical, chemical, biological, and other forms into electrical signals that can be processed by integrated circuits. This in turn makes more different processes susceptible to electronic control.

Selected Consequences of the Information Revolution

All of us experience the consequences of the information revolution.

- We wear quartz wrist watches of great accuracy, instead of the mechanical ones that were common two or three decades ago.
- Cameras and video recorders automatically adjust the exposure required, and often focus automatically.
- Many people have cellular phones they carry in their pocket. They can be contacted virtually anywhere.
- There may be more microprocessors in a typical American home than electric motors, and there are generally more motors in the home than one suspects. (Try to count the number of motors and microprocessors in your own home you will be surprised!).
- New automobiles have several microprocessors, from monitoring combustion and setting the air- fuel ratio to controlling air temperature, audio devices, electronic instrumentation, and other tasks.

- We get cash from conveniently located automatic teller machines, and the cash is instantly debited from our account at the bank.
- Many homes have personal computers, and more and more people are using electronic mail.

The world-wide computer network called Internet had an estimated 17 million users from 173 countries in August of 1993. At the rate of increase of users that was occurring then, one could extrapolate that *every person in the world* would be a user by the year 2002. Clearly the rate of increase will slow and eventually saturate, but not until most people who have personal computers are connected to this network through one means or another. Computer scientists and others involved with computer development have been using precursor networks for a couple of decades. The Advanced Research Projects Agency of the Department of Defense started tests of a 5,000 bits per second network at the end of 1969, called the ARPAnet. Many users found that networking expedited their work tremendously. As demand grew, other networks were started as well. Today, network transmission rates vary from a few thousand bits per second up to over 100 million bits per second, and Caltech and a few other institutions are experimenting with network rates ten times faster still.

Currently, both private and public networks exist, and they are being used for a host of applications. People not only send messages, but documents for review. Multi-authored papers can be written and passed back and forth easily. Bulletin boards of information can be browsed through by network users at their convenience. Clubs are formed of people with like interests whose only connection is a computer network. Conferences can be held using computer networks. Networking is becoming an important new form of communication in today's world.

Satellites are also a source of information that help us plan and improve our lives. Pictures of cloud motion appear on televised weather forecasts, and events taking place around the globe are presented virtually instantly on our televised newscasts via satellite transmission. Scientists learn about ocean currents, ozone holes, and the presence or absence of chemical molecules in the atmosphere around the earth from satellite Monitok. Using electronic equipment linked to global positioning satellites, the position of such equipment can be located to a few inches anywhere on or above the earth. Using such equipment, aircraft will soon be able to land safely in dense fog on automatic pilot, if necessary.

Moving even farther from the earth, exploration of our solar system has been possible using unmanned spacecraft that send back images of the planets and their moons. The two Voyager spacecraft, launched in 1977, have sent back images of Jupiter and Saturn, and Voyager II continued on to Uranus and Neptune, where images of those two planets were obtained. Remember that these two spacecraft used technology prior to the times their designs were frozen, well before 1977. In order to function more optimally during the flyby of Neptune, the outermost large planet, the computers on board Voyager II were reprogrammed from the earth. The excellent images obtained from Neptune, which increased our knowledge of the planet by a significant amount, made this exercise very worthwhile. Magellan has recently produced the most detailed and complete mapping of the surface of Venus, adding to our knowledge of our nearest inner neighbor. Optics, electronics, and electromagnetic communication have greatly improved our understanding of the solar system in which we find ourselves. These are but a small sample of the consequences of the ongoing information revolution.

Predicting the Future

The world, and the world of information, will continue to change. These changes will impact both individuals and nations. Niels Bohr once observed: "It is dangerous to predict especially the future." Nonetheless, there are some changes that can be foreseen. If history is any guide, however, the most important changes will be the ones that we do not foresee. With these caveats, let's examine some of the changes we can expect, both as individuals and as a nation.

Our new understanding of both natural and artificial science will enable us to augment our senses. We see using photons of electromagnetic radiation in the visible range, and our sight brings more information to our brains than any of our other senses. The correction of vision, magnification of images, and other processing of optical information has greatly enhanced our ability to perceive information about the world we live in. There are other forms of electromagnetic radiation at shorter and longer wavelengths than the visible which can also aid our perception of the world, and also are essential for communication of information from one point to another.

While electromagnetic waves bring us information without the need for wires, electronics can be used to process, store, and present that information to us in forms we can readily use, such as light or sound. Night vision is a example of how photons too few for us to see can be detected, amplified, and displayed so that one is able to "see" in the dark. Amplification of the ultraviolet or infrared photons we normally cannot see, and presentation in the visible spectrum we can see, is another example of enhanced vision. As we learn more about human vision, artificial sight for those who have lost their sight becomes a possibility. Similarly with hearing. While great advances have been made already with artificially enhanced hearing, much improved hearing aids will be developed as we better understand human hearing and electronics.

One application of both vision and hearing that has been in the news recently is termed "virtual reality". Artificially generated and present sight and sound are contrived to make the subjects believe that their experience is as near reality as can be artificially produced. "Virtual reality" may be the media experience of the next decade, perhaps even sooner. Rather expensive equipment called simulators have been used for many years to train pilots. Large jet aircraft are so expensive that the expense of simulator training was deemed worthwhile. Now using much less expensive devices, such training will become possible for automobile drivers and others who may benefit from it.

As we gain a better understanding of how our bodies function, new chemical molecules can be devised that can halt harmful processes we call disease. While many strides have been made in the past decades, our understanding of human health is improving rapidly; progress should be much faster in the future. In addition, the practice of medicine will be enhanced by additional knowledge obtained as the human genome is mapped. Progress in this field has been greatly speeded by the development of new instrumentation that enables a technician to sequence a gene in an afternoon that several years ago required a team of Ph. D.s working for a year to sequence. To find a particular sequence in the three billion base pairs that make up the human genome will require powerful information handling techniques only available in a fast computer.

Studies in neural biology are producing information that enable us to understand better how electrical impulses control our thoughts and action. How neurons process information using vast numbers of interconnections, operating all at once instead of sequentially, is starting to be understood better. This knowledge has enabled us to design better concurrent electronic circuits that perform specific tasks faster and better, and there is much more to be learned and to be accomplished in this field as well. Already, however, rudimentary artificial retinas and artificial cochlea have been developed. Their impact on machine vision and hearing, as well as human vision and hearing, should be profound. Here again, improved information processing speeds progress in biology, and improved understanding in biology has led to neural networks and other improvements in information processing.

Instrumentation that enables doctors to see what is happening inside their patients' bodies has improved diagnoses. Advances in science and computation have made magnetic-resonance imaging possible, as well as positron-emission tomography, and other methods of non-invasive imaging. In addition, some of the techniques developed to produce electronic integrated circuits are now being used to produce micromachines. Motors that can fit on the end of a human hair are possible, and some researchers in this field are now working with medical doctors to determine how these mechanical microdevices can be used in medicine, perhaps in microsurgery, or other applications. Applications in fields other than medicine are also being explored, of course.

In a world that seems ever smaller, the economic, physical, and mental well being of each nation is of importance to its citizens. Such well being depends increasingly on information and knowledge. What information is presented to the population determines its mood, its will, and perhaps eventually, its morality. A national mood, will, or morality are important to a nation's future, but particularly in a diverse and pluralistic society, they are issues that are not well understood, nor well quantified. As the world becomes increasingly one global village, where the actions within one nation affect all nations, these are issues that need broader understanding, broader agreement, and concerted action, so that all people can benefit.

Sometimes other consequences of information recording and transmission are unexpected. Who would have expected to see CNN television pictures from Baghdad during the initial moments of the Persian Gulf war? Would the police officers who arrested Rodney King in Los Angeles have behaved differently had they known a video camera was recording their actions? An electronic mail message addressed to a few people maybe printed out and be shown to a much larger audience, causing its sender embarrassment. Information in data bases may be accessed by persons not authorized to do so, and may be copied or altered.

The information revolution increases the importance of many issues that have long been recognized, but have not seemed so urgent. Consider the issue of privacy: what information from a data base should be publicly available concerning an individual? His or her political beliefs? Personal wealth? Social security or other identifying number? Genetic code? Communicable disease? How can unwanted invasions of privacy be prevented? Unwanted telephone calls? Unwanted electronic mail, or fax messages? Unwanted mail? These are political questions about which individuals feel strongly, but about which a national consensus has not yet emerged. They are but a sampling of the range of questions that could be raised at the individual level. Similar questions can be raised at the national, or international, level.

As information is transmitted from place to place more easily and rapidly, national information control becomes much more difficult. During the Tienanmen Square disturbances a few years ago, the Chinese government learned that while they might be able to censor letters, they had not devised a way to stop faxed copies of written information from being received within their country. Such information gave citizens inside China knowledge of how people outside China viewed what was happening there. Official communications were not the only information received by the citizenry, and that may well have tempered events in China during that troubled time.

Many other aspects of the interaction of nations have been changed by this information revolution. Funds can be transferred instantaneously. Global economic transactions are quicker, easier. Businesses can control inventory better, reducing costs, improving efficiency. Skills can be procured where they are best, or the best value, regardless of national boundaries. Jobs lost because they are transferred overseas, or jobs lost because robots can perform the function more efficiently, are both consequences of the information revolution. If the ability of a nation to utilize information is an important measure of its success, then that nation must educate its citizenry to utilize information effectively and efficiently. Information developed in the research laboratory that can improve products or processes must find its way into new products or processes rapidly, or else some other corporation, or nation, will benefit.

Old tensions, between confidentiality to preserve security on the one hand, and open communication to speed scientific progress on the other, are being experienced anew. These tensions cause conflict between honest people who have different priorities, and who see their priority threatened if the other side has its way. Institutions and nations have to deal with these tensions, and hopefully resolve them. What is the best solution for a nation, or for the world, may not be the best solution for a corporation, or an individual. Dealing with these "human" dimensions of the information revolution has barely begun, and may be one of our most difficult tasks in the future.

Summary

The world has entered the Information Age. We can look forward to even more dramatic changes in the future than those we have witnessed in the past. These changes are challenging individuals, institutions, and nations. Even though information transmission, processing, and utilization has increased by orders of magnitude, humans are the beneficiaries of this information. Our ability to absorb and understand information has *not* increased by orders of magnitude. How we learn to cope with the wealth of information available to us will determine whether we ultimately benefit from the information revolution as individuals and as a nation. The future will require us to be adaptable, to continue to learn, and to continue to explore the frontiers of science, technology, and their application. Let us hope that the people of our shrinking planet Earth will find a common goal of individual and global survival, and will utilize technology for the benefits that it can bestow upon the human race.

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