THE JOY OF ENGINEERING

Jack St. Clair Kilby

During my lifetime, the public perception of technology and of engineers has changed. Early in the century, each year brought a new marvel - in transportation, such as trains, ocean liners, automobiles - in construction, with dams, bridges and tunnels - in new sources of power such as steam engines, gasoline engines and electric generators - new materials with plastics, aluminum and improved steel. New consumer products, such as refrigerators and air conditioners, cameras, radios added to personal satisfaction and to the quality of life.

Although this progression of marvels had continued, with television, computers, personal communications. In many forms, and more recently biotechnology, the image of engineers and technology has changed. Engineering enrollments are decreasing in universities across the United States. Technology is considered responsible for threats to the environment and for many of the shortcomings of modern life. An antitechnology movement suggests that the world would be a better place if progress were stopped, or at least slowed.

I strongly disagree. With Dr. Inamori, I believe that man's greatest endeavour is to strive for the betterment of mankind and society. I believe that technology is capable of continuing to improve the human condition, as it has done in the past. New technology and new knowledge will be required to improve the living conditions in the entire world. With Dr. Inamori, I realize that this must be balanced with the development of science and the human spirit.

Technology is important because it causes things to happen. The invention of the automobile, for example, changed the living pattern of people in the developed nations. It has done so in ways which were not anticipated, and some of which now seem undesirable. Nobody wanted traffic jams, accidents or pollution, but in retrospect these seem small prices to pay for our mobility.

Today all of the world wants this capability. New ideas, new technology will probably be needed if it is to be achieved. Engineers will need to find new ways to make people mobile without the intense use of resources which the developed nations have used. If this is to be accomplished, very capable engineers will play an important part in it.

I am therefore proud to say that I am an engineer, and hope that in some way my carrer will lead young people to consider a carrer in engineering and technology.

I was born in 1923 in Jefferson City, Missouri. Both of my parents were born on adjacent farms in Illinois, and both were graduates of the University of Illinois. My father was an electrical engineer, and when I was quite small he became President of a small electrical utility located in Western Kansas. We moved, first to Salina and later to Great Bend.

Both Salina and Great Bend were small towns, with populations at the time of 10,000 to 20,000. Small towns of this type in the Midwest were excellent places to grow up.

I attended the public schools in Salina and Great Bend, graduating from Great Bend High School in 1941. I was not an exceptional student, although my grades were always above average. During this time I traveled with my Father as he visited the utility properties for which he was responsible. At some time during these experiences I realized that I too wanted to be an engineer.

In 1937 a major ice storm struck Western Kansas, downing power and telephone lines across the state. My father used a local amateur radio operator to maintain contact with his scattered operations. This was may first introduction to amateur radio, and I met a number of the other local hams. I began to study Morse Code, and prepare for the license examination. I received a license in 1938, built a transmitter and began to talk to others around the country.

My amateur radio experiences convinced me that I should become an electrical engineer, working in the electronics field. When I graduated from High School in 1941, I wanted to go to the Massachusetts Institute of Technology, a leader in the field. At that time MIT had rigorous entrance examinations, particularly in mathematics. Math had never been a strong subject for me, and I failed the examination by a few points.

I therefore needed to choose another school, and entered the University of Illinois. It was an excellent choice, and probably better suited to my needs than MIT would have been. I enrolled in September 1941.

After Pearl Harbor, I enlisted in the Army. I remained at the University until

June 1943, when I was called up by the Signal Corps, and was trained as a radio operator. Later that year I joined the Office of Strategic Services, and was sent to the Far East, first in India and later in Burma and China. I served as a radio technician, maintaining and repairing radio transmitters. After the War, I reentered the University of Illinois, graduating 1947.

This was an exciting period in electronics. Before the War, radios had been the only significant application of electronics. The War brought large scale use of radar, sonar, electronic control of machines and the first computers. It also showed the efficacy of large scale, organized research to solve engineering problems.

When I graduated from the University in 1947, I knew that I wished to continue in the electronics field. American industry was still downsizing, but I was able to secure a job with the Centralab Division of Globe Union, in Milwaukee.

Centralab was a fortunate choice. They had been the first to develop what would now be called thick film hybrid circuits. Silver paint was deposited on a ceramic substrate to form conductors, and carbon based inks to form resistors. Small capacitors could be formed in the substrate, and larger ones attached. The required vacuum tubes could be attached with sockets, or soldered directoly to the substrate. These products were used in radios, television sets and hearing aids. These markets provided rigorous cost disciplines. Selling prices were measured in tenths of a cent, and designs which sold for more than the cost of the components that they replaced were not acceptable.

Centralab was also a fortunate choice in another way. The group with which I worked was small, so that it was possible to see the entire process, from engineering through sales and production. I had two excellent mentors during this period, A. S. Khouri and R. L. Wolff. Both were experienced and capable engineers, and both quite willing to teach a newcomer.

Because I was working in a new field, it was quite easy to make inventions. Almost anything which departed from the previous designs was novel and probably patentable. I received about a dozen patents for my work during this period, the most notable of which were a capacitor design using the first reduced titanates and a technique for automatically adjusting resistors using a sandblasting technique.

In 1948 the Bell Laboratories announced the invention of the transistor by Bardeen, Brattain and Shockley. Although several yeas would be required before the full implications could be understood, this invention revolutionized the field of electronics. A long life device which did not require a vacuum for its operation, and one which did not need a power consuming filament removed many of the barriers which the field of electronics had faced.

In 1952 Bell offered licenses to interested companies, one of which was Centralab. In June of that year 24 American licensees and four from outside the country met at Murray Hill for a two weeks course in transistor design and fabrication. With R. L. Wolff, I attended the meeting on behalf of Centralab. This meeting began the transistor era, one which continues to this day.

When we returned to Milwaukee, I began to assemble the equipment required to build germanium transistors. To do so, it was necessary to reduce the germanium oxide, refine it, and grow crystals. Although the first transistors were built in this way, it quickly became apparent that grown junctions would be replaced by alloy transistors, in which dots of indium were alloyed to the faces of a small crystal. At Centralab we produced small quantities of transistors of this type, primarily for use in hearing aids.

My work at Centralab was exciting and fun for me. It taught me the joy of working in a new field, and of doing work that had not been done before. It was also a wonderful learning experience, for it was possible for me to be involved with the complete process, from the initial customer contact through design and production. Because we worked with consumer products, it also taught me the importance of cost discipline.

Although Centralab was in small scale production of transistors which could be integrated with their hybrid circuits, by 1958 it became apparent that the field was moving more rapidly than their resources would permit. I determined that it was time to leave, and contacted several other companies in the business. I chose Texas Instruments. TI had also been an early entrant into the field, and had established an excellent reputation. They had produced the first pocket transistor radio design, and begun making transistors for it in quantity. Most important, they had been a leader in the use of silicon as a substitute for germanium, announcing the first silicon transistors in 1954.

The 1950's were a very dynamic period for the transistor industry. Within that time the first point contact transistors were replaced by alloy transistors, then surface barrier transistors, mesa transistors and finally the planar designs. This was also accompanied by a shift from germanium to silicon as the basic material. Few companies could keep up with this progress.

The entire field of electronics was also changing during this period. Radio gave way to television as the largest single products, and to this were added many of the developments of the War—radar, sonar and electronic controls for many different applications. Of even greater importance, the computer era began. From a component standpoint, the computer was of particular importance, because it was built of great numbers of identical circuits, offering an opportunity for volume production.

The computer also made some of the problems of all electronics more apparent. People were able to visualize and design systems which, if they were realized with existing technology, would be too big, too heavy, consume too much power and simply get too hot to work. Because they were painstakingly assembled from tens or hundreds of thousands of individual parts, they would have been unreliable and unaffordable.

By the mid-1950's these problems were visible to many in the industry. A number of companies began research programs to seek a solution. All of the approaches tended to make the individual components smaller, so that the approaches tended to make the individual components smaller, so that collectively they were called miniaturization programs.

Each had a common objective, to build complete electronic circuits. T. R. Reid has pointed out that building a circuit is like building a sentence. There are certain standard components—nouns, verbs and adjectives in a sentence; resistors, capacitors, transistors and diodes in a circuit—each with its own function. By connecting the components in different ways you can get sentences, or circuits that perform in different ways. Over the years, each component had developed a specialized set of processes for its manufacture.

All of these programs fell into three general categories. One group felt that the main problem was the assembly of the individual parts, and that by making all parts the same size and shape they could automate the assembly process. A second group felt that thin film circuits could be built, a more modern form of the thick film technology used at Centralab. Both of these approaches would have used conventional transistors, assembled to the other components.

A third group felt that these efforts were wrong, and that a more radical approach must be taken. They felt that our knowledge of materials was now complete enough so that entirely new structures could be invented to perform circuit functions. A quartz crystal, which performed the functions of an inductor and a capacitor was the favorite example.

When I began to work at Texas Instruments in May 1958, it was understood that I would work on miniaturization. I was free to choose an approach, and began to consider the shortcomings of those that had been proposed. In July TI began a mass vacation. All employees who had worked there for more than a year were expected to take their annual leave. Since I had been there only a few months, I worked.

It was clear that one of the major problems with all of the approaches was that they involved many different materials and fabrication processes. I began to consider an approach which would reduce the number. It was obvious that transistors and diodes could be made of semiconductor materials. Resistors and capacitors could also be made from semiconductors, although both would be relatively expensive and neither would perform as well as the best made with more conventional techniques.

Since all of these components could be made with a single material, it was possible to consider making them all within a single piece of material. By connecting them properly, complete circuits could be formed.

This was the essence of the "monolithic" idea. Simple circuits were quickly made to demonstrate the concept. Although these initial circuits were crude, they demonstrated that many types of components could be formed within a single piece of semiconductor. The first public announcement was made in March 1959.

Initially there was a great deal of criticism. The objections fell into three major categories:

1) Some people felt that the concept did not make good use of materials. Better resistors could be made from tantalum nitride, and better transistors made if compromises were not required to include other components.

2) It was also felt that the yield of good circuits would always be low. If ten components were included each with a yield of 90% - an unlikely result at the time - the overall yield would be less than 35%. Costs would therefore be prohibitive.

3) The circuit designers in the systems houses would be put out of work, because only a few designers would be required by the semiconductor makers.

During the next few years these points were debated at technical meetings throughout the country. The debates were never conclusive, but gradually disappeared as integrated circuits moved into production.

Some of the earliest applications were in the military and space programs. Both the Minuteman missile and the Apollo mission to put a man on the moon required components of the highest reliability. The adoption of integrated circuit technology by both gave the new technology a strong endorsement.

By 1964, integrated circuits were being adopted by a number of the smaller companies for industrial and consumer products. Digital Equipment began to build minicomputers with IC's and Zenith adopted the technique for its hearing aids. By 1968, even the major companies had accepted the idea.

As the concept was accepted, hundreds and later thousands of the best engineers in the world began to work on it. New processes were devised, better transistors invented and sophisticated techniques for computer aided design were developed. Consequently, progress in the field was rapid. The simple chips with a dozen components grew to those with 10,000 by and to several million today. This progress was not the work of any one individual, one company or one country.

The progress was also accompanied by a rapid decrease in the cost of electronic circuits. In 1958 a single transistor cost about $10. Today it is possible to buy a chip with more than four million complete circuits. at that price, and additional decreases can be expected in the future.

This decrease in cost of more than one million has greatly expanded the field of electronics. Today it is possible to buy personal computers for less than $1,000 which are more capable than the $10,000,000 versions of the 1960's. The current models are small enough to fit on a desk, no longer requiring the large air conditioned room of the earlier period. A simple four function calculator can be bought for less than five dollars.

As a consequence, the world wide semiconductor market has grown to about $75 billion, providing meaningful jobs for hundreds of thousands of people around the world. Because of the low cost of integrated circuits the world electronics market is now about 750 Billion dollars, changing the lives of many of the people in the world.

Although a few of these integrated circuits are used for military applications, most are used to improve the quality of life of everyone. Automobiles emit fewer pollutants because of their integrated circuit computers. Radio and television have become more nearly universal, bringing the people of the world closer together.

Today this work continues around the world. Japan has become a leader in the electronics field. Drs. Tokoro, Doi, and Takeuchi of the Sony Computer Science Laboratory, for example, are doing pioneering work in “personifying” computers, making for easier humans to interact with them.

Although I do not consider myself responsible for all of this activity, it is satisfying to have seen its growth. It is this kind of experience which makes engineering such a rewarding profession. To know that you have had even a small part in bringing about such changes provides an experience unmatched in few other fields of human endeavor.

I am proud to be an engineer, and would like to encourage the young people of today to consider a carrer in this exciting and rewarding field.