ELECTRICAL ENGINEERING: THE SECOND CENTURY BEGINS

Edited by
HARLOW FREITAG

IEEE PRESS

ELECTRICAL ENGINEERING:
THE SECOND CENTURY BEGINS


THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, INC.
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HARLOW FREITAG
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FOREWORD

In 1984, the Institute of Electrical and Electronics Engineers–the IEEE–celebrated a Centennial of service of the electrical engineering profession that has led to the improvement of the quality of life throughout the world. During this Centennial year, there were convocations, workshops, conferences, and special events to commemorate the contributions made by the giants of electrical engineering. These events provided opportunities to pay tribute to the many engineers and scientists who contributed to the growth of electrotechnology through their participation in the IEEE and its predecessor organizations, the American Institute of Electrical Engineers and the Institute of Radio Engineers.

Throughout the Centennial year, the members of the IEEE reviewed the outstanding achievements and contributions made by our profession. These achievements have electrified the face of the earth, brought man to the moon, helped us to reach out to the farthest stars and down to the deepest depths of our seas, and led the world from the industrial age into the information age. The accomplishments of this century of electrical progress have touched people all over the world.

The IEEE has continued to build on its proud heritage of promoting the exchange of technical information. The first technical meeting, sponsored by the American Institute of Electrical Engineers, was held at the Philadelphia International Exposition in 1884. Engineers and inventors who attended that first meeting heard papers that discussed the principal technical issues of that day, papers that addressed the distribution of electrical power beneath city streets, and a paper describing what became known as the Edison Effect, the harbinger of the age of electronics. Thus, it was especially fitting that in 1984 the Institute returned to Philadelphia at the Franklin Institute to hold once again a technical meeting to review the principal technical issues of concern to our profession as we embarked on our second century of service.

The Centennial Technical Convocation at the Franklin Institute brought together leaders of the electrical engineering and science professions from throughout the world. These giants of today continued the proud traditions of the exchange of technical information started by our founders a century ago. This volume records the presentations made at this 1984 convocation of technical leaders.

In 1884, scientists, engineers, and inventors from around the world traveled for many days to attend the Philadelphia Exposition and the first technical meeting of the Institute. In 1984, it was especially fitting to use the achievements of communications technology to share the highlights of a session on the future of electrotechnology at the Franklin Institute with thousands of engineers gathered simultaneously at over 80 locations in North and Central America. This program was later sent on video tape to thousands of additional members of the Institute throughout the world.

During the Centennial year, there were technical meetings held around the world that were attended by many of the 250,000 IEEE members from over 128 countries. These technical meetings were sponsored by Societies and Sections of the Institute.

The many programs, meetings, and activities held during the Centennial year helped commemorate the outstanding achievements made during the past century of electrical progress. This volume commemorates the technical achievements of our profession.

RICHARD J. GOWEN
1984 IEEE President

PREFACE

A milestone like the IEEE Centennial is a unique time for honoring the past, celebrating the present, and contemplating the future. There is something daunting in these tasks. As engineers and applied scientists, we seem instinctively to prefer current problems and immediate solutions. The past—particularly the more distant past—is uninteresting and even perhaps boring. We tend to be problem solvers rather than catalogers of past triumphs. The future, too, seems equally suspect. Many feel that speculation belongs to science fiction and not to the pragmatic and logical disciplines of engineering.

Nevertheless, it really *does* pay to review and organize the past and to speculate a bit about the future. These efforts—review and speculation—help us to organize our thinking about the independent events that take place in the course of experimentation and discovery. It brings an order to them, and in this order there is the beginning of an understanding about the broad sweep of technological progress. With such an understanding at hand, it is possible to understand this progress and to realize that our developments are not isolated events but build upon each other in a way that is coherent, even if not planned. Such a view helps us maximize our progress in the future.

DEDICATION

Viewed this way, the exercises of the 1984 IEEE Centennial year are a little like planting a grove of trees. The work is not easy and the early payoff is minimal. The effort is directed to providing rewards for those who follow after us. Therefore, we dedicate this volume to all of those who have helped contribute to the glory that is our present technological prowess, and to the future generations who will benefit from what we have done so far.

ORGANIZATION OF THIS VOLUME

This book is made up of three parts. Part I, "The First Century," consists of a reprint of a booklet published in 1984 under the title "A Century of Electricals." A brief illustrated history of electrical engineers, it was based on an exhibit created for the Centennial.

Part II, "The IEEE Centennial," comprises two chapters. The first is a brief prologue to the IEEE Centennial in which John D. Ryder outlines the gradual awakening of the Institute to the importance of supporting historical research and of writing electrical history. Dr. Ryder goes on to describe the years of planning that preceded the celebration of the Centennial. The second chapter of Part II lists in some detail the many activities of the Centennial year.

The fact that the name of Part III, "The Second Century Begins," is also the subtitle of this book is indicative of the importance of this part. Its 21 chapters are derived from presentations, including a videotaped greeting from President Reagan, given at the Centennial Technical Convocation held in October at the Franklin Institute in Philadelphia. The eminent authors of these chapters look to the future in a variety of key areas of electrical engineering.

The book ends with two appendixes: one a bibliography of books, special issues and articles related to electrical history and the Centennial; and the other a listing of the winners of the IEEE Centennial Medal.

HARLOW FREITAG
Editor

ELECTRICAL ENGINEERING:

THE SECOND CENTURY BEGINS

PART I
THE FIRST CENTURY

A Century of Electricals

A brief history of the electrical engineers
1884-1984

Prepared by the IEEE Center for the History of Electrical Engineering for the Centennial of the Institute of Electrical and Electronics Engineers

This publication has been made possible by a grant from the Hewlett-Packard Foundation

Title Page: Thomas Edison and Charles P. Steinmetz Edison National Historic Site

This publication has been produced by the IEEE Center for the History of Electrical Engineering:

Robert Friedel, *Director*
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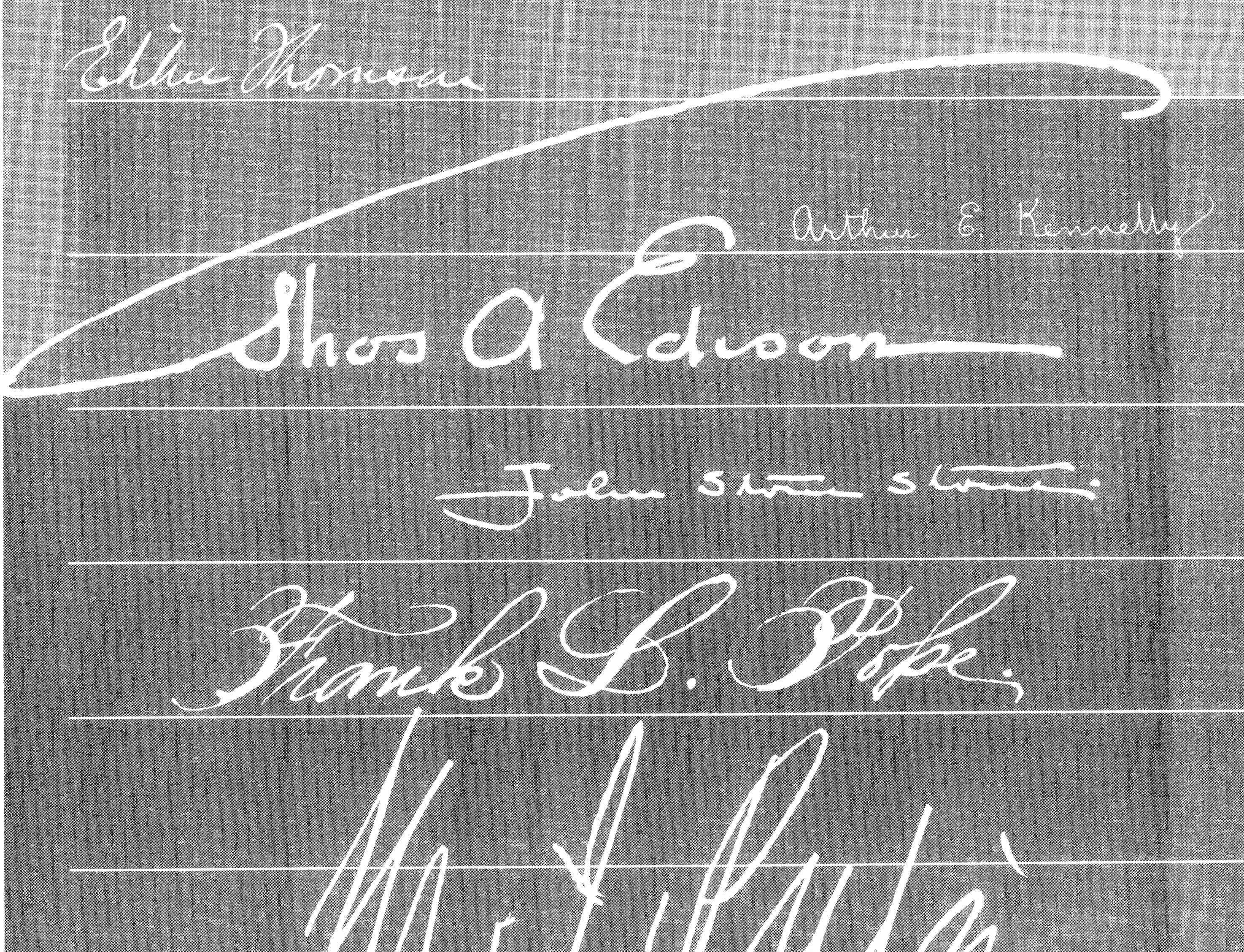


The Institute of Electrical and Electronics Engineers (IEEE) is the world's largest professional engineering society. A transnational organization, it is dedicated to the advancement of the theory and practice of electrical engineering, electronics, computers, and allied branches of engineering and related arts and sciences. The Institute's efforts are also directed toward the advancement of the standing of the members of the professions it serves and the promotion of a broader public perception of the role and influence of electrical science and technology in modern life.

A Century of Electricals

The Electricals—electrical, electronics, and computer engineers—have produced the most dramatic technologies of our time. The world has changed because of the skill and imagination of these men and women.

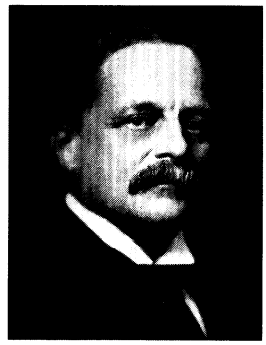
Electric power, telephones, radio, television, and computers are just some of the products of electrical engineering. And we can expect the future to be as exciting and as challenging as the past.

As marvelous and surprising as electrical and electronics technologies are, we must not forget that they are all the creations of people, of individual men and women working together to make the most of their knowledge and training. The Electricals have come from all countries, all backgrounds, races, religions, and ethnic groupings. They are bound together by a common belief in the importance of learning about how the world—especially the electrical world—works, and of applying that learning to useful purposes.

One hundred years ago, the first people to call themselves electrical engineers joined together to foster their new profession. The civil engineers—builders of public works—and the mechanical engineers—designers of machinery and engines—already had societies to promote their common goals. In the 1880s, it was time for the electrical engineers to organize, for their technologies—the telegraph, the telephone, electric light and motors—were becoming increasingly important as they were getting more and more complex.

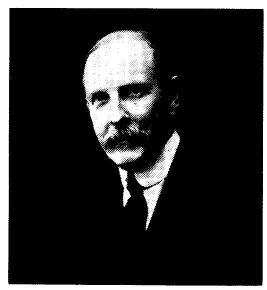
The Electricals, therefore, formed the American Institute of Electrical Engineers—the AIEE—in 1884. This organization was the forerunner of today's Institute of Electrical and Electronics Engineers—the IEEE. In one hundred years, the technologies and activities of electrical engineers have grown more diverse and complicated than the first Electricals could have ever imagined, affecting every area of our lives. The common bonds of the Electricals are still strong, however, and today a quarter-million of them make the IEEE the largest technical society in the world.

One hundred years ago, the Electricals represented a new style and a new direction for technology and the engineering profession. Their century of growth and change tells as exciting a story as the technologies of electrical and electronics engineering themselves. The pages that follow offer a hint of the full history of the Electricals—who they were, where they came from, how they worked, and what difference they made in the world. We hope this glimpse into that heritage will stimulate your own explorations into the world of the electrical engineers.



Elihu Thomson

Franklin L. Pope



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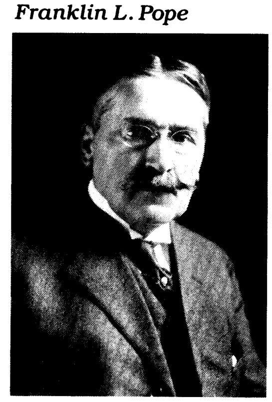

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John Stone Stone


INTERNATIONAL
ELECTRICAL
1884
EXHIBITION
OF THE FRANKLIN INST., PHILADA. PA.
TO OPEN TUE. SEPT. 2nd 1884.
TO CLOSE SAT. OCT. 11th 1884.

Philadelphia—1884

Electrical engineering became a true profession in the 1880s.

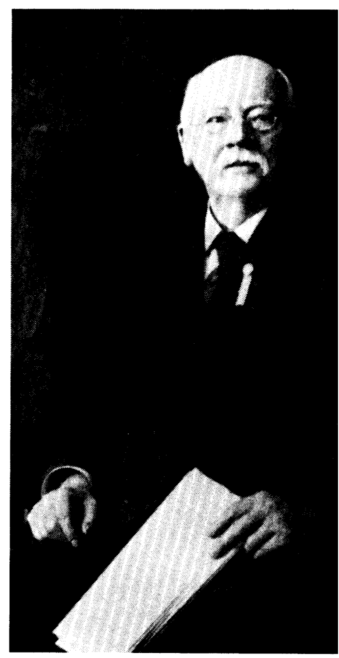
The Electrical Exhibition at Philadelphia in 1884 provided the opportunity for organizing the profession.

The American Institute of Electrical Engineers (AIEE) was formed in the spring of 1884 to unite those involved in the "art of producing and utilizing electricity." The 1880s were a period of rapid change in electrical technology, and 1884 was a particularly good time for the formation of the new society, for in that year Americans were being called upon to display to all the world the great contributions they were making to the most exciting technology of the age.

International exhibitions were the 19th century's most spectacular means for showing off the achievements of a rapidly expanding industrial civilization. Besides large general exhibitions, such as London's Crystal Palace of 1851 or Philadelphia's Centennial of 1876, more specialized shows were popular means for spreading the word of the progress of fast-changing fields—most significantly, electricity. Paris in 1881, London in 1882, and Vienna in 1883 were sites of international electrical exhibitions. Now, in 1884, the Americans felt it was their turn, and they intended to make the most of it.

Philadelphia's Franklin Institute was typically the organizer of such American efforts, so its key role in organizing and hosting the International Electrical Exhibition of 1884 seemed quite natural. In addition to the displays of 196 commercial exhibitors, the formation of a special library of electricity and magnetism, and a historical exhibit that included the first Morse telegraph instrument and devices that had been used by Benjamin Franklin, the Exhibition events included the convening of a "National Conference of Electricians," authorized and funded to the amount of $7,500 by the federal government, and the annual meeting of the American Association for the Advancement of Science. Though high import tariffs on foreign electrical products discouraged European exhibitors, an international flavor was still present. Invitations were sent to members of the British Association to come to Philadelphia following their own meeting in Montreal, and William Thomson, the eminent British physicist and electrical engineer, was selected as vice-president of the Electrical Commission arranging the National Conference.

Both the Commission and the Conference were, however, made up not of electrical engineers but of physicists. Before 1884, only the academic physicists in America had the public recognition and authority to speak about and for the new electrical technology. It was this state of affairs that motivated a New York-based group of practical electrical engineers to call, in April 1884, for a "national electrical society" to receive the foreign "electrical savants, engineers and manufacturers" who were expected in Philadelphia. The American Institute of Electrical Engineers was formally established on May 13, 1884, and scheduled its first technical meeting for October 7 and 8 at the Electrical Exhibition. The engineers' efforts to organize themselves were an unqualified success. It was they who went on to become the creators and spokesmen of the new technology.



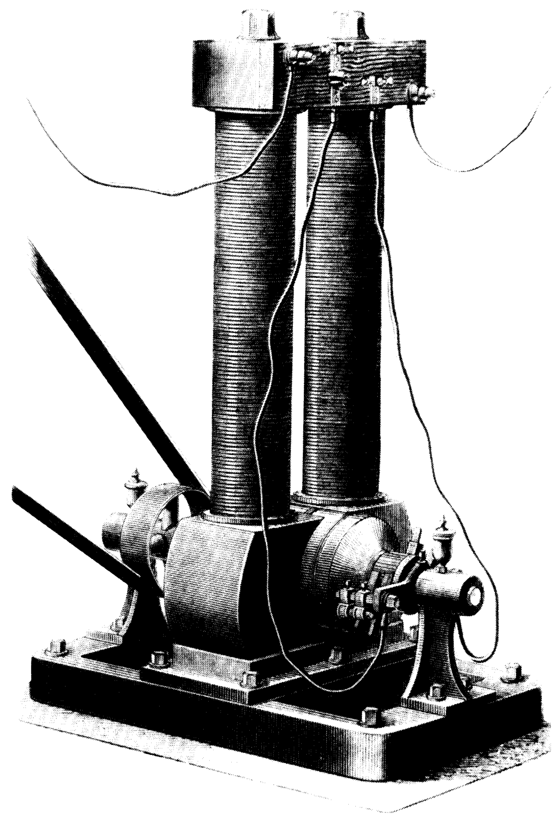
Nathaniel Shepard Keith, author of the "call" to organize the AIEE

International Electrical Exhibition Poster Franklin Institute

Electricity in the 1880s

New electrical technologies were springing up in the 1880s, making changes in life everywhere.

Electricity began to be used for communication, light, power, and transportation.

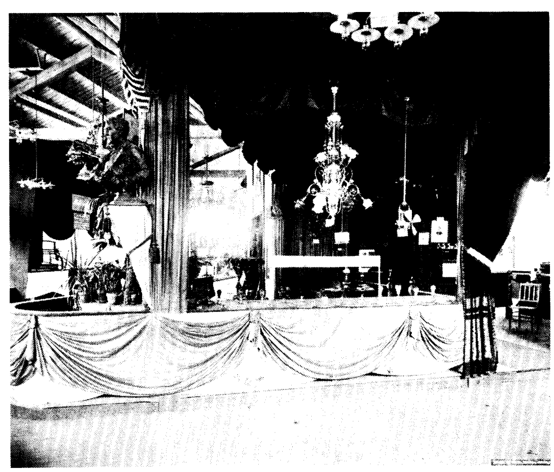


The dynamo invented by Edison in 1879, nicknamed the "long-legged Mary Ann," minimized internal resistance to increase efficiency to more than 80%—30% higher than other dynamos of the day. The "Mary Ann" was an important part of the light and power system Edison was developing. Edison National Historic Site

The organization of the electrical engineering profession in America in the 1880s was no coincidence. It was in that decade that electrical technology finally emerged from the confines of specialized applications that had little direct impact on most people, to be seen as a force for change everywhere. This was especially apparent at the Phildelphia exhibition that gave impetus to the IEEE's birth in 1884.

For nearly a half century, the application of electricity meant telegraphy. It is easy now to forget what a wonderful thing the telegraph was to people in the 19th century, so crude and simple does it seem next to the electrical and electronic marvels of a later day. One must think back to what it meant to introduce instantaneous communication between distant points into a society that had never known anything like it. Although commonplace by the 1880s, the telegraph had not yet lost its fascination and was the only electrical technology known or understood by many in Philadelphia.

The real excitement, however, came from new electrical inventions, some of which had begun their rapid spread across the land into households, shops, factories, and everywhere else that people sought the increased comforts and productivity promised by the most modern technology. The electric light was, of course, the most visible of these. The arc light, with its glaring, unsurpassed brightness, had been available for about a decade, but was in fact still only beginning its spread into use in public places, such as streets, squares, large stores, and theaters. The incandescent lamp, characterized by its soft, yellow glow that seemed so superior to gas, was less than 5 years old, although the efforts of Thomas Edison and a half-dozen rivals were pressing the new light, and the central power system that made it work, into service everywhere.



Edison National Historic Site

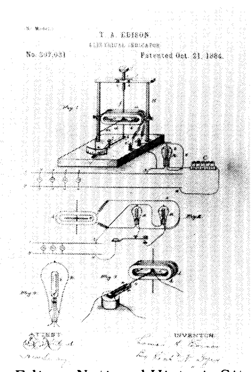
Edison exhibit, Philadelphia, 1884

Edison National Historic Site

Sigmund Bergmann & Co. exhibit, Philadelphia, 1884

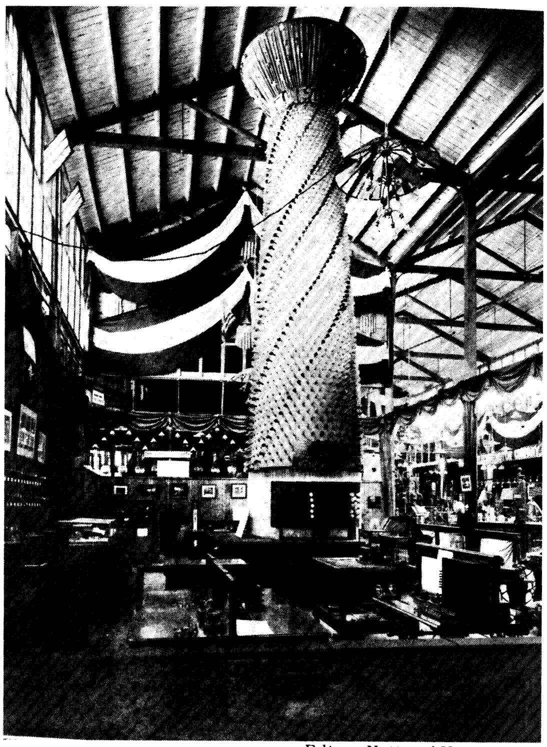
Hard on the heels of the electric light were the attempts of inventors and entrepreneurs to find other applications for the central electrical system. Already, small devices such as sewing machines, pumps, and hoists had been successfully linked with electric motors to make work safer, more convenient, and more productive. A multitude of similar applications seemed just around the corner, and Philadelphia provided a wonderful opportunity for showing them off. And on the horizon, a number of inventors showed, were even greater marvels, such as the application of electric power to the always difficult problem of urban transport.

The present seemed wonderful to engineer and citizen alike during those bright autumn days in Philadelphia, and the future was so full of possibilities that it was hard even to conceive what they might be. It would have taken foresight indeed for anyone to recognize the significance of one odd little item displayed in a corner of the hall's largest single exhibit, that belonging to Thomas Edison. There, labeled simply as "apparatus showing conductivity of continuous currents through high vacuo," was Edison's "Tri-Polar Incandescent Lamp," showing off the "Edison Effect"—the harbinger of electronics.



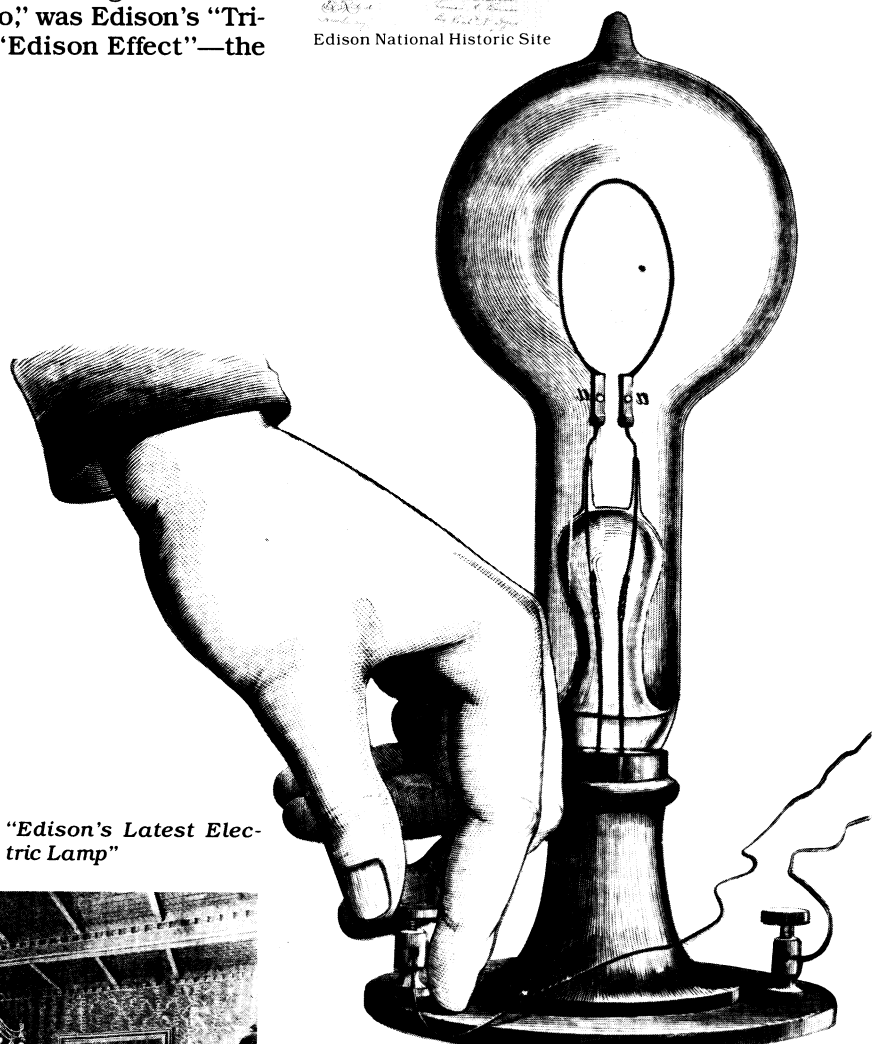
Edison National Historic Site

By showing that a current could flow through a vacuum, the "Edison Effect" laid the groundwork for vacuum tubes and the field of electronics



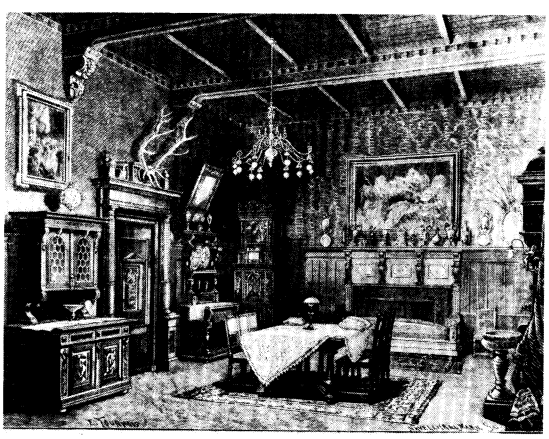
Edison National Historic Site

Edison exhibit, Philadelphia 1884



Scientific American

"Edison's Latest Electric Lamp"



Smithsonian Institution

"A Dining Room Lighted by Incandescent Lamps"

The Telegraphers

Telegraphers provided the foundation for the new profession of electrical engineering.

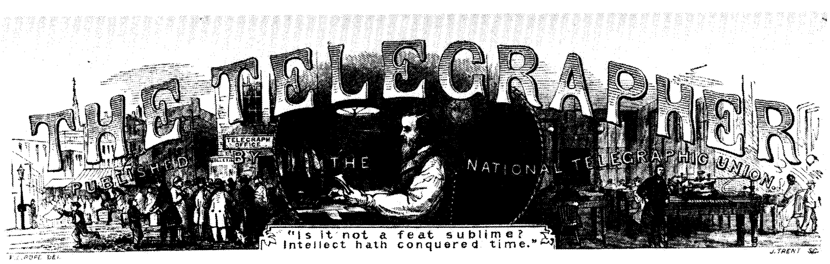
Most electrical engineers got their start like Thomas Edison, working with the telegraph.

The organizers of the AIEE appealed to a broad audience when they issued their call for the new society in the spring of 1884: "Persons who are interested in our electrical, scientific, educational, manufacturing, telegraphic, telephonic, and like concerns as well as the users of electrical appliances generally, will find it to their advantage, personally and collectively, to establish, work for, and generally aid our proposed society."

"It is proposed," the call went on to say, "to make electrical engineers, electricians, instructors in schools and colleges, inventors and manufacturers of electrical apparatus, officers of telegraph, telephone, electric light, burglar alarm, district messenger, electric time, and of all companies based upon electrical inventions as well as all who are inclined to support the organization for the common interest, eligible to membership."

For the most part, in the 1880s, this meant telegraphers and those associated with them. The telegraph was the primary manifestation of electrical technology in the 19th century, and even those whose activities had spread further afield, such as Thomas Edison, had usually gotten their start at the telegraph key.

The telegraphers were prominent in the list of founding members of the AIEE, and the new organization paid further homage to the industry when it elected Norvin Green, head of the Western Union Telegraph Company, its first president.



George Anson Hamilton (1843-1935)

Telegraphy captivated George Hamilton's interest while he was still a boy—to the extent that he built a small telegraph line himself, from sinking the poles to making the necessary apparatus. By the time he was 17, he was the manager of the telegraph office of the Atlantic & Great Western Railroad at Ravenna, Ohio. Hamilton continued to hold managerial positions with telegraph companies until 1873 when he became an assistant to Moses G. Farmer in his work on general electrical apparatus and machinery.

In 1875, Hamilton joined Western Union as assistant electrician and, for the next two years, worked with Gerritt Smith in establishing and maintaining the first quadruplex telegraph circuits in both America and England. He then focused on the development of the Wheatstone high-speed automatic system and was also the chief electrician on the Key West-Havana cable repair expedition. Hamilton left Western Union in 1889, however, to join Western Electric, where he was placed in charge of the production of fine electrical instruments until the time of his retirement.

Telegraph wires in Cincinnati

Smithsonian Institution

Norvin Green (1818-1893)

Norvin Green followed a rather circuitous route to the field of electrical engineering. By the time he was 32, Green had run a floating grocery store on a flatboat up and down the Ohio and Mississippi rivers, worked as a woodcutter, trained as a physician, and been elected to the Kentucky House of Representatives.

In 1853, however, Green abandoned both medicine and politics, and entered the telegraph business. After a period of mutually destructive competition, the two rival telegraph lines between Louisville and New Orleans were consolidated and leased to several men, one of whom was Green. These lines were reorganized as the Southwestern Telegraph Co., with Green as president, and the company began to prosper. Green, however, envisioned a national network of telegraph lines and, pursuant to this idea, instigated the consolidation of six major lines, forming the North American Telegraph Co. in 1857. In 1866, a national consolidation was realized with the founding of Western Union. Green was vice-president of the company until 1878, then president until his death.

Franklin Leonard Pope (1840-1895)

When the American Telegraph Company constructed a line between Pittsfield and Franklin Pope's hometown of Great Barrington, Massachusetts, the 17 year old Pope was chosen by the company to become the town's operator. From this beginning, he went on to be actively involved in several aspects of the telegraph business. During his career, Pope was a circuit manager of the Boston & Albany Railroad telegraph lines; an assistant to the engineer-in-chief of the Russo-American Telegraph Company, exploring the route for a telegraph line between the United States and Europe through the Bering Strait; an editor for various electrical journals; an inventor of telegraph apparatus; a patent expert and solicitor; and a prolific writer.

Ironically, the force to which Pope had dedicated his life was responsible for his death. The Great Barrington Electric Light Company hired Pope as a consulting engineer for its project to convert from a steam to a hydroelectric power plant. Pope had the transformers for this endeavor placed in his basement and, while examining one of them, he was accidentally electrocuted.

Edison National Historic Site

Makers of a New Age—Light & Power

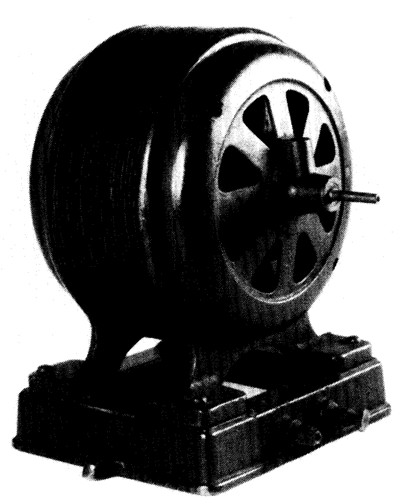
Electric light and power promised in the 1880s to expand the impact and the opportunities of the electrical engineers.

New technologies required new knowledge, skills, and training.

Like today, a century ago electrical engineering was an exciting and rapidly changing technology. Telegraphy had already shown how important electrical technology could be to society and had attracted many an ambitious young man to the ranks of operators and electricians. It was the newer technologies of light and power, however, that suggested the extent of possibilities for the future. These new technologies required new knowledge and new skills, and from these needs emerged the modern electrical engineer.

The telegraphers who were so prominent in the establishment of the electrical engineering profession were largely practical men, whose training had been at the telegraph key, the workbench, and the lines and cables that criss-crossed the country and the seas. Their schooling, where it existed, was often in a field far removed from their profession. This was not to be adequate for the advancement of the newer applications of electricity. The construction of dynamos, the design of central power stations and distribution systems, the making of light bulbs, motors, and a host of auxiliary devices all required a deeper understanding of engineering fundamentals and of electricity itself. The new leaders of the electrical engineering profession would be men whose practical experience was augmented by theoretical training and a concern for establishing the basic principles of their field.

Tesla's induction motor



Smithsonian Institution

Smithsonian Institution

Nikola Tesla (1856-1943)

Nikola Tesla was born of Serbian parents in the village of Smiljan, in what is now Yugoslavia. He showed his technical brilliance early, but felt that his native country offered him only limited opportunities, so in 1884 he emigrated to the United States and began working for Thomas Edison. He soon struck out on his own, however, for Edison had little use for Tesla's bold new ideas—in particular, his brilliant solution to the problems of applying alternating current in light and power systems. Tesla's polyphase ac system was brought to market by George Westinghouse, and after an acrimonious struggle with the Edison interests, who were wedded to the use of direct current (dc), the Tesla system became the standard in the twentieth century. Tesla's other inventions included the synchronous ac motor, devices for generating high voltage and high frequency currents, and contributions to radio technology. Tesla received the Edison Medal of the American Institute of Electrical Engineers in 1916.

Sprague's successful construction of a streetcar system for Richmond, Virginia, in 1888 was the beginning of the great electric railway boom. In less than 15 years, more than 20,000 miles (32,000 km) of electric street railway were built.

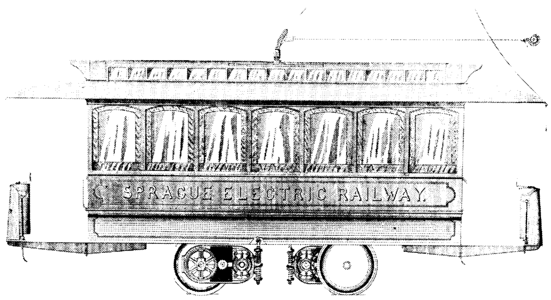
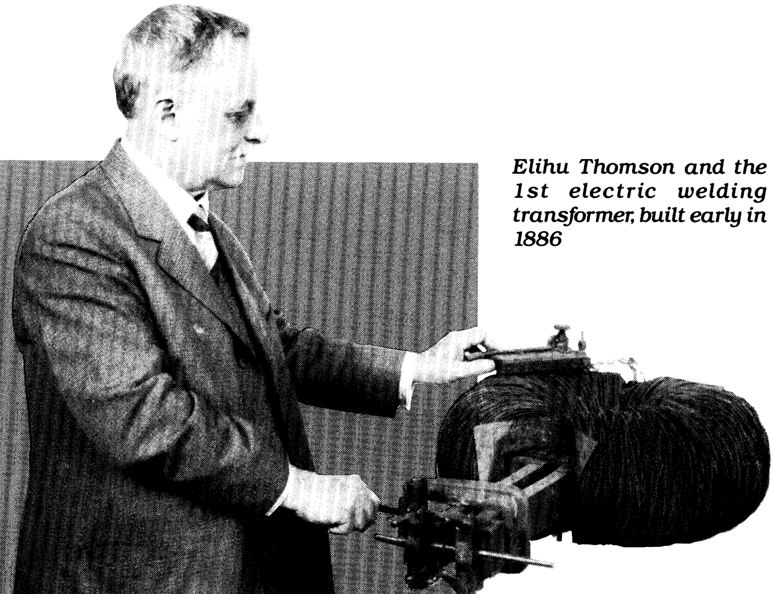


FIG. 2.—NEW SPRAGUE ELECTRIC STREET CAR—SIDE ELEVATION. Smithsonian Institution

Frank Julian Sprague (1857-1934)

Frank Sprague was a true entrepreneur in the new field of electrical technology. After a brief stint on Thomas Edison's staff, Sprague struck out on his own, founding the Sprague Electric Railway and Motor Company in 1884. In 1887, Sprague equipped the first modern trolley railway in the United States, at Richmond, Virginia, and followed this with more than 100 other such systems, both in America and Europe, during the next two years. In addition to his work in railroads, Sprague's diverse talents led to his development of electric elevators, an ac induction smelting furnace, miniature electric power units for use in small appliances, and, as a member of the U.S. Naval Consulting Board during World War I, fuses and air and depth bombs. Sprague was awarded the AIEE's Edison Medal in 1910.

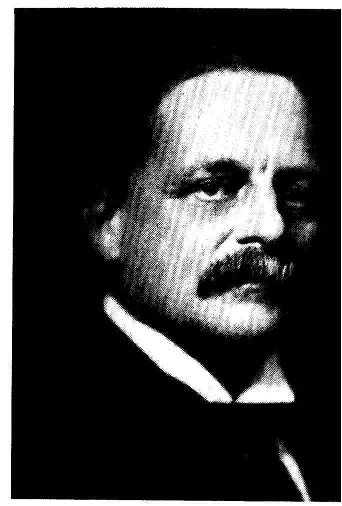


Elihu Thomson and the 1st electric welding transformer, built early in 1886

Elihu Thomson (1853-1937)

The first decade of Thomson's professional career was spent as a teacher at Philadelphia's Central High School. He resigned in 1880, however, to join the American Electric Co., where he turned his full attention to work on applications of electricity, beginning by developing a commercial arc lighting system. Edwin J. Houston, Thomson's colleague at Central High, had also left the school to work for American Electric and the two men obtained control of the firm in 1883, after it had moved to Lynn, Massachusetts, renaming it the Thomson-Houston Electric Co. With Thomson as "electrician and chief engineer," the company came to dominate the arc lighting industry. In 1892, it merged with the Edison General Electric Co. to form the General Electric Co. Thomson maintained his connection with GE for the rest of his life, putting his talents into research and development, rather than administration, as chief engineer and director of the GE Thomson Research Laboratory in Lynn.

Thomson possessed an exceptionally inquisitive and creative mind. He held nearly 700 patents, many of them for fundamental inventions, including electric welding, meters, dynamos, lightning arresters, motors and x-ray devices. His interest in astronomy also led him to develop the fused quartz mirror for telescopes.



Elihu Thomson

Engineering on Display: Chicago and Niagara Falls

In the 1890s, the electrical engineers showed off their new accomplishments and capabilities.

The World's Fair at Chicago and the giant power plant at Niagara Falls displayed what engineers could do.

As the complexity and scale of the new electrical technology continued their accelerating growth at the close of the 19th century, so did electricity's visibility and impact. Nowhere was this more evident than at the two great, though very different, showplaces of American engineering in the 1890s—Chicago and Niagara.

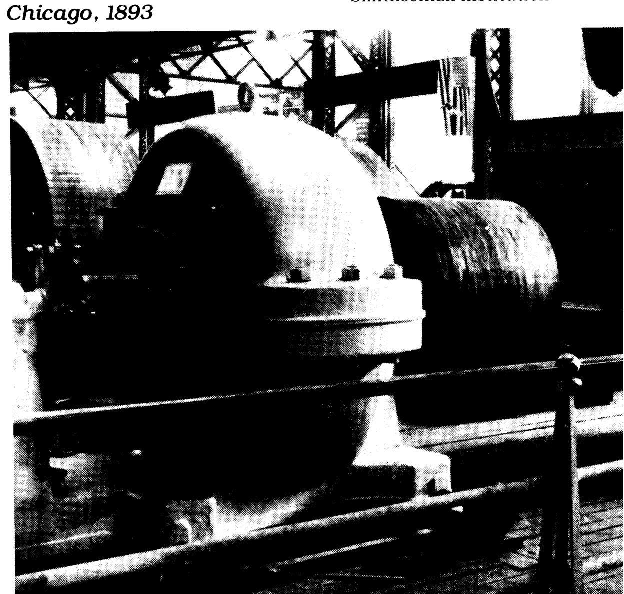
The World's Columbian Exposition at Chicago and the power station constructed at Niagara Falls, New York, were the great stages for displaying how far the electrical engineering profession had come in one short decade. On these stages were acted out not only the triumphs of electrical technology but also the controversies and struggles that accompanied explosive growth.

So grand was the World's Fair that opened in Chicago to celebrate the 400th anniversary of Columbus's discovery of America that no one minded that it was a year late. It was the first fair where electricity was given its own building, but the impact of the new technology was in fact spread throughout the "White City" that rose on the shores of Lake Michigan. The lighting, in particular, made an enormous impression on the millions of visitors who poured in from across America and around the world. The 8,000 arc lights and 130,000 incandescent lamps that the Westinghouse Company installed throughout the grounds represented a technical triumph for a manufacturer whom many still considered an upstart in the electric light and power industry. More important than the size of the effort, however, was that it demonstrated the practicality of alternating current systems, which thereafter rapidly eclipsed the direct current technology of Edison and others.

Just as in Philadelphia in 1884, the Chicago exhibition was seen as a good setting for an electrical conference. The resulting Chicago International Electrical Congress was testimony to the growing prestige of American electrical engineering, for this was a truly international meeting that made great strides in establishing the world's standards for fundamental electrical units. Particularly gratifying to the Americans was the adoption of the "henry" as the international unit of inductance—a proposal that had been advanced by the AIEE to honor one of the founders of electrical science in America.

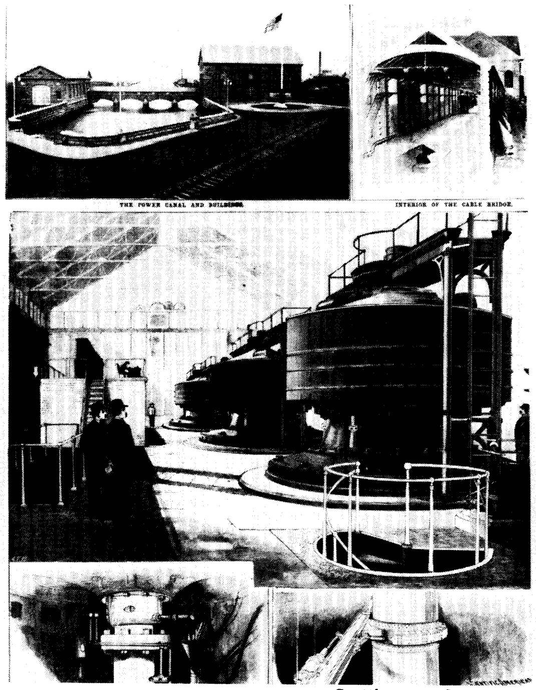
Smithsonian Institution

Chicago, 1893

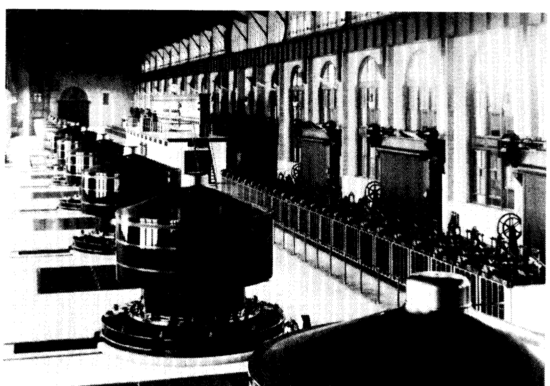


Chicago, 1893

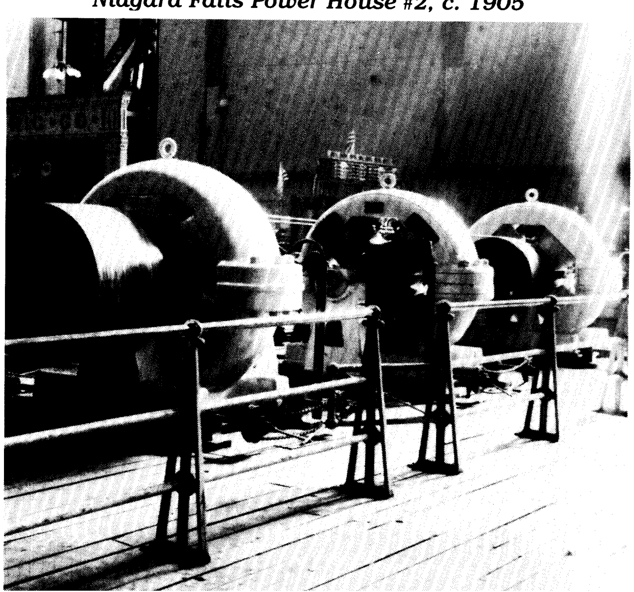
Smithsonian Institution



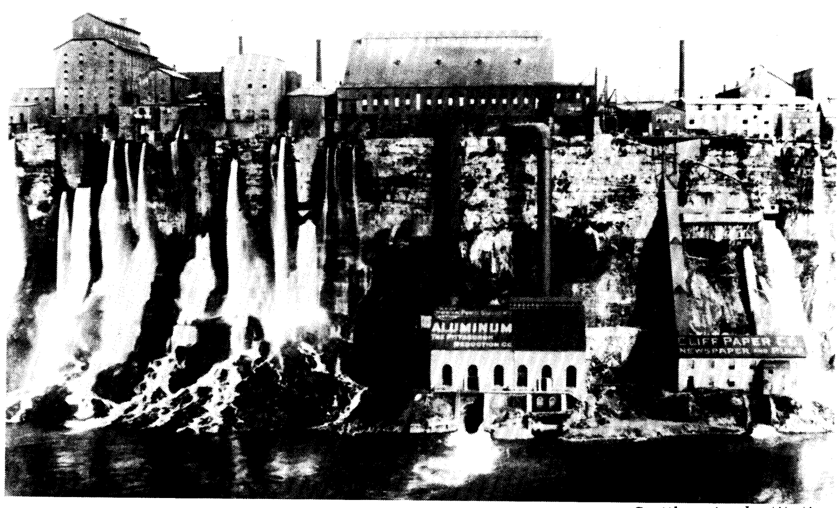
"*The Niagara Falls Power Plant*" Smithsonian Institution



Smithsonian Institution
Niagara Falls Power House #2, c. 1905



Niagara Falls represented a showplace of a very different sort. Here electrical engineers were confronted with one of the great technical challenges of the age—how to harness the enormous power latent in Niagara's thundering waters and make it available for useful work. Years of study and heated debate preceded the start-up of the first Niagara Falls Power Station in the summer of 1895, as engineers and financiers argued about whether electricity could be relied on to transmit large amounts of power the 20 miles to Buffalo and, if so, whether it should be direct or alternating current. The success of the giant polyphase alternating current generators made clear the directions that electric power technology would take in the new century, and the attraction of novel industries that consumed great amounts of electricity, such as aluminum and other electrochemical manufacturers, showed the vast potential for growth and change that electricity held for the future.



Smithsonian Institution

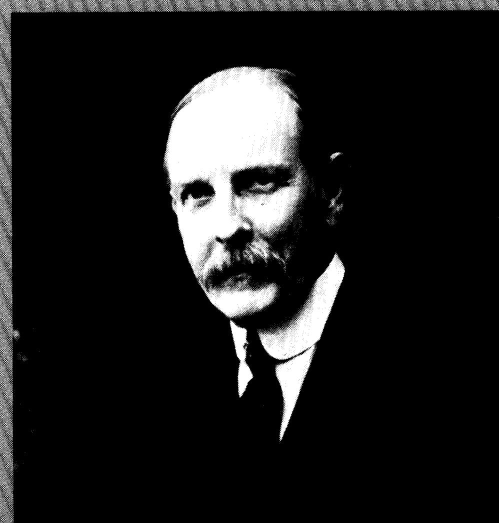
The discovery of how to use electricity to make aluminum in 1886 gave Niagara Falls its first major consumer of power—the Pittsburgh Reduction Company, now known as the Aluminum Company of America (ALCOA)

New Concerns for a New Profession

The pioneering field of electrical engineering raised questions which only the engineers could answer.

Safety, technical standardization, and professional ethics were issues of great importance.

The men who set out to establish electrical engineering as a respected profession were aware that their field posed special opportunities and problems. The new technologies of which they were masters presented technical challenges that needed to be addressed by the profession lest progress be stymied by narrow commercial interests. Many engineers also recognized that public concern about the use and safety of electrical technology reflected on their profession and themselves. Finally, there were those who felt that the social responsibilities of a true profession went beyond purely technical issues to include ethical and political concerns as well. There could be seen in these first decades, therefore, the same variety of issues and viewpoints that would characterize the electrical engineering community for the next century.



Arthur E. Kennelly (1861-1939)

The AIEE appointed its first standing committee on units and standards in 1891, with Arthur Kennelly as chairman. This marked the beginning of his lifelong activity in the area of standardization, which included working with such bodies as the American Standards Association, the National Bureau of Standards, and the International Electrotechnical Commission. Kennelly served as president of both the AIEE (1898-1900) and of the IRE (1916) and received the Edison Medal in 1933 "for meritorious achievements in electrical science, electrical engineering, and the electrical arts as exemplified by his contributions to the theory of electrical transmission and to the development of international electrical standards."

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

HAVEMEYER BUILDING, 26 CORTLANDT STREET. — NEW YORK, N. Y. JUNE, 1899.

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REPORT OF THE COMMITTEE ON STANDARDIZATION.

[Accepted by the INSTITUTE, June 26th, 1899.]

To The Council of The AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

Gentlemen:

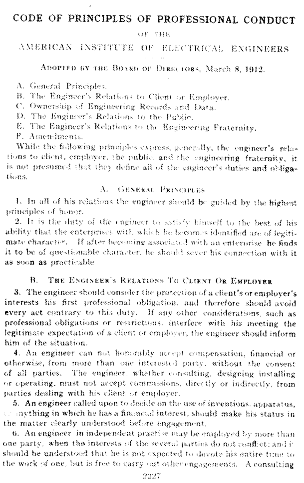
Your committee on Standardization begs to submit the following report, covering such subjects as have been deemed of pressing and immediate importance, and which are of such a nature that general agreement may be expected upon them.

While it is the opinion of the committee that many other matters might advantageously have been considered, as, for example, standard methods of testing; yet it has been deemed inexpedient to attempt to cover in a single report more than is here submitted.

Yours respectfully,

FRANCIS B. CROCKER, *Chairman.*
CARY T. HUTCHINSON.
A. E. KENNELLY.
J. W. LIEB, JR.
CHARLES P. STEINMETZ.
LEWIS B. STILLWELL.
ELIHU THOMSON.

By the time the American electrical engineers took up the problem, the resolution of technical standards and terminology was a widely recognized responsibility of an organized engineering profession. The AIEE's first serious effort in this regard was the appointment of a committee on "units and standards" in June, 1891. Soon afterwards, another committee was formed to make recommendations for a "standard wiring table" to guide engineers in specifying wiring requirements. The overwhelming importance of standardization quickly became apparent in the growing electrical industry, where the intensity of competition led to confusion and conflict in technical specifications, test standards, and even terminology. The engineers recognized an opportunity to rise above commercial considerations by establishing themselves as the authorities for standardization. The AIEE appointed its permanent Committee on Standardization in March, 1898, and from that time, in conjunction with other engineering societies and international groups, the engineers have set the standards for electrical technology and practice.


CODE OF PRINCIPLES OF PROFESSIONAL CONDUCT

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

ADOPTED BY THE BOARD OF DIRECTORS, March 8, 1912.

A. General Principles.
B. The Engineer's Relations to Client or Employer.
C. Ownership of Engineering Records and Data.
D. The Engineer's Relations to the Public.
E. The Engineer's Relations to the Engineering Fraternity.
F. Amendments.

While the following principles express, generally, the engineer's relations to client, employer, the public and the engineering fraternity, it is not presumed that they define all of the engineer's duties and obligations.

A. GENERAL PRINCIPLES

1. In all of his relations the engineer should be guided by the highest principles of honor.

2. It is the duty of the engineer to satisfy himself to the best of his ability that the enterprises with which he becomes identified are of legitimate character. If after becoming associated with an enterprise he finds it to be of questionable character, he should sever his connection with it as soon as practicable

B. THE ENGINEER'S RELATIONS TO CLIENT OR EMPLOYER

3. The engineer should consider the protection of a client's or employer's interests his first professional obligation, and therefore should avoid every act contrary to this duty. If any other considerations, such as professional obligations or restrictions, interfere with his meeting the legitimate expectation of a client or employer, the engineer should inform him of the situation.

4. An engineer can not honorably accept compensation, financial or otherwise, from more than one interested party, without the consent of all parties. The engineer, whether consulting, designing installing or operating, must not accept commissions, directly or indirectly, from parties dealing with his client or employer.

5. An engineer called upon to decide on the use of inventions, apparatus, or anything in which he has a financial interest, should make his status in the matter clearly understood before engagement.

6. An engineer in independent practice may be employed by more than one party, when the interests of the several parties do not conflict; and it should be understood that he is not expected to devote his entire time to the work of one, but is free to carry out other engagements. A consulting

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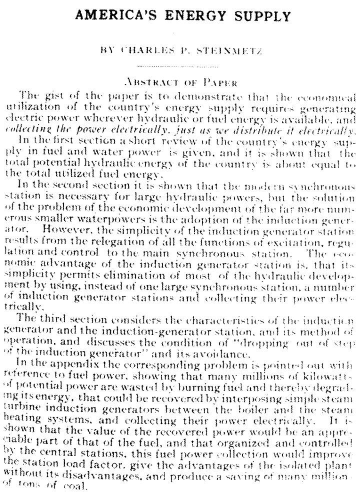

AMERICA'S ENERGY SUPPLY

BY CHARLES P. STEINMETZ

ABSTRACT OF PAPER

The gist of the paper is to demonstrate that the economical utilization of the country's energy supply requires generating electric power wherever hydraulic or fuel energy is available, and *collecting the power electrically, just as we distribute it electrically.*

In the first section a short review of the country's energy supply in fuel and water power is given, and it is shown that the total potential hydraulic energy of the country is about equal to the total utilized fuel energy.

In the second section it is shown that the modern synchronous station is necessary for large hydraulic powers, but the solution of the problem of the economic development of the far more numerous smaller waterpowers is the adoption of the induction generator. However, the simplicity of the induction generator station results from the relegation of all the functions of excitation, regulation and control to the main synchronous station. The economic advantage of the induction generator station is, that its simplicity permits elimination of most of the hydraulic development by using, instead of one large synchronous station, a number of induction generator stations and collecting their power electrically.

The third section considers the characteristics of the induction generator and the induction-generator station, and its method of operation, and discusses the condition of "dropping out of step of the induction generator" and its avoidance.

In the appendix the corresponding problem is pointed out with reference to fuel power, showing that many millions of kilowatts of potential power are wasted by burning fuel and thereby degrading its energy, that could be recovered by interposing simple steam turbine induction generators between the boiler and the steam heating systems, and collecting their power electrically. It is shown that the value of the recovered power would be an appreciable part of that of the fuel, and that organized and controlled by the central stations, this fuel power collection would improve the station load factor, give the advantages of the isolated plant without its disadvantages, and produce a saving of many million of tons of coal.

1st AIEE Code of Ethics, 1912

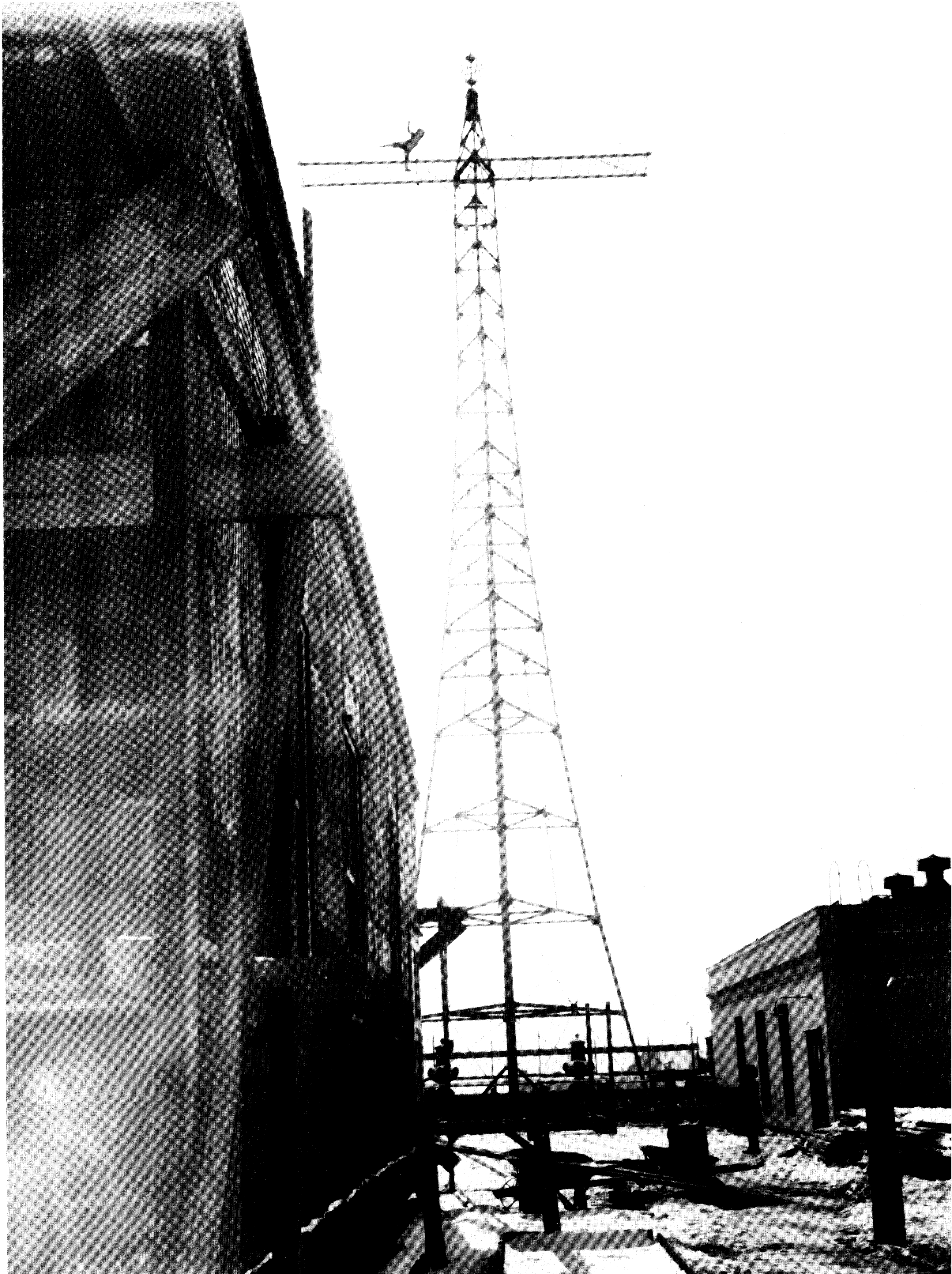
The extent to which the responsibilities of engineers, either as individuals or as organized professionals, extend beyond purely technical concerns was a matter for debate from the earliest years of the AIEE. The conflicts that arise due to the engineer's position as both a professional and, frequently, an employee have always been a source of concern, perhaps best illustrated by the experience of Charles Steinmetz.

Not only was Steinmetz a brilliant engineer, the creator of many of the most important analytical methods for designing and describing electric power devices and systems, but he was also a man deeply concerned about the proper role of the professional engineer in society. As an employee of a very large company (General Electric), Steinmetz was well aware of the problems that the corporate engineer experienced in defining his loyalties and responsibilities. In 1907, conflict over these problems prevented the AIEE from adopting a Code of Ethics for its members. When, five years later, the Institute resolved to try again to develop an acceptable Code, Steinmetz's was an influential voice, speaking out for the engineer's obligation to commit himself to the best possible technical practice while at the same time recognizing that his ultimate loyalty was to his client or employer. Above all, Steinmetz spoke out for his belief that engineers "must be more than mere engineering machines," a belief that still motivates many of the creators of modern electrical technology.

Charles Proteus Steinmetz (1865-1923)

Charles Steinmetz (1865-1923) came to the United States in 1889 from Breslau, Germany, where he was a student at the University of Breslau. He joined the inventor Rudolf Eickemeyer in building electric apparatus at Yonkers, New York, and, at the age of 27, formulated the law of hysteresis, which made it possible to reduce the loss of efficiency in electrical apparatus. When Eickemeyer's firm was bought by General Electric, Steinmetz joined the new company, beginning a 31-year relationship that ended only with his death.

His improvements in methods of making calculations of current in alternating current circuits revolutionized power engineering, and his theory of electrical transients stood as another important contribution. In the midst of his GE career, Steinmetz was also a professor at Union College and a vocal champion of civic and political causes.



The Ether in Harness

Radio was the most exciting and novel electrical technology at the beginning of the 20th century.

The pioneers of radio—men like Hertz, Lodge, and Marconi—laid the foundation for electronics.

The dawn of the present century saw the birth of several technologies that were to be revolutionary in their impact. The most exciting of these was radio, or, as it was generally called at the time, "wireless." No other technology would seem to so thoroughly obliterate the barriers of distance in human communication or to bring individuals together with such immediacy and spontaneity. And seldom had there emerged an activity that seemed so mysterious and almost magical to most of the population—setting apart its practitioners as a special and privileged breed.

Radio was mysterious not only to the layman, but also to many engineers and technically informed individuals. The mystery lay largely in radio's application of principles and phenomena only recently identified by physicists and engineers working at the frontiers of their specialties. The existence of electromagnetic waves that traveled like light had been predicted by the brilliant physicist James Clerk Maxwell in the 1860s and proven by the young German Heinrich Hertz in the 1880s. The possible use of these waves for communicating through space without wires occurred to many. The first practical steps to making radio useful are generally attributed to Oliver Lodge in England, Guglielmo Marconi in Italy, and Aleksandr Popov in Russia. Marconi's broadcast of Morse code across the Atlantic in 1901 first showed to the world just what enormous potential radio had for changing the whole concept of long-distance communication. The next few years saw feverish activity everywhere as men tried to translate the achievements of the pioneers into the foundations of a practical technology.

By 1912, radio technology had attracted a small number of dedicated individuals who identified their own future with the progress of their chosen field. Some of these had organized themselves into small, localized societies, but it was clear to many that a broader vision was needed if radio practitioners were to achieve the recognition and respect of technical professionals. It was with such a vision in mind that representatives of two of these local societies met in New York City in May, 1912, to form the Institute of Radio Engineers. The IRE was to be an international society dedicated to the highest professional standards and to the advancement of the theory and practice of radio technology.

The importance of radio, however, lay not simply in its expansion of the means for human communication over distances, but also in its exploitation and expansion of very novel scientific and technical capabilities, for, as the century progressed, radio would give rise to the 20th century's most revolutionary technology of all—electronics.

Smithsonian Institution

E. H. Armstrong atop WJZ transmitter, New York City, 1923
Smithsonian Institution

A Technology for the Young

Young people were particularly attracted to radio in its first decades and made important contributions.

In 1912, a number of these young men founded the Institute of Radio Engineers.

John Stone Stone, founder of the Society of Wireless Telegraph Engineers, co-founder of the IRE

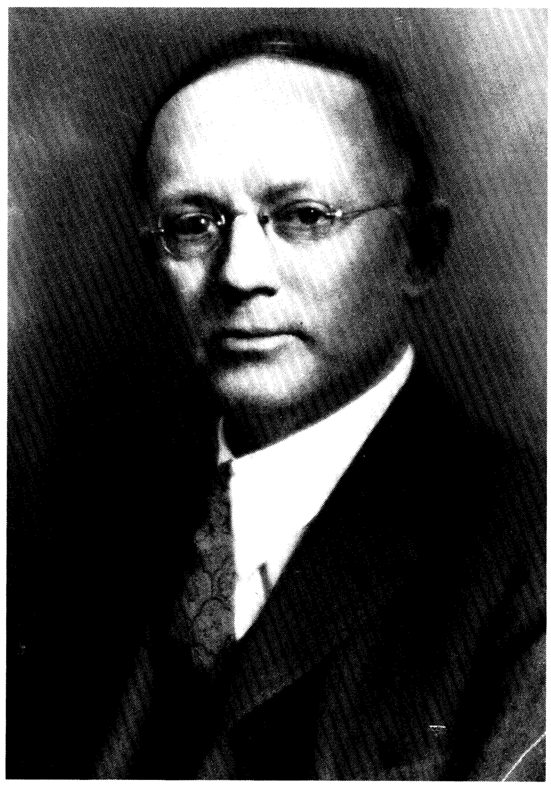
Radio was regarded as a marvelous technology by most people who came in contact with it. In its early years, however, it had a special fascination for the younger generation, those just beginning to make the choices that would determine their careers and the vehicles for their ambition. The extent to which radio was indeed a technology for the young was reflected in the radio clubs that sprang up in cities and towns everywhere, in the popular literature that was published to appeal to young radio buffs, and in the men who gave the impetus to the formation and growth of the Institute of Radio Engineers.

In 1912, the year of the IRE's founding, John V.L. Hogan was only 22 and had already been working with radio inventor Reginald Fessenden for over two years; Alfred Goldsmith was 24 and already had the experience to serve as a radio consultant for the U.S. De-

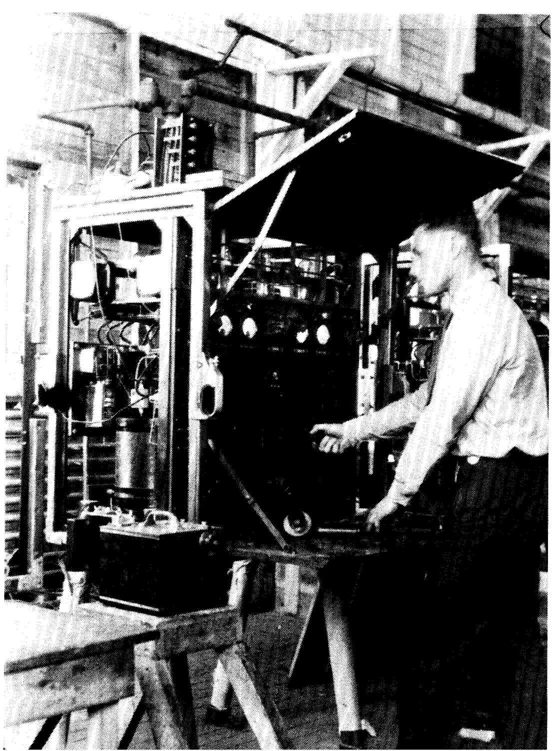
Alfred N. Goldsmith, co-founder of the IRE partment of Justice; Robert Marriott, the IRE's first president, had reached the ripe age of 33, and had more than ten years of radio experience under his belt; and David Sarnoff, just 21, had been working for the American Marconi Company since he had been 15. All of this youth was very much within radio's brief tradition—after all, Marconi himself had been only 21 when he announced to the world in 1895 that he could transmit wireless messages over miles of open country. Not all of the leaders of the radio profession in its early years were quite so youthful; John Stone Stone, one of the key architects of the IRE, was 43 in 1912, and the presidency of the organization was usually given to an older individual in recognition of his age and experience. Nonetheless, the dynamism of the new profession clearly owed much to the youthful ambition of its most active members.

Reginald Fessenden (seated) and co-workers at Brant Rock, MA
Smithsonian Institution

John V.L. Hogan, co-founder of the IRE



Robert H. Marriott, co-founder of the IRE



Edmund Laport, age 21 (1924), working on production model of the BC-127 radio telephone/telegraph transmitter
IEEE, Laport Collection

Radio was a fascinating toy, but few could foresee its impending impact on the world in general.

The sinking of the* Titanic *and the mammoth battles of World War I brought radio to public attention everywhere.

To most people in the early years of the 20th century, radio was a wonderful new invention, but its usefulness and importance for the world of affairs was unclear. At just the time that the radio engineers were organizing themselves, however, there occurred two events that starkly demonstrated just how indispensable the world was to find the new technology. In so doing, they also provided a glimpse at the pivotal role that the new breed of engineers was to play in the turbulent century ahead.

One month before the radio engineers in New York met together to form the IRE, one of history's greatest maritime disasters focused attention on the new capabilities that radio had given the world, both for reporting events as they happened and for affecting them. On the night of April 14, 1912, the White Star liner *Titanic*, with more than 2200 aboard, collided with an iceberg in the North Atlantic and rapidly began to sink. The ship's wireless operator sent out a distress call, which was not received by some nearby ships because their receiving sets were not in operation at the time, but which other ships picked up and relayed to stations on the American mainland. The saving of more than 700 lives was attributed to the work of wireless operators that night. The entire world was caught up in the event by the activity of the mainland operators who passed on the news of both tragedy and survival. Only a few months later, governments everywhere began mandating radio operation aboard ships at sea—radio and its engineers thus became indispensable to world commerce.

THE NAUTICAL GAZETTE

A Journal of Navigation, Shipbuilding, Marine Engineering Naval Architecture and Commerce

Vol. 81. No. 8 Whole No. 2317 — NEW YORK, WEDNESDAY, APRIL 24, 1912. — Ten Cents a Copy $2.00 a Year

Most Direful Disaster of the Deep

Twelve Days from Builders' Yard to the Bottom of the Atlantic, the Great "Titanic" Foundered with Loss of 1,475 Lives

Twelve days from her builders' yard to the bottom of the Atlantic with the greatest loss of life and property on record for a single wreck, was the meteoric career of the great White Star steamship "Titanic," the largest and finest vessel ever constructed. She left Belfast on April 2 and Southampton on April 10. At 10:25 on Sunday night, April 14, she smashed into an iceberg and at 2:20 a. m., on Monday, she went to the bottom, 1,150 miles east of New York, with nearly all her crew and all but 705 of her passengers, a total death list at this writing of 1,475. The survivors were picked up in boats by the Cunard steamer "Carpathia" shortly after the "Titanic" had gone down, and were landed at New York on Thursday night last. The loss in a monetary sense is upwards of $20,000,000, the value of the vessel alone being $7,500,000 without furnishings, cargo, mails and baggage. Among the few men saved was Mr. J. Bruce Ismay, one of the directors of the line. Never before has the civilized world been so stunned by such a wholly unanticipated and stupendous disaster.

AN ICEBERG SEEN IN MID-ATLANTIC LAST JANUARY

* * *

On board the "Titanic" were 3,423 sacks of mail. As the standard ocean mail bag holds about 2,000 letters, it is estimated that in all about 7,000,000 pieces of mail matter have been lost. About 200 bags contained registered matter and these sacks contained on an average about 8,000 letters each. Besides the mails, there were three American postal clerks and two English clerks among the lost.

* * *

It is not likely that the name "Titanic" will ever be used for another ship, but it was of a class of good names, all the same. In Greek mythology Titan was the family name of the twelve children of Uranus and Ge—six sons: Oceanus, Hyperion, Ceus, Kronos, Crius and Japetus, and six daughters: Tethys, Theia, Phoebe, Rhea, Themis and Mnemosyne. Being incited by Ge to rebellion, they overthrew Uranus and established Kronos on the throne, who in turn was dethroned by his son Zeus. Japetus and his children, of giant strength, lawlessness and violence, contended on Mt. Othrys with the gods of Olympus and were finally vanquished and thrust into Tartarus. The Titans are regarded as incarnations of natural forces. Descendants of these children

THE LOST "TITANIC."

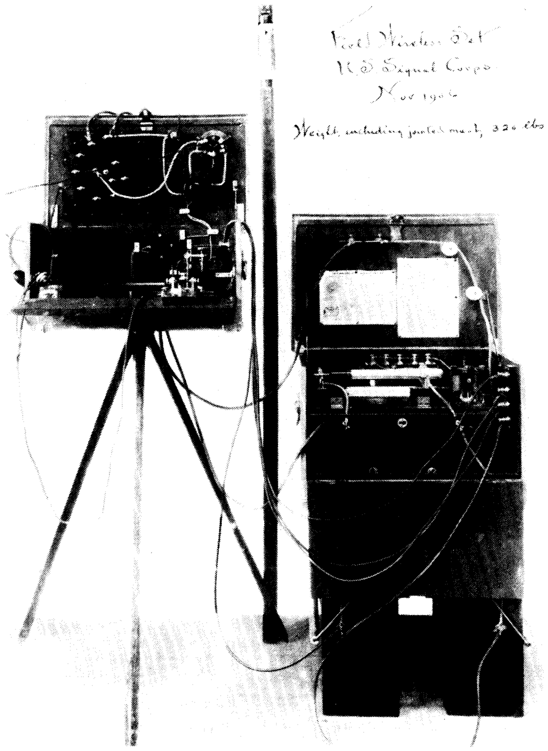
Nautical Gazzette, 1912

Paul D. Andrews operating a Long Wave (VLF) receiver at Otter Cliffs for U.S. Naval Radio Station NBD, ME, 1918

IEEE, Andrews Collection

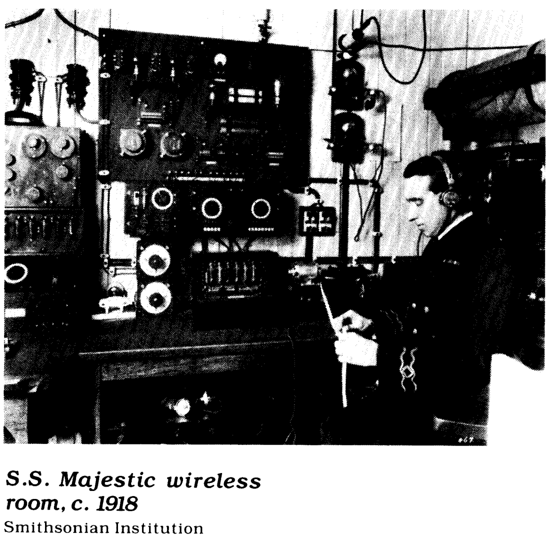
U.S. Signal Corps Field Wireless Set, Nov. 1906

Maj. E. H. Armstrong (rt.), with French and American officials, Paris, 1918

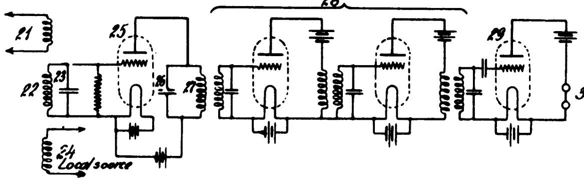


Smithsonian Institution

U.S. Army



S.S. Majestic wireless room, c. 1918
Smithsonian Institution



Armstrong's superheterodyne circuit allowed great and precise amplification of weak signals, making it the basis for most modern radio receivers

If the pursuits of peace were not enough to demonstrate radio's key place in the modern world, then the waging of war would bring the message home with a dreadful finality. When the guns of August began sounding in 1914, the European powers had already begun supplying their armies and navies with the most advanced communications equipment, for the importance of wireless signaling that could be set up instantly anywhere in the field or on the seas was obvious to every strategist. Learning how to use the new tool to best advantage took some time, but the key role to be played by the new devices and the men who made them was recognized early. And when the new radio technology was wedded to the equally new technology of aviation, the whole face of warfare began to change.

The impact of the First World War on radio engineers and engineering was enormous. The needs of war pushed the technology ahead at a pace barely thinkable for peacetime. Radio facilities were placed under direct government control and brilliant young men like Edwin Howard Armstrong were pressed into military service. To develop a radio technology that could be readily used by soldiers and seamen required the rapid advancement of radiotelephony, which began replacing coded wireless everywhere. Such needs generated many technical achievements, of which Armstrong's superheterodyne circuit was perhaps the most brilliant. Just as important, however, was the war's role in exposing much of the population that had been recruited into wartime service to the wonders of radio, thus building the foundations for the boom that was to come. The interaction between military needs and engineering advancement was to be a pattern repeated through the century, with consequences that both the engineers and the public would have to learn to live with.

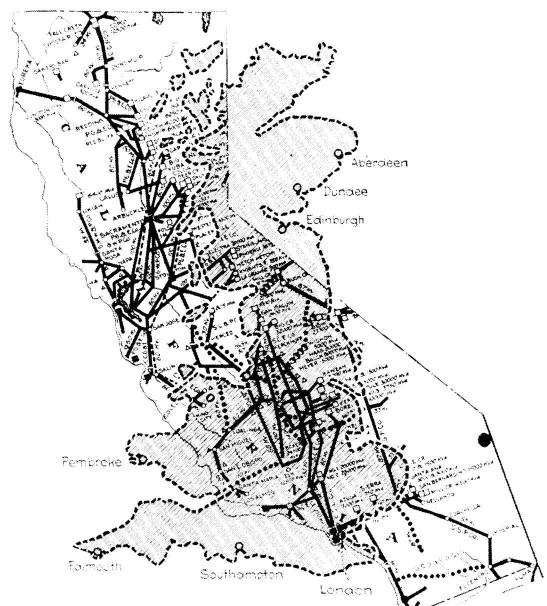
The System Builders

Bringing electric power to everyone was one of the great achievements of electrical engineers in the 20th century.

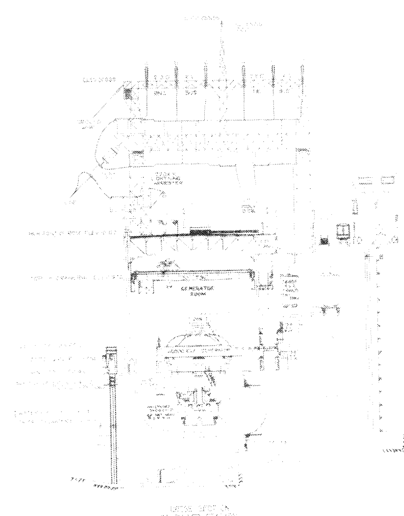
The spread of power required the building of giant systems, such as the Tennessee Valley Authority.

When the 20th century began, electricity was still to most people a very distant and unfamiliar thing, and its applications touched relatively few directly. America, like most of the rest of the world, was largely a country of small towns, villages, and farms, and electric light and power was seldom encountered in such settings. The great work of electrical engineers in the first decades of the century was the bringing of their miracles to the mass of people—to those outside the big cities, to those of average economic and social station. In so doing, the electrical engineers became primary architects of 20th-century life.

In the first decades after 1900, the electric power industry continued its rapid growth. In 1902 the amount of electric power available per person in the United States was about 75 kW; twenty years later this figure was 565 kW per person. The pace of expansion slowed in the 1920s, for the technical challenges of carrying electric power beyond metropolitan areas were complex and expensive. It was no longer possible to sustain growth by simply building on to existing systems—electrical engineers began to think in terms of much larger, extended systems, a concept sometimes referred to as "Super Power." Such systems, which were proposed to bring electricity to large areas, even entire states, raised important social, economic, and political issues as well as technical ones, and the electrical engineers were caught up in the debates over how best to extend access to the new technology to everyone. It became widely recognized, in societies as divergent as the United States and the Soviet Union, that "electrification" was to be the key to national development in the 20th century and that electrical engineering was the profession holding that key.

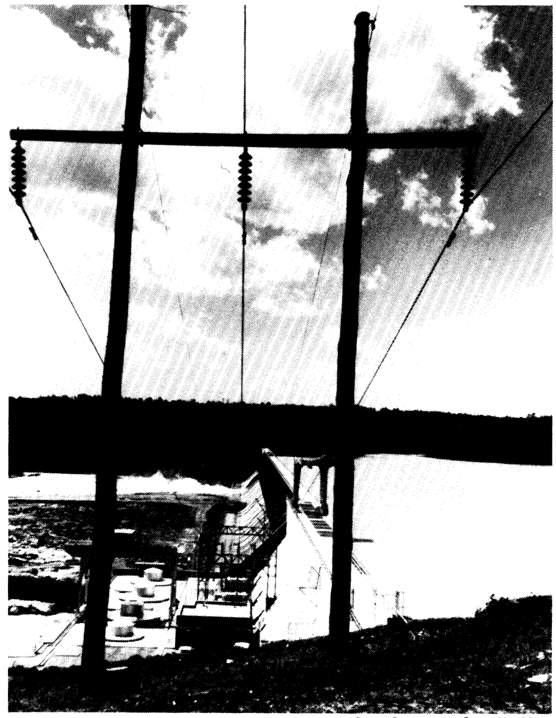


Power distribution in Great Britain & California Electrical World, 1923



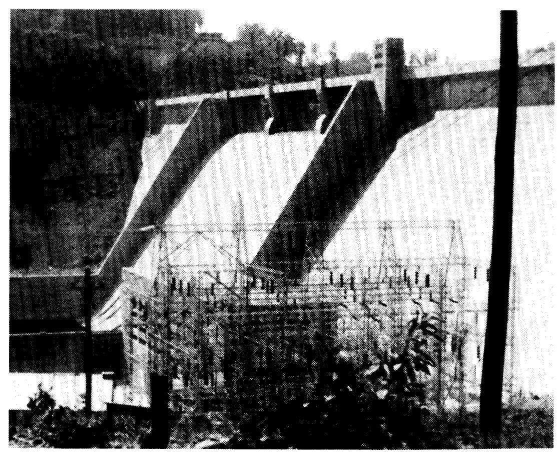
Conowingo Station cross section, 1926

In the 1920s, only a few saw any need to change the way in which electric power was being extended to the people. The Great Depression of the 1930s changed attitudes, however, as politicians and the public sought ways to alleviate the suffering caused in some areas by the economic calamity. The most important single project to result from this was the creation in 1933 of the Tennessee Valley Authority. The TVA was created to administer a multipurpose river project, with responsibility for flood control, fertilizer production, waterway construction, and hydroelectric power generation. It was in the generation and distribution of power that TVA was to make an international reputation for itself, and the electrical engineers who designed and operated TVA's power system became the pioneers of large power systems of the future.



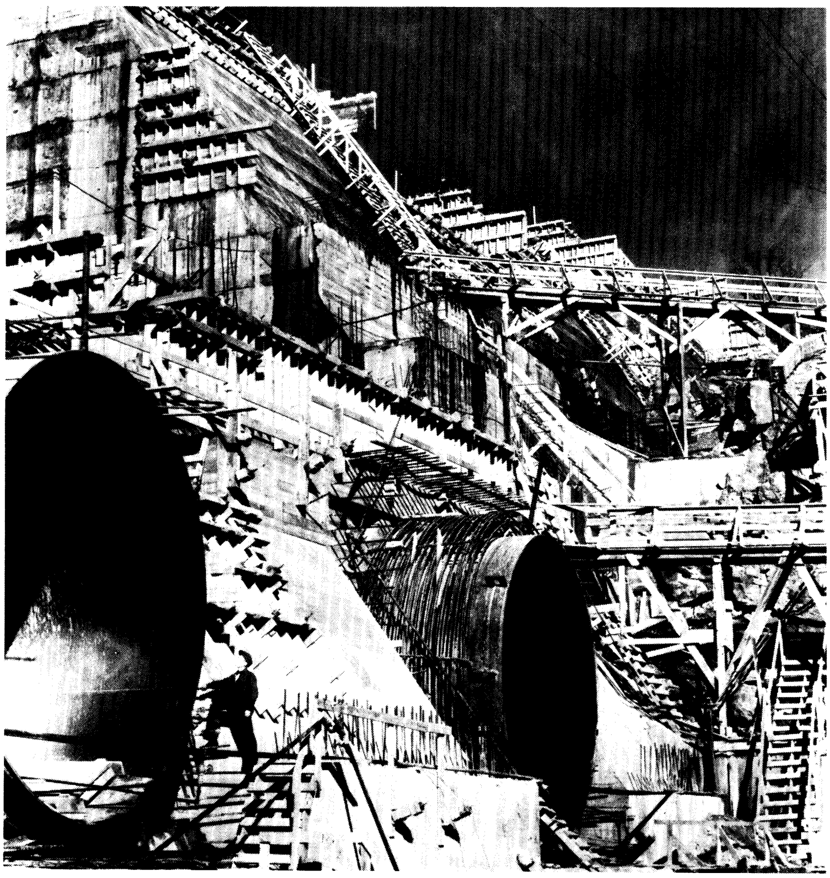
Smithsonian Institution

Chattahoochee power dam



IEEE, Ellenberger Collection

Norris Dam powerhouse and outdoor switchyard, 1936



Construction of Norris Dam TVA

Norris Dam, started in 1933 and completed in 1936, was the 1st dam built by TVA TVA

Education for a New Century

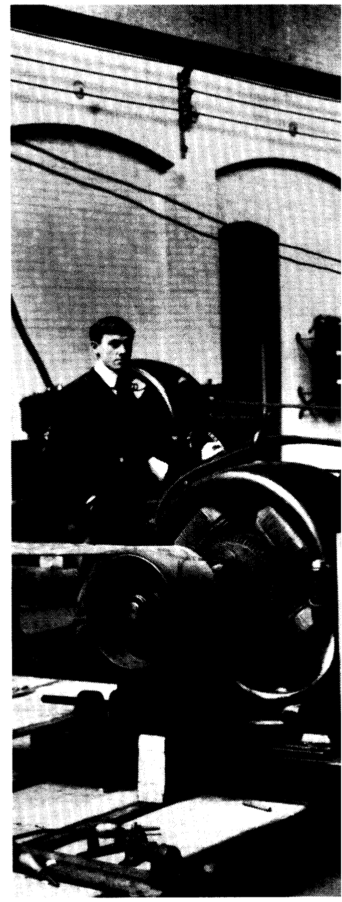
Electrical engineers needed education matched to their new profession and new technology.

The first university programs in electrical engineering drew on physics, other fields of engineering, and the dedication of great teachers.

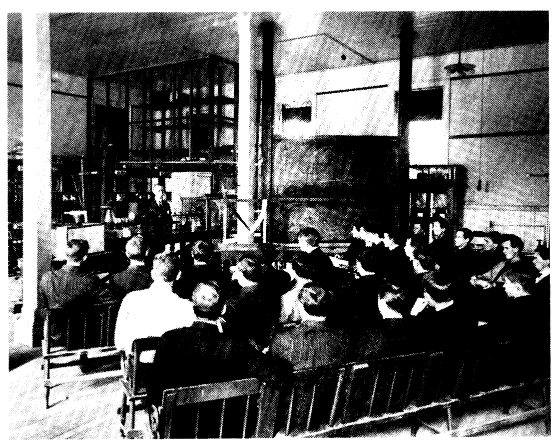
The first electrical engineers had very mixed backgrounds. Some had purely practical training, some had formal education in fields far removed from engineering, and a number were schooled in allied fields such as mechanical engineering or physics. The leaders of the profession, however, were quick to recognize that a new field would require a new kind of education. The first college-level electrical engineering programs were thus established at the same time that the engineers began organizing themselves in the 1880s, and their rapid growth in following decades became one of the sources of strength and unity for the profession.

When the Massachusetts Institute of Technology in Boston established America's first electrical engineering program in 1882, it was attached to the physics department. The curriculum reflected the close ties to physics, and included generous amounts of mechanical engineering and the liberal arts. There was actually little formal study of "electrical engineering" as such, for the subject hardly existed yet. Textbooks, laboratory procedures, trained teachers, and all the other apparatus of an academic subject had to be created. To some, this was one of the most important tasks of the electrical engineers in the twentieth century—one that was carried out with enormous success.

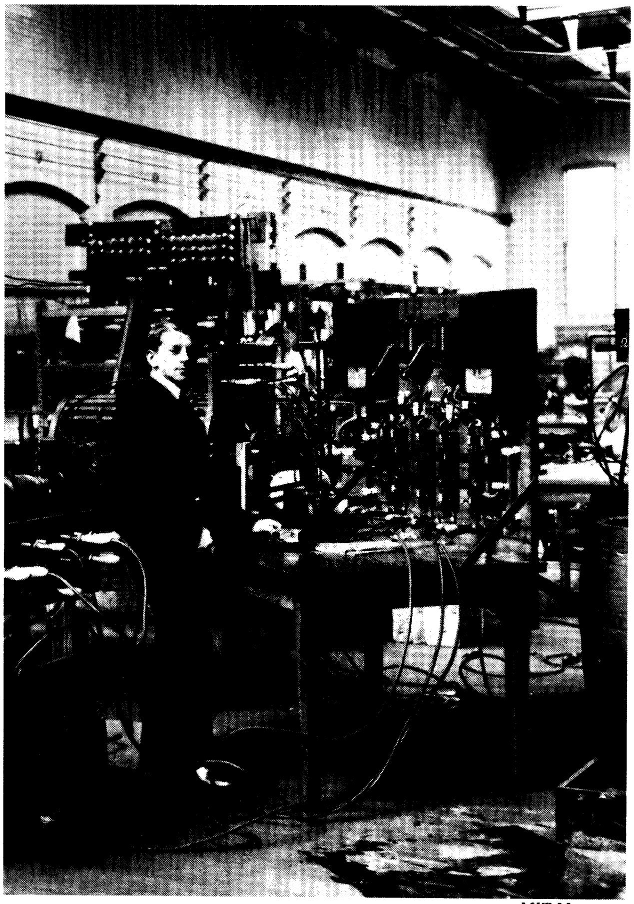
From the beginning, electrical engineering attracted many of the brightest and most ambitious engineering students—by 1892, for example, the field claimed 27 percent of MIT's graduates. For the first several decades, the electrical engineering curriculum was built almost exclusively around power engineering, for the ever-expanding power industry was the chief source of demand for engineers. Furthermore the principles and theory needed for effectively teaching the subject developed rapidly, thanks to the work of power engineers like Charles Steinmetz and Elihu Thomson, who distinguished themselves as educators as well as inventors and researchers. The greatest influence in electrical engineering education was, however, wielded by men who devoted their entire careers to working with students and fellow teachers, men like Dugald Jackson or Harris J. Ryan.



Dugald C. Jackson in his MIT office MIT Museum



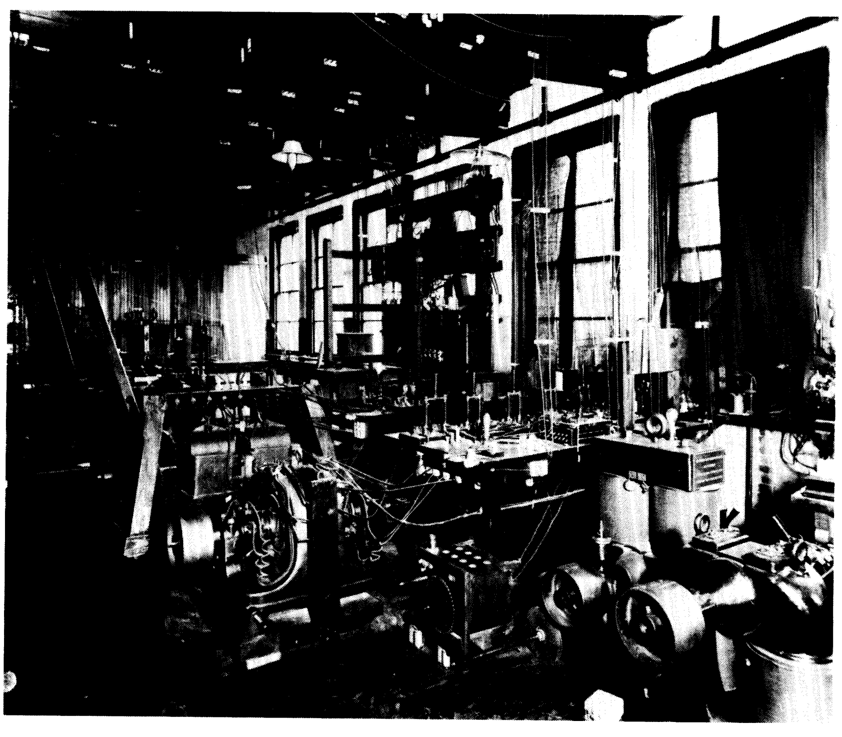
Harris J. Ryan's electrical engineering classroom at Cornell University, c. 1916
Cornell University Libraries



MIT Museum

Dynamo Room, Electrical Engineering Lab, Lowell Building, MIT

After World War I, the importance of radio and of further possible applications of vacuum tubes could not be ignored by even the most power-oriented electrical engineering department. The "communications option" became a more and more common feature in programs everywhere. Other efforts to make engineering education more responsive to the changing technology and needs of industry included the establishment of "cooperative" programs, the most famous of which was that begun at MIT in the 1920s. These saw faculty and students working shoulder to shoulder with company engineers, dealing directly with the practical problems of industry. Although individual professors might make important contributions to electrical technology—the invention of the loading coil by Columbia's Michael Pupin was a key to the expansion of telephone technology—most engineering educators in the early 20th century thought little about research or publication. They sought to make their contribution through teaching and left the creation of new technologies to industry's laboratories. This would change dramatically by midcentury.



Electrical lab, Walker Building, MIT MIT Museum

Cornell University Libraries

Dynamo laboratory, Cornell

The Engineer and Society

With the rapid expansion of electric power and communications industries, government entered the electrical engineer's world.

Engineers and politicians worked together to serve the public interest through effective regulation.

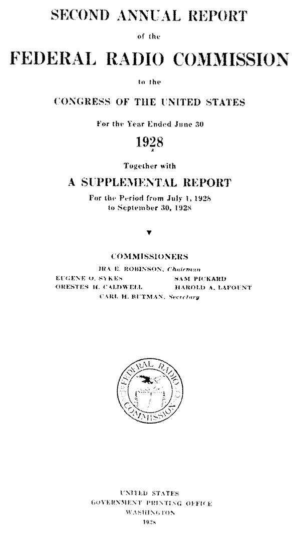
The turbulent first decades of the 20th century, marked by global war, unprecedented prosperity, and then calamitous depression, saw engineers assuming new roles in society. The enormous impact that the work of the engineer had on the lives and affairs of individuals and nations alike was obvious to all. There were some, in fact, who believed that the engineer's responsibilities extended to the management of a more efficient and rational society, that "technocrats" rather than politicians should be looked to as the natural leaders of a complex modern world. Although such views in their extreme form were held by a relative few, they stimulated a wide-ranging debate over the true duties and obligations of the engineer.

In the years after World War I, the relationship between electrical engineers and government rapidly came to be an important issue for many in the profession. The tremendous importance of radio that the war had made clear to all also made clear the need for strong, technically sophisticated government regulation. When the United States entered the war in 1917, the federal government quickly acted to take over all wireless stations in the country. The radio spectrum was obviously too valuable a resource to be left uncontrolled in times of national emergency or unregulated in times of peace. The growth of broadcasting in the 1920s made the need for concerted government action increasingly urgent, and Secretary of Commerce Herbert Hoover called four National Radio Conferences during the decade to bring engineers and politicians together to address both technical and policy issues. Finally, the Federal Radio Commission was established in 1928, and a long tradition of close cooperation between radio engineers and government regulators began.

Herbert Hoover was instrumental in organizing the Federal Radio Commission to regulate the radio spectrum Edison National Historic Site

Radio was not the only area in which engineers found themselves dealing directly with questions concerning the public interest and the engineer's responsibilities toward it. In almost all areas of electrical technology, the rapid expansion and increasing importance of the engineer's work made his activities a matter for public, and hence government, concern. From the beginning of the electric power and telecommunications industries, local government exerted authority over utility construction and competition. In some places, political involvement was limited to rate setting and franchise control, but in other jurisdictions, electrical technology was thought to be so essential that governments took on the complete responsibility for providing power and communications, thus becoming major employers of electrical engineers. The TVA was only the most famous example of government initiative in this area, for local governments in many areas of the country also provided service, and outside of the USA government control of power and telecommunications was the norm.

The increasing complexity of 20th-century technology and the increasing reliance that everyone was forced to place on it put special burdens on electrical engineers. Not only were they to pursue the ever more rapid advancement of their field and the fulfillment of the needs of employers and clients, but they had to be increasingly conscious of their responsibilities to society and, in the dangerous world of the later 20th century, to humanity itself.


SECOND ANNUAL REPORT
of the
FEDERAL RADIO COMMISSION
to the
CONGRESS OF THE UNITED STATES
For the Year Ended June 30
1928
Together with
A SUPPLEMENTAL REPORT
For the Period from July 1, 1928
to September 30, 1928

COMMISSIONERS
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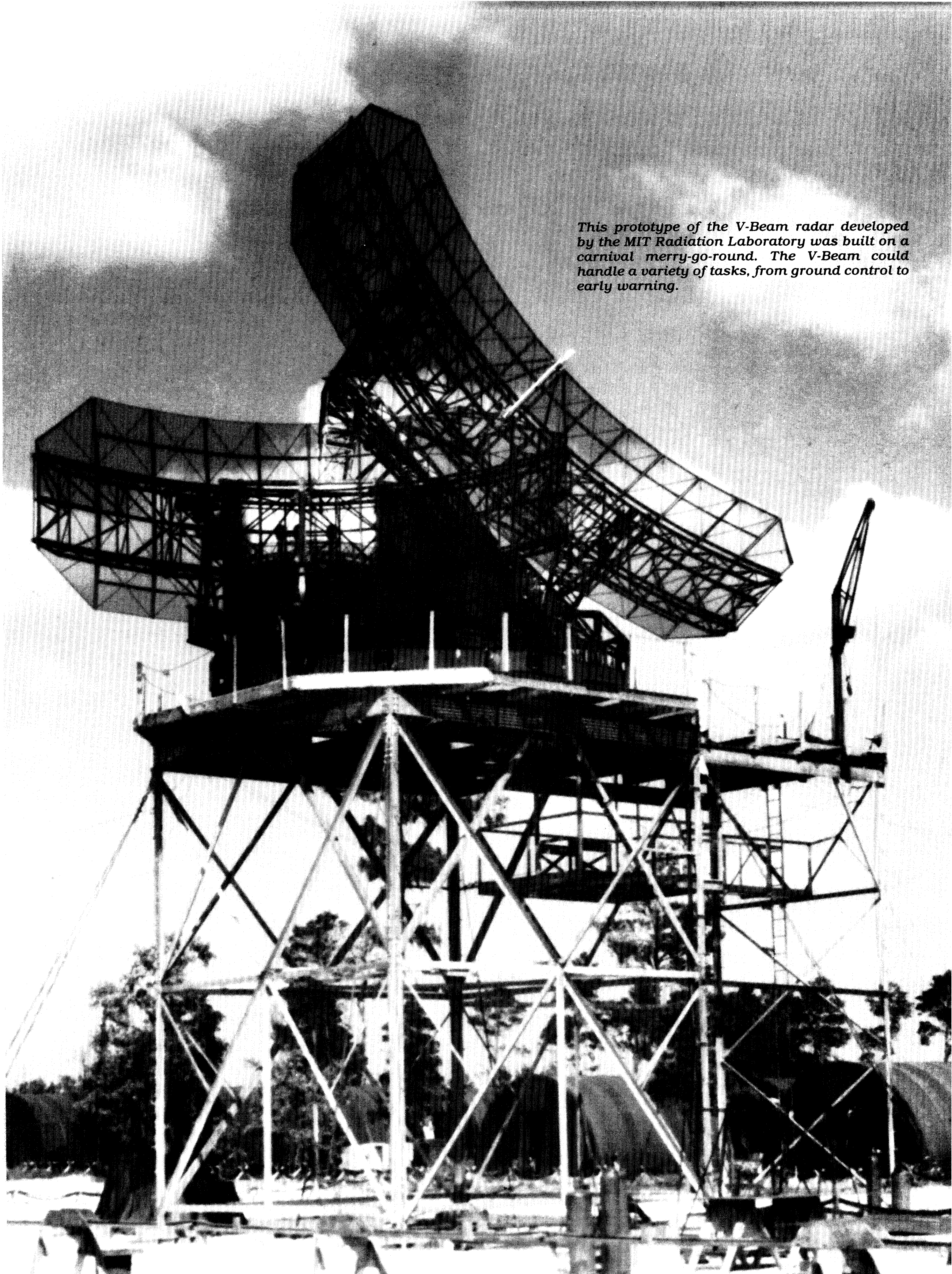
UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
1928

David Sarnoff conducting an inspection tour of RCA transoceanic station at New Brunswick, NJ, 1921. Among Mr. Sarnoff's guests are Albert Einstein, Charles Steinmetz, and Irving Langmuir

RCA



This prototype of the V-Beam radar developed by the MIT Radiation Laboratory was built on a carnival merry-go-round. The V-Beam could handle a variety of tasks, from ground control to early warning.

The New World

World War II transformed electrical and electronics engineering into a necessary part of daily life.

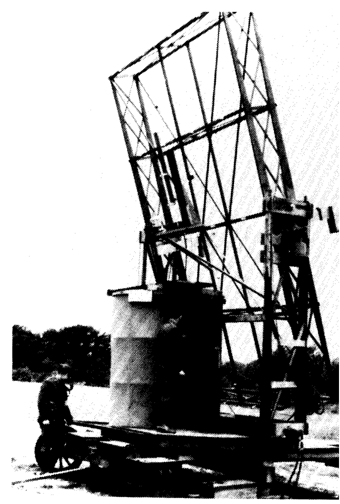
The needs of defense and of the post war consumer society placed special demands on the engineering profession.

No single event had a greater effect on electrical engineering than the Second World War. The years from 1939 to 1945 saw a radical change in the way that the world perceived electrical engineers and in how they perceived themselves. Their field was transformed from a specialty with well-defined applications, primarily in power and communications, into the source for the most powerful and pervasive technologies of the 20th century. As the century matured, as global war gave way to cold war, and as allies became enemies and former foes became friends, the expansion of the electrical and electronics technologies became one of the hallmarks of the age—shaped by as well as shaping history.

In the heat of war, radio engineering was transformed into electronics, and the radio engineers were similarly transformed. Theirs became a technology to harness the most advanced and subtle knowledge of the very parts of matter itself, manipulating electrons and electromagnetic waves almost at will in an effort not simply to communicate, but to detect, control, and even as some saw it, think. The tremendous pressures of wartime development forged a new relationship between engineers and physical scientists. More and more the realms and tasks of both overlapped, for advances in electronics made use of the latest findings, theories, and techniques of physicists and chemists, while scientific discovery came to rely progressively more on the instrumentation created by engineers. This merging of science and technology was one of the war's greatest legacies, and has continued to shape our times.

The enormous demands that war put on the world's economies brought home another lesson about electrical technology—the indispensable and strategic place of electric power. World War II marked the final passage of electric power to the status of necessity, not only swelling the general industrial consumption of power, but also highlighting specialized uses of electricity, such as the production of aluminum and explosives, that were critical to the pursuit of war. In Europe, the targeting of power plants and dams by both Allied and Axis bombers provided gruesome proof of electricity's central place in modern warfare. The harnessing of the technology of peace to the needs of war provided prelude to a fine irony, however, for the most dramatic development in electric power production in the coming decades was the effort to transform the energy in the war's most awful weapon, the atomic bomb, into a servant of power generation.

The postwar years were ones of growth and change, accompanied by tensions and conflicts both within the engineering community and in society at large. Again, war was followed by unprecedented prosperity, but this time it was in a world where the dangers and possible consequences of international conflict were distressingly obvious. The efforts of engineers were thus divided between the creation of a consumer society, powered by electricity and tuned in by electronics, and the demands of national and international security, with their heavy drain on both resources and manpower. Alongside this division was another, as the anomaly of an engineering community split between the AIEE and the IRE became less and less justifiable. In the coming decades, this problem was resolved, as engineers everywhere recognized their common interests.



110-mc radio pulse projector installed on a 5×2 antenna, 1937, developed by the US Army Signal Corps

U.S. Army

MIT Museum

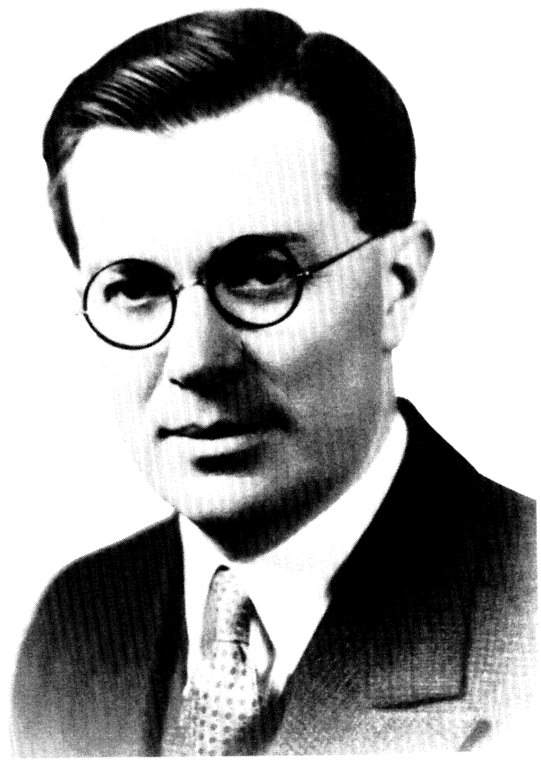
Electrical engineers were organized on an unparalleled scale to create the complex technology needed to win the war.

The MIT Radiation Laboratory united electrical engineers, physicists, and technicians in the intense development of radar.

At least since Archimedes, engineers and scientists have been pressed into service in time of national danger, but never on such a scale as during World War II or with such enormous consequences. From the day that Nazi tanks rolled into Poland in September, 1939, it was clear to everyone that this was to be a war of technology, and the nation that could create and put to use the most advanced science and engineering would have the upper hand.

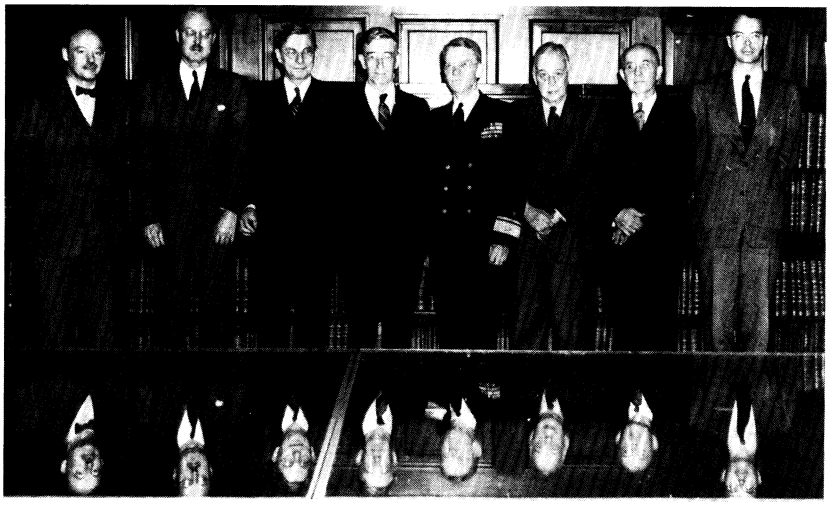
New circumstances required new forms of organization. During World War I, the United States relied on such agencies as the Naval Consulting Board, headed by Thomas Edison, which spent much of its effort simply reviewing ideas for inventions sent in from around the country. Such a mechanism was clearly inadequate for the crisis of total war. Electrical engineers were prominent in creating the new tools required to mobilize the nation's scientific and technical manpower. The most significant of these tools was the Office of Scientific Research and Development, headed by former MIT electrical engineering professor Vannevar Bush. The OSRD was to spearhead much of the war's engineering developments, including the perfecting of sonar for submarine detection, the proximity fuze to increase the effectiveness of ordnance, and shortwave radar, which revolutionized air defense.

Most of the scientific and engineering research carried out during the war was not carried out by the government itself, but in academic and industrial laboratories by people recruited from all technical fields. Numerous special laboratories were set up, and it was in these institutions that many electrical engineers learned how the war was transforming their field. The best engineers of the day were chosen to organize and run the labs, as, for example, Stanford's Frederick Terman, who was called upon to head the Radio Research Laboratory at Harvard, which had the prime responsibility for electronic countermeasures ("jamming").



Frederick E. Terman

Albert E. ('High-pockets') Hayes and other technicians working in main room of the Roof Laboratory, MIT Rad Lab, 1941 MIT Museum



MIT Museum

Vannevar Bush and the OSRD

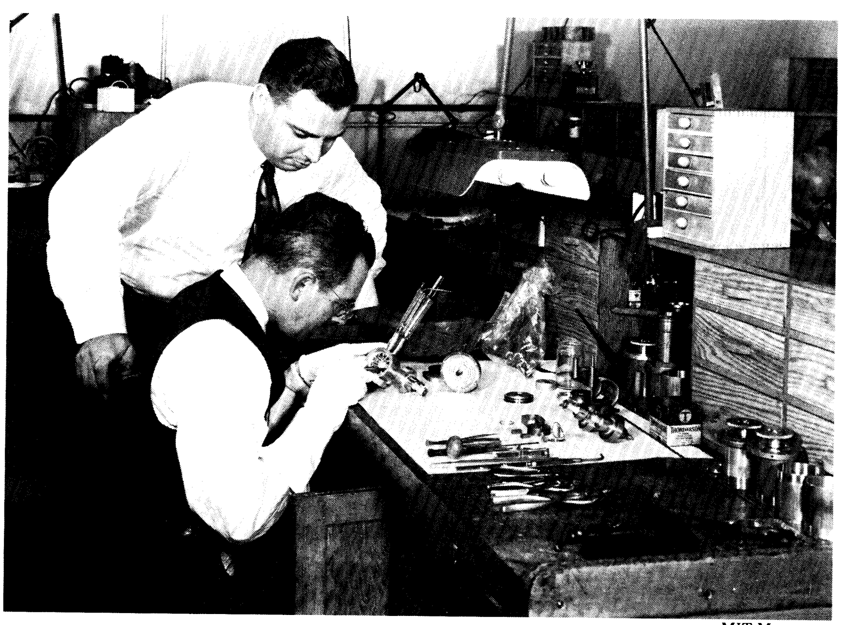
The largest and most prominent of the OSRD-sponsored labs was set up for the development of effective and reliable radar systems. Named the Radiation Laboratory to suggest to the outside world that it was concerned with supposedly more innocent problems in physics, the establishment eventually employed some 4,000 people spread throughout 15 acres of floor space on and around the campus of MIT. At its height, the "Rad Lab" employed fully one-fifth of the physicists in the United States, plus hundreds of electrical engineers from both academe and industry. More money—an estimated $2.5 billion—was spent on radar research, development, and production than was consumed by the work on the atomic bomb, and the technical fruits, although not as spectacular, were from an engineering point of view every bit as impressive. Working closely with British researchers, the laboratory turned out a whole series of sophisticated microwave devices, laying the foundations for a large family of radar and navigation instruments, which were key parts of the war effort and which became mainstays of postwar electronics technology. Above all, the close relationship forged between physicists and engineers under the stress of war gave a glimpse of the ever more complex research environment of the engineer in the late twentieth century.

MIT Museum

MIT Radiation Laboratory

MIT Museum

Loran monitoring room, Chatham, MA



MIT Museum

MIT Radiation Laboratory

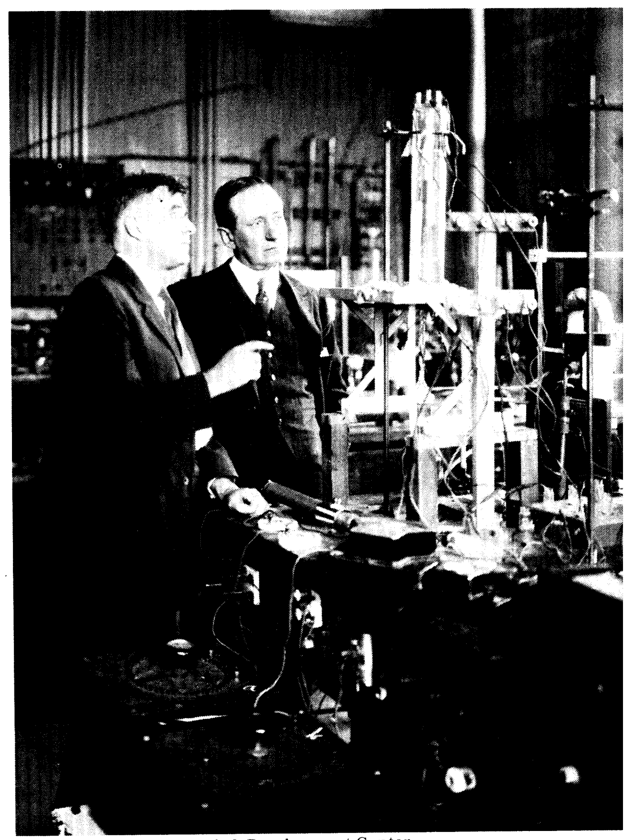
New Horizons

Industrial research laboratories became the primary sources of technological innovation.

Labs in firms like General Electric and AT&T made important breakthroughs, such as the transistor.

The world that electrical engineers faced at the end of World War II was a very different one from that of the 1930s, but the underlying agencies for change were institutions that had been in the making for many years. The most important of these were the industrial research laboratories that a number of the largest electrical technology firms had set up in the first decades of the century. In such laboratories, engineers were brought together with scientists, technicians, and material resources, all organized in an effort to improve the "state of the art" or to create breakthroughs that would extend technological and commercial opportunities into new areas.

The fruitfulness (and profitability) of such efforts was amply demonstrated very early. The laboratory that General Electric's Willis Whitney set up in Schenectady, N.Y., in 1900 was a model for many to follow, and its productivity was a persuasive advertisement for industrial "R & D." William Coolidge's process for making ductile tungsten lamp filaments and Irving Langmuir's improved light bulbs and vacuum tubes were sources not only of profit but of justifiable pride for the G.E. engineers and managers. The policy of trying to put technological innovation on a systematic basis was seen as a resounding success, one to be followed on a large or a small scale by many others.

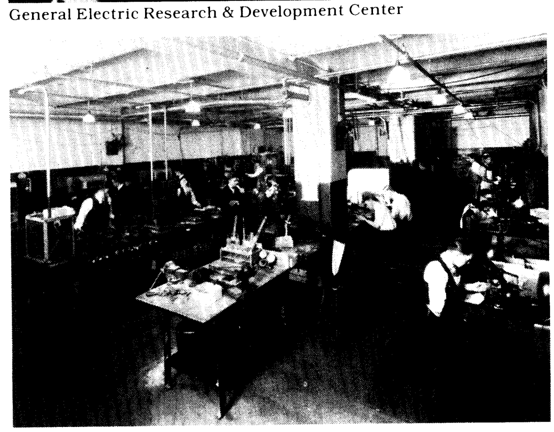


Irving Langmuir & Guglielmo Marconi in General Electric laboratory, Schenectady, NY, 1922

General Electric Research & Development Center

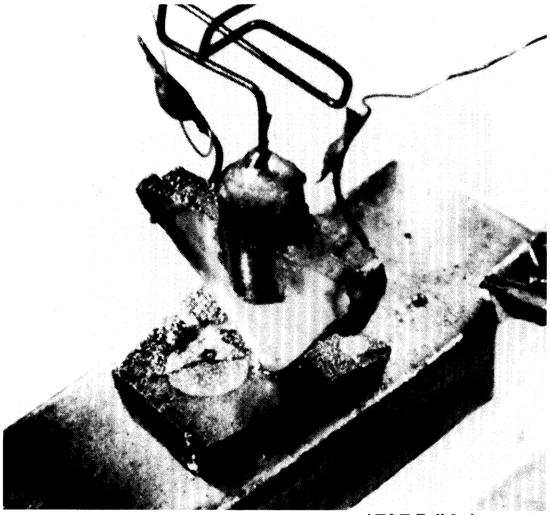
MIT Museum

Willis R. Whitney in his GE lab



Vacuum tube research lab, Bell Laboratories, 1924

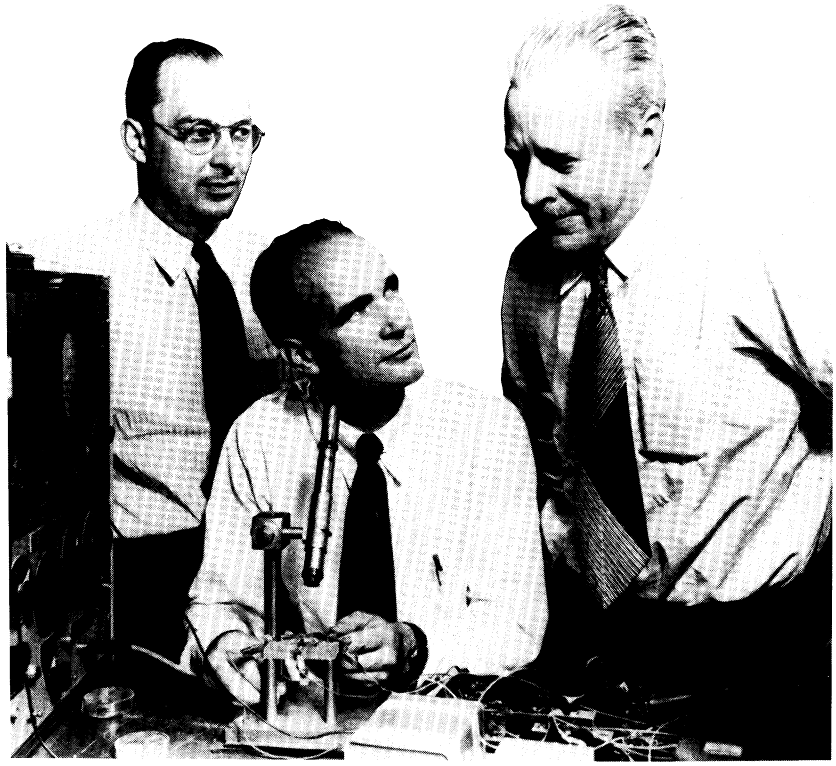
AT&T Bell Laboratories



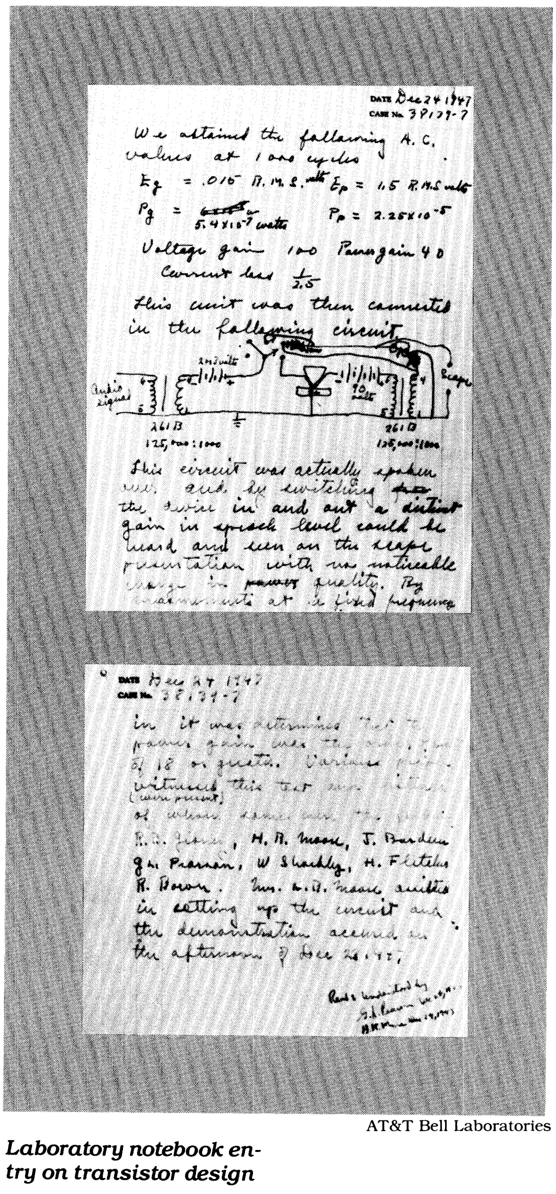
AT&T Bell Laboratories

1st point-contact transistor, 1947

John Bardeen, William Shockley and Walter Brattain, 1948



AT&T Bell Laboratories



DATE Dec 24 1947
CASE No. 38139-7

We obtained the following A.C. values at 1000 cycles

Eg = .015 R.M.S. volts Ep = 1.5 R.M.S. volts

Pg = 5.4×10⁻⁷ watts Pp = 2.25×10⁻⁵

Voltage gain 100 Power gain 40
Current loss 1/2.5

This unit was then connected in the following circuit.

This circuit was actually spoken over and by switching the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in quality. By measurements at a fixed frequency

DATE Dec 24 1947
CASE No. 38139-7

in it was determined that this power gain was [illegible] of 18 or greater. Various people witnessed this test [illegible] (were present) of whom some were [illegible]

[illegible], H. R. Moore, J. Bardeen, G. L. Pearson, W Shockley, H. Fletcher, R. Brown. Mr. H. R. Moore assisted in setting up the circuit and the demonstration occurred in the afternoon of Dec 23, 1947.

[illegible]

AT&T Bell Laboratories

Laboratory notebook entry on transistor design

No one, however, made such good use of industrial research as the American Telephone and Telegraph Company. In 1907, AT&T and the Western Electric Company combined their engineering departments and established the Bell Telephone Laboratory on West Street, in New York City. By 1921, the laboratories constituted the largest industrial research organization in the country, occupying 400,000 square feet in a thirteen-story building in lower Manhattan and employing more than 1500 men and women. The organization was put on a more formal footing in 1925, when Frank B. Jewett was made President of Bell Telephone Laboratories, Inc. In the following decades, the labs distinguished themselves by contributions not only to communications technology, but to basic science as well. The awarding of the Nobel Prize in Physics to Clinton J. Davisson in 1937 was simply the most prominent recognition of the laboratories' scientific work.

The true importance of the fusion of science and engineering in the industrial laboratory was made apparent to all in the years after World War II. In 1947, three Bell Labs physicist-engineers produced the single most significant electronic invention of the era—the transistor. John Bardeen, Walter Brattain, and William Shockley were consciously seeking to exploit new knowledge about the behavior of semiconducting materials when they devised a way to make a crystal of germanium do the work of a triode vacuum tube, the most basic of electronic components. Their work built on the research of many before them, and much had to be done before the transistor and the solid-state devices that followed could become practical engineering tools, but in retrospect it is clear that the transistor gave the engineer the key to a whole new electronic world.

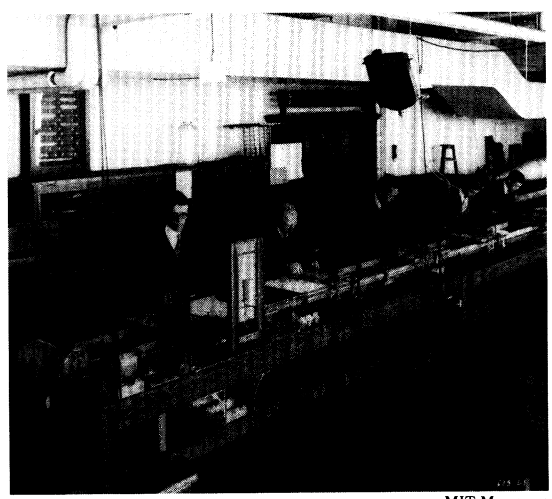
The digital computer was one of the most powerful new tools to emerge from World War II.

Many engineers were responsible for the development of electronic computers during the 1940s and 1950s.

Of all the new technologies to emerge from the tumult of World War II, none was to have such profound and pervasive impacts as the digital computer. Like all of the revolutionary developments of the war and the postwar period, the emergence of the computer owed much to the work of earlier decades. As early as the 1830s, the Englishman Charles Babbage conceived of an "Analytical Engine" that would perform mathematical operations using punched cards, hundreds of gears, and steam power. Babbage's machine was beyond the capabilities of 19th-century technology, but his vision represented a goal that many were to pursue in the next century and a half.

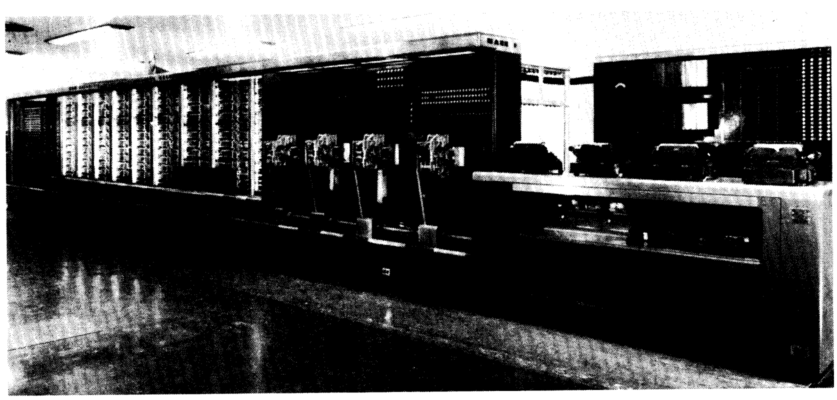
The needs of electrical engineers themselves were to provide considerable incentive to the construction of some of the earliest practical computers. In the mid-1920s, MIT electrical engineer Vannevar Bush devised the "product integraph," a semiautomatic machine for solving problems in determining the characteristics of complex electrical systems. This was followed a few years later by the "differential analyzer," the first general equation-solving machine. These machines were mechanical, analog devices, but at the same time that they were being built and copied, the principles of electrical, digital machines were being laid out. In 1937,

Charles Babbage Burndy Library



MIT Museum

Vannevar Bush and the Product Integraph, 1927



Harvard University

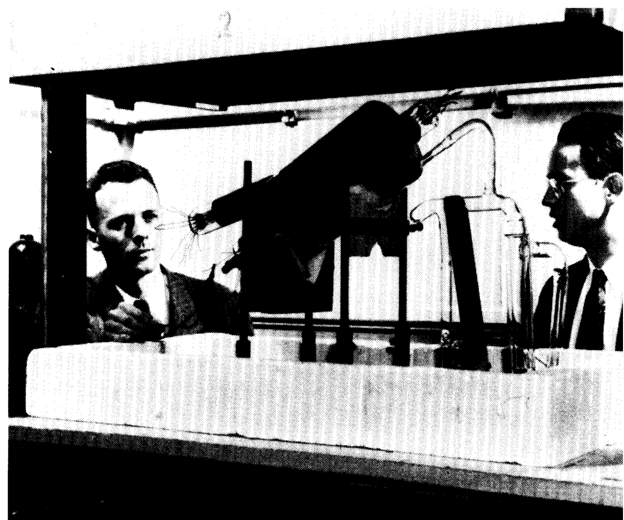
Automatic Sequence Controlled Calculator, the "Mark I"

Claude Shannon published in the *Transactions* of the AIEE the circuit principles for an "electric adder to the base two," and George Stibitz of Bell Labs built such an adding device on his kitchen table. In that same year, Howard Aiken, then a student at Harvard, proposed a gigantic calculating machine that could be used for everything from vacuum tube design to problems in relativistic physics. With support from Thomas J. Watson, president of IBM, Aiken was able to build his machine, the "Automatic Sequence Controlled Calculator," or "Mark I." When it was finished in 1944, the Mark I was quickly pressed into war service, calculating ballistics problems for the Navy.

The usefulness of such machines for the war was widely apparent, and this need stimulated even more rapid development. In 1943, the government contracted with John W. Mauchly and J. Presper Eckert of the University of Pennsylvania to build the "Electronic Numerical Integrator and Computer"—the first true electronic digital computer. When the ENIAC was finally dedicated in February, 1946, it was both a marvel and a monster—weighing 30 tons, consuming 150 kW of power, and using 18,000 vacuum tubes. With all this, it could perform 5,000 additions or 400 multiplications per second, which was about a thousand times faster than any other machine of the day. More than any other machine, the ENIAC showed the immense possibilities of digital electronic computers.

These possibilities were to occupy engineers, mathematicians, and others in the coming decades. The stored-program concept of John von Neumann, the ideal machines of Alan Turing, the memory devices of Jay Forrester, and the program compiler of Grace Hopper were just some of the insights and innovations that went into creating the modern digital electronic computer. Gradually, but surely, the computer wrought a revolution in science, business, government, and engineering, by providing the capacity for handling vast quantities of data very quickly and very accurately. The computer represented another kind of revolution to electrical engineers, however, for it put into their hands the challenge of and the responsibility for the most powerful new machine of the twentieth century.

Jay W. Forrester & electrostatic storage tube for Whirlwind computer memory



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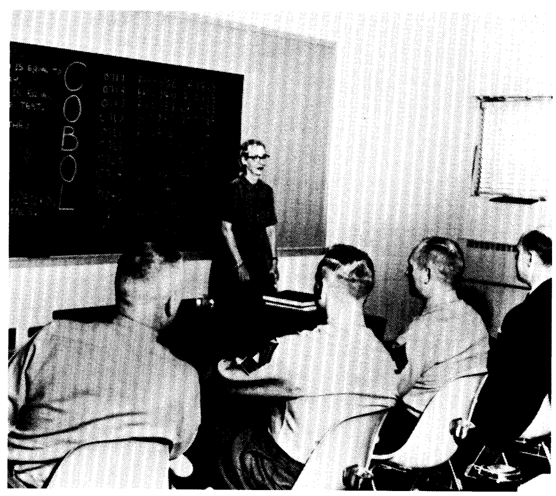
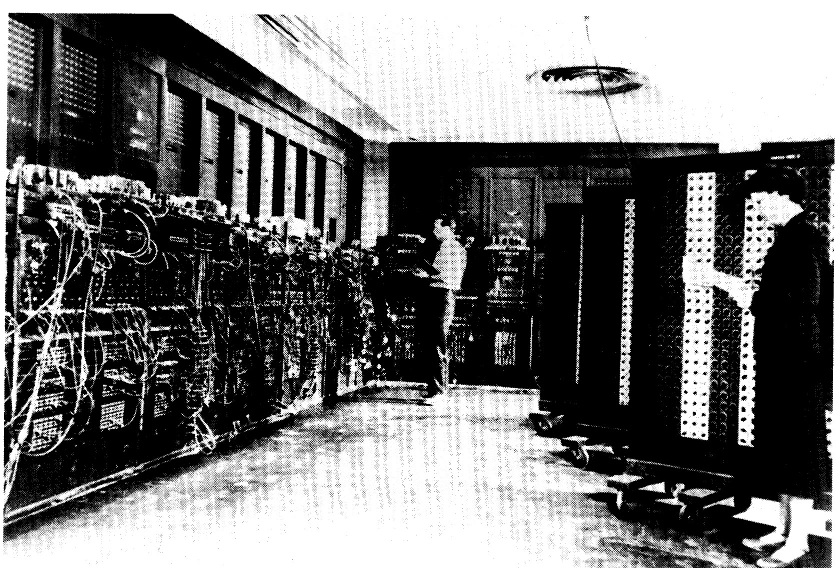


Grace M. Hopper

Sperry Corporation



Smithsonian Institution

ENIAC, 1946

Rivalries Within

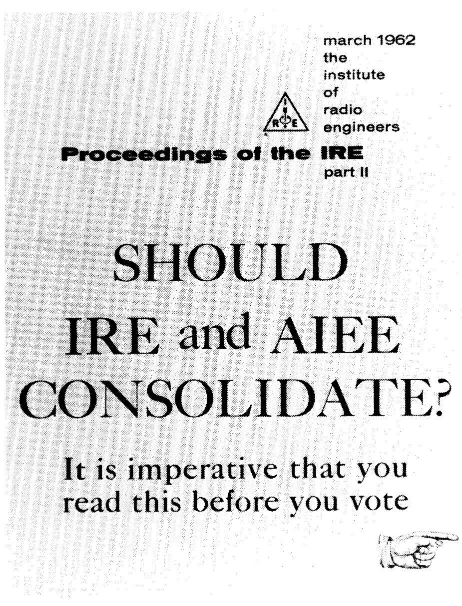
The growth of electronics during and after World War II greatly expanded the electrical engineering profession.

The two separate societies serving the profession, the AIEE and the IRE, joined to form the IEEE in 1963.

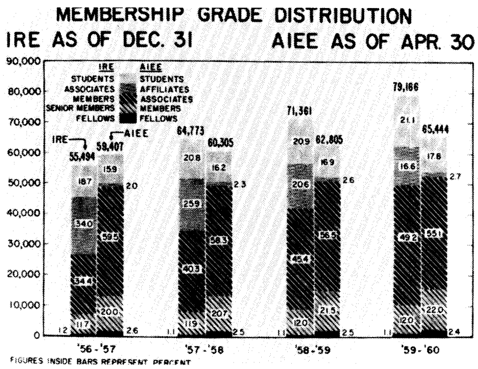
Almost all fields of electrical engineering grew in the years after World War II, some gradually and others explosively. This growth and its different impact on various technical fields and parts of the profession made the 1940s and 1950s a period of both exciting change and of difficult tensions. The tensions were vividly reflected in the changing relationship between the two professional societies that divided electrical engineering between themselves—the American Institute of Electrical Engineers (AIEE) and the Institute of Radio Engineers (IRE). In the early 1960s these tensions were to be resolved in the merger of the two societies to form the IEEE—unifying the profession under a single, trans-national banner.

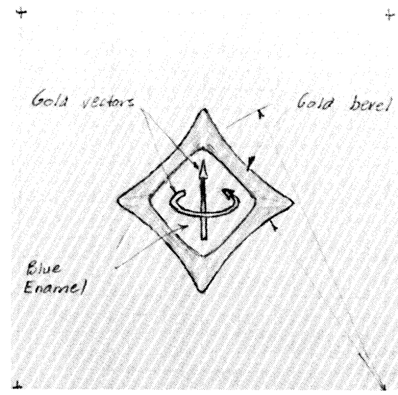
The tremendous growth of electronics was the primary force for change in the profession, even before the end of the World War. The effect of the war could be seen in the membership of the IRE, which grew from 5,200 in 1940 to more than 18,000 by 1946. Membership continued to climb rapidly during the 1950s, finally surpassing the AIEE's in 1957, when total IRE membership, including students, reached 64,773. Students represented one-fifth of that total, and the accelerating growth of the IRE's student membership was evidence of a society that was successfully riding the wave of a technological revolution.

Symposium on proposed AIEE/IRE merger, held during the IRE convention, 1962

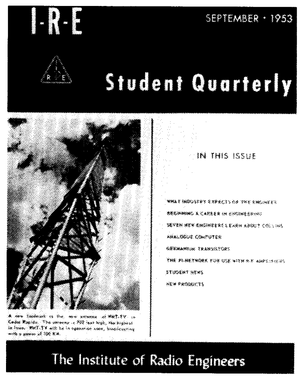


From President Clarence H. Linder's report to the AIEE Board of Directors, 1960





Bernard M. Oliver's sketch for the IEEE badge


I-R-E SEPTEMBER • 1953

Student Quarterly

IN THIS ISSUE

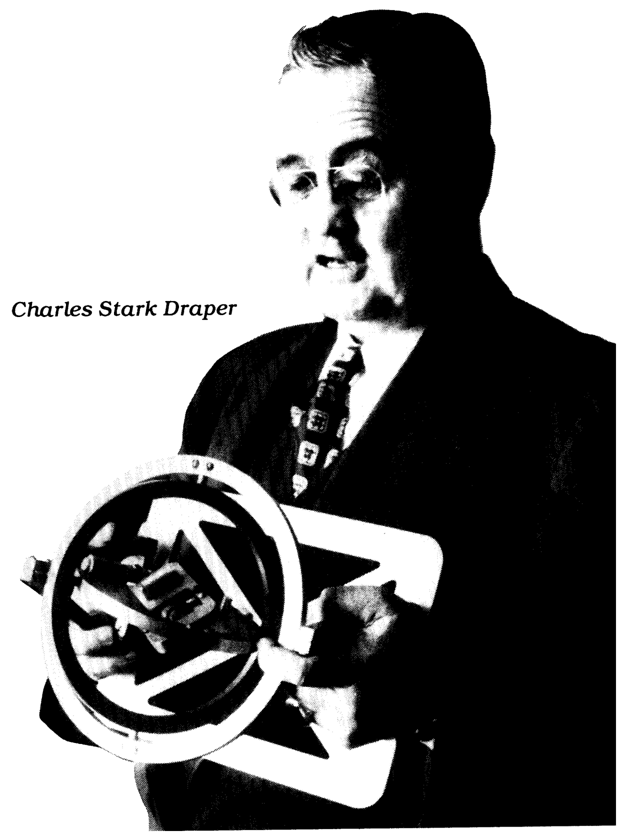
The Institute of Radio Engineers

This success story was not repeated in the AIEE. There, by the late 1950s, overall membership growth had slipped to barely 3% per year, and its student membership was only two-thirds that of the IRE. The organization was by no means moribund, for it had strived throughout the 1950s to adapt itself to the growing status of new electronics and communications technologies. By the end of the decade, the AIEE was not a society of just power engineers—over 30% of its technical papers were in communications, electronics or instrumentation, and participation in joint technical conferences with other societies was rapidly increasing. Still, the society felt a little left behind by the tremendous growth of its younger brother. With greater frequency, questions were raised in both societies about how appropriate it was for the increasingly inter-related fields of electrical engineering to be represented by two large, independent organizations.

The idea that there should be only one organization for electrical engineers was an old one. At its founding, the members of the IRE had consciously decided that the burgeoning new field of radio could be best served by an organization outside the confines of the AIEE, and in those days the technical concerns of the two societies did seem comfortably distinct. By the 1940s, however, the ever-increasing scope of electronics was clearly moving into the power, control and communications concerns of the AIEE. As early as the mid-40s, prominent AIEE members advocated joining with the IRE, a call repeated at intervals during the 1950s. Late in the decade, cooperative arrangements were worked out for members of the two societies, and, finally, in 1961 top officers of the AIEE and the IRE began seriously discussing merger. A joint committee made recommendations, and when merger was put to a vote the following year, 87% of the membership of each organization approved. On 1 January 1963, the Institute of Electrical and Electronics Engineers was officially born.

The close ties formed among the military, industry, universities, and engineers in the name of national defense remained in place after the War.

Defense projects and military-supported laboratories became important centers of electrical engineering activity.



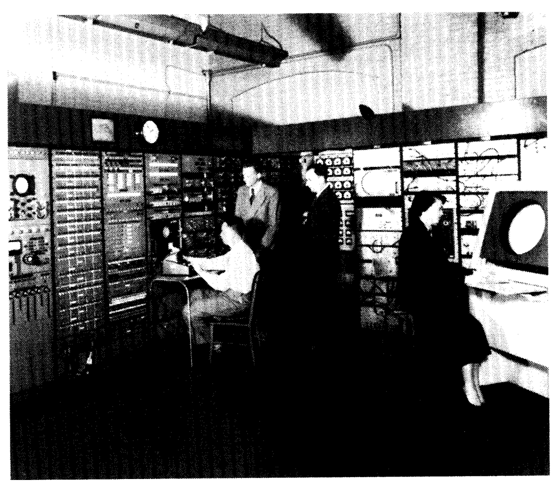
Charles Stark Draper

MIT Museum

The supreme effort necessary to win the Second World War demanded an unprecedented degree of cooperation among the military, industry, and academia. Working together, these institutions developed the technologies necessary to win the war. But the end of the shooting war was followed all too quickly by the cold war; the demand for sophisticated weaponry would not go away. As a result, the alliance of convenience among the military, industry, and academia, forged to meet the wartime emergency, became a permanent part of modern life.

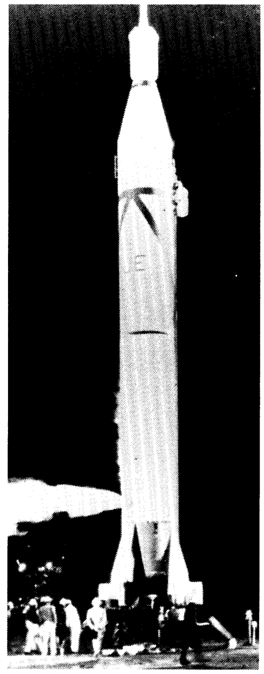
The requirements of the military strongly influenced the direction of postwar technology. Digital computers were applied to the problems of air defense, producing the SAGE (Semi-Automatic Ground Environment) system for coordinating the detection and interception of enemy bombers. The Navy, with its atomic submarines, pioneered the production of electricity from nuclear energy, and the first commercial nuclear generating station in the United States, at Shippingport, Pennsylvania, was based on the Navy designs. Even technologies that did not arise directly from military research were affected. The transistor was a civilian invention, but the development work that made it into a useful, reliable device was funded largely by the military.

A network of organizations grew up during this time to serve defense needs. Some, like the Johns Hopkins Applied Physics Laboratory and the MIT Servomechanisms Laboratory, were formed during World War II. Others, such as System Development Corporation, which provided the programming and training for the SAGE system, were postwar creations. In still other cases established firms, such as General Electric, Westinghouse, and Raytheon, that had done little military work before the war found defense work to be a major component of their postwar activities.



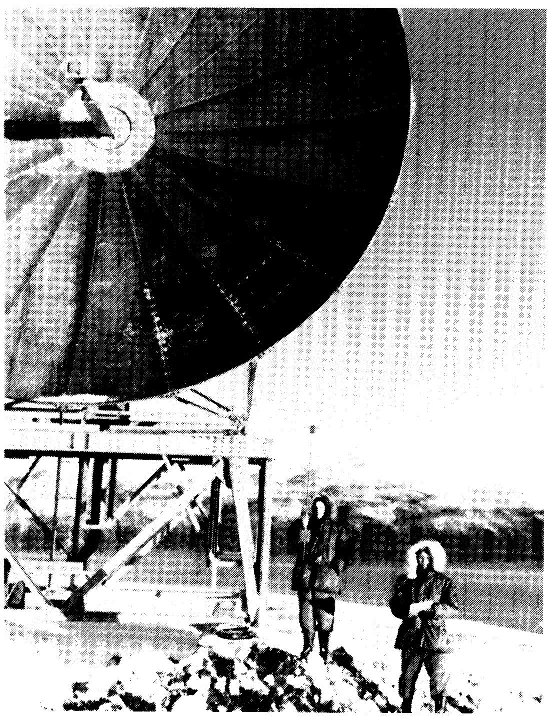
Whirlwind computer, built at MIT with Navy and Air Force funding in late 1940s and early 1950s MIT Museum

The career of Charles Stark Draper illustrates the opportunities and challenges this defense network offered electrical engineers. Working at MIT's Instrumentation Laboratory Draper developed a gyroscopic gunsight which greatly improved the effectiveness of naval gunnery during the war. After the war Draper turned his attention to the problems of navigation and guidance. Nuclear submarines, which could stay submerged for days or weeks, could not depend upon the celestial navigation used by surface ships or conventional subs. In addition, ballistic missiles designed to strike targets hundreds or thousands of miles from the launch site posed formidable guidance problems. Combining gyroscopes with servomechanisms, accelerometers, and electronics, Draper developed inertial guidance sytems that were successfully applied to submarines and the Polaris, Poseidon, Thor and Titan missiles. His crowning achievement was the system that safely guided the Apollo astronauts to the moon and back to earth.



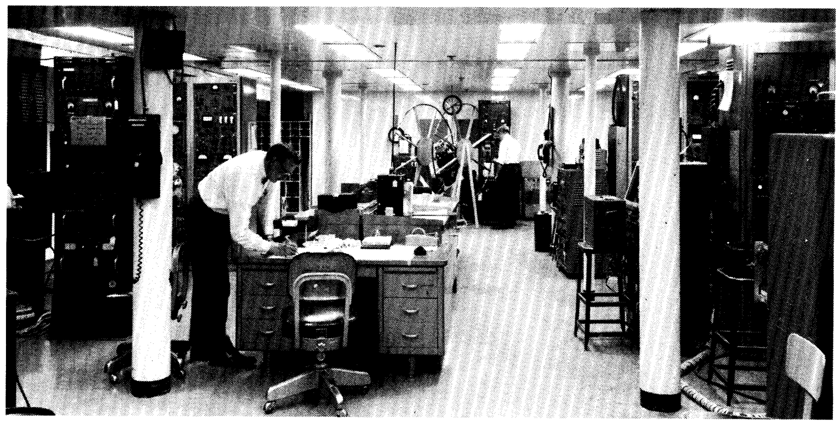
NASA

A Jupiter-C rocket on the launch pad at Cape Canaveral prior to launching Explorer I, the first American satellite, January 31, 1958

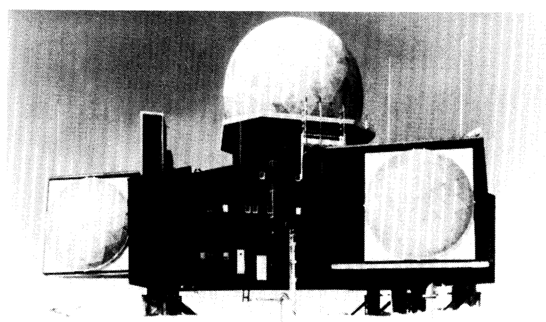


AT&T Bell Laboratories

Part of the "White Alice" system of the Distant Early Warning (DEW) Line, in which stations up to 200 miles apart across the top of the North American continent were connected by microwaves

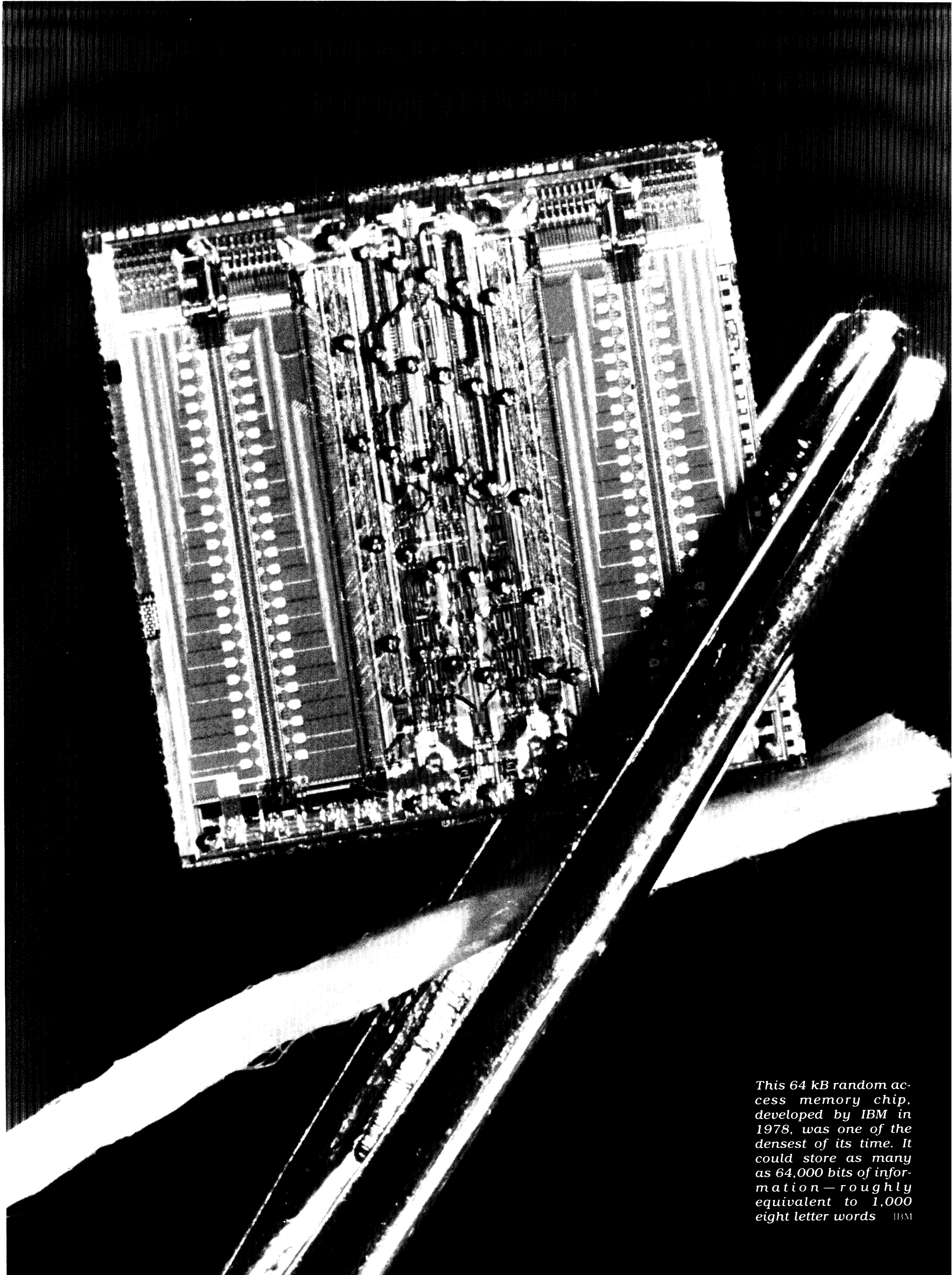


MIT Instrumentation Laboratory Charles Stark Draper Laboratories, Inc.



East station on Greenland ice cap, 1961, of Distant Early Warning (DEW) Line, installed to detect hostile aircraft AT&T Bell Laboratories

The challenge of providing security and readiness in an increasingly dangerous world was the key stimulus to the advancement of electronic technology in the decades after World War II. With the challenge came unprecedented opportunities for engineers to exploit the possibilities of their field without many of the usual constraints of cost and competition present in the commercial environment. Engineers faced another challenge, however, in keeping their independence and professional integrity in an environment dominated by the enormous, impersonal establishment responsible for national defense. For most of the last half of the twentieth century, the public perception of engineers has been shaped largely by how they have met this challenge.



This 64 kB random access memory chip, developed by IBM in 1978, was one of the densest of its time. It could store as many as 64,000 bits of information—roughly equivalent to 1,000 eight letter words IBM

Unity and Diversity

Electrical and electronics technology has continued its explosive growth during the last two decades, increasing its importance to everyone.

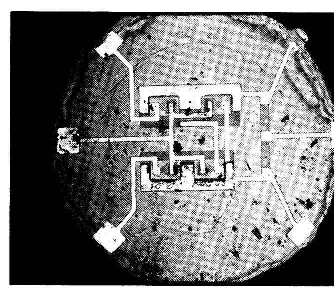
The electrical engineering profession has expanded as well in numbers, influence, and diversity.

The last two decades have witnessed a revolution in electrical and, especially, electronics technology. Paced by changes in solid-state electronics that greatly expanded capabilities while at the same time radically reducing costs, the entire domain of electrical engineering has grown far beyond the boundaries that characterized it just a generation ago. Electrical engineers have become the creators and masters of the most pervasive technology of our time, with profound effects on society and on their profession.

As with all great technological and social changes, the effects of the electronics revolution are complex and difficult to characterize. For the profession, the most obvious impact has been explosive growth—the membership of the IEEE increased by sixty percent in the two decades after 1963. The increase in the number of students studying in the fields covered by the IEEE—computers, communications, power, and the like—continues to be dramatic and shows no sign of slowing. The electrical engineering community thus represents the largest single technical group in the world, and the almost one-quarter million members of the IEEE make up the world's largest engineering society.

The growth of electrical engineering has generated both unifying and dividing forces within the profession and in society at large. Modern electric power systems, for example, allow energy to be applied in fragmented and discrete ways, allowing the wider and wider distribution of productive activity. At the same time, such systems link all users together into a tightly woven net of dependency. Microelectronics has the same dual tendency, allowing individuals to work with powerful computers that are wholly contained on their desks or engage in a variety of commercial or social activities without ever actually dealing with another human being. The same technology that fosters such isolation allows the person with a miniature television or a citizens band radio to be "plugged in" to the world wherever he may be, thus making him truly part of a "global village."

The forces of unity and divergence are also at work in the engineering community. With increasing size and complexity, many of the tendencies that always work to separate the practitioners of different specialties and sub-specialties from one another are harder to overcome. Jargon, differing technical problems, and divergent institutional and economic environments compartmentalize engineers into smaller groups that may have increasing difficulty communicating with one another. On the other hand, the sheer size of the electrical engineering community and the multiplicity of common interests—professional, economic, and technical—has provided considerable common ground for all electrical engineers to meet on. That there does exist a single organization to speak for them in the 1980s is testimony to the enduring legacy of a century of growth and change.



1st commercial integrated circuit, 1961
Fairchild

The American space program in the 1960s provided both technical challenges and personal satisfaction to engineers.

The race to put a man on the moon pushed electronics and computer technology ahead with tremendous speed.

The ideal engineering project is one that is highly challenging, is well funded, offers the opportunity to work with well-qualified people, produces tangible results, and enjoys wide public support. In the 1960s, the American aerospace programs came close to fulfilling these specifications.

The technological fruits of these programs were many, but developments in two areas, microelectronics and computers, were particularly important for electrical engineers. The growth of microelectronics, and specifically integrated circuits, was accelerated by the demand for small, rugged, lightweight electronics packages with low power consumption for use in satellites, aircraft, spacecraft, and missiles. In addition, the massive mathematical challenges posed by spaceflight stimulated the development of digital computers. Large mainframe machines were essential for design and trajectory calculations, and small, on-board computers were needed for guidance and control of manned spacecraft.

Telstar I, launched in 1962, showed the possibilities for sending telephone calls and television broadcasts across oceans and continents via an orbiting satellite AT&T Bell Laboratories

"Buzz" Aldrin on the moon, 1969 MIT Museum

The Apollo moon missions were in a very real sense the pinnacle of the space program, for afterwards shifting national priorities resulted in the dismantling of much of the space apparatus, putting many engineers out of work. By 1971 the unemployment rate among electrical engineers involved in the space related fields of computers, electronics, and systems engineering was over 6.5 percent, twice the rate for all engineers.

A related problem was the fact that engineers in the aerospace industries were highly mobile, moving from job to job as opportunities improved or as contracts were won or lost. The result was that many of these engineers did not accumulate the pension and other benefits that were available in more stable industries. Rising unemployment only exacerbated this problem.

In the end, the "ideal engineering project" left both a technical and a non-technical legacy for electrical engineers. The space program contributed greatly to technological advancement and was a source of justifiable pride to the participants. But the economic dislocation caused by the program's decline led many electrical engineers to urge the IEEE to become more active in promoting the economic interests of its members. This effort was successful in 1973 when the Institute decided to broaden its concerns to include the economic and professional status of its members.

NASA

The shuttle COLUMBIA was launched twice in 1981, representing a new achievement in both the complexity and the reliability of large systems

NASA

Manned Space Flight Network Operation Control Center, Goddard Space Flight Center, Greenbelt, MD.

Telstar earth station, Goonhilly Downs, Cornwall, England

AT&T Bell Laboratories

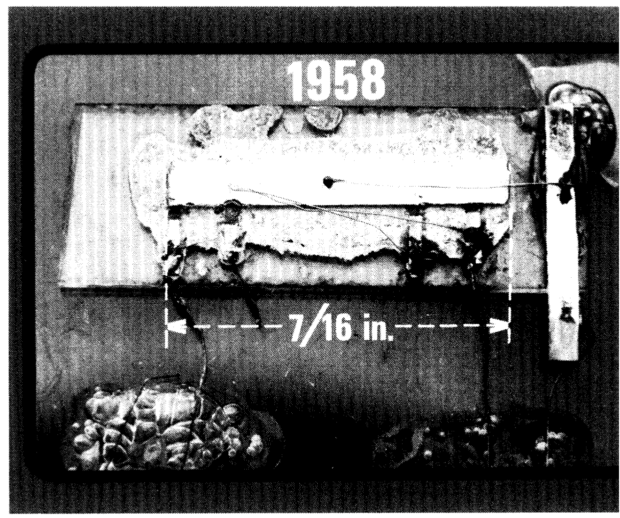
Microelectronics has been the most significant area of development in electrical technology in recent years.

Innovations like the integrated circuit and the microcomputer intensified the impact of electronics everywhere.

Microelectronics and digital computers, both of which received a strong boost from the aerospace programs of the 1960s, developed into the "glamour" technologies of the 1970s and 1980s.

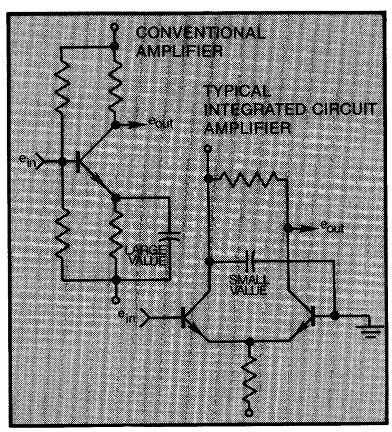
The two technologies have had a profound effect upon the course of electrical engineering. First of all, they have reopened the door to entrepreneurial activity by individual engineers. The technologies are moving so rapidly, innovation is so important, and the capital requirements are, relatively speaking, so modest that a small group of talented, ambitious engineers can start their own company, with the potential for enormous profits.

The integrated circuit was one of the major fruits of this growing entrepreneurial activity. The increasing complexity of electronic devices meant that even transistorized circuits could be too large and heavy, especially for aerospace applications. In addition, the reliability of such circuits was limited by the ever-increasing number of interconnections. The integrated circuit was a solution to both of these problems.



The first integrated circuit was made from a thin slice of germanium. This combination of a bipolar transistor, four input/output terminals, a ground, and gold wires was held together by wax.

Texas Instruments



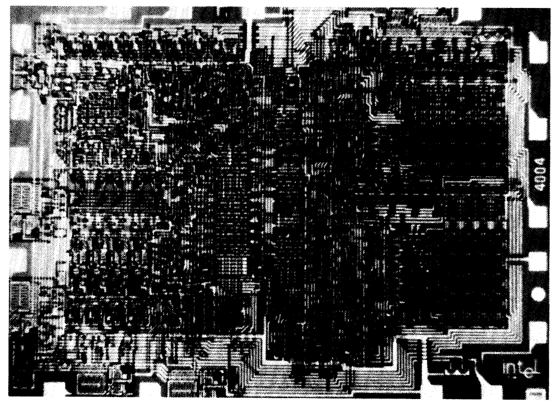
Differences in design approaches between conventional and integrated circuits are illustrated in these two amplifier stages. The integrated circuit design utilizes more transistors but reduces the number of resistors and eliminates the high value of capacitance

Andrew Grove, Robert Noyce and Gordon Moore, founders of Intel Corp.

Intel

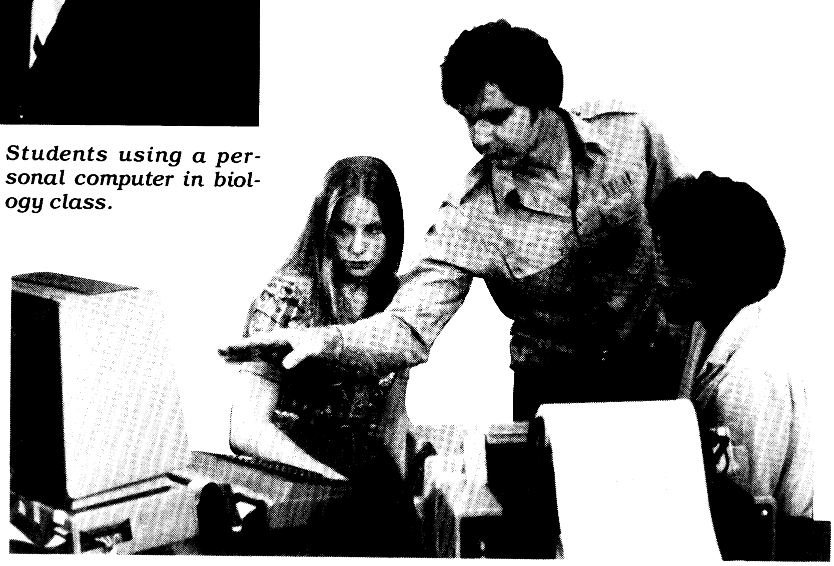
Integrated circuits did more than merely solve a technological problem; they actually changed the way electrical circuits were designed. Engineers had grown accustomed to creating circuits with a minimum of active components, since transistors and diodes were relatively more expensive than resistors and capacitors. But active components are both smaller and easier to put on a silicon chip than inactive ones. Thus, the circuits most adaptable to integration are digital circuits, with many active components performing "yes-no" logic functions. Since these are the sorts of circuits used in computers, the integrated circuit not only made truly small computers possible, it actually encouraged engineers to look for digital solutions to design problems.

The blending of microelectronics and computers has produced the microprocessor, the computer on a chip. This has made possible tremendous reductions in computer size and cost, and consequently has made computers far more available for previously undreamed-of applications. Not since the development of electric power systems began a hundred years ago have engineers produced such a fundamental and far-reaching tool for change. And just as was true a century ago, much of the responsibility for the direction and impact of that change lies with the engineers.



The Intel 4004, the first commercial microprocessor, was originally designed for a programmable calculator. It represented the first consolidation of the arithmetic and logic functions of several chips onto a single integrated circuit. Intel

Frederick E. Terman, the "father of Silicon Valley," with 2 of his students, David Packard (lft.) and William Hewlett (rt.)
Stanford University Archives



Students using a personal computer in biology class.

Technology on the Defensive

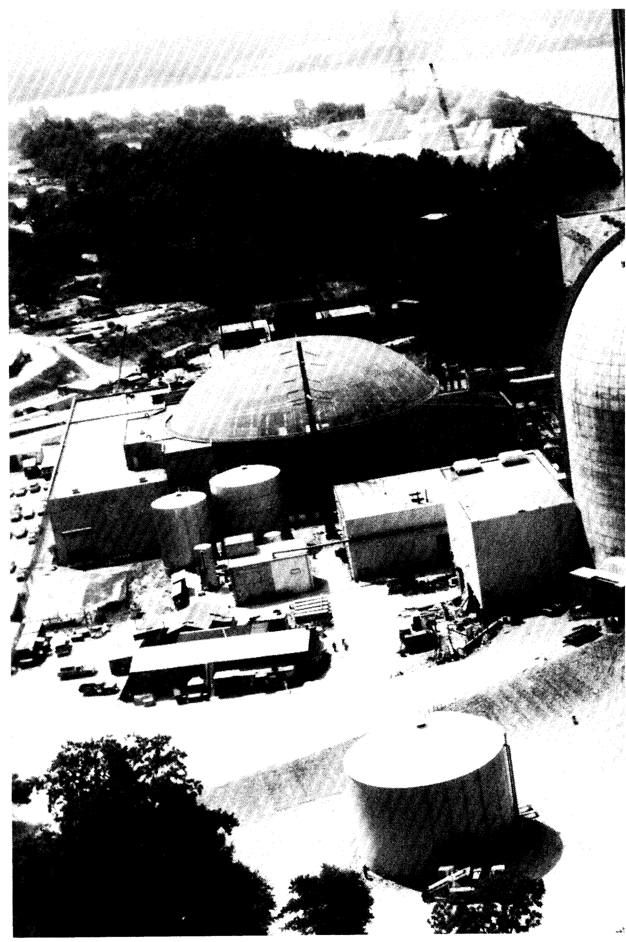
The growing role technology plays in all aspects of life has led many to worry about how it is controlled and by whom.

The Vietnam war, the energy crisis, and environmental concerns have involved engineers in social issues as well as technical ones.

In the midst of the tremendous technical advances of the 1960s and early 1970s, various elements of society began to question the wisdom of many of those advances.

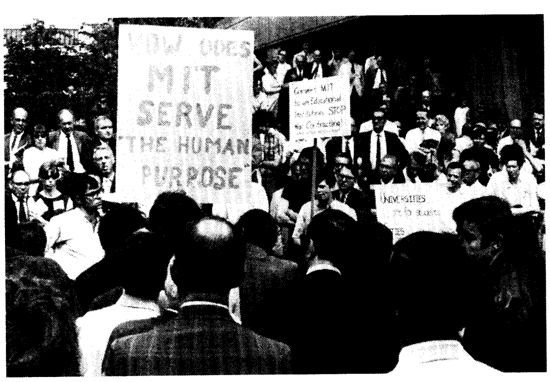
The growing unpopularity of the Vietnam War and the inability of the United States to translate its overwhelming technological advantage into swift military victory tarnished the reputation of defense and aerospace industries. The increasing concern over environmental pollution emphasized the negative effects of technology, which had hitherto been underestimated.

The very generation of electricity itself was challenged. All the major methods of power production were charged with creating environmental damage. Hydroelectric dams caused needless destruction of useful agricultural land and wildlife habitat. Coal-fired steam plants produced large-scale air pollution, and the strip mining of coal did serious damage to the landscape. Oil- and gas-fired plants consumed shrinking, costly natural resources. The most serious and vocal opposition was reserved for nuclear power. A series of accidents at such plants, culminating with the Three Mile Island accident in Pennsylvania, plus the ever-growing cost of building nuclear plants, caused critics to charge that nuclear power was another example of technology that was too big, too expensive, too complicated, and too dangerous.



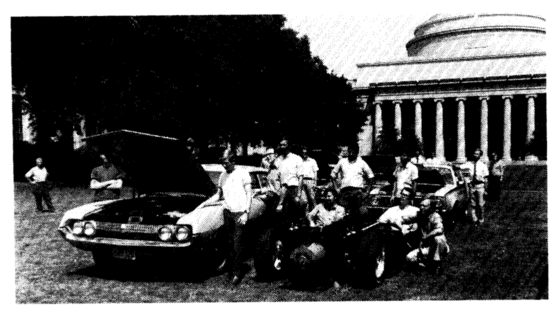
Consolidated Edison

Rally of MIT students protesting defense contracting, 1969

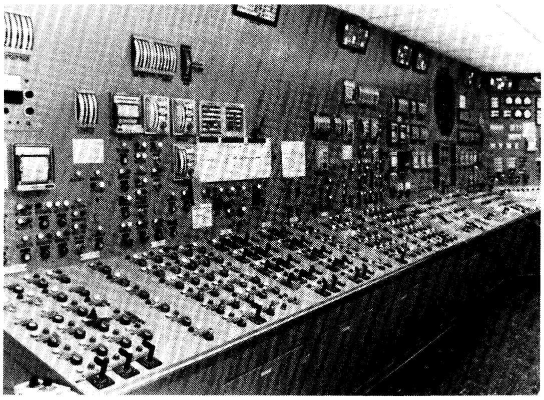


MIT Museum

The Clean Air Car Race, August 1970, one response by engineering students to growing environmental concerns

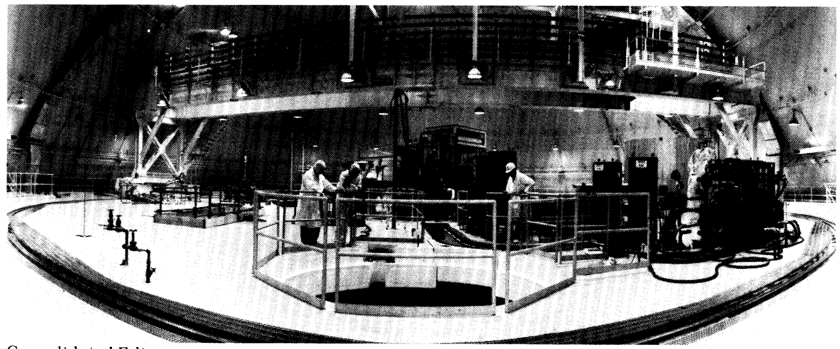


MIT Museum

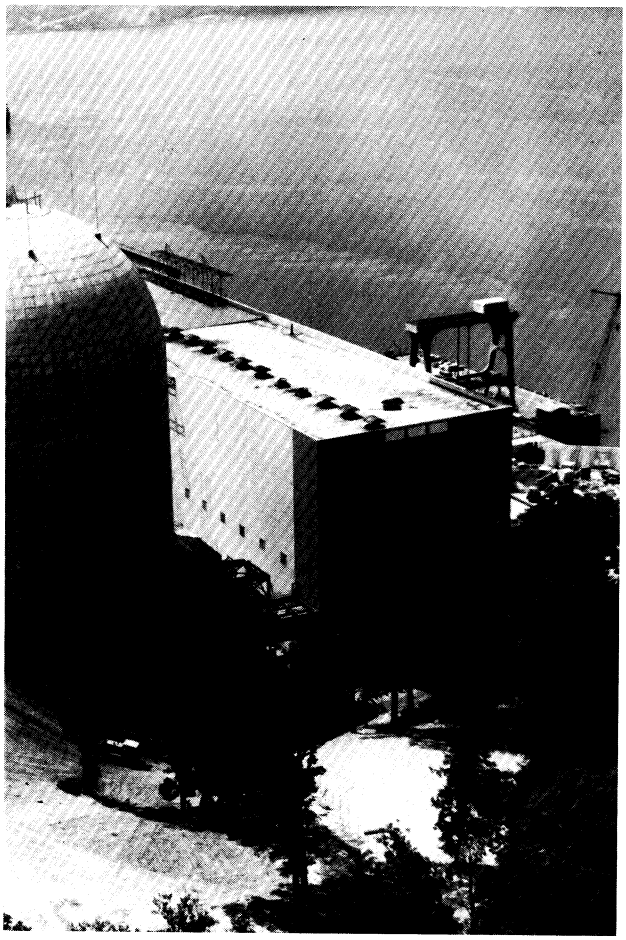


Nuclear power plant control room

Interior of Indian Point nuclear power plant



Consolidated Edison



Consolidated Edison's nuclear power plant at Indian Point, New York, went into operation in 1974

The computer, one of electrical engineering's proudest achievements, was also the object of much scrutiny and criticism. The list of computer related evils seemed endless: unemployment and the devaluing of existing skills; government and business files that were a threat to privacy; computer crime; "computer junkies" who wasted away their lives in front of a terminal; and computer malfunctions that could cause everything from a credit card overcharge to nuclear war.

Engineers who had traditionally seen themselves as problem solvers now found themselves accused of being problem causers. Engineers reacted to this criticism in a variety of ways. Some felt that the answer to the problem caused by technology lay in improving that technology, refining it and often substituting even more sophisticated technology. Others rallied under the banner of "appropriate technology," seeking simple and often decentralized solutions. Still others urged their colleagues to actively enter into the debate over technology, to participate in the nontechnical decisions about how technology was used, and to consider other than strictly technical factors in their work. Finally, many engineers insisted that such involvement was simply inappropriate for engineers; that their job was to provide technical expertise and that to inject subjective elements into the engineering process was to subvert that process.

Growth and Complexity

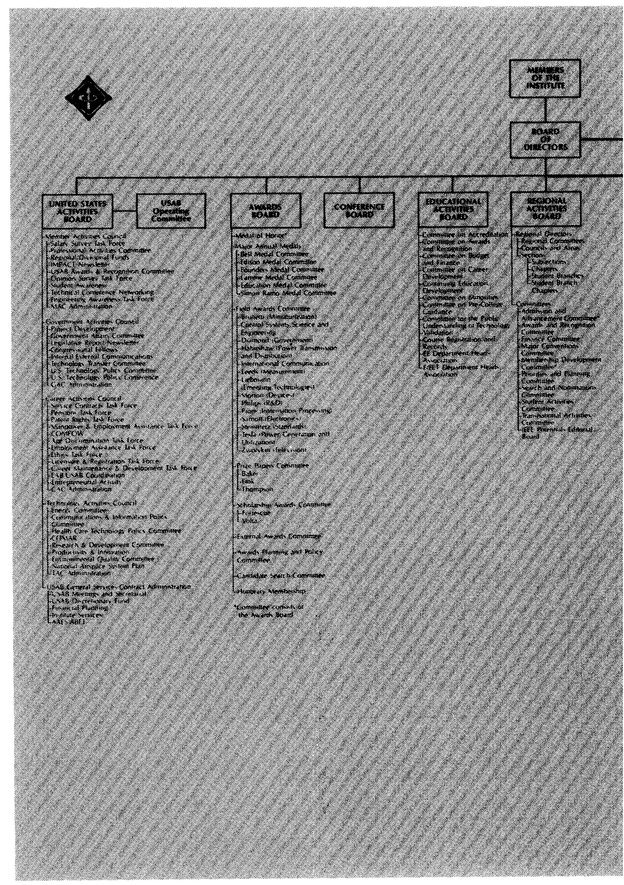
The electrical engineering profession has responded to rapid growth and change by making the IEEE a common meeting ground for widely diverse interests.

The technical and geographic structure of the IEEE reflects both the diversity and the enduring unity of the profession.

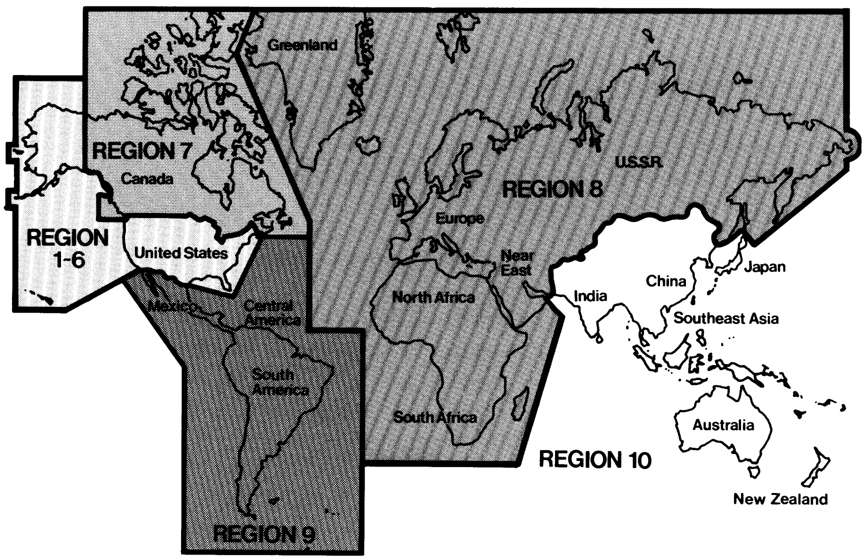
The developments of the past twenty years have had a tremendous impact on electrical engineers as individuals, but they have also had a great effect on the IEEE as an institution.

When the AIEE was founded one hundred years ago, electrical engineering was concerned with wire communication and the production and distribution of direct current electricity for lighting. In the following eighty years, electrical technology expanded to encompass alternating current, high-voltage transmission, radio, vacuum-tube electronics, and solid-state electronics.

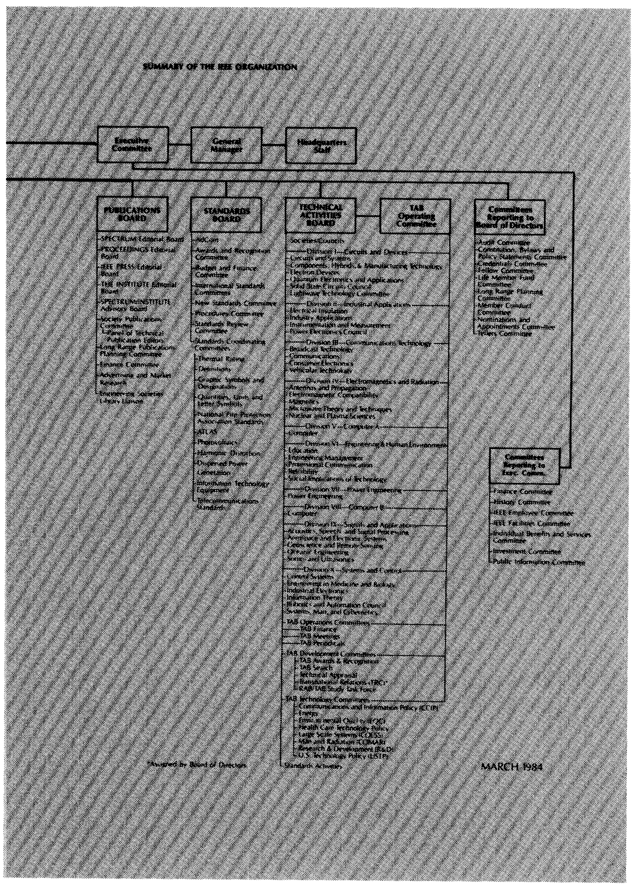
The 1963 merger of the American Institute of Electrical Engineers and the Institute of Radio Engineers came about, in part, because neither organization represented the full scope of electrical technology. The IRE Professional Group system had done much to attract members from the newer fields of electronics, but the IRE held little interest for power engineers. The AIEE, on the other hand, was power oriented, and had, by its own admission, failed to enter new fields. The IEEE resolved not only to merge the two diverse organizations, but to accommodate new technologies as they came along. The new Institute adopted the Professional Group structure of the IRE, which evolved into the present societies. By means of the societies, the IEEE has assimilated such new technologies as microelectronics, satellite communications, and digital computers.



Summary of IEEE Organization



The IEEE, divided into ten geographical regions, claimed about a quarter million members worldwide at the end of 1983



Yet this very effort to accommodate diversity raises its own problems. One such problem is the identity of the profession itself. What is it, beyond a common undergraduate curriculum, that ties together members of the Electrical Insulation Society, the Antennas and Propagation Society, and the Engineering Management Society and makes them all members of the same profession?

A second, related problem is the degree to which the practitioners of a specialty feel that the IEEE serves their interests, and the amount of influence the Institute is willing to grant to a given specialty. As a technical subgroup grows in size and influence the centrifugal forces acting upon the Institute increase. The Computer Society is the best example of this tendency.

The increasing technical diversity of the Institute has been accompanied by rapid growth. Membership has soared from some 150,000 at the time of the merger to over 240,000 today. The sheer size of the IEEE requires special efforts to keep all members adequately informed and to encourage participation by more than an active minority.

In sum, the ever-widening scope of electrical and electronics technology continuously challenges the IEEE to attract the practitioners of new technologies while at the same time defining and promoting the common bonds among them.

Exploring Further

We have presented here only a brief glimpse of the exciting heritage of the electricals. There is much more to be discovered — in books, in museums, and in conversations with the men and women who have created that heritage. Below are some of the places you might start further explorations:

Books

Sanford P. Bordeau.
Volts to Hertz . . . the Rise of Electricity.
Minneapolis: Burgess Publishing Company, 1982. 308 pages, illustrated.

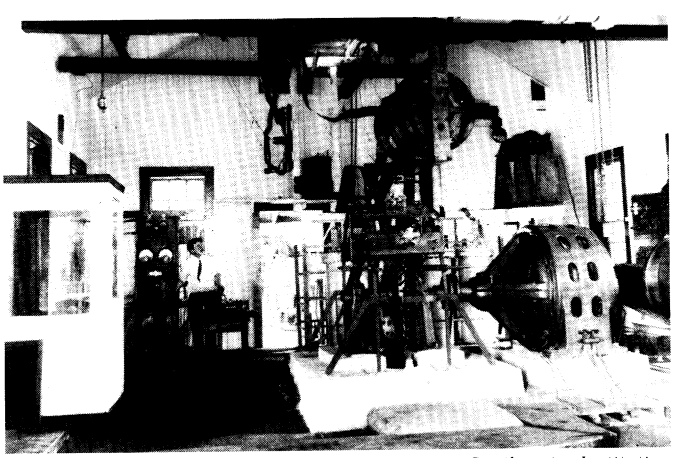
Brian Bowers.
A History of Electric Light and Power.
Stevanage, U.K./New York: Peter Peregrinus Ltd., 1982. IEE History of Technology Series No. 3, 304 pages.

G.W.A. Dummer.
Electronic Inventions and Discoveries.
New York: Pergamon Press, 1978.

Bernard S. Finn and Robert Friedel.
Edison: Lighting a Revolution.
Washington: National Museum of History and Technology, Smithsonian Institution, 1979. 87 pages, illustrated.

John D. Ryder and Donald G. Fink.
Engineers and Electrons.
New York: IEEE Press, 1984. 251 pages, illustrated.

Harold Sharlin.
Making of the Electrical Age: From Telegraph to Automation.
New York: Abelard-Schuman, 1963. 248 pages, illustrated.



Smithsonian Institution

Reginald Fessenden's broadcasting installation at Brant Rock, MA, c. 1905

Museums

Another exciting place to explore the history of electrical engineering is in a museum that has old (and sometimes not so old) electrical devices on display. Here are just a few of these:

United States

California

California Museum of Science and Industry.
700 State Drive, Los Angeles 90037

Foothills Electronics Museum.
Foothills College, 12345 El Monte Road, Los Altos Hills, 94022

Connecticut

Burndy Library.
Electra Square, Norwalk 06856

District of Columbia

National Museum of American History, Smithsonian Institution.
Constitution Ave. at 14th Street, N.W., Washington 20560

Navy Memorial Museum.
Washington Navy Yard, 9th and M Streets, S.E., Washington 20374

Florida

Edison Winter Home and Museum.
2350 McGregor Blvd., Fort Myers 33901

Illinois

Museum of Science and Industry.
57th Street and South Lake Shore Drive, Chicago 60637

Massachusetts

The Computer Museum.
Museum Wharf, Boston

The MIT Museum.
265 Massachusetts Ave., Cambridge 02139

Michigan

Greenfield Village and Henry Ford Museum
20900 Oakwood Blvd., Dearborn 48121

Minnesota

Bakken Library of Electricity in Life.
3537 Zenith Ave., Minneapolis 55416

New Jersey

Edison National Historic Site.
Main Street at Lakeside, West Orange 07051

New York

Museum of Broadcasting.
1 East 53rd Street, New York 10022

Schenectady Museum.
Knott Terrace Heights, Schenectady 12308

Pennsylvania

The Franklin Institute.
20th Street and Benjamin Franklin Parkway,
Philadelphia 19103

Australia

New South Wales

Power House Museum.
Harris Street, Ultimo, Sydney, 2000

Canada

Ontario

The Engineerium.
Niagara Falls L2E 6V6

National Museum of Science and Technology.
1867 St. Laurent Blvd., Ottawa K1A 0M8

Ontario Science Center.
770 Don Mills Road, Toronto M3C 1T3

France

Musee National des Techniques.
292 rue Saint-Martin, Paris Cedex 3

Federal Republic of Germany

Deutches Museum.
Museumsinsel 1, Munchen 22

India

Birla Industrial and Technological Museum.
19 A Gurusaday Road, Calcutta 700019

Japan

Science Museum.
2-1 Kitanomaru Park, Chiyodaku, Tokyo

Sweden

Tekniska Museet.
Museivagen 7, Stockholm

United Kingdom

Science Museum.
Exhibition Road, London SW7 5NH

Joseph J. Thomson and Frank B. Jewett at Bell Labs, 28 March 1923
MIT Museum

A Century of Electricals is based on the exhibit of the same name, created for the Centennial of the Institute of Electrical and Electronics Engineers and sponsored by the IEEE Centennial Task Force, John D. Ryder, Chairman.

We wish to acknowledge here the generous assistance of the following institutions in the preparation of *A Century of Electricals*, particularly in the provision of many of the photographs included herein:

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PART II
THE IEEE CENTENNIAL

CENTENNIAL TASK FORCE

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James B. Owens, *Vice Chairman*
Charles A. Eldon, *Vice Chairman*

John Bardeen
William R. Hewlett
William C. Norris
Robert N. Noyce
Simon Ramo
Ian M. Ross
Roland W. Schmitt
Mark Shepherd, Jr.
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CENTENNIAL PROLOGUE

John D. Ryder

In passing the chairmanship of the IEEE History Committee to me in 1975, Frederick E. Terman stated that the History Committee sorely needed a clientele. I interpreted this statement as a charge to interest more people in reading electrical history, in writing electrical history above the anecdotal level, and in carrying on research in the history of electrical technology and science. These three aims were useful in directing the efforts of the History Committee in the succeeding years.

In 1975–76, as a first step, the clientele was enlarged by an affiliation with the IEEE Education Society, instantly giving material on history a potential readership of several thousand through the TRANSACTIONS ON EDUCATION.

To encourage development of future historians, the History Committee proposed IEEE sponsorship of a graduate fellowship for study in electrical history. This proposal was accepted, and financing for this annual fellowship was provided by a receptive Life Member Fund committee. Some of the beneficiaries of these annual grants are now reporting on their historical research in major publications. This program is probably unique in engineering circles since recipients are not required to have academic training in an engineering field.

It was not to be expected that IEEE members would suddenly begin to write numbers of papers on our history, so it was necessary to interest professional historians of technology, usually with little or no formal engineering training, in exploring historical questions in the electrical field. Fortunately, the History Committee already included several such men, and Dr. James Brittain of the Georgia Institute of Technology was especially helpful in spreading word of the IEEE interest within an existing body, the "Jovians," an electrical subgroup of the Society for the History of Technology. There are many points in our electrical history where the story is unclear and in need of research. The recently released Edison papers provide a wealth of examples.

An augmented program of historical publication began with the IEEE PRESS book *Turning Points in American Electrical History*, edited by Dr. Brittain. This 1977 book was a collection of 64 important "first" papers which drastically altered the direction of our field. The story began with a 1752 paper by Benjamin Franklin, continued with contributions by Steinmetz on hysteresis, Bell on telephony, Houston on the Edison effect, de Forest on the Audion, Black on feedback, and ended with papers by Bardeen and Brattain on the transistor and Brainerd and Sharpless on ENIAC. To retain a true feeling for the history which these papers represent, they were reproduced in original typeface and format. Dr. Brittain set the stage for each paper with introductory comments on the paper itself and on the author.

The value of combining papers by professional historians with papers by engineers who had participated in the developments covered was demonstrated by the September 1976 Bicentennial issue of the PROCEEDINGS OF THE IEEE. This issue, entitled "Two Centuries in Retrospect," was planned and edited by Dr. Brittain and this writer. It included 23 papers whose authors were equally divided between professional historians and engineers. The first century was covered in four papers by historians. The second century was treated under the headings of Telecommunications and Electronics; Power, Light, and Transport; and Social, Professional, and Educational Aspects. Even the cover illustration of the issue was provided by an engineer, the late Daniel Noble of Motorola, painting modernistically under the name of "Elbon."

In August 1980, cooperation between the History Committee and the IEEE Education Society led to a special history issue of the Education TRANSACTIONS, again under the editorship of Dr. Brittain. This issue, largely based on the results of study by historians, emphasized people rather than technological details.

By 1980, these various efforts featuring our history had demonstrated the need for and had culminated in the establishment of the IEEE Center for History of Electrical Engineering (CHEE) under the leadership of a technical historian. The current director, Dr. Ronald Kline, received support for his graduate research and dissertation on the work of Steinmetz as the second recipient of the IEEE History Fellowship mentioned above.

By late 1978, it was recognized by many that the approaching Centennial of the Institute provided a unique opportunity to call the attention of both the engineering profession and, as far as possible, the general public to the accomplishments of electrical engineers over the past century. The Board of Directors appointed an Honorary Centennial Committee of eminent engineers and also established a working Centennial Task Force, with this writer as chairman. In the first meetings of the Task Force in 1979 and

1980, a Centennial logo, a Centennial medal and guidelines for its awarding, and the plans for prospective major events of the Centennial year were developed.

The writing of a history of the Institute was proposed as a suitable project, and contractual arrangements were made in the fall of 1981 with an historian, Dr. Michal McMahon, to undertake this work. The result was the 320-page hardcover book, *The Making of a Profession*, published in late 1984. At the suggestion of Donald Christiansen of IEEE SPECTRUM, it was decided that a popular and less formal history of the electrical field should also be published. The Life Member Fund was approached for money to assist in producing a liberally illustrated volume, and this writer asked Donald G. Fink, the first IEEE general manager, to join him in writing such a book. The fruits of our labor appeared in January 1984 as the 272-page hardcover book *Engineers and Electrons*. Both books were published by the IEEE PRESS.

The various events of the Centennial year, including the impressive Centennial Convocation in Boston in May and the Centennial Technical Convocation at the Franklin Institute in October, are described in the following chapter. Part III of this book is based on material presented at the latter event, which had as its theme "The Second Century Begins."

One thing the events of 1984 brought home to the thousands who participated in them is that the electrical engineering profession has a truly rich and proud history and heritage. Without a doubt, electrical history—and hence the IEEE History Committee—has gained a clientele.

THE IEEE CENTENNIAL

The Institute of Electrical and Electronics Engineers had its beginnings a century ago, on May 13, 1884, when a group of electrical inventors and entrepreneurs met in New York City to form the American Institute of Electrical Engineers (AIEE). They were motivated by the fact that the Franklin Institute was sponsoring an International Electrical Exhibition in Philadelphia during the coming fall and by the realization that no national electrical society existed in America to host the distinguished engineers from abroad who were expected to attend. The first technical meeting of the AIEE was held at the Franklin Institute on October 7–8 during the Exhibition. Thus, the IEEE centennial has especially close ties with the Franklin Institute.

The present Institute of Electrical and Electronics Engineers came into being in January 1963, when the AIEE merged with the Institute of Radio Engineers, which had been founded in 1912.

Planning for the centennial began in 1978, when the Board of Directors formed the IEEE Centennial Task Force under the chairmanship of John D. Ryder. Its mission was to develop and coordinate a broad program of centennial activities and events of an Institute-wide nature. The Task Force was aided by an Honorary Centennial Committee composed of eminent IEEE members. The resulting centennial activities, summarized below, provided a rich variety of opportunities for honoring the past, celebrating the present and contemplating the future.

HONORING THE PAST ...

Remembrance of the past 100 years of electrical progress took many forms at the IEEE: special meetings, commemorative artwork, proclamations and souvenirs. And in a separate gesture, the United States Postal Service issued four stamps honoring a quartet of great electrical engineering inventors: Charles Proteus Steinmetz, a pioneer in the field of ac systems, high voltage power, and electrical engineering theory; Edwin H. Armstrong, a radio pioneer who developed FM broadcasting; Nikola Tesla, inventor of the induction motor; and Philo T. Farnsworth, the developer of electronic television.

In January of 1984, a Founders Program at the Winter Meeting of the IEEE Power Engineering Society in Dallas launched the Centennial Year. More than 1,800 people attended the conference, which focused on the dramatic development of electric power over the past 100 years.

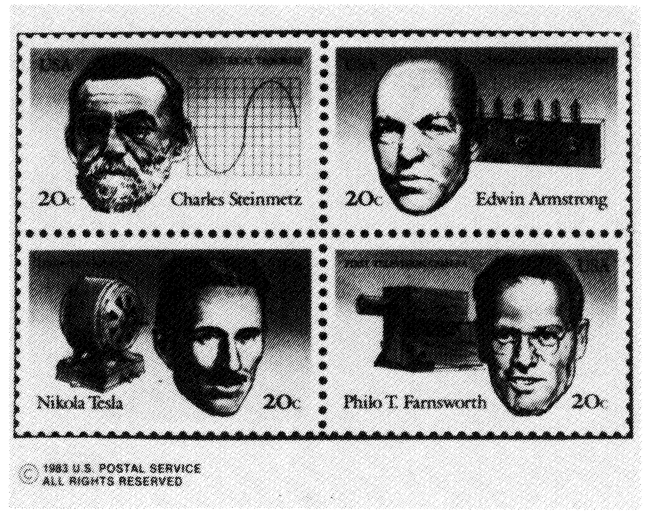

Fig. 1: Four great electrical engineers

The IEEE Center for the History of Electrical Engineering organized and produced "A Century of Electricals," an exhibit of 24 graphic and narrative posters tracing the history of electrical engineering. The exhibit was later reproduced in publication form with the help of a grant from the Hewlett-Packard Foundation and is reproduced elsewhere in this volume. And, in an IEEE-sponsored art contest, Joaquin I. Ballestero's interpretation of "a century of electrical progress" took First Prize. This and five other artistic renditions depicting communications, computers, instrumentation, power engineering and solid-state electronics were made into posters.

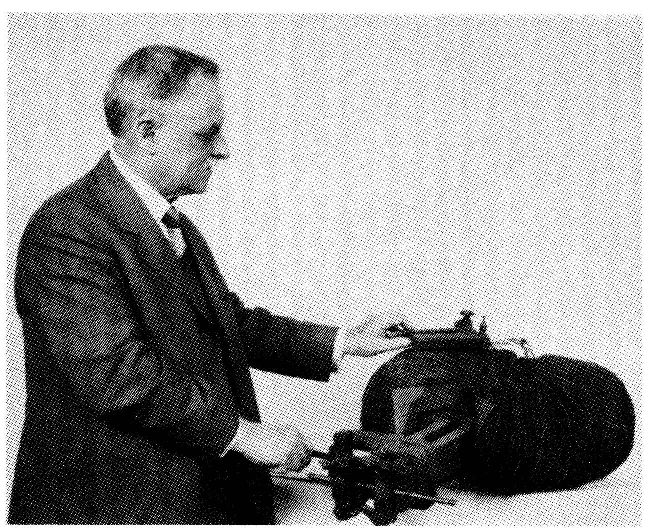

Fig. 2: Elihu Thomson

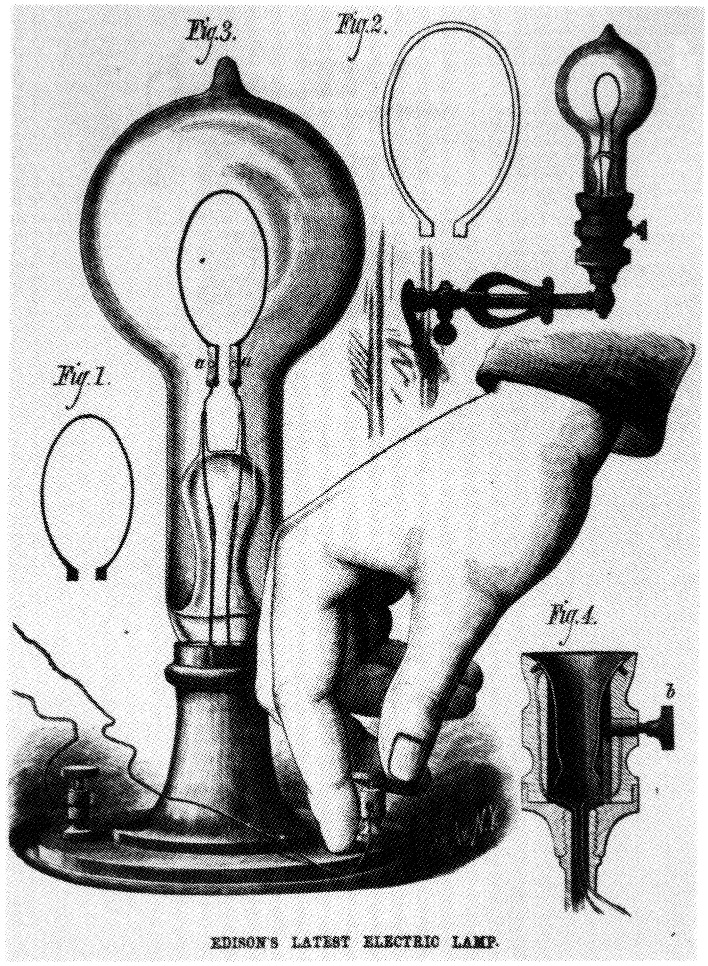

Fig. 3: Edison's Electric Lamp, early 1880's

Two commemorative plaques were unveiled during the year: one at the Franklin Institute, marking the anniversary of IEEE's first technical meeting in 1884; and one at the United Engineering Center in New York City, site of IEEE's headquarters. Numerous commemorative souvenirs were designed and made available, and 1,984 Centennial Medals were cast in bronze. These were awarded to IEEE members selected for special recognition by each of the IEEE's 250 Sections, 33 Societies, and seven major Boards. A list of the members so honored appears elsewhere in this volume. A single gold medallion was struck for U.S. President Ronald Reagan.

On the IEEE's 100th birthday in May, New York City Mayor Edward I. Koch issued a special proclamation to commemorate the founding of the AIEE in New York City 100 years earlier. And, on June 14, Senator John W. Warner (D–VA) delivered a short speech to the Senate about the IEEE. The address is now part of the Congressional Record.

CELEBRATING THE PRESENT ...

Present-day issues and state-of-the-art developments in electrotechnology were at the heart of several Centennial activities. Examining governmental policy that restricts the flow of technological information, and keeping the media accurately informed of the IEEE's work were but two typical concerns in 1984.

In February, the Technical Activities Board (TAB) sponsored a Centennial Briefing for the Media, while the United States Activities Board (USAB) sponsored a Conference on U.S. Technology Policy in Washington, D.C. Representatives from industry, government, the media, and the engineering profession gathered to deliberate on technology and related policies with such speakers as Nobel Prize Laureate Kenneth Wilson, Presidential Science Advisor George A. Keyworth, Energy Secretary Donald P. Hodel, Under Secretary of Defense Richard D. DeLauer, TRW Director Simon Ramo, and IBM Vice President (now National Science Foundation Director) Erich Bloch.

The Centennial Convocation, held in Boston from May 13–15 to mark the actual date of founding of the Institute, was the centerpiece of the year. An estimated 1,200 people attended this three-day gala, which began on the 13th with the presentation of the IEEE Medal of Honor, six major medals, and other awards of the Institute. Newly-elected Fellows and Honorary Members of the Institute were also recognized.

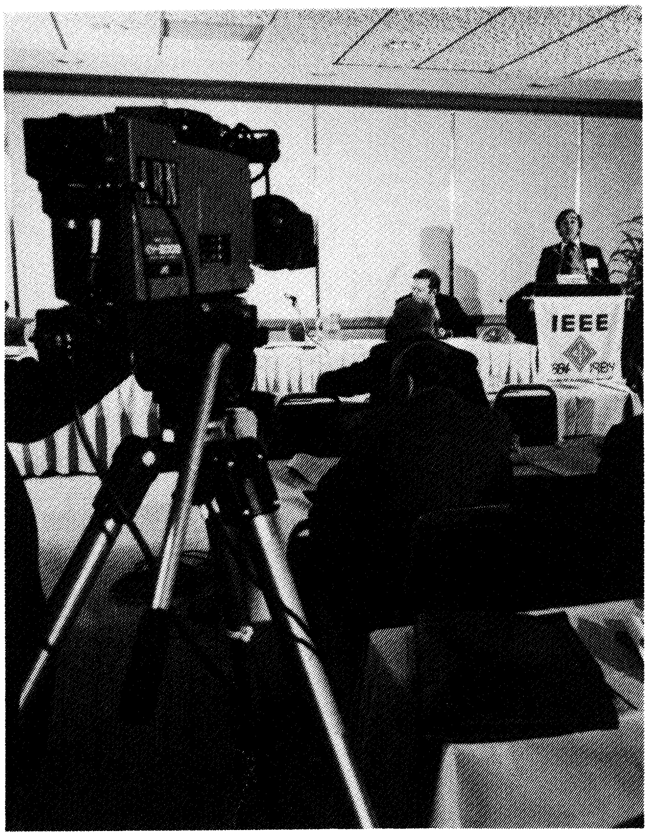

Fig. 4: Centennial Briefing for the Media

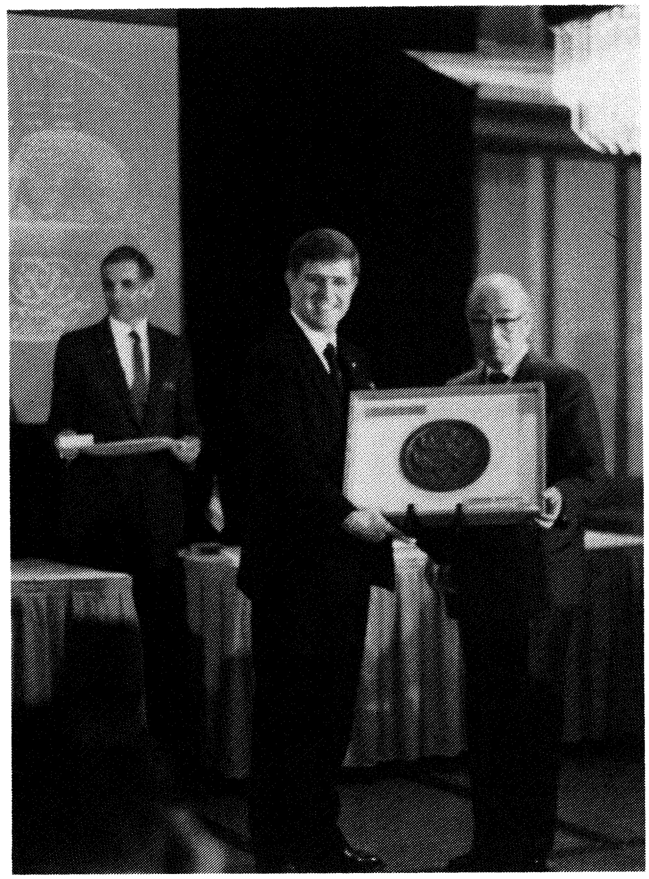

Fig. 5: Learned Societies luncheon presentation

On the second day, representatives of approximately 90 scientific and learned societies from around the world presented gifts to the Institute at a special luncheon in their honor. On behalf of the IEEE, each visitor in turn received a Centennial Medal. The reception for the learned societies was also chosen as the setting for the premier of a 28-minute film, "The Miracle Force." Narrated by Orson Welles, the film focuses on a group of typical engineers who describe their work in electric power, communications, computers, aerospace, and biomedical engineering.

That same morning, the results of an IEEE *Spectrum*/Harris poll on "Electrotechnology and the Engineer" were revealed at a press conference. Controversial survey findings sparked a debate among industry leaders about the way electrical engineers view their jobs and their industry.

The Centennial Banquet was held later that evening. Heading the list of 850 attendees was the Honorary Centennial Committee and 40 past presidents of the IEEE and its predecessor societies. Other special guests included Gioia Marconi Braga, daughter of Guglielmo Marconi; Robert Lucky, of Bell Labs (acting as Master of Ceremonies); and David Packard, Chairman of the Board, Hewlett-Packard, who was the principal speaker.

The evening's festivities culminated with an original theatrical presentation, "Generations of Giants," in which actors and multimedia projections dramatized major characters and events that laid the foundation of electrotechnology.

The last day of the Convocation was one for assessing the present and planning for the future. The Technical Activities Board hosted a Centennial Division Breakfast, where IEEE members and representatives from industry, government, and academia participated in roundtable discussions on the issues affecting electrotechnology. A Centennial Education Forum, sponsored by the Educational Activities Board, engaged speakers and audience on the question, "How should traditional engineering be modified to make engineering graduates more responsive to the needs of industry?"

Fig. 6: Past presidents of the IEEE

Fig. 7: Gioia Marconi Braga

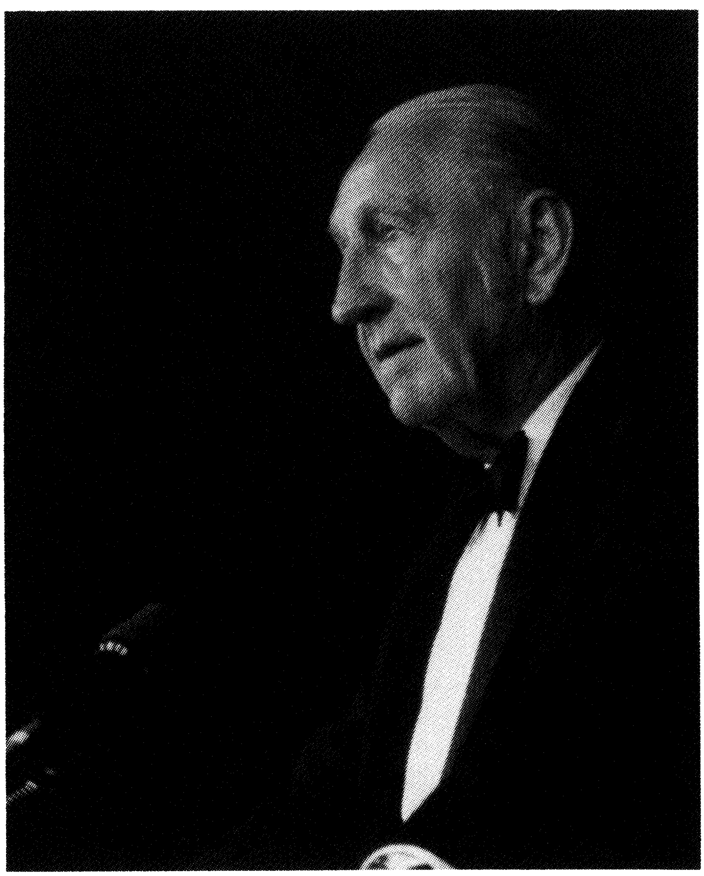

Fig. 8: David Packard

Fig. 9: Generations of Giants' Ben Franklin

Also that day, delegates representing the majority of the Institute's 250 Sections convened for a special Congress. Preparation for the Congress involved interviews with more than 2,000 former, current, and prospective IEEE members on the subjects of Section and Region operations, continuing education, technical and professional activities, technical publications, and membership benefits.

CONTEMPLATING THE FUTURE ...

Optimism ran high throughout 1984, as the IEEE prepared several activities to pave the way to the future.

On October 8, the Institute's Centennial Technical Convocation, titled "The Second Century Begins," took place at the Franklin Institute in Philadelphia. A joint effort between the IEEE and the Franklin Institute to commemorate the site of the AIEE's first technical meeting, the Convocation was considered the largest geographical gathering in the history of the Institute. More than 5,000 people across the U.S. and in Canada, Mexico and Puerto Rico tuned in by satellite with those at the Franklin Institute for the interactive telecast of the banquet program.

The telecast began with a videotaped address by U.S. President Ronald Reagan, who accorded special recognition to the technical milestones achieved by electrical, electronics, and computer engineers.

In the keynote address following President Reagan's speech, Bernard M. Oliver, retired Vice President for Research and Development at Hewlett-Packard, spoke on "The Second Century Begins." A discussion addressing the social implications of technology ensued among Dr. Oliver and panelists Edward E. David, Jr., President of the Exxon Research and Engineering Company, who acted as moderator; Joshua Lederberg and Charles H. Townes, Nobel Prize winners; and Alvin Toffler, author of *Future Shock* and *The Third Wave*.

In addition to the banquet program, the Convocation included a day and a half of sessions featuring

Fig. 10: Bernard M. Oliver, left, and Alvin Toffler

eminent speakers and discussants. The banquet and session presentations appear elsewhere in this volume.

The Centennial Members' Forum for Planning IEEE's Future, which took place in Toronto, Canada, in August, sought to make IEEE leaders aware of members' needs. More than 2,000 members were interviewed by the seven major IEEE Boards among their respective constituencies, including all IEEE Sections and Societies. The most important observations were:

* Provide more applications-oriented material, not only in publications but also in meetings and

Fig. 11: Centennial Keys to the Future presentation

continuing education programs;
* Develop more affordable continuing education courses;
* Improve the image of electrical engineers among employers, the general public, and government;
* Reinstitute an annual meeting of the IEEE;
* Give greater recognition through IEEE awards for contributions to engineering practice;
* Strengthen industry relations;
* Enhance influence within the government;
* Establish a publication devoted to professional activities that reaches all members.

Major Centennial celebrations came to a conclusion on November 30 as more than 600 IEEE members and representatives from industry, government and academia gathered in San Jose, California for two events. The Young Engineers Forum included a luncheon and three panel discussions that zeroed in on educational and career-related matters. After an evening reception, a banquet set the stage for the "Centennial Keys to the Future," presented by each of the 33 Societies to young engineers representing the Societies' technologies. Dr. Gordon E. Moore, co-founder, Chairman, and Chief Executive Officer of Intel Corporation, addressed the gathering with a forecast of technological breakthroughs to come.

And so the second century began.

PART III
THE SECOND CENTURY BEGINS

PRESIDENT RONALD REAGAN'S MESSAGE TO THE IEEE

Ladies and gentlemen of the Institute of Electrical and Electronics Engineers, I am delighted to have this chance to talk to you at your Centennial Technical Convocation at the Franklin Institute in Philadelphia. On behalf of the American people, I congratulate you on your 100th anniversary. The history of IEEE spans a remarkable century of technological progress. Over the years your members, now a quarter million strong, have proven there is nothing we can't do if we set our minds to it. And each breakthrough lifted us to a new, better, and higher plateau, paving the way for the great gains in our daily lives in the security of our nation and for the next generation.

I can remember—believe me, it doesn't seem long ago—those first days of radio. And as I think back to my early broadcasting days in Iowa, it's almost unbelievable to think how far we've come—from radio to TV, transistors, computers, fiberoptics, microelectronic chips, and so much more. Yours is the work of a true revolution and one that rises from the deepest yearnings of the human spirit to challenge the limits of knowledge and to put the power of discovery at the service of progress. You've been and you remain the pulse of America's technological power, the cutting edge of our worldwide technological leadership. You apply the theories and principles of science and math to practical problems, and your work serves as the link between scientific discovery and everyday application. You're the real heroes of high-tech, and you have good reason to be proud of your countless achievements. And today you and your industry continue to lead us into the future with expanding markets, new jobs, and exciting progress. You've opened the door to great advances in productivity which would have been considered unthinkable only a few decades ago.

No wonder electronics has been at the forefront of America's wonderful economic expansion, and I don't doubt that you'll remain right there. We look to you for innovation and excellence and you've never let us down. And nowhere is this more true than America's new frontier, the vast frontier of space. We already benefit daily from a modern revolution in worldwide communications. We can anticipate tomorrow's weather and prepare for it. Space technology has brought one lifesaving breakthrough after another. Our space shuttle system is opening a new era to pursue exciting scientific, medical, educational, industrial and commercial opportunities of space, and none of this would have been possible without the contributions of the IEEE members.

Call me an optimist, but I am convinced that we've only seen the beginning of what we can accomplish in space and right here on the ground. When I read the theme of your Centennial Convocation—The Second Century Begins—I couldn't help thinking that, as you sit in Philadelphia, the spirit of Benjamin Franklin is still there with you. It's been said of Franklin that he was not one of those men who owed his greatness merely to the opportunities of his time. In any age, in any place, Franklin would have been great. Mind and will, strength and grace, for the benefit of our fellow man.

It is this spirit that carries you forward into your Second Century. From the shrinking microchip to the expanding horizons of space, your work is going to continue to dazzle our imagination and continue to move us forward by leaps and bounds.

To your president, Dick Gowen, and to all of you, congratulations once again on your anniversary and best wishes for a successful and enjoyable convocation.

Thank you and God bless you all.

THE ENGINEER'S ROLE IN DETERMINING PUBLIC POLICY

William C. Hittinger

It is a hundred years to the day that the IEEE held its first meeting. Out of curiosity, I had someone look up the headlines that appeared on the front page of *The New York Times* this day in 1884. Here is an abbreviated list: The lead story reported on proposed financial reforms in Egypt. Another reported that the City of New York had to pay $1.5 million for unused water meters. (Nothing new in either of those stories.) However, we have such stories as: "Lord Litton's Love Letters," "Eloping with a Boston Drummer," "Killed by a Pumpkin," and my favorite for the day's news on October 8, 1884: "How New Jersey Snakes Get Milk."

While the Institute's first meeting did not make the front pages of the *Times*, it has been a participant in the great technological changes of the century, a century that has seen the taming of the electron and the birth of the age of information. Alvin Toffler calls this new age the Third Wave.

Throughout the history of this Institute, the emphasis quite rightly was on science and engineering and the exchange of knowledge, ideas, and concepts. The focus was on the technical. As scientists and engineers, we tend to leave the political arena to others. Some of us may even regard the art of politics as lacking the objectivity and knowledge of science.

As we look to the next century and the challenges that we will face, we must examine the notion that public policy issues have scientific and engineering implications. If this is so, it means that we as scientists and as engineers must take a greater role in how these issues are resolved.

This is not a new idea. The precedent for such a major change in the direction of this Institute goes back to the days of the Republic's founding fathers, who often combined their interests in science and politics. Benjamin Franklin and Thomas Jefferson are two examples that come to mind.

Politics and science are—to borrow C. P. Snow's phrase—two cultures that are more often than not considered separate entities unto themselves. In fact, science and politics are truly inseparable. It is just that those who practice science and those who practice politics tend to see themselves as citizens of different cultures.

There are many examples throughout history, but one—although obscure—illustrates my point. In the 19th century there was an economist and political scientist, Henry Charles Cary, who is credited with introducing the experimental method into the social sciences. Karl Marx called Cary, who incidentally was a Philadelphian, the only American economist of note.

Prior to the Civil War, Cary wrote to Lincoln, calling for the industrialization of the South. Once industrialized, Cary believed, the South would no longer depend on selling its cotton on the English market or on buying English manufactured goods. In his view, the ensuing prosperity would bring increased economic benefits to both planter and slave and would soon lead to emancipation.

Cary pressed Lincoln to build a great highway across the South, linking it to the North and thereby establishing closer economic relations between the two regions.

From the perspective of hindsight, which is always 20-20, it is easy to see how different our history might have been if Cary's advice had been taken. Of course, this does not mean that Lincoln was wrong. His concern was preservation of the Union and human rights—political issues. Cary's vision bridged the scientific and the political. It is this vision that is needed today.

We are already in the midst of the age of information and cresting on Mr. Toffler's Third Wave. This new age brings with it new opportunities for human progress, but it also poses formidable political challenges. It has been said that up to the Middle Ages, power attracted money. From the Renaissance on, money attracted power. I believe that in this new age, information will attract power. How this power will be used is a political concern and a proper issue for public policy debate. It also seems to me that as scientists and engineers we are at the leading edge of this new age and, therefore, should have more than a passing interest in how the instruments we create are to be used.

Daniel Yankelovich, the public opinion researcher, writing in the fall issue of *Issues in Science of Technology*, notes: "Science in its institutional forms—the professional associations, faculties, and academies—can also join the debate as social-political entities concerned with the health of the larger society. There are a handful of pressure points where the disparity between scientific accomplishment and social arrangements are most acute. As a second strategy, official science may wish to gain a better understanding of these pressure points and help to formulate action to relieve them, even though they involve knowledge that transcends scientific competence in the narrow sense."

The pressure points in the new age of information that impact our areas of concern involve education, industry, and government. In education, the central question is how to provide literacy in the age of information. We have already seen the slide rule replaced by the personal computer. Our children and grandchildren are beginning to use computers in grammar schools. At the university level, the concern is with course content—not only in engineering—but also how to organize arts, science, and engineering in a university structure. Then there is the challenge of providing self-renewal and training for older individuals.

The continuing growth of service industries will accelerate as we move to the information society. As a consequence of mechanization, there is reduced labor content per unit of production in many fields—manufacturing, agriculture, transportation, and commerce. This will continue. At the same time, newer industrial societies, particularly in the Pacific basin, are becoming more competitive. Manufacturing will not disappear from the U.S. scene, but we will be more hard pressed than ever with worldwide competition.

The age of information will create new products and services and will continue to grow. Its new business opportunities and its risk of failure will be greater than ever.

How do we deal with these new issues and the pressure points that they create? It seems to me that their scope is beyond the capability of any one organization or segment of our society. There is a definite need for combining various elements in government, industry, and academia to leverage their talents and resources in shaping public policy on these issues. The agenda for such consortia might include such subjects as supporting basic research, devising ways to improve the investment climate, sorting out the fair-trade issue, and addressing the issue of the need for a national industrial policy.

Let me take a few of these issues and outline how I view them. In basic research, we have to stress that basic commercial research is just as important to the national interest as basic defense research. As you know, half of all basic research in this country is defense related. Industry did not—probably cannot—devote the necessary investment to basic research because the payoffs are too remote and highly risky. Yet the continued growth of our economy in terms of employment and income may well depend on the advances created in our great industrial and university laboratories. R&D is the seed corn of our economy, and this is especially true in the age of information. Within this context, the subject of a national industrial policy is currently a very hot issue.

I suppose we can consider an industrial policy comparable to the industrial policy of Japan or France. Following those examples, we could set up certain national goals—certain national energy, housing, and trading goals.

More and more talk is coming out of rather unexpected quarters about this kind of thing. Lee Iacocca has talked and written articles about a national industrial policy. Felix Rohatyn has written some brilliant articles about it. Henry Ford has talked about cooperation between government and industry in the style of the Japanese or the French.

This is an argument that could go on forever, and I know each of you has a different point of view on it. My point of view is that a national industrial policy probably could not come to pass in the United States, even if it were desirable. The conditions of the past and our concept of the marketplace are too deeply ingrained. I do not think these perceptions could change in time to help us recreate industry and thereby recreate wealth in the United States.

Given the complexities of these issues, what should the role of the IEEE be as it moves into its second century? I believe that the Institute should continue its role both as a source of education for its members and to the nation in addressing technological issues. I also believe that the resources of the Institute could be used as a major technical forum. In effect, to become a MITI of the United States.

MITI, the Ministry of International Trade and Industry in Japan, by itself is probably not the sole reason—perhaps not even a major reason—for Japan's economic success. MITI's forte seems to be its ability to bring divergent points of view together in creating national policies that are generally acceptable to its society. Its effectiveness is not measured by the size of its budget, but by the web of communications and the close coordination it has established with the private sector. This coordination and communication tends to set priorities and to focus resources. What is done in this country in an individualistic, haphazard way is done there in a rational, systematic way. I believe that the IEEE should examine MITI as a model and evaluate it as an instrument that would make significant economic and technological contributions to the nation.

I know that the course of action that I suggest is a difficult one, fraught with controversy. It represents a major course change in the traditional role for an institute with a century of heritage behind it. Yet we are about to embark on a second century—a century that will undoubtedly see unprecedented technological and social change.

My suggestion is offered primarily to stimulate debate and dialogue in the formal and informal sessions of this convocation. We have some of the greatest scientific and engineering minds in the country here, and I look forward to the spirited and stimulating discussions on this issue.

William C. Hittinger *was executive vice president, corporate technology, RCA Corporation, and a veteran of over thirty-five years in electronics, having held positions with Western Electric, National Union Radio, and Bell Laboratories. He also served as president of General Instrument Corporation and as president of Bellcomm, Inc., an AT&T affiliate in systems engineering for NASA's manned space flight program. Mr. Hittinger served in the U.S. Army, is an IEEE Fellow, and a member of the National Academy of Engineering.*

THE IMPACT OF ELECTRICAL AND ELECTRONICS TECHNOLOGIES ON HUMAN ENDEAVOR IN THE SECOND CENTURY

Robert A. Frosch

One hundred years is a long time, and predicting the future has a very poor history. No one I know of has succeeded in predicting the future by statistics, or by numerical manipulation, or by the examination of trends. Indeed, this is not surprising because it appears in hindsight that the future depends on what I can only describe as very tiny giant steps which frequently are not recognized for what they are at the time, but which later lead to significant growth and have an important history.

What one can do, which is just as chancy but may be more interesting, is to discuss the creation of the future. What are the things that it would be interesting and useful to try to do, given the tools we now have on hand and the way in which they are developing? I would like to outline at least one such possible course. We can only set a course and be prepared to adjust it, and look at the tools and possibilities that are thereby conjured up. This is an exercise of the imagination, but it has to be confined in certain ways and it always is a personal view. I can best describe the exercise of imagination by quoting Arthur Clarke: "Any sufficiently advanced technology is indistinguishable from magic." I caution you to note that it is not the case that any magic is indistinguishable from a sufficiently advanced technology. I also note a caution in the words of Francis Bacon: "Nature to be commanded must be obeyed." We will have to live within the framework of whatever the rules of the universe turn out to be as we learn them in the course of the next 100 years.

Keeping this in mind, I would like to describe a possible future. I start from what I will take as my own hypothesis for a direction to be gone into in space. I take it because I think it is the right one, obviously. I take it also in this hall because I think it is one that Benjamin Franklin would have been extremely sympathetic with, if not a leader in. And I take it because I think we are facing some problems in the human future on this planet that make some alternatives at least interesting, if not important. The end desire, I take to be for the next 50 to 100 years, is to explore and use the solar system. I may caution you, however, that the history of space thus far has had its accomplishments always occur before the time at which they were predicted. We have already been talking about exploring the solar system, and to some degree we have actually been exploring it throughout the history of NASA and the space program; occasionally, we have also talked about using it. I will leave the question of the rest of the universe for later in my talk.

When I say understanding, exploring, and using, I literally mean them in the sense of using energy and materials elsewhere, as well as understanding what is there. Why should we want to do that? In the first place, because it is a continuation of something we have been doing as a species for at least 50,000 or 100,000 years, namely, exploring, looking, and using. Second, I would assert that some of the problems that we are facing as a species on this planet suggest that we may in fact succeed in making it a difficult place in which to live. I am not particularly suggesting the question of nuclear war, but just the problems that are creating pressure concerning our use of the biosphere and its systems as a consequence of our own numbers and existence, and our activities. Starting as a scientist, I guess I have become enough of an engineer, so that I always like a hedge position in my technology. I think it would be nice for this species to have another place to live besides the one that it is now engaged in changing drastically. It seems clear that the rest of the solar system is the other place. Unfortunately, it is another place in which it is neither simple nor natural for us to live, but perhaps this can be remedied.

At the moment, it is extraordinarily expensive and difficult to do anything off this planet. In fact, the problem is that the expense is such that we are looking very hard for ways to find things whose value justifies this expense commercially. We have found a few, global communications being one, and some particular uses of low gravity being others, that are developing at the present time. However, the question remains, how could we make it economical and economically sustainable to be elsewhere than on this planet? What we are looking for is some form of self-sustaining economic system upon which we can base our exploration, our development, and our use of the rest of the matter and energy in the solar system.

This, too, has precedent in the history of human exploration. It is called "living off the land." That is, you don't go to the new continent or the far west carrying with you everything you will need to sustain yourself. You propose to go carrying the tools that will enable you to do most of the things you need when you get there; but of course there are certain things that you expect to continue to import from the home country.

How can one go about doing this? It is my contention, and I borrowed the idea from many colleagues, that we are embarked in technological directions that will bring us automatically to the technological possibilities for doing so. Out of the technological materials of computers, communications, electric motors, network thinking, system ideas, software, and the whole litany of things that constitute the electro-technological revolution, we have begun to construct systems that are more and more self-sustaining. Ten years ago I think this was a laboratory discussion; today, it is a factory reality, and while much of it is still an aspiration for factories, it is an aspiration that is rapidly being constructed. The productive unit, and let us not argue about whether it is a whole factory or part of a factory, is in fact becoming a self-operating unit on a fairly large scale. We are building and talking about self-operating manufacturing cells—certainly those that take in partly finished parts and end up with assembled units, and many that take in raw materials and end up with partially finished parts. It is not a tremendous step to do mining on the same kind of basis. We can do most mining procedures perfectly well without most of the people in the mines; we still need people to run the machines from elsewhere by remote control and sensing: teleoperation. We can certainly do the chemical beneficiation, the chemical separations, and the creation of the materials mostly without people. I maintain that one can, in the course of time, assemble what amounts to a self-replicating machine, which starts with raw materials and solar energy and is a factory that ends up with the capability to construct another factory next to itself like the first one.

There are many questions concerning the convergence of this process and whether one can do everything that is required in it. For the purposes of economics, exploration, and use, however, it is really not necessary to have a completely convergent self-replicating system. In fact, we probably would not trust it if we had one, as the history of nearly any industrial process and all of the historical events in the space program tend to suggest. There are moments when you really need somebody to kick the wheels or unstick the hinge, or to fix the software that was developed five years ago and was perfectly adequate, but is not quite right now, and so on. Perhaps we can only get to automatic self-replication less epsilon (almost but not quite automatic), and epsilon is extremely important because it is why we need people there: to make sure the system continues to work. Epsilon can be described as the piece that makes the difference between "it works" and "it almost works."

I would call this idea of the "nearly self-replicating system" the robotics route to a self-generating economic system. The energy and the materials are available, and although some of them are a little more dilute and not as easily available as we would like, I think we are developing the necessary technology to use such materials.

Why is this concept economically interesting? If one constructed a first machine or two of this kind and simply set them out in a suitable place, after a while there would be four machines and then eight machines, and you all know the biological meaning of an exponential. This concept does not violate the first and second laws of thermodynamics. We are using a very hot heat source, the sun, there is plenty of material, and we are rejecting to a very cold heat sink, the rest of the universe.

This all seems a perfectly reasonable technological direction, one that would make it possible, except perhaps for epsilon, to build an industrial capability off the planet using a single export of machines to the moon, an asteroid or elsewhere in the solar system in order to start. We would send some people with the machines, both because we want to be there and because of epsilon.

Now there may be lots of things which, like the pioneers going west, we do not care to try to manufacture *in situ*. It would be easy enough to import and export them. For example, in the current technology we might want to export the computer chips from the ground, at least for a while. What would we pay for them with? This is an economic question and not a technological one. We might want to export gold, uranium, or energy, if anybody wants it. We would not necessarily ship radiant energy; energy can be shipped in solid and liquid form, and beneficiated minerals can be considered as either materials or energy, depending on how you choose to use them.

From an investment point of view it is a very large investment, but the ultimate gain is presumably infinite. There is a wearout time for each machine, but the ordinary terms of depreciation and amortization do not apply for this situation. We might have to worry about software mutations, but I lump that with the other epsilon problems for the people to control.

What would such a program look like? The central core of the technological program, that is, the self-replicating machine, is simply a continuation of the industrial program on which many corporations have already embarked. I know of nobody who has embarked on the entire program; everybody seems to pursue a piece of the program. It seems probable that such a technology will develop in the normal course of events from our current developments in electrotechnology, materials, and mechanics.

What we do not understand nearly so well are the details of how to operate under the various conditions that will exist at the manufacturing site, wherever we choose it to be. Nor do we really understand the industrial conditions when vacuum is free, but materials mostly do not come very neatly concentrated. We do not really know the value of being able to operate without gravity forces, or with low forces, because we have never tried to design industrial processes for the free fall situation. We need some starting point from which to learn how to begin to use such a technology, and this is really where the significance of the space station lies for me. It is likely that there will be some commercial enterprises that will be important in a space station, and it is certain that we will perform a good deal of science from it, as well as a great deal of scientific exploration quite independent of it, but perhaps most important is the fact that it will be a place in which we can tinker with things. The history of science and technology demonstrates that one of the most important possessions of the technical professions is a place and an opportunity to tinker under circumstances that are interesting. After all, low-temperature physics was not invented and the experiments were not conjured up without somebody having available a low-temperature laboratory in which to try things. This also holds true for electricity and other disciplines. If you want to find out whether it is interesting to do things in zero *g*, then you had better go there and make a few mistakes of the kind that will enable you to discover some phenomena that you would not have found otherwise.

I think this is a first step. The technological directions are being fixed. The question now is, what is the right mix of people, machines, and aspirations to begin to consider carrying out such a program? I would argue that if it becomes possible, as indeed I have suggested, to be economically viable and perhaps nearly independent of the earth, in an industrial operation elsewhere—on the moon, an asteroid, or Mars—then a number of questions will arise concerning the relationship between the new places and the old place; these are economic, and will certainly be political.

I described the new place, wherever it is, as being a hedge against some problems in the old place. It cannot be so unless it becomes a living place and unless we solve the biological problems that go with some places that are at present sterile compared to where we live now. In the long run this implies some program of technology that we now do not understand, except in the vaguest outlines, that deals with the construction of ecological situations in circumstances where now there cannot be said to be any ecology at all, but only the possibility of totally artificial arrangements. This, too, has to become part of the program. While we are beginning to see the outlines of what a large-scale biotechnology would look like, the relationship of those outlines to our current electrotechnology is scarcely clear at all, although these technologies will certainly involve communication, sensing, control, and computing, so that surrounding the biology, there is increasingly an atmosphere of electronics, electricity, and computing.

I said that I would come back, toward the end of my talk, to the rest of the universe, and this of course is where the great difficulties really arise as we see physics at the present time. That is, there is nothing all that mysterious about going out and doing something in the solar system. The times to get there and the energies and the expenditures are commensurate with what we know and understand, while the rest of the universe has times and difficulties that are not commensurate with what we understand. But on the 100th anniversary, it is worth making at least the following comment. One hundred years ago we did not even know that the velocity of light is a natural speed limit for velocity in the universe; we had no idea, at that point, that there was any time and speed barrier to doing what we wanted. I have no idea, and none of us does, whether there is any way around this problem. It is certainly clear, however, that the universe is being seen to consist of some very curious physical objects. Whether in the next 100 years that will change our ideas about how to move around in the universe and what we can do, is not clear but, if I may, I would like to conclude again by quoting Francis Bacon, whose comment I leave you to interpret: "They are poor sailors who do not believe in the land when all they can see is the sea."

Robert A. Frosch, *vice president, General Motors, is a former administrator of NASA. He also served as deputy director of ARPA and as Assistant Secretary of the Navy for Research and Development. In the United Nations, he held the rank of Assistant Secretary General, serving as Assistant Executive Director of its Environment Program. Dr. Frosch was president of AAES, received the NASA Distinguished Service Medal, is a member of the National Academy of Engineering, and a Fellow of the IEEE.*

THE FUTURE OF "NEAR EARTH SPACE"

James C. Fletcher

Talking about the space program, I have to go back to 1958 and remind you of a question that was asked of a very distinguished government official, whom we all know: "What are your plans for the space program?" The answer, which seemed humorous at the time, but seems very á propos today, came back: "Space is a place, not a program." As time goes on, we are becoming more and more aware of that. Dr. Frosch has talked about big space, like the universe, and about small space, like where resources might be, but let me remind you that space begins somewhere between 20 and 100 miles up, and they are still arguing in the United Nations about the boundaries between air and space. It must be lower than 100 miles because we have space things going around at 100 miles up and no Russians are complaining, and it must be above 20 to 30 miles because we have airplanes flying at 20 miles up and balloons at 25 miles. So it is somewhere in between where space begins.

On the other hand, the far end of space must be at least 15 billion light-years away. So we really have to focus first on what we might call "near earth space." Near earth space is from the bottom, the lowest altitude, whatever we want to define it at and goes as far as the moon, or at least the moon and the nearby Apollo asteroids belt, which are the potential sources of materials for space manufacturing. I left out Mars, and maybe this is wrong, but if in the near term we want materials to be collected and mined and used in the self-replicating system prospect by Dr. Frosch, we have to look at the Apollo asteroids. These are in the same orbit as the earth around the sun, and periodically they come very close to the earth. We can see only those that are about 2 kilometers in diameter. The moon, you all know about. That is where resources are most likely to be. I guess we could collect solar dust and things of that sort, but this is not the best place to start. We can start on the moon or on the Apollo asteroids.

Thus, looking at that region and thinking about it, 20 miles up embraces a region within 20 miles of every country in the world, which is not too different from the situation of our oceans. Oceans have been investigated intensively over the millennia and have been used over this period for both commerce and warfare. If you like, you can extend the analogy a little further and say it is not unlike air. In the early days of aeronautics the Wright Brothers' experiment was kind of a gimmick for them, although they had some vision, maybe a bit fuzzy, of the future. Nevertheless, for *them* it was an experiment in this sense: "Let's see whether we can't sustain flight for a period of time without any help from the ground." For 15 years after the Wright Brothers' experiment, the United States did very little else but stunts—circuses, if you like, but without any concept of the future potential. With World War I it became quite clear that aircraft were being used by the Europeans for military observations. You may not remember this—it was before your time. My father remembers it very well, and perhaps Dr. Kobayashi, who is a friend of my father's, might remember those days. Aircraft were used extensively during World War I, and the United States found itself way behind. You all know the story of the National Advisory Committee for Aeronautics (NACA), why and how it was created. We saw ourselves falling behind the Europeans in the whole aeronautic arena and needed some mechanism to exploit the Wright Brothers' historic experiment.

Space is not all that different. We started with considerable anxiety because of Sputnik. In reaction to that anxiety, NASA was established. It evolved partially out of NACA, but more importantly, it was created in part by adding elements of the large rocket program that really came from Germany. It actually came from Germany by way of the United States and Russia, starting with Goddard in the United States and continuing with Tsiolkovsky in the U.S.S.R., and with Oberth in Germany. By the way, Hermann Oberth, who was the German pioneer and who wrote many of the early books on space travel, is still alive, and his birthday will be celebrated, I believe, this month or next.

Let me continue with the analogy between air, sea, and space. They started out as military ideas, both on the oceans and in the air, but soon, in the course of decades, these ideas became, at least in the case of air, viable commercial enterprises; this is where we are now. We have television satellites and communications satellites, which are very successful. They were an obvious extension of something we already knew about. We did not have good ways of getting television overseas, and so commercial space started with television. Then, gradually, it expanded into telephony, and in addition to being transoceanic, it became domestic. It is not so obvious what has been happening with earth observations. The projects were mostly government supported; for example, the government owns all weather satellites, which people now take for granted. We also have Landsats and the beginnings of Oceansats, which are in part experimental satellites.

We could go on and on, and although we do not yet know where commercial enterprises will end, I am sure that within three decades we will be mining the moon or the asteroids, whichever turns out to be easiest. We have been to the moon, but we have not yet visited the asteroids. I think one of the obvious uses of materials will be to build other space-based stations. Dr. Frosch calls them self-replicating stations; I will call them lunar colonies á la Gerald O'Neill at Princeton. There certainly will be either L-5 colonies or something similar to them, or there will be bases on the moon for either scientific of self-replicating purposes. It is not so obvious that you can build colonies with Apollo asteroids, but this will flow naturally out of some of the spin-offs from the space programs sponsored by NASA or the military.

I would like to touch on one other aspect of the program, and I do not believe that this is in any way trying to downgrade this projection of the future. Over the millennia we had to protect our freedom of the sea. We had to protect navigation and our various commercial enterprises from those adventurers who wished to interfere with these enterprises—pirates or hostile countries—by patrolling the seas. Nations that patrolled the seas frequently also controlled the ocean commerce (e.g., Great Britain), and that is what we are now facing in terms of the newly coined phrase "space warfare." In recent months it has been a popular phrase with politicians and the media, but those of us who have been involved in the business know that space warfare really started in 1944 with the V2's—rockets with ordinary chemical warheads that were launched from Germany to the United Kingdom. These V2's had to travel through space to arrive at their targets. The first space program started very soon thereafter in 1946 in this country, when it was observed that if you wanted to get higher than airplanes and look at what the other country was doing, you needed an observation satellite. I believe it was in a division of Douglas Aircraft, which became the Rand Corporation, that the concept for the first observation satellite was born. We now use these satellites to monitor the various treaties that we signed, mostly with the U.S.S.R., and so the U.S. space program was born. The space programs at NASA, at the Defense Department, and in the U.S.S.R. were all born out of these two enterprises, both of which were military—the V2 and military observation satellites.

In 1954, the Von Neumann Committee observed properly that what we had previously thought was a "gimmick," namely, that larger V2's could travel across the ocean, could become a reality. It became quite clear to that committee that it was possible to construct nuclear warheads, that is, hydrogen bombs, in a very small size. Combining these two technologies it became possible for one country to more or less annihilate another by using nuclear warheads on the newly named ICBMs. I happen to have been involved in that program, and I hope I will not become involved in another one, because this is space warfare of the worst kind, offensive space warfare. ICBMs have to travel above the space limit, typically at 400 miles if it is an ICBM with a 6000-mile range, lower if it is an SLBM, still lower if it is an IRBM, and even lower if it is a Tactic Ballistic Missile (TBM). It is inconceivable to me that we have continued this long to have the capability of passing weapons through space without having some sort of a "space patrol." It took some of the younger scientists to remind us of this. It had never been on my mind when I was working on the ICBM program. The ICBM program started with Thor, a little one, then Atlas, which was a little bigger, and finally Titan. These have been mostly forgotten as military weapons. We found that we had to put them underground to protect them, and that is when the Minuteman was born. Small, solid-propellant ICBMs were easier to protect underground. We had Minuteman I, then Minuteman II, leading up to the present MX. The Russians meanwhile did the same. We all thought that going underground or underwater was the way to protect our offensive assets, but it did not occur to most of us that you ought to have a way of preventing these things from going from one country to another. Just recently, within the last 20 years, we began to think of ways of stopping these warheads from coming through space.

"Space patrolling" started before defensive weapons were much discussed. We began to watch what other countries were doing. We are now no longer allowed to watch by flying over other countries' territories with airplanes; this is termed "illegal." But apparently it is not illegal if we use satellites. Satellites pass over everybody's territory several times a month. NASA, for example, has a satellite looking down on every part of the world from 550 miles above the earth and passing by every nine days. Thus we are beginning to patrol in a sense of "watching." We have begun to monitor some of the treaties such as SALT I and the ABM treaty, and there can be no treaty without satellite verification: "If we agree to do this and you agree to do that, we will watch to make sure that you do what you say you were doing with the appropriate observation satellites." However, we no longer talk about "verification;" we talk about "enforcement." This is a different kind of problem because we say: "All right, so I noticed that you were cheating on the agreement that you made with me, what do I do about it!" We discovered that we can do a great deal. This leads us to think that treaties of the future ought to have some sort of enforcement mechanism. By "enforcement" I do not mean dropping our bombs on the other country either. That is not a very good way to do it. Let me just suggest that because space is a place and it is only 20 to 100 miles from all countries, we really have to think about the problem of keeping space peaceful, not just by agreement, but by means of enforcing the peace. The strategic defense initiative, dubbed "Star Wars," is one way of "enforcing" peace, but clearly some agreement must be made about "rules of the road" regarding such enforcement. I think that none of the things Dr. Frosch talked about, including going to the next star, look too difficult to me. All you need is a more efficient propulsion system and a little courage to wait. It might be four years each way, as a minimum, and that is not too bad. I think all of these things can be worked out, but we do have to make space peaceful by some device for effective patrol. If we continue in a wise and careful way, I think that space as a "place" and as a "program," both military and civil, will flourish for decades and hopefully for many centuries to come.

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MEDICINE AND BIOLOGICAL SYSTEMS

Herman P. Schwan

EMERGENCE

Biomedical engineering, biophysics, and medical physics emerged almost simultaneously. Early beginnings date about 40 to 50 years back and occurred at different places in numerous countries. At that time, no real differences were apparent between the three disciplines, and after a period of differentiation and separation, we witness again much cross-fertilization. No formal training was available, and motivation to enter these interdisciplinary fields varied from case to case and frequently demanded optimism with regard to an uncertain future, uncertain recognition, and little financial reward. I myself entered the field with great skepticism. Biology appeared to be extremely complex, and it seemed almost hopeless to apply the scientific approach of the engineer and physicist to live systems.

At that time the sensational potential of X-rays to visualize anatomical structures in the live body had been well established. But little was known about the hazardous effects of such radiation, and there continued great activity in advancing the technology of diagnosis and, eventually, therapy. Little had been done to search for additional applications of physical forms of energy in medicine and biology and to study systematically the properties of live matter which govern the propagation of other modes of energy through the human beings.

Laboratories in this field emerged during the 1920's. They were few in number, and I am not aware of the existence of any formal academic programs that would have led to advanced degrees in the fields of biophysics or biomedical engineering at these early times. In most of these early institutions, engineers joined with physicists and medical doctors, attracted by the possibility to apply the analytical power of the physical sciences and their instrumentation to problems in biology and medicine. There was a good mixture of fundamental and applied research. The more basically oriented work was, in most cases, undertaken to eventually solve problems of practical importance, that is, purpose-oriented basic research. Early research was concerned with the effects of ionizing radiation and X-ray technology, electrophysiology, and studies of the electrical properties of live matter and relevant applications in physical medicine.

After World War II it became apparent that rapidly developing electronics should be able to offer much to medical practice and biological research. Interest began to focus on such medical applications, and the term "medical electronics" was coined. The relevance of engineering to biological research and medical applications became increasingly obvious, and today the term "biomedical engineering" stands for the application of engineering concepts and tools to both medicine and biology.

In this climate biomedical engineering emerged fairly rapidly. In the early 1950's the annual conferences of engineering in medicine and biology were attended by about 100 people, who listened to some 20 or 30 papers. Today, members of relevant societies approach 20,000, attending close to one hundred meetings a year, where thousands of papers are presented.

The Institute of Radio Engineers (IRE) and the American Institute of Electrical Engineers (AIEE) established administrative committees interested in fostering engineering in medicine and biology. Together with the Instrument Society of America, they also formed a committee to organize annual conferences of engineering in medicine and biology, which continue to this day to be focal events.

During the late 1950's the National Institutes of Health became increasingly supportive of biomedical engineering activities and established a large program for higher education. The first programs to receive federal funding for training leading to a Ph.D. in bioengineering were established at the Universities of Pennsylvania, Rochester, and Johns Hopkins, and around 1960 the first departmental and doctoral programs were created at the University of Pennsylvania and elsewhere.

THE PRESENT AND NEAR FUTURE

Academic and Industrial Growth

Today, the IEEE Society for Engineering in Medicine and Biology alone has more than 5000 members, and a large number of our engineering schools have either departments, programs or institutes dedicated to this interdisciplinary field. The total academic effort as measured by student enrollment and the number of programs and departments may now approach a plateau. Biomedical engineering has clearly established itself as a productive and important academic discipline. However, much relevant research is also carried out in many other departments, such as radiology, biophysics, physiology, and in traditional engineering departments.

Industrial activities as reflected by medical technology continue to increase substantially. A U.S. market research company forecasts a fivefold increase in coronary angioplasty for the removal of coronary artery blockages and predicts the sale of cardiovascular surgical equipment to increase by 47 percent by 1988. New scientific advances and the aging population are projected to account for a 79 percent growth of the orthopedic implants market. An increasing annual growth for artificial elbows, shoulders, and ankles is envisaged. Bone growth stimulators and power tools will be some of the most dynamic segments in the implants industry and electronic devices market. If clinical success for bone growth stimulators is proven, as appears the case, the market will more than double by 1991, according to the same survey.

In a recent survey of some 17 electrical engineering specialties conducted by *IEEE Spectrum*, the field of biomedical electronics was judged to be the third most promising career path, surpassed only by computer software and communications.

A recent survey by *INC* magazine concludes that health care service and equipment companies are among the fastest growing in the United States. It concludes also that out of 100 publicly owned companies judged to be pacesetters, 24 are health care or medical equipment suppliers. This is the largest single category, ahead of the 21 companies in the category of computer and related products.

Any precise prediction of the future of the medical technology market is difficult. While growing rapidly, it is far from settled. New potential applications of modern engineering advances to medicine and biology continue to appear on the horizon. Many will run into difficulties, while others emerge with promise and a potential impact that is often entirely unpredictable at the outset. There is no doubt that increasing medical demands and public interest will assure rapid continued growth of the medical technology market.

Scientific Meetings, Journals, and Specialties

Biomedical engineering research at universities, industrial medical technology, and the academic educational effort at universities are reflected by the rapidly growing number of professional meetings in the field. For a number of years it has become impossible to attend all of them in order to obtain a full concept of ongoing activities. I estimate the total number of meetings per year on the order of 100, representing more than 20 societies with a primary interest in the field or some of its subdisciplines, with a total membership of about 20,000. They typically sponsor the presentation of several hundred papers and are attended by more than 1000 individuals.

The number of journals dedicated to the field and its subdisciplines is also growing rapidly. Indicative is the journal *BECAN* (Bioengineering Current Awareness Notification) published by Taylor and Francis. At present, it has a data base of some 40,000 reference publications, adding annually some 2500 and scanning some 600 journals. The rapid growth in presentations and published papers is indicative of an unusual growth rate of the field, complementing the one in medical technology summarized above.

The growth of biomedical engineering reflects its two-dimensional character. In one dimension we may subdivide the biomedical field into n subdisciplines, in the other we list m specialties of the engineering fields. Almost all combinations of m and n establish potential fields of biomedical engineering activities. Initially only a small fraction of this matrix was activated. The number is now much larger, as reflected by the increase in specialization indicated by the growing number of societies and journals. Yet many spaces in the matrix are still inactive, in part due to being without present promise or being clearly without sense, and in part to be filled in time, provided the proper stimulus becomes effective. Will there be any saturation to this process in time? I do not believe so, unless there will be in the supporting engineering and biomedical disciplines. As long as engineering continues to grow and as long as there is an interest in improving health care and biological insight, biomedical engineering will almost by definition continue to grow.

Basic Research and Technology

To the outsider the justification of a scientific or technological activity is solely provided by its product, its salability, and its obvious utility. However, we are all aware of the importance of related scientific principles. Unfortunately, there is in most cases a significant time lag between the emergence of a scientific principle and technological achievement, and frequently only a fraction of more basically oriented sciences yield practically useful results. Unfortunately, it is difficult to predict those that will. The field of biomedical engineering is no exception. I indicated that during earlier times much of the more basic work was nevertheless somewhat purpose related. This is still true and may be the reason why a good fraction of the more basic pursuits in the field have been productive from a practical point of view. Yet there are many exceptions. For example, there exists a rather advanced understanding about the mechanisms that determine the electrical properties of biological cells. However, no attempts have yet been made to examine cells with arrays of many electrodes and thus to create images that reflect various cellular properties depending how frequency or pulse duration or both are chosen. Another example is the ultrasonic field. Much is known about the mechanism responsible for tissue attenuation, but much less about tissue scattering properties. I submit that research dedicated to improve this insight cannot fail but result in further improvements in medical ultrasonic tissue visualization. Another example is the rapidly emerging field of imaging technology using nuclear magnetic resonance. This field is becoming a particularly important addition to existing medical imaging technologies. But the understanding of the nature of normal and tissue water and the signals they emit as utilized in nuclear magnetic resonance technologies is still incomplete. Typically, the National Institutes of Health have recently called for the submission of research grant applications to fill this basic gap. Many more examples of the sort could be listed to illustrate the need for more purpose-related basic research. Government agencies such as the National Institutes of Health frequently expect the demonstration of a health-related potential before providing funds for the needed basic research. I submit that this is unwise, though understandable.

Some Factors Limiting Growth

Another problem contributing to the gap between scientific insight and technological achievement is well known. Universities provide little incentive and reward for contributions to the translational process from basic principles to product. And industries, particularly in the health care field, are reluctant to contribute to this process. Federal funds to contribute to this process are virtually nonexistent. I submit that a large program is called for consisting of three parts: (1) more systematic study of the electrical, acoustic, and mechanical properties of live matter, (2) systematic study of the interaction of all sorts of energies, electromagnetic and mechanical, with live matter, and (3) screening of these efforts to select those interactions that appear particularly productive for whatever diagnostic and therapeutic purposes. It is true that much has been accomplished along these lines. But past efforts are incomplete and advancements have come frequently almost by accident while research intended for other purposes was being undertaken.

Such an undertaking would also contribute substantially to another field. Interest in the interaction of energies with live matter has created increasing concern about related potential health hazards. Not only ionizing radiation but also the broad spectrum of electromagnetic nonionizing fields is claimed by many to be dangerous. Initially this had little effect on technological progress, but it may soon change. Already the installation of many communication facilities has been either delayed or permanently blocked, the Defense Department's attempts to install low-frequency communications facilities with submarines has been successfully delayed several times, the construction of high-voltage transmission lines has been impaired or blocked, and it is entirely possible that severe restrictions may be imposed on the power emitted by radio and television stations. These are but a few examples of a rapidly increasing number of limitations imposed on the growth of technology by health considerations. They call for educated scientific insight about biological interactions in order to combat public fear of the unknown and superficial speculation.

Let me now list a few examples with comments made to illustrate these remarks, and let me conclude by bringing up one of the most important issues, the need to provide ever better care at an ever decreasing price, a need that can only be satisfied by clever utilization of biomedical engineering and medical technology in combination with equally important social, economic, political, and administrative considerations.

SOME MODERN EXAMPLES OF SUCCESSFUL HEALTH CARE AND BIOTECHNOLOGIES

The Pacemaker

Perhaps the greatest technological contribution to advance life expectancy significantly is the cardiac pacemaker. About 500,000 persons in the United States benefit from it, and about the same number in other countries of the world. Originally a rather simple device, it has evolved to a fairly sophisticated yet small instrument which performs monitoring and diagnostic functions in addition to its primary task of stimulating cardiac tissues. It performs as demanded by the heart and appears to have become an even more sophisticated appliance, able to respond to varying physiological requirements. Improvements in electrode design and battery life expectancy have been substantial and reduced initial replacement needs significantly.

Imaging Technologies

The diagnostic potential of ultrasound is based on its ability to be beamed or focused and to penetrate deeply into tissues. It has found increasing use since its early introduction during the 1950's. Echocardiography, the ultrasonic examination of heart function, came about during the 1960's, adding a new noninvasive technique to the earlier electrocardiography, and is now utilized universally.

Modern advances in X-ray diagnostics are largely due to a sophisticated interpretation of signals, leading to computerized axial tomography. This great technological diagnostic achievement was appropriately recognized by an award of the Nobel prize to its two chief developers. Interestingly enough, one of the laureates chose to speak about the great potential of the emerging nuclear magnetic resonance technology. Indeed, nuclear magnetic resonance imaging techniques promise perhaps even greater potential for diagnosis.

There are several other imaging technologies that have attracted the attention of both the engineer and the medical community, such as positron emission tomography, ultrasonic tomography, and various other attempts to investigate the merits of other physical signals, including low-frequency currents and microwaves. In all these cases the task is how to extract information about the interior from signals registered at the surface of a bounded volume. The relevant mathematical principles had been developed long ago, but the arrival of modern computers first provided the ability to process the large amounts of data needed in some diagnostic imaging technologies.

The Coulter Counter

This is in principle a very simple instrument which is based on the fact that biological cells conduct low-frequency alternating currents poorly, at least as compared with a typical biological fluid. It is used to rapidly count cells and to measure their individual sizes. Almost every biological laboratory now has one since it became a valuable tool in cellular studies. The Coulter Counter has become a much more sophisticated device with time. Its full potential has not yet been realized. The use of multiple electrodes, network analyzers, or time domain spectroscopy can help to provide a very rapid evaluation of cellular size and shape, membrane properties, and cytoplasmic interior. Electronic imaging techniques at the microscopic level now appear entirely feasible with the tools that have recently become available.

Cellular Manipulation by Electromagnetic Fields

It has been known for some time that electromagnetic fields impart forces on cells that may lead to such effects as destruction, fusion, shape changes, rotation, or cytoplasmic streaming. Until recently these effects were of interest only as a curiosity, and little research was done to understand them fully. In more recent times cell fusion has become of prime importance in one of the most important fields to affect future health programs, namely, the biotechnology concerned with the transfer and manipulation of genetic information. The electrical cell fusion technique, using alternating-current fields, has developed as the most promising tool to combine cells and their genetic contents. Further refinements of this technique, and in general the electromagnetic manipulation of cells for all sorts of purposes, promise to result in entirely new biotechnologies.

Many more examples could be listed, but the four chosen to illustrate therapeutic and diagnostic advances, as well as biotechnologies, may provide an idea of the broad spectrum of opportunity, spanning across all medical and biological specialties. The technologies directly related to health care such as pacemakers, artificial organs, limbs, and prosthetic devices will always be of particular interest to the public. But the contributions of electrical engineering to biology, such as the electron microscope, evolving cell fusion techniques, and applications of the electric field theory to the understanding of cellular functions and electric responses, are equally important.

WHAT PRICE TO PAY?

The potential of biomedical engineering and medical technology is almost unlimited. The application of rapidly growing engineering abilities to biomedical problems, particularly in electrical engineering and the computer field, will no doubt result in ever more sophistication and productivity. With the tools available, and to become available, we can address medical instrumental problems that at present can only be dreamed about. It is no longer unrealistic to predict that electrical techniques can eventually become as important to health care as chemistry did. However, increasing technical sophistication comes only at an increased price.

Limitations in individual and federal resources may well place bounds on our ability to reach for the sky. Medicare and individual health expenditures have been increasing more rapidly than other expenditures. This trend is likely to continue unless mechanisms become effective that limit further expensive sophistication in the interest of simpler and hence cheaper technologies. Usually, competition will help to bring this about in most technical fields. But thus far competition has not been very effective in the health care field. These facts have been well recognized. Two articles in the first issue of our National Academy's new journal, *Issues in Science and Technology*, highlight this situation. Here are a few examples: Total health care costs rose from 6 percent of the gross national product in 1965 to 10.5 percent in 1982 and are anticipated to reach 12.3 percent in 1990. Medicare costs increased from $9.5 billion in 1973 to $57 billion in 1983, and this in only 10 years. While inflation during the past year was only 4 percent, health care costs increased 12 percent. The pervasive influence of rising health care costs on our industrial performance is also indicated by the following figures: For General Motors these costs nearly tripled from 1975 to 1983, and a customer now pays an estimated $430 in medical costs when buying a new car. Medical costs are judged by Ford Motor Company to be six times higher in the United States than for the Japanese competition. Some steps have been taken to bring this catastrophic development under control, for example, Medicare's prospective payment system.

However, some analysts demand that a successful policy of cost containment address the entire health care system.

Past growth figures indicate that individual and federal expenditures for health care may well approach or surpass those for other categories such as defense, other entitlement programs, and all internal federal projects combined if no limiting factors emerge. This raises many questions. Is it in the end not cheaper to spend money for preventive medicine? Should we strive for ever more sophisticated medical technology? Is the health care field not slowly becoming a mixed field of health care and technology? What will be the future role of the engineer in this field, on health care boards and at relevant federal agencies?

These are problems which are bound to become more important. How they will be solved will greatly influence the growth of biomedical engineering and medical technology in the future. In fact, biomedical engineering and technology should play a key role in alleviating these problems.

Most of engineering is dedicated to the task of improving our lot, namely to defend our country, to make our lives and work easier, to communicate better, to produce cheaper and more efficient energy, and to provide better learning and entertainment. But equally important to us is the goal of healthy and joyful living extending to an increasingly older age. I see no limitations to what biomedical engineers might accomplish to achieve these goals if these growth problems can be solved, as they will be.

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TECHNOLOGY AND THE FUTURE OF HEALTH CARE

Leon Kaufman

Over the years there has been a large increase in the cost of medical care, and this is well documented. But I also know that while today I would rather buy a new 1955 Chevy (with shoulder belts and a collapsible steering wheel) than anything else produced by General Motors, I would not like to go into a medical institution that practices 1955 medicine. We are not comparing the same services. In fact, my telephone does not work as well as it used to, even before AT&T had an excuse, and I pay more for the service. The key is that in medicine we are not comparing the same level of service. The technology and outcome have changed. If costs are to be brought under control, there are only two ways that this will happen. One is to limit the access to medical care. I am all in favor of that, as long as it applies to the audience from this line to the back row, but I do not want to hear of limiting access to medical care for my family. Those who can afford it will get first class service, as demonstrated in England. I believe that in a country like ours, with its unique legal and political processes, limited access is not going to be acceptable, and we are not going to stand for a two-tier medical system. This view is exemplified by an ad from the Catholic Health Association, which states: "In the present public debate about medical costs, with its talk of 'cost shifting' and 'two-tiered health care,' the poor and underprivileged seem almost to have been forgotten... We believe that society has an obligation to make necessary health care available to all persons—whether rich or poor. In our efforts to find solutions to the current cost crisis in health care we must not ignore the special needs of the disadvantaged." To the extent that institutions that share such beliefs may be willing to lobby the legislative process and seek satisfaction through the courts, their success will negate the concept that limiting access to medical care will reduce costs. Therefore the second alternative to raising costs is that technology will have to come in to make up the difference. It is people and real estate that drive costs, not technology. As an example, in mid-1983, to put a child in the hospital for 48 hours of intravenous injection of penicillin, with the most complicated technological procedure being the placing of an IV line in the wrist, it cost over $2500 without doctor's fees. A $50,000 machine that can monitor temperature and inject penicillin so that you can send the child home with it will pay for itself in just one year. This is a hypothetical example of how technology can provide the means both to avoid the two-tier medical system and to be able to afford the consequences.

I wish to give you an overview of recent developments in diagnosis. If we are to make an informed decision as to what needs to be done to a person, where and when to intervene in the body, we need information. If the way of finding out that information is worse than the cure, or potentially worse than the cure, we are not going to choose to do it, and consequently we will be working from an incomplete data base. Exploratory surgery is obviously the most accurate and direct way of finding out what is going on inside the body, but there may not be anything wrong, and surgery is too invasive and costly to be an effective diagnostic or screening tool. In addition, some parts of the body cannot be reached this way. We therefore need safe ways to look into the human body, and this is what diagnostic imaging does.

At the early stages of development of new diagnostic modalities, even before the potential had been recognized by the medical community, the IEEE was a leading source of engineering talent and a unique forum for the discussion of new ideas. X-ray imaging is an invasive technique, not so much because of the accompanying ionizing radiation, but because of the frequent need for injection of hundreds of grams of iodinated contrast media, with attendant side effects from the media themselves, from the arterial catheters used for injection, and, for myelography, from the need to reach into the spine. In the 1960's we saw the advent of the first truly noninvasive techniques. One of these was nuclear medicine. Small amounts of radiopharmaceuticals are injected, typically in a vein. The radiation dose is minimal, and toxicity is nil for the nanogram amounts used.

The second modality introduced in the 1960's was ultrasound, a tremendously powerful technology. Both nuclear medicine and ultrasound are hampered by the need for competent interpreters to look at the image and understand what it has to say. As soon as such a requirement is imposed, the diagnostic value to the overall population decreases, since the quality of service is dependent on local factors. It is because of this that we try to improve the fidelity with which the instrument maps the body. In ultrasound, image quality has improved steadily by advances in transducer design and signal processing (Fig. 1). Market pressures have been to a large degree responsible for the impetus behind the improving technology. Because of the relatively low cost of ultrasound equipment, small companies can come into the field with technological advances that force further improvements from competitors. In nuclear medicine the conventional technology in use has matured, and only new technology can provide dramatic improvements. We, and others, have demonstrated that it is possible to advance nuclear medicine instrumentation beyond current levels, but the need for drastically changed technology, the risks associated with such changes, a leveling purchase base, and the inherent conservativeness of the large corporations involved with nuclear medicine have made it impossible to carry this work past the demonstration stage. That the potential for improvement is there is evident from the clinical example shown in Fig. 2.

Another approach toward improving visibility in nuclear medicine is tomography, which has received a great deal of attention, but has been hampered to a large degree by the use of planar imaging technology adapted to tomography. The effort has concentrated not only on adapting the hardware, but also on software to compensate for hardware imperfections. A variant of particular interest is positron tomography. The discussion of the instrumentation and algorithms of both forms of tomography has found a unique home in the IEEE journals.

In the mid-1970's X-ray computed tomography (CT) was touted as the ultimate answer to the diagnostic problem. Essentially, tomographic sections of X-ray absorption coefficients were mapped as high-quality images. In placing high expectations on CT, the radiologic community overlooked the fact that although the display format is different, the information source is still that of all other forms of radiography. It quickly became apparent, for instance, that contrast

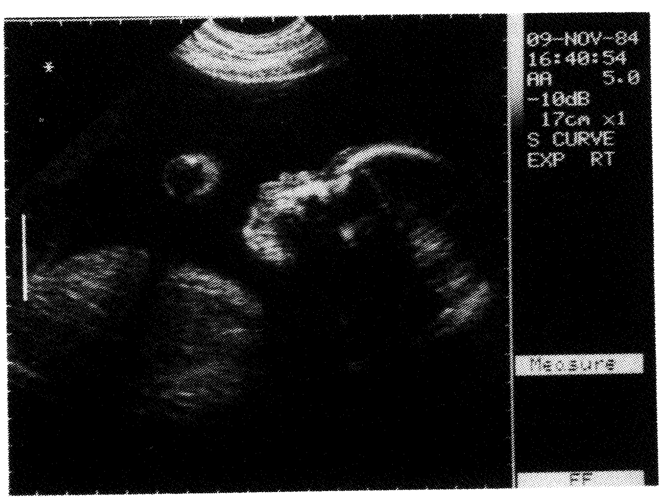

Fig. 1

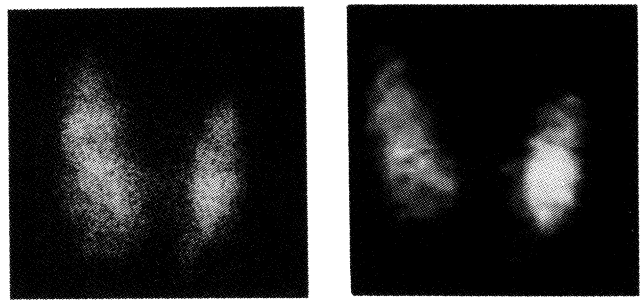

Fig. 2

media would be needed with CT just as with radiography. Ten years after its introduction, CT is an imaging technology rapidly obsolesced by nuclear magnetic resonance imaging (or MRI, as it is called in radiology). We may ask why CT manufacturers have so eagerly jumped into MRI. The answer is that rather than jumping, they were pushed. Early on, in the mid- and late-1970's, funds for MRI research came from commercial sources that had done poorly in X-ray CT and were hoping to occupy unused plant and personnel with MRI, and recoup their losses. The more successful CT companies had less of an incentive to fund development of a technology that could compete with products they were already selling. Also, to a great extent, success in CT tended to blind them to the threat to these products posed by MRI. Nevertheless, the success of university-based programs here and in England, supported by government and "loser" companies, forced the established manufacturers of diagnostic imaging equipment into unprecedentedly expensive programs.

Today, MRI is firmly established as an important, rapidly diffusing imaging technology. To convey some feel for the reason behind the excitement that this technology produces, I would like to show you some of the views of the body and its diseases that it provides (Fig. 3–5). Having learned to obtain these images, we are now learning of ways to manipulate the acquisition process of the data to extract or highlight features of interest (Fig. 6–10).

At first glance MRI appears as an expensive technology. The instrument costs $1.5 million, and siting can add another $1/4 or $1/2 million to the start-up costs. Yearly operating costs, including depreciation of capital equipment and plant, salaries, and cost of money are in the range of $1 million. But the terms "expensive" and "cheap" make sense only within the context of the capabilities of the modality. A liver transplant operation costs $400,000 and helps just one person, and a kidney transplant operation with no complications costs $55,000. Among the "cheapest" surgery procedures, septalplasty costs $1200 plus professional fees. Each procedure helps one person. By comparison, a $1 million per year MRI site can help 10 to 15 patients a day, 250 or more days a year. It can avoid the need for abdominal exploratory surgery, which

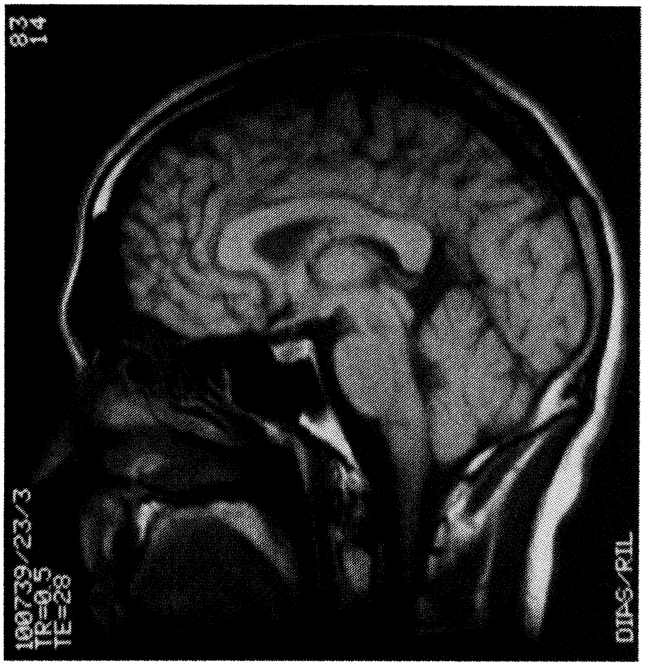

Fig. 3

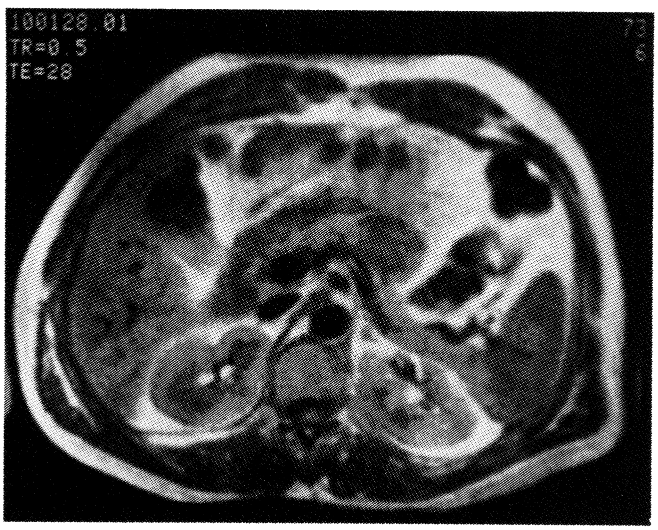

Fig. 4

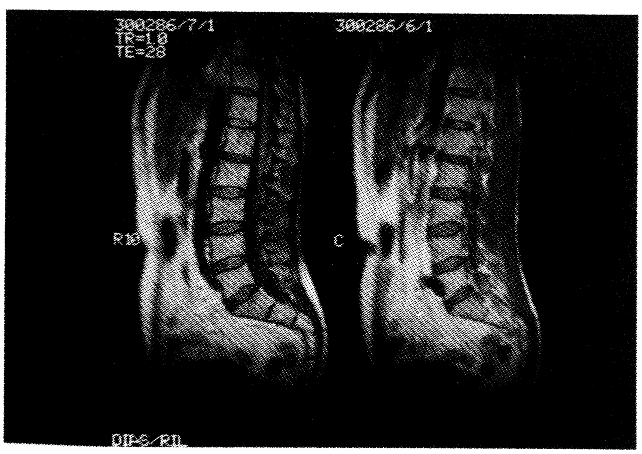

Fig. 5

Fig. 6

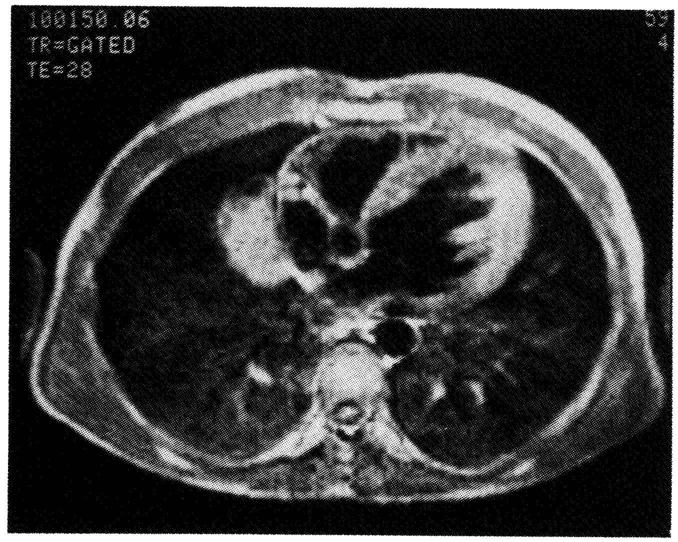

Fig. 7

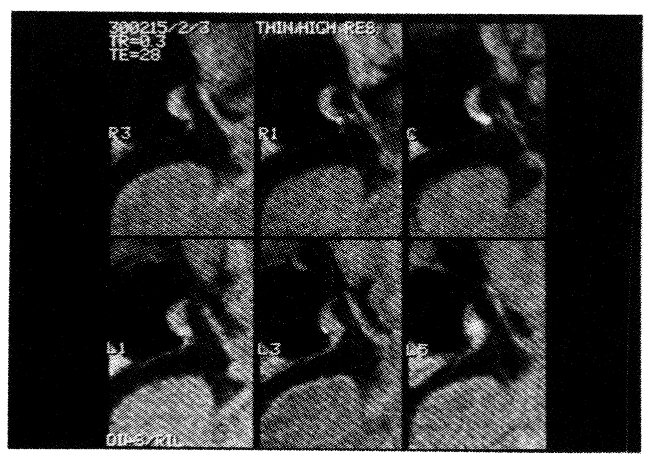

Fig. 8

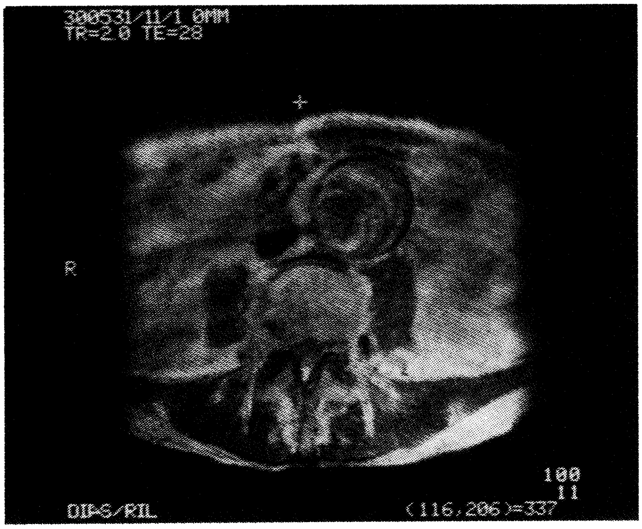

Fig. 9

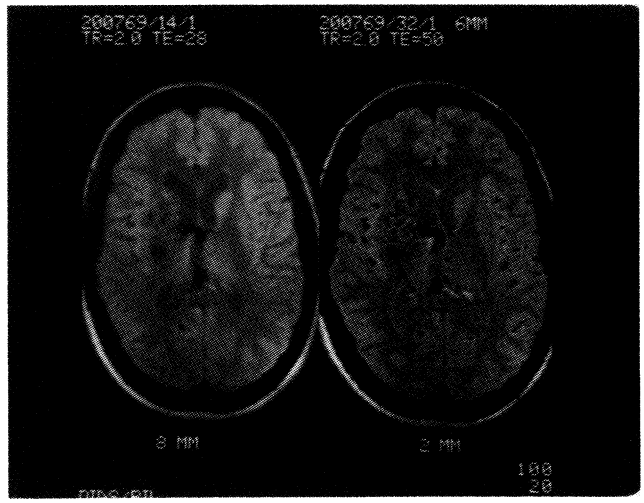

Fig. 10

costs $4000 exclusive of professional fees and requires a week of hospital stay; it can replace a $1250 aortogram (which requires a day's hospital stay for an additional $400) or a $500 myelogram (which requires a painful lumbar puncture). Placed in that perspective, MRI is cheap in dollars and in pain and suffering. Even so, in terms of per capita dollars (rather than per patient), MRI could indeed become more expensive than the procedures it replaces. The latter are invasive; therefore risk—benefit assessments place a constraint on their use, so that cost—benefit ratios need not be considered. For MRI, cost—benefit is the major constraint on use. Since cost is a term relative to income, it would appear that the use of MRI in low-yield procedures (migraine) or as a screening tool (atherosclerosis, prostatic changes, etc.) will be sought by those who can afford them. We then return to the question of a two-tier medical care system, and whether its existence is consistent with sociopolitical factors in this country. I do not know what the answer is, but I do know that we do not have the money or the equipment needed to screen all that could benefit the U.S. population. Neither do we have the physicians needed to interpret the images that would be generated in such an enterprise.

I do not know what specifically is going to happen with MRI and other beneficial medical imaging technologies. However, there is no question in my mind that technology is going to be the only answer that will allow us to have an affordable health care system, one which will address the perceived and real needs of people.

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THE SECOND CENTURY BEGINS

Bernard Oliver

I would like to sketch the development of our electrical and electronics technology over the past century. Then I will try to make some projections into the century ahead—things that may happen if present trends continue. Finally, I would like to suggest that present trends will not continue unless we take some concerted action to educate the public about technology and what it means to society.

It would be wrong to give the impression that the age of electricity is only a century old. It really began in 1800 with the invention by Volta of the electric battery. Before then, in the cat's fur and amber days, electricity was only a scientific curiosity. Of course, in these surroundings it would be a mistake not to mention Ben Franklin and his kite. His experiments led to the concept of the lightning rod, but they did nothing to harness electricity for use by humanity.

Large primary batteries provided for the first time electric currents of substantial magnitude. That is what enabled Ampere, Ohm, Henry, and Faraday to discover the laws relating electricity and magnetism.

It is interesting that the first practical use of electricity was in the transmission of information. Joseph Henry invented the electromagnet in 1827 and almost immediately built the first electric telegraph, a simple signaling device in his shop that let his wife call him to dinner.

The true telegraphs of Wheatstone and Morse were invented three years later. The telegraph was needed by, and grew along with, the railroads. Steam and electricity united these United States.

Forty-six years after the invention of the telegraph a patent for an electric telephone was issued to Alexander Graham Bell. Soon the streets of our cities were disfigured by a maze of telephone poles, crossarms, and wires. One has only to look at these early pictures to realize what an important invention the telephone cable was. Today, hundreds of times as many telephone lines lie buried out of sight.

The really high-power uses of electricity—lighting, heating, electromotive power—had to await the development of the dynamo. Batteries are not adequate sources of energy for these applications.

The laws of Ampere and Faraday provided in 1831 the scientific basis for all motors and generators, and crude motors and generators were made at the time. But while these laws defined the *topology* of the intertwined iron and copper, it took nearly fifty years to refine the *geometry* to the point where efficient motors or generators were built. It took that long to learn how, as Feynman so nicely says, "to wrap some copper around some iron in the right way so that water falling at Boulder Dam can lift elevators in Los Angeles."

Why did it take so long? I suspect because the few people who thought about the problem at all were untrained and largely empirical in their approach. There were no electrical engineering departments and there was no IEEE.

But this brings us to 1884 and both the birth of the IEEE and the first electrical engineering graduates from MIT. Other institutions soon followed: Cornell University, University of California at Berkeley, and Stanford University, to name a few. There can be no doubt that the academic training provided by these early institutions was largely responsible for turning the empiricism of the early inventors into true engineering. The strong theoretical training received by electrical engineers then has grown even stronger today and probably accounts, more than any other single factor, for the way electricity and electronics have penetrated every aspect of our society. The trickle of the 1800's has become a torrent.

The major applications of electric power for the two decades before and after the turn of the century were in electric light, first arc and then incandescent light; in the electrification of factories where electric motors replaced steam; and in electric streetcars, interurban railways, and trains.

But there was activity in communication, too. The theoretical work of Maxwell and Hertz led to the discovery of electromagnetic waves, which Marconi, in 1901, showed could cross the Atlantic.

Wireless long-distance telephony, radio broadcasting, and talking pictures were the principal developments of the early decades of this century.

World War II greatly expanded the scope of electronics. The cavity magnetron suddenly provided a source of million-watt pulses a millionth of a second long at frequencies so high that modest antennas could produce sharp beams. This beamed electromagnetic thunderclap was exactly what was needed to scan the skies for approaching aircraft or the surface of the seas for ships. Earlier, radar equipment at Pearl Harbor gave clear warning of the impending Japanese attack, but no one trusted the new gadget enough to believe the awful truth, so the mute warning went unheeded—for the first and last time. Months later, radar was sinking unseen ships and turning the tide of war in the Pacific.

Sonar, automatic guidance systems, proximity fuses, and servo systems were other World War II developments.

After the war came such a flood of new applications and developments that I can only mention a few: commercial television, digital computers, the transistor, and the laser, and in more recent years the integrated circuit, which allows hundreds of thousands of transistors to be interconnected on a tiny chip of silicon.

The enormous versatility of these devices has led electronics into every conceivable field: astronomy, medicine, process control in factories, business, banking, aviation, and space, to name a few.

Our whole space program would not be possible without modern electronics, nor would it be as valuable. Today, communications satellites link the entire world with television as the telegraph once linked cities. Spacecraft send us pictures of the surface of Mars or the moons and rings of Jupiter and Saturn. Recently, we have seen photos of Olympus Mons, the largest volcano in the solar system. It is on Mars. Thirty years ago I would never have thought, in my wildest dreams, that I would ever see such a sight.

From farther out in space radio telescopes are revealing new facts about the structure and evolution of galaxies. Charge-coupled device arrays are replacing photographic film in optical telescopes, giving a hundredfold increase in sensitivity.

The present rate of technological advance shows no sign of slowing down. In fact, it still appears to be accelerating.

What will the next century bring? All anyone can do is to extrapolate present trends a little way into the future. No one can predict the big discoveries like the vacuum tube, the transistor, or the laser. These produce revolutionary changes. They are what makes life truly interesting. I have heard some people complain of "future shock." *Future shock is what keeps me alive.*

Looking ahead we can see computers becoming much more powerful and much less expensive. We can see optical fibers linking homes, stores, and offices as telephone wires do today. This will greatly change our lives by providing high-quality point-to-point closed-circuit television. Television conferencing will replace much of our business travel. Wide-band access to large computers and data bases will be possible from the home.

With video disks and other large-scale memory devices, together with cheap computers, I can see the day when our schools will offer not computer-aided education but computer-based education, with teachers playing the role of interactive tutors rather than the primary source of information. One advantage of such a system is that the teachers might get educated, too.

Nuclear magnetic resonance is developing rapidly into a safe and powerful diagnostic tool. Like the X-ray CAT scanner, these NMR scanners can reveal small tumors anywhere, but without exposing the patient to radiation.

Laser surgery of brain tumors will become a standard operational procedure. Already gliomas, once thought to be inoperable, have yielded to precise location methods and to delicate laser surgery.

Electronics, which has so broadened our range of communication on earth, putting us in close touch with any human on earth, may some day put us in communication with intelligent life on planets around other stars. I am personally involved in the early R&D phase of a search for extraterrestrial intelligence. It is a long shot, but success would have such a profound effect on our future that many scientists believe it is worth the effort. The chances of success with present receiving antennas are small, but we should start out using them. Only after failure can we argue that a larger dedicated facility is necessary. If we persist with ever larger and more sensitive receivers, the day will come when we find ourselves in touch with the galactic network. Technology will then have ended our isolation among the stars. It may even happen in this century.

The microprocessor is finding uses in everything from quartz watches and pocket computers to self-diagnostics in automobiles. One rapidly developing application is in robotics. We are not building robots yet that stalk about and glare at you with deep-set red eyes. We probably never will, except for sci-fi films. What we are building are manipulative arms with sensors that can do an increasingly complex set of jobs such as welding, painting, parts insertion, and assembly. Distributed intelligence is needed for the automated factory. We are not there yet, but many tedious jobs are being done faster and better by these so-called robots.

The unions may resist these robots, as they have resisted previous labor-saving devices, on the grounds that they will displace labor. That is true, they do. But after awhile the unemployed find other, and usually more satisfying, jobs and the unemployment gets distributed throughout our society in the form of shorter working hours. We call it leisure time.

We work half the hours our grandparents did, and yet our lives are far richer. This is the true consequence of our technology. Yet how often we hear technology blamed for many of the world's ills.

My favorite character is the guy who wakes to his radio alarm, shaves with his electric razor, showers while his automatic pot brews his morning coffee, backs his car out as the garage door automatically opens, then shuts, rides to work listening to music and world news, ascends to his office in an automatic elevator, has his secretary get him reservations on the jet for a speaking engagement in Chicago, then picks up his tape recorder and dictates his speech: a scathing denunciation of modern technology.

The major change in our society over the last century has been its conversion from a technologically primitive one that everyone understood, to a technologically sophisticated one, understood by only a few. This widespread ignorance about technology and science is at the root of many of our problems today.

When I was in college, I was forced to take history, foreign languages, and other liberal arts courses, whether I wanted to or not, on the grounds that I would not have a broad enough education to understand the world unless I did. Today, most college graduates are technologically illiterate. I think the time has come to require every student to have a certain minimum exposure to science and technology on the grounds that otherwise they will not have a broad enough education to understand the world.

Unless the majority of our citizens are at least well enough acquainted with technology not to fear it, we cannot expect good political decisions when technological issues are involved.

A case in point is the needless breakup of the Bell system. Believing only that big is bad, even when regulated, and not understanding the technological rationale for monopoly in public utilities, our heroes in the Justice Department have succeeded in crippling the greatest telephone system the world has ever known, as well as the greatest research facility in the world, Bell Laboratories.

Another case in point is the great controversy over nuclear power. The public first became aware of the power of the atom after the first atomic bomb. Because of this violent introduction and because of the irresponsible way the military ignored the hazards of radioactive fallout during the Nevada and Pacific tests, nuclear has come to mean danger in the public mind.

A parallel situation arose a century ago when alternating current was introduced. Alternating current had first come to the public's attention with its use in the electric chair at Sing Sing, and a controversy arose over its safety. I am told that at noon every day, in Central Park, protesters would demonstrate the danger of alternating current by electrocuting a dog.

Some day, the public may accept nuclear power the way it has accepted alternating current today, but to reach that happy state we are going to have to bring the facts before the public.

There are some antitechnology activists at the core of the antinuclear movement, modern Luddites who say, "Even if I were convinced that nuclear power were absolutely safe, I would still be against it." But the vast majority in the movement are simply ignorant of the facts and therefore easily scared by anyone who intones "what if?"

It is time we took a look not at "what if," but "what is." Of the 1.1 million accidental deaths in the United States in the decade from 1967 to 1976, about half were due to auto accidents. This is perhaps no surprise. But it is a little surprising that about 170,000 deaths came from falling. Next, drowning and fires killed about 60,000 each. Poison took 52,000 lives in this period, and guns killed another 24,000. Aircraft accidents, including private planes, accounted for 17,000 deaths, and 11,000 people were accidentally electrocuted. Perhaps then, the bad thing about nuclear power is not the "nuclear"—it is the "power."

Finally, at the bottom of the list of accidental deaths, we find that 5700 came from mining accidents; 1100 people got hit by lightning. And now the cause of all the furor—radiation—killed 3 people. But none, I might add, in nuclear power plants.

It needs to be said loud and clear that the nuclear power we already have has injured no one; rather, it has saved hundreds of coal miner's lives.

It needs to be said loud and clear that the difference between weapons material and nuclear power fuel is the difference between gasoline and asphalt. One will explode; the other will not.

It needs to be said loud and clear that we live in radiation all the time, and that nuclear power would not significantly increase this *natural* background.

It needs to be said loud and clear that the radiation from nuclear plants is less than that from coal plants. There is not a single coal plant that comes within a factor of 10 of meeting NRC radiation standards for nuclear plants; this is in addition to the carbon dioxide and acid rain they produce.

It needs to be said loud and clear that waste disposal is a problem with coal, but not with a nuclear plant, because there is so little of it.

Finally, it needs to be said that there are 4.3 billion tons of uranium in the sea, enough for a million years of electric power for the whole world. And it appears economically feasible to extract it.

These things not only need to be said, *we* need to say them.

Another important reason for going nuclear is to save our oil and gas for mobile power. We have this fine, abundant, and safe source of electric power in the atom. But we cannot run tractors or fly planes on nuclear power. We may be able to find a renewable or inexhaustible source of hydrocarbons in the vegetable world, perhaps in latex-producing plants, perhaps in genetically modified methanogenic bacteria or algae, or in that fabulous copaiba tree. This remarkable tree already is known to produce 10 gallons, and may be able to produce 200 gallons, of diesel fuel per tree per year. If the latter figure is true, the Amazon valley could produce three times the present world oil needs.

Forever. That would be a good way to harness solar energy: let it grow green things; it does that very well.

I would think that research into the organic production of hydrocarbons would have top priority today, but I am not aware of much activity in this area. Until we have a solution at hand, we should not waste our oil, gas, or coal generating electricity.

It will take some time to reorient school and college curricula to include technology education for all. I am afraid we cannot wait. If the public is to be reoriented in its attitudes about nuclear power and about technology in general, *we scientists and engineers are going to have to take a more active role.* In a recent issue of IEEE's *The Institute*, Al Trivelpiece has an interesting suggestion. He proposes that October be designated "Science and Technology Awareness Month" and that during this month, members of the Physical Society, the Chemical Society, the IEEE, and others volunteer to give jargon-free talks on what we do and why it is important to the world. Talks are to be given before the Chamber of Commerce, the Lions, Kiwanis, Rotary, or any appropriate civic or service group. I would add schools to this list. He says: "I find that the public is fascinated by science and technology and is willing to learn about them and the things they produce. It helps if things are put in terms they understand and if the explanation comes from a friend or neighbor." I think this is a great and timely idea.

It is time we began to think about survival not for just another century, not for just a millennium, but for a billion years or more. It is time we began to develop the technology that will enable our indefinite survival rather than the technology that threatens our sudden extinction. If we can do all this, and I think we can, we face an exciting and indefinitely long future.

Bernard M. Oliver, *recently retired board member and Vice President for Research and Development in the Hewlett-Packard Company, continues to serve Hewlett-Packard as technical advisor to the President. He was an early participant in television and radar development at Bell Laboratories, is an IEEE Fellow, and has served as both Vice President and President of the IEEE. Dr. Oliver is a member of the National Academies of Engineering and Sciences and a recipient of the 1986 National Medal of Science.*

ELECTRICAL TECHNOLOGY AND THE MOLECULAR BIOLOGIST

Joshua Lederberg

My career is that of a molecular biologist. But when you visit my office, you will notice that my diploma as a member of the Institute of Radio Engineers is one of the very few that I keep on my wall. It recalls to me the very exciting time that I had working with Lloyd Berkner when he was Chairman of the National Academy of Sciences Space Science Board. He recruited me into the IRE in January 1961 when he was president of that organization, predecessor to the IEEE.

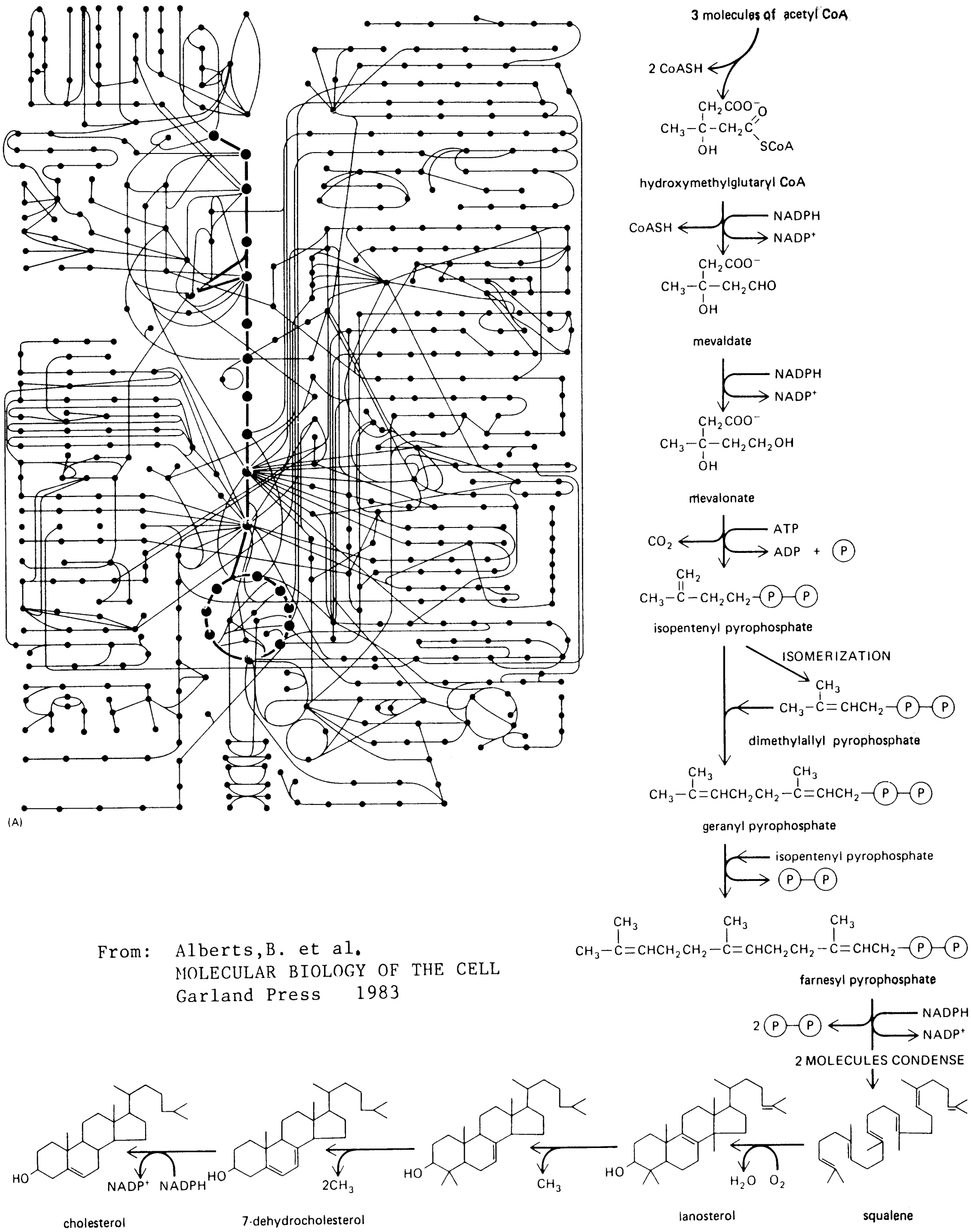
In fact, the first issue on my member's subscription was a special one on artificial intelligence. It included articles by John McCarthy and Marvin Minsky that were influential in drawing my own interest into that field. Why would a molecular biologist care about computers and, particularly, about artificial intelligence? I felt that we were reaching the limit of our intellectual capability of modeling the complexity of the living systems, the molecular biology that was just growing up. These are systems whose complexity is the fruit of four billion years of evolution under spontaneous mutation and natural selection, plus, and very importantly, every trick of molecular chemistry with which God had invested the earth from the beginning, and many of these we are far from understanding fully. So I joined with Ed Feigenbaum and Carl Djeressi, and I had fun *discovering* (rather than inventing) expert systems.

This meeting is a celebration of electricity, but this now also means software, as betokened by the Computer Society within the IEEE.

Twenty years ago, I did prognosticate; I was looking forward to what molecular biology might bring to our future, and I have to say, as I look over my writings, most of the things I talked about have come to pass. If I was in error in a few places, then some advances were even more rapid in their substantiation than I cared to dream about at that time. So it is not out of modesty about my box score in that prophetic mode that I decided not to pursue that mode tonight. Rather, in reflecting over my own career, I cannot see how those prophetic remarks, however correct or incorrect, have made any difference whatsoever. The things that were to come about have come about. If I have made any contribution to the present state of science, technology, or any other aspects of the world's condition, it has been entirely through my laboratory investigations, through the actual study of the nature of living organisms.

Thus I thought I might focus on that and on the ways in which there are, in our future, very strong intersections of my field and yours, which I have tried to internalize in my own interests. Fig. 1 is a flowchart that shows something of the complexity of intermediary metabolism. This is a crystallization of 50 years of biochemical investigation, which have revealed to us the larger number of the substances involved in the degradation of food stuffs into common small carbon constituents; their oxidation; the conversion of their chemical-free energy, usually into the common medium of adenosine triphosphate; and the use of that energy in a variety of metabolic cycles to fire up other biosynthetic mechanisms. If you walk into almost any biochemist lab, you will see the same chart; it will cover a whole side of a room, because each node will have the name and the molecular formula of a given substance on the chart. There are about 400 molecules of molecular weight averaging 150 or 200 that have been pretty thoroughly worked out, and they probably account for most of the simple building blocks of our bodies. However, these unit blocks, like the bits in a computer, are assembled into much more complex architectural constructs.

The flowchart shows the conversions that these compounds undergo: how glucose goes into small carbon fragments, and how those small carbon fragments can be built up again into amino acids, purines, and other growth factors. (Sometimes we must get these from synthetic activities of other organisms.) The chart shows nothing of the regulatory mechanisms, which must be very exquisitely controlled. It simply will not do if you produce twice as much tryptophan as you need for the manufacture of your own proteins, and have a deficiency of other amino acids. Very carefully crafted regulatory mechanisms have evolved in order to achieve that result. We do not make our own tryptophan, we get it from green plants; they have to adjust the catabolism of these nutrients accordingly. So this chart is only the beginning of the complexity of metabolism. It only shows the principal nodes; the edges are the catalytic factors which are responsible for the interconversion of one substance into another. Each edge may be one enzyme or a whole chain of enzymes, which catalyze these inter-



From: Alberts, B. et al.
MOLECULAR BIOLOGY OF THE CELL
Garland Press 1983

Fig. 1

conversions. Of these we have a few hundred whose actions we can designate. In a limited number of cases we have actually isolated and extracted these substances so that we can demonstrate the catalytic activity of these edges in the test tube. In a still more limited number of cases we have enough detailed information about the structure of these protein enzymes that we can begin to rationalize how they behave, although we are far from a complete theory of the action of any enzyme.

A group of people like you is the very best gathering before whom to exercise a few of the cardinal numbers of biological systems (Fig. 2). These deal very closely with the question Dr. Townes asked as to whether

A Primer on Human DNA

- 3,000,000,000 units in a human cell (uncoiled = 2 meters)
- 10,000,000 genes possible
- Information content comparable to a full set of *Encyclopedia Britannica*
- Only about 1% active (rest 'selfish'?)
- 100,000 proteins probably make up the constituents of the human body
- About 1000 proteins have names AND can be guessed to be present in the body
- About 100 proteins have been isolated and definitely characterized in humans
- About 10 human proteins have *medical uses* today
- If DNA were scaled to width of magnetic tape, it would stretch round the world
- Until recently, DNA was the most asymmetric physical object in the universe. (Now there are commensurate optical fibers 10^7 meters long)

Fig. 2

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ATPase , protein 6
Adenylate kinase 1
Alpha crystallin
Alpha-1-acid glycoprotein
Alpha-1-microglobulin
Alpha-lactalbumin
Amyloid protein AA
Angiotensinogen
Antithrombin-III
Apolipoprotein A-I
Apolipoprotein A-II
Apolipoprotein C-I
Apolipoprotein C-II
Apolipoprotein C-III
Apolipoprotein E
Basic proline-rich protein
Beta-2-microglobulin
Beta-thromboglobulin
Big gastrin
C-reactive protein
Calcitonin
Calmodulin
Carbonic anhydrase II
Ceruloplasmin
Choriogonadotropin
Choriomammotropin
Collagen
Complement C1q
Complement C3a anaphylatoxi
Complement C4a anaphylatoxi
Complement C5a anaphylatoxi
Corticotropin-lipotropin
Cytochrome b
Cytochrome b5
Cytochrome c
Epidermal growth factor
Factor IX
Factor XIII
Ferritin
Fibrinogen
Follitropin
Glucagon
Glutamate dehydrogenase
Glutathione reductase
Glyceraldehyde 3-phosphate
Glycophorin A
Haptoglobin
Hemoglobins
Histocompatibility antigens
Histones
Hypoxanthine-guanine phosph
Ig alpha-1 chain C region
Ig delta chain C region
Ig epsilon chain C region
Ig gamma-1 chain C region
Ig heavy chain V-I region
Ig lambda chain V-VI region
Ig mu chain C region
Insulin-like growth factors
Interferon alpha-1
Interleukin-2
Keratin, epidermal
Kininogen
Lactotransferrin
Lutropin
Lysozyme
Metallothionein-2
Myelin basic protein
Myoglobin
Neurophysin 1
Osteocalcin
Oxytocin
Pancreatic hormone
Phosphoglycerate kinase
Plasminogen
Plasminogen activator
Platelet factor 4
Prealbumin
Proenkephalin
Proinsulin
Prolactin
Proparathyroid hormone
Protein HC
Prothrombin
Retinol-binding protein
Serum albumin
Serum amyloid P-component
Somatoliberin
Somatomedin B
Somatostatin I
Somatotropin
Statherin
Superoxide dismutase
Thyrotropin
Thyrotropin-gonadotropin
Transferrin
Troponin C, skeletal muscle
Trypsin inhibitor
Ubiquitin
Urokinase
Vasopressin-neurophysin
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Fig. 3

there is a practical finitude to these expansions of knowledge. If you run out of particles and physics, I suggest you start looking within the cell; there will be some more to do for some time to come. One of the marvels of contemporary biological science is that we have a metric of complexity of the human organism at the level of DNA. Each of us carries in every nucleus of every cell of our body approximately three billion nucleotide units. These are the base pairs of the Watson-Crick double helix. The three billion units, when extended into that double helix form, would range 2 meters in length, tightly coiled into a little sphere approximately 5 micrometers in diameter. This would be enough to encode for ten million gene products if each of them were informationally active, an information content approximately that contained in a few sets of the Encyclopaedia Britannica. This is the genetic code that is inscribed in the zygote and in every cell of our body produced by it.

Happily, for investigative purposes, only about 1 percent of that DNA is believed to be informationally active, so what we have to look forward to is a roster of 100,000 proteins, give or take a factor of 2, which make up the human body. Of those 100,000, where there is informational coding, we can guess at the names of 1000; about 100 have actually been isolated and definitely characterized in the human organism. I actually compiled a list. (All of this has to be done on the computer, which makes it very convenient to bring this information to you; see Fig. 3.) So, at the protein level, we can inventory 1/1000 of the constituents of which our bodies are formed.

We have a glimmer of the mode of action of a few dozen of these. There is a good story about how hemoglobin works, as well as a few others. Others have regulatory functions in controlling the rates at which certain edges will be functional in the graphs that I just indicated. They may have many, many other interactions, one with another, of which we only have a glimmer. Just to discover these one at a time is an enormous side of the enterprise. To comprehend the total is one of the major challenges of all of the electricity that we are going to be able to muster for the next 100 years.

Joshua Lederberg, *president of Rockefeller University, has served as consultant to the Arms Control and Disarmament Agency and as a member of the Advisory Committee on Medical Research of the World Health Organization. He is a member of the National Academy of Sciences, the Royal Society of London, the U.S. Defense Science Board, and an Honorary Life Member of the New York Academy of Sciences. Dr. Lederberg received the Nobel Prize in Physiology and Medicine in 1958 for research in genetic mechanisms of bacteria and has played an active role in the Mariner and Viking missions to Mars.*

DEALING WITH TECHNOLOGICAL AFFLUENCE

Alvin Toffler

We are living in the midst of a profound revolution which is not just technological, and I like the emphasis we are placing on aspirations, which is another way of saying values. It seems to me that there are some very profound questions posed for the society as a whole by the activities of our scientists and engineers, and while we may differ heatedly over whether Bell should be broken up or whether nuclear power is good or bad, the deeper issues involve our entire attitude toward technology.

This society is rapidly moving beyond what has been called the Smokestack Era. Traditional industrial society, based on mass production, mass consumption, mass distribution, and mass communication, is undergoing a fundamental transformation. A new kind of society is emerging which I believe is much more heterogeneous, much more differentiated. It is no longer an industrial mass society. And as we move into some new social economic and technological stage, we must do better than divide ourselves into technophobes and technophiles.

Technology has such complex impacts on society as a whole that to simply line up on one side or the other of that divide is indeed naive. The notion that technology is neutral in its effects, or that more is necessarily better, reflects an earlier age. We have been through a lot. The world is fully aware of the negative effects of technology. If I had to rank myself as between technophobe and technophile, I would probably be somewhere on the technophile side. But even so, we live in a world which has some pretty hideous characteristics, a good many of them related to technology.

We have, by and large, selected our technologies according to rather simple criteria. An earlier speaker said that we have moved from a period of technological primitiveness to a period of technological sophistication. That is correct. The phrase I frequently use is slightly different. I believe we have gone from technological poverty to technological affluence.

We have so many choices in our laboratories that it is impossible for us to fund them all, develop them all, and apply them all. And that raises the question of what are the criteria by which we make the selections. Until now—and what follows is an exaggeration—the criteria have been basically: "Does it make a buck or does it make a bang?" But the exaggeration is not too far off target. In either case, if the technology could promise profit or military power, chances were it would be adopted. It at least had a chance in the competition of technologies.

The market has been a phenomenally good mechanism for accelerating technological development. The market is an incredible invention of the human race, and it has had profound and worthwhile effects, driving technology, as well, in good directions. And certainly the military has stimulated technology, including many innovations that have proved socially beneficial.

But the question remains as to whether those two criteria are adequate. After all, the rejection of certain technologies is a normal and natural feature of evolution. Societies have often rejected certain technologies because they did not fit into an evolutionary niche in the system or fit into the value system. Alexandria had a steam engine, but it did not know what to do with it, and the engine died out, as we know.

The point is that there is a powerful feedback relationship between the values of the society and the technologies of the society. This will be particularly true as we move into a period of what might be called cultural technologies—artificial intelligence, speech recognition, automatic translation, video animation, and graphics—all of which act on how we think. That, in turn, acts on what our values are and that, in turn, acts on who gets what dollars for research and what directions the technology takes.

Both the technophobes and the technophiles share rather mechanistic assumptions about the way technology fits into the society. Frequently they lump together technologies that do not belong in the same category. For today's Luddites, a computer, a satellite, or a genetic development are all part of the same thing. It is all technology, isn't it?

We need a more refined view because the social and environmental impacts of technologies are differentiated. The second-, third-, and *n*th-order effects, and especially their interrelationships, are very complicated, and as the society itself grows more differentiated, those consequences become even more complex. And so, should the mere availability of some technology drive the system? Is it sufficient to judge by the criteria of economics and military power?

I remember a conversation with a U. S. Army general not so long ago, who complained that our military lacked strategy, that basically the defense contractors presented various technologies, and then the military said: "Well, what can we do with these?" The general's complaint was that technology was driving strategy, instead of strategy driving technology. Isn't the same true for society as well? And should it be?

Why do we have Luddites? One can feel sorry for the original Luddites, some of whom ultimately lost their lives in their rebellion against the spinning frames, yet they failed to block technological development. Why do we have Luddites today? Why are there some people who are prepared to blow up computers or to wreck havoc on technology?

There are many reasons. One reason is that there are not very many legitimate, institutionalized ways for the public to participate in technological decision making—ways to express its fears about ecology, social change, its political concerns, its fears about war, privacy, and the possible division of society into the information-rich and the information-poor. These are all legitimate questions for all of us to ponder.

If there were more systematic and legitimate channels for their discussion, and if that discussion were linked to public education, then perhaps the opposition might be less emotional, less ignorant, and less negativistic.

Moreover, if the public needs to know more about technology and science—which I heartily believe—young engineers would not be harmed by studying some political history, anthropology, sociology, psychology and, yes, even some futuristics.

I'm not arguing C. P. Snow's division of the world into two cultures. As the society becomes more diverse and differentiated, we are living in a multiculture. In fact, the multiplicity of cultures is growing all the time. This is something scientists and engineers do not yet appreciate.

We also hear a lot today about changing paradigms in the Kuhnian sense, in physics, biology and other fields, where there seems to be a shift from an emphasis on studies of equilibrium to the study of systems in nonequilibrium conditions. For example, Ilya Prigogine and René Thom and people like them are all looking at nonlinear relationships and turbulent systems and chaos.

This new emphasis is part of a larger transformation of our thinking, a change in the direction of science itself, but not just in science. It is related to the development of new social models, too, and new ways of thinking about society. To understand the way the technological subsystem fits into the larger cultural system that we call civilization, I think we need to recognize that society is increasingly affected by nonlinear forces. It is far from equilibrium; it is extremely vulnerable to outside impacts. Chance and necessity both play a role in our society. For these reasons, we need to discard the assumption that society is anything like a physical or Newtonian system—or that technology is necessarily either good or bad.

The advance of technology offers fantastic promise for the human race and not just for the rich nations. I believe it holds out fantastic promise for the poor of the world as well. But what we need even more than technological advances are conceptual advances. We need a more complex appreciation of the feedback between the technological revolution and the social, economic, familial, psychological, and cultural revolutions that proceed with it and feed it, as it feeds them. We are in a society itself caught up in revolutionary change as it transitions beyond the industrial age, and I believe that the people in this room and listening out at the remote locations have an enormous opportunity to make that transition smoother rather than potentially dangerous.

Alvin Toffler *is a scholar, author, and futurist best known for his analysis of contemporary social change. His books, including* Future Shock *and* The Third Wave, *have been published in more than thirty languages; his most recent book,* Previews & Premises, *is now in translation in many countries. He holds five honorary doctoral degrees, is a member of the International Institute for Strategic Studies, a Fellow of the American Association for the Advancement of Science, and is the recipient of France's Prix du Meilleur Livre Etranger and the McKinsey Book Award in the United States.*

THE POSSIBILITIES OF EXPANDING TECHNOLOGY

Charles Townes

I would like to make three points. First, Dr. Oliver has commented that progress does not seem to be slowing down and may instead be accelerating. This raises the question: how far do we have to go—how far will knowledge be taking us? Is the realm of technical knowledge infinite, or will our job of exploring science and technology sometime be complete? One might, for example, imagine that knowledge is like an island which we approach from its shores. We explore all the island and then know what is there; the physical universe might possibly be like that. Or we might imagine expanding knowledge from a center, so that as we push back the boundaries, exploring continually, the boundaries simply enlarge. As we progress we can see a little bit further into such a universe, but there is always more in front of us than when we started, even though we have learned much more and explored a great deal of territory.

My view is that knowledge and technology are more like the latter case. Consider, for example, the world of physics. When I went to school the most fundamental and, we thought, simplest part of physics, the fundamental particles, was comprised of only a few elements: the electron, the proton, and then the neutron. Further examination showed that these are made up of further systems, which in turn are made up of further ones and, as far as we can see, the particle physicists simply proceed into an unknown region of apparently growing size. Even in this relatively simple and fundamental area, no limit has yet appeared and our progress can fortunately continue. This has been an exciting and exhilarating century, and one can hope that there are no limits to the contributions engineers may make in the still longer run to the knowledge and scope of the human race, and to its welfare.

My second point is that our field is a very young, bumptious, and still maturing one. If, for example, we say that the modern aspects of electrical engineering were born 100 years ago, I suppose we are now only in late adolescence or perhaps young maturity. The field is growing, becoming stronger, and is ready to take on still more responsibilities. With the present characteristics of the field and its importance to our civilization, those increased responsibilities seem destined. If we are in adolescence after the first century, there are still many centuries ahead. Any nearby limitation will not, I suspect, be due to the inherent nature of science and technology; the limitation may be us. We may just develop into good sedate members of society who allow our field to advance very successfully into a middle-age slump. That clearly has not yet happened. Nevertheless, such age effects can occur and we must be alert to them. How can they occur? Consider that the United States has been blessed with rapid development, even an explosion of developments, which have made us feel optimistic about the future, free to speculate hopefully, ready to experiment, to accept new ideas, and to welcome people from all fields into our own or to transmit ideas rather freely across all boundaries. That is an important part of what has made for the greatness of American science and technology. It has also required a willingness to take chances.

In the business world, I think everyone recognizes the importance of the small entrepreneur who takes chances and the entrepreneurial company which, while it may fail completely, will on occasion succeed beyond the wildest dreams. We also recognize in principle the importance of letting everybody try new ideas and of supporting research which explores the unknown. However, it is much harder to be convincing about the latter. The reason is that research takes so long to develop into visible uses. I would say, for example, that the transistor really began in the 1930's when Mervin Kelly, at Bell Laboratories, decided to support substantial fundamental work on the new solid-state physics. The actual invention came later, and any real applications success at least 20 years later. This is common with research results, which cannot be completely predicted. And it is the surprises and the unpredictable that often produce the real breakthroughs. But the unpredictable is very unsatisfactory for the politician or even the corporate officer to support. We all like to try to figure out the consequences of our decisions. We also like to see results happen within our term of office. In the field of research, where one cannot know, this puts us in a difficult position. Hence long-term research, the wild chances, the freedom for individuals to try ambitious but uncertain ideas, are always difficult to support. I hope we can avoid the middle-age slump of overcaution, or of planning only for the plannable, and support a reasonable fraction of the long chances which may develop only slowly if at all, the small and off-beat operators, or the new ideas that not everybody believes in. This is what will ensure that the spirit of youth and growth can continue.

The third point I would like to make is that the future is very much affected not only by the nature of our field, but also by human aspirations. Almost anything can be done that is not contrary to some basic physical law. What actually gets done is primarily determined by human aspirations. In that sense it is often interesting and revealing to look at science fiction, which in a certain sense represents humanity's dreams. The science fiction of the Greeks about the flight of Daedalus took a while to come true, but is now eminently real. *20,000 Leagues Under the Sea* came true a little more rapidly. Mankind wanted to go to the moon, and we did. Those things to which we really aspire, even if apparently improbable, are actually likely to happen. I sometimes think that the interest in laser beams is associated with Zeus' bolt of lightning and Buck Rogers' ray gun. Those were some of mankind's dreams, too.

In our aspirations, however, there are frequently conflicts. There are the aspirations of individuals or of nations to be completely free and independent, to be able to make their own decisions, but also the aspiration for safety, fairness, and orderliness, which all require organization of society. More starkly, we must recognize that there are even aspirations for dominance and control of other people in parallel with that for freedom. Such mixed and conflicting aspirations give us deep trouble and uncertainties, and are partly responsible for the terrible problem we have with the threats of war. The third world also has its critical aspirational conflicts. There is the desire for a higher standard of living, with abundant natural resources for each individual, but at the same time aspirations for procreation and many offspring. This dilemma of the third world and its poverty are only enhanced and emphasized by the richness of technology. Technology, training, and education are themselves a form of wealth. We shall become, I am convinced, less and less dependent on the normal products of the third world as technology makes mankind more flexible in the use of alternate resources and less dependent on what goods and services the third world has to offer.

How can talents be unleashed and made fruitful in further manifestations of the type of creative surge we technologists have experienced during the last century? Certainly we need to think carefully about our aspirations and where they lead. With appropriate and self-consistent aspirations, I believe that the human being's increasing understanding of the physical world and the potentials of technology make almost anything realizable during our next century.

Charles H. Townes *is professor of physics at the University of California, Berkeley. Previously he held positions as a member of the technical staff at Bell Laboratories and on the faculties at Columbia and at Massachusetts Institute of Technology, where he also served as provost. He has served as a member and vice chairman of the President's Science Advisory Council and as chairman of the Scientific and Technical Advisory Commission for Manned Flight. Among other honors, Dr. Townes is a recipient of the Nobel Prize for Physics for developing the maser and laser principle of producing high intensity radiation, the IEEE Medal of Honor, the Ballantine Medal of The Franklin Institute, and is a member of the National Academy of Sciences.*

MICROELECTRONICS: THE NEXT 100 YEARS

Robert N. Noyce

In this centennial year for the IEEE, we have a tendency to look backward and forward. In that sense, it is living up to one of my tenets, which is that we tend to look forward about as far as we can look back. But when we start talking about microelectronics, it is not really possible to look back a century.

As a matter of fact, the seminal events were in the mid-1940's. Harvard Mark I, the first of the electromechanical calculators, was introduced in 1944. ENIAC, with its vacuum tubes, came in 1946, the same year as von Neumann's computer concept. And then, of course, in 1947 Bardeen, Brattain, and Shockley invented the transistor, which marked the birth of microelectronics technology as we know it today.

If I follow my rule and try to look forward about as far as I can look back, that suggests we can look ahead to around 2020, a year that was mentioned earlier in the conference. If I recall correctly, that was the time by which we felt all books could be put on one disk.

But since today's subject is a look at the technology for the next century, I will try to stretch a little bit. In doing so, we will find that we run into some very hard limits with the approaches that we are taking today—and those approaches are indeed going to become obsolete. I will speculate as to how we might get around some of those limits to find a path so that microelectronics will not become an extinct species. We are already beginning to look at biological models to suggest answers to the problems that we will be encountering; I suggest that inquiry into these systems will increase in the future. I would also like to speculate about how the next century's technology will affect our society, and vice versa.

Talking about limits—if we do extend our sightlines for another century and look at what we may encounter, then perhaps the song from "Oklahoma" gives us a fitting theme: "We've gone about as far as we can go." Within this time frame, we will have to change the current course drastically, because we will run into some very hard walls. I see three main limits on the horizon: the limits of our computing elements due to basic physical laws; the economic limits, that is, how much money will our society be willing to spend on these devices; and finally, the limits on the usefulness of the approaches we are now taking.

Let us take a look at the physical limits. Some 20 years ago, Bob Keyes talked about three limits on semiconductor computing elements. Fundamental limits on the power and speed performance are indeed imposed by the uncertainty principle. They are imposed by the power required to propagate signals above the noise level at high speed, and they are limited by thermal energies.

Let me concentrate on the thermal energy. The limitation that Keyes saw there is kT. This implies that we have 1 electron crossing 1 thermal barrier, that is, the total energy involved is about 1/40 of an electron-volt at room temperature. It is indeed hard to see how we could get a computing element to dissipate less than that. We could lower the temperature, but then the other limits that Keyes mentioned would block us in somewhat tighter than this limit implies.

If we look at the rate of progress toward that kT limit over the last 20 years and assume that the same rate of progress will continue, we find that we will run into that fundamental limit near the year 2020 (Fig. 1). Realistically, we will reach the limit sooner, because we will have to have more than 1 electron crossing the thermal barrier, and that barrier will have to be higher than thermal energy in order to keep it there. If, for example, the necessary number is 10 electrons and the barrier height has to be 10 kT, then we are now a factor of some 5000 away from the fundamental limit.

As we get closer to that limit, random errors are going to creep in. Consequently, we will no longer be able to rely on any discrete element to provide the value. That suggests that the approach we are now taking to logic will become obsolete; something will have to change.

The second limit is an economic limit (Fig. 2). If the rate of growth in the value of microelectronics were to continue as it has in the past, the sales of microelectronic devices in our country would equal the projected gross national product for the United States in about the year 2020. I suggest that this will not happen. We will have other things to do in our society besides building MOS devices. Something will have to give. The last limit I would like to talk about is the limit to the usefulness of today's approach. We have a great deal of capability with our highly integrated processors, dense memories, and other similar devices. And we will be able to make much more complex devices in the future—but will they be useful? Let me give you a simple example of the limit of today's approach.

Even as an infant, you were able to recognize your mother long before you were able to talk, but that is still something we cannot yet do with a computer. We

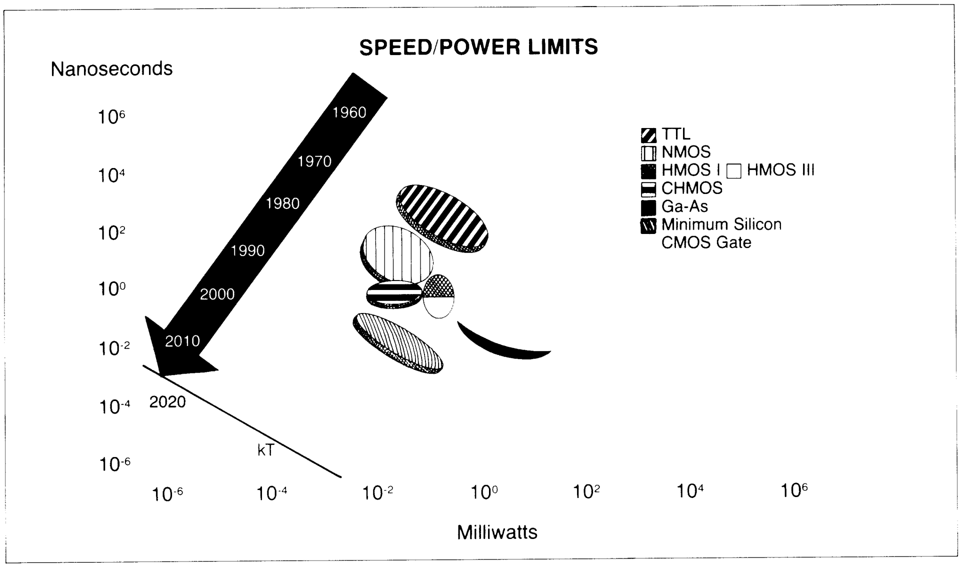

Fig. 1: Current process technologies like CMOS and HMOS are pushing the limits of silicon. Based on past developments, we would probably hit the fundamental limit of switching energy by 2020. More likely, we will come up against a real physical limit sooner.

could say that the computer is in its early infancy. The simplest task that the child takes on cannot yet be accomplished by the computer, and yet we are increasingly asking the computer to do jobs that humans do. That is what artificial intelligence and the orientation of the fifth-generation project in Japan are all about.

In the next century, we will certainly see even more exploration of new architectures to perform jobs for which the von Neumann architecture is ill suited. These jobs take all shapes, including that of recognizing mother, or any other pattern. And although the computer in my car calculates the right amount of fuel hundreds of times a second, I think very few of us would trust a computer to drive us to work and do all the pattern recognition that is required for that job.

Looking again at biological systems, they are in large part self-healing or self-repairing. We have not yet devised a way to make computer systems adept at those tasks. Perhaps one of the most astounding capabilities of biological systems is self-reproduction. And although computers are used to design or make computers, this kind of reproduction is not nearly as complete as it is in biological systems. I believe that the incapability of our present systems to do tasks that we would deem desirable will lead inexorably to new approaches to computer systems.

In spite of the limitations on the usefulness of our

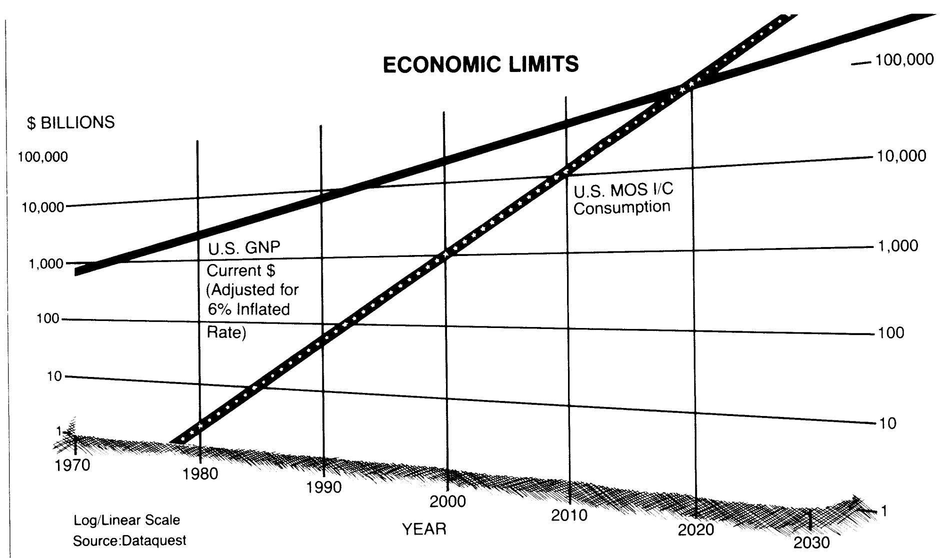

Fig. 2: Were U.S. annual microelectronic device revenues and the U.S. gross national product to continue their current rates of growth, they would intersect somewhere in the 2020 timeframe. This economic limit spells change ahead.

current machines, their range of applications is very broad and will certainly continue to expand rapidly over the next several decades. Semiconductor device engineers will continue to make more complex devices in ever-shrinking dimensions. Our lithographic techniques will become more and more sophisticated. We will use more layers of thin films to extend the usefulness of the underlying silicon or other material. And yet, these approaches will also run out of steam and be their own limitations.

Biological systems may offer us a way around these systems. The basic characteristic of a biological system seems to be that it is self-organizing. In some sense we already used self-organization to aid our production of semiconductor devices. Techniques such as self-aligned gates, where the existence of one pattern determines the geometry of the second pattern, might be one example. Hopefully, we can extend those techniques even further by looking for affinities within materials that would allow the materials to organize themselves.

Another type of self-organization comes in the form of redundancy. As we push the limits of silicon, we find that the incidence of errors will increase more and more, and redundancy will be required to assure that stored information has a high probability of being preserved correctly. The redundant rows and columns in memory circuits that exist today are perhaps the precursors of a broader use of redundancy. Error correction on memories that we now use at the systems level is another example of self-healing. Like redundancy, error correction will also probably be reduced to the chip level. In sum, these approaches can be seen as part of a growing tendency toward self-diagnosis and self-healing.

There is another limitation that increasing complexity suggests to us. By 1980, the complexity of our design was on too steep a rise to continue in its existing format (Fig. 3). If we look at the issue a bit more quantitatively, we find that the productivity of our designers is not keeping pace with the demands made upon them for new designs. Design times are increasing exponentially, and we know that anything that increases exponentially eventually runs out of steam. The answers to this have been the various attempts at design automation.

Design automation has many different levels (Fig. 4). The design process itself has a variety of levels and many different representations of the final product—from the architectural design and specification of the product, to chip layout, to a test program that the chip must pass. Thus far, design automation has concentrated on the lower levels of this design process. These levels are relatively easy to automate, and it is fairly easy to verify the correctness of the solution.

The creative part of the work—the part that is much more difficult to automate—is the synthesis involved both in understanding what the market will require as the final product specification, and in actually developing that new architectural specification. Yet, as time goes by, automation will move up this hierarchy and will be applied to the more complex problems.

I can cite as an example the design of a 32-bit successor to a popular 16-bit microprocessor. One of the requirements was simply that the successor be software compatible with its predecessor. In achieving that compatibility, the design effort took between 15 and 20 person-years. Yet that is a relatively straightforward job, and it would have been—as far as I am concerned—far more preferable to have had a primitive instruction in the CAD system which simply said that the new product was to be compatible with the old one.

Every time in the past that an extrapolation of

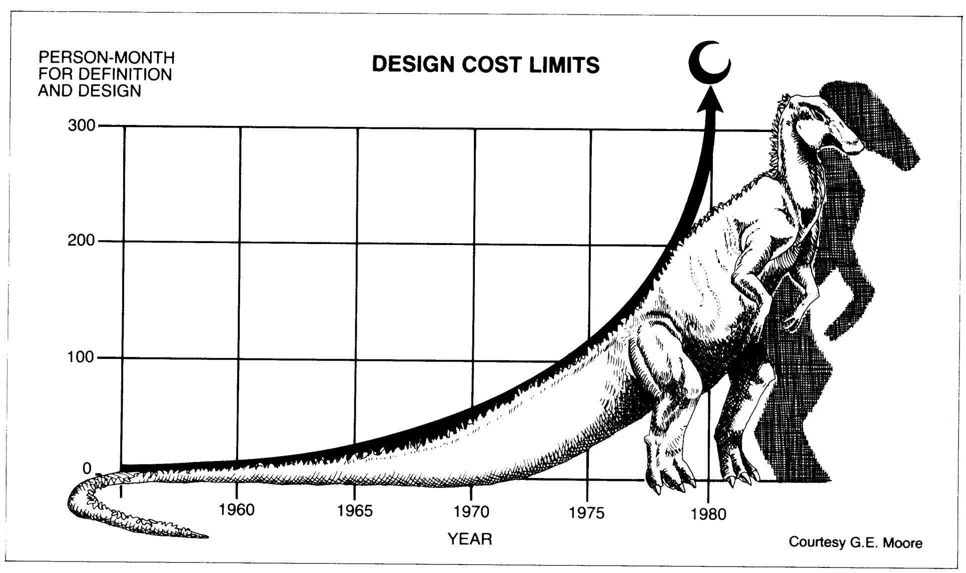

Fig. 3: By 1980, VLSI design costs were getting out of hand. Without changes in approach, the cost of producing future products could limit their scope and usefulness.

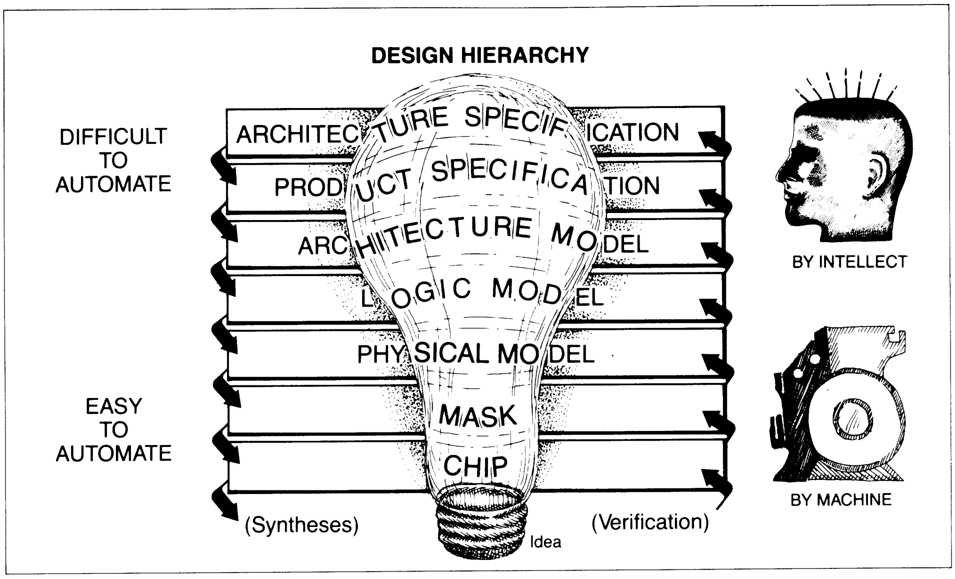

Fig. 4: Design automation offers a way around spiraling development costs. The question is: how far up the design hierarchy will automation prove to be fruitful?

existing trends has grown to ridiculously large numbers or created awkward design parameters, there has been either a change in methodology, or we have suggested that it is a job for the government to do.

In the mid-1950s, for example, we learned that larger scale computers could not really be built, because the reliability of the wires and sockets and soldered joints would not be adequate to let the computer operate long enough to be useful. In the mid-1960's, by extrapolating the design trends in integrated circuits, we determined that we would need to have more than all the engineers in the world designing integrated circuits in order to use large-scale integration properly—very similar to the telephone operator problem.

We cut off that extrapolation by finding new ways to do things. In this case, we used programmable circuits—whether they were PROMs, programmable logic arrays, or microprocessors—which could be programmed to many different applications. This eliminated the tyranny of having so many designers coming up with a unique design for each application.

If history is any example, then we are rapidly approaching the time when we will have to create a new design approach in order to take full advantage of the capabilities that we have built for ourselves. What new approaches might we think of?

In this presentation I made references to self-organizing and self-healing systems—ideas that come straight from biology. I think there are other aspects of biology that suggest a path for the future. Biology not only gives us a way of *building* structures, but it is itself a model of a system that has been extremely successful over time. It functions with less-than-perfect devices—and I might add that our industry is very good at making less-than-perfect devices.

It seems to work on a basis of statistical accuracy, rather than absolute accuracy. Input/output channels have their own processing. There is self-diagnosis; there is redundancy; there is adaptive behavior; and there is trainability. These are all hallmarks of biology's levels of compatibility that are either unattainable or poorly implemented in our current architectures.

A recent article in *Science* noted that "the brain is beating out computers with neurons that operate a million times slower than silicon. And the secret, of course, is in the wiring."

That, incidentally, is what microelectronics is all about—the wiring. Any yield model will say that the individual transistor is cheaper to make than the transistor in the integrated circuit, because you do not have the multiplication of yield factors.

Comparisons like these imply that the von Neumann machine may go the way of the brontosaurus or the woolly mammals and be a dead-ended response to the requirements and the dynamics of the world around it.

We indeed have a long way to go. The U.S. market for semiconductor devices is about 10^{10} dollars per year (Fig. 5). If all of those devices were made up of memory bits—the cheapest element that the semiconductor industry produces—the cost would be about $\$10^{-4}$ per bit. Consequently, the total market would be somewhere along the order of 10^{14} bits per year. But this is probably obsolete by now; it may have been true two weeks ago. Note that this number is about equal to the number of synapses in the human brain.

Turning to biological systems, we have a long way to go if we are going to begin to match the human brain in complexity. If we look at all the production from last year as, for example, a single entity, then that entity's complexity is roughly comparable to that of the

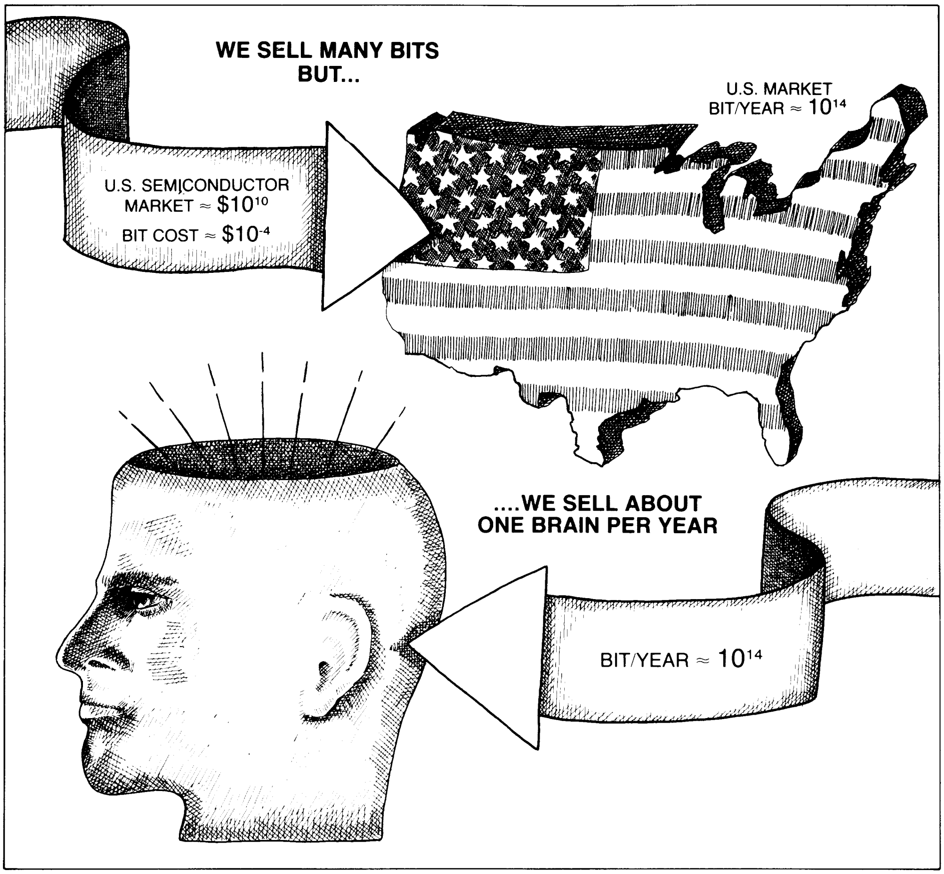

Fig. 5: The U.S. market for semiconductor devices—about 10^{14} bits per year—appears large and healthy. However, considering that one human brain has approximately 10^{14} synapses, the semiconductor figure does not seem quite as impressive: we sell about one brain per year.

human brain. This suggests that we are far from exhausting the possibilities; there seems to be some reason to have on the order of 4 1/2 billion human brains on this planet today.

I might also note parenthetically that if we were to continue the same rate of increase in the number of devices that we make, we would have produced about the number of elements that exist in all human brains, again by 2020. It would appear that by the early part of the next century, we are going to run out of steam on all of our projections.

In contrast to the amount of brain power that we produced, in the production of artificial muscle power we have gone far beyond human muscle power. If we look at the energy output for world oil consumption alone, it is equal to about five times the total human energy output today. This suggests that we still have a long way to go with brain enhancers, as well as muscle enhancers.

Another telling facet of biological systems is that they seem to use constructive methods to put things together, rather than the subtractive methods used in our photolithographic processes. In the biological system, there is an environment where raw materials exist to build cells, a pattern is introduced, and the molecules are formed upon that template. This molecular process could conceivably provide a way of achieving the new supercomplex, superfine structures that we would like to have, and allow nature to help us build the complex structures of tomorrow.

As we further examine biological systems, we find that the input and output channels are quasi-analog, quasi-digital. The signals along the nerves appear to be digital signals with analog amplitudes or timing. And indeed, our sensors do a great deal of the processing at the sensor site itself, as studies of the human eye have shown.

Furthermore, with the biological system's very high degree of connectiveness, truth can only exist statistically, so that the failure of any single element will not cause the failure of the entire organism. Even in cases of major failure, the body can, in many instances, adapt to that failure and continue to function. The ability to adapt will likely become another important part of the architectures of tomorrow.

Adaptation is part of the quality that we call intelligence: the ability to learn from the environment and to adapt to it, to react to and anticipate change. We are beginning to recognize that the ability to deal with fuzzily defined problems is essential to the development of an adaptive capacity, and to the development of artificial intelligence.

There are those who feel that artificial intelligence is an abstract problem, and that it is not related to the physical structures embodying that intelligence. Increasingly, there is a school of thought which believes that basic structures will have to be changed in order to realize that quality which we call intelligence. For this to happen, the pathways of knowledge and communications will have to be increasingly connected.

Borrowing again from Rodgers and Hammerstein, who wrote that "the cowboy and the farmer should be friends," for maximum advancement I believe *the engineer and the biologist should be friends*. Progress will only come from the cross-pollination of various fields of knowledge. This cross-pollination will offer new approaches to the solution of ever more complex problems.

As we learn more about how the brain functions, our increased understanding will spark new ideas for organizing electronics systems. Of course, we do not need to know exactly how the brain works in order to build devices that incorporate some of its capabilities. We can build airplanes, for example, that are powered by different mechanisms than those by which birds fly. The point is that if we want to generate approximate solutions to fuzzily defined problems, and if we want to provide superprocessing input/output devices like the eye or the ear, it will probably require an interdisciplinary approach.

Until now we have been going the other way. In order to understand the brain, we have tried to use the computer as a model. Perhaps it is time to reverse that reasoning. To understand where we should go with the computer, we should probably use the brain as a model. If we do so, we may find that today's computer is indeed the fossil of our age.

With increases in knowledge, each generation has faced a more exciting challenge than the previous one. In this respect, the future would appear to be no different than the past: this means we have both opportunities and problems. The new technology will solve some of those problems as it expands our capabilities, and it will create other problems as it makes us more godlike in our ability to mimic nature. At the same time, information is becoming a strategic resource, just as physical wealth has been in the past.

The change in our capabilities will mean a change in our society. Just as the age of mechanization moved most people in the world from subsistence agriculture to manufacturing, the increasing level of automation will mean that human activity will concentrate more and more on those things that machines are unable to do. Consequently, as the machines become more capable, the definition of work will change.

There is certainly going to be opposition to that change, just as there has been opposition to change in the past. But there is little doubt that the more powerful information machines will someday be like telephones—we will all have them, we will not think twice about using them, and we would not want to live without them.

In conclusion, the next century will bring many challenges and changes. We will reach the limits of our traditional approaches to devising new computer elements, and we will reach the limits of the utility of our present architectures. Approaching those limits, we will look for new ways to progress. Biological models hint at a coming mutation in methodology; without question, there are certainly enough problems and opportunities to keep us occupied for a century to come.

Robert N. Noyce, *vice chairman of the board of Intel Corporation, was its co-founder and former president and chairman. Earlier, he was a member of the Shockley Semiconductor Laboratory, which he left to co-found Fairchild Semiconductor Corporation. Dr. Noyce is co-inventor of the integrated circuit, recipient of the National Medal of Science, the IEEE Medal of Honor, the IEE Faraday Medal, the Harry Goode Award, and the Ballantine Medal of The Franklin Institute. He is an IEEE Fellow and a member of the National Academies of Engineering and Sciences.*

EXPANDING APPLICATIONS FOR SEMICONDUCTORS

Carver A. Mead

It is interesting to look at an industry—the industry we have come to call the semiconductor industry—which has evolved in its basic technology over a factor of about a million in the last 20 years. Unfortunately, there has not been concomitant progress in the kinds of systems that are being manufactured with this wonderful technology. Today's microprocessors are still based on the single idea presented by Alan Turing in the mid-1930's.

We have not yet begun to see commercial use of the semiconductor technology for anything except cost reduction of old ideas. It is just now that we are beginning to see it used at the research level as a medium for innovation in new kinds of systems.

Current computers are really good at doing extremely well-defined problems in a very precise way and getting very precise answers. But many of the hardest problems cannot be formulated in this way. One of the things you notice when you try to work real system problems is the exponential explosion of computation bandwidth as you get right to the inputs or right to the outputs. The problems that come to mind are image and auditory processing on the input end—seeing and hearing, if you like. On the output end, the generation of graphic images or high-quality sound are also highly demanding computationally. I will discuss two examples from my own lab because I am most familiar with that work.

The first example is the generation of high-quality music. Music has been an important part of human culture for a long time, and it is natural that we try to use our latest technology to do a really good job of making musical instruments. When you look at that problem hard, as we have done, it becomes clear that a really fruitful approach to synthesizing music is to build a model of a physical instrument. It does not have to be an existing instrument, but it can be. It can also be an imagined physical instrument. There are continuity properties of sound and sound sources that allow this kind of synthesis to do a very good job.

If you run a program that does that kind of synthesis on an ordinary midsized computer, it takes about ten minutes to generate one second of sound for one voice, like one string on a guitar or one bar of a marimba. With the approach that we have been taking, modeling these equations with finite difference schemes, you can do this kind of synthesis in real time with a dedicated architecture on one chip. In this application, because of its dedicated architecture, one chip is able to bring a tremendous amount of concurrency to bear on the problem. It is doing as much computation as about 600 medium-sized computers.

Fig. 1 shows an experimental chip which we have been using for this job. In each of the horizontal slices is one small finite difference engine. The new chip we have under design right now will have about 60 of those finite difference engines together with the interconnect scheme, which allows them to synthesize musical sounds. Even though this is a well-defined problem, solved in a very precise way with digital technology, there is still a factor of 104 to be gained by architectural innovation.

One thing you notice if you are in this game a while—the game of mapping real applications down onto silicon—is that they are all different. Musical synthesis is really very different from image processing. I have tried myself, and many people have tried to find the general-purpose highly concurrent system. At this point I do not believe such a system exists. When you get to highly concurrent systems, the algorithms are inseparable from the architecture. That tells me

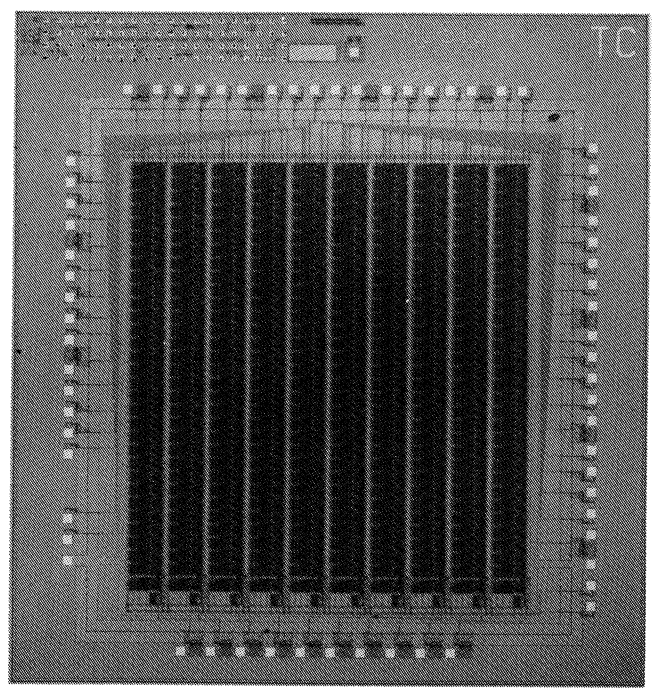

Fig. 1

that there will be more and more direct mapping of applications down onto silicon—what today's newspapers call custom chips, or application-specific integrated circuits.

We noticed an important thing when personal computers became popular. Most of us remember when computer companies thought they should write all the software there was in the world. As a consequence there was not much software, and what there was did not work very well. When we got the personal computer, it decoupled the creation of the computing engine from the creation of the software and the applications. There has been an enormous wave of innovation in software due to this decoupling.

The same phenomenon is starting to happen with silicon. The mapping of applications onto silicon is not the province of a semiconductor company. The advent of silicon foundries, which will fabricate designs made by people who are good at mapping applications onto silicon, is really rejuvenating the whole industry. Instead of a single monolithic standard component business, as we had them in the past, we are seeing an industry that is growing a new structure, as shown in Fig. 2.

Alongside that standard components business, imbedded in all the applications, we see semiconductor fabrication services: people in the business of fabricating wafers for those that have applications to put on them. We also see the evolution of a new design tool industry, which provides the bridge from system applications to the silicon. The new structure is much more representative of a mature industry, in which people do what they are best at and buy the rest from others.

So far I have not looked very far into the future, but have given a background for the direction in which things are evolving. There will be a great deal of

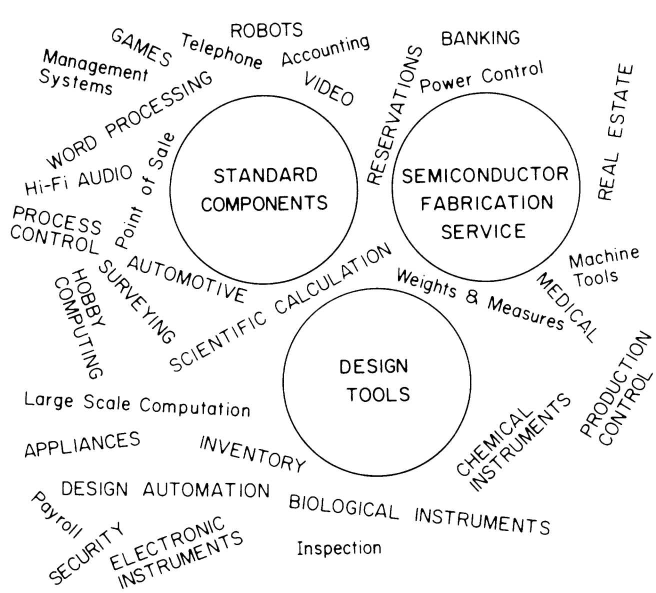

Fig. 2

perceived progress in the directions noted above, but all the conceptual foundations have already been established. The really exciting potential for the future lies in the areas where we have not yet put a conceptual framework together. In no field is the potential higher, and the conceptual framework more fragmented, than in the application of biological principles to electronic computation. Even the most casual observer is immediately struck by the awesome computing capabilities of the brains of even very simple animals. The particular example I will discuss is vision. This task is, by its very nature, not well-defined. It has no precise answers. Rather, it requires a very fast, approximate solution to an ill-posed problem. As you all know, our eye can do with millisecond logic a task that our most powerful computers take hours to do—a factor of least 10^{10}, and perhaps much more. This enormous discrepancy between our best man-made systems and their biological counterparts suggests that there are fundamental organization principles of which we are completely ignorant. One remarkable result of these principles is that biological systems are robust against the loss of a significant fraction, 10 percent or so, of their active devices.

One conclusion is abundantly evident—we have at our disposal a microelectronic fabrication technology that can already produce wafers containing in excess of 10^8 interconnected devices, and will be producing 100 times that many within a decade. If we can learn enough about the organizing principles of neural systems, we can build systems that take advantage of the entire scale of the wafer. These systems will be unlike any designed before.

Fig. 3 shows an experimental silicon retina, which we have just designed and with which we are experimenting at the present time. It starts with fully integrated photosensors and contains the first few levels of processing found in living visual systems. This entire design was motivated by our intention to understand how the mammalian retinas work. As near as we have been able to reconstruct, it is a cell-for-cell embodiment of our understanding of how the first few stages of the biological system work.

One of the striking things about this technology is how much more we understand and appreciate biological systems after we have tried to build one ourselves. The interaction of biology and engineering is not a one-way path. Most biologists tend to view themselves as strictly observational in their interaction with biological systems. Engineers tend to view themselves as synthetic, and there is a lot of feedback between the two approaches. We are learning a lot more about biological vision systems as we try to build our own silicon vision systems.

The retina shown in Fig. 3 is a very small fragment of what corresponds to the peripheral visual system in an animal. Since we do not have the many layers of nerve cells that the living system does, we have had to

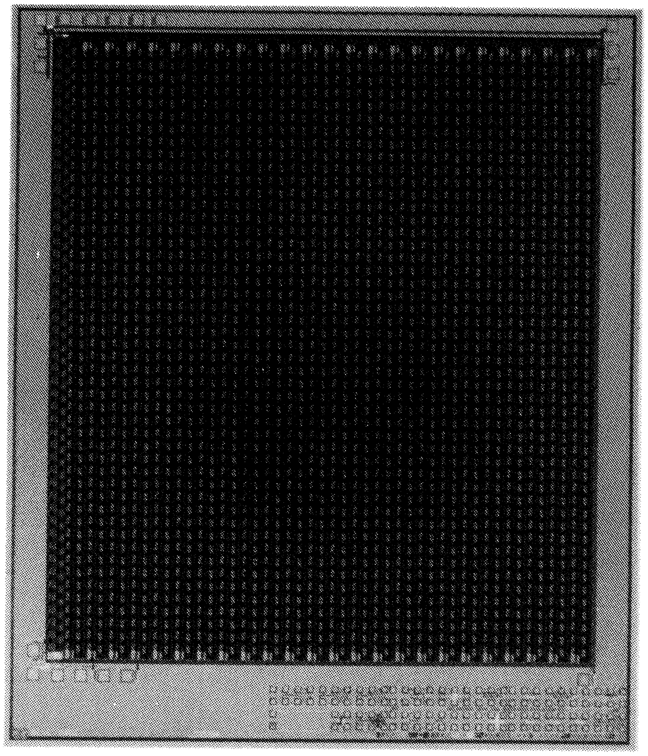

Fig. 3

map what would be different levels in the retina down into two dimensions. Nonetheless, it is a real-time vision system, albeit a small one. Within the next decade we will unquestionably have built very authentic real-time vision systems on silicon.

If we look back, there have been major revolutions in electronics—the transistor, the integrated circuit, and the microprocessor. We notice that these revolutions have happened on about a 12-year cycle. Things happen very fast in this industry. Looking forward from 1984, where we are standing now, I think this centennial year will be remembered as the year of the silicon compiler. There are a number of products appearing on the market this year that allow system designers to experiment directly with architectures on the silicon without the intermediary of the 100 person-years to get it translated down into little colored polygons and rectangles.

As we look into the future, I can see another 12 years. I think 12 years from now we will have real collective computation systems, those modeled in some sense after biological systems. They will use this peculiar mixture of analog and digital processing that you find in biological systems. They will be robust against the failure of individual components, as living systems are. Each piece of silicon will do much more computation in real time than even the most powerful general-purpose computers of today. I believe we will find some real applications running 12 years from now.

Carver A. Mead *is the Gordon and Betty Moore Professor of Computer Science at California Institute of Technology. He has worked in the fields of solid-state electronics and the management of complexity in the design of very large-scale integrated circuits. His recent work is concerned with the modeling of neural networks with analog VLSI systems. Professor Mead is a Fellow of the American Physical Society, a member of the National Academy of Engineering, a foreign member of the Royal Swedish Academy of Engineering Sciences and has been elected to Life Membership in The Franklin Institute. He is also the recipient of a number of awards, among which are the T. D. Callinan, Electronics Achievement, Harold Pender, The John Price Wetherill Medal, and the Harry Goode Memorial Award.*

THE COMPUTER EVOLUTION

Ralph E. Gomory

I am usually very pessimistic about predicting the future. Things vary a great deal in their predictability. For example, the motion of the planets is notoriously predictable. But if you pick up a stone while standing on a hill and throw it down the hillside you do not know where it will end up—the surface is too complicated, too bumpy, too rough, and the outcome too dependent on detail.

When it comes to predicting the course and impact, especially the impact, of future technologies, I think it is a problem of the second type, like the stone. I do not know how to do that predicting, and I am not sure anyone does. So I will confine myself to talking not so much about prediction but about some of the technical forces which are currently at work. The outcome of those forces acting in our society I will leave to your imagination, with confidence that you will reach a variety of different conclusions.

One of those forces is the development of the technology of smallness. I am using unfamiliar words to describe something whose present-day manifestation is, first of all, the semiconductor industry. One can say that the reason why computers make so much progress in their interior workings—and I will distinguish in this talk between their interior workings and the problems of getting things in and out of them—is basically due to the fact that they are only bit handlers. All they do is make and compare or occasionally add bits. As long as you can read it and write it, a small bit is as good as a big bit; and if you can make it out of less silicon, it is cheaper and usually faster. So there is a fundamental motivation to make things small.

Consequently, we see the evolution of ever better lithographic devices, ever cleaner areas, and the increasing problem of keeping those areas free of tiny particles which have the capability of disrupting the functioning of very small devices. Perhaps soon we will have to exclude people from these areas as people seem to emanate small particles all the time. We are creating this technology of smallness in the area of semiconductors.

But the technology of smallness is more than the familiar semiconductor example. A second aspect of making things small that is very important for computers, though perhaps less familiar, is the problem of fabricating the interconnections, or packaging. If chips are to talk to each other—and I think that will be necessary for quite a while—they have to somehow transmit their signals over wires, and those wires need to be very small.

The problem of chip interconnecting really comes from the problem of laying the interconnecting wires down between the chips, getting them up and down to the chips, and somehow building an underlying structure, the package, that is capable of supporting those wires. This in itself is an enormous task. Today, for high-speed computing, this structure, the first-level package, is 33 layers of ceramic with wiring in between. All those layers are needed to allow the degree of wiring required to interconnect the chips.

It is necessary in such a package to have very smooth surfaces. And this notion of smoothness is very closely connected with that of smallness. If you have a rather coarse wire, you can have a rather bumpy ceramic surface and you can lay the wire down on it and the bumps will make the edges look a little ragged, but it will not part the wire. On the other hand, if you want to continue making progress in miniaturization and deal with ever finer wire, you must make concurrent progress in the smoothness of that surface. And this opens up the question of how do you make supersmooth ceramic, which opens up the question of how do you make the little particles that make up the ceramic of a uniform size, and how do you make them fall together in structures that end up being very smooth?

Another aspect of miniaturization, which is not strictly semiconductor, deals with the making of disks. Again, making progress by making bits small dominates the technical problems in disks. Disks are basically like phonographs. They have an arm which swings out to some position over the disk and then tries to sense the magnetized areas of the disk as they rotate by underneath it.

The way to make progress in disks is to make the bits in the surface (the magnetized areas) smaller and smaller. This unfortunately means that the head must fly closer and closer in order to pick up their signals. And the coil structure, which is a vital part of the head, has to get smaller and smaller. Fig. 1 shows a coil structure in a head. The coils are made by the same techniques used to make semiconductors; miniaturization processes reach out beyond the area of semiconductors.

To understand how demanding the smoothness and smallness issues are in this area of computing, I might add that today's heads are passing over the surface at a height that is a fraction of a wavelength of light.

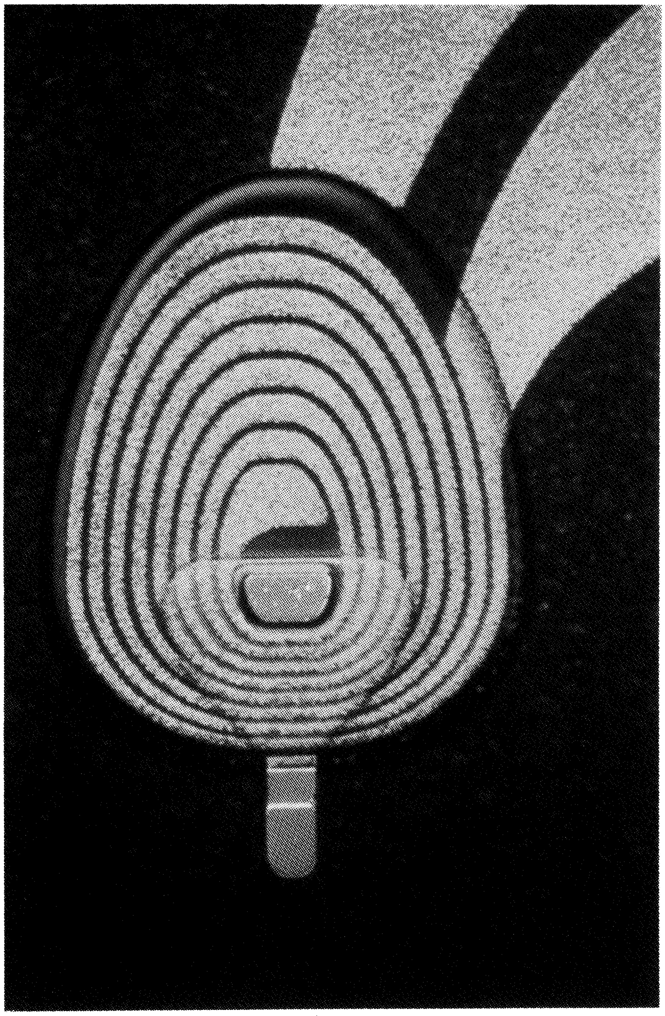

Fig. 1: Thin-film magnetic head.

Curiously enough, we deal here with dimensions smaller than those typical of semiconductors.

An analogy is useful in appreciating the small dimensions in disks. If you were to scale the head and disk up until the head was the size of a 747 aircraft, the 747 would be flying over the surface (the surface being the disk surface) at a height of only a fraction of an inch, and at full speed. Clearly, it is very important not to have any bumps.

Again, we encounter the need for smoothness in order to have smallness. And smallness is what you want when you are dealing with bits.

The technical problems of disks would be much easier if the 747 did not have to fly that close to the surface, if it could just rise up a yard or two. With magnetism, we do not see how to do that. But if we substitute a laser beam for magnetism so that the 747 can shoot little holes in the surface, or otherwise mark the surface, you ease that difficulty. Of course, you create other difficulties instead.

There are technical difficulties associated with optical storage in its various forms. For example, to write bits directly onto the surface with the laser beam, we need to bring about some sort of a change in the material, preferably reversible change, so that it is not a write-once device. One of the candidate phenomena is phase change, that is, you will crystallize the material. But in order to erase it and rewrite it, you have to uncrystallize it. So you run into a host of material problems having to do with the creation and subsequent abolition, and creation and abolition, perhaps a billion times, of very small crystalline areas.

We are seeing that the desire for information processing is creating a whole host of scientific and engineering challenges having to do with smallness and smoothness, and problems having to do with the fine structure of materials. In dealing with these problems we will have created a vast array of tools, fabrication ability, and materials understanding. This knowledge, once created, will probably not be limited in its applicability to information processing.

For example, one interesting development is the use of microfabricated structures for the separation of uranium isotopes. Basically, once you know how to make very tiny structures, it becomes possible to make very tiny metal nozzles—nozzles with a radius of curvature of 3 microns. Then, if you shoot gas around this curve, which is a very tight curve by normal standards, the separation effect for the isotopes is very intense. Indeed, you can build a whole cascaded sequence of these since they are so tiny. All together, they have very intense separation power.

Microfabrication techniques, once created, may extend to other areas. Some of the processing needed in packaging encourages you to use lasers to promote, for example, electrodeposition at a particular spot. Electroplating in the presence of a laser beam goes forward more rapidly than electroplating without it. Therefore you can create, so to speak, spots of metal by the use of a laser beam. Again, we see this notion of doing things very locally and understanding in some detail what is happening there. This notion of using certain kinds of lasers for localized effects is a natural for eye surgery, and is being explored in that realm.

I think one of the things that we are going to see is a continual pressure to learn how to microfabricate, driven by the information processing—a small bit is better than a big bit notion. The microfabrication, once created, could develop into an industry of its own, as if you had created a steel industry or something of that sort.

Within the computer, miniaturization can be regarded as a dominant means of progress. All that computing goes on inside the computer, but eventually you have to do something with it. You have to make it visible on the screen or you have to print with it. You somehow have to deal with the human scale and show things that are visible to the human eye. At this point, progress becomes harder, that is, there is no simple high road of progress like miniaturization once you reach the human scale.

However, because there is enormous progress in information processing within the machine, enormous demand is created for progress in printers and displays, not to mention more unconventional schemes for input and output.

In a variety of ways, we can confidently predict in the immediate future the improvement of displays. Certainly in 10 years we will all have high-resolution displays, 5–10 million dot displays. They may be flat, if flatness matters for other than portability reasons. For instance, you may want the display to lie down rather than to stand up stiffly in front of you. You may want to poke at the screen with its high resolution and give it a few bits of information. Color should also be a part of this picture because it is a way of conveying information.

There is an enormous challenge. With all the information being carried around inside computers, somehow you have to get it across to the user. And that gateway to the user, which is what the display or the printer is, is really worth improving. The technical capabilities for doing that are there.

The same forces drive printing, and there is a proliferation of new printing technologies. Certainly impact printing will continue. Electrophotography is a tremendous and major printing technology. But we also see, mainly driven by new demands on printing, the emergence of a whole host of other technologies such as ink jet and various forms of thermal printing. The new demands come from the personal use of computers. It does not matter if the printer prints 30,000 lines a minute, which in fact some printers do; what does matter is that it goes fast enough for one user. It does matter that it is quality printing, because the user, not some anonymous other person, reads it; and it matters that it is quiet, because it is sitting right next to the user.

These are the demands that have spawned, for example, ink jet or IBM's Quietwriter technology. And again, because you may want to print both beautiful font and high resolution for pictures, you need an all points addressable rather than a character printer.

There is progress in these areas, in some sense as a derived progress from the progress brought on by smallness. The demand is created by smallness and affects the human interface.

Let us assume that all this progress takes place. Ten years from now with these forces acting, I think we can safely predict that the ordinary mass-produced workstation or personal computer (the equivalent of today's mass-produced PC) will be a powerful engine. It will have, let us say, a single-chip microprocessor in the 10–20-mips (million instructions per second) range, which means as large as today's largest ordinary machines. It will have 16 megabytes of memory. It will have a beautiful CRT or other display of high resolution. And it will have a high-quality printer. Also, there will probably be removable optical storage of two gigabytes, and half a gigabyte of magnetic recording technology.

What I mean by a beautiful printer, which we do not take for granted today but we will within 10 years, is the kind of quality shown in Fig. 2. This is the quality of printing that can be done today, and this picture happens to have been created by an ink jet. It could be created by other means. The challenge is only to make it economically viable.

In addition to these microprocessors, there will be large systems, 100- or 150-mips systems, employing all the advanced technology, that is, there are chips with a powerful interconnect system, and all are jammed into a few cubic inches. However, this is where you start to see that there are many difficulties. Aside from the limits already described at the chip level, the business of jamming all this material into a few cubic inches, which you must do because of speed of light consideration, will be a limiting factor on the speed of very large multichip machines. I think that in the range of, for example, 150 mips, it will be very difficult to make progress beyond that, because there are engineering barriers, and very difficult ones, to get all that power in and out of the system.

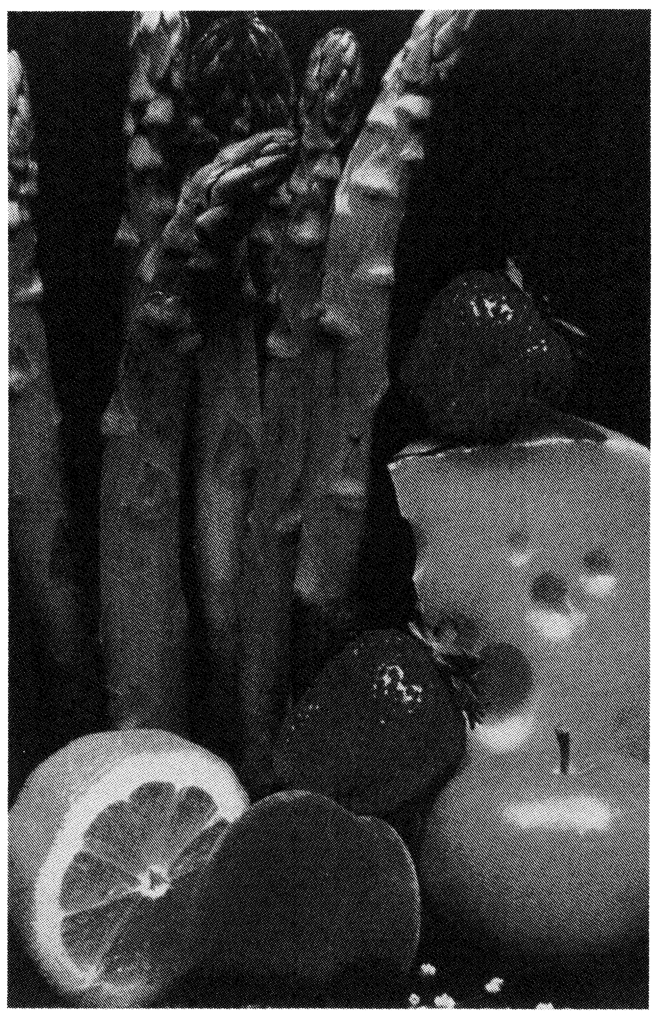

Fig. 2: Ink jet printing.

Will that power suffice for the future? I think there are many applications which call for far more than that. I am going to give you a list of driving forces. They will be forces driving computers, and in most cases they will call for the creation of either special-purpose or highly parallel machines. I will use the term "highly parallel" to cover them all, because machines can be parallel in many ways. Some special-purpose machines are merely parallel machines that are parallel at a very low level.

Number one on the list are the conventional applications–all those machines that do data processing. The demand for the large machines, the mips, is growing faster than our ability to make uniprocessor (single-processor) machines for conventional applications. Already, the commercial machine is slowly evolving into a multiheaded machine.

Second, the desire to have a high degree of reliability or availability, which is most easily obtained by duplication in the processor and in the storage elements, again drives you toward multiheaded machines.

Third, there is the promise of wholly new and exciting applications, such as very large scientific calculations, which people are already doing, and for which they are building special-purpose machines. One of the machines that we are building in our research labs is to do quantum chromodynamic calculations. It is relatively easy to build a special-purpose machine, and it tends to be successful. If you name the problem, I will give you the machine. And it will go very fast. We should not, however, confuse this with the problem of devising a general-purpose parallel machine or multipurpose parallel machine, these being more difficult and requiring more speculative endeavors.

In addition to massive scientific and engineering calculations, there are, for example, calculations of design automation for which we have built special machines to simulate the logic of computers. One of the ways to reduce the design cost is to build a special-purpose machine for that very demanding purpose. And again, if you have one special purpose, you can build a machine for the purpose.

Another challenging area is artificial intelligence. One application is what is called an expert system. Fig. 3 gives a very simple example. Suppose you have a data base of facts about airlines and their flights. You may want to ask the system a variety of questions, preferably with minimal programming. One of the things that you can store is a number of facts about the system other than data, which are simple rules about the way it works.

For example, if a flight goes to the destination on the day that you want it to, then it is a possible flight for your purposes—a very trivial remark. Or if the flight is possible and if it offers a special reduced fare and a few other conditions, then it is one you might be interested

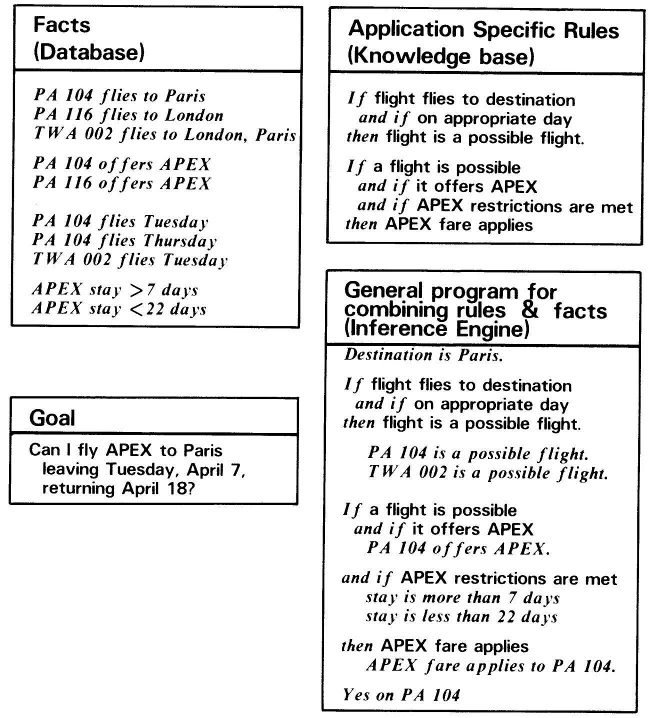

Fig. 3: Expert systems.

in. You can write down a string of rules like this. Then, if you ask questions like what flights go to Paris on the day I want to and give me an APEX fare, the system can start going through the rules. The first rule finds what flights listed in the data base are leaving on the desired day and have Paris among their list of destinations. Then the restricted list of flights is tested against your other conditions.

This kind of processing is a very trivial example of what is called a rule-based system. I want to point out a couple of things about it. It opens up the possibility of asking many different questions about a set of data provided that you have built in the proper set of rules.

Second, it is very computation-demanding. This trivial example does not show it but you will normally find that these systems end up doing a great deal of relatively blind searches. In some sense, this is another extension of the way we make progress in programming; that is, we do less and less art and use more and more computing power. However, given the progress of machines, this is fundamentally the right way to go. We have an expert system in one of our labs that parses English and takes about 20 million instructions per sentence; it is a very demanding user of machines.

Fig. 4 shows again the example of Fig. 3 only written in PROLOG, which is one of the languages used for the expert systems. You can, as a first approximation, think of the fifth-generation effort in Japan as the development of parallel and special-purpose machines and the software to do this kind of work. There are a lot of other things on it, like natural language, but I would say this is the technical core of that effort.

program to book a flight

```
book-flight<-read(Origin,Destination,Dept-date,Ret-date)
    &flight-list(flight(Origin,Destination,*,*,*,*,*),List)
    &check-flights(List,Possible-flights,Dept-date,Ret-date)
    &sort-by-fare(Possible-flights,Flights)
    &show(flights)
    &read(f-number) &book(f-number)
```

rules for fares and restrictions

```
check-flights(Flight.Rest,Possible-flight.Other flights,Dept-date,Ret-date) <-
    fares(Org,Dest,Airline,Fare-class,Fare,Restriction) &
    check-class(Fare-class,Restriction,Org,Dest,Dept-date,Ret-date) &
    check-flights(Rest,Other-flights,Dept-date,Ret-date)
check-class(y,ex/Note-nbr,Org,Dest,Dept-date,Ret-date) <-
    restrictions(Note-nbr,Start-date,End-date,Min-stay,Max-stay) &
    length-of-stay(Dept-date,Ret-date,Los) & ge(Los,Min-stay) & le(Los,Max-stay)
```

database of flights, fares and restrictions

```
flight(newyork,paris,1300,jfk,2245,cdg,af,002,r).
flight(newyork,paris,1845,jfk,0745,ory,pa,114,y).
fares(newyork,paris,af,r,2060.00,fixed).
fares(newyork,paris,pa,y, 629.00,ex/4157).
restrictions(4157,6/19,6/30,14D,2M).
restrictions(4409,5/15,9/14,7D,3M).
```

Fig. 4: PROLOG example.

Another tremendous user of mips and driver for mips that probably cannot be supplied by the ordinary machine is the user interface. There are several; one is a sort of unconventional input/ output, for example, speech recognition. It is a tremendous mips burner. The best estimates I can make on the subject are that to do any kind of reasonable continuous speech, many hundreds of mips would be required. These estimates are suspect because to do continuous speech is an ill-defined term. One has to be concerned with what error rate, over what vocabulary, in perhaps a limited range of discourse, or other concerns. The main message is that trying to recognize speech is another enormous mips demander. Similarly, the understanding of hand-written input and of natural language is also, I believe, feasible, and both are enormous mips burners.

Finally, there is the direct manipulation of objects in place of programming, which I will mention very briefly. I am going to put it in the somewhat exaggerated way that programmers are really used to dealing with a conceptual structure which is the machine. For example, they talk about memory locations. They imagine they are putting things in the memory registers. Now, there are new departures and new models that allow you, instead of the machine, to manipulate the objects.

For example, take the desk top image in which you do things by pushing around on a desk top things that look relatively real, such as putting a piece of paper in a wastebasket. Actually, what you do is a mixture of symbolic processing and moving images. This is a significant input/output operation that will again be very demanding in mips because there is so much to be done that requires enormous power to translate it into usable form. That transformation, whether it is through speech recognition or maneuvering objects, is another tremendous demander of mips.

All of this leads to the study of unconventional architectures and, especially, parallel architectures, because it is basically out of parallelism that you get the increase in mips for your special purpose. It is nontrivial to try to develop the proper parallel machines.

It is relatively straightforward to develop some types of special-purpose parallel machines. But the notion of a general-purpose parallel machine is a much more elusive and difficult thing. There will be tremendous needs and pressures to create an understanding of parallel algorithms and to create software to run these parallel machines.

Interconnecting multiple discrete processors will emerge as a discipline of its own. It is not simply a question of hanging processors on a bus. The interconnect structure will probably be critical and will have a great deal of structure itself. It will be more than a simple switch in all probability. The need for mips will not be satisfied by the conventional machine. Those pressures will create new architectures, and a whole new family of progress is needed.

In this direction, some of the most demanding users of this new power will be software itself. The creation of software is one of the most complex things that people do. It is a somewhat maligned subject because of its proximity to hardware. Hardware makes progress at an extraordinary rate because of the smallness issue. We can make progress in computers through making things small. Most technologies do not have such a magic formula. Automobiles do not and almost anything else you think of does not. Software is in the ordinary category. Its misfortune is that it is sitting next to something very unusual. I think we should stop demanding of software that it make the extraordinary progress of its neighbor. It is ordinary. It is its neighbor that is extraordinary. Software benefits from that hardware progress, and it will continue to do so. It will continue to develop as an engineering discipline of its own. Better interfaces and an increase in computing power will benefit it, and it will develop its own engineering procedures. The software generation procedures will become both more disciplined and more perfect.

Finally, I would like to say a few words about robots. Those of us who were brought up on H. G. Wells remember the clanking mechanical monsters that did such wonderful things or such evil things, depending on what story it was. As a child, I wondered why it was we couldn't build those when I could see all around us equally complex machines. After a lot of thought, I reached the conclusion that something was lacking. I mean that if I imagined myself building it, there was no way to direct it.

When I became the director of research for IBM in 1970, we had labs full of people working on intelligence, but none on mechanical motion. After a while, we started a robot project, and today we have a small robot business.

The essential ingredients are there. The ability to power mechanical motion has been there since the industrial revolution. The ability to do a great deal of thought-like work is here today. It is relatively straightforward—everything is straightforward in the perspective of 100 years—to equip these creatures with sensors and with vision. Robots and mechanized production are definitely coming.

One of the forces at work is the creation of a technology of miniaturization. It will continue to enable us to make progress for some time, and it will have its own consequences. We will, by the extrapolation of the doctrine of smallness, have machines of enormous power and interfaces providing great ease of use. Nevertheless, as we approach the limit of these machines, parallelism and special machines in all their forms will become necessary and challenge us in many ways—scientifically, algorithmically, and in other ways.

Robots are a real possibility because the ingredients, physical and mental, are present. This combination of forces will have a most profound effect on the world.

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COMPUTING IN 1984

Andries van Dam

I would like to enthuse about the state of computer hardware and mention how rapidly increasing computing power is facilitating user-computer interaction based on pictures, not just text. I would also like to discuss software, artificial intelligence, and the application of computer graphics to education.

As far as our 1984 baseline is concerned, we have hardware magic, and cheap, reliable computing is going to become more and more available. I believe that, for all practical purposes, there is, for the first time ever, enough computing power available to go around (although many of us could easily take advantage of an increase in performance of several more orders of magnitude for our professional work). My assertion refers to the use of computers, especially micros, in offices, in factory automation, in laboratories, in schools, in the home. For example, computers have become not only affordable but indispensable in engineering, design, and manufacturing.

In many ways, personal microcomputers in particular have become a commodity item, much like calculators. We buy them, see them eclipsed by newer machines in about a year, give or throw them away in several more, and buy something new that is twice or three times as powerful and considerably cheaper. Not too long from now they will be as pervasive as the telephone and in the near future not much more expensive.

The Dick Tracy-style wrist computer and communication console has already been met to a first approximation: my Epson RC-20 prototype has the power of ENIAC, but in a vastly smaller package, no bigger than a conventional watch. It contains a Z80 microprocessor, which is certainly more powerful than ENIAC and, indeed, than the IBM System/360-50 "mainframe" computer that served the entire community at my university in the 1960's. It has 8K of read-only memory and 2K of random-access memory. That 2K can be downline-loaded with programs and data through a little cord coming out of the side, which is an RS232 port that you can attach to your personal computer. It has an all-points-addressable LCD screen to show text and graphics and it is touch sensitive, so you can "key in" information with your fingertips. It has a simple editor built in so you can update your appointments and your calendar, for example. This is only the beginning; wristwatch television is not far away.

Throughout our engineering profession, we are seeing the increasing dominance of computer technology. "Beyond '84," the June 1984 issue of *IEEE Spectrum*, has as its subtitle "EE Specialties: Computers Are Pervasive." And in the January 1984 technology issue, of all the articles that talked about all the various subdisciplines in electrical engineering, I believe there was only one in which the topics "computer" or "microprocessor" or "displays" did not appear. Thus my first comment is summarized by the cliche that largely because of the semiconductor revolution, computing is all-pervasive.

Turning to my second observation, one of the most exciting things we can see now is that we are moving away from a preoccupation with obtaining raw power to demanding what I think of as refined power—power in the service of the end user. We are now deluged by the terms "user interface" and "user-friendliness." A modern user interface is based on a liberation from single-font, text-only screens (and documents) by the inclusion of multiple fonts and styles as well as graphics.

Humankind has a long history of producing writings and art containing both text and graphics, a classical example being Egyptian temple and tomb paintings/inscriptions. With modern personal computers and work stations typically providing "bit-mapped" raster graphics displays, we can finally produce such materials routinely. By what is essentially the electronic equivalent of pointillism, the intensity of color of each pixel on the all-points-addressable screen can be controlled to create various character fonts and styles, and entities such as spreadsheets, tables, charts, graphs, and other forms of presentation graphics, as well as "synthetic photographs." Icons may be used to represent file drawers, printers, telephones, alarm clocks, mailboxes for electronic mail, calculators of various sorts, and other electronic realizations of common office objects, along with their expected functions.

What is important about the type of mouse-driven, menu-picking, form-filing iconic interface popularized by Apple's Macintosh is that it avoids a lot of typing by eliminating the dependency on the textual specification of commands. We can specify simple commands such as cut-and-paste by pulling down menus, and the many options of a complex command by filling out a form or picking options from a textual or iconic menu.

Icons are in vogue because they are typically language independent and appeal to our strong visual memories. For example, it is easier to delete a file folder by moving its icon into the wastebasket icon than to remember all the forms of delete commands, especially if one uses multiple systems, each with its own idiosyncratic syntax. Furthermore, the wastebasket icon carries with it the intuitive notion that until it is definitively emptied, one can still retrieve a thrown-away object; this mode of operation is now a common feature of these user interfaces.

Through the power of all-points-addressable bitmap displays, we can create any visual abstraction we like, including more complicated pictures of three (or higher) dimensional objects not yet routinely available on personal computers because they are still a little short of processing power and memory. Producing the types of images seen in television commercials and science fiction films may take hours per image on modern mainframes. When one realizes that soon personal computers will be more powerful than, for example, our departmental VAX at Brown, such currently compute-intensive picture making will become more generally affordable. Within the decade the capabilities of today's multimillion-dollar flight simulators should be available in our desktop workstations!

Realistic "synthetic photographs" are typically produced by first creating the objects with a solids modeling system, and then processing that model through a multistep image synthesis pipeline. It is not the image synthesis step that primarily concerns us today, because, by and large, the basic algorithms are now well understood and simply require very large amounts of computing power, especially for moving images. Much of that power will in the future be provided by special-purpose VLSI "coprocessors," just as floating-point computation is handled today. The real concern is that we do not yet understand very well how we create models of objects of which we want to take pictures. What we still lack is a fundamental understanding of object modeling and construction.

In the words of Alan Kay, we do not just want pictures that look good; we want pictures that *are* good because they are based on what might be called a deep structure (borrowing a term from artificial intelligence). We must develop a better understanding of how to model fundamental components mathematically and of the operations we use to put them together in modeling systems, which are still very much in their infancy. At the same time we need much better user interfaces for specifying operations on three-dimensional objects via their two-dimensional projections on flat screens. The development of "true" three-dimensional displays will also help reduce that interface problem.

We also need a lot more work on the formalisms and the interactive specification of real-time motion and animation. Also, there is much exciting research today on modeling body movement and on modeling complex textures such as natural terrain with plants and trees; skin, hair, and clothing also offer formidable challenges.

But pictures are not the be-all and end-all; other multimedia possibilities are beginning to be developed. For example, sound is starting to come into its own. Segmented speech recognition is beginning to be commercially viable for limited vocabularies of several thousands of utterances. There is naturally much interest in the very difficult problem of natural language speech input to computers, especially for ideogram-based languages such as Chinese and Japanese, where keyboarding has been a very difficult matter. Sound feedback can be very useful as well. There are some nice laboratory demonstrations of force-feedback devices, in the molecular modeling domain particularly, where one can "grasp" atoms and molecular substructures and bend and twist them while seeing them in stereoscopic depth. Slowly but surely, our field is progressing toward what one might think of as a total sensory environment.

Some of the types of interaction are still a little distance away. While eye tracking, for example, has been done in a lab, it still is far from being a commercial reality. Brain wave monitoring has the potential to help badly handicapped persons to specify commands, but it is even more in the basic research stage. Even before we can interact on the level of brain waves, however, we definitely want to have multimedia interaction—text and graphics, sound and spoken natural language, in and out. These are the kinds of problems on which we will be working during the next decade and into the next century.

Once we have something that approaches an ability to model the deep structure of objects, we can then begin in earnest on a very interesting project, which at Brown we call automated authoring of electronic books. We have a very early prototype of a system that combines expert-system technology with image synthesis to cope with the problem of having to author presentations "by hand." For standardized presentations of standardized phenomena, such as repair of electronic equipment, one would like to be able to proceed from a problem description to a sequence of pictures accompanied by appropriate text and sound that explains a required action to a maintenance and repair technician. In essence, the expert system embodies rules pertaining to the subject matter as well as to the organization of explanations and the creation of the individual graphical, textual, and sound elements in the explanations. Such automated authoring techniques could be used to create explanations from an electronic encyclopedia or specialty knowledge base for students and professionals, each at the reader's appropriate level. I think there will be a major industry in learning to create and producing those kinds of multimedia presentations with the aid of computer-based knowledge representation.

The next subject is software factories. Hardware is "under control," and software is the gating item. In many ways it is the Achilles' heel of the computer industry. It costs too much and takes too long to produce. Unreliability and maintainability are endemic problems. Software is not extensible. These and others are well documented problems, and I will not dwell on them.

In a sense, we are coming out of what might be called the age of naivete, an age that Alan Kay characterized so nicely: "People thought that you simply asked the software fairy to sprinkle some systems dust on the hardware and magically the system as a whole would work." We now know that tremendous labor and investment are required, and we are reverting to the old 80/20 rule: 80 percent of the costs will soon be in the software rather than in the hardware.

What we are seeing at long last is much more sensitivity to the need to integrate hardware and software from the beginning of a design. And indeed, some of our engineers are finally beginning to get an integrated education in both of those very important and intersecting skills and fields.

Speaking about skills, despite the notoriously slow evolution of software, we are now beginning to see some skill displacement. COBOL programmers are becoming a glut on the market, while there is a tremendous undersupply of people who, for example, know UNIX and other "modern" operating systems.

The current undercapitalization of software people and the trend toward capital-intensive software technology is discussed in the July 1984 issue of *IEEE Software Magazine*. Peter Wegner describes, in a sequence of articles, the tools and methodologies that finally will have some impact. We are moving away from the "shoemaker's children" syndrome: programmers had trouble justifying a terminal on their desk five years ago, whereas hardware engineers were routinely working with $100,000 to $150,000 worth of CAD workstations. That discrepancy is becoming less marked. Because cheap, yet high-powered, workstations are becoming increasingly available, software people are now getting them on their desks, and "software environments" which are very rich tools for producing good software are becoming common.

In the first article of last July's *IEEE Software Magazine*, Wegner talks about capital-intensive software technology in terms of modules and how we build and reuse them, and about the notion of abstraction. We are learning to get away, as Ralph Gomory said, from the preoccupation with memories and registers and low-level, hardware-related details, and are talking in terms of the high-level abstractions and metaphors that suit our particular problem. That notion is also highlighted in the very useful "Beyond '84" *IEEE Spectrum* issue.

Wegner's second article is about programming in the large, and about life-cycle paradigms and application generators. Application generators and fourth-generation application languages really spell out one bottom line: we are increasingly taking software development out of the hands of typically unschooled application programmers and turning it over to end users who fill in forms, who program by example (as in query-by-example and office-by-example developed at IBM). These users basically say *what* they want to do and the program then figures out for them *how* to do it, rather than having to specify or have specified for them in minute detail all of the basic operations.

The third thing that Wegner talks about is knowledge engineering. This, as far as I am concerned, is the real growth industry and the real new frontier. He asserts that knowledge engineering will, in the 1990's, have a status similar to that of software engineering in the 1980's.

Indeed, this subject brings me to a few layman's observations on artificial intelligence. My feeling as a layman is that there is quite a bit of hype at this point, and that the field as a whole is oversold—despite the cautions its practitioners often provide us with. We are, of course, in this field as in all others, going to move nonlinearly, alternating growth with a series of plateaus. We make rapid progress and things stay the same for a while; then there is another burst of creativity and energy and a lot of new things happen. We need to spend a lot of our resources on the problems of artificial intelligence because there is tremendous mileage there. That is where we are finally going to realize the potential of computers as intelligence amplifiers, not merely as reducers or eliminators of drudge labor for routine data processing, calculation, plotting, and the like. Using the computer to assist with donkey work is something we are doing today. What we are really not yet doing nearly well enough is providing what we all want—the "X's assistant," that is, the programmer's assistant, the physician's assistant, the lawyer's assistant, the financial advisor, and so on. And these expert system programs are now being developed. To no one's surprise, it appears very difficult to codify expert knowledge—the easy things are easy to do and the hard things are always very hard to do. Exceptions are the rule.

What is usually involved is taking knowledge that is implicit—decision making skills that we, as imperfect biological devices, perform so astonishingly well—and trying to put it down on paper so that we can put it in the machines, making explicit and tangible that which is implicit and intangible. And that is a really tough intellectual task. It will take many years, even decades, and we will undoubtedly need systems of thousands of rules or more in order to get genuinely useful and insightful, realistic systems.

Speech recognition, natural language understanding, and vision are all beset by problems of ambiguity and context, and deep knowledge is required in order to resolve them. New theories about human information processing will probably be required to stimulate our thinking on new theories for machine information processing. If you want to be humbled about how difficult the vision problem is, for example, visit the Franklin Institute exhibition on visual and optical illusions and see how good the eye is at detecting the signal in the noise, filling in the gaps, seeing things that are not there.

Finally, there is robotics. My challenge there is: build me a robotics system that is sufficiently dexterous to tie those silly bow ties that most people cannot even tie right. The problem of picking up parts on the conveyor belt is a lot easier than that of manipulating arbitrarily complex and flexible objects.

About education—I believe the computer has a tremendous capability as the tool par excellence to help us with modern education. There is no royal road to mathematics or to anything else, but sugar coating can be used effectively to help motivate; to help us visualize complex and abstract phenomena; and to customize education to our particular needs, our skill levels, the way in which we like to get information, and the media we like to use.

Many subjects in science and engineering in general and in computer science in particular involve dynamics, not statics. I claim again that computer graphics is the tool with which to illustrate dynamic phenomena. Blackboard presentations and viewgraphs do not work effectively when it is the dynamics of a process that we really need to understand. Let me show you a couple of examples, chauvinistically chosen from Brown University, of the use of electronic books in the classroom.

Bob Sedgewick in 1979 conceived the idea of building a special classroom for the use of graphics-based workstations in teaching (Fig. 1). There are 55 1.5-megabyte Apollo workstations in that one-of-a-kind classroom today, used routinely during both introductory and advanced courses in computer science and several other disciplines. That is more computing power than I could have dreamed of ten years ago for the campus as a whole, and it is all here in one classroom, networked together so that I can broadcast from my instructor station at the front and have all the students watch and interact with the demonstration during the course of classroom teaching.

For example, using BALSA, the Brown Algorithm Simulator and Animator designed by Sedgewick and graduate student Marc Brown, I can now teach binary tree manipulations and recursion in a single lecture to beginning programmers (Fig. 2). In the left window on the screen we have procedures overlaying each other as they are called, and on the right there are various graphic representations of the binary tree and its list-structured implementation. These multiple views are synched together so that as we single-step through the program, all the views update appropriately. Students can ask and are asked questions as they interact with the material during the course of the class. This is not classical, self-contained computer-aided instruction—it is more like an electronic blackboard to assist the lecturer. In addition to watching a broadcast, they can, however, run the programs on their own whenever they like, at their own speed. And we have found that

Fig. 1

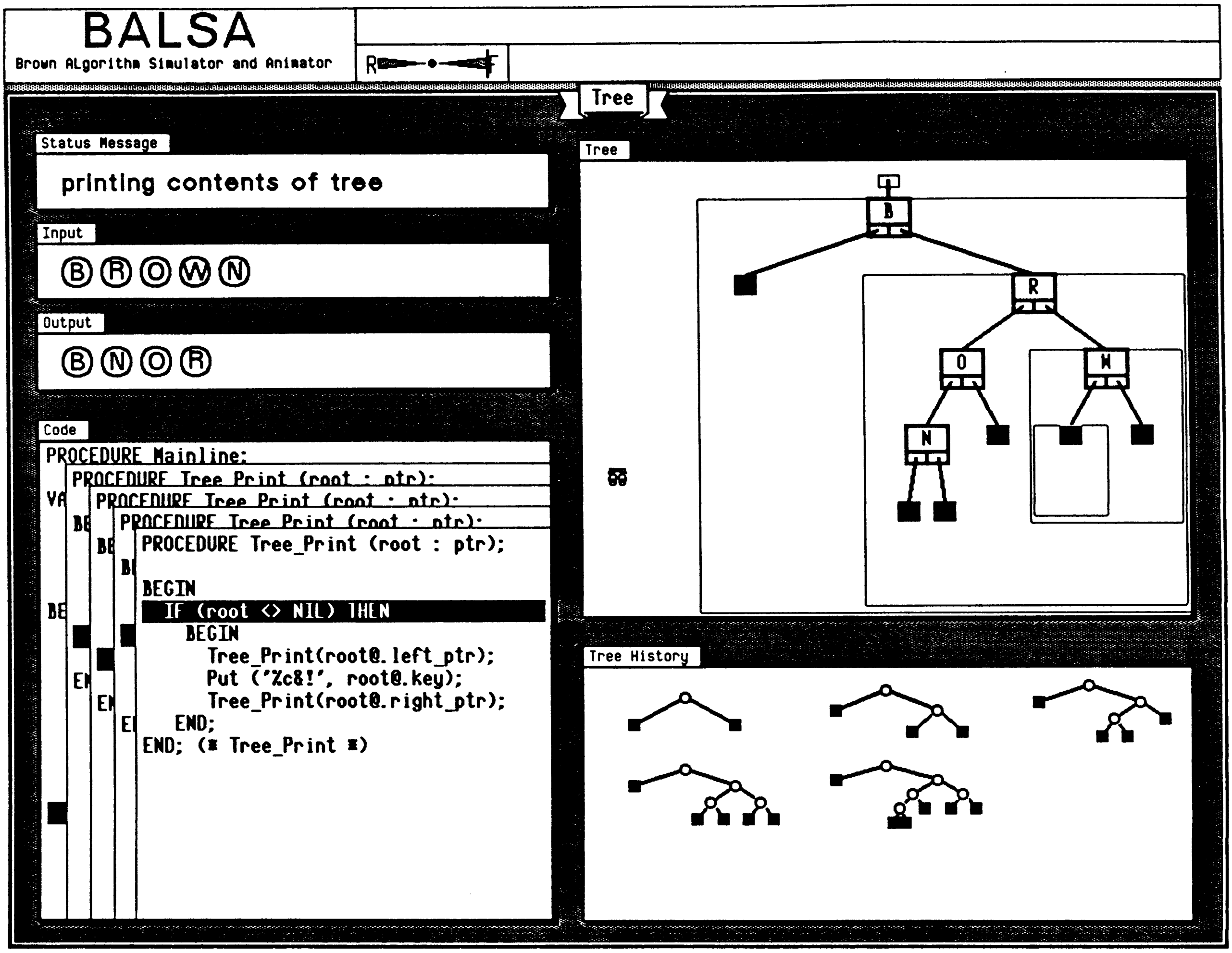


Fig. 2

the distinction between passive lecture-listening and active laboratory work diminishes greatly as students get involved with the material as early as possible.

After several semesters of production use, we think this technique works very well. We are very excited about the technique of showing graphic representations of dynamic phenomena and interacting with them during the course of a class, and especially doing this in fields in which computers have not been traditionally used. Indeed, we are planning to introduce this type of software in many disciplines and courses over the next few years as workstations become more and more available.

Let me finish here by saying that I really subscribe to the theme of one of the computer conferences many years ago: "The past is prologue." I am glad to be alive in this century to see the monumental progress we are making and to realize that we have only scratched the surface of what will be possible with computers, if we can learn to manage their humane use.

Andries van Dam *is past chairman of the Department of Computer Science at Brown University. His research has concentrated on software in general and computer graphics, text processing, mini- and microcomputers, and personal workstations in particular. Much of his career has been devoted to the design of "computer books" based on high-resolution graphics displays. He is co-author of the standard text* Fundamentals of Interactive Computer Graphics. *He holds membership in IEEE and the Association for Computing Machinery and was a cofounder of ACM's SIGGRAPH. He is presently an editor of ACM's* Transactions on Graphics.

ENERGY USE PATTERNS AND THEIR IMPLICATIONS FOR THE SECOND CENTURY

John G. Kassakian

I would like to take this opportunity to share with you some observations regarding our energy use patterns, and in particular their implications for our second century.

There is no doubt that we have become an energy conscious society, and the *economics* of energy is largely responsible. However, our changing patterns of energy use have been driven by much more than economics. In 1970, I used to buy gas for my BMW 2002 for 35 cents a gallon at a Clark station in Minneapolis that sold only leaded premium. Gasoline now costs about $1.35 a gallon—that is economics. You could not find leaded premium today if your life depended on it—that is the environment. BMW no longer makes the 2002—and that is a shame.

Whatever the reasons, the numbers support the fact that we, as a society, are using less energy, and this while the gross national product continues to grow.

Fig. 1 shows the gross national product since 1950 in constant dollars. You might fit a curve to these points differently, depending upon whether you are for Mondale or Reagan, but it would be difficult to interpret the data as a decreasing gross national product. Of more interest to us, however, is the energy used to generate each dollar of gross national product as illustrated in Fig. 2. I have shown the data in detail for the last decade to point to its small scatter. After two decades of a nearly constant 60,000 Btu per dollar of gross national product, the behavior of this parameter for the last decade is startling. An explanation that comes easily is "energy crisis and conservation," but I believe the real reasons are far more complex, and have major significance for our second century. Indeed, one could compellingly argue that from the point of view of the structure of our basic industries, our second century began in 1974.

An even more interesting trend is the electric energy content of each Btu, as shown in Fig. 3. In 1950, 3 percent of each Btu of energy consumed was electrical. By 1983 it had risen to 10.5 percent. While total energy use *declined* by 5 percent during the last decade, electric energy use *increased* by 25 percent during the same period; and while total *industrial* energy use declined by 18 percent, industrial electric energy use increased by 12.5 percent over the past 10 years.

For certain these statistics reflect in large measure

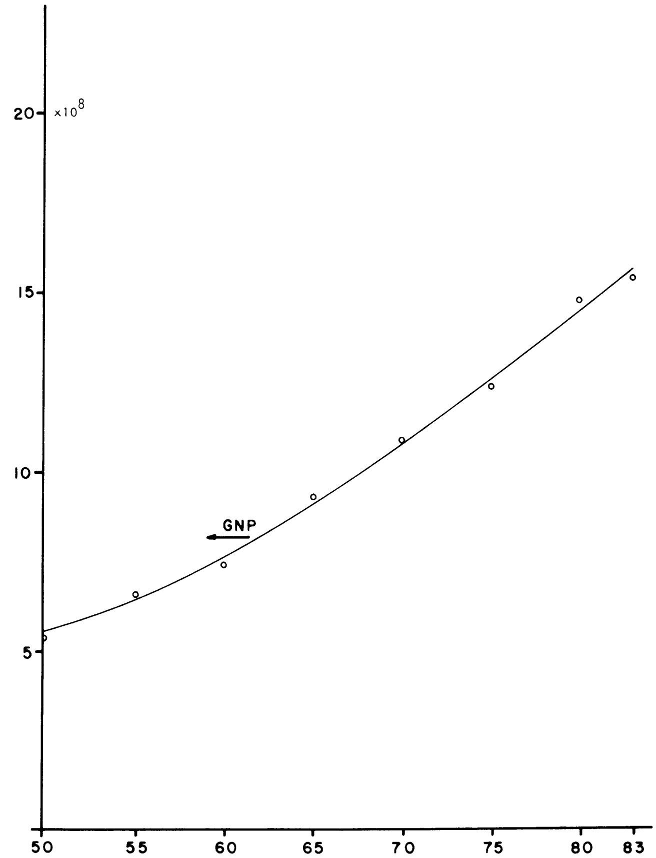


Fig. 1

the decline of some of our mature heavy industries, a decline that one might compellingly argue was inevitable and not a product of the energy crisis. But what these data also reflect is an increasing demand for high-quality energy, for energy that can be controlled precisely and "squirted" where we want it.

Last night I was watching a Channel 3 news broadcast of yesterday's centennial events and some of the Franklin Institute's exhibits. A 7-year-old boy was marveling over what the Van de Graaff generator was doing to his hair. The reporter asked him what was causing the phenomenon. "Electricity," he answered. "What is electricity?" the reporter asked. His response was, "I'm not sure, but electricity is very powerful and *it can do almost anything.*" Now some may argue that he is a product of a deteriorating educational system, but the fellow is very observant. And the fact

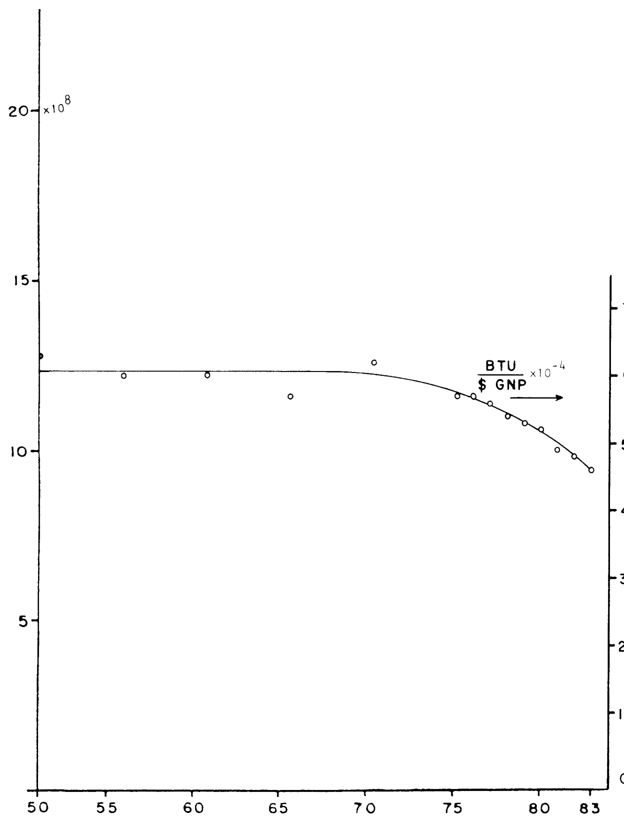


Fig. 2

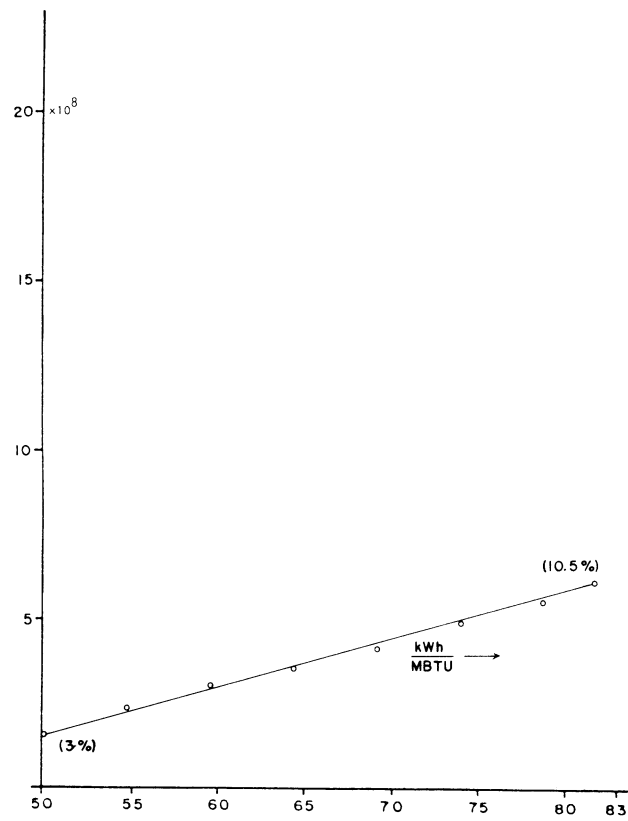
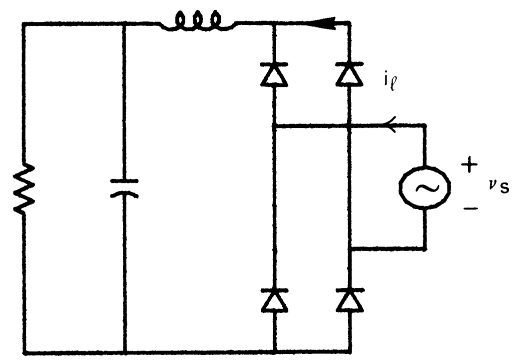


Fig. 3



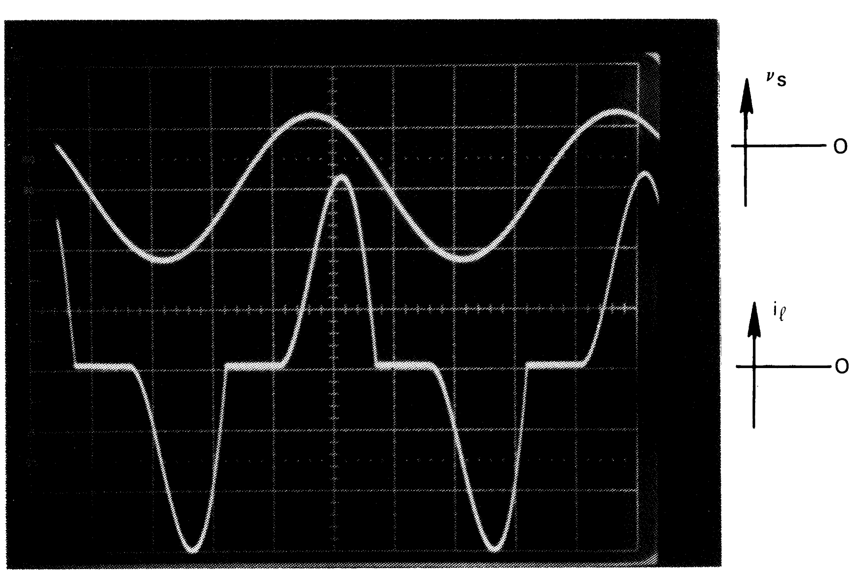


Fig. 4

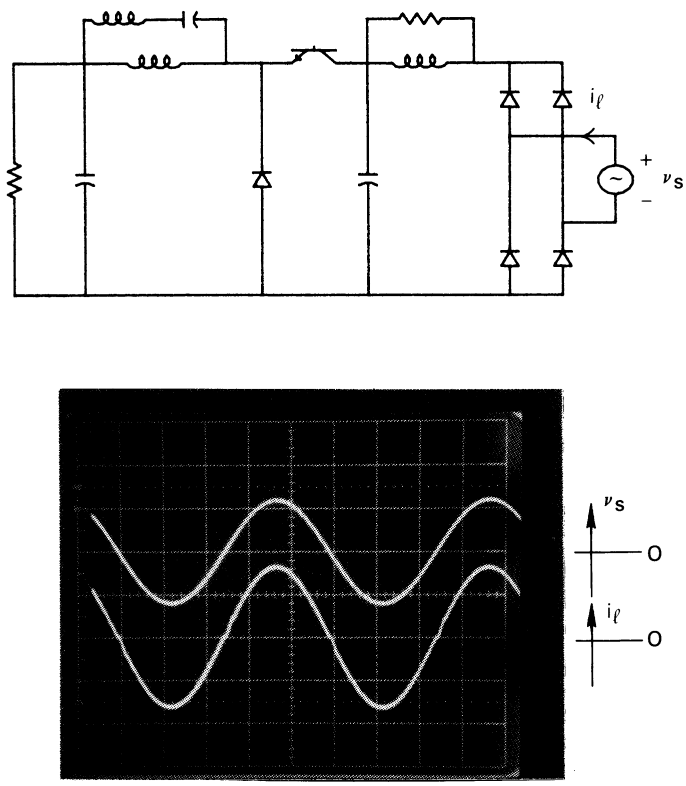


Fig. 5

that it *can* do almost anything is why demand for electricity will continue to grow while demand for other forms of energy declines.

This demand has been created by the availability of components and processes made possible by the technologies we have been discussing—technologies which are producing a dramatic and fundamental change in the structure of electric energy demand. An integral part of these new electric loads is the power electronic circuit that both forms and squirts the energy. Let me give you an example of the role which such circuits can play, even in relatively mundane applications.

Fig. 4 shows a conventional single-phase full-wave rectifier, operating at a power level of 4 kilowatts. The peak energy stored in the filter in this circuit is approximately 170 joules. This number can be translated into pounds of iron and copper, or cubic inches of Mylar. The ac line current is rich in harmonics, has a high ratio of rms to fundamental, and a poor power factor. Harmonics cause interference, and a poor power factor loads the line unnecessarily. What you see here is typical of the line current in your television or personal computer. In fact, it is probably somewhat better.

Fig. 5 shows the addition of a high-frequency modulating stage, which creates the sinusoidal line current. The transistor is controlled by a microprocessor using a switching pattern stored in RAM. Although the circuit has been complicated, the total energy storage is only 17 joules (10 percent of that in the previous circuit), the quality of the direct current is 10 decibels better, and the response time of the circuit is 10 times faster.

I believe that the increasing demand for electric energy is being driven, and will continue to be driven, by applications made possible, in part, by power electronics. It is significant that the first 6-inch wafer fabrication facility in Silicon Valley was initially intended not for VLSI, but for the production of power devices. It is also my opinion that the changing nature of the electric load will have a significant and challenging effect on the electric utility industry. Power engineering is going to have a new identity in the century ahead.

John G. Kassakian *is professor of electrical engineering and Associate Director of the Electric Power System Engineering Laboratory of the Massachusetts Institute of Technology. His principal research concern has been energy conversion and control using power semiconductor devices, especially at very high frequencies. Dr. Kassakian served in the U.S. Navy and is a Senior Member of IEEE.*

INTEGRATED MANUFACTURING TECHNOLOGY IN COMPLIANCE WITH THE ADVANCEMENT OF COMPUTER AND COMMUNICATIONS SYSTEMS

Koji Kobayashi

INTRODUCTION

The advancement of science and technology should contribute to the development of society and the well-being of humanity. Therefore it is necessary that its end result be manufactured as products, and that they be widely circulated and effectively utilized. Research and development of manufacturing technology is vital to bring about an innovation in the production process. This will enable the products to be manufactured inexpensively at higher quality. Whatever superb possibilities a product may have, if the product quality is poor, successful technological innovation cannot be achieved.

At present, the interests of engineers tend to focus mostly on spectacular product innovations. Because of this, it is very significant that integrated manufacturing technology has been selected as one of the priorities for the second century of the IEEE. I would like to express my respect for the acute awareness of the task faced by industry to the planners of this centennial technical convocation.

In the little more than 200 years since the industrial revolution, the industrial society has grown and matured and is now rapidly advancing into the age of the information society. And if the inventions of the spinning jenny and the steam engine were the motive power for the curtain raising of the industrial society, computers, modern communications technologies, and transistors can be said to be acting as motive power for the information society. I have advocated for several years that the integration of computers and communications, which I call C&C (Fig. 1), is essential to the development of the information society, and that in order to realize it, the advancement of microelectronics technology and software technology is indispensable. This is because I believe that C&C is vital for any individual to access needed information at any place and time, to process it to match the individual's purpose, and to use it. C&C technologies can be said to be closely related to the integrated manufacturing technology essential to the information society.

The desires of people in the information society are

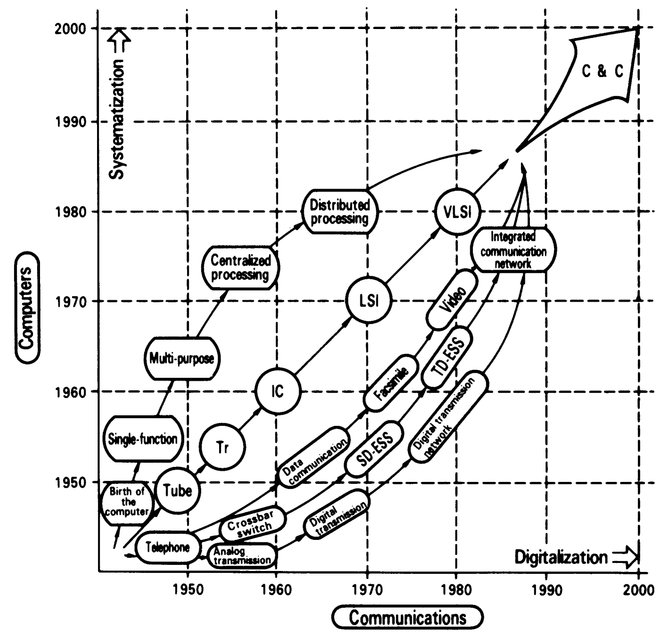


Fig. 1: Perspective of C&C.

diverse. In order to respond to these desires exactly, a flexible manufacturing system should develop in which small quantities of various kinds of products are produced efficiently at dispersed manufacturing bases. Moreover, in order to make effective production and circulation possible within plants and among markets over a wide area, the flexible manufacturing system will become the C&C manufacturing system itself. With all these advances in new production techniques, manufacturing activities should always revolve around the interests of human beings, and the quality of their life and work must not be ignored. I think that advances in production technology should conform to the concept of a "Man and C&C" manufacturing system, centered on human beings (Fig. 2).

In this presentation I would like, first of all, to consider the significance of manufacturing in the information society. Next, I will discuss the production system in the information society, and the manufacturing technology to realize it. Lastly, I will consider

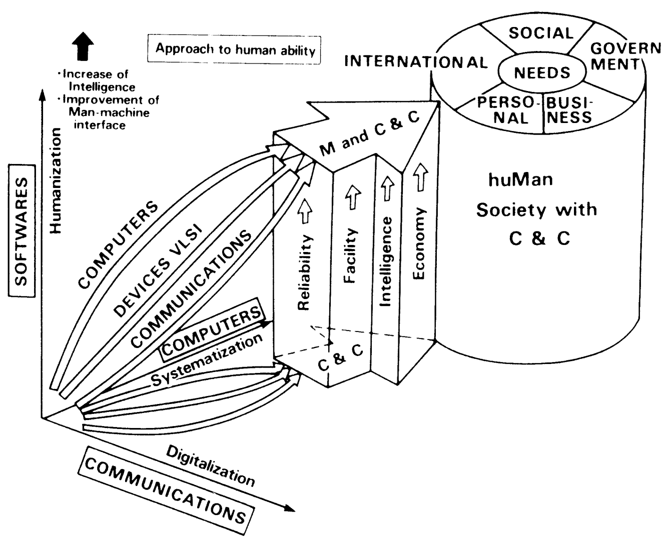


Fig. 2: Concept of C&C manufacturing system centered on human beings.

the prospects for the manufacturing technology in our second century as centered on human beings.

MANUFACTURING IN THE INFORMATION SOCIETY

Manufacturing is the activity of processing and converting intellectual and physical raw materials and elements into hardware and software products, which can be easily utilized by the consumer. Since the industrial revolution, advances in energy conversion technology promoted the invention of production machines that greatly raised productivity. As a result, mass production and distribution of hardware were made possible, which greatly contributed to the material wealth of society.

As the quality of life and the level of education of the general public rise, their desires become more complex and sophisticated. It has already become difficult for products designed for general purposes to meet the demands of the general public. Intelligent products that are easy to use and tailored to suit each user's individual needs are strongly desired. In order to manufacture a wide variety of products designed to meet each consumer's personal requirements in small quantity and high quality with high efficiency, a remarkable amount of information must be utilized promptly and exactly compared to the production processes in the industrial society. Further, the manufacture of information indispensable for intelligent products, namely, software and data base, cannot help but carry a heavy weight in production activities. In the information society, the manufacture of information occupies an important position in industry, and at the same time information plays an important role in manufacturing activities.

Let us consider a series of processes ranging from the input of information on the customer's product demands to a design center via communication circuits, the input of tailoring information processed at the design center to the production plant closer to the customer, the input of processed information to the production lines, and finally to the delivery of products to the customer. The integration of computers and communications, that is, C&C, becomes essential for manufacture in the information society. C&C technology guarantees a balance between the various aspects of society with regard to the problems of time and space, and the varied interests of people in the information society. Also, it is this technology that makes diversification possible, particularly in the manufacturing activity.

In a series of cycles from product design to process/assembly, test, and maintenance service, the automation of process/assembly and test, which are the main areas of activity in a production plant, will be promoted by computer-aided manufacturing (CAM) using computers and robots. Design and maintenance service are areas difficult to automate in view of the importance of communication with the customer. However, effective service operation will be promoted by incorporating customer information and production information into the data base, and by using computer-aided design (CAD) and computer-aided maintenance service (CAMS), which are interactive between humans and the machine. Furthermore, customers, design centers, production plants, maintenance service centers, and control centers, which are geographically dispersed, will be integrated by C&C. Thus it will become possible to manufacture and service products which best suit customer's requirements at higher quality and lower costs, and with greater speed (Fig. 3).

Manufacturing in the information society will go through many large changes in responding to changes in the structure of society and the advance of technology. The direction is toward diversification, distribution, automation, and effective integration of each activity function, namely, systematization. As the needs of the general public become more varied, the demands on people engaged in production will also

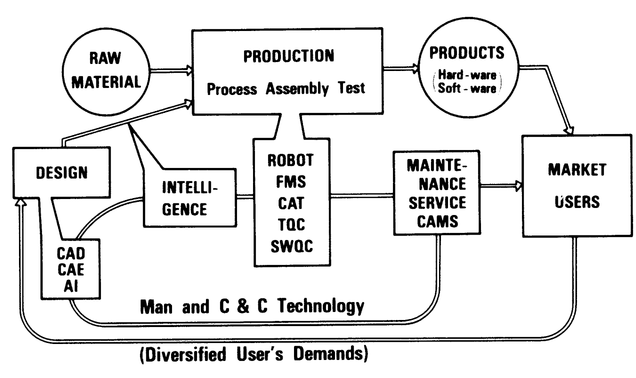


Fig. 3: C&C manufacturing system.

become diversified. An integrated manufacturing system is the outcome of a compromise between human beings, technology, and economic efficiency.

I am one of the members who first introduced quality control activities to Japan in 1946 at the recommendation of the occupation forces. From the quality control methods that we learned from the United States, the quality of Japanese products improved remarkably, and this promoted the development of our industry. We are very grateful to the many people who guided our quality control activities. During the course of integrating quality control into our corporate activities, however, I raised several questions in regard to the American quality control concept. The first question was the validity of statistical quality control. Statistical control by the quality control department alone is liable to become a static manufacturing activity. I felt that there must be quality control activities based on the dynamic feedback concept, in which customers' claims are fed back not only to the sales and production departments, but also to the research and development departments and management. In this way, the entire company dynamically cooperates in manufacturing high-quality products. The second question was the validity of quality control from the top down only. The more complex production systems and processes become, the more difficult it is to secure quality only through the aims and awareness of top management. Quality is ensured by integrating the awareness and ideas of all the people who are engaged in manufacture. The ideal quality control activity is one where everyone cooperates in the task of quality improvements, both from the top down and from the bottom up. This concept was developed into total quality control, covering customers, all employees, and management.

I think that total quality control is indispensable for building and operating an integrated manufacturing system in the information society. Educating all the people who work in production and raising their awareness is very important. Therefore education will play a more and more important role.

MANUFACTURING SYSTEMS IN THE INFORMATION SOCIETY

Just as we are told to put new wine into fresh wineskins, so it is most important that, in the information society, production systems be constructed that are appropriate to the social environment. Products to be manufactured will include not only those hardware products that were a major force in the industrial society, but also computer software in the narrow sense and software products in the wide sense, which are information products. The day will come when the creation of new information, knowledge, and technology will be included in the concept of manufacturing.

It is not going too far to say that the role of the IEEE in its second century is to promote the innovation of technology and its applications to support a healthy development of the information society. From the viewpoint of manufacturing technology, its role will be to promote the innovation of manufacturing technology and systems, in which small quantities of various kinds of hardware and software products, designed to meet individual needs, are produced with high quality and at low cost, rather than the mass production of a few kinds of general-purpose products. For this purpose the development of flexible manufacturing technology and systems is essential.

Fig. 4 shows the system diagram of a flexible manufacturing system for hardware products. This system consists of a technical information processing system, a management information processing system, a production system, and a performance processing system. As can be seen, there are two major flows in the manufacturing system. One is information flow and the other is material flow. As a manufacturing system advances to a flexible manufacturing system, information flow plays an increasingly important role in the system. It is difficult to free material flow to any extent from geographical and time restrictions. However, information flow has been rapidly freed from geographical and time restrictions, thanks to the development of C&C. It is possible to distribute the production systems close to markets, and the technical information processing system and the manage-

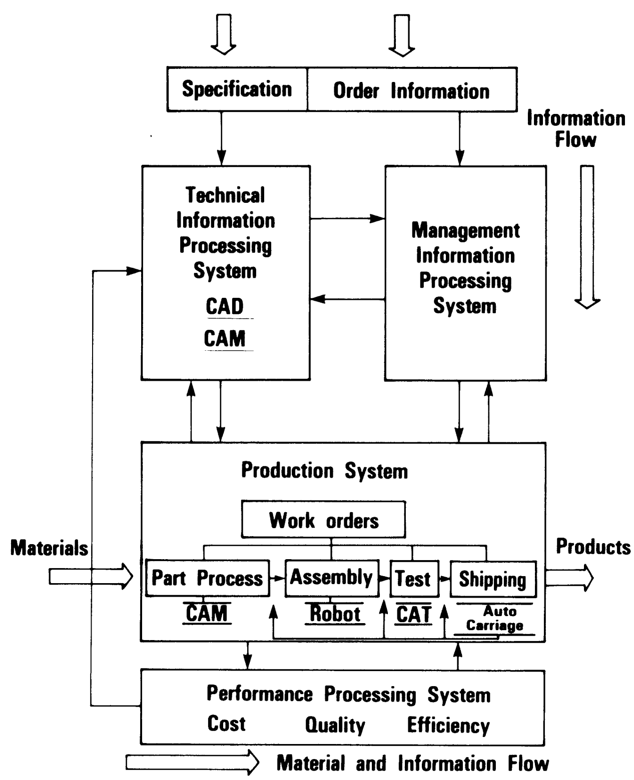


Fig. 4: Flexible manufacturing system for hardware production.

ment information processing system at the most appropriate places.

As shown in Fig. 5, each distributed manufacturing system function can be operated effectively by integrating it in a C&C network. Such a system can be called the C&C manufacturing system.

The automation of production systems for mass-producing fixed products will be rapidly realized by the application of current computers, robots, numerical control machines, and so on. However, for the purpose of meeting diversified needs flexibly and exactly, it is important to develop a design system which responds to individual customer's requests, that is, an individual response design system. Moreover, it will be necessary to develop a design system that defines individual product specifications based on customer's conceptual demands, namely, a creative design system. The concept of a virtual plant may not be just an engineer's dream. In the virtual plant, the customers themselves can control, via the C&C network, all the manufacturing processes, starting by submitting their product concepts and ending by obtaining their exact products. Furthermore, we can expand our dream to the development of resource sharing plants, in which production facilities and materials can be effectively shared among plants and enterprises dispersed throughout the entire world.

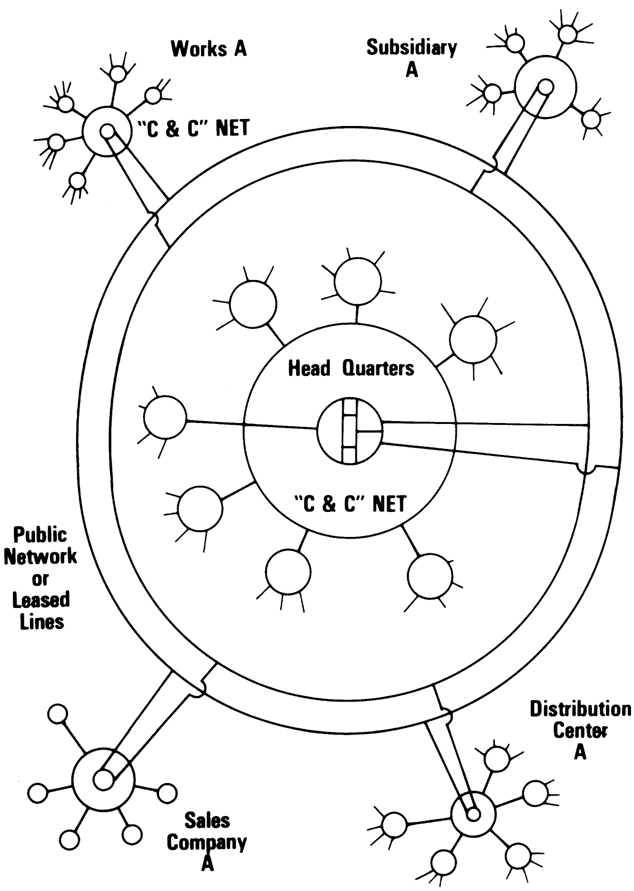


Fig. 5: Distributed manufacturing system.

Before building a C&C manufacturing system, it will be necessary to solve many technical and system problems and to accumulate a great deal more know-how. It will be necessary to construct the system so that each intraprocess, interprocess, and interplant system can be gradually integrated into a total system, aiming at the creation of a C&C manufacturing system. Fig. 6 shows a concept by which an individual production system is improved to become an integrated manufacturing system and further to become a C&C total manufacturing system. The horizontal axis shows organizational and geographical expansion, which is governed by improvements in communications technology. The vertical axis shows information levels increasing toward higher intelligence, with a corresponding need for the increased use of computer technology.

The system at the bottom left is to improve efficiency within the intraprocess and intraplant systems. In the system at the center, the function is expanded to a liaison system between individual processes and plants for maintaining continuity of manufacture, and it has an intelligent capability so that production directives can be given on-line. The system at the upper right becomes the C&C total manufacturing system, where manufacturing is effectively conducted by integrating all functions from customers, material and component suppliers, production plants, design and management centers, and to distributors.

TECHNOLOGY TO REALIZE NEW MANUFACTURING SYSTEMS

In order to realize new manufacturing systems, it is vital to systematically integrate widely existing tech-

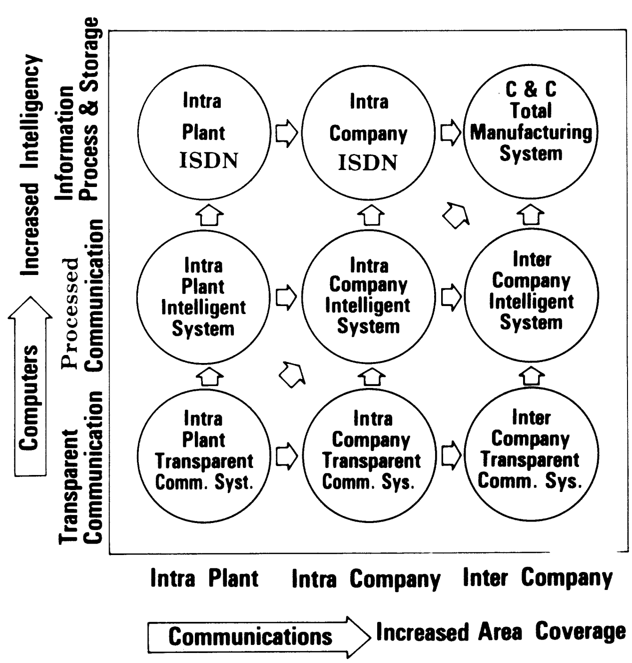


Fig. 6: Process of individual production system becoming integrated and finally C&C total manufacturing system.

nologies, but it is also necessary to adapt newly innovated technologies and frontier knowledge. Keeping in mind the hardware manufacturing system shown in Fig. 4, I would like to consider future trends in some important technologies.

Automation of each subsystem in the production system is rapidly progressing by the use of computer-aided manufacturing technology, robotics, and computer-aided testing technology. However, intelligent robots must be developed for the purpose of processing, assembling, testing, and completing various kinds of products, particularly parts for products that have different shapes and functions. These robots must be able not only to repeat programmed motions, but also to recognize cubic objects three-dimensionally, to process different products flexibly, and to assemble and inspect them based on instructions changing every moment.

The most labor intensive area in present production lines is the loading, unloading, and transfer of materials and parts between processes. If it were possible to load or unload differently shaped parts without damage at the most appropriate places in the transfer-handling cassette by intelligent robots, the material flow efficiency could be greatly improved.

Present robots are large and heavy and can only perform simple actions compared with human workers. Much greater advances in material and control technology are still required. Also, progress in sensor technology is necessary, especially the improvement of sight, pressure, position, and angle sensors. Fig. 7 shows a linear sensor and an angle sensor using multilayer ceramic technology. These ceramic sensors can output position and angle information directly in digital form and, therefore, should greatly contribute to cost reduction in digitally controlled machines.

Fig. 8 exaggerates the simplicity of an actuator utilizing multilayer piezoelectric ceramic technology. This will enable us not only to control the position and angle of machines precisely, but also to replace pulse motors, and it will greatly contribute to the miniaturization, low power consumption, and cost reduction of robots. Advances in microelectronic technology are essential for raising the intelligence of all machines, including robots.

The rapid progress in laser technology will bring about a huge revolution in manufacturing technology. Fig. 9 shows a conceptual diagram of a superhigh-performance flexible manufacturing system complex utilizing lasers. Optical fibers are used for the communication of information between the process control center and each process machine or robot in order to avoid system trouble caused by electromagnetic induction and to secure reliability.

At this stage, great advances in the technology of technical information processing systems are far more necessary than improvements in production system technology. In order to realize a design system able to interact with the individual response design system and the creative design system, considerable progress in the following technologies will be required:

1. Knowledge processing technology for efficiently and promptly analyzing customer's requirements, and for designing specific products and production procedures.

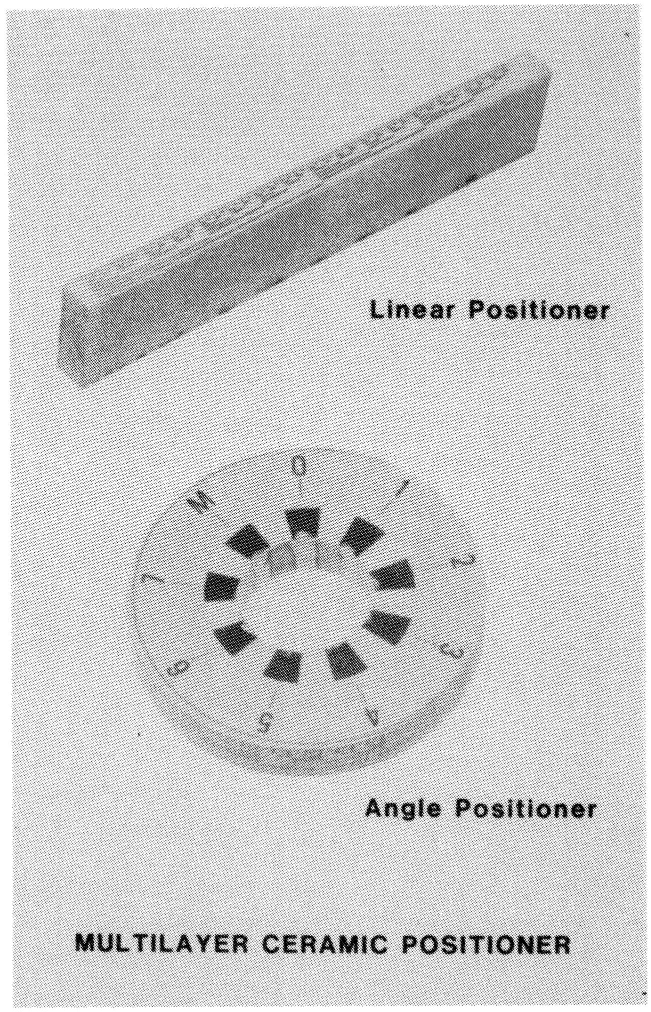


Fig. 7: Multilayer ceramic positioners.

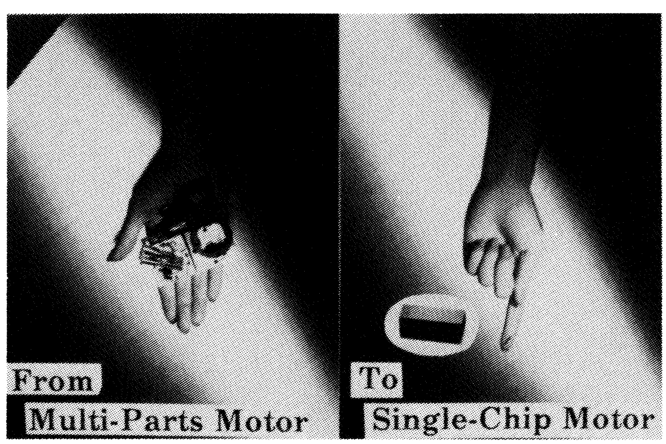


Fig. 8: Transition from multipart to single-chip motor.

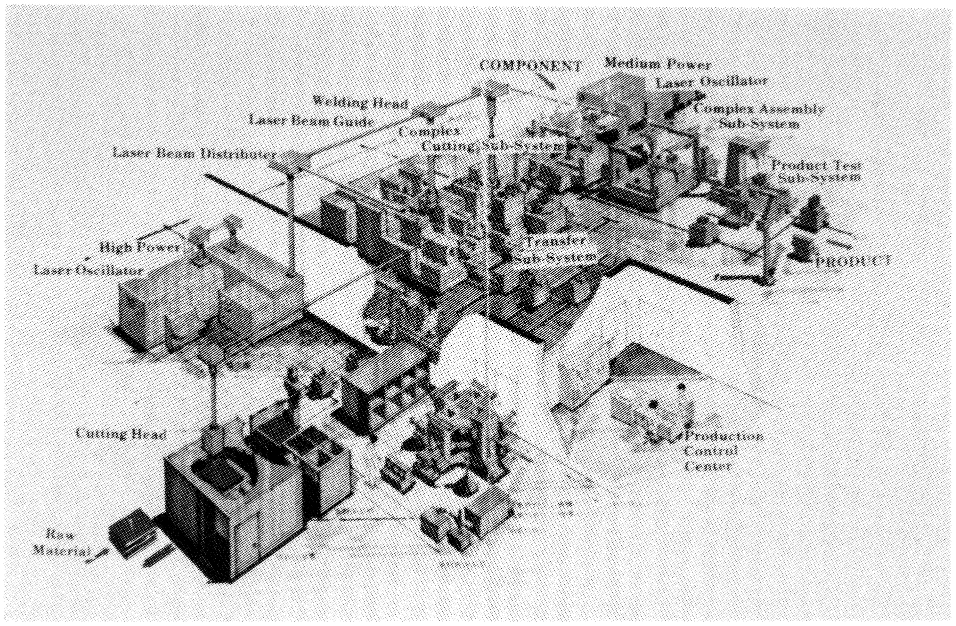


Fig. 9: Concept of superhigh-performance flexible manufacturing system complex.

2. Knowledge-based technology for accumulating the design know-how and engineering data base required for knowledge processing, so as to enable effective accessing.
3. Analysis and synthesis technology for effectively and promptly executing modeling and simulation.
4. Man-machine interface technology for designer workstations, so as to enable designers to communicate with customers and computers effectively.

In order to realize the C&C total manufacturing system, the virtual plant and the resource-sharing plant have to be realized. To do so, advances in the following technologies are required, in addition to those mentioned before:

1. C&C technology for organically connecting customers and production systems dispersed over wide areas.
2. Information hierarchy technology for effective operation through each increasingly complex layer of design, production, control, and management.
3. High-grade software technology required for the creation and alteration of systems, information control, and distribution control.

From those technologies, you can see that advancement is needed in software technology far more than in hardware. Without profound progress in software production technology in particular, it is not possible to respond to the development of manufacturing systems and their diversified needs.

When I explain the importance of software production technology, I often make an analogy with Mt. Fuji, the beautiful sacred mountain of Japan (Fig. 10). The base of the mountain below the fifth station is vast and gives us a great feeling of stability. If we compare software markets to Mt. Fuji, the area below the fifth station would represent the markets for the general public, centering on application software, and the area above the fifth station would be the markets for high-grade software.

Until the time a paved road was constructed to the fifth station, it took great effort to climb that far. However, at present, children and aged people can reach the fifth station easily by car. If we develop software production tools that correspond to the road and cars, anyone ought to be able to produce, without trouble, software for the general public. Just as more than 90 percent of the bulk of Mt. Fuji lies below the fifth station, so the majority of the software market is aimed at the general public.

The software production system may be realized by deleting technology related to material flow from the hardware manufacturing system.

Manufacturing systems in the information society must be intelligent and friendly to anyone, so that everyone is able to participate in manufacturing. The integrated manufacturing technology for such a system must be composed of the most advanced technology available, not only robotics and computer-aided engineering technology, but also communications, computers, microelectronics, optoelectronics, software technology, as well as basic science, new materials, quality control, human engineering, and management engineering.

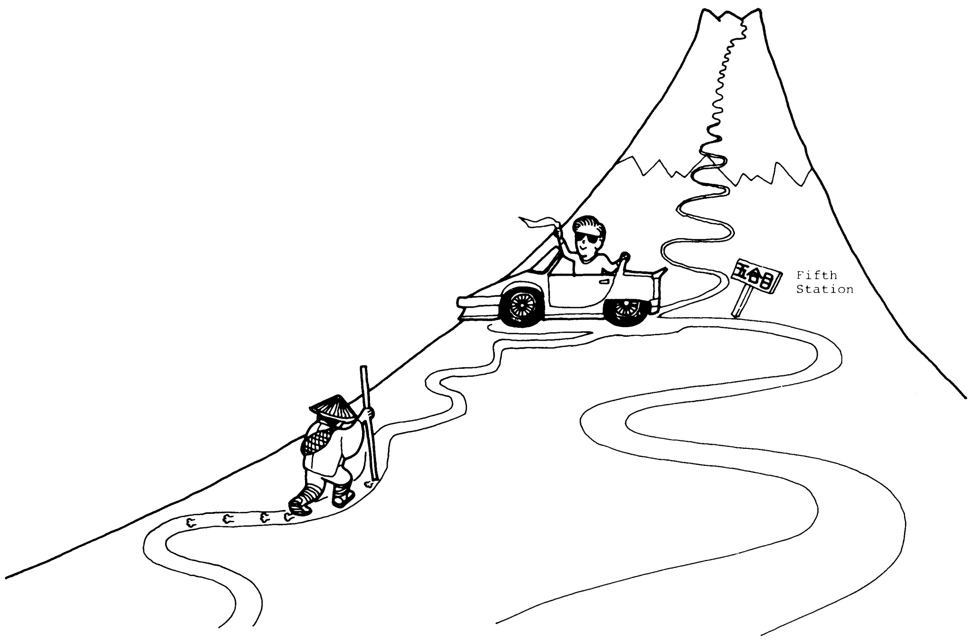


Fig. 10: Analogy of importance of software production technology.

MANUFACTURING TECHNOLOGY FOR HUMAN BEINGS CENTERED ON HUMAN BEINGS

The advancement of integrated manufacturing technology and systems will make production more efficient and able to meet a greater variety of needs. There are loud voices citing the fear that the improvement in production and distribution efficiency might cause a reduction in employment opportunities, and that the eager pursuit of greater productivity would cause the production system to ignore the human needs of the workers. If enterprises pursue short-term profits only and forget their responsibilities as members of society, these fears could become a reality. However, technology should be for the quality of life. Therefore human beings ought to be the focus of all production activities, and technology should continue to progress toward the realization of "Man and C&C" manufacturing systems centered on human needs. It is for this reason that we have expanded quality control activities to total quality control activities, and that we, workers, researchers, and management, have aimed to develop manufacturing activities integrated with the social system, learning from the demands and complaints of customers.

The ideal that the "Man and C&C" manufacturing system is aiming at is to create comfortable, natural working conditions for the workers, where they can interact easily with intelligent machines. As computers and robots are introduced into the production system, the retraining and transfer of skilled workers has become an important social task. This is because the workers need specialized training to utilize machines owing to the present immature technology of computers and robots. As technology advances and machines become intelligent, the man-machine interface will become friendly to human beings, making learning and operating an easy task for anyone.

It has also been pointed out that if the technology of advanced industrial countries progresses, the gap between them and developing countries will further expand, and the north-south problem will become worse. Some people propose to restrict technological progress in order to narrow the north-south gap. I cannot agree with this proposal. Advancement in technology is a result of human wisdom, and no one can hold back technological progress. I believe that the best way to help the poorer countries is by the advance of technology. The essential thing is to raise the level of education of the people in developing countries so that they can select the appropriate road and utilize the available technology.

The NEC Corporation has been engaged in research on voice recognition and synthesis technology for many years in order to make conversation between humans and machines possible. Moreover, NEC has been challenging the development of machine translation technology, particularly an automatic interpretation telephone (Fig. 11), so that people speaking different languages can communicate more easily and so that internationally dispersed resource sharing plants can be freely utilized. To realize the automatic interpretation telephone, advances in knowledge processing technology are indispensable. This technology is essential for the realization of the individual response design and creative design systems. The development of the fifth-generation computer is a step toward the realization of these objectives.

I have been studying English for over 60 years, but I still cannot communicate to my satisfaction. It is necessary to learn each language and culture for deepening international understanding. I hope that

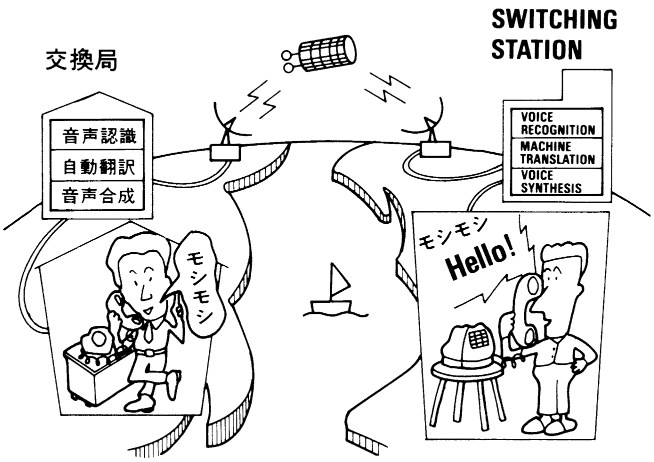


Fig. 11: Automatic interpreting telephone.

the automatic interpretation telephone will make it easy to learn foreign languages and cultures and that it will improve international communication. The technology developed during the realization of the automatic interpretation telephone will lay the technological foundations needed for the production systems of the coming information society.

As we move from industrial society to information society, the industrial structure will change. Whether or not there is a revolution in manufacturing technology, employment confusion in the transition period will be inevitable. In order to make this confusion as small as possible, and to get it under control in as short a period of time as possible, technology must advance, and new employment opportunities must be created. For this purpose, positive innovations in manufacturing technology will be a priority in the second century of the IEEE.

Koji Kobayashi, *Chairman of the Board and Chief Executive Officer, NEC Corporation, has spent his entire professional career with that organization. He received his academic training at Tokyo Imperial University and has received numerous awards for his contributions to both the technical and the industrial development of Japan, including both the Purple and the Blue Ribbon Medals from His Majesty, the Emperor of Japan. Dr. Kobayashi is a past chairman of the IEEE Tokyo Section, a Life Fellow of IEEE, a recipient of the IEEE Founders Medal, and a Foreign Associate of the National Academy of Engineering.*

EVOLUTION OF FACTORIES OF THE FUTURE

Raj Reddy

Dr. Kobayashi has presented a number of important concepts for manufacturing systems of the future. In this discussion, I will highlight the implications of some of the key concepts proposed by him, and I will suggest a research agenda for the second century of our society that is a consequence of such concepts and goals.

COMPUTERS, COMMUNICATION, AND MANUFACTURING

The main theme of Dr. Kobayashi's talk was that computers integrated with communications will be the foundations of manufacturing systems of the future. This important concept is being widely acknowledged, as can be seen from the recent arrangements between General Electric and Ungerman-Bass and the acquisition of Rolm Corporation by IBM. However, what probably is not clear are the full implications of Dr. Kobayashi's far-reaching proposals on virtual factories and resource-sharing enterprises of the future.

Imagine a customer in a remote location submitting a product concept, controlling the design and manufacturing personally to obtain a custom-tailored product to suit a specialized need. Fantasy? Not necessarily. It appears that earth stations based on spectrum techniques might be available in large quantities for less than $1000. This makes it possible for every remote village to have a village information center equipped with powerful personal computers connected to a low-cost earth station. Such a center would provide many services, including entertainment, education, and advice on local problems of health care, agricultural production, and pest control. "Science fiction," you say. How can an illiterate person who does not speak English, in a village without power, with no understanding of computers and electronics, operate, maintain, and utilize the most sophisticated invention of the human race?

Interestingly, we already have technical solutions to most of these problems. Can we have a system that will converse in the native language of the user? Indeed, yes, especially in situations involving a restrictive natural language that is task dependent. Dr. Kobayashi's company, NEC, recently demonstrated a translating telephone from Japanese to Portuguese involving a restricted dialogue.

Can we build a rugged supercomputer with a mean time between failures of over 20 years? Again, yes. Current nonstop computer designs have a mean time between failures of over 10,000 hours, or over one year of continuous operation. Increasing the mean time between failures to 20 or even 100 years is purely a question of architecture, not technology. Supercomputers capable of executing a billion instructions per second and having a billion bytes of memory will require less than a 1000 square centimeters of silicon by 1985 and will require no peripherals other than voice, vision, and a link to the satellite earth station.

Can we build a computer that is battery operated and can be charged by solar cells? Again, obviously. The recent Data General portable computer designed and built in Japan weighs less than 4 kilograms and has an IBM-PC compatible system with full 25-line display, and it runs for eight hours without recharging. Can we build a system that can diagnose itself and assist in its own repair? I will come to this question a little later.

I know that Dr. Kobayashi's vision of virtual factories, distributed factories, and resource-sharing plants does not have to be a pipe dream. Indeed, at Carnegie-Mellon Robotics Institute we have been working on similar concepts for several years.

Dr. Kobayashi raises a number of interesting points, many of which are worthy of careful attention. For example, he predicts the transition from mass production to special-purpose custom production. He believes that we will be manufacturing many software products in the information age just as we manufacture hardware today. He suggests that augmenting statistical quality control with dynamic feedback from customers, sales, production, and R&D provides real-time feedback to manufacturing. This will only be possible with an integrated computer and communications system. He proposes the distribution of the production system close to the markets while concentrating the knowledge and management of the manufacturing where the brains are. He predicts the need for white collar robotics, knowledge-base systems for planning, scheduling, simulation, and product management—tasks that are usually done by white collar workers in a factory.

FACTORIES OF THE FUTURE

I would like to discuss some other concepts that are likely to alter significantly the nature of manufacturing in the second century.

First is the concept of a *self-operating factory*, a factory that can convert raw materials into finished products with little or no human intervention. One can add other concepts to this basic notion. For example, the concept of a *microfactory*, a small facility that can produce a personal computer with the same economy as mass-produced personal computers; the concept of a *multipurpose factory*, a factory that produces personal computers one day, television sets the next day, and transistor radios the day after; the concept of an *inventory-less factory*, a factory (to use Dr. Frosch's term) that can virtually live off the land, using the raw materials available locally. A factory that possesses all these attributes must capture the knowledge about the products to be made, the raw materials to be used, the tools and fixtures required. Such a factory, if it is to be multipurpose, would have to be generic. We must accelerate research about generic raw materials, generic tools, generic fixtures, and so on.

A self-operating multipurpose microfactory that can live off the land comes close to the ideal Dr. Frosch wants for space manufacturing. Such a factory would be valuable here on earth if it can be produced economically.

Second is the concept of a *self-improving factory*, a factory that can learn from observation and improve with practice. Consider a human apprentice at a small motor manufacturing facility; he or she can look over the shoulder of an expert assembling a motor and learn to duplicate the sequence of the steps with little help. We are several years away from a computer that can look over the shoulder of a human expert and learn how to assemble a motor by itself, that is, a system that can write its own program for assembly from observation.

A human apprentice has another important attribute. He or she improves performance with practice. We have no examples of computers that improve their performance with practice. Even though we are far away from a computer system that can examine its programs, identify the potential sources of improvement, and compile the knowledge leading to a better performance, we must begin now so that one day we will have systems that can improve themselves.

Third is the concept of a *self-diagnosing factory*, a factory that can monitor its own well-being and discover the occurrence of abnormal conditions. The techniques of knowledge-base diagnosis have been studied in artificial intelligence. Expert systems need human experts to provide the cause and effect rules. While this technique could be used in a self-diagnosing factory, we are likely to need an army of knowledge engineers to codify the knowledge. More importantly, a human expert may not even exist for a newly designed machine. What is required is a system that can learn or discover its own cause and effect rules. To do this, a system has to have knowledge about itself.

Given a self-description in the form of structure and function and a number of sensors monitoring the status of the machine, it is possible to learn normal states of the sensors and flag abnormalities when they occur. The knowledge about the possible cause of a problem can be inferred from the structure-function relationship, or more simply by keeping a data base of cause and effect rules acquired from observations of other systems of the same type.

Fourth is the concept of a *self-repairing factory*, a factory that can repair a malfunctioning unit. Such a repair could be accomplished in a number of ways: It could be done by replacing the malfunctioning part. Where does this part come from? It could be from inventory; it could be manufactured *in situ* from generic raw materials; or it could be produced through the use of automated reverse engineering techniques in which a new design would be automatically generated to make a newly manufactured part using three-dimensional vision and process planning techniques.

There could be repair by technology insertion, where a functionally equivalent and compatible part, which is not structurally the same, can in fact be inserted for a repair of the system. The knowledge of the structure and function of the system must now be augmented by assembly and disassembly instructions, part-whole relationships, and manufacturing instructions for the parts to be made *in situ* requiring raw materials, tools, fixtures, and so on.

If we are successful in developing a self-operating multipurpose microfactory that can live off the land, and can also diagnose and repair itself, then we are not far from the *self-replicating* factory of Dr. Frosch or, going further, from a self-replicating factory, even a small factory, that can produce larger new factories. This could lead to an evolutionary growth of manufacturing facilities so that space colonies can be self-sufficient to a large degree.

What is needed is the same knowledge that has been developed for self-operating, diagnosing, and repairing functions. Given one such facility, the desired parts could be made, assembled, tested, diagnosed, repaired if necessary, and integrated into the rest of the factory. No new techniques will be necessary beyond the ones we discussed.

What I have just proposed is an ideal. Many of these things might appear to be too farfetched. But even if we can accomplish 90 percent of each of these goals, this means that only 10 percent of the time there are human beings in a self-operating factory, that is, only 10 percent of the time we need human beings to diagnose the factory, 10 percent of the time we need human beings to repair, and so on. Even if we could do these tasks 90 percent of the time, we would already have accomplished a major breakthrough in manufacturing. This is the agenda for the second century.

SOCIAL IMPLICATIONS

Finally, Dr. Kobayashi raises two very important social concerns. One concerns jobs, and the other concerns the poor and the disadvantaged nations of the world. It has been observed by a number of futurologists that jobs in manufacturing will follow the pattern of agriculture and that all of the manufacturing in the United States will require less than 5 percent of the work force, or a potential loss of over 20 million jobs in the United States alone. What will these people do?

It is hoped that the emerging technologies will create many more new jobs than the jobs that have been lost. And Dr. Kobayashi suggests that the retraining and transfer of workers from outmoded job skills to new technologies is an important responsibility for society at large and for IEEE in particular in the second century.

The second concern he raises is that the technological progress will widen the gap between the haves and the have-nots, increasing the north-south disparity between the industrial and the developing nations of the world. The answer seems to be not the transfer of wealth from north to south as suggested by the Brandt Commission and the Cancun Conference, nor the shipping of tons of wheat and corn to the hungry, but rather the transfer of knowledge, know-how, and literacy.

The great Chinese philosopher Kuan-Tzu once said: "If you give a fish to a man, you will feed him for a day. If you give him a fishing rod, you will feed him for life." We must go one step further: if we teach him how to make that fishing rod, we will feed the whole nation.

Sharing the knowledge and know-how in the form of information products is surely the only way to reduce this ever-widening gap between north and south. The current technological revolution provides a new hope and new understanding. The computer and communication technologies will make it possible for a rapid and inexpensive sharing of knowledge. This technological progress will make it possible to have a global electronic society in which high-quality custom products are produced economically and efficiently by the users themselves, using distributed microfactories, virtual factories, and multipurposere source-sharing factories as envisioned by Dr. Kobayashi. I applaud his vision for the future.

Raj Reddy *is professor of computer science and Director of the Robotics Institute at Carnegie-Mellon University, where he has been active in teaching and research in artificial intelligence for twenty years. Dr. Reddy's research interests in computer science are in the areas of artificial intelligence and man-machine communications. He is working on speech input to computers, robotics, and task oriented architectures. He is on the editorial boards of* Spectrum, Proceedings of the IEEE, *and* Computer Vision, Graphics and Image Processing. *He is a Fellow of IEEE and the Acoustical Society of America and a member of the National Academy of Engineering. He is president-elect of the American Association for Artificial Intelligence (1986–87). Dr. Reddy was awarded the Legion of Honor for his work as chief scientist of the World Center in Paris, France.*

PRIORITIES IN ENGINEERING EDUCATION FOR THE SECOND CENTURY

John G. Linvill

Engineering education through the first century of the IEEE reflected the evolution of the electrical engineering profession during that period. The birth of the profession occurred with the development of the electric power industry. The vacuum tube brought radio and electronics; computing machines changed from mechanical and electromechanical to electronic and, finally, to digital electronic form. Particularly with World War II, the emphasis on electronics vastly expanded, and the government came into the education scene with levels of support and long-term involvement that had never occurred before. But the most rapid change during the first century was reserved for the last part of it. The transistor and the integrated circuit, combined with computing and information processing, brought a rate of change previously not equaled. At the end of the first century, the relative importance of electronics and electrical engineering has greatly increased from its start a century ago, and the rate of change of the technology and its applications are growing at an unprecedented speed. Rapid growth and dynamic change represent the initial conditions for engineering education as we enter the second century of the IEEE.

To match the growing importance of electronics and electrical engineering in general, the educational community—including its support base in the government and in industry—must establish the appropriate priorities for the second century and implement plans to act vigorously in accord with these priorities. One can identify many important directions and important goals for engineering education. Many of these correspond to the goals that have been established and are accepted these days in the education community, but the situation is considerably different looking into the next century than it was looking through the first century. I want to put emphasis on three major directions for engineering education—to identify three priorities for the next century. I will state them first in introductory terms and then deal with them in sequence.

The rapidity of change in electrical technology has continuously shortened the effective lifetime of an engineering education, particularly the master's degree level of that education, with the result that education must be an ongoing process. *A dominant priority for engineering education is to develop a process for that education which continuously prepares and adapts the professional to change from the beginning and throughout his or her professional career.*

Electronics has brought powerful tools for education. Television and the video screens of computers impact all parts of American life. They have come into the educational process by intent or automatically. The tools technology has created must be used imaginatively by the engineering sector to promote the education of new and practicing professionals. *An important priority of engineering education is to utilize technology to enhance technological education.*

Today, engineering education is going through a significant crisis. There is a severe shortage of faculty members qualified and interested to pursue an academic career. Those academically qualified for the teaching profession have recently found it more attractive to pursue careers in industry. An incentive system for education is lacking in which productivity and excellence in the profession are sufficiently rewarded to make academic careers attractive. In fact, the entire education enterprise would strongly benefit from a significant incentive system for faculty members but also for other sectors, as I will explain. *The provision of an incentive system for engineering education is a major priority for the next century.*

TO EDUCATE FOR CHANGE

A significant measure of the present rate of change of technology is the fact that for a period of approximately 20 years the number of elements on a silicon chip doubled each year, while the price of the chip remained essentially constant. This relationship, which was pointed out by Gordon Moore, presently Chairman of Intel Corporation, has been frequently referred to as Moore's law. The result is that the effectiveness of an integrated circuit chip changed roughly by a factor of a million over this period of time. The impact on the computer, on telecommunications, on electronics in general, has been profound. The microprocessor, the computer on a chip, evolved in this environment, changing rapidly both the power of the electronic systems that are possible and the way in which these systems are designed and used.

The engineering curriculum at the M.S. level is the part most affected by changing technology and has itself exhibited corresponding change, as is illustrated in Fig. 1.

The undergraduate curriculum necessarily involves large components of mathematics and science which change less rapidly. The new parts of the M.S. curriculum are of key importance to practicing professionals since these new parts provide their agenda for study to maintain and build their professional competence on a dynamic basis. For example, the design of systems involving microprocessors is presently only a decade old in the curriculum, and courses in the layout of large-scale and very-large-scale integrated circuits are only half a decade old. The breadth of utility of microprocessors and custom integrated circuits means that electronics professionals must learn to use these implements, no matter when it was that they received their own master's degrees. Electronics professionals literally face the challenge of a continual process of education, which must be lifelong. The industry which employs them must face the challenge of maintenance of the effectiveness of its work force, the central component of its base of competitiveness. How can lifelong education be most effectively carried out, and who will be responsible for the process and system?

One possible answer was provided in 1982 by a centennial study at MIT reported in "Lifelong Cooperative Education," by Professors J. D. Bruce, W. M. Siebert, and L. D. Smullin under the chairmanship of R. M. Fano. The proposal of the MIT study is that industry and the university must cooperate in the lifelong education of the professional engineer. Moreover, the MIT study recommends the method of tutored videotape instruction initiated by Professor J. F. Gibbons at Stanford for providing the education. In tutored videotape instruction (TVI), videotapes are made of regular classes, paced by a live learning audience. The videotapes are played before a small group (not more than 10) by a tutor. When one of the small group does not understand a point, he asks a question and the tape is stopped by the tutor, who facilitates a discussion of the matter not understood, but does not immediately answer the question or give a minilecture. When the point is understood, the tape is started again. Gibbon's supposition that course material would be effectively learned in the little "intellectual communities" formed by the viewers and the tutor was verified by numerous tests in which the videotape viewers took the same examinations as the regular class. The viewers performed just as well as regular students. Moreover, there is economic gain since the same lecture is presented to a larger audience and the tape can be viewed anywhere a tutor is located with a video player.

There are other important means to implement ongoing professional education in this environment of change. The program and publication functions of the IEEE play a very important part. In conjunction with major regular meetings, tutorials and workshops on forefront technology have become commonplace. They play an important role in the education process and should strongly continue. The importance and effectiveness of short courses is apparent from the fact that groups of professionals, frequently educators, have made successful businesses conducting them.

How should professionals view the environment of change in which we now exist? In a word, enthusiastically. It is not the imposition of a drudgery upon the profession, but the injection into it of an exciting, continuously renewing experience. It is clear that some of the learning must represent an investment by the professional himself. Some of it must be provided by the employer, and some of it represents a new investment by society at large through a governmental system. All three sectors—the individual, his or her company, and the government—will in the long term significantly benefit by the process set up. The benefits of the output of the technical professional work force will return a handsome benefit to all sectors making the investment.

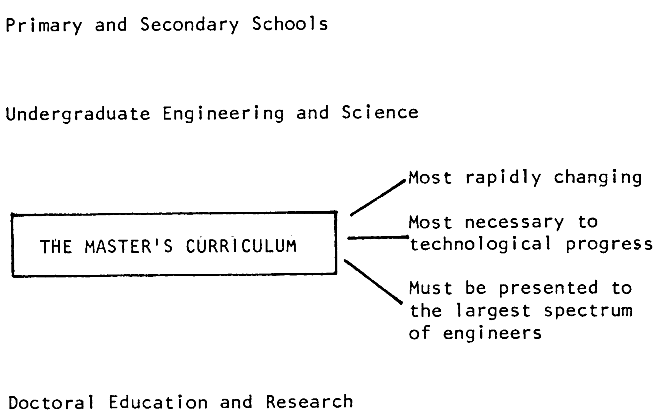


Fig. 1: Education for engineering.

TECHNOLOGY TO ENHANCE TECHNOLOGICAL EDUCATION

In the June 1984 issue of *IEEE Spectrum*, which looked at technology and the individual beyond 1984, two significant papers were presented regarding technology in education. Professor Van Valkenburg, in his article entitled "Technology as a Tool for Teaching EEs," made a compelling case for the attractiveness of technological aids for education. He points out numerous examples of the effective use of electronic recording, both video and audio, in the educational process. In addition, he shows the significant impact which the introduction of the computer as a teaching aid already has made. In the end he concludes, and I certainly agree, that the use of technological aids increases the efficiency of education. The number of effectively taught students per professional teacher will increase significantly.

In the same issue, President Cyert of Carnegie-Mellon, in "New Teacher's Pet: The Computer," points up the use of the computer in the broader base of secondary and undergraduate education. Cyert believes that increased access to computers with short response times removes the major limitation that has prevented computer-aided education in the past from achieving the success he now anticipates. The creation of software for computer-aided education is a major task. The consortium of universities organized by Carnegie-Mellon to build and share a software base is an important step.

Graduate education in technology, particularly the part involving experimental research, requires experimental equipment which is expensive and changes rapidly. At the same time, there is no effective substitute for hands-on experience in the learning process. In the experimental research arena, the same class of equipment is necessary in the university as in the industrial research laboratory. The cost of equipping and maintaining a research laboratory in integrated circuits or semiconductor physics is comparable per doctoral student to the cost per technical professional in the corresponding industrial research laboratory. The implication is clear—a new, higher level of capital investment is essential in the graduate schools at present and in the future.

An alternative method of achieving hands-on contact with the professional implements is for the student to have this contact in conjunction with an industrial operation. One sees in this situation a merging of the educational operation with the industrial operation. Technological education, by its very nature, will have a content which is essentially more industrial than it has ever been before. At the same time, professionals in industry must have a continual educational experience to remain effective in their professional careers. At present and in the future, their activities must contain a significant educational part. The inescapable result of this situation is that the functions of industry and educational professionals must be merged, at least to some degree. If this process is done with vision and effectiveness, each sector will benefit by the presence of the other. The confluence of industry and technological education occurs primarily beyond the bachelor's degree. There has been, and will continue to be, significant interaction between industry and the university in undergraduate programs, but changes here are small in prospect compared to those applying to master's level education and beyond.

INCENTIVE SYSTEMS FOR EDUCATION

There are two aspects of incentive systems which I want to discuss. First, I shall consider an incentive system for teachers. The shortage of faculty members, particularly professors, in the areas of computer science and systems is strong evidence that the education profession has lost comparative attractiveness to industrial careers. An American Electronics Association blue ribbon committee characterized this situation as "industry having eaten its own seed corn." For the technical industry in particular, but for all of society as well, the problem of faculty shortage is a very serious one. What we as a society must do is to establish incentives that make the teaching career attractive to the most able professionals inclined toward such a career.

Up to a certain level, regular salary is a primary incentive. The investment of larger amounts of money for teachers' salaries is essential for the educational system. Only by providing suitable salaries can society make outstanding teaching careers attractive to new Ph.D.s. Graduate students preparing for a career in education must be able to project an economic scale that does not imply financial sacrifice. In the presence of an adequate base salary, external incomes from consulting, publishing, and lecturing are effective and attractive.

There are other important incentives to educators in addition to salary. Social recognition of outstanding performance of educators by professional societies, by government, and by industrial entities all have a powerful role in stimulating such performance. Our professional societies and government agencies can focus additional attention on the education profession to bring it effectively to the attention of graduate students. The American Electronics Association has established a very attractive fellowship program whereby its member companies have provided forgivable loans to selected candidates. The loans are repaid by years of service as faculty members. Though the program is new, its positive effect can already be detected at Stanford in the response of our doctoral students.

A university creatively administered offers a very attractive life to a faculty member. Many of us in the academic community find the continual contact with growing and inquiring minds a unique, stimulating environment. The university atmosphere is a significant attraction to the academic profession when the most serious impediments are removed.

Let me turn to incentives for a different player in the education game. That player is industry. Throughout this presentation, I have pointed out the projected large increase in interaction between industry and the university in engineering. The mutual user—supplier relationship of industry and the university is illus-

INDUSTRY NEEDS: (University Supplies)	UNIVERSITY NEEDS: (Industry Supplies)
Fundamental Research	State-of-the-Art Technology
Selected, Prepared Candidates for Employment	Powerful Research Equipment
Imaginative, Speculative Projects	Professionals Addressing Current Problems
Effective Educational Materials	Market for Educational Materials
[SECURITY FOR PROPRIETARY ADVANTAGE Industry Constraint]	[OPEN COMMUNICATION University Constraint]

Fig. 2: A mutual user-supplier relationship.

trated in Fig. 2. Here, a strong basis for mutual activity is apparent. Security versus openness is the only conflict of constraints. A midground must be negotiated in which industry minimizes its demands for security, and the university minimizes its inclination to disclose sensitive information not essential to objectivity.

Of course, the bottom-line question is: "Who bears the cost of industrial involvement with education?" Is it an unavoidable tax on industry for the benefit of society at large? Or must our public tax system in some way reimburse industry for this important contribution? First of all, I firmly believe that participation in the education process must have incentives to the industries participating to assure that participation will be of high quality and of continuing duration. There is no "free lunch" and there is no "free education." At the same time, industrial involvement in the educational process brings significant benefit to industry when that relationship is carried on in an effective way. Contact with the graduate population being produced in the university gives industry facilitated access to the ideas which they generate and facilitated access to them as emerging professionals when they are ready to enter the employment market. The worth to technological industry of an early and effective contact with a Noyce, a Pierce, or a von Neumann is very great indeed. To the outstanding individual, contact with an effective industrial employer has great rewards as well. When a creative individual is placed in an industrial position configured to exercise his creative talents to the limit, society is the major winner.

But who must ensure that incentives to industry are in place? Finally, educators and the government entities which support education must assure that the incentives for industry are there. These can be tax incentives provided through the political system or they can be the benefits implicitly available in the user—supplier relationship. When the appropriate incentive system is in operation for all players, our educational system will show effectiveness far beyond what was experienced in the first century of the IEEE.

John G. Linvill *was on the faculty at Massachusetts Institute of Technology and a member of the technical staff of Bell Laboratories before joining the faculty at Stanford University. Formerly chairman of the Department of Electrical Engineering and associate dean of the School of Engineering, he is now professor of integrated systems and codirector of the Center for Integrated Systems. Dr. Linvill is an IEEE Fellow, a recipient of the IEEE Education Medal, and a member of the National Academy of Engineering.*

ENGINEERING EDUCATION IN THE 21ST CENTURY

John B. Slaughter

Dr. Linvill's presentation addressed three of the most important issues in engineering education: (1) Engineering education must develop a method to educate the professionals for change. (2) Engineering education must utilize technology to enhance technological education. (3) We must develop an incentive system to interest engineers in becoming educators.

Note the emphasis on change in all three of his points. These are certainly priorities for engineering education for the 21st century—not all of the priorities by any stretch of the imagination, but arguably the most important ones. I want to mention briefly a few others that engineering education must deal with, but first let me comment on John Linvill's point about incentives.

Paul Gray, President of MIT, said that one of the major problems facing education today is that an academic career is becoming increasingly less attractive—a point that John Linvill made very clear. It is my belief that higher education needs to steal a page or two from Peters and Waterman's successful book, *In Search of Excellence*. That book, which points out eight principles practiced in abundance by America's most successful corporations, provides us with a rare opportunity to compare and contrast how academic institutions deal with challenges, with opportunities, and with incentives.

I argue that there is no systemic reason why the same successful approaches cannot be employed in higher education. Professors, researchers, students, football coaches, housekeepers, provosts, and deans need supporting environments, incentives to excel, rewards if they do, room to take risks, opportunities to practice entrepreneurship, a sense of community, and reasons to feel pride in themselves and the institution of which they are a part. Too few educational institutions in my mind have shown the willingness to move away from those practices that prevent them from being the 3Ms, the Wangs, the Intels, and the IBMs of academia.

For over 30 years I have heard the argument that engineers, by necessity, are trained rather than educated. I think the charge is badly overdrawn, but to an extent, it is true. Thirty years ago, if it was true, it was much less important. Today, however, I believe it is more worthy of our concern. As our knowledge of science and technology expands almost without bounds, the five years of undergraduate education required of most engineers compels us to provide our students with more, not less, mathematics, physics, chemistry, and metallurgy. But the expanding set of social, economic, and cultural interrelationships associated with our rush toward high technology call for a much deeper and more professional understanding of these issues as well.

A well trained but undereducated engineer has limitations—limitations that are present in his or her designs, theories, and products. I believe that education must learn to deal with this reality.

Roger G. Smith, Chairman of the Board of General Motors, spoke of the importance of these considerations when he said that business is not so much the movement of products as it is the relationship between human beings. That view was echoed by Charles O. Brown, Chairman of the Board of AT&T, who said: "My own experience has shown that it is the conceptual issues and problems in business—the humanistic concerns, if you will—that are the most difficult to deal with and the most crucial to resolve. And so, there is a place," he continued, "a central place, for the humanities and the liberal arts. That's the good news. The bad news is that the good news is not better known."

No discourse on educational priorities in the future can be considered complete in my opinion until we deal with this issue. It is more important perhaps than those topics that occupy much of our time and concern now—industry/university cooperation, new instrumentation in our laboratories, new computers in our classrooms. At some point educators must come to grips with the need for engineering students to have a greater appreciation for both Milton and molecules, Carlyle and chemistry, Picasso and potassium.

In an ever-changing society, such as the high-speed, high-pressure, high-technology one that we are helping to build, there will be a greater need than ever before for those persons who take our places 50 years from now to have a better education and better abilities in the humanities and the social sciences than we do.

Finally, I remain concerned about the slow progress we as a profession are making in improving the presence and the quality of that presence of women and minorities in engineering. A look around this hall confirms that our generation has not been very successful in that regard. I would hypothesize that at the beginning of the 21st century, women will have a more commanding presence in engineering based upon their present enrollment in our colleges of engineering, but I am not at all sanguine that Blacks, Hispanics, or American Indians will be more evident than is currently the case.

In the 1970's business and industry took the lead to increase the number of minorities graduating from our engineering schools from between 1 and 2 percent of the total to some higher level. That effort was successful in doubling the number of minorities, but has now plateaued and, in fact, has even wilted because of the confluence of a number of economic and political reasons.

The engineering profession itself has never mounted a major effort in this regard and has tended to discount the argument that there is any reason to be concerned. The responsibility in the future, therefore, in my opinion is one that will have to be carried largely by the educational community from preschool to doctoral levels.

The reason this is important is not because of some appeal to our conscience or the need to satisfy some affirmative action laws. It is important because our nation needs all the intellectual skills it can muster to deal with the pressing technical, economic, and social problems that face us. We are dealing with problems that affect our industrial and production capacity—problems that will not be solved unless all of America's potential, not a portion of it, has a fuller opportunity to contribute.

All of us have become painfully aware of the problems in our public education system which were highlighted by the numerous reports that came out in 1983. The response of school boards, administrators, and the public toward improving schools has been encouraging. I trust that that momentum will continue. Higher education is beginning to respond as well. The new cooperation will, I believe, produce much improvement. But we need to recognize that serious disparities still exist, disparities that deny many disadvantaged young persons the necessary exposure to science and engineering that can ignite the spark that will make it possible for them to pursue these fields of discovery.

Priorities for education are great. They underlie all the other priorities that are before us. They include producing the finest scientists and engineers, a knowledgeable, well-informed citizenry, and a national climate of enlightenment and tolerance. The future of our country depends to a large extent upon our commitment to meet those priorities.

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RESEARCH AND DEVELOPMENT MANAGEMENT

George E. Pake

At the outset, with a title like research and development (R&D) management, let me make the following statement lest there be any doubt. When it comes to R&D, I'm for it. Attempting to produce thoughts that might be applicable to a forthcoming century was an awesome task. One way to view the problem is to ask what would one have said about my topic in 1884, as the first century began? And if I could figure out an answer to that question, what meaning might that answer have had in the last few decades of the first century?

I feel confident that the phrase R&D management would have drawn puzzled reactions in 1884. First of all, the technical pioneers of those days were probably far less lazy grammatically than we are today. Since the New Deal was 50 years in the offing, the language had not been corrupted by alphabet soup, or by acronyms. Fortunately, we do not normally attempt to pronounce R&D, although I have been told that the Rand Corporation was named as a kind of acronym for R&D. I do not know whether that is historically accurate. But in general, we do not refer to R&D by attempting to pronounce it.

Even if one were to imagine speaking in 1884 of research and development rather than, cryptically, of R&D, I have serious doubt that the two words were in those days frequently associated. The notion of research as a basis for the development of products and services and the concept of a flow from research to development is, I suspect, entirely a 20th-century thought pattern. This gives me considerable pause. What will R&D connote in the year 2084?

I am sure that the word research had full meaning to IEEE members in 1884, though it would not have brought to mind large industrial organizations of professionals such as Dr. Gomory and I have responsibility for in our respective corporations. Those did not begin to appear until the very beginning part of the 20th century. Instead, research would have had primarily an academic association. I am less sure what meanings in a technological context the word development might have had in those days.

I plan, following these reflections, to give you my definitions of research and of development, so that you will better understand what I am talking about. But my assigned topic also requires that I introduce and expand upon the *management* of R&D processes, which is surely a 20th-century concept.

This is my definition of research: research is the active, aggressive quest for knowledge or innovative concepts. And if one does not consider it superfluous, I would say for *new* knowledge.

In the context of the R&D process, people sometimes wish to make a distinction between two kinds of research—basic or fundamental research on the one hand, and applied research on the other. Only occasionally do I find this a useful distinction. It is much dependent on the motivations of the investigators, and it is not an intrinsic property of the work nor of the resulting knowledge. Most of the results of so-called basic research find ultimate utility. Does it then instantaneously transform into applied research?

In fact, this brings to mind an anecdote. We have heard of the marvels of NMR (nuclear magnetic resonance) imaging. Immediately after World War II, I was a graduate student at Harvard working with Ed Purcell, who was doing the pioneering work on nuclear magnetic resonance that would ultimately earn him a Nobel award. In those days I remember writing a letter to my parents and pointing out that I was learning about the properties of the nucleus and how the nuclear magnet—that is, the gyroscopic entity inside an atom or a molecule—was very sensitive to its immediate atomic and molecular environment.

Remember now, this was in the wake of World War II, which brought to mind, when one did physics and said something nuclear, either nuclear bombs or nuclear energy; perhaps my parents might have thought about the practicality of radar and devices of that kind. I said, "However, this is just basic knowledge. This will never have any application," which shows how wrong I could be. First of all, this is a warning to you if I am going to project for the second century. But I clearly did not foresee even the applicability of the NMR spectrascopy to analytical chemistry.

We could readily understand, from what we were learning, the way in which the immediate environment of the nuclear magnet influenced the resonance spectrum. We could understand that you could learn a great deal about the atomic and molecular environment. But I could not at that time conceive of the data processing capability that would permit the kind of real-time analysis that goes on with the NMR tomography of the type that now constitutes NMR imaging technology. I thought I was doing basic research: I now discover I was doing applied research.

In some respects I find it more useful to distinguish between long-range and short-range research. Although most basic research is long range in its outlook, the converse is not true.

Development, as a process step following research, is an organized effort to apply the new knowledge gained from research to devising a commercially or socially useful product or service. It therefore contains a substantial component of engineering. A senior level technical manager in my corporation has made the distinction that in our business context, research aims at expanding the corporation's technical alternatives, whereas development seeks to narrow down or focus on a particular alternative in an effort to produce a particular cost-effective and reliable implementation.

Some other comments about distinctions between research and development: research is more often the province of scientists, and development is more often the province of engineers, but each activity has a substantial requirement for the experience and skills of both scientists and engineers.

Another point is that in some elemental sense, development is more expensive than research. The design and construction of implementations requires, for hardware, the cutting, bending, or molding of metal or other structural materials; and for software, the careful production of reliable, debugged systems and programs, all of which consume many person-hours of work by skilled professionals. And those person-hours cost lots of money.

The number of research person-hours required to generate and demonstrate at the bench a technology that forms the basis of a new product concept is typically very much smaller than that needed to develop a durable, reliable, and manufacturable implementation of the concept. But it would be wrong to conclude from this last statement that research budgets need be only a tiny fraction of development budgets.

It takes a number of research investments, some of them quite long term, before we pursue one that succeeds in exhibiting the potential for a new technology, which in turn generates a new product or service concept. Once a new technology is launched in the marketplace, a substantial ongoing research effort is mandatory, I believe, to build the knowledge base for both sustaining and extending that technology in the field. As each research success is launched in the marketplace by a successful development effort, an added obligation falls to the research organization to build into its base program a sustaining and extending effort on behalf of the newly succeeding technology. There is no such thing as a technology that you suddenly research, understand, and throw into the marketplace and then just forget about. You can try that, but I think with very large business risks.

My next problem is with the notion of managing research. I characterized research as the active quest for new knowledge and concepts. This means looking to the group of researchers for innovation and creativity. How does one manage the creativity of others? In my experience the attempt is quite often ineffective and often counterproductive. I believe that the role of management is to create and maintain an environment supportive of and encouraging to creativity and innovation. In fact, my brief prescription for managing industrial research would be something close to what follows: (1) Recruit the best and most creative researchers you can find. (2) Give them the most supportive environment you can visualize providing. This includes ample amounts of the most advanced instrumentation. Holding tight on capital spending is a foolish attempt at economy. In fact, it is a false economy when you consider the cost of principle (1). If you are going to hire first-rate people and pay their salaries, it is utter folly not to provide them with the very best technical tools. (3) Work the business needs of the corporation (or whatever the entity is) into the program through selective budgetary preferences.

There is little success likely to come from showing researchers to a laboratory, describing in detail a desired technology or process that does not now exist, and then commanding "thou shalt invent." Instead, the enterprise seems to go better if some overall goals or needs are generally described and understood, and proposals for research projects or areas of investigation are solicited from the creative professionals. Managing the research then consists of adjusting the respective budgets for the projects or programs so as to give selective and therefore sometimes differential encouragement. There are many subjective criteria for this selective support, including, of course, the goal or objective of the project in relation to the potential needs, and especially including the creativity, innovativeness, and productivity of the key researcher or researchers on the team.

This recommendation for the selection process and differential budgetary tuning by the research manager or director of the research organization may seem to some degree to fly in the face of the time-honored advice of Dr. C. E. K. Mees, who was Vice President of Research for Eastman Kodak for quite a period of time. He offered the following lessons, at a time that was just about halfway through the first century of the IEEE. Here is his statement of October 22, 1935: "The best person to decide what research work shall be done is the man who's doing the research." (I believe we should say the man or woman doing the research.) "And the next best person is the head of the department who knows all about the subject and the work. After that, you leave the field of the best people and start on increasingly worse groups, the first of these being the research director who is probably wrong more than half of the time, and then a committee which is wrong most of the time, and finally a committee of vice presidents of the company which is wrong all of the time."

Now in spite of my subscription to these principles set forth by Dr. Mees many years ago, I do not wander away and ignore my research groups and their scientists, nor did Dr. Mees. There is a very important role in guiding, challenging, and continually reassessing the selection process at all levels. And it is surely the responsibility of research management to pose those problems that are most likely to be the problem domains of business importance to the corporation.

When it comes to selecting projects, the research management is, I believe, best advised to tune the research program by using the budgetary power to adjust emphases. In some cases that may mean shutting something off completely, or occasionally giving birth to a whole new project or activity. But these steps should be taken with continual consultation and discussion up and down the entire hierarchy of research management, which in my corporation is only three levels deep in each of the three research centers.

To my mind, it is this all-important process of selecting the research to work on and allocating resources to it that is the essence of what we call research management. It draws upon the combination of technical knowledge, business strategies, research experience, understanding the psychological makeup of research scientists, and above all, what I will call technical taste. The research manager at any level brings all of this to bear in a necessarily subjective way.

I have already expressed my worry over how to have a vision on R&D management that can retain validity for a good portion of the century. However, in spite of my trepidation, I am willing to make one prediction that parallels a significant event of the first century.

The Institute changed its name, and I believe it will do so again in the second century. After being born as the American Institute of Electrical Engineers, the AIEE, as we all know, became the IEEE, the Institute of Electrical and Electronics Engineers. My prediction is that it will become something equivalent to the IEEEOE, the Institute of Electrical, Electronics, and Electrooptical Engineers. This also tells us something about the nature of the new R&D domains that will be important for the present IEEE.

At the beginning, long before AIEE took steps to put the word electronics (I feel sure that it should have been the adjective electronic) in its name, people would possibly have had little reason to believe that research on electron processes in vacuum or, more recently, on electron energy bands and impurity states in semiconductors would be relevant to electrical engineering. We have now arrived at a point where research on electrooptic materials and optical data transmission is extremely germane to electrical engineering. As we see more applications of electrooptical phenomena, the name IEEEOE will become especially appropriate.

We have also seen that some of the soft sciences, psychology and sociology, are increasingly important to electrical engineering. I am not going so far as to suggest that some of those names will be thrown into the title of the IEEE, but it's worth considering that over the next century those disciplines will have considerable bearing on how the IEEE and its descendant organization will progress. I suppose even if one went back to 1884, the notion that physics would have much to do with electrical engineering during the first century might have been regarded with skepticism by some of the hard-bitten electrical engineers of 1884. They probably thought of physics as a soft science in those days.

I believe that clearly we have a very exciting century ahead for the IEEE and whatever else it becomes: I have suggested IEEEOE.

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RESEARCH AND DEVELOPMENT MANAGEMENT—CIRCA 2000 AD

George H. Heilmeier

In this discussion of research and development (R&D) management, circa 2000 and beyond, I would like to focus on two questions, namely, what things will change in the next century and what things are going to remain the same. Let me begin by addressing the question: "What things are likely to change?"

I think one of the more noticeable changes likely to occur in the next century is that the coupling between engineering and marketing is going to become even tighter. By marketing, I do not mean sales. Marketing is a separate discipline from sales. What I mean by marketing is the discovery and understanding of the customer's problems and the implications of solving those problems.

A second aspect that I believe is going to change in the next century is that compensation and incentives will be quite different than they are today. They will be much more entrepreneurial-like in nature. Straight salary will still be used, but it will be augmented by compensation and incentive schemes, which are much more characteristic of the venture capital world today than they are of more conventional industrial employment.

The third thing that is likely to change is the capitalization per professional. It is going to be higher. Computational plenty means more capability for more people, and it means lower cost per unit. But that will not necessarily keep pace with the demand for ever-increasing capability and a more pervasive fan-out of that capability.

The fourth thing that is likely to change is the workplace, because I think we are going to see much more extensive use of what I shall call the extended workplace. This means more work at home in addition to more work in the office. It means prime-time work at home made possible by the pervasiveness of networking capability.

The fifth thing that is likely to change are industry/university relationships. I think they are going to be much closer. Some may say that this is a shotgun marriage, but I believe it is inevitable for both economic and professional reasons. But as the poet Gibran once said about marriage "the pillars of the temple should be close, but not too close."

Finally, I think we are going to see much more extensive use of internal education. The reason for this is that the pace of technological change makes this inevitable. In our profession, as in many other professions, one must either learn and grow or die. Technology can bring the best lecturers into our facilities on our terms, at times of our choosing. Paraphrasing what Raj Reddy has said, I see the formation of the micro-university, or the virtual university, in our plants and facilities.

Now I would like to turn to the things that I think will remain the same.

I believe that blocking and tackling in our business means people, ideas, and the management of change. To me this is what R&D management is all about, and no matter how much we push and shove and tug, this is not going to change.

Second, I believe that personal and professional pride are going to remain unchanged. No matter what we managers do, in the final analysis we are really only coaches, chaplains, and patrons of our professional people who, for reasons of personal and professional pride, drive themselves far harder than we could ever dream of driving them.

Third, we have all heard the question: "What have you done lately?" That is not going to change. I would like to paraphrase the words of Geraldine Ferraro in the context of another discussion; "Those of you who have CEOs concerned about this year's earnings, you know what it's like."

In the fourth instance, I believe that R&D productivity measures will still be elusive. We will keep trying to measure R&D productivity in quantitative terms, but I do not think we will be very successful. It is still, after all, a business that puts a premium on insight and vision, and those are not very quantifiable terms.

A fifth aspect of R&D management that is not likely to change is how you communicate to your people. In my view, policy statements, speeches, and things of that nature may be the popular mode of communicating to your people but, in the final analysis, the action that speaks the loudest about what you really stand for is the kind of people that you promote, and that is not going to change.

Finally, the characteristics of innovative organizations are not going to change very much. Too often we focus on innovation as a synonym for invention. Innovation has another dimension, and that is execution. You cannot have an innovation without execution as well as invention.

Innovative organizations spend less time debating the obvious than the other kinds of organizations. They have close contact with the customer at all levels. They have very low NIH, or "not invented here." They have a minimum of formal communication mechanisms and a maximum of ad hoc communication schemes. They have a strong personal incentive system, and they are not afraid of failure. They try more things and they risk failure or embarrassment without animosity or scorekeeping. Finally, they have leaders who know the business. Unfortunately, there are a number of people who think because one has an M.B.A. degree that he or she can run any business. I do not subscribe to that theory at all.

I looked for an appropriate quote with which to end my brief look at the next century, and I find that I am not sure just what side of this quote I would like to be on. But I think Lord Melbourne said it best in 1834 when he observed: "What all the wise men promised has not happened, and what all the damned fools said would happen has come to pass."

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APPENDIX I
BIBLIOGRAPHY

BIBLIOGRAPHY OF IEEE ARTICLES AND BOOKS RELATED TO THE CENTENNIAL

A lasting achievement of the Centennial was the publication of numerous IEEE articles and books on the history, status, and future prospect of almost every field of electrical and electronics engineering. Six books and booklets were published in this vein, ranging from the scholarly *The Making of a Profession* to the popular *Engineers & Electrons* and *A Century of Electricals*. Nearly 300 articles of a similar character appeared in IEEE periodicals. The majority of these covered the history of technical developments and IEEE entities, but many also looked into the future to predict the contours of the "second century." As a special feature, the *Proceedings of the IEEE* reprinted classic papers by such famous engineers as Charles P. Steinmetz, Edwin H. Armstrong, and Claude E. Shannon.

The "Centennial" books and articles are listed below by type of publication: book, general IEEE periodical, Society periodical, and conference record. In regard to Society periodicals, all papers appearing in a "Centennial Issue" were selected unless the issue contained "regular papers." In that case, only the articles in the Centennial section were included. A few special issues that appeared in late 1983 and early 1985 are also listed because they relate directly to the Centennial. Additionally, any historical article published by the IEEE in 1984, whether in a Centennial issue or not, was selected. Although not included here, notices of many Centennial publications of IEEE Sections can be found in the *Newsletters* of the IEEE Center for the History of Electrical Engineering.

It is hoped that this bibliography will provide a useful guide to the wealth of information published about the history and future of electrical and electronics engineering on the occasion of the IEEE Centennial.

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APPENDIX II
CENTENNIAL MEDAL WINNERS

RECIPIENTS OF THE IEEE CENTENNIAL MEDAL

To help make the centennial a truly Institute-wide celebration, the 250 Sections, 33 Societies and 7 major Boards of the IEEE presented a total of 1984 IEEE Centennial Medals during the year to individuals who in their judgment had made outstanding contributions to the Institute and the profession. The following is a list of recipients of the IEEE Centennial Medal.

M. Robert Aaron,
Holmdel, NJ
George F. Abbott,
Durham, NC
Bobby J. Able,
Arlington, TX
Henry L. Able, Jr.,
Mt. Pleasant, SC
George Abraham,
Washington, DC
Melvin N. Abramovich,
Garrett Park, MD
Richard L. Abrams,
Los Angeles, CA
Anibal Acosta Ayala,
Boqueron, PR
Stephen F. Adam,
San Jose, CA
James G. Adams,
Winston-Salem, NC
Robert Adams,
Indianapolis, IN
Willis A. Adcock,
Dallas, TX
Robert Adler,
Glenview, IL
Abdel-Latif I. Ahmed,
Cairo, Egypt
S. Basheer Ahmed,
Princeton, NJ
Wilfredo Albanes,
Huntsville, AL
Robert T.H. Alden,
Hamilton, Ont., Canada
Jose C. Aleluia Costa,
Salvador, Bahia, Brazil
J. A. Alencastro e Silva,
Brasilia, Brazil
Charles K. Alexander,
Cookeville, TN
Phillip E. Alexander,
Fort Wayne, IN
Igor Alexeff,
Oak Ridge, TN
William K. Allan,
Kelowna, B.C., Canada
George L. Allerton,
Orefield, PA
Everett D. Alton,
Iowa City, IA
Helmut M. Altschuler,
Washington, DC
Joseph L. Alvis,
Wichita, KS
Salah Amer,
Cairo, Egypt

Constantine Anagnostopoulos,
Mendon, NY
D. B. Anderson,
Whittier, CA
John G. Anderson,
Schenectady, NY
Lawrence K. Anderson,
Allentown, PA
Ross C. Anderson,
Houston, TX
Stephen R. Anderson,
Anchorage, AK
Walter L. Anderson,
Washington, DC
Del L. Andrews,
Boise, ID
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