AD-A171 610 ANNIVERSARY OF THE JOINT SERVICES ELECTRONICS PROGRAM (40TH)(U) ANALYTIC SERVICES INC ARLINGTON VA A SHOSTAK 1986 DAAG29-81-D-0100 1/2

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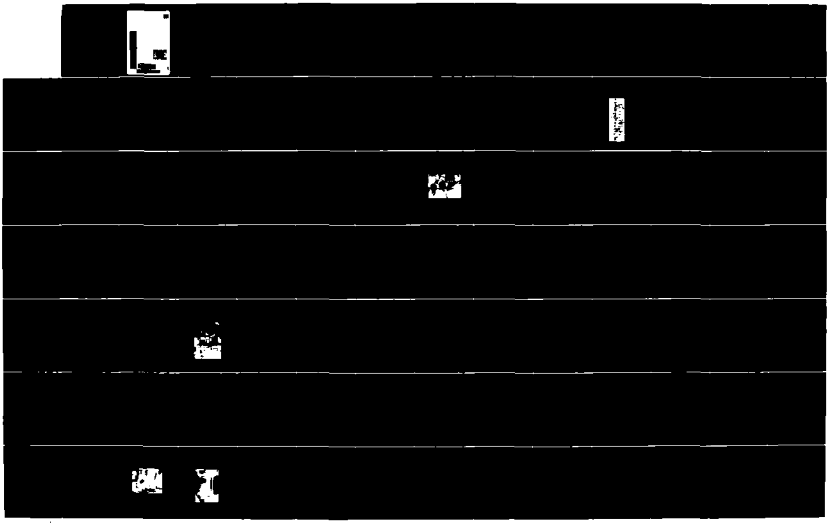

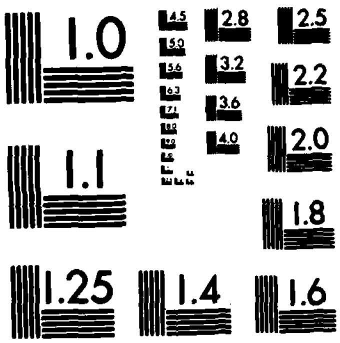

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AD-A171 616

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: ---
2a. SECURITY CLASSIFICATION AUTHORITY: ---	3. DISTRIBUTION/AVAILABILITY OF REPORT: APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: ---	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): ---	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: ANSER; 6b. OFFICE SYMBOL (If applicable): ---	7a. NAME OF MONITORING ORGANIZATION: ---
6c. ADDRESS (City, State and ZIP Code): SUITE 800, 1215 JEFFERSON DAVIS HIGHWAY, ARLINGTON, VIRGINIA 22202	7b. ADDRESS (City, State and ZIP Code): ---
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: U.S. ARMY RESEARCH OFFICE; 8b. OFFICE SYMBOL (If applicable): ---	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: DAAG 29-81-D-0100, DO 1981
8c. ADDRESS (City, State and ZIP Code): P.O BOX 12211, RESEARCH TRIANGLE PARK, NORTH CAROLINA, 27709	10. SOURCE OF FUNDING NOS.: PROGRAM ELEMENT NO. ---; PROJECT NO. ---; TASK NO. ---; WORK UNIT NO. ---
11. TITLE (Include Security Classification): 40th ANNIVERSARY OF THE JOINT SERVICES ELECTRONICS PROGRAM	
12. PERSONAL AUTHOR(S): EDITOR, ARNOLD SHOSTAK	
13a. TYPE OF REPORT: PROCEEDINGS; 13b. TIME COVERED: FROM --- TO ---	14. DATE OF REPORT (Yr., Mo., Day): --- 1986; 15. PAGE COUNT: 133
16. SUPPLEMENTARY NOTATION: PROCEEDINGS DOCUMENT	
17. COSATI CODES: FIELD; GROUP; SUB. GR.	18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
19. ABSTRACT (Continue on reverse if necessary and identify by block number): ----	
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL: ARNOLD SHOSTAK	22b. TELEPHONE NUMBER (Include Area Code): (703) 685-3313; 22c. OFFICE SYMBOL: ---

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Contents

Introduction

The importance and impact of technology evolved as the result of basic and applied research in the various scientific disciplines became most visible in the period when the United States was involved in World War II. Radar, sonar, advanced communications, and identification systems are but a few of the items of warfare introduced and used by our armed forces during that dismal epoch. These systems and their uses were the products of a broad program of intensified study in physics, electronics, mathematics and, indeed, the various disciplines of biological and behavioral sciences.

When World War II ended, not only was there the rush by U.S. service personnel to return to their civilian occupations, but in addition, the numerous scientific groups who had volunteered for military research and development service in our country's laboratories were also disbanded.

Almost 40 years ago, far-sighted Americans, recognizing the need for a continuation, in some form, of the university/military research program, propelled the establishment of the Joint Services Electronics Program (JSEP), with which this volume is concerned. It is published in commemoration of this Fortieth Anniversary.

There now exist 12 university research activities in that program. Histories, accomplishments, current thrusts, and future trends of each of these JSEP activities are here recorded. Of particular significance to all who are involved in research are the metamorphic threads appearing in this documentation, showing the evolution of research programs and their important scientific and technological outpourings.

It will be apparent to the reader, perusing this volume, that the contributions to our nation's civilian and military posture and strength made by this program are numerous and of the most impressive consequence. The program, which is guided in an enlightened way jointly by representatives of Army, Navy, and Air Force, has been expanded where necessary and possible and will continue as a seeding fount about which university researchers in the electronic sciences may flourish.

JSEP has always been a powerful contractual vehicle, combining the interests and resources of Army, Navy, and Air Force in the search for scientific advances and know-how that can lead to improved modern equipments and technologies in peace and war. This program has served as a model, illustrating co-operative ventures and accomplishments by the government and universities.

Along with the abundant research productivity of this program, one must note the continued wide-latitude support of students and other research personnel. These people, along with the directing faculty members, have participated in industrial entrepreneuring and consultation and in supplying technical and administrative leadership to U.S. government laboratories and offices, as well as to university programs themselves.

To provide a background setting for the individual JSEP programs, a brief overview, in the nature of an historical perspective has been excerpted from a report by Drs. A. L. Gilbert and B. D. McCombe. This report was prepared in 1985 for the U.S. Army Research Office.

In the following pages the JSEP universities have been invited to present some historical aspects of their association with JSEP and to highlight the most interesting accomplishments that have occurred over the years. These contributions give a vivid and

convincing argument for the strength and dynamics of the Joint Services Electronics Program and its far-reaching impact on U.S. science and technology.

The Joint Services Electronics Program

An Historical Perspective

A. L. Gilbert and B. D. McCombe

World War II changed modern warfare. Upon entry into the war, Britain recognized that technology would be critical to its ability to defend itself against Germany. One of the first deficiencies addressed was the detection of bombers. In 1935 Watson Watt had patented RADAR for tracking clouds. Practical airborne radar systems did not exist, and the National Defense Research Committee (NDRC) in the United States was requested to aid in the development of such a system. This project was entrusted to the newly formed Radiation Laboratory at MIT. So began the involvement of the academic community in this country in direct support of military technology. Yet this involvement was on the government's payroll, since the Radiation Laboratory belonged to the NDRC.

In 1939 the NDRC had been organized to begin conducting defense-related research, and it created the MIT Radiation Laboratory in 1940. During the war the Office of Scientific Research and Development (OSRD) was created under Dr. Vannevar Bush. A temporary measure intended to be disbanded after the war, OSRD established the institute concept where scientists and engineers taken from universities and industrial laboratories were placed together and given assignments directed at exploiting existing science and developing technology of importance to the war effort. It was too late to develop much new science. Fortunately, the first part of the century had been full of scientific exploration and many opportunities existed for developing technologies that ultimately made the difference in the outcome of the war. It is impossible to measure the relative importance of any single technological development in producing an

Allied victory, although several devices and technologies have been cited throughout the years as playing a key role. Often the relative importance of these technologies depends upon the perspective of the writer, but it is probably beyond argument that Airborne Radar Systems, the NORDEN bombsight, improvements in navigational techniques including electronic methods such as radio direction finding and LORAN, improvements in radio communication techniques, the atomic bomb, etc., were of immense importance. But these were the result of pre-existing science and the efforts of scientists and engineers working as technologists under OSRD during the war.

Even during the early years of the war, thinking men within the Department of Defense recognized that a new era of dependence upon rapid exploitation of technology for warfare had begun. Efforts to create the Office of Naval Research were begun in 1943, although they were not successful until late 1946. It had become apparent to some that defense should be an influencing factor in developing science and technology and not just a user of that which had been developed for other reasons.

During the war OSRD built up a valuable technology base, including scientists, engineers, and facilities of importance to the national defense. Grave concerns existed at the end of the war, and even before, as to whether this national resource would be lost at the disbanding of OSRD. No agency within the federal government existed with a mission to provide for continued funding and conduct of defense-related research. In March 1946, the military services, recognizing the problem and the critical need to preserve the R&D capability created during the war, joined together in a tri-service committee to fund the continued research efforts at MIT, Harvard, Columbia, and Stanford. Predating any existing federal agency for the sponsorship of research, the tri-service agreement results in the Joint Services Electronics Program (JSEP). JSEP has been continually funded since 1946 and is the oldest university research sponsorship program in the federal government. As such, for 38 years it has been a model of research funding mechanism and success.

Since 1945 the government has played an important role in influencing the direction of scientific investigation and in the production of defense-related technology. World War II was a turning point, since it both established the importance of technology in support of warfare and produced the concept of government investment in science and technology in support of defense. It is that very technology base that has preserved our leadership in military capability in the post-war era. Since much of the domestic technology that allows us to enjoy our particular life-style in this country has resulted from defense-related research, the benefits have certainly exceeded the expectation of the military.

At the close of World War II the federal government recognized that it was critical to the future of this nation to preserve a significant research base in support of the Department of Defense. While the National Science Foundation was proposed at the end of the war to take over the functions of the OSRD that was being liquidated, political issues delayed its creation for several years. It is to the credit of the military services themselves that they undertook to protect a national resource and investment in technology and research facilities through JSEP. This tri-service agreement was first implemented at MIT to protect the Radiation Laboratory assets belonging to OSRD. Had the government not taken such an action, undoubtedly the personnel assembled at MIT, Columbia, Harvard, and Stanford would have been disbanded, and the post-war history of technological advances in the United States would have followed a much different course.

With the task contract with MIT's Research Laboratory of Electronics (RLE) in March 1946, the JSEP was born. Within approximately the following year, Harvard, the Columbia Radiation Laboratory, and the Stanford Electronics and Microwave Laboratories were added to the program. The JSEP approach was to provide block funding in programmatic areas directed at fundamental research. Equipment and facilities belonging to the Department of Defense at these universities were preserved for their use through this continuity of research effort. Key researchers and their graduate students had the funding necessary to continue scientific investigation and exploration into electronic phenomena. Broad discretionary powers were given to the laboratories to investigate phenomena of interest. It is most instructive to consider the exact language of the task statement for RLE, which reads (in part)

> "The Massachusetts Institute of Technology, through its Research Laboratory of Electronics, shall undertake a program of research with a view of extending the useful range of the electromagnetic spectrum from the region currently exploited by ultra-high frequency techniques through that employed by microwave radar and communications systems to a region of shorter wavelengths, approaching ultimately that of infrared radiations. It is contemplated that this program shall include the following, but may be extended to related studies as may appear desirable:
>
> a) A search for useful generators of power at frequencies falling within this designated range, including their modulation and control, and a study of the theory of their operation;
> b) Research on basic components and techniques necessary for the practical

utilization of this region of the spectrum, including circuits and instrumentation;

c) A study of the spectroscopy of the region including propagation and absorption, and in general the interaction of electromagnetic fields at such frequencies with solids, liquids, and gases;

d) The conversion of electromagnetic energy to sound vibrations at these frequencies and the employment of such vibrations as a tool for further studies of the structure of matter."

It was this document which brought broad-based peacetime research sponsorship by the Department of Defense to the academic community. Although other NDRC contracts had existed with the universities, they focused on specific issues rather than whole technologies. JSEP is a changing program, adapting itself to the research and military environment in which it must function. In the ensuing years many universities have been added to the program, and several dropped. Current member universities include MIT (1946), Harvard (1946), Columbia (1946), Stanford (1947), Polytechnic University (1955), University of Illinois (1959), University of California at Berkeley (1961), University of Southern California (1963), University of Texas (1964), Ohio State University (1978), Georgia Institute of Technology (1980), and Cornell (1980). Previous members include Purdue (1966- 67), Northwestern (1966-67), California Institute of Technology (1978-80), and Texas Tech (1979-82). Numerous other institutions have applied over the years and have been considered for membership.

In the early days of JSEP, it was probably the most significant source of research funding at each participating school. On December 8, 1961, Dr. R.

Novick, Director of the Columbia Radiation Laboratory, in a letter to Dr. L. Wood, Director of the Physical Sciences Division at AFOSR, called his attention to the fact the JSEP had sponsored the work of three Nobel Laureates at that school (C. H. Townes, P. Kusch, and W. E. Lamb). In more recent years the impact of JSEP has clearly been reduced since, even though the budgets have been growing, the "real dollars" invested have been greatly diminished. As an example, JSEP funding in 1959 was $3,730K for 6 universities, while in 1979 it was $6,892K for 12 universities. In fact, MIT and Illinois were at the same dollar support level in 1979 as they were in 1959. The greatest impact of the program, then, would clearly be expected to have occurred in its earlier days. The most recent Nobel prize awarded as a result of JSEP research was to N. Bloembergen at Harvard in 1981 but for work in laser spectroscopy having a long history within the program.

One of the most important reasons for the success of the program has been the high level of cooperation between government and laboratory personnel. While the charter of the program has been intentionally broad, the actual conduct of the program has been guided continually by the Technical Coordinating Committee (TCC) and the Technical Review Committee (TRC) on the side of the government. The laboratory directors from the JSEP schools also meet as a committee and work closely with the TCC in insuring that the program remains responsive to DOD needs.

The JSEP program is quite dynamic and continually evolving. Emphasis areas are added and deleted. Work units are evaluated and dropped if they are not perceived by the TCC as being oriented to a DOD need. While the laboratory director has discretionary authority to start new work units, these are routinely reviewed and guided by the government. The laboratory directors have generally been highly responsive to

JSEP management, and hence the program remains focused on DOD-related research needs. The necessary stability of funding to allow institutional planning and commitment has been maintained, resulting in valuable long-term research programs.

University of California, Berkeley

W. Oldham and D. Angelakos, JSEP Directors

I. Formative Years

The Joint Services Electronics Program at the University of California, Berkeley, began in 1961 by combining a number of existing grants and contracts. The original programs receiving support were bioelectronics, integrated circuits, microwave antennas and radiation, microwave electronics, solid-state electronics and system theory, and energy conversion and control. The first program director was Donald O. Pederson with key scientific researchers from the various fields within Electrical Engineering. In the formative years of JSEP at Berkeley the leaders included Professors P. Morton, E. Kuh, S. Silver, D. Angelakos, J. Whinnery, T. Everhart, L. Zadeh, C. Desoer, and E. Jury.

The objectives of the first JSEP contract were to provide general support for a broad spectrum of basic research activity and to insure that every qualified graduate student in electronics would be able to receive financial support. The program came at a critical period of development of Electrical Engineering at Berkeley and provided a needed financial base for the overall research program. Measurable output, such as journal articles, technical talks, and nucleation of major research activities increased dramatically in the years immediately following the start of the JSEP program.

II. Avenues of Research under JSEP

Initially, the JSEP program was broadly focused, encompassing the areas mentioned above. Over time, the program evolved to focus more sharply on those areas of direct interest to DOD. The original emphasis on microwave electronics, for example, has evolved to include quantum electronics and millimeter wave integrated circuits. The original component research has evolved into an activity in computer-aided design (CAD) of integrated circuits, an area which continues to grow in importance. The microwave and antenna segment continues to be a strong activity. The original portion on System Theory, Energy Conversion, Control, and Computer Systems has continued and now is focused on optimization of complex systems and control of nonlinear systems. JSEP was instrumental in establishing a viable bioelectronics program, which is now supported by other agencies.

Throughout its history, the JSEP program has involved a stream of new, young investigators. This has kept the program dynamic and has resulted in the program moving into new research areas in a timely manner. This ability to support young investigators has contributed a continuing vitality to the program.

III. Results of JSEP-Supported Research

The JSEP program at Berkeley has provided early support for many projects that later produced important results. In some cases the complete project was carried out under JSEP support, while in other cases the JSEP support allowed the initial exploratory work to be done, after which other support was obtained for the later portions of the project. Several of the contributions are summarized below.

a. Computer-Aided Design

Computer aides for integrated circuit design and evaluation have been an integral part of the integrated circuits program at the Electronics Research Laboratory at U.C. Berkeley since its establishment in the early 1960s. Initially the research was concerned with development of special purpose computer programs to analyze devices and circuits or adaptation of existing design programs. These original efforts led to the development of Simulator Program with Integrated Circuits Emphasis (SPICE) as well as a host of other integrated-circuit simulation programs.

The early work of Professors Pepper and Pederson and co-workers (beginning in 1965) on computer-aided design of special purpose devices and circuits was initially supported by JSEP and continued with support directly from DOD agencies.

The first integrated circuit program developed was BIAS in 1968; this was followed by CANCER and TIME. These developments were also supported by JSEP and ARO. By 1971 the initial work in SPICE had been published. Two other major computer programs for integrated circuit simulation were developed at Berkeley during this period, SLCI (Simulator for Linear Integrated Circuits) and SINC (Simulator for Nonlinear Circuits).

SPICE 1 was first issued and made widely available in 1972. It was quickly adopted for practical integrated circuit simulation and design by many major industrial concerns. Over a period of three years there were 17 releases of SPICE 1. The CDC version was provided to over 60 industrial users and more than 40 academic institutions. Various versions of SPICE are presently in use by the integrated circuit industry worldwide. Due to this widespread distribution and use by the integrated ciruit industry and the generic nature of the technology, it is practically impossible to follow the trail clearly from research to a particular military system. On the other hand, precisely because of its wide dissemination and use by the integrated circuit industry and the importance of this ubiquitous technology to the military, the work at Berkeley has clearly had tremendous impact.

b. Relational Data Base Systems

The INGRES project (Inter-Active Graphics and Retrieval System) was started in late 1972 by Professors Eugene Wong and Michael Stonebraker with the objective to build a full function relational data base management system. The majority of the initial funding was provided by JSEP. When the project goals were more clearly defined and an initial prototype had been constructed, subsequent funding was obtained from other DOD sources.

INGRES was one of the first (if not the first) working relational data base systems. Not only did it embody the relational concepts suggested originally by E. F. Codd, but it also contained novel concepts in the areas of query optimization, support for views and integrity control, and multiple-access methods.

The success of the INGRES project is readily documented. By 1978 there were more than 200 users of the system worldwide. By 1982 at least four companies had picked up the software and were attempting to commercialize it. By 1985, INGRES formed the basis of the data base management software for two successful companies. In 1985 a book containing 20 of the more prominent research papers that came out of the project was published by Addison-Wesley. There are now at least 3,000 installations of various versions of the INGRES system, many within DOD.

c. Quantum Electronics and Optics

Studies of thermal lens effects under Professors Whinnery and Hu led to a new, simple, and efficient method of measuring the thermally induced index changes arising from absorption of a laser beam in a low-loss material. This has become a standard method of photo-thermal spectroscopy.

The use of edge techniques for the fabrication of small-area junctions was pioneered by Professors Wang, Whinnery, and Gustafson in their work on Metal-on-Metal (MOM) diodes in the mid-1970s. At the time, these diodes represented the fastest diodes achieved, and the edge technique has become a widely used technique for making small-area junctions.

The theoretical and experimental work carried out by Professors Wang and Whinnery on distributed Bragg reflector (DBR) and distributed feedback lasers (DFB), and interference lasers, including coupled-cavity lasers, contributed to the early theoretical and experimental foundations of this important field. DFB and DBR lasers have the important property of being able to retain single-wavelength operation in the presence of high-speed modulation, a critical aspect for communications applications.

d. Electromagnetics

A key contribution under JSEP has been the method of moments for calculation of fields associated with wire antennas. This method, developed under the direction of Professor Ken Mei in the late 1960s and early 1970s, is now the most widely used technique for the calculations involving this type of antenna. A second more recent contribution of this group involves time domain computation of electromagnetic scattering. Work related to this on scattering from buried targets is currently used, for example, by the Army to study detection of plastic land mines by radio waves. Much of the theoretical work has been tested on a scattering range designed by Professors S. Silver and D. J. Angelakos.

e. *Superconducting Electronics*

The model for semiconductor-coupled Josephson Junctions proposed by Professor T. Van Duzer and his students in the early 1970s has become the standard model for these devices and has been used in virtually all subsequent studies. In the technological aspects of this Josephson work, a new method for the preferential etching of silicon was investigated and experimentally confirmed. There has been extensive industrial interest in and application of this method for etching silicon in the past several years.

f. Information Systems

The fundamental conditions for the existence of value in a two-person zero-sum differential game were derived by Professor Varaiya and his group. These conditions laid a more promising foundation to the study of differential games than the previous work of Isaacs, which was based on use of the Hamilton-Jacobi equations.

Professors Varaiya, Wong, and Zakai, together with their students, were responsible for some of the most basic work in modeling, filtering and estimation, and control of stochastic systems, i.e., systems subjects to random perturbations and which are observed through noisy channels. The University of California at Berkeley was among the first to introduce the so-called "martingale" approach (a scheme for determining whether residual error has "white noise" characteristics) to the study of such systems. Subsequent developments showed that this was indeed the correct way to formulate and study these problems. The approach has proved useful for both continuous (Brownian) and jump (Poisson) distributions.

Most recently attention has turned to the study of communication and decision making by a multiplicity of "agents" or "controllers" each of whom has only partial knowledge of the system and each of whom can only partially govern the system. Specific problems considered include: distributed estimation where a collection of sensors must jointly estimate a random variable; distributed data bases where query processing, consistency, and updating of data bases must be done in a distributed manner; and distributed resource sharing as in computer systems and broadcast communication channels. The faculty members involved in this effort are Professors Varaiya, Walrand, and Wong.

g. Impact of JSEP

The results of the work carried out under JSEP have been communicated to industry and DOD in many ways. A very large number of conference and journal publications have come out of this work. Also, Electronics Research Laboratory (ERL) memoranda describing the work and results have received wide distribution.

With regard to communications with industry, an important avenue has been the Annual Research Summary and the Annual Research Review Meeting. The former is a book published in March summarizing the research carried out during the past year in the Electronics Research Laboratory and the Department of Electrical Engineering and Computer Science. The latter is a review meeting held once per year in March for the purpose of communicating our research results to industry.

In addition to these avenues, numerous visits have been made to DOD laboratories by the Director of ERL and a number of the principal investigators over the years.

The existence of JSEP support has had significant impact on the Department, the College, and the University. This form of continuing support of basic work acts as a seed from which research areas and topics can develop, which in turn allows the development of more support from industry and other DOD sources. The importance of funding basic work on a continuing basis cannot be overemphasized.

IV. The Current JSEP Program at Berkeley

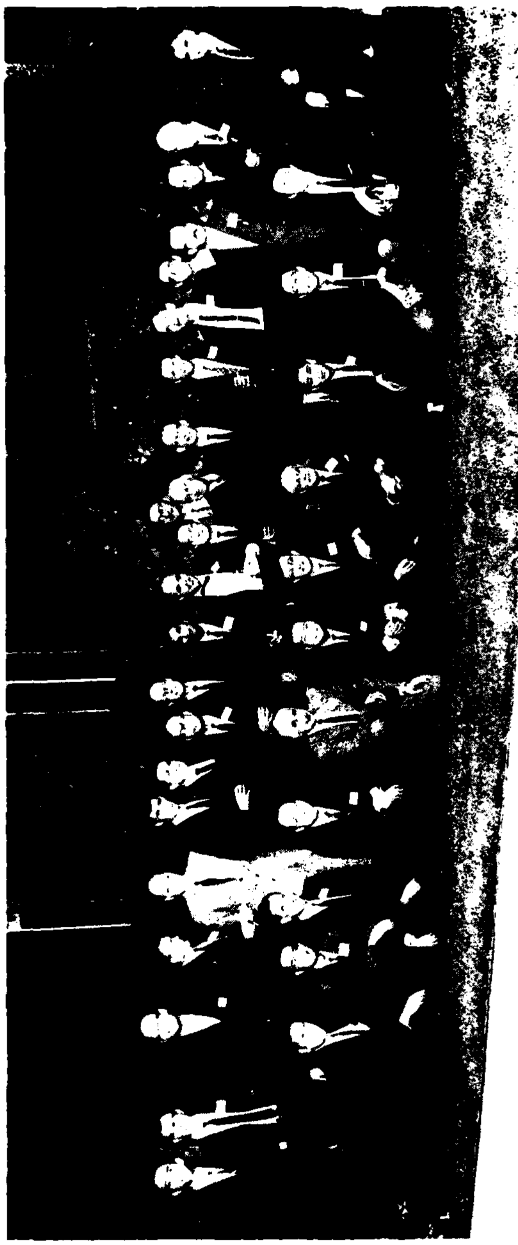
The current JSEP program is divided into efforts on quantum electronics, electromagnetics, solid-state electronics, and information systems. Counting students and faculty, some 30 individuals are engaged in a large number of exciting basic studies, which have the potential of continuing the important JSEP contributions to the nation's electronics capability.

The uniqueness of the JSEP program at Berkeley comes from the breadth of the high calibre of the investigators involved in the program and the excellent facilities for carrying out research in the subject areas. The recently completed microelectronics facility at Berkeley provides state-of-the-art integrated circuit fabrication capability with lithography capable of defining submicron structures. All major capabilities required for microfabrication are present, including lithography, ion implantation, plasma etching, oxidation and diffusion, and packaging. This facility, together with other large pieces of experimental equipment, such as the molecular beam epitaxy (MBE) facility and the electron beam lithographic facility in the electronic research laboratory, provides the JSEP investigators in quantum electronics and solid-state electronics an overall microfabrication capability that is unsurpassed in any university in the world.

A second unique aspect is the computing environment. The JSEP investigators are located in Cory Hall and can utilize the Cory Hall network to access any one of approximately 50 minicomputers in the building, as well as other machines across the campus, including the campus mainframe computers. The same network can be used to access supercomputer facilities off campus. Thus the computing environment is extremely rich.

In summary, the JSEP program has provided the means to initiate a number of exciting and productive research programs at U.C. Berkeley. Significant accomplishments have been achieved in a wide range of fields including systems circuits devices and quantum

electronics. We can look forward to JSEP continuing to foster innovative and important research in the future.



A government-university group at the Electronics Research Laboratory, University of California, Berkeley, on the occasion of a JSEP meeting.

Columbia University

G. W. Flynn and R. M. Osgood, JSEP Directors

I. Early History of the Columbia Radiation

The Columbia Radiation Laboratory was organized under the directorship of Professor I. I. Rabi, who was assisted by associate director Dr. J. M. B. Kellogg, during the war years, 1942-46. Professor D. P. Mitchell, who assumed the directorship from 1946-50, was succeeded by Professor C. H. Townes, 1950-52; Professor P. Kusch, 1952-60; Professor R. Novick, 1960-68; Professor S. R. Hartmann, 1968-76; Professor W. Happer, 1971-79; Professor G. W. Flynn, 1979-present; Professor R. M. Osgood, 1984-present. Professors Hartmann and Happer served as Co-Directors during 1971-76, as do Professors Flynn and Osgood at the present.

The initial work of the Columbia Radiation Laboratory was done during World War II. The Laboratory was established on March 1, 1942 under the Office of Scientific Research and Development Contract OEMsr-485. It operated under the direction of Division 14 of the National Defense Research Committee, with a program designed to meet the immediate objectives of military planning. The primary assignment was to develop microwave components functioning at a frequency range far above that available in hitherto developed devices.

There were several factors that contributed to the desirability of establishing a Radiation Laboratory at Columbia University. The location was central with respect to the radar industry; a well-equipped laboratory and untapped sources of suitable personnel were available. It was believed that some National Defense

Research Committee (NDRC) work should be conducted in a location removed from the immediate service pressure on the Radiation Laboratory at the Massachusetts Institute of Technology.

The specific original assignment given the Laboratory was the development of a pulsed transmitting tube designed to operate in the wavelength region of 1 cm. This was an essential step in meeting an urgent need to extend the operation of radar systems to shorter wavelengths. The practical advantages sought were higher resolution for the user and greater difficulty in jamming for the enemy.

In June 1943, the Laboratory received a second general assignment to produce a tunable pulsed transmitting microwave tube operating in the 3-cm range. The purpose of the tube was to prevent jamming by multiple friendly radar systems operating in the same band and in the same spatial neighborhood. The assignment led to the invention and development of the "crown-of-thorns" tuning mechanism. The magnetron incorporating this principle was so successful that it served as a prototype for tunable magnetrons at other frequency ranges.

A problem arose in the summer of 1944 when tests made by the Radiation Laboratory indicated that the performance of experimental airborne K-band radar systems was not up to expectations. It was known that a water-vapor absorption line was located in the general vicinity of the wavelength used (1.25 cm) and some experimental evidence indicated that the water-vapor content of the air might be limiting the useful range of these systems. The Columbia Radiation Laboratory was instructed to devise and perform an experiment that would locate and map out this water-vapor absorption line. The ensuing investigation revealed that water vapor does indeed have an absorption line reaching its maximum at 1.3 cm. The experimental techniques developed were the beginning of important later work in microwave spectroscopy.

II. Scientific Avenues of Research in the Columbia Radiation Laboratory

The initial CRL scientific program was mandated by the need for microwave tube development during the World War II (1942). This particular aspect of CRL work actually continued into the late 1950s. These initial activities were followed about two years later by the first microwave spectroscopic studies designed to determine the importance of absorption by water vapor at 1.25 cm, the wavelength of operation for K-band radar being developed for the war effort at the time. This was in some sense a most important shift in CRL scientific activity since spectroscopic studies and techniques have occupied a central position in CRL efforts for more than 40 years. Following World War II, major efforts were mounted to determine and understand the microwave spectrum of molecules and the exact nature of the hydrogen atom spectrum. The hydrogen atom work eventually led to a Nobel Prize for Professor W. E. Lamb in 1955 for determining the "Lamb" shift in the hydrogen spectrum. The microwave work led to the development of the MASER concept by Professor C. H. Townes in 1951, its first successful operation in 1954 (ammonia maser), and the award of a Nobel Prize to Townes in 1964. At about the same time as these spectroscopic techniques were being developed, the molecular beam laboratory became part of CRL and both microwave spectroscopy and maser spectroscopy were coupled to the molecular-beam technology. Professor P. Kusch received the Nobel Prize in 1955 for his work in determination of the anomalous magnetic movement of electrons.

After the development of the maser at Columbia, attention turned to the extension of the maser concept to short wavelength devices (visible and IR) culminating in a seminal paper by Townes and Schawlow in 1958 describing the possible use of Fabry Perot resonators for optical masers, the first report in 1960 of optical maser action in Ruby by Maiman and, a few months later, in helium-neon gas mixtures by Javan, Bennett, and Herriott. Although these last developments did not occur at Columbia, they were heavily influenced by the CRL "alumni," Townes, Schawlow, Javan, and Bennett.

In the late 1950s and early 1960s, the spectroscopic techniques developed at CRL were turned to the study of astrophysics, eventually leading to the establishment of the Columbia Astrophysics Laboratory under the direction of Professor R. Novick. The major activities of the Laboratory from about the mid-1950s through the late 1970s, however, involved a literal explosion in studies and development of infrared, visible, and ultraviolet lasers. Thus began activities to study atomic and molecular collisions, relaxation rates, and electromagnetic propagation phenomena. The intent was to develop more powerful, efficient, and useful laser devices and to apply these devices to the study of fundamental physical processes in nature. Thus a concept born out of fundamental ideas in physics (maser) led eventually to the establishment of the field of quantum electronics. In the mid-1960s, the first photon echoes were observed at CRL, beginning an era of activities in the field of superradiance and continuing the long-standing CRL interest in electromagnetic wave propagation phenomena.

In the mid-1970s, a critical decision was made by Co-Directors Hartmann and Happer to expand CRL's scientific activities into the Departments of Chemistry and Electrical Engineering. This led eventually to the present organization of CRL as an integrated, interdisciplinary laboratory with a broad range of activities in solid state and microelectronics, signal processing, picosecond phenomena, photochemistry and surface photoetching, and surface and solid-state physics.

In following the scientific program of CRL and its beginning in 1942, the changes that have occurred can be seen to be the result of the programmatic needs of the DOD and the natural force and excitement generated by new scientific ideas. Vitality and excellence have been maintained by a continual but rarely abrupt change in senior scientific personnel and by sound long-range financial support from DOD.

As the JSEP program has evolved, its concerns have mirrored general research interests of the DOD. Thus, at the outset, the Columbia Radiation Laboratory was concerned with microwave tube developments and atmospheric transmission of microwaves. These interests evolved into a major effort in quantum electronics as the DOD became interested in laser development and eventually focused on solid-state and microelectronics.

III. Results of JSEP-Supported Research

The major accomplishments of the Columbia JSEP have been in the development of new microwave tubes and the maser. New fundamental ideas were developed in spectroscopy, masers, photon echos, energy transfer, collision phenomena, and photochemical etching. Six Nobel Prizes were conferred upon scientists who participated in the Columbia Radiation Laboratory program: Professor I. I. Rabi, 1944; Professor P. Kusch, 1955; Professor W. E. Lamb, Jr., 1955; Professor C. H. Townes, 1964; Dr. A. A. Penzias, 1978; and Professor A. L. Schawlow, 1981. A truly amazing number of present day U.S. scientific leaders and administrators were educated under the Columbia JSEP. Many of these scientists are or have been directors of major national laboratories (e.g., the Naval Research Laboratory and Scripps Oceanographic

Institute), scientific leaders at major industrial laboratories (e.g., Bell Telephone Laboratories and IBM Watson Laboratories), and professors at major research universities.

The results of Columbia JSEP activities at CRL literally permeate the scientific and engineering communities in the United States and for that matter, the entire industrialized world. The entire field of quantum electronics can be directly traced to the work of Townes and his colleagues at Columbia in the early 1950s. In addition, CRL and its alumni became major players in the development of lasers and quantum electronics during the 1960s (Javan, Bennett, Hartmann, Giordmaine, Zeiger, Gordon, etc.). Today the impact of CRL's work by Osgood in photochemical laser etching is already being felt in device development for the DOD and in the microelectronics industry. It is perhaps worth noting that the present CRL co-directors were both trained in quantum electronics by a former CRL graduate, Ali Javan (Flynn as a post-doctoral fellow at MIT in the mid-1960s and Osgood as a student in the early 1970s)!

In many cases the scientific discoveries made at CRL have been so singular that news of their verification has propagated rapidly throughout the world's scientific community. Nevertheless, the major and almost universal method of communicating results has been through published papers in refereed scientific journals. In addition, preprints and reports are sent regularly to DOD sponsors, other JSEP laboratories, and frequently to interested scientists throughout the world.

The JSEP program at Columbia has created a justifiably proud record of accomplishments that strengthen research in the University by drawing senior scholars, post-doctoral fellows, and students to the University. In addition, long-range, flexible funding provides an atmosphere in which new concepts and ideas can be quickly tested and pursued. The present day JSEP/CRL activities are remarkable for their interdisciplinary nature, drawing together in a single program chemists, physicists, applied physicists, and electrical engineers. Such interdisciplinary programs are relatively rare in universities, which normally have a very tight departmental structure. CRL actually manages to transcend this structure and act as an umbrella for faculty members in several departments.

IV. Current Joint Services Electronics Program at Columbia

The current JSEP activities at CRL support modern electronics research through three broad areas of activity: (1) solid-state electronics and opto-electronics; (2) quantum detection, generation, and control of optical radiation; and (3) energy transfer and chemical dynamics as related to quantum electronics and microelectronics. The program thus integrates extraordinarily well activities in solid-state and quantum electronics with fundamental investigations of physical and chemical phenomena in both chemistry and physics. Quantum electronic devices are being used to develop better microelectronic etching techniques to study solid-state electronic materials, to investigate collisional energy transfer processes of importance in quantum electronics, to study fundamental photochemical events, which impact on laser photoetching techniques, and to develop better methods for control and generation of short- and long-wavelength radiation.

We expect the major contributions of the present JSEP to be recognized 20 years from now as having been in the development of new ideas and fundamental concepts. This is completely in keeping with the historical picture of the development of the maser under JSEP at CRL. Some 20 years ago Professor Townes told one of the present co-directors that his suggestion to build a maser device was not greeted with great enthusiasm in 1951. Yet today the development of the maser is clearly recognized as the intellectual precursor or "sine qua non" of the quantum electronics field. Indeed, so closely are the maser and laser concepts connected that almost everyone working in the laser development field referred to laser devices as optical masers into the late 1960s! Perhaps no less important than the development of ideas and concepts, however, is the education and nurturing of young scientific minds. As noted above, the past record of achievement by CRL "alumni" is stunning. We expect the future to produce equally productive and exciting scientists. To borrow the essence of an old phrase, "People and ideas are our most important product!"

V. The Future of JSEP

The JSEP program at Columbia has recently emphasized the basic and applied interactions of laser light with matter. The current evolutionary trend is to explore the interaction of laser light and solids and solid surfaces. About one-half of the the program is devoted to understanding the fundamental chemistry and physics of solid-surface interactions while the other half is concerned with the statistical properties of solid detectors or sources and transient optical phenomena in solids. The applications of this work point to new processing technology and devices for microelectronics.

The Columbia Radiation Laboratory maintains extensive interactions with neighboring industrial facilities at Phillips, Bell Telephone, IBM, ITT, and other laboratories. Through these contacts, the most pressing needs of the electronics industry can be seen to be high-speed (optical) technology, new processing techniques for high-density ICs, and new approaches to device structures. Repeatedly our industrial contacts insist that the role of the university is to generate new ideas and to investigate effectively the basic science inherent in devices and device processing. The Columbia program addresses these concerns by having an integrated research effort, which spans a range of activities from basic surface physics to the development of new types of optoelectronic devices.

The Columbia Radiation Laboratory has sought continually to bring into its program new areas of emphasis in electronics. For example, we have recently added Professor Osgood's effort in photon processing technology and Professor Fossum's effort in GaAS Charge-Coupled-Devices (CCDs). In addition, the research efforts of the older members of the CRL/JSEP are continually evolving. For example, Professors Flynn and Eisenthal have recently turned their efforts toward the study of surface chemical phenomena, and Professor Yang has redirected his research toward investigations of epitaxial interfaces.

The Joint Services Electronics Program at Columbia has had a truly marvelous record of both achievement and long-range support of scientific research. Thus it was one of the first umbrella research contracts and even one of the first programs to support research and development in the United States, actually predating the establishment of the National Science Foundation. We expect the program to develop even more of an interdisciplinary character than it now has, because the problems in modern quantum and solid-state electronics span such a wide variety of disciplines. Furthermore, to be certain that future developments in electronics are made and exploited, the program must keep its emphasis on the fundamental aspects of both electronic phenomena and the physics and chemistry that underlie electronic processes. Only in this way can we hope to discover concepts of impact equal to that of the maser.

Whatever the future of the world, electronics is sure to play a major role for the DOD since future defense activities will depend heavily on electronic and/or quantum electronic devices. The dramatic emergence of computers in almost everyday life, the concomitant injection of these and laser devices into the industrial arena by Japan, the United States, and other countries, makes the future industrial need for electronic development clear.

In a healthy intellectual environment, such as that at CRL, scientific programs will always remain responsive, current, and at the forefront of research activities provided (1) sufficient numbers of senior investigators (recognized world leaders) are involved, forming a critical nucleus; (2) new junior and senior scientists can be brought into the program every few years in response to the inevitable changes in any scientific area; (3) funding is maintained at a sufficiently high (critical) level to induce participation by the best people; (4) research support is kept flexible both with regard to areas of investigation and long-range commitment.

Three men who have directed Columbia's Radiation Laboratory (left to right): I.I. Rabi, Polykarp Kusch, and Robert Novick.

Cornell University

L. Eastman, JSEP Director

The Joint Services Electronics Program at Cornell was established in 1977, in the area of compound semiconductor materials, electronic and opto-electronic devices, and circuits. It was coordinated with other DOD and industrial support in that area and was the core support of a large effort. The main thrust of the program is directed toward device research and engineering. In the early years it emphasized the growth, by liquid-phase epitaxy (LPE), of very high purity GaAs, AlGaAs, InP, and GaInAs. The first reproducible rectification of the AlGaAs/GaAs "n-type" heterojunction was obtained. Two prizes were won for the best student papers in the Journal of Electronic Material, on current-controlled LPE growth of GaAs and on high-purity InP. The more advanced crystal growth techniques of molecular beam epitaxy (MBE) and later metalorganic vapor phase epitaxy (MOCVD) were then initiated. Many new structures were made by MBE. Two other Cornell students in the MBE portion of the program won prizes for the best paper in the Journal of Electronic Materials on optimized single GaAs quantum wells and for the best paper at the Electronic Materials Conference. In a cooperative effort with Hughes, electron-beam lithography and self-aligned ion implanted contacts were used to make the world's fastest metal-semiconductor FET (15 psec).

Recently, a new, high-purity semiconductor barrier for electrons in GaAs as been pioneered, using InGaP. It is expected to be free of the electron traps present in doped AlGaAs. Abrupt interface growth of OMVPE has been studied using transmission electron microscopy and Raman scattering of light. Superlattices with about 8 angstroms period have been made and are under study. State-of-the-art graded index, separate confinement heterojunction lasers have been made by MOCVD, as well as MBE. A new optical detector with fast response times (<100 psec), known as the OPFET, with gain as high as 14 was invented. It has promising applications for optical communications systems. The OPFET has been integrated with MESFETs to create integrated optical receivers.

There have been about 50 advanced degrees on this JSEP program so far and about twice that many on about 15 post doctoral studies and closely related other programs.

Georgia Institute of Technology

D. T. Paris and R. W. Schafer, JSEP Co-Directors

Georgia Tech is a relative newcomer to JSEP. In 1976, the U.S. Army Research Office (ARO) made four grants to Georgia Tech to support research in two-dimensional digital signal processing, multi-dimensional system theory, hybrid optical/digital signal processing, and holographic information storage. On January 15, 1978, these four grants, together with a new work unit on parallel computational architectures, were folded into a single, block-funded program. Besides more efficient funding administration, this consolidation created a cohesive program of research in signal processing and information storage. The principal investigators in the initial program were Professors T. P. Barnwell III, A. M. Bush, T. K. Gaylord, E. W. Kamen, R. M. Mersereau, W. T. Rhodes, and R. W. Schafer, all members of the Faculty of the School of Electrical Engineering. Early in 1979, the JSEP Technical Coordinating Committee (TCC) accepted Georgia Tech into JSEP as an Associate Member. On January 15, 1980 Georgia Tech became a full member of JSEP, and at this same time the scope of the program was broadened by the addition of two new work units on electromagnetic measurements under the direction of Professors E. B. Joy and G. S. Smith. The first full three-year program went into effect in April 1981, and this was followed by a second full three-year phase of participation in JSEP in April 1984. From its beginning, the Co-Laboratory Directors of the Georgia Tech program have been Professors D. T. Paris and R. W. Schafer.

This research program has already produced many significant results. A notable example is the rigorous coupled-wave theory of grating diffraction developed by T. K. Gaylord and his associates. For the first time, this new and powerful theory allows the diffraction by both dielectric and metallic gratings to be analyzed simply and without approximations. Although developed in the context of research and holographic information storage and optical computing, the theory has wide ranging implications in such areas as acousto-optic signal processing, integrated optical spectrum analysis, and holographic head-up displays.

Another area where significant results have been obtained is in parallel digital processing. T. P. Barnwell III and his students have developed a new conceptual framework and formalism for the description and manipulation of synchronous multiprocessor implementations of highly structured algorithms such as those that are common in digital-signal processing. This research has shown how to define useful optimality criteria and has discovered procedures for automatically determining optimal multiprocessor implementations of a large class of algorithms. Other significant research results have been made in a general theory for representation, processing, and Fourier analysis of nonrectangularly sampled two-dimensional signals; the invention of a new class of imaging systems for predetection image enhancement; a new theoretical and experimental investigation of circular-loop antennas; and an approach to correction for probe-position error in near-field antenna measurements.

Many of the above results, although relatively recent, are already having significant impact in areas of importance to national defense. The research of T. K. Gaylord and W. T. Rhodes in optical signal processing, computing, and information storage has lead to new optical computing projects now being supported under the Strategic Defense Initiative. The theoretical concepts of cyclo-static parallel processing implementations are now being realized in hardware as a "DSP supercomputer" with support from DARPA. A final notable example of technology transfer is E. B. Joy's research on probe-position error correction. This research played a significant role in the alignment of the Navy's Aegis phased-array antenna system.

JSEP support of research at Georgia Tech has had a dramatic and measurable impact. The basic JSEP funding has been the catalyst for the establishment of world-class laboratory facilities and the development of internationally recognized programs in digital signal processing and optical computing. Over half of the principal investigators have become Fellows of their professional societies on the strength of their JSEP-supported research. The existence of strong research programs in turn has made it possible to attract outstanding young people to the faculty of the school. JSEP support has also been a major factor in the dramatic increase in Ph.D. degrees granted by the School of Electrical Engineering in recent years.

The future of the Georgia Tech JSEP program will be determined by past research results and perceptions of future industry and defense needs. Present activities are focussed on the important areas of two-dimensional signal processing, parallel processing, optical computing, and time- and frequency-domain electromagnetic measurements. Future work will continue in all of these areas of communication, automation, and national defense. A recently initiated new project seeks to apply the theoretical results on cyclostatic parallel processing to VLSI implementation of DSP supercomputer algorithms. This project and other new activities in integrated optics are now possible at Georgia Tech through the rapidly emerging capabilities of the Microelectronics Research Center. Research on new algorithms for representation and processing of two-dimensional signals will push forward with awareness of the possibilities and limitations of new approaches to implementation of digital computation. A major thrust of future research in optical computing will be to continue to explore possibilities of ultra-high-speed digital parallel computation using content addressable memories for table look-up implementation of computations. Research will continue on electromagnetic measurements, with more emphasis on high frequencies.

Harvard University

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M. Tinkham, JSEP Director

I. The Early History of JSEP at Harvard

Near the end of World War II after the Officers' Training Course at Harvard had ended, its director, Professor E. L. Chaffee, enlisted members of the former teaching staff in a new organization that for a time had the name Central Communications Research. Scientists from the Radio Research Laboratory at Harvard and the Radiation Laboratory at M.I.T., which were being terminated, also joined the new research staff. This was organized in three groups. The first, under Professor Chaffee, pursued research on microwave and millimeter-wave generators; the second, under Professor H. R. Mimno, worked on wave propagation in the ionosphere and radio aids to navigation; the third, under Professor R. W. King, investigated problems in electromagnetic radiation and antennas. Toward the end of 1945, Professor Chaffee interested Admiral Furer, Head of the U.S. Navy's Office of Research and Invention (changed to the Office of Naval Research in 1946), in supporting and expanding the research effort. This was formalized early in 1946. Before the end of the year, the Signal Corps of the U.S. Army joined the ONR in supporting the work. The U. S. Air Force completed the triad in 1948. Professor Chaffee, who later received the IRE Medal of Honor, continued as director of the Harvard program until his retirement in 1953, when the administration was taken over by a committee chaired by the Dean of Applied Science, J. H. Van Vleck, for a few years, then Harvey Brooks, aided by Assoc. Dean, F. Karl Willenbrock. (This arrangement continued until

Professor Bloembergen became JSEP director in 1966; he was succeeded in 1983 by Professor Tinkham.)

One of the notable members of the early staff was Professor Leon Brillouin, who served on the Harvard Faculty for several years. His famous book, Wave Propagation in Periodic Structures (1946), and his basic paper on the theory of the magnetron, were particularly relevant to the work of the group. Also a member of the group was Dr. David Middleton, who became a pioneer in the development of statistical communication theory, continuing work started with Van Vleck during World War II. In 1949, a junior fellow, Nicholas Bloembergen, joined Chaffee's group to study the interaction of microwaves with magnetic materials.

Professor Mimno's group included a number of former members of the Radiation Laboratory, notably J. A. Pierce who was a major contributor to the development of Loran (1941-1946) and who, during his long career at Harvard with JSEP support, developed Omega (1955-1974). He received the Navy's Conrad Award (1975).

The early staff of Professor King's group included: Dr. D. D. King, who pioneered in work on microwave measurements with JSEP support and who later became President of the Philips Research Labs in New York; Drs. Chen-To Tai and C. H. Papas, who went on to distinguished careers as professors at the University of Michigan and California Institute of Technology, respectively; and Professor Erik Hallen (of the Royal Institute of Technology, Sweden), pioneer in the integral-equation approach to antennas, who was on the staff for one year (1947), supported by JSEP.

II. Evolution of the Harvard JSEP

The activities of H. R. Mimno and J. A. Pierce on radio navigation and ionospheric studies led to the introduction of the Omega navigation system in the mid-1950s and ended with its perfection in the early 1970s.

The program on electromagnetic radiation initiated by Professor R. W. P. King led to a large body of work on antenna configurations of all kinds. Both theoretical and experimental problems are studied in depth. The direction of this program, which continues to be active in attacking problems of current interest, is now in the hands of Professor T. T. Wu, a former Ph.D. student of Professor King.

The most dramatic evolution has occurred in the area of microwave electronics, started by Professor Chaffee. Already in 1946 he was aware that more progress might result from study of the interaction of microwaves with atoms, molecules, and condensed matter than from the study of electron beams in vacuum. When Bloembergen wanted to study basic ferromagnetic resonance phenomena at microwave frequencies in 1949, Chaffee gladly offered him hospitality in the JSEP laboratory. (Bloembergen had been a graduate student with E. M. Purcell and had worked on fundamental studies of nuclear magnetic resonance.) The importance of magnetic resonance phenomena for electronic devices soon became clear. Professor C. L. Hogan joined JSEP and started a research project on ferromagnetic and ferroelectric materials, later taken over and expanded by Professor R. V. Jones. This program contributed a great deal to the development of microwave devices, such as isolators and circulators, now widely used in radar and other microwave installations. At the same time, Bloembergen's group demonstrated the existence of different spin temperatures in a magnetic system, the principle on which he developed the three-level solid-state maser. This invention, for which Bloembergen was awarded the IEEE Medal of Honor in 1983, made possible extremely sensitive microwave receivers, which were used in the early DEW-line of radar defense, as well as in large radio telescopes. Without making any formal proposal for a change because of the freedom provided by JSEP support, Bloembergen then pursued the same type of physics into the optical region, where he opened up the field of nonlinear optics, for which he received the Nobel Prize in 1981.

In parallel with these developments, the effort in solid-state electronics was broadened in 1953 to include work in the burgeoning field of semiconductor physics by W. Paul and in solid-state theory by Harvey Brooks (carried on later by Henry Ehrenreich). Considerably later, in the early 1970s, a new activity in superconducting electronics was added, led by M. Tinkham. At about the same time, P. S. Pershan branched off from Bloembergen's area to initiate work in liquid crystals and x-ray studies of surface features.

The early work on statistical communication theory of Middleton evolved under Professor A. E. Bryson in the later 1950s into the new field of Decision and Control theory, marked by Bryson's famous theory of the "minimum-time-to-climb" aircraft trajectory. Subsequently, Professors Y. C. Ho and R. Brockett joined the effort in this new systems area, contributing to a study of nonlinear problems in controls and estimation, often with reference to aerospace systems.

Thus, of the three initial areas of research, the one of Professor Chaffee spawned many new areas of activity, now carried forward under the headings Solid-State Electronics, Quantum Electronics, and Information Electronics. In addition, the Electromagnetic Theory area continues to be active as our fourth major area of activity.

III. Results of JSEP-Supported Research

A. Research on Radio Aids to Navigation

In the postwar years, research on radio-wave propagation as affected by the ionosphere and on radio aids to navigation were the subject of much JSEP-supported work in the group of Professor H. Mimno and Dr. J. A. Pierce; their radio towers on top of the Cruft Lab were a campus landmark. Their work on ionospheric effects showed that the uncertainties in time referencing for navigational purposes were primarily a function of the height of the reflecting layer, rather than the type of signal. They proposed a low-frequency system called Radux, which was implemented on an experimental basis in the Navy starting in 1950, but never was adopted as an operating system. Rather, based on their experiments on precision frequency comparison of signals from the British Greenwich Observatory with those from the U. S. Naval Observatory, in 1955 they proposed a new system, "Omega," to JSEP for development. This development took almost 20 years to reach full fruition, marked by propagational studies in Navy-supplied antennas from Hawaii to Wales, analytical studies of diurnal and annual variations in transit time of signals, and development of techniques of synchronization of stations, reaching interim operational status in 1966. Subsequent work led to improved ways of eliminating or greatly reducing various sources of error due to transmission "anomalies," such as those caused by the effects of solar activity on the ionosphere.

B. Electromagnetic Phenomena

The continuity of this program of research has been maintained without interruption for 40 years. Its primary aims are to advance the foundations of electromagnetic theory and its manifold applications in communications, telemetry, radar, remote sensing, diagnostics, and hazards, including EMP. Under Professor T. T. Wu, now director of the group since Professor King's retirement in 1972, the electromagnetic group has contributed immeasurably in ideas, mathematical techniques, understanding of physical principles, and insistence on precise experimental verification of any theoretical approximations. With the help of analytical, numerical, and experimental methods, currently relevant and useful problems were solved while building a permanent foundation of knowledge and providing an education for future scientists and engineers so broadly based that they have been able to work in many fields.

Many new subfields of research were introduced in response to requests from one of the services or NASA, including the scattering and diffraction by surfaces of complex shape, the horizontal-wire (Beverage) antenna for application in over-the-horizon radar, the reflection of electromagnetic waves from sound waves, the study of subsurface communication including antennas in material media and wave propagation along boundaries, the properties of antennas in plasmas and magnetic materials with potential applications in the space shuttle, the properties of EMP simulators, and the generation of electromagnetic pulses that travel with minimum loss of energy. Examples of the fruits of this research include a new, general and accurate theory of antenna arrays; new theories for the loop antenna and the electrically long antenna; a new general analytical treatment of the propagation of lateral electromagnetic waves; and the development of a simpler and better EMP simulator.

Direct applications of specific research include a new basis for the accurate design of antennas and arrays, an antenna for the hyperthermia treatment of tumors, antennas for subsurface communications with missile silos, an antenna for over-the-horizon radar, antennas for communicating from below the Arctic ice, the accurate theory and practice for remote sensing to locate underground caverns of oil, and the complete theory of antennas and the fields they generate for communicating with submarines.

The many significant advances in scientific and technical knowledge made by the group are recorded in published papers and technical reports that number in the thousands for the full 40-year period. The principal research up to 1981 is integrated into a definitive form in the following books by members of the staff: Measurements at Centimeter Wavelengths, by D. D. King (1952); Theory of Linear Antennas by R. W. P. King (1956); The Scattering and Diffraction of Waves by R. W. P. King and T. T. Wu (1959); Arrays of Cylindrical Dipoles by R. W. P. King, R. B. Mack, and S. S. Sandler (1968); Antennas and Waves by R. W. P. King and C. W. Harrison, Jr. (1969); Tables of Antenna Characteristics by R. W. P. King (1971); Antennas in Matter by R. W. P. King, G. S. Smith, M. Owens, and T. T. Wu (1981). A new edition of the book Electromagnetic Engineering by R. W. P. King, which was published in 1945 at the beginning of the JSEP program, will appear in 1986 under the title Fundamental Electromagnetic Theory and Applications, by R. W. P. King and S. Prasad. The several new chapters on applications are based on research supported by JSEP. A book on the recent work on lateral electromagnetic waves is in preparation.

C. Magnetic Resonance and Solid-State Masers

While the highlight of the magnetic resonance studies was the development of solid-state masers as extremely low-noise microwave receivers, for which Bloembergen received the IEEE Medal of Honor, numerous other effects of magnetic resonance were also discovered. These include the establishment of indirect nuclear spin exchange interactions in metals and insulators, the anistropy of the "Knight" shift, the relation of NMR with the structure of alloys, cross-relaxation phenomena between spin systems, and the influence of applied electric fields and high pressures on magnetic resonance phenomena. This body of work was recognized by the award of the Buckley Prize of the American Physical Society in 1958. With the advent of lasers in 1960, Professor Bloembergen shifted his attention to optical phenomena. Some of the highlights of this work are summarized below.

D. Establishment of the Fundamentals of Nonlinear Optics (1962)

The basic laws of light propagation of high intensity beams in nonlinear optical media and the laws of nonlinear reflection and refraction at their boundaries were established in JSEP Technical Report 358, March 1962; the basic material was published in the Physical Review later in the same year. The operation of many electro-optical devices, including light modulators, parametric optical oscillators and converters, harmonic generators, and other nonlinear optical devices that later found widespread application, is squarely based on these early developments. Numerous features of the propagation characteristics of high-intensity laser beams were subsequently also verified and studied experimentally in JSEP at Harvard University.

E. Developments in Nonlinear Spectroscopy (1964-present)

The investigation of spectroscopic phenomena, which characteristically occur only at high light intensities, is a new branch of the discipline of optical spectroscopy. Although it is difficult to identify specific military systems that depend on one particular spectroscopic finding, it is nevertheless clear that the aggregate of high-energy laser systems and limitations of the propagation of high-intensity laser beams through the atmosphere requires a knowledge of basic nonlinear spectroscopic phenomena. The

Harvard JSEP has made many significant contributions to this field, including the following:

a. Quantitative understanding of the simulated Raman effect, including the anomalies caused by self-focusing (1964) and transient Raman-pulse propagation (1969).
b. First experimental demonstration of stimulated concentration scattering (1969).
c. First experimental demonstration (simultaneously with a French group) of Doppler-free, high-resolution, two-photon absorption spectroscopy.
d. Determination of the frequency dependence of the elements of the third-order nonlinear susceptibility tensor, including the interference effects between the nonresonant part and the two-photon and Raman-type resonances (1971-1976).
e. Theory (1969) and experimental demonstration (1976) of nonlinear conical refraction.
f. First theoretical and experimental investigation of the phenomenon of collision-induced coherence (1981).
g. The study of ultrafast phase transitions by picosecond irradiation of semiconductors and metals (1980-present).

F. Laser-Induced Breakdown in Transparent Optical Materials (1971-1976)

High-energy laser systems are limited by the damage of optical components, including mirrors, lenses, windows, coatings, etc. Even when the materials are chemically and physically pure and all absorbing inclusions and submicroscopic dust particles have been eliminated, a fundamental breakdown threshold remains, characteristic for each material. This breakdown mechanism was identified in 1971 by E. Yablonivitch, working in the Harvard JSEP, with additional support from ARPA, as avalanche ionization. The breakdown threshold at 10.6μm and 1μm infrared radiation is essentially the same as the dc breakdown threshold. The dependence of the threshhld has subsequently been measured in relevant optical materials in the visible and ultraviolet regions of the spectrum. This work was summarized in a review article in IEEE Journal of Quantum Electronics (1974).

G. Ultrashort CO_2 Laser Pulses by Plasma-Breakdown Switching (1975-1976)

The pulses from conventional TEA CO_2 lasers have a duration of about 100 nanoseconds. It has been possible to produce cut-off of the pulse in a few picoseconds by creating a plasma in a pure gas, such as hydrogen, helium, or nitrogen, of sufficient density in the focal area. After the focus the beam passes through an absorption cell with hot CO_2 gas of moderately high density. The free induction signal following the cut-off of the incident pulse by the plasma switch has a pulsed character with a measured duration between 30-50 picoseconds. These short pulses are useful not only in plasma diagnostics, but also in the study of molecular dissociation by CO_2 laser pulses. This work has an impact not only on laser-induced isotope separation, but also on the development of laser photochemistry in general.

H. Coherent Optical Interactions (1981-present)

Professor Mossberg has shown that laser pulse shapes can be stored in inhomogeneously broadened absorbing materials. The pulse shape, which may represent a large amount of digitally encoded information, is stored in the frequency spectrum of the absorber at a single spatial location. Indications are that extremely high storage density, high-speed optical memories may someday be constructed using this principle. It has also been shown that an inhomogeneously broadened absorber illuminated by two optical signals emits a coherent output signal representative of the cross-correlation or convolution of the input optical waveforms. This result may be useful in optical processing schemes.

I. Infrared Multiphoton Excitation of Polyatomic Molecules (1984)

A central question in this field is how, under collisionless conditions, the absorbed infrared energy is distributed over the different vibrational degrees of freedom. Professor E. Mazur has built an apparatus in which scattered light has been reduced so much as to permit measurement of spontaneous Raman scattering in gases at very low densities (below 1 torr). By performing time-resolved Raman scattering of infrared multiphoton-excited molecules in this apparatus, he has been able to directly monitor the collisionless redistribution of vibrational energy among the various modes and to present the first quantitative results on this issue.

J. Determination of Semiconductor Band Structures by Pressure Studies

By making all manner of measurements, in many cases for the first time, of the pressure dependence to resistivity, magnetoresistivity, Hall effect, Haynes-Shockley drift mobility, optical absorption, optical reflectivity, Faraday rotation, photoluminescence, etc., Professor Paul and his group were able to clarify the properties of semiconductors at atmospheric pressure. A key example (1963) was the use of measurements of conductivity and Hall effect versus P and T to establish the band structure of grey tin. This has a degeneracy at the zone center which serves as both top of the valence band and bottom of the conduction band. This serves as the prototype band structure for HgTe, HeSe, etc., and therefore gives the basis for the band-gap tunable $Hg_{1-x}Cd_xTe$ alloys, which are of great importance to the Services.

K. Hydrogenated Amorphous Semiconductors (1970-present)

Professor Paul's group introduced the notion of adding hydrogen to passify defects in amorphous (and also crystalline) semiconductors, especially silicon. A whole new discipline of research has developed from this pragmatically motivated seminal idea. A characteristic feature of their research has been guiding the community to recognize the importance of measuring as many properties as possible on codeposited films, rather than assuming that nominally similar films prepared in different laboratories are indeed the same.

L. Microwave Ferrite Research (1954-1970)

This program, supported by JSEP and the USAF, started when Professor C. L. Hogan came to Harvard in the early 1950s after playing a key role in the development of the microwave gyrator and related devices at Bell Telephone Laboratories. Initially, this program continued Hogan's work on ferrite devices with a special emphasis on the understanding and improvement of ferrite materials. In 1958, Professor R. V. Jones assumed direction of the "ferrite" research. The discovery in 1956 at Grenoble of the rare earth-iron garnets marks a crucial event in the evolving understanding of magnetism since they provided, for the first time, a medium for the systematic study and correlation of a host of magnetic properties. Primarily as a result of a strong materials capability, the Harvard ferrite group was able to capitalize on this opportunity and played a leading role over some 14 years in garnet research. Although the work emphasized the dynamic magnetic properties of significance in device applications (e.g., magnetic switching, frequency-dependent magnetic susceptibilities, spin-wave dynamics, magneto-acoustical interactions, etc.), there also was corollary work in static magnetic properties, low temperature specific heats, neutron diffraction, nuclear and paramagnetic resonance, magneto-optics, and materials development. Over the 16 years of JSEP support, the ferrite group provided the research environment for 31 Ph.D. graduates and seven post-doctoral fellows.

M. Optical Properties of Liquid Crystals (1971-present)

Light scattering studies of nematic and smectic liquid crystals by Pershan and Clark have led to a basic understanding of the hydrodynamics and the mechanism for phase transitions in liquid crystals. The existence of a new ferro-electric phase was predicted and discovered at Harvard by R. G. Meyer in 1974. Through his work, electro-optic properties of a variety of liquid crystal materials are better known and understood. Some of the newly discovered materials and phases have the potential to improve liquid crystal displays.

N. X-Ray Reflectivity Measurement of the Structure of the Surface of Water (1984)

Professor Pershan and collaborators have recently made the first measurement of the x-ray reflectivity of the surface of water using the synchrontron radiation facility in Hamburg, W. Germany. The angular dependence of the x-ray reflectivity from a surface is theoretically expected to follow a law depending on the wavelength, the dielectric constant of the material, and the mean square surface roughness σ^2. A simple model attributing the surface roughness of a liquid to thermally excited capillary waves predicts σ^2 as a function of the surface tension, the spectrometer resolution, and the molecular dimensions. The data agree with the expected functional form and yield a value for σ of 2.8A, while this model predicts 3.2A. The predicted proportionality to $1/\gamma$ is confirmed by our recent measurements on CCl_4. Although there has been considerable theoretical research into the surface roughness of simple liquids, this is the first measurement on the molecular length scale.

O. Superconductive SQUID Devices (1970-1975)

Professors Tinkham and Beasley participated in the development of useful magnetometers and voltmeters using feedback to linearize the ultrasensitive but extremely nonlinear SQUID (Superconducting Quantum Interference Device) sensor. SQUID magnetometers are now commercially available and form the basis for advanced submarine detection systems as well as possible ELF communication systems. SQUID voltmeters as first developed had sensitivities of 10^{-15} volts with a response time of 1 second. Subsequent development in the use of feedback demonstrated their operation as extremely low noise amplifiers with bandwidths extending into the kHz range, which are superior in performance to the best room temperature amplifiers for source impedances below about 30 ohms. Our analysis of the noise-bandwidth tradeoffs in these devices has brought out the complete duality between electronic systems based on low-impedance superconductive devices that sense magnetic fields and high-impedance FET devices that sense electric fields.

P. Josephson Devices for Submillimeter Waves (1975-present)

As shown by Octavio, Skopol, and Tinkham in 1976, metallic superconducting weak links have inescapable problems for submillimeter wave detector applications because of electronic heating effects. Tunnel junctions minimize this problem, but control of capacitative shunting requires junctions of microns or smaller size. Point contacts achieve this, but are unstable in practice. Harvard JSEP work by Danchi, et al. (1982) has been the most comprehensive in the world in testing and theoretically interpreting results obtained with micron-size fabricated tunnel junctions at up to 600 GHz frequencies. This work shows that sensitivities approaching the quantum limit should be attainable, while demonstrating that electronic shot noise is the dominant noise source when operating at the several millivolt level associated with these high frequencies. Very recent (1984) experiments have demonstrated that "chaotic" responses can result and give intolerable noise levels if system parameters are chosen unwisely.

Q. Optimization of Trajectories (1963)

The method of steepest descent was generalized by A. E. Bryson, Jr., to problems of the calculus of variations and provided a successive approximation algorithm to compute optimal trajectories for general dynamic systems. This method was applied to the "minimum time to climb" for a Navy aircraft, and the actual flight data completely confirmed the theoretical prediction, which was contrary to simple intuition. This work gave major impetus to the modern theory of control and its aerospace applications.

R. Differential Games and Many-Person Decision Theory (1965)

A natural extension of modern control theory involves optimization problems with more than one controller. In a seminal paper in 1965 Y. C. Ho showed that the well-known proportional navigation law in fact constituted a solution to a differential game of pursuit and evasion. On one hand, this led to an entire branch of mathematical endeavor on differential games as two-sided calculus of variations. On the other hand, it inspired more general conceptual formulations of dynamic optimization and decision problems such as dynamic team theory, information structure theory, etc., which are still alive today.

S. Discrete Event Dynamic System (1982)

This topic of research started as the ad hoc situation of a long-standing problem in production lines. Gradually, it was realized that it has considerable generality as an analysis and optimization technique for a general class of dynamic systems, such as manufacturing cells and computer/communication networks. The breakthrough came in 1981-1982 when this technique, called perturbation analysis, was generalized to arbitrary queueing networks. Since then the subject has evolved to a minidiscipline with many workers outside Harvard.

T. Geometric Methods in System Theory (1970-80)

In a systematic attack on nonlinear control problems, Professor Brockett and his group identified a classification system and a rich body of methods based on differential geometric techniques which extend our ability to analyze and design systems. Two specific central ideas, which were developed at Harvard, are feedback linearization of nonlinear systems and the Volterra series algorithms/convergence proof. As recently as last year, NASA was flight testing a helicopter control system whose design was based on principles coming out of this work. In the area of nonlinear filtering/estimation, research prior to 1978 was largely devoted to numerical solution of the conditional density equation and ad hoc linearization schemes. Over the next two years, the subject changed greatly under the impact of the introduction by Brockett and Clark of the geometric Lie algebraic method of understanding the sufficient statistics problem, as was shown by many papers at the NATO Study Institute on "Stochastic Systems" in 1980.

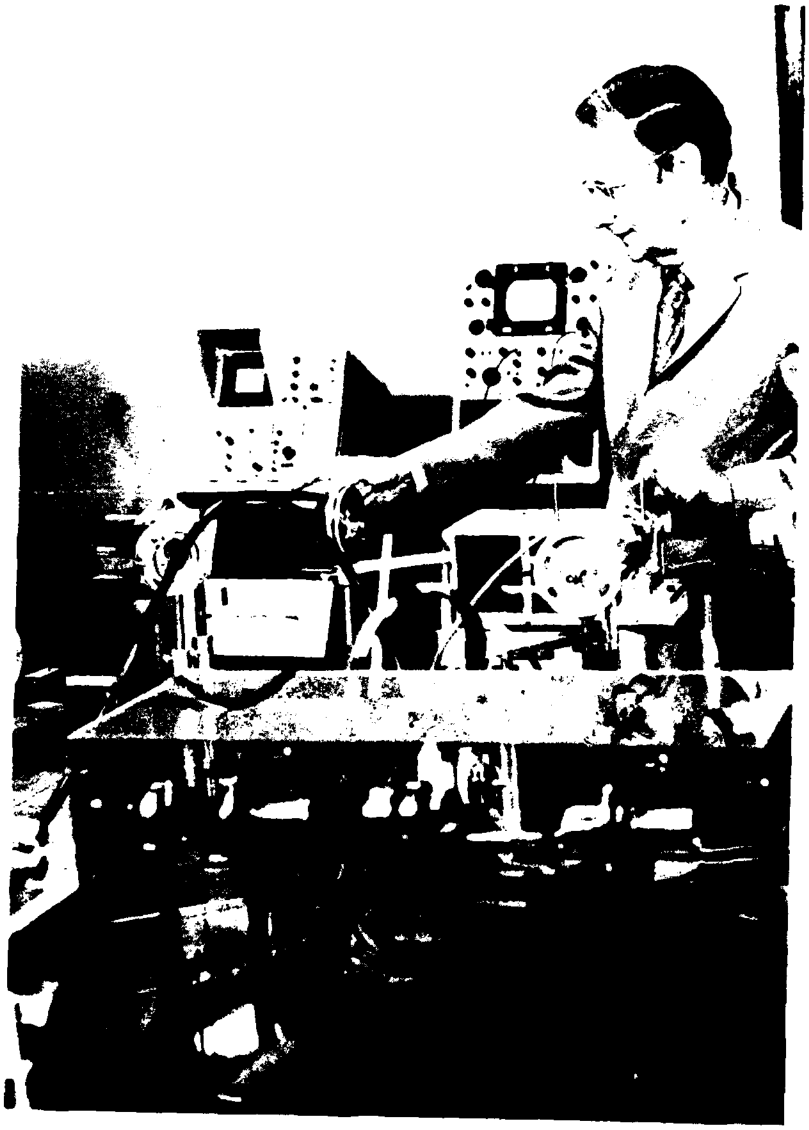
U. Major Honors of Staff and Alumni of Harvard JSEP

Those elected to the National Academy of Sciences include: Benedek, Bloembergen, Brooks, Bryson, Redfield, Sorokin, and Tinkham. Those elected to the National Academy of Engineering include: Bloembergen, Bryson, Granger, Hogan, Kaminow, and Willenbrock. The IRE/IEEE Medal of Honor was awarded to Chaffee (1958) and to Bloembergen (1983); the IRE Liebmann Prize to Pierce (1953) and to Bloembergen (1959), the latter shared with C. H. Townes of the Columbia University JSEP. The Buckley Prize of the A.P.S. was awarded to Bloembergen (1958) and to Tinkham (1974). A Presidential Certificate of Merit was awarded to Pierce (1948), and Bloembergen received the National Medal of Science from the President of the U.S. (1974). Other major honors of Professor Bloembergen include the Ballantine Medal of the Franklin Institute (1961), the Lorentz Medal of the Royal Dutch Academy of Sciences (1979), the Frederick Ives Medal of the Optical Society of America (1979), and the Nobel Prize for Physics (1981).

IV. Current Status and Future Outlook of the Harvard JSEP

The current activity of the Harvard JSEP is organized in four major areas: Solid-State Electronics, Quantum Electronics, Information Electronics, and Electromagnetic Phenomena. It is anticipated that future work will continue in each of these areas, since all offer opportunities for basic research, which has direct impact on the long-term development of the art of electronics. An important characteristic of the Harvard program is the close coupling of theoretical and experimental work of high quality in each area.

The great advantage of the JSEP support is its stability, combined with flexibility for local management to use funds to help launch new young investigators and new programs, which often become major thrusts in later years. The historical record provides numerous examples of the benefits of this flexibility, epitomized by the constant evolution of Bloembergen's JSEP activity from microwave ferromagnetic resonance to the solid-state maser, and then on to nonlinear optics and quantum electronics.



Dr. Nicholas Bloembergen in his JSEP-sponsored laboratory at the Division of Engineering and Applied Physics, Harvard University.

University of Illinois

T. N. Trick, JSEP Director

I. Early History

A. The Control Systems Laboratory

The Control Systems Laboratory (CSL) was organized early in 1951 under the impetus of urgent military needs brought about by the national involvement in the Korean War. The Laboratory program was formulated in an awareness of the technological potential in the new areas of information theory and automatic computers that, combined with radar developments emerging in 1946 and not exploited since, could be expected to prove revolutionary in impact on the military problems of command and control, including battlefield surveillance.

Led by Professors F. W. Loomis, L. Ridenhour, and F. Seitz, a group of University of Illinois staff members, which included R. I. Hulsizer, P. G. Kruger, A. Longacre, E. M. Lyman, A. Nordsieck, H. Quastler, C. W. Sherman, A. H. Taub, and N. Wax, laid plans for a broad technical program in a number of significant directions during the first year of operation. In the following year, Professor F. W. Loomis returned from his work in organizing Project Lincoln, now Lincoln Laboratory; at the request of Dr. Seitz and the heads of the divisions at CSL, he became Director of the Laboratory, with Professor Seitz as Technical Director.

In the span of six years, the relatively small staff, which was built up at CSL, originated and then demonstrated the technical feasibility of several completely novel ideas, most of which have since formed the nucleus of important military weapons systems. These included: (a) Coherent Doppler Radar,

(b) the Cornfield System--a radar-based, computer-controlled air traffic surveillance and control system, (c) the All-Weather Attack System--an airborne, non-coherent Doppler radar, (d) a man-transportable sentry radar that became designated the AN/TPS-21, (e) the side-looking radar, and (f) the ground observer corps. As early as 1953, the Laboratory was financed under a single contract administered by one of the services but sponsored by all three services in a format similar to that of the Joint Services Electronics Program. This tradition of a single contract for the entire Laboratory was continued at least until 1960.

B. Reorganization: The Coordinated Science Laboratory

In 1959, the University administration in consultation with the Joint Services Committee approved a recommendation of the Laboratory staff to formally reorganize the Laboratory into an interdisciplinary and interdepartmental graduate research center in the College of Engineering and renamed the Coordinated Science Laboratory, with Professor D. Alpert as Director.

The year 1959 thus marked the beginning of a new set of objectives and activities in the Laboratory, both for established and for newly formed groups. A serious effort was undertaken to incorporate graduate research and graduate students into the programs of the Laboratory, and virtually all the senior staff assumed a teaching role in the College of Engineering. Since a majority of the senior staff was associated with the Physics Department or the Electrical Engineering Department (both in the College of Engineering), the Laboratory administration was enlarged to include Associate Directors from each of these areas. The first appointees to these positions were Professor C. W. Sherwin (Physics) and Professor M. E. Van Valkenburg (Electrical Engineering).

II. Scientific Avenues

During the early years of CSL the principal areas of research were the electric vacuum gyroscope, surface and vacuum physics, plasma physics, plasma display device, computers and their application to modern systems problems, and system theory and computer science. As in any active scientific and engineering research enter, rise, there has been an evolutionary change in emphasis over the years. For example, the electric vacuum gyroscope project was terminated after successfully demonstrating how industry could proceed with further development and production for military use. The plasma display device project and the PLATO computer-based instruction projects were shifted to a spin-off laboratory, i.e., the Computer-Based Education Research Laboratory, with Professor D. L. Bitzer as Director. New units on semiconductor research have been added over the years.

Changes in the research emphasis during the last 25 years were largely based on changes in perceived long-range needs of DOD, changes in the active areas of electronics research throughout the country, and changes in the key research faculty affiliated with CSL. These changes positively impacted DOD in the sense that CSL research has remained in the mainstream of electronics research.

During the first few years of operation of CSL, the JSEP contract sponsored essentially the entire laboratory.

III. Results of JSEP-Supported Research

A. Electric Vacuum Gyroscope

The pioneering work at CSL of an experimental model of an electric vacuum gyroscope, conceived by

Professor A. Nordsieck, provided the basis for successful development work at General Electric, Minneapolis-Honeywell, and Autonetics Companies. Precision electrostatic gyro navigation systems are now incorporated in the Trident submarines' navigation system.

B. Plasma Display Panel

This device, invented under the leadership of Professors D. L. Bitzer and H. G. Slottow, is a thin, flat panel that combines properties of display and memory, accepts digital information directly from the computer, and stores it in a form that is accessible to the computer.

The plasma panel is one of the most important electronic display devices and for large displays it is the only viable alternative to the Cathode Ray Tube (CRT). These panels are used around the world in banking terminals, graphics display terminals, and in numerous military applications.

C. Side-Looking, High-Resolution Surveillance Radar

The ability of early combat surveillance radar to resolve objects of military interest was limited by antenna size. Professor C. W. Sherwin conceived of a new idea of producing the equivalent of an extremely long antenna by processing successive returns from a moving radar to synthesize an extremely long antenna and accomplish a very high angular resolution. Based on experimental feasibility demonstrations at CSL, this work eventually led to the Army AN/UPD-1 (XPM-1) combat surveillance radar system. The same concept had been used for side-looking sonar applications.

In 1982 J. D. O'Brien and Professors W. K. Jenkins and D. C. Munson, Jr., discovered a mathematical commonality in image reconstruction in x-ray tomography and spotlight mode synthetic aperture radar. This discovery led to a new mathematical model for SAR that clarified the role of Doppler in SAR and cleared the way for the development of a new class of SAR reconstruction algorithms that appear to be well suited for modern VLSI implementation. This work has been recognized as a basic contribution in the field.

D. Schuemann Suppressor Ionization Gauge

This device for measuring pressure in ultra-high vacuum was invented at CSL. The gauge could measure pressure tens of thousands times lower than could be previously measured. It was patented, and it is now commercially manufactured. It has widespread use in numerous laboratories that are simulating the ultra-high vacuum conditions of outerspace, calibration of gauges to be used aboard satellites and in studies involving ultra-clean surfaces.

E. The PLATO Systems for Computer-Aided Instruction

Programmed Logic for Automatic Teaching Operations, the PLATO system, was conceived by C. W. Sherwin, then demonstrated and developed at CSL under Professor D. L. Bitzer. It can provide simultaneous and personalized instruction to a large audience. The PLATO system supports about 1,100 terminals in its present version, at a capacity of over 1.6 million terminal-hours per year. It has been used in various DOD training and research programs. Material for over 6,000 instructional hours is available. The PLATO system is currently marketed industrially.

F. Multimodeling and Large-Scale Systems

Large systems typically involve decentralized information, decentralized control, and different models of the same system. Professors T. Basar, J. B. Cruz, Jr., P. V. Kokotovic, and W. R. Perkins and their students have developed several new concepts including multimodeling, leader-follower control strategies, incentive controls, robust adaptive control, chained aggregation, and equilibrium theory for stochastic systems with multiple decision makers. Control systems work at CSL is preeminent and widely known.

G. Computational Gas Dynamics

CSL was a center for activity in this area in the early 1960s, due to the efforts of Professors A. Nordsieck and S. M. Yen. The first Boltzmann Conference was held at CSL in the late 1960s.

H. Integration of Stiff Differential Equations

In the early 1960s Professor A. Nordsieck developed powerful methods for integrating stiff differential equations associated with systems containing slow and fast phenomena. Professor N. Wax contributed to this activity, and he also contributed to oscillator theory using singular perturbation methods.

I. Singular Perturbations

In 1968 Professor P. V. Kokotovic introduced singular perturbation methods in control engineering. Among the applications of singular perturbation theory are trajectory optimization, aircraft maneuver optimization, minimum-time turns for the F-106 and F-4E aircraft, electronic network parasitics, jet engine controls, and air combat strategies. Literally every paper on this subject has reference to earlier or current work at CSL.

J. Sensitivity Principles

For the last 20 years Professors J. B. Cruz, Jr., P. V. Kokotovic, and W. R. Perkins and their students have developed various sensitivity principles including comparison sensitivity and sensitivity points useful for sensitivity analysis, optimization, adaptive control, and computer-aided network design.

K. Analysis of Nonlinear Oscillatory Circuits

A new algorithm was proposed in the early 1970s by Professor T. N. Trick for the analysis of nonlinear oscillatory circuits and systems. Professor Trick and his students received several awards based on this key paper. The algorithm has been used in industry for the analysis of oscillators, frequency multipliers, power supply circuits, and other nonlinear oscillatory circuits.

L. Glow Discharge Optical Spectroscopy (GDOS)

In the mid-1970s, Professor J. E. Greene developed GDOS for real-time quantitative elemental microanalysis of metal and semiconductor materials. GDOS has a detection limit of the order of parts per million even for very thin layers. It is now a mature diagnostic technique used routinely in industry as well as in industrial research laboratories.

M. Ion Implantation Doping of Compound Semiconductors

Professor B. G. Streetman developed ion implantation methodology for compound semiconductors during the 1970s and early 1980s. Industrial laboratories now use Streetman's methods for the fabrication of compound semiconductor devices.

N. Atomic Diffusion of Metals

No quantitative information was available about atomic motion on single crystal planes until Professor G. Ehrlich applied the field ion microscope in the early 1970s. The field ion microscope makes it possible to form perfect surfaces. A single atom can then be deposited on a selected crystal plane and its motion can be followed directly.

O. Acoustic Charge Transport

Acoustic Charge Transport (ACT) is a new method to store information in analog form. Professor Hunsinger and Dr. Hoskins developed ACT delay lines using the electric fields produced by surface acoustic waves to transport charge in GaAs. Devices using this technology have low noise, large dynamic ranges, and wide bandwidths. This device promises significant breakthroughs in signal processing applications. RADC and DARPA now fund a substantial ACT development program. In addition, several industrial organizations have followed the lead of the University of Illinois and are presently pursuing the development of this new technology.

P. Combined Detection/Estimation Algorithms

Professor H. V. Poor has developed a number of design techniques that have been applied by the U.S. Army Missile Research and Development Command for design and analysis of robust tracking filters for use in tracking missiles. The application has led to improvement over existing algorithms in the developmental and experimental stages of system deployment for systems such as laser-tracked artillery rockets and other air-defense rockets.

Q. Spread Spectrum Communications

The present comprehensive research program in spread-spectrum communications originated in 1974 with an investigation of the multiple-access capability of direct-sequence (DS) spread spectrum. This research produced methods for signal design and performance analysis that are in widespread use today. CSL faculty identified key sequence correlation parameters and formulated algorithms for the optimization of sequences. The synchronization sequence in the Army's spread-spectrum Single-Channel Ground-Air Radio System (SINCGARS) was designed by CSL researchers using these algorithms.

The work of T. Kasami in coding (Kasami sequence) has made its impact in the area of spread-spectrum communications systems. Work at CSL in special decoding and processing methods has contributed significantly to the Jam-Resistant Digital Voice Modem study (U.S. Air Force RADC) and the SINCGARS Packet Overlay study (U.S. Army CECOM).

R. Automatic Logic Minimization

A design automation technique for minimizing networks of NAND gates was developed during 1966-68 by Professor E. S. Davidson under Professor G. Metze's supervision. It was incorporated with minor modifications by Texas Instruments in their powerful design-automation package for internal and customer use along with layout, routing, and simulation programs.

S. Computer Pipeline Modeling

Research completed by Professor Davidson's group in 1976 on pipelining in computers has led to unified techniques for systematic modeling, performance analysis, design, and control of pipelined processors.

T. Self-Diagnosis Techniques

The problem of diagnosing one part of a system by another received early attention almost twenty years ago by Professors S. Seshu, F. P. Preparata, G. Metze, and R. T. Chien. Extensions of this work have been explored at numerous other universities.

Fault diagnosis on the gate level, using the classical stuckline fault model, suffers primarily from the need to consider large numbers of fault patterns. Methods for reducing the number of faults to be considered were developed by Dr. D. Schertz and Professor Metze and these results led to subsequent work at other universities.

U. Multiprocessor Cache Memories

Research conducted in 1983 by Professor Patel has produced a low-overhead cache coherence solution for multiprocessors organized on a time-shared bus. This solution has influenced the designs of several multi-microprocessor designs and the IEEE P896 Futurebus Standard.

V. Testing of Complex Integrated Circuits

Professor J. A. Abraham has developed innovative techniques for generating tests for large, complex integrated circuits. Extensions of his work have been carried out in this country and abroad, and many of his algorithms have been successfully applied in industry.

W. Semiconductor Physics

Several new semiconductor device concepts have been co-invented under the leadership of Professor K. Hess. Of special significance is the concept of real space transfer (also experimentally demonstrated at CSL) and superlattice avalanche photodiodes. This concept is recognized as a new oscillator and also a new transistor principle. Devices are currently fabricated at Bell Laboratories and exhibit astonishing properties. As negative differential resistance devices, real-space transfer transistors (diodes) have exhibited peak to valley ratios of 300 (a value 150 times larger than in Gunn diodes). Superlattice avalanche photodiodes are currently investigated in many laboratories and show great promise.

For the first time, a complete pseudopotential band structure in simulations of devices and transient (ballistic) electronic transport has been developed. Several theoretical concepts originating in this group, such as doubly stimulated emission (of phonons and photons) in quantum wells, have received widespread attention.

X. Molecular Beam Epitaxy

The Molecular Beam Epitaxy (MBE) program, during its short history, has made substantial contributions to the semiconductor physics and device field. The group, headed by H. Morkoc, has pioneered research into all aspects of the new field effect transistor called the Modulation Doped Field Effect Transistor (MODFET), the fastest three-terminal semiconductor device. Research has been carried out on the material and device characteristic, as well as on the development of new theoretical models. The world's best quantum well structures were also prepared and used to study the details of atom-by-atom growth by MBE. Most recently, FET and bipolar technologies on Si substrates were developed in this laboratory. These are having a great impact in industry.

IV. Current Joint Services Program

The current program at CSL under JSEP support is divided into 10 research areas and a total of 26 research units. The areas are: (a) semiconductor research, (b) surface studies, (c) quantum electronics, (d) electromagnetic communication, radiation, and scattering, (e) decision and control, (f) digital communications, (g) analog and digital circuits, (h) computer architecture and computation, (i) fault-tolerant computing, and (j) digital signal processing.

The present program has a strong emphasis on semiconductor device and materials research, electronic systems, computer systems, and communications and control. These programs have relevance to applications in microelectronics, communications, computers, and systems.

V. Future Thrusts

Our plan for JSEP-supported activities at CSL is to capitalize on areas of electronics where we have strength and that have high potential for pay-off although there is accompanying high risk. Research results at CSL and many different major research centers suggest that technologies based on compound semiconductor materials show great potential for breakthroughs in the performance of high-speed electronics and optoelectronics. Development of these new technologies requires concentrated interdisciplinary research efforts on compound semiconductor materials, synthesis, characterization, device physics, and processing physics, as well as new research directions in computer and system design, and VLSI modeling for compound semiconductor electrical and optical circuits. The JSEP program has been instrumental in bringing together faculty and students from various disciplines to address the fundamental problems in these areas. To facilitate this research effort the University of Illinois has established four new centers: (a) a facility for artificially structured materials, (b) a facility for ultra-high purity semiconductor analysis, (c) a facility for sub-micron fabrication, and (d) a facility for ultra-high speed optical and electrical measurements. In addition to the microelectronics center, the National Center for Supercomputer Applications at the University of Illinois is equipped with a multiprocessor Cray X-MP. This system will be used by JSEP-supported personnel for semiconductor device simulation.

Our second supercomputer center, the Center for Supercomputer Research and Development, is developing hardware and software techniques for high-speed parallel processing. Future JSEP research on reliable computing, parallel and distributed computing, parallel architecture, VLSI circuits, and multisensor array processing will benefit from the expertise available in this supercomputer center.

Stimulated by demands for greater survivability, higher performance, and manufacturability of complex electronic systems, we plan to have several new cross-disciplinary thrusts in computer, communication, and control. The common theme will be networks research. Emphasis will be on: (a) investigation of effective routing and flow control policies and scheduling algorithms for networks, such as those arising in flexible manufacturing systems, communication networks, and computer networks, (b) development of design methodologies for robust stabilizing controllers for large-scale engineering networks, and (c) development of asynchronous learning algorithms for the computation of equilibria in stochastic decision problems with partially unspecified statistics. We will focus on distributed computation and parallel computation networks. For example, for distributed data base implementation we will investigate algorithms for file placement, query processing, concurrency control, deadlock detection, and deadlock recovery.

Trade-offs among communication costs and synchronization costs incurred in accessing shared resources will be examined. We will focus on gaining understanding of the parallelism inherent in combinatorial and numerical problems that arise in applications, considering both shared-memory machines and direct-connection machines. One application area for parallel computation is image analysis for which we will investigate multiprocessor architectures. The two centers in supercomputing mentioned earlier will be of significant assistance in performing some of these large-scale networks research.

Research Laboratory of Electronics, Massachusetts Institute of Technology

J. Allen, JSEP Director

I. Early History

During World War II, the MIT Radiation Laboratory was established to bring together talents in electrical engineering and physics in order to address urgent problems created by the war. A staff of 4,000 people focused on problems of electromagnetic propagation at microwave frequencies, the design and construction of microwave power sources, and a variety of communication techniques. Emphasis was placed on problems associated with high-performance radars, particularly with respect to spatial resolution performance.

As early as the invasion of Normandy in June of 1944, Professor John Slater, head of the MIT Physics Department, had envisioned a new electronics laboratory organized and operated jointly by the departments of Physics and Electrical Engineering. Many discussions followed that involved MIT President Compton, Dean of Science George Harrison, and Professors John Slater, Harold Hazen, and Julius Stratton. At the time, Professor Hazen was Head of the Electrical Engineering Department. Professor Stratton was on leave as expert consultant to the Secretary of War and had come to appreciate the importance of an interdisciplinary laboratory preoccupied with practical and theoretical questions ranging from microwave generation and high-frequency circuit design, to the properties of electron gases and the study of electromagnetic radiation and boundary value problems. Professor Stratton was to be extremely influential in maintaining continuity from the wartime Radiation Laboratory to the new peacetime laboratory.

Following V-J Day, August 14, 1945, the National Defense Research Committee voted to continue basic research under the Radiation Laboratory contract. This proved to be an important transition until the Research Laboratory of Electronics (RLE) was established on January 1, 1946, with JSEP as its main support. By the spring of 1946, 22 MIT faculty members and 16 RLE staff members constituted RLE's senior research personnel. Many activities were already underway, including research on high-power magnetrons, microwave accelerators, gaseous discharges, noise and distortion in modulation schemes, waveguide studies, and circuit synthesis. It is important to realize that, at this early stage in RLE's development, an emerging national policy was beginning to focus massive federal support on basic research, and the National Science Foundation had yet to appear.

The JSEP program at MIT was essential in maintaining the momentum created by the wartime Radiation Laboratory and in providing a focus for many electrical engineering and physics faculty members and their graduate students. Many of these students have emerged as outstanding contributors in their fields. Their early studies included: multi-path radio transmission by Professor Lawrence Arguimbau; waveguides by Professor Lan Chu; pulse-modulation phenomena by Ernest Kretzmer (who went on to a subsequent career at Bell Laboratories); locking phenomena in microwave oscillators by Professors Jerome Wiesner and Edward E. David, Jr. (who went on to become Science Advisors to Presidents Kennedy and Nixon, respectively); the introduction of signal flow graphs into linear system theory by Professor Samuel Mason; and fundamental work on circuit synthesis by Emanuel Cerrillo and Professor Ernest Guillemin, where a thesis on amplifier gain bandwidth products was completed by John Linvill (who later served as Head of Stanford's Electrical and Engineering Department).

RLE's first director was Julius Stratton. In the beginning, RLE brought with it a great sense of intellectual excitement. There was a spirit of open inquiry that led talented investigators into whatever directions seemed natural in order to solve challenging problems of signal source generation, propagation, and communication (viewed both physically and abstractly). In retrospect, it appears that RLE's hallmark, specifically its interdisciplinary nature, gave investigators an implicit license to redefine boundaries imposed by conventional disciplines and to seek out active collaboration with scientists and engineers of all persuasions who could bring insight and ingenuity to the solution of broad problems subsumed by RLE's interests.

In 1948, one year after the invention of the point contact transistor, Norbert Wiener's highly stimulating cybernetics book appeared. His influential book on extrapolation, interpolation, and smoothing of stationary time series (classified in its earlier form during the war), achieved broad circulation in 1949. Claude Shannon's initial papers on communication theory also appeared in 1948. Thus, it was natural for a great amount of interest to be generated in new techniques for amplification and modulation, the introduction of abstract measures for the quantification of information and how noise forced a statistical view of communication. Although RLE's technical interests were wide ranging at that time, perhaps Norbert Wiener was the most dominant personality. In his daily visits through the laboratory, he generated and propagated a great sense of what could be accomplished in the study and characterization of random processes and how they could be utilized in highly effective communication systems. The field of communication was broadly perceived, and phenomena of detection were seen in terms of both physical and human systems, with much interest focused on perceptual mechanisms. Similarly, physical acoustics blended into psycho-acoustics, and physiological studies were initiated to seek explanations for cognitive behavior. The JSEP program facilitated the collaboration of many experts in these various disciplines. It is doubtful that any union of smaller, more tightly focused projects could have achieved the overall interdisciplinary thrust into these priority areas as evidenced within RLE from its inception.

II. The Dynamics of Scientific Investigation Within RLE

Since its beginning forty years ago, the JSEP program within RLE has experienced many changes while following a path of natural evolution. Continuing investigation has led naturally to new areas of research interest, and the evolving technology in instrumentation capability has also opened up new research possibilities on a continuing basis. Occasional spin-offs from the parent body can also be observed resulting from a variety of forces such as the need for classified research programs and the desire to establish highly focused projects not part of RLE's mainline activities. Examples of these phenomena include the formation of Lincoln Laboratory in 1951. Today, Lincoln Laboratory conducts a wide variety of studies (often classified) related to the nation's defense. Another example was the formation of Project MAC in 1963, focused on the investigation and construction of a large, interactive time-shared computer system that heavily emphasized operating system methodology. These spin-offs have sometimes gone through several stages. This is illustrated by artificial intelligence, first practiced by Professors John McCarthy and Marvin Minsky within RLE, then as a part of Project MAC, and finally in its own growing laboratory. Similarly, a new focus on networks developed in the Laboratory for Information and Decision Sciences, which was built by some RLE investigators who had been part of the heavy emphasis on information theory and propagation studies in communication systems. This has been a natural evolution, bearing witness to the inevitable tension that develops when organizations become increasingly diffuse over a wide range of interests. Nevertheless, RLE and the JSEP program have continued to serve as a cohesive force by integrating many divergent interests while focusing on the basic problems in science and engineering related to electronics.

At the outset, in 1946, there were two major JSEP emphases. One was microwave and physical electronics coupled with basic studies of microwave physics. The second emphasis was on communications and related projects. There was also some activity on electronic circuits and on aids to computation to support the work in theoretical design and statistical communication. Over the years, both the microwave and communication emphases have grown in many directions. Since the declassification of basic work on thermonuclear fusion in 1958, which followed the first International Conference on the Peaceful Uses of Atomic Energy, RLE built up a large effort in plasma dynamics.

There was major emphasis, in RLE's early days, on microwave studies focused on the generation of powerful radar transmitter pulses. Professors William Allis, Sanborn Brown, and Malcolm Standberg established RLE as a major research center for gaseous electronics with special emphasis on radio frequency and microwave breakdown and spectroscopy. Over a period of time, however, interest shifted to the study of hot, dense plasmas, which included studies of the radiation from plasmas and the first quantitative measurements of cyclotron emission and bremsstrahlung, under the guidance of Professor George Bekefi. Wave instabilities were studied leading to the first classification of these difficult phenomena. Also arising from this work has been the generation of coherent electromagnetic radiation and the development of novel microwave and millimeter wave devices. This developed in the 1960s and 1970s and culminated in a strong effort to build free-electron lasers.

Professor Bruno Coppi studied the magneto-hydrodynamics of hot fusion plasmas and developed the the high-field tokamak concept that has been realized in several forms. In 1980, the evolution of plasma work resulted in the formation of the Plasma Fusion Center, a large, mission-oriented laboratory. This marked a diminution in plasma activity within JSEP.

Another branch resulting from the initial emphasis in microwaves was the concern with physical electronics and the subsequent interest in atomic and molecular beams. This work, under the direction of Professor Jerrold Zacharias, contributed directly to the first practical demonstration of atomic clocks. There is a continuing emphasis within the JSEP program today on fundamental atomic and molecular physics aimed at ultra-high accuracy standards for the measurement of time and mass. The interest in physical electronics also resulted in an evolving interest in solid-state physics, both oriented to fundamental problems in condensed matter physics, as well as basic problems in electronic materials and structures. In this way, emphasis on electronic properties in gaseous discharges and plasmas in the JSEP has resulted in a strong emphasis on the study of phase transitions at surfaces and surface reconstruction. This effort, led by Professor Henry Smith, is conducted by a strong group of experimental and theoretical physicists, and is supported by the invention of x-ray lithography and the technology to assist in the construction of a wide variety of submicron structures.

Early emphasis on high-performance amplifiers led naturally to an evolving interest in radio astronomy, where extremely high frequencies are required, and to the exceedingly long-range and fundamental interest in the detection of gravitational waves, where extremely low-noise measurement techniques are required. While these efforts were natural outgrowths of early JSEP research within RLE, they have now become substantial efforts outside of the JSEP program.

Early studies of physical electronics also inspired much interest in characterizing semiconductor noise, the lower bound of which is unfortunately proportional to the amplifier's frequency of operation. These studies have resulted in a natural transition from electronic amplifiers to the study of optical systems. This effort is directed by Professors Hermann Haus and Erich Ippen within JSEP. Although the noise properties of high-speed optical systems are not encouraging for practical application to analog-based communications, the ability to produce ultra-short optical pulses has been extremely important for digital optical communication and the study of fundamental electronic properties. The optics effort within JSEP at RLE is also characteristic of many JSEP efforts since fundamental research in these areas not only produces important results within a specific area, but also provides the basic tools that give the spatial and temporal resolution needed to investigate many other phenomena. Consistently, the JSEP program within RLE has blended these two aspects of research into one program in a highly coordinated way. As a final example of the continuing evolution of interests stemming from the microwave activities of the early days, there has been an ongoing interest in electromagnetic propagation through a variety of media (including remote sensing) currently directed by Professor Jin Au Kong. This work is now focused on the highly difficult, but important, constraints posed by multi-level interconnect structures in advanced electronic systems. It also illustrates how continued fundamental expertise has been refocused into appropriate areas of timely concern to DOD.

The evolution of communication studies within RLE has been particularly important within the first twenty years, although there is much less emphasis in this area within current JSEP activities. At the beginning, the influence of Wiener and Shannon together with Professors Jerome Wiesner, Robert Fano, and Peter Elias formed a formidable arsenal of talent to create the first clear-cut formulation of communications theory as a statistical problem. Interest in statistical communication theory, information theory, and modulation theory boomed in the early days of the JSEP program at RLE. Many people flocked to RLE at that time to be part of the ongoing excitement in this area. Professors Yuk Wing Lee and Wilbert Davenport, Jr. produced important books on these activities, and Wiener's thoughts provided continuing inspiration for many communication processes, not only man-made, but also human in nature. Thus, it was natural for Professors Kenneth Stevens and Wilbert Davenport to study the analysis of speech, and for Professors Warren McCulloch and Walter Pitts to study neurophysiological systems in an attempt to characterize the human detection process. Sensory replacement was a natural evolution, and the speech analysis work, complemented by early interest in mechanical translation, resulted in a large increase in linguistic activities. These activities were fueled by Professor Noam Chomsky's contributions to syntax in the late

1950s, the formation of a graduate linguistic program in 1961, and the important book, Sound Patterns of English, written by Professors Noam Chomsky and Morris Halle in 1968. Artificial intelligence was also part of this early interest in viewing humans as an important aspect of communications processes, as was the LISP programming language invented by Professor John McCarthy within the JSEP program at RLE in the late 1950s. While studies of language, speech, hearing, and other human cognitive processes have continued to be important aspects of RLE, they are no longer present in the JSEP program. The JSEP program is now focused exclusively on aspects of physical science as it relates to electronics.

In the above description it is evident that many interests have grown, coalesced, and led to other activities within the JSEP program. At other times these interests have brought about RLE activities outside of JSEP, and still, at other times, they have led to entirely separate laboratories. These changes have reflected the main interests of DOD, and in more recent times, have sought to emphasize basic science in the service of high-performance electronic systems.

III. Major Results of JSEP-Supported Research

Surveying the 40 years of research under the JSEP program at RLE, it is difficult to select from the many results. But, there are several achievements that cannot be overlooked. Basic research on the measurement of nuclear magnetic moments by molecular-beam techniques contributed to the development of the cesium frequency standard by Professors Jerrold Zacharias, John King, and Campbell Searle. This standard is used commercially and is centrally important to many scientific observations as well as terrestrial and space navigation systems. Fundamental work in microwave spectroscopy by Professor Malcolm Strandberg advanced to the notion of quantum mechanical amplifiers. This, in turn, contributed to the invention of devices that generate coherent radiation by stimulated emission (such as the maser and laser). These devices have been fundamentally important in communication systems. Nuclear magnetic resonance techniques were developed by Professor Francis Bitter, first under JSEP in RLE, and later at the National Magnet Laboratory, which bears his name. The gamut of activities ranging from theoretical and experimental studies of microwave discharge to major emphasis on high-temperature, high-density fully ionized plasmas constitutes a major accomplishment of the JSEP program. Important applications have included re-entry physics, ionospheric communication, and research on the development of fusion-based power generation. Professors Lan Chu, Henry Zimmermann, and C. L. Searle developed fundamental phase-sensitive microwave systems used in guidance applications, and in the very-long baseline interferometers necessary for high-precision navigation. A major contribution has been the entire area of statistical communication theory conducted by Professors Norbert Wiener, Yuk Wing Lee, Jerome Wiesner, Robert Fano, Amar Bose, and Harry VanTrees. Large sections of modern modulation theory, detection, and estimation theory as well as many of the basic results of information and coding theory essential to military applications were developed under the JSEP program. Fundamental work on the synthesis of sequential switching circuits, which served as an important basis for modern digital system technology, was performed by Professors David Huffman, Amiel Feinstein, and Steven Unger. JSEP has also supported a wide variety of studies in speech analysis and synthesis directed by Professors Kenneth Stevens and Jonathan Allen. All commercial synthesis systems are based on concepts established in their research.

Under the guidance of Professor Alan Oppenheim, a major thrust in digital signal processing sponsored by JSEP at MIT has yielded homorphic signal processing techniques necessary to image processing, speech processing, and seismic data processing. Professor George Bekefi's work on radiation processes and plasmas has been a fundamental source for important military work including the development of high-power free-electron lasers. Professors Bernard Burke and Alan Barrett have used very long baseline interferometry to correlate radio signals in order to observe stellar masers. For this work, they have been awarded the Rumford Prize from the American Academy of Arts and Sciences. Professor Shaoul Ezekiel has contributed several laser frequency stabilization techniques and has used them to create a new type of optical gyroscope based on the Sagnac effect.

New techniques for the construction of submicron structures, developed by Professor Henry Smith, have enabled the production of high-quality electronic materials and submicron devices essential to the development of high-performance military electronic systems. Studies of the surfaces of electronic materials, including phase transitions and reconstruction as well as binding and cohesion, have been guided by Professors Robert Birgeneau, John Joannopoulos, and Marc Kastner. This work is the scientific basis for important fabrication processes such as epitaxy. Finally, there are strong JSEP activities within RLE focused on picosecond optics directed by Professors Herman Haus, Erich Ippen, and Michael Salour. These techniques have generated pulses as short as 16 femtoseconds and have provided the means for studying ultra-fast electronic phenomena, as well as the basis for optical computation.

These results represent a spectrum of fundamental scientific achievement and have contributed to important industrial and military applications. The JSEP program has provided an effective vehicle for some of the best research within MIT, and its reputation continues to attract the most outstanding scientists and engineers.

IV. Current Joint Services Electronics Program

Today's JSEP program in RLE is focused on fundamental studies of electronic and optical processes. An important emphasis of RLE's approach is not only the development of scientific understanding, but also the construction of novel theoretical and experimental tools to produce and observe the phenomena under study. Many studies are concerned with states of matter, in model systems designed to provide fundamental understanding of basic processes in novel states of matter. The research focuses on extremely small dimensions and ultra-fast phenomena. JSEP basic research in RLE has often led to the construction of new techniques, which are then exploited to discover other phenomena that are once again exploited to provide a continuing set of probe techniques and fabrication processes.

One major emphasis is the study of high-speed optics. Research is focused on the development of picosecond optical processes, high-speed semiconductor lasers, techniques for probing fundamental dynamic processes and the development of waveguides and other structures for optical communication and new devices for optical signal processing.

A second major area is the study of surfaces and phase transitions. This area addresses the experimental and theoretical interface problems in electronic systems that are directly relevant to practical electronic fabrication techniques. Studies focus on chemical reaction dynamics on semiconductor surfaces as well as the surface binding of metals on semiconductors and surface reconstruction studies that are fundamentally important to epitaxial growth.

A third major effort is a set of studies focused on submicron structures, electronic conduction, and interconnect properties. Research is concerned with the ability to construct high-quality electronic materials and to structure them at submicron dimensions that are appropriate for highly aggressive device behavior. The ability to make these structures has resulted in fundamental studies of electronic conduction in one dimension. This is typical of the results necessary to achieve high performance in future military technologies. *Grain growth* techniques, used to achieve high-quality device material and metallic interconnect, are also under study, in addition to the basic modes of electromagnetic waves in multi-layer interconnect structures typical in large computer systems.

The current JSEP program also focuses on fundamental studies in atomic and molecular physics. This research promotes understanding of how radiation can be suppressed and detected and develops precision measurements of mass and time using trapped atomic particles. Coherent atom field interactions are also being studied in order to develop new clocks.

The JSEP program possesses a unique strength in these four major areas. It is well focused on the fundamental science needed to build integrated electronic and optic systems essential to high-performance electronic systems of the future. The JSEP program within RLE brings together a very high quality selection of research aimed at ultra-precise understanding of very small and very fast electronic and optical phenomena. This must be the basis for lasting innovation in this field.

V. The Future of JSEP

The JSEP program's most important role in the future is the effective integration of optics and electronics research focused on both science and technology to design high-performance systems. Unquestionably, the JSEP program at MIT provides the framework for the effective collaboration of basic science and technology. A recent example is the study of one-dimensional MOSFETs. This research was made possible by JSEP-funded submicron technology combined with the theoretical and experimental physics expertise to design and execute the experiments and interpret their results. In the future, it is expected that the JSEP program will provide even greater interaction between scientists and engineers since each group must understand the other's language and results in order to perform their best work. The JSEP program continues to attract high-quality research, and by emphasizing the fundamental aspects of studies, promotes scientific results that complement achievements in industry and DOD laboratories. The increased interaction between electronic and optic studies provides an opportunity for the JSEP program within RLE to respond to priority areas of future scientific research in electronics.

Professors Julius Stratton, Albert Hill, and Jerome Wiesner of the JSEP program at Massachusetts Institute of Technology.

Dr. Norbert Wiener at the blackboard.

The Ohio State University

L. Peters, JSEP Director

I. Early History of the OSU JSEP Laboratory

The Ohio State University has been a member of JSEP since 1977, with Professor C. H. Walter as the first director of this laboratory. The program consisted of diffraction studies, hybrid techniques, antenna studies, surface cell modeling, antenna type and location synthesis using characteristic modes, transient electromagnetic studies, and adaptive arrays. JSEP was established here at OSU because of the university's strong background in electromagnetics. This is exemplified by the number of papers in the following special issues: (1) Proc. IEEE on Scattering, August 1965; (2) Proc. IEEE on Rays and Beams, November 1974; and (3) Target Imaging, (IEEE Transactions on Antennas and Propagation, March 1981). In addition, the books Horn Antennas and Geometrical Theory of Diffraction have been published.

II. Scientific Avenues of the OSU JSEP Laboratory

Principle activities pursued under JSEP sponsorship include investigations in the theory of electromagnetic-wave diffraction, advanced techniques for solution of integral equations involved in surface-cell modeling (including the so-called "Physical Basis Function Method") and broad studies in theory and experiment in transient electromagnetics. Adaptive array research is another area that has received attention in the program.

III. Results of JSEP-Supported Research

Professor Compton is completing a text on adaptive arrays. Professors Kouyoumjian and Richmond received Centennial Medals from the Antennas and Propagation Society (of the IEEE) for technical achievements. There were 18 such medals issued. Professors Burnside, Compton, Peters, Kouyoumjian, and Richmond have been elected Fellows of the IEEE.

The NATO Advanced Research Workshop and the book Inverse Methods in Electromagnetic Imaging were dedicated to Professor E. M. Kennaugh because of his extensive and numerous contributions to this field.

Fourteen JSEP-funded Ph.D. graduates have found employment in DOD labs, universities, and DOD-oriented aerospace industrial organizations. The ESL has become a recognized leading laboratory in the nation in two areas of study that have been initiated or pursued under JSEP support. These include (a) diffraction studies and hybrid analysis and (b) compact range technology. These studies have established an eminent position in two other JSEP-supported areas of integral-equation studies and time-domain analysis.

The Compact-Range technology was funded initially by JSEP. It has since been transferred to other DOD/Aerospace agencies. Many Aerospace and DOD laboratories have been interested in this study. It is of extreme importance since vital antenna and scattering measurements that previously required large amounts of real estate can now be made in an anechoic chamber with improved reliability and security. A short course taught by a mix of OSU, DOD, and industrial lecturers at OSU for the past two years that discusses compact-range technology has been very well received.

The Geometric Theory of Diffraction (GTD) research area has been available to DOD in the form of computer codes for obtaining desired radiation and scattering properties of military vehicles. These codes have led to reduced cost and improved reliability. These have been distributed to DOD agencies and aerospace companies at a rate of approximately 40 per year. JSEP's role in these important applications is to provide the basic relations to be encoded to ensure the continuing development of these very important codes.

Existing singularities in the GTD had made this technique somewhat impractical. Researchers at OSU have made this solution uniform and extended it so that it is now one of the fundamental techniques for analyzing scattering and radiation problems. This Uniform Theory of Diffraction (UTD) is now referenced by all authors working in this area. The UTD has been highly developed for conducting bodies, with the exception of the conducting corner. For the past six years, OSU has offered a GTD short course (taught almost exclusively by our JSEP staff). The bulk of the audience has been engineers who are working on DOD problems.

Richmond's integral equation work has been used as a basis for many recent computations by others. The early work dealt primarily with thin wires and perfectly conducting surfaces. This work included the first integral equation and method of moments solution for the junction of a thin wire and a perfectly conducting plate. Much of this basic work has been put in the form of user-oriented codes that have been distributed to over 50 organizations.

IV. Current Joint Services Electronics Program

Most of the research in the diffraction and integral equations areas is now focused on treatment of penetrable bodies. These studies bring to bear our electromagnetics expertise on these very difficult analyses. It is important because most vehicles are partially coated with penetrable materials and absorbers.

The K-pulse concept has been developed at OSU at a very low support level. It is sufficiently promising now that it should lead to significant target identification results.

V. The Future of JSEP

The complete analyses of the electromagnetic properties of penetrable bodies (composites, absorbers, etc.) will be as difficult as were the theories leading to the Uniform Theory of Diffraction. It is expected, however, that as these results are forthcoming they will not only be published but also incorporated in the computer codes.

The Transient Studies have been evolving under support and guidance from ONR and Naval Weapons Center (NWC). The support from these agencies makes use of the basic research conducted previously under JSEP and suggests new basic problems.

The Electro Science Laboratory (ESL) is in continuous contact with approximately 20 sponsoring agencies whose needs are reflected in our JSEP program by uncovering new basic topics to be researched.

Polytechnic University

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A. A. Oliner, JSEP Director
E. E. Kunhardt, Co-Director

I. Early History of the Microwave Research Institute

The urgent need for improved radar performance during World War II prompted the establishment of a Microwave Research Group (MRI) at the Polytechnic Institute of Brooklyn. Dr. Ernst Weber was named Official Investigator of Contract No. OEMsr-335 in June 1942 by Dr. Vannevar Bush, Director of the Office Scientific Research and Development; in the framework of this contract, the Polytechnic interacted during the war with the MIT Radiation Laboratory and achieved substantial momentum in the field of microwave engineering. The principal contributions related to microwave measurement techniques and to the invention and development of basic components for microwave systems, such as attenuators, connectors, and power meters. Chapters summarizing accomplishments were included in the MIT Radiation Laboratory series of books, and Dr. Weber was awarded the Presidential Certificate of Merit for his role.

Just after the end of World War II, the Microwave Research Group was formally named the Microwave Research Institute , a research department affiliated with the Electrical Engineering Department, with Dr. Weber serving as both E.E. Department Head and Director of MRI. Dr. N. Marcuvitz, who was at the MIT Radiation Laboratory during the war years, returned to the Polytechnic in 1946 and became the focus of a dynamic and rapidly expanding program in basic electromagnetics. By the late 1940s and early 1950s, with the support of research contracts with agencies including ONR, Bureau of Ships, Army Signal Corps, RADC, and AFCRC, the program broadened to include all aspects of the microwave field and then expanded further to encompass topics such as coding, information networks, electron tubes, and nonlinear magnetics.

The vision of Dr. Weber and the encouragement of Drs. E. Piore and A. Shostak of ONR in the early 1950s led to a novel symposium series, the first of which was held in April 1952 and was sponsored by ONR. Its title was "Symposium on Modern Network Synthesis," and its distinguished list of participants, including E. A. Guillemin, S. Darlington, E. C. Cherry, and S. A. Schelkunoff, set the tone for future symposia. The theme of this series of symposia, topics at the forefront of electronic science and technology, captured the interest of the Army and Air Force, and all of the subsequent symposia were co-sponsored by all three services. Later, these symposia, sponsored directly by JSEP, were held essentially annually. Proceedings of all 24 of them were published by Polytechnic Press, with Mr. J. Fox as editor.

In view of the high quality of the research programs at MRI, particularly those in electromagnetics and microwave engineering, in which MRI was already enjoying a distinguished international reputation, and in the light of the successful tri-service sponsorship of the MRI Symposium Series, a Joint Services Electronics program was established at the Polytechnic in 1956, under the broad theme "Transmission Systems Research."

II. Scientific Avenues and Broad Impact

The Polytechnic University Joint Services Electronics Program, since it began at the Polytechnic about 30 years ago, has always been associated with the Microwave Research Institute. Dr. E. Weber played a fundamental role as the founder of MRI, and he was its Director throughout the early years. By 1957, when Dr. N. Marcuvitz became the Director, the more applicational contracts were being phased out and replaced by those of a basic nature. The scope of the research was also expanded during this period to include electronics-related contributions from other departments, a trend that was accelerated further after Dr. A. A. Oliner became the third Director in 1967. Photographs of the three Directors appear in this write-up.

Electromagnetics and microwave techniques remained as the principal strength in the program, and it is that area that has produced the greatest impact on the electronics field. Not only did MRI produce many important research results in electromagnetics and microwaves, but it also trained a whole generation of microwave engineers. The journal, Microwaves, based on a series of interviews with many microwave engineers, reported in 1968 that more microwave engineers graduated from the Polytechnic than from any other school.

The research achievements of MRI and its key scientific personnel in these areas received recognition in many ways. For many years, they attracted post-doctoral researchers from around the world to spend a year or more at the Polytechnic. Many of those researchers have since become famous in their own right. A second measure of international recognition is indicated by invitations that were extended by the Soviet Academy of Sciences in 1971, on the occasion of the URSI Symposium on Electromagnetic Theory held in Tbilisi, the only one ever held in the Soviet Union. Of seven invitations made worldwide, five were extended to the United States, and of these five, three came to the Polytechnic, to Drs. L. B. Felsen, N. Marcuvitz, and A. A. Oliner. Domestic recognition was also clearly indicated in the form of the Microwave Career Award, the highest award of the IEEE Microwave Theory and Techniques Society, to Dr. Weber in 1978, to Dr. Oliner in 1982, and to Dr. Marcuvitz in 1985. This prestigious award has so far been given to a total of only 15 people.

MRI faculty have authored over 20 technical books that were outgrowths of their JSEP research efforts. The wide impact of many of these books led to the award of the IEEE Educational Medal to several Polytechnic researchers, including Drs. E. Weber (1960), J. G. Truxal (1963), M. Schwartz (1983), and A. Papoulis (1984). Five MRI researchers are members of the National Academy of Engineering.

MRI researchers have interacted with the DOD in various ways. Most notably, Dr. N. Marcuvitz served in the Pentagon as Assistant Director (Research) in the Office of Defense Research and Engineering in 1963-64, and Dr. E. Weber was appointed to several DOD advisory councils, including the Army Scientific Advisory Panel in 1957, the Defense Science Board in 1963, and its Executive Committee in 1964. Several researchers have spent summers at DOD laboratories, including RADC, AFCRL, and Ft. Monmouth, and have interacted with these and other laboratories in many other ways, including advising and evaluating programs for ONR, ARO, and the RADC unit at Hanscom Field.

III. Results of JSEP-Supported Research

Consistent with the origins and the early history of MRI, many of the more significant results of JSEP-sponsored research were in the field of electromagnetics, but highly important contributions were also made in other areas, such as network theory, surface acoustic waves, x-ray diffraction, surface physics, control systems, image processing, and electromechanical power conversion. For most of these accomplishments, interaction occurred with the DOD and/or industry, recognition was achieved in the form of prizes or awards, and often the research led to publications of books.

A number of key contributions have been made to the analysis, design and technology of phased-array antennas, beginning in 1960 and continuing until the present. These include: (1) the high-speed ferrite-latching phase shifter, a key element of phased arrays that, for well over a decade, was the type most widely employed in military radar systems; (2) the basic unit cell method of analysis, the first systematic approach to permit array design under scan conditions, taking mutual coupling into account; widely used today; (3) studies of blindness effects, first observed unexpectedly on a full-scale antenna, where, at some scan angles, the antenna does not radiate and cannot detect an incoming signal; the basic studies explained why and when blindness occurs and established design criteria for avoiding it; (4) systematic analytic tools for designing conformal arrays on curved surfaces such as the skin of aircraft or missiles.

Throughout this period, strong interaction was established with the DOD, and since the early 1970s, with industry. During the early 1960s, Oliner collaborated with the MIT Lincoln Laboratory on phased-array antenna design, and from 1965 on, close collaboration was established with the Army Ballistic Missile Defense Agency (ABMDA), continuing today with A. Hessel and J. Shmoys. Because of Polytechnic's leadership in this area, it was asked by ABMDA in 1970, to organize a Symposium on Phased Array Antennas. Proceedings of that Symposium, edited by Oliner and G. H. Knittel, have been published.

Other major contributions in electromagnetics have been made in the fields of:

(a) Lumped-distributed microwave filters and the theory of broad-band matching (the latter applied to microwave networks, transistor amplifiers, and antennas): Results of this work have been incorporated into many textbooks on network theory. For these contributions, D. C. Youla and H. J. Carlin received the Air Force System Command "Award for Outstanding Achievement" in 1965; Youla received the IEEE Baker Award in 1964 and the Guillemin-Cauer Award in 1973.

(b) Electromagnetic theory, including investigations of a large variety of wave types propagating along interfaces: These have had far-reaching impact on the state-of-the-art, altering concepts and opening the way for new applications. The properties of leaky waves and complex guided waves have been elucidated. A. A. Oliner and T. Tamir in 1964 received the Institution Premium, highest award of British IEE, given for the first time to an American.

(c) Radiowave propagation in forest or vegetation environments: During the summer of 1966, at Army Electronics Command, Ft. Monmouth, T. Tamir used the theory of lateral waves to explain successfully, for the first time, data taken in Thailand jungles.

(d) Guiding and scattering by periodic structures: During the 1950s, microwave network approaches by N. Marcuvitz placed analyses of periodic waveguides on a systematic basis for the first time. In 1959, the first rigorous solution for radiation from an open periodic structure was contributed by A. A. Oliner and A. Hessel. This has been widely reproduced in textbooks and has led to a new class of antennas.

(e) Novel hybrid ray-mode methods for high frequency and transient guiding and scattering: A technique that combines ray and mode fields in an optimum way to dramatically improve field convergence has been developed by L. B. Felsen. This method has

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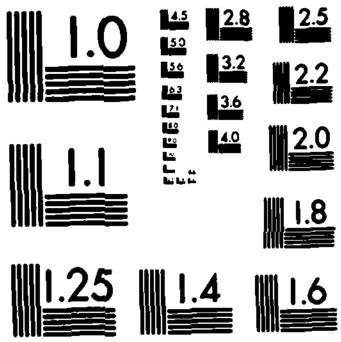

ICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

application to multimode guides, radomes, and broadband scattering by targets. For earlier work, Felsen received the URSI Van der Pol Gold Medal in 1975.

(f) Equivalent networks for discontinuities in strip transmission line: A. A. Oliner derived expressions for a large variety of discontinuities in the center conductor of strip lines, thus providing the only available design formulas in this area for a decade. This contribution was awarded the IEEE Microwave Prize in 1967.

(g) Leaky wave antennas: In the late 1950s, A. A. Oliner developed systematic microwave network methods for a variety of practical antennas, mostly in direct collaboration with AFCRL (now RADC) at Hanscom Field. Results are quoted widely in textbooks and handbooks.

Significant accomplishments in the JSEP program were made in the fields of acoustic waves, solid-state electronics, information electronics, and electromechanical power conversion. These include:

(h) Acoustic wave convolver: A device of great potential utility in signal processing, pulse compression, and optical imaging; now widely used. Invented by W. C. Wang, presented at JSEP review in 1966, Wang received basic patent in 1974.

(i) Experimental determination of the phases of x-ray reflection: It had been historically accepted that only x-ray amplitudes can be measured. B. Post in the late 1970s developed a novel experimental method for determining phases in an unambiguous way, thereby changing the basic outlook in the field. In 1982, received the Warren Award of the American Crystallographic Association.

(j) Design of optimal multivariable feedback controllers: In the mid-1970s, D. C. Youla and J. J. Bongiorno, Jr., developed a completely new approach to providing an optimal controller, insuring an asymptotically stable and dynamical closed-loop configuration.

IV. Current Joint Services Electronics Program

The current program consists of research units in three broad areas: electromagnetics, solid-state sciences, and information electronics. In the electromagnetics area, the program has historically been concerned with systematic and thorough investigations of fundamental challenges and, in the process, major impact on the development of electromagnetics as a whole has been made. The current program seeks to both understand new physical effects and to develop new or improved analytical procedures. More specifically, the general theme of the present electromagnetics program under JSEP is guidance, propagation, and scattering in open regions, usually involving dielectric boundaries. A large portion of the program has application to millimeter-wave integrated circuits and to integrated optics, and another portion includes applications to time-harmonic and transient-wave propagation in complicated environments or wave scattering by complicated targets. The current program in the solid-state area addresses problems relating to the surface or interface regions of solids. Elements of the program are concerned with the detailed and microscopic processes at surface and boundary configurations, but also include new fabrication techniques for thin layers whose general properties remain to be investigated. Specific research areas include novel high-resolution x-ray techniques, the investigations of resonant microstructures as they dramatically influence various inelastic processes, dynamical and nonequilibrium phenomena at surfaces and interfaces involving both electronic (transport) and structural (diffusion) features, and a novel employment of IR-laser-assisted MOCVD. The information electronics program concentrates on new techniques in image processing, system identification, and related topics, with the goal of developing systematic practical design procedures.

V. The Future of JSEP

We expect that our future program will still retain the three broad fields that comprise our present program, but that expansions into new areas will take place. One of these areas is that of nonequilibrium and high-speed phenomena, involving wave-matter interactions down to femtosecond pulse lengths; these studies should shed light on the dynamics of power switching devices.

Another broad area of future interest is that of the nonlinear behavior of wave types on surfaces with amplitude-dependent properties. The specific motivation arises in connection with the current investigations of microparticles, where it has been recently shown that nonlinear microspheres can exhibit optical bistability. These studies indicate the possibility of an optical transistor composed of a single microsphere, which could yield the world's smallest and fastest optically bistable device evolved so far.

There have been some recent changes in laboratory management. Dr. Oliner has resigned his position as director of MRI, and he will be replaced in that capacity by a new faculty member, Dr. Erich Kunhardt, whose specialty is plasma electronics and whose research is currently in the space power area, with high power switching one of the major concerns. With respect to the JSEP at the Polytechnic, Dr. Oliner will remain as Director and Dr. Kunhardt will assist him as Co-Director.

With the new leadership, the name of the laboratory is also being changed. It is now called the Weber Research Institute, with Dr. E. E. Kunhardt as its Director. The choice of name is singularly appropriate in view of Dr. E. Weber's fundamental roles as the founder of the research institute and its director throughout its formative years.

Dr. Ernst Weber.

Dr. Nathan Marcuvitz.

Dr. Arthur A. Oliner.

University of Southern California

W. H. Steier, JSEP Director

I. Early History

The Joint Services Electronics Program began at the University of Southern California in July 1963 under the first director, Zohrab A. Kaprielian, who played a key role in initiating the JSEP Program at USC. Dr. Kaprielian was the architect of the current strong electrical engineering program at USC, which has undergone dramatic transformation and development over the past 25 years.

Dr. Kaprielian joined the University of Southern California in 1958 as Assistant Professor of Electrical Engineering. At the time, the department was a small and undistinguished program with only six faculty members and no sponsored research. Soon after his arrival, Dr. Kaprielian secured the department's first research grant, from the Air Force Office of Scientific Research, to continue his Ph.D. research on artificial dielectrics. In 1962, he was appointed Chairman of the department. He immediately began to take aggressive and imaginative actions to change the character of the program. He had vision to see its enormous potential by virtue of its location at the heart of the great electronic and aerospace industrial activity of Southern California.

At that same time, the University was embarking on an academic development program called Enterprise and Excellence in Education, and Dr. Kaprielian convinced the University administration to make the building of engineering and allied sciences one of the cornerstones of the master plan. A major building program was launched, and resources were provided to attract recognized senior faculty in engineering, physics, and chemistry. Particular emphasis was given to the development of a major capability in the solid-state sciences.

Establishment of the Joint Services Program at USC provided a major, critical impetus to the accomplishment of Dr. Kaprielian's plans and hopes for the development of electrical engineering at the University. In 1963, several new senior faculty members had already been recruited, and their presence was vital to the success of the JSEP site visit and the subsequent admission of USC to the Joint Services Program. USC's selection was the catalyst for the two decades of dramatic growth and development that were to follow, not only in electrical engineering, but all aspects of the solid-state sciences on the campus. The number of faculty members in electrical engineering grew from 12, when the JSEP program began, to over 80 today, and graduate student enrollment grew from 70 to nearly 800.

The JSEP Technical Coordinating Committee's decision to admit USC into the program was based largely on their faith in Dr. Kaprielian's drive, commitment, and passion for academic excellence and his ability to "make things happen." In the early 1960s there was only marginal research capability in the entire School of Engineering. However, the committee's faith and its investment in USC over the years has returned fruitful dividends to the nation's research capabilities and the DOD's electronics research base. In the 1982 National Science Foundation's rating of graduate electrical engineering programs, USC was ranked fifth nationally.

In the first years of JSEP at USC, solid-state research included work in semiconductors, magnetism, crystal imperfections, and superconductivity. The information sciences area covered control systems, bioelectronics, and coding theory for communication systems. Studies of the properties of plasmas, wave propagation in plasmas, and electromagnetic waves in stratified media comprised the electromagnetic research program.

In the 1960s and early 1970s, JSEP was the cornerstone of electronics research at USC, representing a major share of the support. The program continues to provide stable funding for some of the most productive research faculties and provides flexibility to provide quick startup funding for new faculties and for promising new research initiatives.

II. The Evolution and Accomplishments of the Program

The JSEP program is dynamic, following the advancing frontiers of electronics research and the changing interests of the faculty. The role of the director is to assure that the program is always at the cutting edge.

The following statistics give some indication of the changes that have occurred over the years: In the five-year period from 1976-1981, there was a 53 percent turnover in faculty and research topics, while in the 1981-1985 period, there was an additional 69 percent. While these numbers do not necessarily relate to changes in program quality, they do indicate the competitiveness and dynamics of the program.

The quality of the program is best evidenced by its major research advances or by the important new technologies that received critical early support by the JSEP program. Several examples can be cited for the USC program.

The birth of digital image processing at USC occurred under JSEP funding. The early work of W. Pratt, H. Andrews, W. Meisel, and N. Nahi laid much of the framework for the now widely used techniques for digital image enhancement and digital image transmission. This work became the basis for the Image Processing Institute at USC and for a major technology that now plays an important role in smart weapons systems, space exploration, and robotics.

The work in nonlinear optics by R. Hellwarth and M. Levenson led to their development of the Raman Induced Kerr Effect (RIKE). This spectroscopic technique provides the Raman spectra of a medium in a very short time scale without the difficult experimental problems of earlier techniques. RIKE has great potential and is currently being used in diagnosis of very fast chemical interactions of flame and combustion typical of rocket engines and of plasmas.

The fundamental research on Raman spectroscopy done in Sergio Porto's laboratory was supported by JSEP. Dr. Porto was one of the early and leading proponents of the application of lasers to Raman spectroscopy, and his work played a major role in development of this technology. Lasers and Raman spectroscopy have combined to make a powerful and now extensively used analytic tool.

JSEP also supported basic research directed toward understanding the roles of impurities and defects in the properties of semiconductors. F. A. Kroger's work in defect chemistry led to an understanding of defect structure and the thermodynamics of point defect formation in solids. W. G. Spitzer studied the localized infrared vibrational mode absorption associated with impurities. Both defect chemistry and localized mode analysis are basic to the understanding of semiconductors and contribute to the practical realization of many current semiconductor devices and circuits.

The success of the JSEP program at USC can also be measured by the attainments of the faculty members who have participated in it over the years. Sixteen members of the faculty supported by the program have been elected Fellows of the IEEE, three have been elected Fellows of the Optical Society of America, and three have been elected Fellows of the American Physical Society. Three participating faculty members have been honored by membership in the National Academy of Engineering.

Since its initiation, the program has provided support for over 300 graduate students, which is far more than any other program in the University. These graduates have gone on to assume posts in industry, government, and academia, and many have achieved major leadership roles. Indeed, the numbers and quality of graduates that JSEP has supported must be listed as one of the major accomplishments of the program.

In the early years of the program, the annual site visit and program review of JSEP were combined with a general review of the total electronics research. The review brought leaders in electronics from DOD, industry, NSF, and other universities to the campus. In 1972, TCC agreed to experiment with a new format for the reviews. Instead of covering all facets of a particular school's program, the reviews would be topical, covering a selected area of electronics research with contributed talks from all of the JSEP schools and possibly from government and industry. USC agreed to host the first of these topical reviews in 1973 in the area of high power and tunable lasers. Technical papers were delivered by faculty from eight different JSEP universities. The entire program was broadcast live over the USC Educational Television Network to local industry and was videotaped and distributed to interested research centers around the country. It was generally agreed that this format successfully brought representatives from all of the JSEP schools together on a focused topic and provided high visibility for the JSEP program. The topical review format remained for several years until the current format of an in-depth review of the JSEP program at each school was initiated.

III. The Current Program

The dynamic nature of the JSEP program results in a continuous change in faculty and research topics. These changes are the responsibility of the director under the guidance of TCC and with the advice of the faculty. At USC, an advisory committee, composed of senior faculty from the three major areas of research advises the director and provides valuable expertise in deciding on the future directions of electronics.

The current research program comprises 13 research tasks. In solid-state electronics, the research of P. D. Dapkus on Metal Organic Chemical Vapor Deposition (MOCVD) growth of heterojunction materials and the uses of these materials in new electronic and optical devices is included. An experimental and theoretical program of Molecular Beam Epitaxial (MBE) growth of the GaAs/AlGaAs and the GaAs/InGaAs systems is under A. Madhukar. A. Tanguay's research is concerned with the growth of electro-optic materials and their use in spatial light modulators. The research of a new faculty member, S. R. Forrest, on semiconductor evaluation techniques using organic contact barriers will soon be started.

Four research tasks are covered in the quantum electronics area: E. Garmire is conducting research on the realization of room temperature lasers operating at 3μm. M. Gundersen is exploring the spectroscopy of the basic processes involved in electrically excited materials. The motivation for this basic research is the need for new high-current, high-speed switching devices. W. H. Steier is working on novel opto-optical switching technologies that have potential applications in optical interconnects and optical networks. J. Feinberg is pursuing a basic study of phase-conjugating mirrors and the properties of some novel optical devices that employ these mirrors.

The current research in information electronics covers five areas. D. Moldovan and G. Bekey are studying algorithms for the design of parallel processing systems. V.O.K. Li is conducting basic research on problems of concurrency control, query processing, and file allocation in C^3 distributed data bases. The possibility of using differences in textures for image processing and the techniques for recognizing differences in textures is the subject of the research under A. Sawchuk. The research of D. McLeod is on improved methods to allow end-users to design and manipulate computerized databases particularly on personal computers. The extension of the optimal phase-matching algorithm to compute reduced models for large distributed systems is the focus of the work under L. Silverman and E. Jonckheere. A new research area under R. Chellappa in the very important topic of robotic vision has been recently added.

IV. The Future

One of the future directions for the research that will be encouraged under JSEP is the study of materials, device, and systems issues of light wave technology. This photonics area couples already active programs in compound semiconductor growth and characterization, with device processing and analysis, and optical systems analysis. This area of research thus involves all areas of the JSEP program: quantum electronics, solid-state electronics, and information electronics.

A strengthening of the compound semiconductor growth program in the areas of MOCVD, MBE, and LPE will be part of this effort. Crucial to success in this new research direction are improvements of device processing facilities at USC. The primary role of JSEP in this expansion of photonics research will be to provide seed money to initiate new programs.

The future of JSEP at USC is dependent upon the budget outlook in the years ahead. The large number of important scientific advances that can be traced to JSEP support that are documented in this and accompanying articles convincingly make the case that JSEP is one of the most successful research programs in DOD's history and one in which DOD can point to with pride. JSEP has proven to be a successful format for univeristy defense-related research, and every effort should be made to maintain the scope and size of the program in the coming years.

Dr. Zohrab A. Kaprielian, first director of the Joint Services Program at the University of Southern California.

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Stanford University Stanford Electronics Laboratory and Microwave-Ginzton Laboratory

S. E. Harris and J. S. Harris, JSEP Directors

I. Introduction

Historically, there have been two administratively separate JSEP programs at Stanford, related originally to the scientific interests and departmental connections of the two founders, F. Terman of Electrical Engineering and W. W. Hansen of Physics. Broadly speaking, the Stanford Electronics Laboratory program has been concerned with all the conventional fields of electrical engineers (circuits, systems, electron tubes and semiconductor devices, radio wave propagation, communications theory and physical electronics) with the emphasis changing as various fields developed, while the Microwave Laboratory (now the Edward L. Ginzton Laboratory) has been more narrowly focused on physical electronics (e.g., high-power microwave tubes, microwave acoustics, and superconducting materials and devices), with both JSEP programs heavily involved in some areas such as microwave tubes and quantum electronics.

Over the 37-year history of JSEP at Stanford, there have been four directors of the Stanford Electronics Laboratory program (F. E. Terman, W. R. Rambo, J. D. Meindl, and J. S. Harris) and four directors of the Microwave-Ginzton Laboratory program (E. L. Ginzton, M. Chodorow, A. E. Siegman, and S. E. Harris).

II. Early History

A. Stanford Electronics Laboratory

The JSEP program of the Stanford Electronics Laboratory originated in work previously done under four separate Office of Naval Research (ONR) contracts. In 1947, these contracts were consolidated into a single contract with added support by the Army and Air Force to establish the JSEP program.

The original ONR program was in the areas of Radio propagation, with work on meteor reflections, low-frequency propagation, and ionospheric sounding under the direction of O. G. Villard, Jr., R. A. Helliwell, and L. A. Manning; Microwave electron devices, under the direction of K. R. Spangenberg and W. W. Harman; wideband network studies under the direction of J. M. Pettit. This research was continued under JSEP sponsorship and was further expanded with the addition of new faculty and students. Many of the faculty and students in this early period of the JSEP program had come to Stanford as a result of their work in radar and countermeasure systems with F. E. Terman at RRL (Harvard) during WW II. There was thus a strong team of scientists assembled at Stanford who were knowledgeable about such systems and interested in advancing the basic science and technology of such systems.

The broad objective of the JSEP program in the Electrical Engineering Department was to support and encourage basic research in electronics (of a character suitable to a university) that would provide new ideas and new data on electron devices, electronic systems, and electronic phenomena of possible interest and importance to government and industry and which would simultaneously train a new generation of electronic research scientists to fill the obviously great needs of government, industrial, and university laboratories. This program, at the time, was staffed by leading research faculty and graduate students (working toward advanced degrees) who brought both a high degree of technical skill and tremendous enthusiasm to the program. As a measure of the research potential of this type of program, the number of Ph.D. candidates increased more than eight-fold in the period between 1948 and 1960, when the JSEP program represented a sizable fraction of the Stanford Electronics Laboratory support.

The focus of the early Stanford Electronics Laboratory JSEP program was on the basic theory of microwave-electron interactions, radio wave propagation, solid state electronic circuits, and information theory. During the Korean War, the participating laboratories provided numbers of highly trained people and made important contributions to the defense effort. One specific example was the development of a rapid-scan intercept receiver using, as its major component, a dispersive traveling-wave tube initially developed under the basic research program. This intercept receiver was the forerunner of a whole series of such components (and even countermeasure systems) that today are integral portions of DOD programs. It is important to point out that, while this specific piece of hardware was of urgent utility, the essential component was developed under basic research within the JSEP framework by L. M. Field, and not in response to a set of narrowly defined objectives. The low-noise TWT research has had an even greater impact. These and similar examples demonstrate the important virtues of the joint-services type of program that not only provides a foundation of new applied research but can respond in an organized manner and short time scale to a critical need. Once this immediate need ended, the program returned to its original objectives, but with some modification in emphasis, as the invention of the transistor began to impact the world of electronic circuits and systems. The increased emphasis--first on transistors and then integrated circuits--increased the laboratory needs substantially. JSEP provided some of the early seed money to establish the first integrated circuits laboratory at Stanford and the first work on processing and fabrication. This activity has grown immensely (largely through outside funding) and is now the largest single activity and laboratory resource at Stanford. It was, however, typical of the program goal of seeding important new activities at a point when other sources were not readily available.

B. Microwave/Ginzton Laboratory

The JSEP program in the Microwave/Ginzton Laboratory was started in 1950. Its planned objectives were the logical continuation and extension of an ONR program on high-powered, microwave (MW) amplifiers that were already underway in that laboratory. The activities of the laboratory were started in 1945 by Professor William I. Hansen, who had returned to Stanford from wartime leave at Sperry Gyroscope in Garden City. William I. Hansen was the inventor of the cavity resonator (1935) and of the idea of using the high electric fields easily produced in such a resonator for accelerating electrons to produce high-voltage x-rays. He was also one of the co-inventors (1937), with the Varian brothers, of the klystron, an electron tube that combines the cavity resonator with suitable control of the dynamics of the electron beam (the bunching concept) so as to be suitable for amplification or generation of very high frequency electromagnetic waves. Hansen had worked at Sperry during the war largely on microwave problems, radar, and active and passive devices and was one of the world's greatest experts on all aspects of microwaves.

Hansen had returned to Stanford with the aim of applying the radar lore developed during the war to physical research. A particular goal was to use his old cavity invention to accelerate electrons to high energies by using a linear array of cavities with suitably phased voltages. He started a program (ONR) to construct such an accelerator in the Microwave/ Ginzton Laboratory, as well as a number of other microwave projects.

He was joined in his efforts by two former colleagues from Sperry--E. L. Ginzton late in 1946 and M. Chodorow in early 1947. Ginzton had worked with the Varian brothers and Hansen on the development of the klystron at Stanford from 1940 to 1941, when the whole group was transferred to Sperry to continue further research there. Hansen's accelerator design, as was true of all other similar efforts, consisted of a series of cavities coupled through apertures in the center of the cavity, with the cavity fields suitably phased through proper choice of dimensions so as to continuously accelerate electrons passing along the axis of the accelerator. In 1945, the obvious choice of power source was a pulsed magnetron--efficient, capable of high pulsed power of the order of a megawatt, but commonly having small variations in frequency from pulse to pulse. These frequency characteristics would be acceptable in a short accelerator (a meter or two) where the frequency-related variation in phase shift over such a length of accelerator would be acceptably small. This restriction in length would limit acceleration to about 10 to 15 MeV.

Ginzton, upon his return to Stanford, suggested examining the possibilities of high power, multi-megawatt klystron amplifiers as the microwave power sources for an accelerator. A series of high-gain amplifiers (30 to 50 dB of gain), all operating at the same frequency and each feeding successive stages (contiguous sections) of a long accelerator with a single electron beam, would, in principle, provide unlimited accelerator possibilities (proportional to the number of accelerator sections). Simple phase control of the input drive power of the successive amplifiers would synchronize the fields along the whole accelerator and, in principle, permit building any length of accelerator desired.

With separate support from ONR, Ginzton and Chodorow began to study the problems and obstacles in designing a klystron and associated equipment (pulsers, magnets, etc.) to produce 30 MW power at 2856 MHz. The tentative specifications were 250 amperes and 400 kV with an estimated efficiency of 30 percent. This would be about 35 dB greater power than any previous klystron amplifier. The preliminary study indicated no fundamental obstacles (at least in theory) to meeting these objectives. Detailed studies continued on various aspects of the design, focusing magnets, cathodes, modulators, etc.

In June 1948, the two separate contracts in the Microwave/Ginzton Laboratory--one for a 1 GeV accelerator and one for 30 MW klystrons--were combined into one contract, and work on the combined projects continued.

In March of 1949, the first successful klystron was demonstrated at 14 MW. The success of the accelerator program seemed assured and, indeed, that program did proceed (over the next several years) to build the world's first multi-MeV (actually, 1,000 MeV) linear accelerator, including the klystrons, modulators, etc.

These programs instigated a large number of similar accelerator projects and klystron activities worldwide in the next several years. The group at Stanford headed by Ginzton and Chodorow (Hansen had died in 1949) realized that there were many important implications of the successful klystron program and many applications for high-power, multi-megawatt amplifiers other than for accelerators. Consequently, in March 1950, a separate high-powered tube program was initiated as a separate JSEP activity under the direction of ONR.

Ginzton had become Director of the Microwave/Ginzton Laboratory and was responsible for the accelerator construction and, together with Chodorow, directed the JSEP program on high-powered microwave tubes. The intent of this JSEP program was initially to explore the possibilities and limitations of multi-megawatt pulsed amplifiers (which also had obvious possibilities of achieving much higher average powers than magnetrons).

A great deal of the JSEP program, then, for the first 10 years or so, was concerned first with research on high-powered (multi-megawatt) klystrons and subsequently with broader-band traveling wave tubes with equivalent powers. The results revolutionized the whole technology and scope of radar with enormous impact on the DOD. Successful progress on this program principally required research on the dynamics of high-current, high-voltage electron beams and the applications of electromagnetic theory and measurement techniques to the design and study of suitable propagating microwave circuits (coupled cavities, etc.) suitable for such devices. These kinds of problems constitute a portion of what has sometimes been referred to as physical electronics. The objectives of the research and background required made this a very suitable program for the training of both electrical engineers and applied physicists.

In 1957, Ginzton left the program to direct the planning of the 2-mile accelerator to be built at Stanford (SLAC). M. Chodorow succeeded Ginzton as Director of the Microwave/Ginzton Laboratory at that time.

III. Scientific Avenues

After about 1963, it became apparent that the area of microwave tubes, electron guns, design of circuits, etc., was becoming less conceptual and increasingly technological in nature and more suited for an industrial rather than an academic environment. This period also coincided with the invention of the laser and with the emergence of the field of microwave acoustics. Work on the JSEP program at Stanford moved rapidly in these latter directions. Conceptually, there were close relationships between quantum electronics, microwave acoustics, and microwave tubes--in all cases involving the interaction of electrons or atoms with waves and appropriate "circuitry" (resonant cavities, grids, reflectors, couplers, etc.) for controlling these waves. The concepts and methods of calculation were easily moved from such traditional electronics to both quantum electronics and to microwave acoustics.

The importance of the work at AT&T Bell Laboratories to both of these emerging fields should be noted. New laser materials, new concepts, and, especially, new electro-optic and piezoelectric materials such as $LiNbO_3$, were rapidly invented and introduced to the technical community. In the Center for Materials Research at Stanford, the development of $LiNbO_3$ was begun and soon had broad impact on both the acoustic and laser programs. Of note is the similarity between this program and the original high-power klystron program where, in both cases, it was not possible to proceed in a useful and creative scientific fashion unless one provided the appropriate technological facilities.

IV. Results of JSEP-Supported Research

A. Stanford Electronics Laboratory

Other developments of the Stanford Electronics Laboratory JSEP program are summarized here, touching only some major accomplishments.

1. Initial low-noise studies on the interactions between circuits and electron streams proved to be of major interest and were reported in 1951. Later they led to the theoretical discovery of the reduction of noise in an electron beam in a low-potential region. This, in turn, led to traveling-wave and backward-wave amplifiers with noise figures in the 2-3 dB range. All low-noise tubes later produced depend on noise reduction obtained by this means (originally developed under JSEP support).
2. The theoretical analysis of the gain, bandwidth, and noise figure of parametric amplifiers by Heffner and Wade is a classic in the field. It was the first thorough treatment of the performance of the parametric amplifier and has served to guide workers throughout the country in this field of endeavor.
3. The Solid State Electronics Program has been a major JSEP activity. The initial emphasis was almost entirely on circuits; however, today, the major emphasis is on device research and on the explanation of the fundamental processes involved in solid state devices and integrated circuits. Stanford established an early leadership position in this very competitive field. Among the important early contributions of the JSEP program were the results of Middlebrook's work on equivalent circuits describing the high-frequency behavior of transistors. Middlebrook's book, and subsequent papers by Scarlett, were widely accepted as fundamental to the development of transistor circuit modeling--an area in which Stanford still has a preeminent position. In 1956, Gibbons developed the

design theory for multistage transistor amplifiers meeting maximum-gain and prescribed stability-margin requirements. Methods of aligning such amplifiers were developed that are applicable even in the presence of internal feedback. Significant contributions were also made to the understanding of hot electron behavior and metal silicon-dioxide capacitors.

4. Another major activity of the JSEP program with great impact has been radio-propagation. One of the earliest successes was the detection of meteors by means of HF radio waves, showing that relatively low power sufficed to give excellent signal-to-noise ratios. This work, which initially used backscatter geometry, showed later that ionization trails also reflected efficiently in the forward direction and led to the concept of using meteor reflections for communication purposes. (Western Union now exploits this technique to collect hydrologic information in the western United States.) As part of the basic research on meteors, the true origin of long-distance ground backscatter was established, and it was shown to be ground clutter as mirrored in the ionosphere. Applications included a technique for displaying those regions to which HF communication is possible, and this proved useful for precision command and control. Another application was a means for remotely sensing disturbances in the ionosphere (both fixed and traveling) caused by earthquakes, nuclear explosions, rocket launches, etc. These typically show up as disturbances to the ionospheric "mirror"; such disturbances can then be sensed at great distances. As can be surmised, a large number of practical applications grew out of this work, including the 440L Ballistic Missile Early Warning system and an AFTAC nuclear explosion sensing system. The application of meteor burst communication to naval shipboard communication has also been important. Conventional

HF transmissions betray the location of the source to distant direction finders. However, when the transmission reaches an interceptor via a transitory ionization column, the problem of radio location becomes vastly more difficult, thereby permitting ships to communicate with significantly less likelihood of interception.

Basic information on the interaction of meteors and the upper atmosphere has had important applications in problems arising in connection with reentry of satellites and guided missiles into the atmosphere. For example, these early JSEP studies have led to an ARPA-supported Downrange Anti-Missile Program (DAMP), with the research being carried out by the Stanford Research Institute using the vessel Arcania.

B. Microwave/Ginzton Laboratory

The JSEP program at the Microwave/Ginzton Laboratory has had a major impact on the Department of Defense and on science and technology. As described earlier, the JSEP program was initiated to exploit the earlier demonstration of very high-peak power from klystron amplifiers. Within a short time, this resulted in the first sealed-off pulsed klystron ever constructed. Several prototypes were delivered to the MIT-Lincoln Laboratory and had an immediate and major impact on its future program. This prototype later evolved into an important radar tube, the Varian VA97. This was shortly followed by a collaboration of Stanford University and Litton Industries to develop the well-known (AF) L3035 tube. Although not financed by JSEP, this project leaned heavily on JSEP know-how and personnel. The electrical design, fabrication, and testing of early tubes was done at Stanford, while the mechanical design and later fabrication and testing were done under the guidance of Litton. The L3035 tube became the transmitter for one of the most widely used radar systems in the Air Force. The availability of these high-power pulsed amplifiers revolutionized radar technology.

It soon became plausible that one could use many of the same techniques developed for klystron design, but with different microwave circuitry, to provide traveling wave tubes with greater bandwidth capability. These would be aimed at megawatts of peak power and kilowatts of average power and could not use the conventional fragile helix circuits commonly employed. Over the next several years, several circuits were invented and tested, including the so-called "coupled-cavity," "clover-leaf," and "cross-wound helix" circuits. The coupled-cavity circuit was first developed under the JSEP program and is particularly well suited for peak powers in the range of tens to hundreds of kilowatts and is probably the most widely used pulsed radar tube today. (Since it was first used in radar by Hughes Aircraft, it is sometimes referred to as the "Hughes circuit," but it was first conceived and tested at Stanford.) The clover-leaf circuit was designed to overcome some of the peak power limitations of simple coupled-cavity circuits and is capable of operation at multi-megawatt powers. Finally, the cross-wound helix (or ring-bar) circuit is intended for use at tens of kilowatts peak power and with large bandwidths. This tube has been widely used as a driver in high-powered radar systems. These three circuits, or variations thereof, constitute essentially all the high-power traveling wave circuits used the world over, including, for example, the two radars in the Safeguard ABM system. The JSEP program was, again, responsible for this major change in radar practice throughout the world.

As a final contribution in microwave electronics, another result of the early JSEP program may be noted--the first demonstration of undulator radiation. This was the production of very short wavelengths (0.1 mm) by passing a high-voltage electron beam through a series of magnets with alternate polarity. Professor Hans Motz and students were associated with this experiment. This technique was the predecessor for that now used to generate intense x-ray radiation in storage rings throughout the world and also came close to the free-electron laser concept.

One other indirect result of the JSEP program was the development in 1956 of the first klystron-driven medical electron accelerator intended for x-ray therapy. The first use was in the Stanford Medical School in 1956, and the hundreds now in use have had enormous impact in many types of radiation therapy.

The existence of the Stanford Linear Accelerator Center (SLAC) at Stanford (one of the most successful high-energy research programs in the world) and all other linear accelerators the world over, is, of course, also a direct consequence of the high-power klystron work first supported by JSEP.

Next may be noted the consequences of an extensive program, employing high-frequency acoustic waves, that began in about 1961. As in many other areas, this program was supported by many contracts with individual services as well as by the JSEP program, and it is therefore difficult to allocate separate contributions. The net result has been an enormous impact on many DOD activities. The present use of surface acoustic wave delay lines for a wide variety of signal processing applications (pulse compression, convolution, correlation, filtering, chirping, etc.) can be traced to the original work of Professors Auld, Kino, Quate, and Shaw in the Microwave/Ginzton Laboratory. Perhaps the most important contributions were the design of the first efficient interdigital surface wave transducer by Shaw and the first surface wave convolver by Kino. A specific direct JSEP contribution involves an electronically scanned acoustic imaging array system that has led to the development of many new types of acoustic transducers and imaging systems. The transducer technology is now widely employed in medical imaging systems. Applications to nondestructive testing have also become important, both in the electric power industry for the examination of reactor components and in the Air Force for looking at airplane body and engine components.

Another important outgrowth of the surface acoustic wave program is the semiconductor storage correlator invented by Kino and Kayakawa at Stanford (and, almost simultaneously, by Ingebrigpsen at Lincoln Laboratories). This device provides a much-needed link between high-speed surface acoustic wave devices and slow digitally based signal processing systems. The device is also capable of storing a surface wave signal as charge in a semiconductor layer for later readout.

One of the most important impacts of the JSEP acoustics program, in recent years, was in providing the scientific and technological milieu for the invention and development of the acoustic microscope by Quate and his colleagues. In 1973, Quate realized that since the velocity of sound in many solids is much greater than in water (relative index > 5), a single spherical liquid-solid interface lens could focus sound in water (and other liquids) to a nearly diffraction-limited spot without significant aberration. Such an axial focus is sufficient for the construction of a mechanically scanned microscope that reproduces the image point-by-point. Such a microscope (in water at room temperature) approaches optical resolution and, in liquid helium, has attained a resolution of 500 A. This device is now available commercially. Since acoustic waves require no staining of specimens to get adequate contact, this device has great impact in many areas of biological and medical science. Since the acoustic beam can be focused below the surface of materials that may be optically opaque, this instrument can also have unique applications in surface science. As an example, extensive work on high-resolution examination of surface and subsurface structure in integrated circuits has been done with this instrument under JSEP auspices.

Professor Auld has also made major contributions to the microwave acoustics work at Stanford. His well-known text, Acoustic Fields and Waves in Solids, provides a foundation for acoustic and microwave acoustic devices of all types. He has also contributed specifically to the surface wave programs and has generalized these ideas to include surface transverse waves on corrugated surfaces. His most recent contribution to the JSEP program was to provide means of domain wall control in certain ferroelastic materials. This holds promise for the development of a variety of programmable optical and acoustic filters and delay lines for signal processing devices.

This program has also included contributions in the area of low temperature devices. In particular, an effort led by Professor Beasley has resulted in the fabrication of Josephson junctions, with transition temperatures as high as $20^{o}K$, a range where small cryogenic refrigerators are available. This work has led to the fabrication of complete superconducting integrated circuits that operate at these relatively high temperatures. The technology developed holds immediate promise for high-speed analog signal processing circuits and, in the longer run, an integrated circuit technology in the mm/sub-mm-wave region.

Work on lasers, later to be termed quantum electronics, began at Stanford in the early 1960s. Professor Siegman, who had previously been working on microwave masers, began an effort to demonstrate optical communication with laser beams.

The results of the Stanford quantum electronics program have been many and varied. Only a few are named here. One of the most important is the invention by Siegman of the unstable optical resonator. By providing a large mode volume for a given cavity length, together with near diffraction-limited beam quality and all-reflective optics, the unstable optical resonator provides much higher powers and energies than would otherwise be possible and is widely used throughout the laser industry. This work has led to a new understanding of optical beams in all types of resonators, as well as in homogeneous media.

Other early results in quantum electronics at Stanford included the first observation of axial and transverse modes in a ruby laser, the first demodulation of both amplitude-modulated and frequency-modulated laser beams at microwave frequencies, and the invention of the FM laser.

Professor Pantell's early work on nonlinear optics and Raman scattering has also had wide ramifications. In particular may be noted polariton scattering that was used to generate the first tunable radiation in the far infrared.

Extensive and widely referenced work on mode locking was done at Stanford--frequency-domain formulations by Harris and time-domain formulations by Siegman and Kuizenga. Siegman's work on short pulses and mode locking led to the invention of a number of ingenious optically induced grating and four-wave mixing techniques for the measurement of picosecond and subpicosecond lifetimes in chemical and electronic processes.

An extensive program on nonlinear optics was also, in part, supported by the JSEP program. Stanford contributions included the first demonstration of optical parametric fluorescence by Harris and the first visible range optical parametric oscillator by Harris and Byer. This was followed by Harris' invention of frequency-mixing techniques in metal vapors that have, in subsequent years, opened up the coherent spectral region from 2000 A through about 300 A. Other ideas and techniques introduced that have many applications in the soft x-ray region of the spectrum include laser-induced collisions and the spontaneous tunable anti-Stokes x-ray radiation source invented by Harris.

Professor Byer's work on nonlinear optics has been prolific. Infrared optical parametric oscillators spanning the spectral region between 1μm and 20μm are now used throughout the world. Byer introduced the use of the unstable resonator to Nd:YAG lasers, which led to a generation of nonlinear optical products.

In the late 1970s, the JSEP program had a project under Professor Shaw on high-speed fiber optic signal processing using tapped optical fiber delay lines. Under JSEP, it was possible to address new and speculative approaches to the problem. It was soon recognized that, in a new applications area of fiber optics--that of fiber optic interferometric sensors--such a component, in the form of a fiber optic analog of a classical bulk optic beam splitter, had the potential for overcoming serious existing sensitivity barriers. In 1979, such a component, the form of a fiber optic counterpart of a (microwave) long-slot directional coupler, was developed under the JSEP program. This coupler had very high-performance characteristics and has had an enormous impact on fiber optic research in the laboratory and worldwide. It formed the basis for obtaining other support for a greatly expanded research program in fiber optic sensing and signal processing that led to the rapid development of other components--the demonstration of a fiber gyro with sensitivity increased by several orders of magnitude into the range needed for inertial navigation, and to a new class of devices for high-speed signal processing. This work created the class of devices that have come to be widely known as all-fiber devices.

We should note that perhaps the majority of the funding for the projects noted in the preceding paragraphs was supplied by other agencies of the Department of Defense and sometimes also by industry and private foundations. By providing seed money and continuity, the JSEP program has played a much more pivotal role in what has been accomplished than measured by its precise share of the total laboratory funds.

V. Current Direction of JSEP

A. Stanford Electronics Laboratory - Current Activities

The current SEL program includes studies in techniques for improved semiconductor device design and performance, lateral isolation technology, efficient insulators, effective CMOS devices that are cooled to liquid nitrogen temperatures, and investigations in the application of ternary compounds, such as InGaAs in optical devices and circuits. Also, a variety of investigations go forward in semiconductor surface properties, ultra-small dimension electronic devices, models, theories of Schottky barriers and ohmic contacts, and the use of channeled radiation to determine properties of semiconductor and multi-layer superlattice structures. In the field of communications sciences, real-time statistical data processing methods and naval coding techniques are under investigation.

B. Microwave/Ginzton Laboratory - Current Activities

The central theme of the Stanford JSEP program at present is the development of new material and device technologies that ultimately will allow ultra-high-speed electronic and optical processing of information. The programs that are now underway involve the physics and technology of linear and nonlinear optical materials and fibers, of acoustic surface waves and their interaction with discrete and distributed circuit elements, of picosecond and subpicosecond optical and electrical signals and their interaction with semiconductor materials, and of tunneling microscopes with angstrom-scale resolution. Studies are pursued in methods for characterizing and measuring electronic and electro-optical devices, in the growth of single fibers of various materials used in optical technology, in improved sensitivity, in the use of tunneling microscopes, and in methods of very high-microwave-frequency signal processing.

VI. The Future of JSEP

Since 1950, the JSEP program at Stanford has provided an important source of research funding. The program has been characterized by the continuity of the funding and by the freedom of the director to have reasonable discretion as to its application. It is believed that this latter point is of importance to the future. If JSEP money is to be used to support the most novel, innovative, and therefore risky of our projects, it is best that it be free (or nearly so) of the usual proposal-evaluation cycle. Also, it is believed that, when possible, this money should be used as seed money and that support for a particular project should be decreased as longer term and stable funding becomes available.

It appears that, once again, we are entering an exciting and promising era in electronics and opto-electronics. The possibility of constructing devices and materials on an atomic scale by molecular beam epitaxy (both of semiconductors and metals) by new methods of controlled sputtering, and by techniques related to tunneling microscopy, opens a new dimension of small-scale fabrication. The primary electronic effect of these ultra-small dimension structures is to create discrete electronic states, separated by a gap where there was a continuum of states for a normal three-dimensional solid. Thus, entirely new states and transitions between them are available to create new electronic and optoelectronic devices. This, in turn, also opens a new dimension for high-speed information processing with the requirement for new technologies for measurement on a picosecond time scale.

There are other areas of science and engineering, not now represented in our program, that also show promise for breakouts in electronics technology. The class of relativistic free electron lasers, Cerenkov lasers, and stimulated atomic scattering phenomena offer prospects for new electronic devices that span the spectral region from the far infrared to the soft x-ray region. The interplay of laser-produced x-rays and synchrotron-produced x-rays is rapidly opening an era where the physics of core-excited atoms becomes much more accessible to the physicist and device engineer. Here, too, new methods of diagnostic and material processing are on the horizon. These avenues also offer the prospect of new linear and nonlinear optical materials with unique information processing capabilities.

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University of Texas

E. J. Powers, JSEP Director

I. History

The Department of Defense Joint Services Electronics Program was established at the University of Texas at Austin in 1964. It was administered by the Laboratories for Electronics and Related Science Research (later renamed the Electronics Research Center in 1968) with Professor Arwin A. Dougal and Professor A. H. LaGrone serving as Director and Associate Director, respectively. In one sense the program grew out of an AFOSR contract on quantum electronics, with Professor Dougal as the Principal Investigator. The initial program had work units dealing with biomedical electronics; information sciences; physical, quantum, and plasma electronics; and space, atmospheric, and earth radio sciences.

The University of Texas Joint Services Electronics Program has been a dynamic one in that both the faculty involved and the focus of the research have continually evolved over the years. Dr. Arwin Dougal served as Director from 1964 to 1967, whereupon he accepted an assignment at the Pentagon as Assistant Director of Defense Research and Engineering (Research). Dr. C. L. Coates, a former Chairman of the Department of Electrical Engineering, served as Director from 1967 to 1971. Dr. Dougal again took over the Directorship in 1971. In 1977, Dr. Edward J. Powers was appointed Director, a position he still holds. Approximately 60 faculty members have participated in the Joint Services Electronics Program with the vast majority being drawn from the Departments of Electrical Engineering and Physics. For many of that faculty, JSEP provided seminal support for programs that were ultimately spun off and supported by DOD and/or other federal agencies. It has always been the policy of the JSEP program at Texas to have a mix of faculty participants that is both multidisciplinary and spans an experience spectrum ranging from new assistant professors to highly productive senior professors. This mix has contributed greatly to the vitality of the Texas program.

II. Accomplishments under JSEP Sponsorship

A synopsis of major accomplishments is given in the following paragraphs. In recognition of such accomplishments many of the faculty have been elected Fellows of the Institute of Electrical and Electronics Engineers or Fellows of the American Physical Society. In addition, the technical expertise and leadership of the JSEP faculty have been recognized in terms of their serving as editors and on the editorial boards of many of the top scientific and technical journals published in the U.S.A. Other recognition comes in the form of awards such as the Pattern Recognition Society's 1975 best paper award presented to Drs. J. K. Aggarwal and J. K. McKee for their work entitled, "Finding the Edges of the Surfaces of Three-Dimensional Curved Objects by Computer." Finally, the substantial contributions of many generations of graduate students should be acknowledged.

During the early years of JSEP, biomedical engineering activities were included in the program. The most significant research involved fundamental studies of the thermal response of tissue to laser irradiation. Early work initiated by JSEP and continued by the Air Force helped establish an internationally recognized laboratory for investigation of laser-tissue interactions. Recently the laboratory director (A. J. Welch) participated in a project for the Army to develop a battlefield simulation computer model to evaluate the effect of laser weapons on vision.

Solid-state electronics has been an integral part of the University of Texas JSEP Program. During the period 1965-70 W. H. Hartwig conducted extensive research in understanding residual RF losses in superconductors. Utilizing these findings Hartwig was able to design and fabricate superconducting resonant cavities with extremely high Q's (in the range 10^7 to 10^{10}). These cavities subsequently found many applications including relativity experiments and precision time-of-flight measurements.

Much of the solid state research during the period 1971-78 was focused on investigating the properties and applications of transition metal oxide thin films fabricated by chemical vapor deposition (CVD). W. H. Hartwig and K. J. Sladek conducted extensive research to define the basic process parameters of the deposition of TiO_2 thin films, to investigate and model the CVD reaction mechanisms, to model the formation and structure of the amorphous oxide, and to develop electronic devices exploiting their unique characteristics. In 1978, M. F. Becker and R. M. Walser reported the results of the first picosecond time-resolved phase transition in the solid state. Their work on processing and characterizing VO_2 was subsequently utilized by many DOD contractors employing these thin films for spacecraft thermal control and nuclear flash detection. Becker and Walser subsequently collaborated (during 1980-85) on studies of short-pulse laser damage in solids, especially semiconductors. They discovered widely used techniques for its systematic characterization. These methods are currently being used to specify the expected lifetime of optical components in high-power short-pulse laser applications.

In 1975, R. W. Bene and R. M. Walser became interested in understanding the interface reactions that occur at transition metal-silicon interfaces and lead to the formation of silicides. Their model of first compound formation in interface reactions successfully predicts the first phase formed in all transition metal and silicon and germanium diffusion couples and was the first compound selection rule developed for understanding phases selected by kinetics, rather than equilibrium thermodynamics. In addition, the work of Bene and Walser over the next few years was the first to show the importance of thin amorphous interphases on non-equilibrium interface reactions and demonstrate their role in determining the Schottky barriers at transition metal-semiconductor interfaces. These concepts found extensive use in understanding interface degradation in a variety of integrated circuit devices and in synthesizing contacts and barriers by solid-solid reactions.

Since 1981, J. L. Erskine has been studying similar issues in silicide planar growth processes. Using in-situ, angle-resolved photoelectron emission spectroscopy, in conjunction with theoretical calculations by L. Kleinman, he made the first detailed study of electronic states in silicides. He was also the first to report the role of diffusion layers in the formation of epitaxial nickel silicides. This work provided the first direct experimental verification of the selective growth mechanism associated with planar silicide growth.

The electromagnetics program dates back to 1964 and subsequent years when H. W. Smith and F. X. Bostick made significant contributions in the area of geomagnetics at extremely low frequencies such as 0.001-1.0 Hz. In addition to fundamental measurement of geomagnetic perturbations caused by solar wind interactions with the magnetosphere, the experience gained has been applied to problems important to DOD such as detection of ship movement from measurement of man-made perturbations. The magnetotelluric measurement system has been developed and used for characterizing subsurface resistivities. The system has been useful for site surveys for project Sanguine/Seafarer.

Since 1979, T. Itoh has studied wave interaction with devices and circuits for millimeter-wave integrated circuits. To alleviate deteriorating performance of active and control devices at millimeter-wave frequencies, structures based on distributed interactions have been analyzed and tested. (As the wave is guided in such structures, it interacts with the gain or control mechanisms). Examples studied include distributed IMPATT diodes, distributed Gunn diodes, nonreciprocal directional coupler and slow-wave distributed Schottky phase shifters. As the frequency is increased, these configurations provide greater potential as alternatives for conventional devices. Further, they are suited for monolithic configuration. Several industrial companies are attempting to make these devices.

In recent years, E. J. Powers has developed a number of digital time series analysis techniques that have proven extremely powerful in analyzing and interpreting fluctuation data associated with nonlinear wave and turbulence phenomena in a variety of different physical media. Many of these techniques have been adapted and applied by a variety of research groups around the world to nonlinear wave problems in oceanography, ionospheric physics, plasmas, and transition to turbulence, for example.

Early work in quantum electronics included fundamental work in laser-induced breakdown in super-high-pressure gases, self-induced transparency, laser scattering from rough surfaces, and the first holograms of optically polarizable materials through development of laser microholography, to cite but a few examples. L. Frommhold provided basic input for the analysis of the far infrared spectra collected by NASA's Voyager Missions, from first principles. Based on his fundamental JSEP work, he was able to show that unexplained structures in the IRIS spectra are due to $(H_2)_2$ and H_2N_2 van der Waals dimers, thus making available new diagnostic features of planetary atmospheres. In 1982 J. Keto could, for the first time, show the temporal development of the energy flow by a two-photon UV excited Xe atom in a dense Xe gas. Molecular species at high temperatures show particular reactivities. The understanding of the reaction dynamics was the goal of M. Fink's work in this area. The investigating tool was an electron diffraction apparatus with sufficient sensitivity to record data with less than 0.001 Torr vapor pressure. He demonstrated that most highly ionic salts vaporize with significant cluster formation and the cluster structures deviate significantly from previous predictions. These results are of great interest to all vapor deposited thin-film-forming amorphous solids.

The information electronics program has addressed a variety of theoretical and pragmatic problems in areas including digital signal and image processing, nonlinear estimation, pattern recognition, quasi-perfect codes, parallel processing architectures, automata, optimal adaptive control, and natural languages. Highlights of some of the major accomplishments include the following selected examples: Eighteen new quasi-perfect double error-correcting codes were discovered by T. J. Wagner. These codes have technological applications in defense communication, computer, data storage, and retrieval systems. S. I. Marcus has investigated the problem of extracting information about a system from noisy measurements by means of nonlinear state estimation. He has discovered new finite dimensional recursive estimators for certain classes of problems, and he has shown that no such estimators exist for other classes of problems. J. L. Speyer has designed a new nonlinear estimator, the Modified Gain Extended Kalman Filter. This filter has applications in advanced missile guidance with bearings-only measurements. Some fundamental properties of time-varying digital signal processing systems were discovered by J. K. Aggarwal in 1980. By developing a systematic theory, he has shown explicitly the errors committed in approximations made by several earlier researchers. Filters designed on the basis of the above results have found extensive use in the seismic data processing industry. C. V. Ramamoorthy, K. M. Chandy, and M. J. Gonzalez formulated their early ideas in 1972 on optimal scheduling strategies in a Multi-Processor System. These ideas are among more fundamental contributions in this area.

It should also be noted that the Joint Services Electronics Program at The University of Texas played a key role in the development of the graduate research program of the Department of Electrical Engineering, now the Department of Electrical and Computer Engineering. Also the program has favorably impacted the Department of Physics, particularly in the quantum electronics area. JSEP has provided a source of stable funding that, in addition to supporting well defined research goals, has also permitted young faculty to inititate their research careers and at the same time permitted senior faculty to pursue high-risk research programs. It is in this sense that JSEP is truly unique amongst university research programs.

III. Present Status of JSEP at University of Texas, Austin

The University of Texas JSEP Program has four major thrust areas--solid-state electronics, electromagnetics, quantum electronics, and information electronics. The overall theme of the program is to undertake fundamental, and in some cases high-risk studies that, if successful, should have quite a high payoff.

Solid-state electronics constitutes approximately 40% of the program and is concerned with fundamental studies in semiconductor physics and technology. The program is designed to address basic problems that must be solved for development of the next generation of electronic and optical devices. In the electromagnetics area, several novel monolithic millimeter-wave integrated circuit structures are being investigated for use as quasi-optical array elements. In other work, advanced higher-order spectral analysis concepts are being utilized in fundamental studies of nonlinear wave phenomena.

Quantum electronics research has as its overall theme the study of optical quantum effects with emphasis on nonlinear optical phenomena such as optical bistability and nonlinear Raman scattering. It is the general objective of the information electronics research program to address the difficult questions of analyzing and implementing systems that are nonlinear, time-variant, or stochastic, or that are not accurately described by well-defined mathematical models, and that arise in numerous applications. Current research in information electronics centers around two specific topics: the application of artificial intelligence techniques to the development of rule-based methods for the extraction of information from signals and nonlinear estimation and detection.

As was mentioned previously, JSEP played an extremely important role in the evolution of electronics-related graduate research program at the University of Texas at Austin. Twenty-one years later we find this University engaged in an almost unprecedented acceleration of its graduate research program in science and engineering. For example, 30 new faculty positions were created in 1983 for microelectronics, computer engineering, and computer science. In 1984, the University announced the creation of 32 one-million dollar endowed chairs. Of particular importance to JSEP is the fact that four each are dedicated to microelectronics, materials science and engineering, physics, and chemistry. Thus, it is clear that many new faculty (both junior and senior) will be joining the University of Texas over the next several years, and it is almost a certainty that many of them will participate in future JSEP programs. The professional research interests of these individuals will play a key role in defining future thrust areas of the JSEP program as they relate to the scientific and technology needs of both industry and the DOD.

Finally, the role that JSEP at the University of Texas and other schools plays in the education of graduate students should not be overlooked or underestimated. For example, the three Texas JSEP directors all received their graduate education at JSEP schools (MIT, Stanford, and University of Illinois). Similarly, many of the Texas JSEP graduates are playing key roles in academia, industry, and government. It is the combination of new research results combined with the continuous generation of well-educated scientists and engineers that has made JSEP one of the most beneficial research programs to the DOD and the country as a whole.

Acknowledgment

The members of the Technical Coordinating Committee (TCC) wish to express their great appreciation for the many hours spent by the JSEP Laboratory Directors and numerous other current and former JSEP university participants in the thoughtful and skillful preparation of material for this commemorative volume. Without dedicated effort such as this, the JSEP 40th Anniversary Celebration would not have been possible.

The JSEP TCC:

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Jimmie R. Suttle, Army Research Office
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This book was produced by ANSER (Arnold Shostak, editor) under contract DAAG29-81-D-0100 from Battelle Columbus Laboratories.

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