THE HISTORY OF
ELECTROMAGNETIC THEORY

by

Frederick B. Wood

Electrical Engineering 298
University of California
January 10, 1947

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

The object of this paper is to summarize the history of electromagnetic theory from an engineering point of view preparatory to the investigation of some specific problem involving the application of electromagnetic theory. To determine how this paper should differ from a review paper of the type published in Reviews of Modern Physics, let us examine what is meant by an engineering point of view. The Engineers' Council for Professional Development, which is jointly sponsored by the principal engineering societies including the American Institute of Electrical Engineers, has published the following on engineering:

> The engineer may be regarded, therefore, as an interpreter of science in terms of human needs and a manager of men, money, and materials in satisfying these needs.[1]

The mention of "human needs" raises many questions which initially submerge the mathematical and physical aspects under a deluge of social problems involving economic, psychological, political, legal, ethical, and religious arguments. This results in a serious problem of establishing a perspective by which recognition can be given to the social aspects without losing sight of electromagnetic theory.

The E.C.P.D. has described the research function of engineering as follows:

> Research is the process of seeking new knowledge or a better understanding of the significance and relationship of facts already known--the "scientific method" of working from known facts toward the unknown; toward new ideas, facts, principles, materials, or processes. The "pure scientist" is interested mainly in discovering something new; the engineer is interested mainly in turning that something new into something useful.[2]

Mention of "useful" raises the question of what it is useful for--murder or improvement of the welfare of mankind? This appears to require that the perspective have a large time scale so that the present social problems become very small compared to the total progress of mankind.

To establish this necessary perspective a distribution of emphasis as shown in figure 1 has been employed. The expected distribution for a physics paper is shown compared with the distribution used in this paper. The gap between this paper and the actual investigation of a specific problem is also illustrated. This gap consists of two parts: additional study of the mathematical and physical research previously done in some branch of the application of electromagnetic theory such as microwave wave guide transmission; and a careful survey of the work being done in the social sciences relating to the interpretation of "human needs" and the meaning of "useful". The procedure results in reduction of the coverage of the mathematical and physical aspects of the subject at this stage in order to live up to the responsibilities of an engineer.

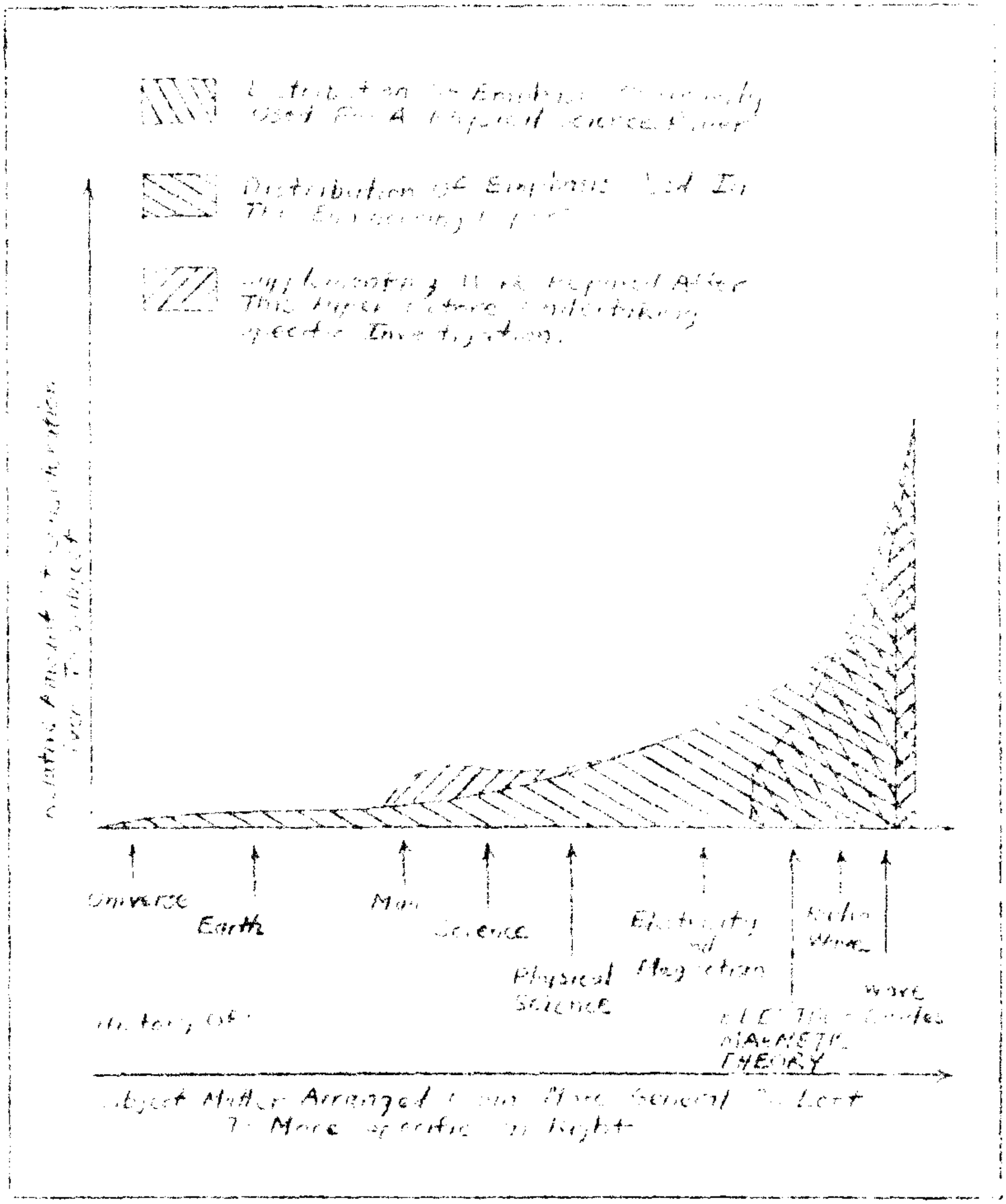


Figure 1 - Approximate Distribution of Emphasis In This Report

II. PERSPECTIVE

The great advances in our scientific knowledge in the last fifty years have been accompanied by an increasing degree of specialization. This procedure of concentrating upon a narrow portion of a particular field is necessary for the discovery of new knowledge, but has suffered from defects due to the ignorance of some specialists concerning the relationships between their work and the general problems of mankind.

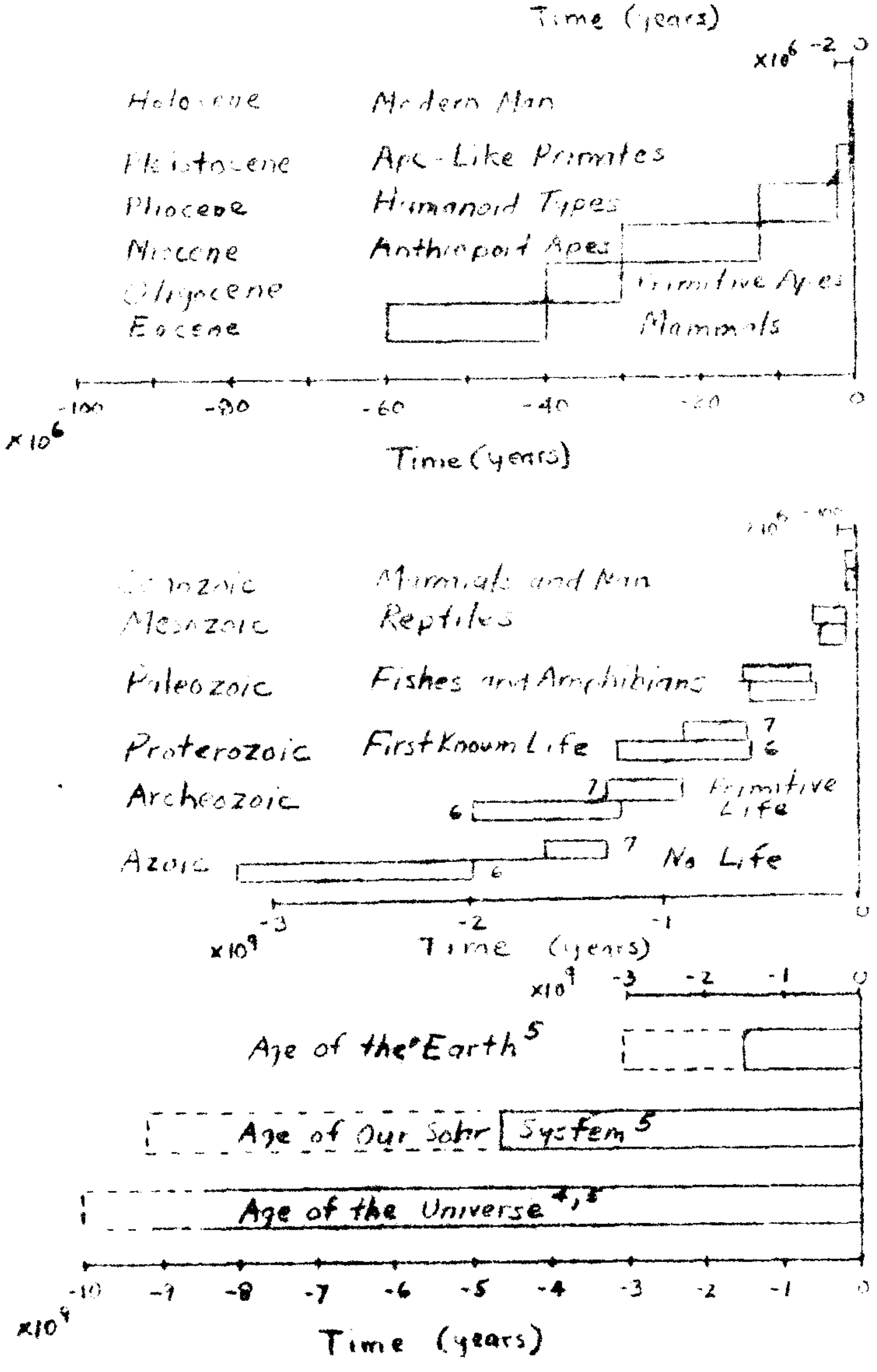
To avoid serious difficulties in the consideration of the history of electromagnetic theory, a perspective is here developed to briefly indicate the relationship of progress of our knowledge of electromagnetic theory to human progress in general. This perspective can be divided into three parts--present, historical, and future. The present and historical aspects are briefly mentioned in this chapter while the future aspects are considered in the appendix. Much of this material on perspective is quite elementary. However, it is included here, because there are indications that the neglect of this material may be a contributing factor to the confusion of some engineers and scientists.

The present perspective concerns the understanding of the relationship between different types of natural phenomena. By considering only the more elementary phenomena, we can arrange them in an order of increasing dependency upon the preceding types of phenomena. For brief discussion the following oversimplified arrangement, similar to that of August Comte,[3] can be used in which each type of phenomena is dependent upon the types below it:

Social
Psychological
Biological
Chemical
Physical

Electromagnetic phenomena are basic physical phenomena, and they are [illegible] basic to all natural phenomena.

The historical perspective covers the period of the assumed existence of electromagnetic phenomena. Figure [illegible] illustrates the approximate sequence of events of the universe; important to mankind, geological eras of the earth, the development of man, and the evolution of man's thinking. The development of the scientific method appears as something very new in respect to the span of time covered. The rise and fall of various civilizations and the confused state of our present civilization do not show up on this historical perspective. To avoid lack of balance from disregard of discontinuities and cycles in the evolutionary progress of mankind, so a kind of future perspective appears necessary as discussed in the appendix.



Geological Periods of Cenozoic Era

Geological Eras of the Earth 6,7

Figure 2 - Historical Perspective (Part One)

From EE 298 Seminar Paper, "History of Electromagnetic Theory," 1/10/47.

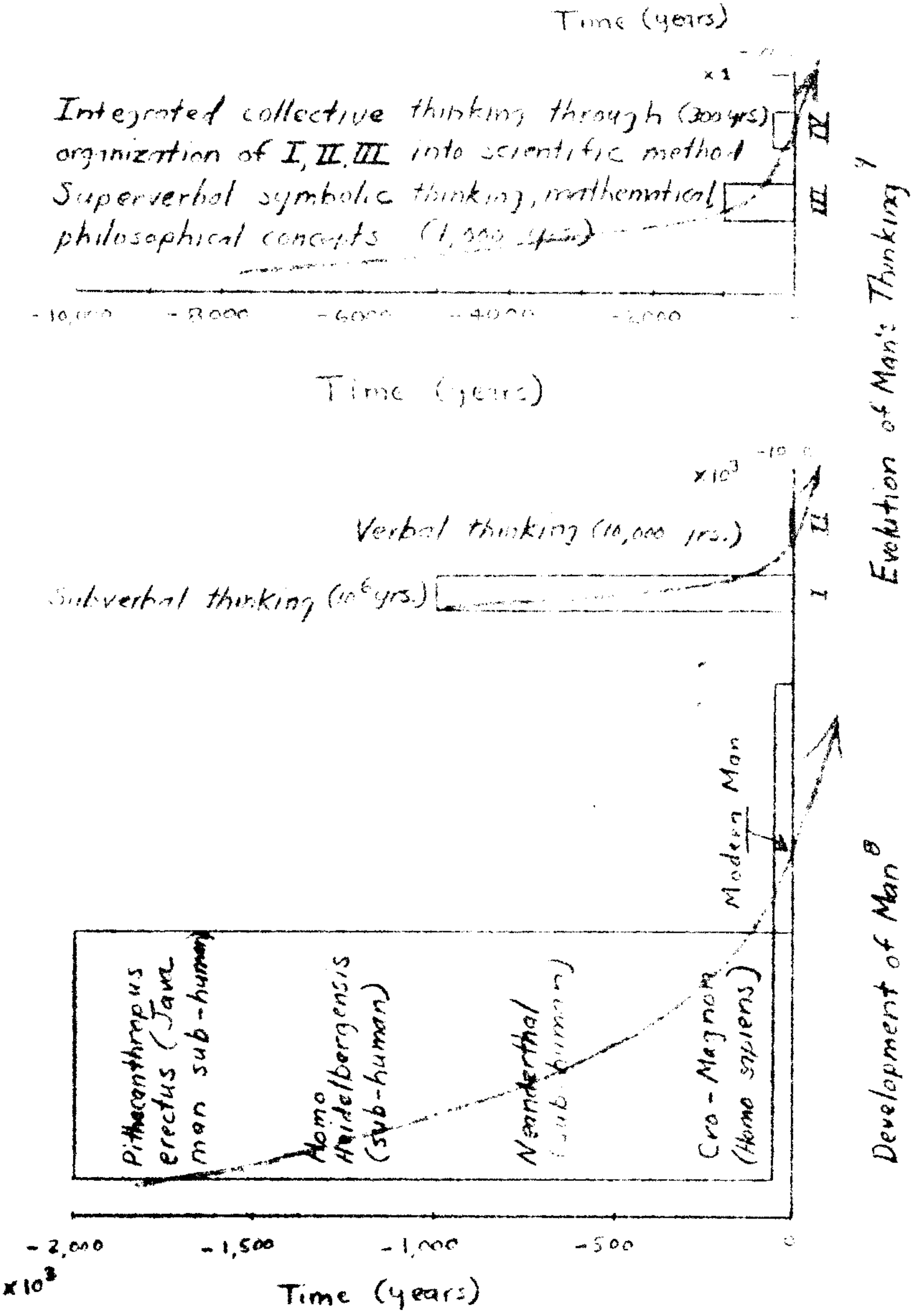


Figure 2 - Historical Perspective (Part Two)

III. OUTLINE OF HISTORY OF ELECTRICITY AND MAGNETISM[10, 11, 12]

A. Static Period, 1600-1799

1600: William Gilbert published his researches on magnets, magnetic bodies, and electrical attractions, entitled *De magnete, magneticisque corporibus, et de magno magnete tellure*.

1752: Benjamin Franklin identified atmospheric electricity with static electricity.

1766: Priestly concluded that inverse square law applies to electric charges.

1785: Coulomb established with precision the inverse square law for magnetic poles suggested by John Michell.

B. Current Period, 1799-1831

1800: Volta developed the voltaic pile (battery) following investigations of frogs legs by Galvani.

1820: Oersted discovered that a wire carrying a current produced a magnetic field.

1820: Ampere established law of force upon a current element in a magnetic field.

1825: Ampere showed that an electric circuit is equivalent in its magnetic effects to a magnetic "shell," magnetized at right angles to the surface, whose boundary coincides with the circuit.

1826: Ohm established Ohm's Law through analogy of heat flow.

C. Electrotechnical Period, 1831-1865

1831: Faraday discovered electromagnetic induction of currents; made first dynamo.

1832: Henry discovered self-induction.

1833: Faraday found that the mass of substance liberated in electrolysis is proportional: 1) to the quantity of electricity passed through, and 2) to the chemical equivalent weight of the substance liberated.

1845: Faraday found that the plane of polarization of light is changed by passing through glass between the pole faces of a magnet. He found all substances have some magnetic properties; defined diamagnetic and paramagnetic.

1846: Kirchoff developed a theorem of the currents in a network.

1847: Helmholtz proposed the principle of conservation of energy.

1856: Weber and Kohlrausch measured the ratio of electromagnetic units to electrostatic units.

D. Systematic Period, 1865-1895

1865: James Clerk Maxwell developed the fundamental equations of the electromagnetic field after studying Faraday's experimental work. He suggested that light consisted of electromagnetic waves.

1873: Maxwell published his Treatise on Electricity and Magnetism.

1876: H. A. Rowland showed experimentally that a moving electro-static charge produced a magnetic field like a current in a conductor.

1883: Fitz Gerald showed theoretically that a coil carrying a rapidly alternating current should radiate electric waves on the basis of Maxwell's theory.

1886-1888: Hertz experimentally verified the existence of electromagnetic waves formulated by Maxwell. Waves from a spark gap oscillator were detected by another spark gap.

1886: Michelson and Morley found insufficient experimental evidence for a fixed ether (first exp. in 1881).

1887: Hertz showed that the electromagnetic waves he produced were plane polarized.

1893-1895: Fitzgerald and Lorentz explained results of Michelson-Morley experiment by theory of contraction of length with velocity.

1896: Marconi used electromagnetic waves for signalling.

E. Atomic Period, 1895-1915

1895: Roentgen discovered X-rays. In 1881 J. J. Thomson had pointed out that the sudden stopping of cathode rays should in accordance with Maxwell's theory produce electromagnetic radiation like light waves.

1896: Becquerel discovered radiocactivity.

1897: J. J. Thomson's demonstration of electrostatic as well as magnetic deflection of cathode rays established the electron theory which had been in process of development by Franklin (1756), Faraday (1833), Weber (1871), Crookes (1879), and Stoney (1891).

1900: Max Planck developed quantum theory of radiation for energy emitted by a black body.

1905: Einstein postulated photoelectric law in which energy radiated consists of discrete quanta. Einstein developed special theory of relativity applying to systems with uniform velocity; principle of relativity of uniform motion; principle of the constancy of the velocity of light.

1909-1913: Millikan accurately determined ratio e/m and proved existence of a unit charge, the electron.

1912: J. J. Thomson developed mass spectograph.

1913: Niels Bohr developed theory of atom in which electrons may have only certain orbits, and radiate electromagnetic waves when of discrete quanta when electrons change from one orbit to another.

1913: Laue measured wavelength of X-rays and studied crystal structure by studying the diffraction of X-rays by crystals.

1913-1917: Einstein developed general theory of relativity: an extension of special theory to the case of accelerated systems.

F. The Quantum Period, 1915-1926

1916: Millikan experimentally proved Einstein's photoelectric law, accurately determined Planck's constant.

1919: Rutherford showed that the nucleus of an ordinary element could be changed by bombardment with high-energy alpha particles.

1923: A. H. Compton showed that X-rays scattered by crystals have an increase in wavelength that is in agreement with quantum theory.

G. The Wave Mechanics' Period, 1926-1931

1925: de Broglie proposed the concept of a wave-electron, combining quantum theory and wave theory.

1926: Schroedinger developed wave equations.

1927-1928: Heisenberg and Dirac developed quantum mechanics using matrix calculus.

1927-1928: Davisson and Germer and also G. D. Thomson obtained experimental proof of the wave-electron.

1928-1929: Stern found that shooting molecules onto the atomic lattice at crystal surfaces formed scattering patterns which confirmed the wave mechanics theory.

H. The Nuclear Period, 1931-

1931: E. O. Lawrence developed cyclotron for acceleration of ions for use in study of atomic nuclei.

1931: Anderson discovered position.

1932: Chadwick discovered neutron.

1934: Curie-Joliots produced artificial radioactivity.

1934: Fermi proposed bombardment of nuclei with neutrons.

1936: Barrow and Southworth independently demonstrated possible practical use of wave guides.

1939: Hahn and Strassmann discovered that an isotope of barium was produced by bombardment of uranium with neutrons.

1939: Frish and Meitner predicted that absorption of a neutron by uranium sometimes causes nuclear "fission" with release of enormous energy.

1940: Over sixty articles on transmission of electromagnetic waves in waveguides had been published.

1940-1945: M.I.T. Radiation Laboratory in coöperation with industry and governmental agencies applied electromagnetic theory to the design of microwave radar.[13]

1941: Over one hundred articles on nuclear fission had been published, plus several review articles and books.

1942-1945: O.S.R.D., Manhattan Project, and coöperating agencies applied nuclear physics to the problem of releasing nuclear energy for military purposes which resulted in development of atomic bomb.[14]

IV. BASIC HISTORY OF ELECTROMAGNETIC THEORY

A. Action at a Distance Theories

Early attempts to formulate theories of electricity and magnetism were based on finding applications of gravitational theory which would explain electromagnetic phenomena.

Newton had clearly and rigorously formulated the inverse square showing the gravitational attraction between two bodies as follows:

$$F = G \frac{m_1 m_2}{r^2} \tag{1}$$

Where G is a constant; m_1, m_2 are the masses of the two bodies; and r is the distance between them. Following the work of Priestly, Michel, and others, Coulomb's Laws for electric charges and magnetic poles were established as follows:

$$F = C_1 \frac{q_1 q_2}{r^2} \tag{2}$$

$$F = C_2 \frac{p_1 p_2}{r^2} \tag{3}$$

Where F is force; C_1, C_2 are constants; q_1, q_2 are electric charges; p_1, p_2 are magnetic pole strengths; and r is distance between charges or magnetic poles.

Laplace invented the method of considering the components of a vector as the first derivative of a certain function of the coordinates with respect to the coordinates.[15]

Lagrange developed such a function V in gravitation theory such that the force on a particle satisfies Laplace's equation:

$$\nabla^2 V = 0 = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \qquad (4)$$

Where V is the sum of the mass of each particle divided by its distance from the point. Poisson showed that many concepts from gravitation theory could be used in electrostatics. He showed that the distribution of charges on a conductor can be obtained through solution of Laplace's Equation (eq. 4). Poisson's equation relating potential and charge density at a point is:

$$\nabla^2 V = -\frac{4\pi\rho}{\epsilon'} = \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2} \qquad (5)$$

Where V is the potential at a point, ρ is electric charge density, and ϵ^1 is specific inductive capacity. When the charge density is zero eq. (5) reduces to (4). Green gave the name potential to the function V in eq. (5) and extended the work of Poisson. Green developed a theorem connecting surface and volume integrals.[16]

B. Faraday's Researches

Michael Faraday's discovery in 1831 that electric currents are induced in conductors moving with respect to a magnetic field[17] laid the basis for Maxwell's formulation of the basic equations of electromagnetic theory. Faraday's experimental demonstration of magnetic rotation of the plane of polarization of light[18] in 1845 increased the evidence of a relationship between light and electricity and magnetism. In

1852 he discussed lines of magnetic force as physical lines of force quite different from gravitational forces.[19] Faraday reported his researches in great detail, using extensive word descriptions of his ideas and experiments. There was considerable question as to whether Faraday's views or the theories of action at a distance were correct. Maxwell undertook to study Faraday's researches and put them in mathematical form. Maxwell comments on his analysis as follows:

> When I had translated what I considered to be Faraday's ideas into a mathematical form, I found that in general the results of the two methods coincided so that the same phenomena were accounted for, and the same laws of action deduced by both methods, but that Faraday's methods resembled those in which we begin with the whole and arrive at the parts by analysis while the ordinary mathematical methods were founded on the principle of beginning with the parts and building up the whole by synthesis.[20]
>
> In a philosophical point of view, moreover, it is exceedingly important that two methods should be compared, both of which have succeeded in explaining the principal electromagnetic phenomena, and both of which have attempted to explain the propagation of light as an electromagnetic phenomenon and have actually calculated its velocity, while at the same time the fundamental conceptions of what actually takes place, as well as most of the secondary conception of the quantities concerned are radically different.[21]

C. Maxwell's Equations

Maxwell extended Faraday's ideas by mathematical formulation and by the concept of displacement current. Maxwell expressed his equations in quaternions and also in complete form for all three components in Cartesian coördinates. Other scientists later translated Maxwell's equations into the vector form now used. In Gaussian units Maxwell's equations for bodies at rest are:

$$\text{curl } \overline{H} = \frac{4\pi}{c}\overline{I} + \frac{1}{c}\frac{\partial \overline{D}}{\partial t} \tag{6}$$

$$\text{curl } \overline{E} = -\frac{1}{c}\frac{\partial \overline{B}}{\partial t} \tag{7}$$

$$\text{div } \overline{D} = 4\pi\rho \tag{8}$$

$$\text{div } \overline{B} = 0 \tag{9}$$

In 1866 Maxwell published his mathematical theory of the electromagnetic field and predicted the existence of electromagnetic waves traveling with the velocity of light.[22] From equations (6) and (7) he obtained:

$$\frac{\partial^2 E_Y}{\partial t^2} = c^2 \frac{\partial^2 E_Y}{\partial x^2} \tag{10}$$

From the general equation for plane waves

$$E_y = f\,(x - vt) \tag{11}$$

he obtained:

$$\frac{\partial^2 E_Y}{\partial t^2} = v^2 \frac{\partial^2 E_Y}{\partial x^2} \tag{12}$$

The similarity of equations (11) and (12) when $v = C$ suggested that electromagnetic waves should travel in free space with the velocity of light.

The Faraday-Maxwell theory of electromagnetic phenomena was only accepted by part of the scientific world. The lack of experimental verification of electromagnetic waves appeared to be the largest obstacle to general acceptance. Sir William Thomson, Feddersen, and others had pointed out the oscillatory nature of the Leyden jar discharge. Fitzgerald in 1883 showed from Maxwell's equations that a coil carrying a rapidly alternating current should radiate electric waves.

D. Experimental Verification and Interpretation of Electromagnetic Waves by Hertz.

Heinrich Hertz conducted a series of experiments starting in 1886 for the purpose of testing the hypothesis of Maxwell's theory. He used an induction coil and spark gap as source. Sparks were found to occur across a gap in separate enclosed loop of wire placed near the spark gap. Phenomena not explainable by theories of action at a distance are reported in 1887 and 1888. The most convincing proof of Faraday's and Maxwell's theory was his demonstration that plane polarized waves existed by rotation of the secondary loop and that they had a finite velocity akin to that of light by measurement of wavelength of standing waves on a wire and checking of velocity of propogation in space by interference between standing waves on the wire and the waves propagated through space.[23] He also demonstrated reflection and refraction of electromagnetic waves.[24]

Hertz showed that electric oscillations could be explained without making distinction between electrostatic and electromagnetic forces. He introduced a vector Π which is now called the "Hertzian Vector."[25]

Π is a function of ρ, z, t which satisfied the equation:

$$A^2 \frac{d^2\Pi}{dt^2} = \nabla^2 \Pi \qquad (13)$$

for the case where the electric force is symmetrical about the z - axis

$$\rho = \sqrt{x^2 + y^2} \qquad (14)$$

A = reciprocal of velocity of light

Components of electric force		Components of magnetic force	
$X = -\frac{d^2\Pi}{dx\,dy}$	(15a)	$L = A\frac{d^2\Pi}{dy\,dt}$	(16a)
$Y = -\frac{d^2\Pi}{dy\,dz}$	(15b)	$M = -A\frac{d^2\Pi}{dx\,dt}$	(16b)
$Z = \frac{d^2\Pi}{dx^2} + \frac{d^2\Pi}{dy^2}$	(15c)	$N = 0$	(16c)

This Hertzian vector satisfies its equation throughout space except at the z - axis where it is discontinuous for a wire, or at the origin for a rectilinear oscillator.

E. Interpretation and Development of Electromagnetic Theory

Stratton has pointed out that Maxwell did not devote very much space in his writings to his own most important equations.

> The pattern set nearly 70 years ago by Maxwell's Treatise on Electricity and Magnetism has been a dominant influence on almost every subsequent English and American text, persisting to the present day.... from the single point of view of Faraday. Thus it contained little or no mention of the hy-

> potheses put forward on the continent in earlier years by Riemann, Weber, Kirchhoff, Helmholtz, and others.... Only the original and solitary genius of Heaviside succeeded in breaking away from this course.
>
> For an exploration of the fundamental content of Maxwell's equations one must turn again to the Continent. There the work of Hertz, Poincairé, Lorentz, Abraham, and Sommerfeld, together with their associates and successors, has led to a vastly deeper understanding of physical phenomena and to industrial developments of tremendous proportions.[26]

Jeans relates that at the end of the nineteenth century scientists believed that the way opened by Maxwell would lead to an explanation of the whole universe in terms of electromagnetic theory.[27] This view was checked by the Michelson-Morley experiments which made the existence of the ether doubtful and by the verification of the quantum theory in which some phenomena were not satisfactorily described by electromagnetic theory. Stratton states that the statistical average of quantum electrodynamics over large numbers of atoms must lead to Maxwell's equations.[28]

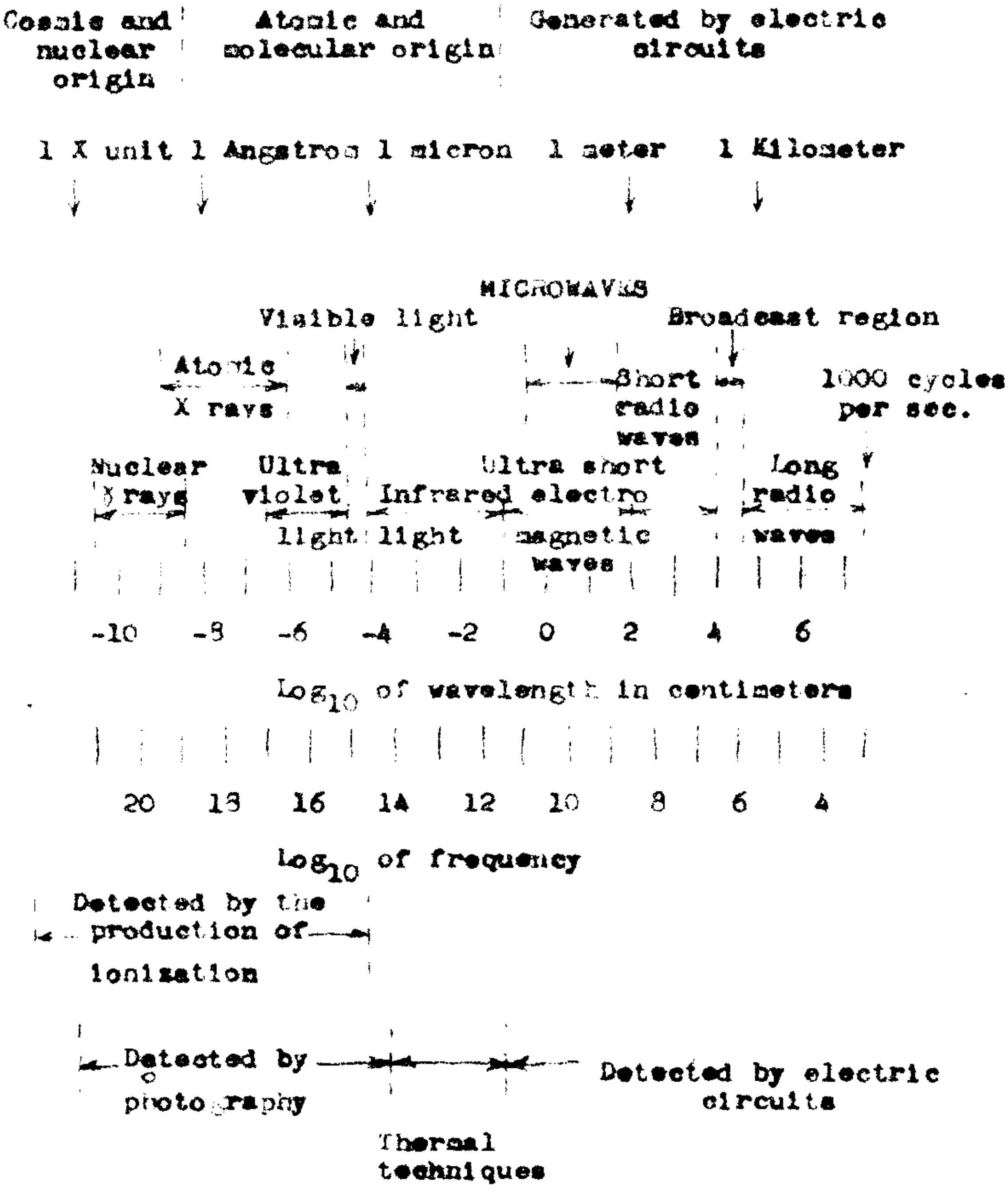
Maxwell's equations do not conflict with relativity theory. They can be mathematically derived from the relativity geometry of Weyl.[29] They can also be derived from the physical picture of electric lines of force consisting of elements moving with the velocity of light by applications of the theory of relativity in the manner described by Page and Adams as the emission theory.[30]

V. APPLICATION OF ELECTROMAGNETIC THEORY

A. Electromagnetic Spectrum[31]

The extension of our knowledge of the electromagnetic spectrum started before Maxwell by the experimental discoveries that there were radiations outside the visible light spectrum. Herschel found infra-red radiations in 1800 and Ritter and Wollaston independently found ultra-violet rays in 1802. By 1850 these radiations had been experimentally proved to have the properties of reflection, refraction, polarization, and interference of visible light.

Maxwell's electromagnetic theory of 1865 and the experimental work of Hertz of 1888 related waves generated by electric circuits to light waves. Röntgen discovered X-rays in 1895 and Villard discovered gamma rays in 1900. X-rays were not accepted as a part of the electromagnetic spectrum until Laue established the diffraction of X-rays by crystals. Rutherford and Andrade showed that gamma rays were of the same nature as X-rays in 1914. Numerous scientists not mentioned here have filled in the gaps to make our knowledge of the electromagnetic spectrum cover the region shown in figure 3.



McGraw-Hill Book Co.

Figure 3 - The Electromagnetic Spectrum [32]

The application of electromagnetic theory to the whole electromagnetic spectrum has greatly expanded our knowledge of natural phenomena. For this paper we shall concentrate on the application of electromagnetic theory to communications.

B. Communications Applications

Faraday's discovery of electromagnetic induction expedited the development of the practical dynamo and the practical electric telegraph which started the two principal branches of the electrical industry--electric power and electric communication. The early inventions which made electric power generation and communication by telegraph practical while dependent upon the existing knowledge of electricity and magnetism, resulted more from trial and error experimenting than upon mathematical theory. As the development of the electrical industry progressed, the careful application of mathematical theory became more important.

The more significant communication applications of electromagnetic theory and the more important implementing inventions are listed in the following table:[33]

1827: Savary magnetized a steel needle from Leyden jar discharge.

1832: Morse conceived the idea of the dot-dash-space type of code using electromagnets as telegraph instruments after hearing of Faraday's discovery of electromagnetic induction of 1831 and that an electric charge travels on a wire with an almost instantaneous velocity.

1837: Crooke and Wheatstone patented electric telegraph in England, and Morse patented electric telegraph in the United States.

1840: Henry produced high-frequency electric oscillations.

1865: Maxwell developed electromagnetic theory.

1876: Bell invented the telephone.

1879: Hughes discovered the phenomenon upon which the coherer is based.

1883: Fitzgerald showed theoretically a method of producing electromagnetic waves.

1886-1888: Hertz experimentally verified existence of electromagnetic waves.

1896: Marconi used Hertzian waves for wireless telegraph use over a distance of one and three-quarter miles.

1897: Marconi established ship to shore radio telegraph transmission over 18 mile distance.

1898: First paid radiogram transmitted.

1903: Transatlantic commercial radio telegraph was established.

1906: De Forest patented vacuum rectifier (audion).

1907: Baekeland discovered the first phenol formaldehyde resin which was manufactured as Bakelite. This was an important step in making possible the mass production of radio and telephone parts.

1912: Federal laws regulating use of radiotelegraphy were established to promote safety at sea.

1912: First practical trials with radio telegraph on railroad trains were made.

1912-1914: Development of the thermionic tube made possible the development of radio telephone during World War I.

1914: Armstrong was issued patent on regenerative circuit.

1915: American Telephone and Telegraph Co. and Western Electric Co. established experimental radio telephone communication from Arlington, Virginia, to Hawaii and Paris.

1919: DeForest experimented with radio telephone broadcast of music.

1920: Commercial broadcasting was established.

1922: Wire telephone lines were used to interconnect radio stations for simultaneous broadcast of the same program.

1922-1924: Regulation of radio broadcasting and assignment of frequencies was accomplished by cooperation between the Department of Commerce and representatives of the radio broadcasting industry.

1923: Haseltine developed neutrodyne system of neutralization of grid-plate capacity in triode tubes.

1925: Radio-compass direction finder came into general use on ships.

1926: National Broadcasting Company was organized by General Electric Company, Westinghouse Electric and Manufacturing Company and Radio Corporation of America.

1927: Federal Radio Commission was established after court decision held Department of Commerce had no authority to deny licenses or to enforce frequency assignments.

1928: Development of cathode ray tubes had advanced to point where electronic television appeared possible.

1934: Federal Communications Commission was established to handle national broadcast regulation and also interstate and foreign telephone and telegraph communication by wire and radio.

1936: Armstrong showed that frequency modulation could be used to reduce interference.

1936: Television broadcasting started in England.

1939: Public television broadcasting was started in the United States.

1940-1945: Radar was used in World War II.

1942-1945: Radar countermeasures were developed by the Harvard Radio Research Laboratory to counteract German, Japanese, and Italian radar.

C. Relations with Social Problems

The early stages of the development of communications facilities through the application of electromagnetic theory were marked by many benefits which fulfilled human needs for rapid communication. As the communications industry developed, many problems came up as to how these new instruments could best serve human needs. The American Academy of Political Science published studies of the political and social problems related to radio broadcasting in 1929,[34] 1935,[35] and 1941.[36] The Federal Council of Churches of Christ in America has studied the ethical problems related to radio program planning and advertising.[37] The National Association of Broadcasters adopted a code in 1939 to set standards for radio programming to avoid the danger of getting more stringent government regulation.[38] The Library of Congress periodically prepares bibliographies of articles on radio and radio broadcasting.[39]

J. G. Crowther wrote the following comments on the social problems related to radio in 1937:

> ... Radio is in some ways the most powerful instrument ever put into the hands of man. With it, one person may address instantly the whole world. It has been of immense aid to governments and especially

> to dictators. The same idea may be put simultaneously into everybody's head. This produces uniform thought, which facilitates dictatorial discipline.[40]

> The radio, which has given so much aid to dictators, was developed into a practical form chiefly by Marconi. This Italian scientist and inventor joined the Italian Fascist Party at the early date of 1923.[41]

> But the improvement of technique does not always favour the aggressor, or those who at the moment control the military equipment. Radio assists dictators so much at the present time because, at the present stage of development of radio technique, large-scale equipment is required. As this is expensive it may be owned only by wealthy corporations or governments.... Further improvements of radio technique is making apparatus smaller and smaller, and more and more sensitive. In the future, every man will be able to make his own radio transmitter, and carry it about with him in his coat pocket.... So it is possible to hope that radio, which at present aids dictatorship, will presently work in favour of democracy.[42]

The utilization of the instruments derived from the application of electromagnetic theory for anti-social purposes may be related to the slowness of the development of the social sciences in comparison to the rapid advance of physical science. A study of the history of the Royal Society reveals that political problems were avoided in the seventeenth century because of the social conditions existing at that time. The prohibition of consideration of political problems may have delayed the discovery of important relationships between physical, chemical, biological, psychological, and social phenomena.

> The group tabooed theology and politics, and discussed medicine, anatomy, geometry, etc.... The

> group wished to be unnoticed by the theological and political contestants, and held its meetings in modest obscurity.... The Royal Society's relative lack of interest in the social relation of science since the end of that century [17th] until today is a reflection of an unchanging conception of the relation of science to society in the intervening period.[43]

One can understand why the Royal Society avoided the investigation of problems related to politics, by noting the fate of some of the individuals who dared to question the political and religious ideas of their time. Joseph Priestly (1733-1804), who is noted for his achievements in chemistry, published in 1767 a treatise on the History and Present State of Electricity which contained some original work. He was also a minister of religion. His inquiry into philosophical and theological problems was not appreciated by the church authorities, and in 1791 his chapel, house, and laboratory in Birmingham, England, were burned and wrecked by a mob. He and his family escaped, but all his books, notes, and laboratory equipment were destroyed.

There is another type of relationship between physical science such as electromagnetic theory and the social sciences which is not well understood. The philosophical ideas of scientists who have a clear and comprehensive understanding of their work in relation to the strivings of mankind throughout history have a potential effect upon the solution of social problems. The following quotation from Karl K. Darrow is a sample of such a thought.

> .... All that is perpetual is something of which they all are made, incarnating itself in all of them by turn, and passing unimpaired from form to form. For this immortal substance the least inadequate name, I presume, is "energy"; the name is of little concern. To this have we come by applying the methods of physics to the rubbing of amber and to all that followed from it; how great a way, from so humble a beginning! The stone which so many builders rejected became the cornerstone of the temple; the little effect which seemed so trivial to so many of the wise became the key to wisdom, and supplied a physical meaning to two of the most ancient tenets of philosophy. Atomic theories existed long ago, but ours is the generation which, first of all in history, has seen the atom. The belief that all things are made of a single substance is old as thought itself; but ours is the generation which, first of all in history, is able to receive the unity of Nature not as a baseless dogma or a hopeless aspiration, but a principle of science based on proof as sharp and clear as anything which is known.[44]

There are, of course, many other social problems related in some way to electromagnetic theory, but they cannot be all mentioned here. An electrical engineer cannot go into detail regarding all related problems, but he must take the responsibility of seeing that the appropriate specialists are examining the phases of his problem which lie in their respective fields of specialization.

VI. HISTORY OF THE APPLICATION OF ELECTROMAGNETIC THEORY TO MICROWAVE WAVE GUIDE TRANSMISSION

A. Lord Rayleigh (1897)[45]

In 1897 Lord Rayleigh analysed the passage of electric waves through tubes. He took the case of a dielectric cylinder infinitely long and of arbitrary cross-section. From the wave equations:

$$\nabla^2 \bar{E} = \frac{1}{V^2} \frac{\partial^2 \bar{E}}{\partial t^2} \qquad (17)$$

$$\nabla^2 \bar{B} = \frac{1}{V^2} \frac{\partial^2 \bar{B}}{\partial t^2} \qquad (18)$$

and the boundary condition that components of electromotive intensity parallel to the conductor surface shall vanish, he obtained two solutions. The longitudinal direction is the z-axis and V is the velocity of light. P, Q, and R are the x,y, and z components of $\bar{E}$ and a, b, and c are the components of $\bar{B}$.

$$k^2 = \frac{p^2}{V^2} - m^2 \qquad (19)$$

$k^2 = p^2/V^2 - m$

k is limited to certain definite values.

He obtained a solution for vibrations of the first class in which R= 0 at the boundaries by using a solution for the free transverse vibrations of a stretched membrane.

$$P = \frac{iq}{k^2} \frac{dR}{dx} \qquad R = R$$

$$Q = \frac{iq}{k^2} \frac{dR}{dy}$$

$$(20)$$

$$a = -\frac{m^2 + k^2}{ipk^2}\frac{dR}{dy} \qquad e = 0$$

$$b = \frac{m^2 + k^2}{ipk^2}\frac{dR}{dx}$$

p128
(16)

For vibrations of the second class in which $R = 0$ throughout, the problem was similar to the case of the two-dimensional vibration of a gas within a cylinder which is bounded by rigid walls, or the vibration of a liquid under gravity in a vessel.

$$P = -\frac{ip}{k^2}\frac{dc}{dy}$$

$$Q = \frac{ip}{k^2}\frac{dc}{dx} \qquad R = 0$$

$$a = \frac{im}{k^2}\frac{dc}{dx} \qquad e = 0 \qquad (21)$$

$$b = \frac{im}{k^2}\frac{dc}{dy}$$

$x = 0, x = \alpha$
$y = 0, y = \beta$

For a rectangular cross-section with wall widths α and β, he obtained the following solutions:

First Class: $R = e^{i(mz+pt)} \sin\left(\frac{\mu \pi x}{\alpha}\right) \sin\left(\frac{\nu \pi y}{\beta}\right)$ ✓ (22)

Second Class: $c = e^{i(mz+pt)} \cos\left(\frac{\mu \pi x}{\alpha}\right) \cos\left(\frac{\nu \pi y}{\beta}\right)$ (23)

$$k^2 = \pi^2\left(\frac{\mu^2}{\alpha^2} + \frac{\nu^2}{\beta^2}\right) \quad ✓ \qquad (24)$$

where μ and ν are integers.

For Circular cross-section he obtained the following where r' is the radius of the cylinder and n is an integer:

See Theory of Sound §195

First Class: $R = e^{i(mz+pt)} J_n(kr) \cos n_\theta$ (25) ✓ R(31)

k is limited by $J_n(kr') = 0$ (26) ✓ R(32)

the smallest kr' being 2.404

Second Class: $Z = e^{i(mz+pt)} J_n(kr) \cos n_\theta$ (27) ✓ R(41)

k is limited to $J_n'(kr') = 0$ (28) R(42)

the smallest kr' being 1.841

The equations for the other components can be readily derived from these equations.

B. Related Developments (1897-1936)

Hondros and Debye[46] in 1910, Zahn[47] in 1916, and Schriever[48,49] in 1920, made investigations of electromagnetic waves in dielectric wires which were related, but did not bear directly on waveguide transmission. Hollow conducting cylinders described by Rayleigh were investigated by Bergmann and Kruegel[50] in 1934, who measured the field inside a short cylinder and the radiation from an open end.

More thorough investigation of waveguide transmission waited from Rayleigh's theoretical investigation (1897) until more powerful techniques of generating and receiving radio waves were developed at lower frequencies and then extended to the higher frequencies.

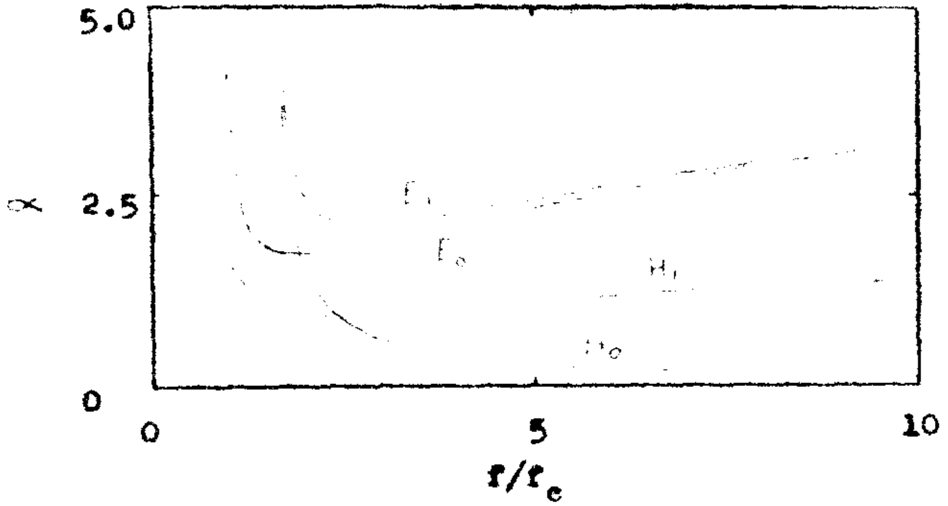
C. Independent Work of Barrow and Southworth

In 1936 both Barrow[51] of M.I.T. and Southworth[52] of B.T.L. independently published results of investigations of electromagnetic waves in hollow tubes of metal. They took into account the dielectric constant and permeability of the dielectric filling the hollow tubes and the conductivity and permeability of the metal conductor, so that Lord Rayleigh's analysis was extended to practical cases. At B.T.L. the mathematical theory was investigated by Carson, Mead, and Schelkunoff.[53] The attentuation vs. frequency curves for four modes in cylindrical wave guide are given in figure 4.[53] Barrow gave the attenuation curve for the E_0 mode.

The different nomenclatures used for modes in wave guide are:

1st Class	2nd Class
Longitudinal	Transverse
E-wave	H-wave
Transverse Magnetic	Transverse Electric

Bell System Technical Journal



To get attenuation in db/mile, multiply $\propto$ by A_o.

$$A_o = \frac{1.89\sqrt{f_o}}{d} \text{ for copper}$$

f = frequency of oscillation $f = \left(\frac{f}{f_c}\right)\left[\frac{2.30}{d} \times 10^4\right]$ mc/sec.
f_c = cutoff frequency of E_o-wave mc/sec.
d = diameter of cylinder in centimeters

Figure 4 - Wave Guide Attenuation
Curves (Circular Cross-Section)

D. Fundamental Developments (1936-1941)

Brillouin analysed the results of Southworth and others of B. T. L. from a point of view of interference and reflection of plane waves.[54] Page and Adams also showed that the waves investigated at M.I.T. and B.T.L. could be constructed from plane waves.[55] In 1937 Schelkunoff published a paper on the transmission theory of plane electromagnetic waves, including guided waves,[56] and Southworth published two papers on experiments with waveguides.[57, 58] In 1938 Chu and Barrow reported a more complete study of transmission in rectangular waveguide.[59] Chu also published an analysis of elliptic waveguides.[60]

Brillouin analysed the stability of different modes for deformation of cross-section and the transition from elliptical to rectangular cross-section.[61]

Barrow and Green analysed the radiation from open ends of rectangular waveguides.[62] Hansen published a paper on resonant cavities of cylindrical, square, spherical types, including an analysis of Q.[63] The simple forms of resonant cavities are derived directly from wave guide theory. In 1939 Hansen and Richtmeyer published a study of reentrant type resonators suitable for Klystron oscillators.[64]

Barrow and Chu developed electromagnetic horn by use of tapered wave guide.[65,66] Barrow and Schaevitz in 1941 made an analysis of folded wave guides, including septate coaxial cable.[67] Barrow and Mieher in 1940 published an analysis of the first twelve modes in coaxial, cylindrical, and transition type resonators in which a change in linear dimensions was shown to cause a proportionate change in wavelength.[68] Condon published a paper on the computation of coupling coefficients and impedance of resonant cavities.[69]

In 1942, Slater published a book on microwave transmission.[70] Selected bibliographies covering this period of development appear in books by Skilling,[71] Terman,[72] and Schelkunoff.[73] More complete bibliographies are included in books by Lamont,[74] Brainerd,[75] and Sarbacher and Edson.[76] Chapters on waveguides are included in books by Ware and Reed,[77] and by Ramo and Whinnery.[78]

E. Practical Applications (1941-1946)

After the fall of France in June, 1940, Great Britain was subjected to terrific bombings and faced a threat of invasion. The development of aerial interceptor radar for use on night fighters to reduce the German bombing raids was pushed. The Massachusetts Institute of Technology Radiation Laboratory[13] was established to develop a microwave radar, since the British, who had already developed longer wave radar equipment, were short on personnel and facilities. Longer wave radar equipment developed previously by the U. S. Army and U. S. Navy are not mentioned in this section on microwave radar. Coaxial lines were used in the earlier radars, but wave guides were used in the shorter wavelength radars and some of the higher power radars put into use later in the war.

The practical use of wave guides was dependent upon the development of high power microwave oscillator tubes. High power magnetrons were developed during the war.

In general, ordinary transmission line theory was applied to wave guide transmission line design problems and corrections needed at junctions determined by empirical measurements. Components such as adapters from coaxial line to wave guide, transmit-receive tube cavities, rotating joints, T-junctions, frequency meters, attenuators, directional couplers, etc. were designed partially by theoretical analysis and partially by empirical data for particular frequency bands.

As the war went on, more advances were made in the mathematical theory.

In the development of radar components, it was necessary to develop satisfactory connectors, bends and junctions in wave guide. N. H. Frank investigated junction effects in wave guides in 1941.[79] Frank also investigated wave guides partly filled with dielectric,[80] the similarities and differences between transmission lines and wave guides,[81] and tapered wave guides.[82] Chu and Frank analysed T-junctions[83] in wave guide and prepared design formulas and curves in 1942.[84] In 1942 and 1943 Frank prepared a handbook summarizing important formulas and empirical data useful in the design of wave guide components.[85] In 1943 H. A. Bethe published a theory of wave guides of arbitrary cross section.[86] In 1943 the theory of obstacles in wave guides was extended by Schwinger[87] and further analysis of bends in rectangular guide was made by Marshak.[88] Experimental data on corners, bends and twists in rectangular guide was published by R. M. Walker in 1944,[89] and mathematical analysis by use of Schroedinger equation with perturbations was made by K. Riess.[90]

Resonant cavities were developed following Hansen[63] for measuring frequency, for use in transmit-receive switches, for stabilizing oscillators, and for measuring sensitivity of radars. Slater investigated cavity resonators in 1942.[91] Bethe and Marshak made a theoretical analysis of the transmit-receive switch in 1943.[92, 93] Samuel and others at Bell Telephone Laboratories were working at that time on gas-discharge transmit-receive switches. Their work is summarized in a 1946 article.[94]

Bethe and Schwinger made further studies of resonant cavities through use of perturbation theory.[95] The coupling of resonators to wave guide and similar problems were investigated by Bethe,[96, 97, 98, 99, 100] Frank,[101] A. E. Heins,[102] Bethe, Schwinger, Carlson, and Chu;[97] and Bowers, Hurwitz, and Levine.[103] Experimental data on windows in wave guides was reported by Walker[104] and Slehak.[105]

In 1942 Fenn reported experimental work on the use of resonant cavities called "echo boxes" for radar testing.[106] A resonant cavity was coupled to a radar so that the energy in the resonant cavity was built up during the radar pulse.

Then the exponential decay curve of the resonator could be observed on the radar oscilloscope. The time it took for the "echo" signal from the resonant cavity to decay to noise level was an indication of radar performance. The development of echo boxes at Bell Telephone Laboratories is reported by I. G. Wilson, C. W. Schramm, and J. P. Kinzer.[107] Theoretical analysis of wave guide and resonant cavity problems by Lagrangian procedures was done. P. D. Crout,[108, 109, 112, 114, 115, 116] W. H. Painter,[109, 112, 113] A. Baños, Jr.[110, 111] J. M. Wolf developed an "echo line" consisting of a long wave guide for 1 cm. range wound in a coil so that the reflection from the shorted end could be used for radar testing.[117]

The need for a reliable method of coupling from wave guide to test equipment led to the development of directional couplers in which the energy coupled out of a wave guide is not affected by reflected energy in the guide. The basic type consists of spacing two holes or probes a quarter wave length apart so that the waves going one direction add and in the other direction subtract. The work of Bethe and Schwinger on coupling from wave guides resulted in improved types of directional couplers. The theory was summarized by Lippmann in 1945.[118] Design considerations have been summarized by R. J. Harrison.[119]

A method of making rotating joints in rectangular wave guide by using the $TE_{1,0}$ mode in rectangular guide and transforming to the $TM_{0,1}$ mode in circular guide at the rotating joint and then back to $TE_{1,0}$ mode in rectangular guide was described by Preston in 1942.[120] F. E. Ehlers[121] described improved designs in 1945 and H. K. Farr[122] developed a theory to explain the resonance difficulties of such rotating joints.

In 1942 E. G. Linder showed that wave guide smaller than critical size has attenuation that approaches straight line asymptotically.[123] S. G. Sydoriak developed variable attenuators using wave guide beyond cutoff to get attenuation linear in decibels for large attenuation.[124] A special wave guide in which the cross-section changes with length was used to make the guide wavelength shorter than the wavelength in air for use in microwave antenna arrays. In 1942 G. G. Harvey reported on corrugated wave guides.[125] Slater's theory of linear slot magnetron was applied in 1944 to corrugated wave guide by H. Goldstein.[126]

In 1941 bench testing equipment was developed at the M.I.T. Radiation Laboratory for measurement of wave guide components at wavelengths of around 3 centimeters. In 1942 sufficient components and instruments were designed for experimental work around 1.25 centimeters wavelength.[127] In 1943 the M.I.T. Radiation Laboratory issued a handbook on microwave technique.[128] Catalogs were issued in 1944[129] and 1945[130] covering microwave test equipment available from manufacturers for use in the 10, 3, and 1.25 centimeter wave length bands. In 1946, articles summarizing the more important equipment and techniques for microwave testing developed at the M.I.T. Radiation Laboratory[131] and Bell Telephone Laboratories[132] were published.

A series of twenty-nine volumes are being published on the work of the M.I.T. Radiation Laboratory[133] during World War II. At the time of writing this paper, this series of books had not become available.

VII. CONCLUSIONS

The history of electromagnetic theory has been examined from an engineering point of view in which the function of an engineer "as an interpreter of science in terms of human needs" has been kept in mind. In the study of the material for this report, it was found necessary to develop a perspective to prevent confusion over human needs from retarding the study of the physical and mathematical aspects.

The past and present aspects of this perspective have been achieved through approaching the physical and mathematical aspects, first from the organic whole, and then working down through narrower and narrower subdivisions of the subject toward a specific physico-mathematical problem. The possibilities of establishing the future part of the perspective through raising the hump over man and science as shown in figure 1 is discussed in the Appendix. It appears that when a reasonable start has been made toward this perspective of the future, that the supplementary work needed to proceed with a physico-mathematical investigation of the application of electromagnetic theory to some branch of microwave wave guide transmission can proceed rapidly.

APPENDIX I

FUTURE PERSPECTIVE

The development of the historical perspective and present perspective has helped clear the way for future physico-mathematical study. Yet there appears to be a need for a balance obtainable through what I am calling the future perspective. It is possible that, if this balance is not maintained, that which has been achieved in the way of past and present perspective will become an opiate or will become meaningless. I find that some attitudes that existed prior to the founding of the Royal Society in 1660 are still with us today. It appears that these attitudes of using strong emotional appeal coupled with violence or threat of violence in the solution of the problems of society have forced scientists to turn to the physical sciences in order to avoid the violent attacks of people who object to the study of social problems. This has apparently resulted in a failure of the social sciences to achieve the degree of success needed to supplement the great advances made in the physical sciences. Apparently, the application of physical knowledge, such as electromagnetic theory, to industrial development has resulted in serious maladjustments in our society. These maladjustments appear to lay the basis for the destruction or radical change of our civilization.

This situation appears to put the physical scientist and the engineer in the position of accelerating the collapse of our civilization through the failure of society to provide for the proper use of the products of physical science. There are organizations proceeding with useful research on important problems, but it is questionable as to whether or not they can cope with the problems with the speed and on the scale necessary to meet the present situation. This situation suggests that tremendous effort should be made to increase the research in the social sciences.

Perhaps the adoption of some program or policy through which scientists in different fields would have a means of discharging their responsibilities is necessary. It appears that such a program would require some kind of overlapping of fields of specialization in order to achieve a fruitful coöperation and to give experts in one field confidence that the other parts of the whole problem, of which they are working on a small part, are being adequately investigated.

Furthermore, a satisfactory relationship between scientific research and the people must be established in a democracy. The position of the scientists and engineering scientists must be that of an advisory capacity in a true democracy. This brings up the problem of education and organizational procedure.

A comprehensive study dealing with both physical and social phenomena requires a synthesis that would be very difficult to achieve in an age of extreme specialization. The following is a suggestion as to how this perspective of the future could be maintained. Figures 5A-E illustrate some aspects of the problem of the attempt to obtain a synthesis in a situation where extreme specialization is necessary in order to make advances in our scientific knowledge of natural phenomena. The plotting of a measure of one's specialization against type of phenomena utilizes some of the ideas of Auguste Comte, Herbert Spencer, and Lester Ward[134] together with some of P. A. Sorokin's[135] criticism of their classifications of the sciences.

In figure 5A consider a case where an engineer (a) working on problems in which he is applying our knowledge of physical phenomena to the design of instruments for human use. If he assumes the responsibility of considering the related social problems he must consult a social scientist (e) or take time out from his primary work to study social phenomena himself. Usually he does not take time to study social phenomena himself,[136] with the exception of some phases of economics. If he consults with a social scientist there may be difficulty due to each specialist not knowing enough about the other's field to efficiently consider the problems.[137] If one person tries to spread the time usually spent in studying in one field over the whole range of natural phenomena,

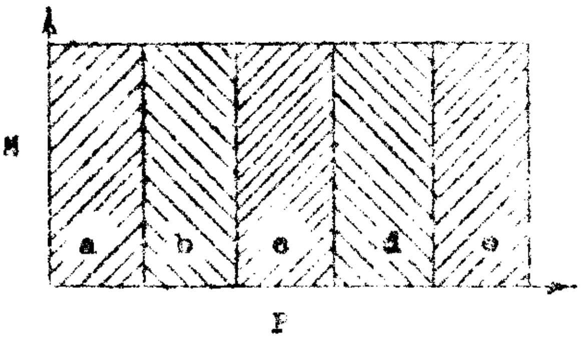


Figure 5A

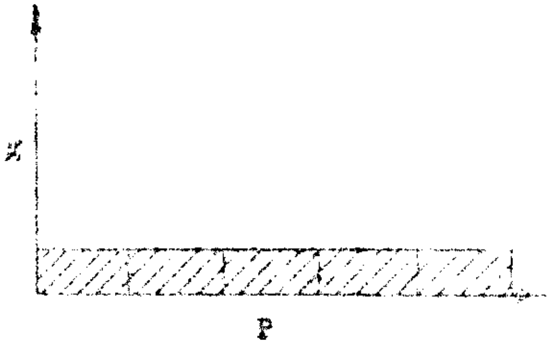


Figure 5B

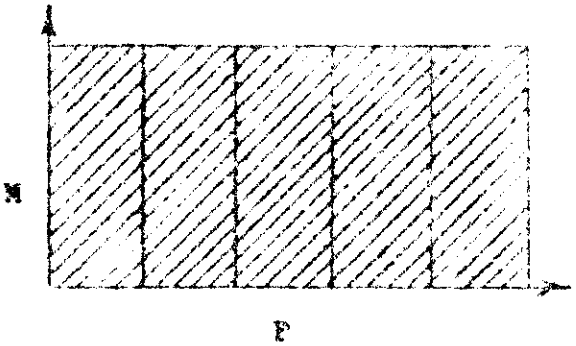


Figure 5C

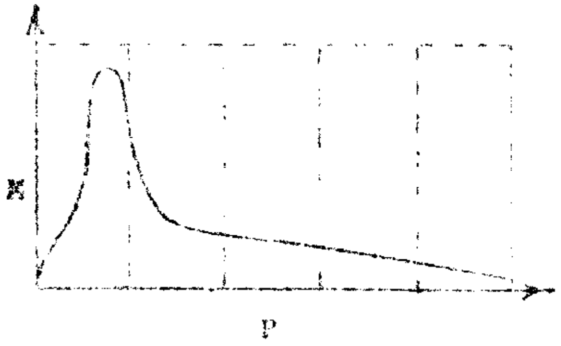


Figure 5D

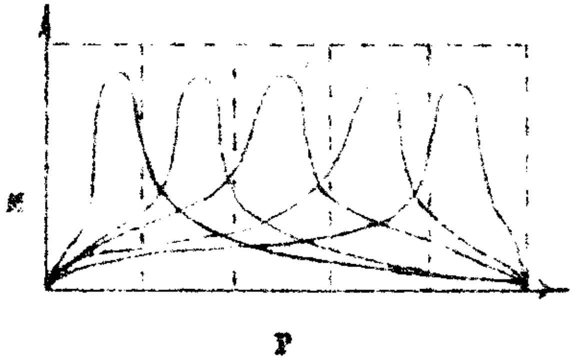


Figure 5E

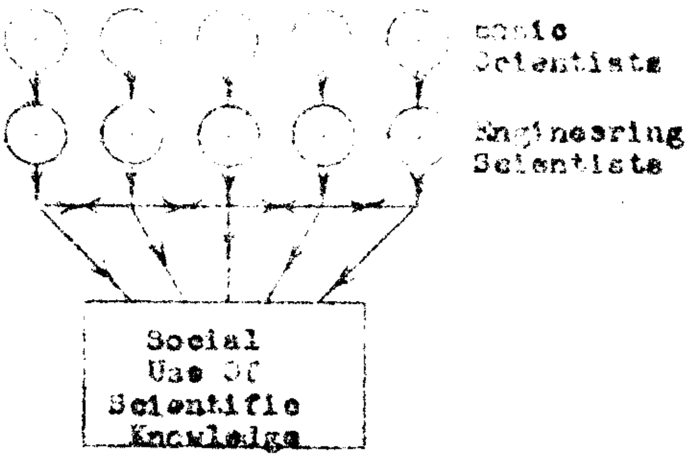


Figure 5F

M = A measure of one's specialization in the study of phenomena P.

P = Type of phenomena, varying from left to right, through physical, chemical, biological, psychological, and social phenomena.[1]

[1] Note: This is an oversimplification for approximate discussion. In practise many phenomena are mixtures of the types specified here.

Figure 5 - Social Use Of Scientific Knowledge

one would not know very much about any class of phenomena as illustrated in figure 5B. To become an expert in all fields as illustrated by figure 5C would require so much time that one would not be able to make very much use of one's knowledge after acquiring it.

These problems suggest a solution which may be already practiced in some fields, but not in others. An ideal set-up might be to have a certain number of basic scientists who specialize in narrow fields like figure 5A. In addition there might be a certain number of engineering scientists similar to the physical engineering scientist shown in figure 5D. These engineering scientists would have training based upon a specialized study in one field, but not as specialized as the basic scientists, combined with an elementary training in several other fields. Then committees of engineering scientists (physical, chemical, biological, social, etc.) might be more adequately prepared to apply the discoveries of the basic scientists to social use as illustrated by figure 5F.

When the engineering scientists arrive at recommendations, there must be educational procedures to disseminate the ideas. Also, the general public must know more about the scientific method. To avoid waiting a generation for each step forward, adult education must be adequately utilized. Organization must proceed along as democratic lines as are possible under the circumstances. Evolutionary change must be in progress all the time to avoid revolutionary changes in society.

There are some places where coöperation among specialists is already proceeding. Remarkable success has been obtained by the Tennessee Valley Authority in getting experts from many specialized fields to see the whole picture.[138] A committee of M.I.T. and Harvard faculty has been established to explore the possibilities for coöperative research and action by social and physical scientists in the field of atomic energy.[139] With these and other signs of potential establishment of future perspective, it seems appropriate to conclude with the words of the Rev. Frank W. Sterrett:

> We must keep it clearly before us that our goal is not the mere creating of material things, nor the contriving of new ways of enjoyment, but the making real, lasting and accessible to men of good will everywhere a life not soft and easy, but worthwhile in a world of friendly neighbors.[140]

> Many a battle has been lost because men lacked confidence in the outcome. That has not been characteristic of the Engineer. He is accustomed to face hard tasks demanding his best. The rebuilding and the restoring of an ordered world present such a problem. Some of us will have a part in it, but we all can help by keeping clearly before us an understanding of a worthwhile purpose and faith in its conclusion. In such a view, it seems to me there is a continuing place of dignity for the Engineer of tomorrow.[141]

REFERENCES CITED

[illegible] CITED

1. "Engineering as a career," Engineers' Council for Professional Development, p. ~~8~~, 1942.
6

2. Ibid.

II

3. Lichtenberger, "Development of social theory," The Century Co., p. 566, 1923.

4. Edwin Hubble, "The problem of the expanding universe," Science in Progress, Third series, Yale Univ. Press, pp. 22-44, 1942.

5. Pascual Jordan, "Die physik des 20. jarhunderts," 1936, trans. by Eleanor Oshry, "Physics of the 20th century," p. 29, 1944.

6. Ibid., p. 176 (from a compilation by G. Holm.

7. John Phelan, "Anthropological backgrounds," in Elmer Pendell (ed.), Society under analysis, An introduction to sociology, p. 9, 1942.

8. Ibid., pp. 16-17.

9. Selden Smyser, "Logics: Subverbal, and superberbal," in Papers from the First American Congress for general semantics, March 1935, Arrow editions, N.Y., 1940.

III

10. Subdivisions into periods from L. B. Loeb, Fundamentals of electricity and magnetism, John Wiley & Sons, pp. 16-17, 1938.

11. "Electricity," Encyclopaedia Britannica, VIII, pp. 182-197, 1945.

12. "Magnetism," Encyclopaedia Britannica, XIV, pp. 636-640, 1945.

Faraday [illegible]

13. Joint Board on Scientific Information Policy, "Radar--A report on science at war," U.S. Govt. Printing Office, pp. 1-53, August 15, 1945.

14. H. D. Smyth, "Atomic energy for military purposes," Princeton Univ. Press, pp. 1-264, 1945.

IV

15. J. C. Maxwell, "A treatise on electricity and magnetism," Clarendon Press, vol. I, p. 14, 1873.

16. H. A. Wilson, "Electricity," Encyclopaedia Britannica, VIII, p. 186, 1945.

17. W. F. Magie, "A source book in physics," McGraw-Hill Book Co., pp. 472-485, 1935 (from Phil. Trans., p. 125, 1832).

18. W. F. Magie, ibid., pp. 352-354 (from Phil. Trans., p. 1, 1846).

19. W. F. Magie, ibid., pp. 506-511 (from Proc. of the Royal Institution, June 11, 1851).

20. J. C. Maxwell, "A treatise on electricity and magnetism," vol. I, p. x, 1873.

21. J. C. Maxwell, ibid., p. xii.

22. W. F. Magie, op. cit., pp. 528-536 (from Phil. Trans., vol. 155, p. 459, 1865).

23. Heinrich Hertz, "Electric waves," trans. by D. E. Jones, Macmillan & Co., pp. 29-53, 80-94, 107-123, 1893 (from Wiedemann's Annalen, vol. 31, p. 421, 1887; vol. 34, p. 155, 1888; vol. 34, p. 551).

24. Ibid., pp. 172-185 (from Wiedemann's Annalen, vol. 36, p. 769).

25. Ibid., pp. 137-159 (from Wiedemann's Annalen, vol. 36, p. 1, 1889).

26. Stratton, "Electromagnetic theory," McGraw Hill Book Co., 1941.

27. J. H. Jeans, "The mathematical theory of electricity and magnetism," Fifth edition, Cambridge Univ. Press, p. 4, 1927.

28. Stratton, op. cit., p. vii.

[illegible]

29. J. H. Jeans, op. cit., pp. 623-628.

30. Page and Adams, "Electrodynamics," Van Nostrand, pp. 129-160, 1940.

V

31. E. N. da C. Andrade, "Radiation, rays (1928)," Encyclopaedia Britannica, XVIII, pp. 876-879, 1945.

32. G. P. Harnwell, "Principles of electricity and electromagnetism," McGraw-Hill Book Co., p. 531, 1938.

33. Encyclopaedia Britannica, 1946, "Broadcasting," IV, pp. 210-213; "Radio," XVIII, pp. 885-886; "Telegraph," XXI, pp. 880-893; "Telephone," XXI, pp. 894-895; "Wireless telegraph," XXIII, pp. 663-673; Britannica book of the year 1946, "Radar," pp. 617-619; "Radar countermeasures," pp. 619-620.

34. Irwin Stewart, "Radio," Annals of the Amer. Acad. of Political Science, supplement to vol. 142, March 1929.

35. Herman S. Hettinger, editor, "Radio: the fifth estate," Annals of the Amer. Acad. of Political Science, vol. 177, Jan. 1935.

36. Herman S. Hettinger, editor, "New horizons in radio," Annals of the Amer. Acad. of Political Science, vol. 213, Jan. 1941.

37. Federal Council of Churches of Christ in America, "Broadcasting and the public: A case in social ethics," 1938.

38. Robert West, "The rape of radio," Rodin Pub. Co., 1941.

39. U.S. Library of Congress, "Radio and radio broadcasting in the United States and foreign countries; A bibliographical list of recent references," July 24, 1935 (310 items).

U. S. Library of Congress, "Radio and radio broadcasting: A selected list of recent references supplementing previous lists," April 12, 1939 (609 items).

40. J. G. Crowther, "The social relations of science," Macmillan Co., p. xvii, 1941.

41. Ibid., p. xviii.

42. Ibid., p. xix.

43. Ibid., pp. 372, 373, 386.

44. K. K. Darrow, "The renaissance of physics," The Macmillan Co., p. 301, 1936.

VI

45. Lord Rayleigh, "On the passage of electric waves through tubes," Phil. Mag., vol. 43, p. 125, Feb. 1897.

46. D. Hondros and P. Debye, "Elektromagnetische wellen an dielektrischen drähten," Ann. d'Phys., vol. 32, pp. 465-76, 1910.

47. H. Zahn, "Uber den Nachweis electromagnetische wellen an dielektrischen drähten," Ann. d. Phys., vol. 49, pp. 907-33, 1916. (Detection of electromagnetic waves in dielectric wires.)

48. C. Schriever, "Electromagnetische wellen an dielektrischen drähten," Ann. d. phys., vol. 63, pp. 645-73, 1920 (electromagnetic waves in dielectric conductors).

49. O. Schriever, "On the use of waves in tubes as transmission channels," Telefunken Hausmittel, vol. 20, p. 55, 1920 (measured velocity of propagation in cylinders of water).

50. L. Bergmann and L. Kruegel, "Messungen in strahlungsfeld einer in innern eines metallischen hohlzylinders erregten linear-antennen," Ann. d. Phys. vol. 21, pp. 113-38, Oct. 1934.

51. W. L. Barrow, "Transmission of electromagnetic waves in hollow tubes of metal," Proc. I.R.E., vol. 24, pp. 1298-1328, October 1936.

52. G. C. Southworth, "Hyperfrequency wave guides - general considerations and experimental results," B.S.T.J., vol. 15, pp. 284-309, April 1936;

53. John R. Carson, Sallie P. Mead, S. A. Schelkunoff, "Hyper-frequency wave guides - mathematical theory," Bell System Tech. Jour., vol. 15, p. 310, April 1936.

54. Leon Brillouin, "Propagation of electromagnetic waves in a tube," Rev. gén. élec., vol. 40, p. 227, Aug. 1936.

55. L. Page and N. I. Adams, "Electromagnetic waves in conducting tubes," Phys. Rev., vol. 52, p. 647, Sept. 1937.

56. S. A. Schelkunoff, "Transmission theory of plane electromagnetic waves," Proc. I.R.E., vol. 25, p. 1457, November 1937.

57. G. C. Southworth, "Some fundamental experiments with wave guides," Proc. I.R.E., vol. 25, pp. 807-822, July, 1937.

58. G. C. Southworth, "New experimental methods applicable to ultra short waves," J. Applied Physics, vol. 8, pp. 660, 1937.

59. L. J. Chu and W. L. Barrow, "Electromagnetic waves of hollow metal tubes of rectangular cross section," Proc. I.R.E., vol. 26, pp. 1520-1555, Dec. 1938.

60. L. J. Chu, "Electromagnetic waves in elliptic hollow pipes of metal," Jour. Applied Phys., vol. 9, pp. 583-591, Sept. 1938.

61. L. Brillouin, "Theoretical study of dielectric cables," Electrical Communication, vol. XVI, No. 4, pp. 350-372, April 1938.

62. W. L. Barrow and F. M. Greene, "Rectangular hollow-pipe radiators," I.R.E. Proc., vol. 26, pp. 1498-1519, Dec. 1938.

63. W. W. Hansen, "A type of electrical resonator," Jour. App. Phys., vol. 9, pp. 654-663, Oct. 1938.

64. W. W. Hansen and Richtmeyer, "On resonators suitable for klystron oscillators," Jour. Applied Phys., vol. 10, p. 189, March 1939.

65. L. J. Chu and W. L. Barrow, "Theory of the electromagnetic horn," Proc. I.R.E., vol. 27, no. 1, pp. 51-64, Jan. 1939.

66. L. J. Chu, "Calculation of the radiation properties of hollow pipes and horns," J.A.P., vol. 11, pp. 603-10, Sept. 1940.

67. W. L. Barrow and H. Schaevitz, "Hollow pipes of relatively small dimensions," Elec. Eng. Trans., vol. 60, p. 119, March 1941.

68. W. L. Barrow and W. H. Mieher, "Natural oscillations of electrical cavity resonators," Proc. I.R.E., vol. 28, p. 184, April 1940.

69. E. V. Condon, "Forced oscillations in cavity resonators," Jour. Applied Phys., vol. 12, pp. 129-132, Feb. 1941.

70. J. C. Slater, "Microwave transmission," McGraw-Hill Book Co., 1942.

71. H. H. Skilling, "Fundamentals of electric waves," John Wiley & Sons, 1942.

72. F. E. Terman, "Radio Engineers' handbook," McGraw-Hill Book Co., pp. 251-273, 1943.

73. S. A. Schelkunoff, "Electromagnetic waves," Van Nostrand Co., pp. 242-330, 376-440; 1943.

74. R. L. Lamont, "Wave guides," Methuen & Co. (London), 1942.

75. J. G. Brainerd (editor), "Ultra-high-frequency techniques," D. Van Nostrand Co., 1942.

76. H. I. Sarbacher and W. A. Edson, "Hyper and ultrahigh frequency engineering," John Wiley & Sons, 1943.

77. L. A. Ware and H. R. Reed, "Communications circuits," John Wiley & Sons, 1942.

78. S. Ramo and J. R. Whinnery, "Fields and waves in modern radio," John Wiley & Sons, pp. 280-417, 1944.

79. N. H. Frank, "Report on junction effects in wave guides," M.I.T. Radiation Laboratory, Report 124 (V-115), Nov. 1, 1941.

80. N. H. Frank, "Propagation in wave guides partly filled with a dielectric," M.I.T. Rad. Lab., Report 174 (43-1), April 27, 1942.

81. N. H. Frank, "Transmission lines and wave guides, similarities and differences," M.I.T. Rad. Lab., Report T-5, June 4, 1942.

82. N. H. Frank, "Reflections from sections of tapered transmission lines and wave guides," M.I.T. Rad. Lab. Report 189 (43-17), Jan. 6, 1943.

83. N. H. Frank and L. J. Chu, "T-Junctions in rectangular wave guides, Part I:Theory," M.I.T. Rad. Lab., Report 179 (43-6), July 27, 1942.

84. L. J. Chu and N. H. Frank, "T-Junctions in rectangular wave guides, Part II: Final formulas and curves," M.I.T. Rad. Lab., Report 180 (43-7), July 19, 1942.

85. N. H. Frank, "Waveguide handbook," M.I.T. Rad. Lab., Report T-9:I, Properties of ideal wave guides, Sept. 24, 1942; II, Attenuation in wave guides, Oct. 2, 1942; III, Obstacles in wave guides, Oct. 27, 1942; IV, Bends and T-junctions in wave guides, Dec. 4, 1942; V, Dielectric structures in wave guides, Feb. 9, 1943.

86. H. A. Bethe, "Formal theory of wave guides of arbitrary cross section," M.I.T. Rad. Lab., Report 198 (43-26), March 16, 1943.

87. J. S. Schwinger, "Theory of obstacles in resonant cavities and wave guides," M.I.T. Rad. Lab., Report 205 (43-34), May 21, 1943.

88. R. E. Marshak, "Theory of circular bends in rectangular wave guides," M.I.T. Rad. Lab., Report 206 (43-35), June 24, 1943.

89. R. M. Walker, "Corners, bends, and twists in rectangular waveguide," M.I.T. Rad. Lab., Report 585, July 6, 1944.

90. R. Riess, "Electromagnetic waves in bent pipe of rectangular cross section," Brown Univ. Quarterly Applied Math., VI, No. 4 (January 1944, pp. 328-33. Mathematical analysis by use of theory of Schroedinger equation with perturbations.

91. J. C. Slater, "Forced oscillations in cavity resonators," M.I.T. Rad. Lab., Report 188 (43-16), Dec. 31, 1942.

92. H. A. Bethe, R. E. Marshak and J. Schwinger, "Theoretical results on the T-R box," Cornell University, N.D.R.C. Report 14-116, Jan. 20, 1943.

93. H. A. Bethe, "Theory of the T-R box," Cornell Univ., N.D.R.C. Report 14-128, May 14, 1943.

94. A. L. Samuel, J. W. Clark and W. W. Mumford, "The gas-discharge transmit receive switch," B.S.T.J., vol. 25, no. 1, pp. 48-101, Jan. 1946.

95. H. A. Bethe and J. Schwinger, "Perturbation theory for cavities," Cornell University, N.D.R.C. Report 14-117, March 4, 1943.

96. H. A. Bethe, "Theory of diffraction by small holes," M.I.T. Rad. Lab., Report 128 (V-155), Jan. 23, 1942.

97. H. A. Bethe, J. Schwinger, J. F. Carlson, and L. J. Chu, "Transmission of irises in waveguides," Cornell University, N.D.R.C. Report 14-111, Nov 3, 1942.

98. H. A. Bethe, "Lumped constants for small irises," M.I.T. Rad. Lab. Report 194, March 24, 1943

99. H. A. Bethe, "Theory of side windows in wave guides," M.I.T. Rad. Lab., Report 199 (43-27), April 4, 1943.
PB 2837 (I-200)

100. H. A. Bethe, "Excitation of cavities through windows," M.I.T. Rad. Lab., Report 202 (43-20), April 9, 1943.

101. N. H. Frank, "Coupling between inductive windows in wave guides, M.I.T. Rad. Lab., Report 197 (43-25), Feb. 27, 1943.

102. A. E. Heins, "Susceptance of assymetrically located windows in rectangular wave guides," M.I.T. Rad. Lab., Report 183 (43-10), Oct. 16, 1942. PB 3736 0.50

103. W. A. Bowers, H. Hurwitz, and H. Levine, "Theory of thick inductive windows with small openings," Cornell Univ., N.D.R.C. Report 14-171, Nov. 26, 1943.

104. R. M. Walker, "Dielectric windows in waveguide," M.I.T. Rad. Lab. Report 567, June 29, 1944.

105. W. Sichak, "One-sided inductive irises and quarter-wave capacitative transformers in waveguide," M.I.T. Rad. Lab., Report 426, Nov. 17, 1943.

106. W. H. Penn, "The resonant echo box," M.I.T. Rad. Lab., Report 277 (55-1), Sept. 4, 1942.

PB (no.) Mi. (po
in b

107. I. G. Wilson, C. W. Schramm and J. P. Kinzer, "High Q resonant cavities for microwave testing," B.S.T.J., vol. 25, no. 3, pp. 408-434, July, 1946.

108. P. D. Crout, "An extension of Lagrange's equations to electromagnetic field problems," M.I.T., Rad. Lab., Report 626, Oct. 6, 1944. PB 2678 0.50

109. P. D. Crout and N. H. Painter, "A treatment of echo box problems by Lagrangian procedures," M.I.T. Rad. Lab., Report 629, Jan. 13, 1945. (Part I) PB 2748 1.00(

110. A. Baños, Jr., "Theory of ringing time of tunable echo boxes," M.I.T. Rad. Lab., Report 630, Nov. 3, 1944. PB 2681 1.00 ( )

111. A. Baños, Jr., "Design of an improved X-band echo box," M.I.T. Rad. Lab., Report 631, Dec. 7, 1944. PB 2811 0.50(

112. P. D. Crout and N. H. Painter, "A treatment of echo box problems by Lagrangian procedures, Part II," M.I.T. Rad. Lab., Report 696, March 16, 1945. PB 2527 0.50 (20

113. N. H. Painter, "Calculation of the resonant frequencies of a torus by Lagrangian and variational methods," M.I.T. Rad. Lab., Report 924, Nov. 14, 1945.

114. P. D. Crout, "An extension of Lagrange's equations to electromagnetic field problems, equivalent networks, Part II," M.I.T. Rad. Lab., Report 1046, Jan. 15, 1946.

115. P. D. Crout, "The determination of fields satisfying LaPlace's, Poisson's and associated equations by flux plotting," M.I.T. Rad. Lab., Report 1047, Jan. 23, 1946.

116. P. D. Crout, "A flux plotting method for obtaining fields satisfying Maxwell's equations, with applications to the magnetron," M.I.T. Rad. Lab., Report 1048, Jan. 16, 1946. PB 13 277 0.50 (1153)
J.A.P. 18:4, pp 348-355, April 1947.

117. J. M. Wolf, "K-band echo line," M.I.T. Rad. Lab., Report 974 (in pub. 1946).

118. B. A. Lippmann, "Theory of directional couplers," M.I.T. Rad. Lab., Report 860, Dec. 28, 1945.

119. R. J. Harrison, "Design considerations for directional couplers," M.I.T. Rad. Lab., Report 724, Dec. 31, 1945.

120. W. K. Preston, "Rotary joints with E_0 stub transformers," M.I.T. Rad. Lab., Report 243 (53-12), Dec. 18, 1942.

121. F. E. Ehlers, "E_0 rotary joints for the 3 centimeter band," M.I.T. Rad. Lab., Report 853, Dec. 4, 1945.

122. H. K. Farr, "A theory of resonance in rotary joints of the TM$_{01}$ type," M.I.T. Rad. Lab., Report 993, Jan. 15, 1946.

123. Linder, E. G. "Attenuation of electromagnetic fields in pipes smaller than critical size," I.R.E. Proc., vol. 30, no. 12, pp. 564-56, Dec. 1942.

Theoretical, experimental discussion of electromagnetic fields in pipe smaller than critical size, especially with regard to attenuation, and based upon wave guide theory; it is shown that rate of attenuation, as wavelength increases and passes through critical value, approaches high asymptotic value; simple formulas for attenuation included.

124. S. G. Sydoriak, "R-F attenuators," M.I.T. Rad. Lab., Report 404, Sept. 7, 1943. PB 2519 1.00 (759)

125. G. G. Harvey, "Information on corrugated coaxial lines and wave guides," M.I.T. Rad. Lab., Report 264 (54-16), Dec. 11, 1942.

126. H. Goldstein, "Theory of corrugated transmission lines and waveguides," M.I.T. Rad. Lab., Report 494, April 3, 1944.

127. E. M. Purcell, "Wave guide components and instruments for the 1.25 cm region," M.I.T. Rad. Lab., Report 165 (41-6), Dec. 3, 1942.

128. J. M. Petersen, editor, "Microwave technique as of May 1943," M.I.T. Rad. Lab., Report T-13, May 5, 1943.

129. F. B. Wood (ed.), "Catalog of microwave test equipment," M.I.T. Rad. Lab., Report S-28, Sept. 30, 1944.

130. E. A. S. Jacobsen (ed.), "Catalog of Microwave test equipment," M.I.T. Rad. Lab., Report S-41, Aug. 25, 1945.

131. F. J. Gaffney, "Microwave measurements and test equipment," Proc. I.R.E., vol. 34:10, pp. 775-793, Oct. 1946.

132. E. I. Green, H. J. Fisher, and J. G. Ferguson, "Techniques and facilities for microwave radar testing," B.S.T.J., vol. 25, no. 3, pp. 435-482, July 1946.

133. M.I.T. Radiation Laboratory Series (29 volumes).
Vol. 1. Radar system engineering;
Vol. 8. Principles of microwave circuits;
Vol. 9. Microwave transmission circuits;
Vol. 10. Waveguide handbook;
Vol. 11. Technique of microwave measurements;
Vol. 12. Microwave antenna theory and design; McGraw Hill Book Co., 1946-1947 (publication in process).

Part of the material is covered in Mass. Inst. of Technology, Radar School, "Principles of radar," 2nd ed., McGraw-Hill Book Co., 1946.

APPENDIX I

134. John E. Bently, "Visual outline of philosophy," Longmans, Green & Co., p. 109, 1939; Lichtenberger, "Development of social theory," The Century Co., p. 368, 1923.

135. P. A. Sorokin, "Contemporary sociological theories," Harper & Bros., 1928.

136. For a discussion of the failure of our educational system to resolve this problem, see Elton Mayo, "The social problems of an industrial civilization," Harvard Univ. Press, p. 120, 1945. "As a consequence we are technically competent as no other age in history has been; and we combine this with utter social incompetence."

137. Mayo, op. cit., 115. "We had not sufficiently realized the truth and relevance of A. N. Whitehead's assertion that there is no substitute for firsthand knowledge (Aims of education and other essays, p. 79). Nevertheless the theory that the meeting in conference of a sufficient number of eminent specialists drawn from widely different fields will in some fashion produce the firsthand knowledge required is still widely held, even in universities."

138. David E. Lilienthal, "TVA democracy on the march," Pocket Books, pp. 73-82, 1945.

139. "Cambridge Conference of Natural and Social Scientists," Bulletin of the Atomic Scientists, vol. 2, nos. 9 and 10, p. 32, Nov. 1, 1946.

140. F. W. Sterrett, "Philosophical thoughts upon the life and work of the engineer in the advance of civilization," Newcomen Society, p. 18, 1941.

141. Ibid., p. 23.

NOTE

Some papers which should logically be included in this list have been omitted, because it was not considered worthwhile to do so until certain papers and books on related subjects known to be in process of publication become available. The titles and abstracts of some foreign papers not yet examined indicate possible duplication of some developments made in secrecy in this country during the war. Some of the recent journal articles have omitted data that might prejudice patent applications now pending. It appears that the backlog of journal articles and books withheld from publication during the war will be well cleared up within the next few months.