THE HISTORY OF ELECTROMAGNETIC THEORY

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Electrical Engineering 298
University of California
January 10, 1947

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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.

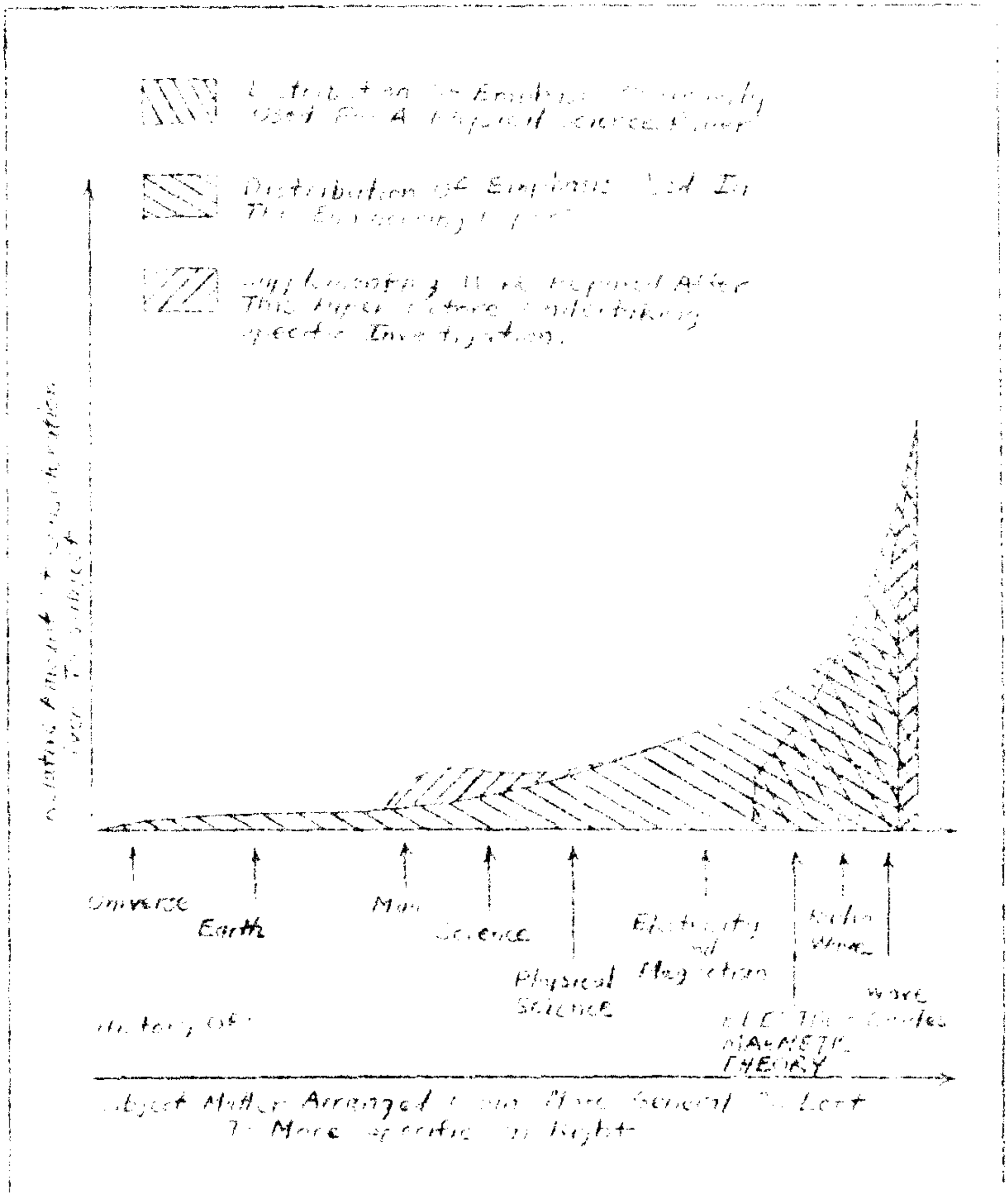


Figure 1 - Approximate Distribution of Emphasis In This Report

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 then are [illegible] to all natural phenomena.

The historical perspective covers the period of the assumed existence of electromagnetic phenomena. Figure [illegible] illustrates the approximate occurrence 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.

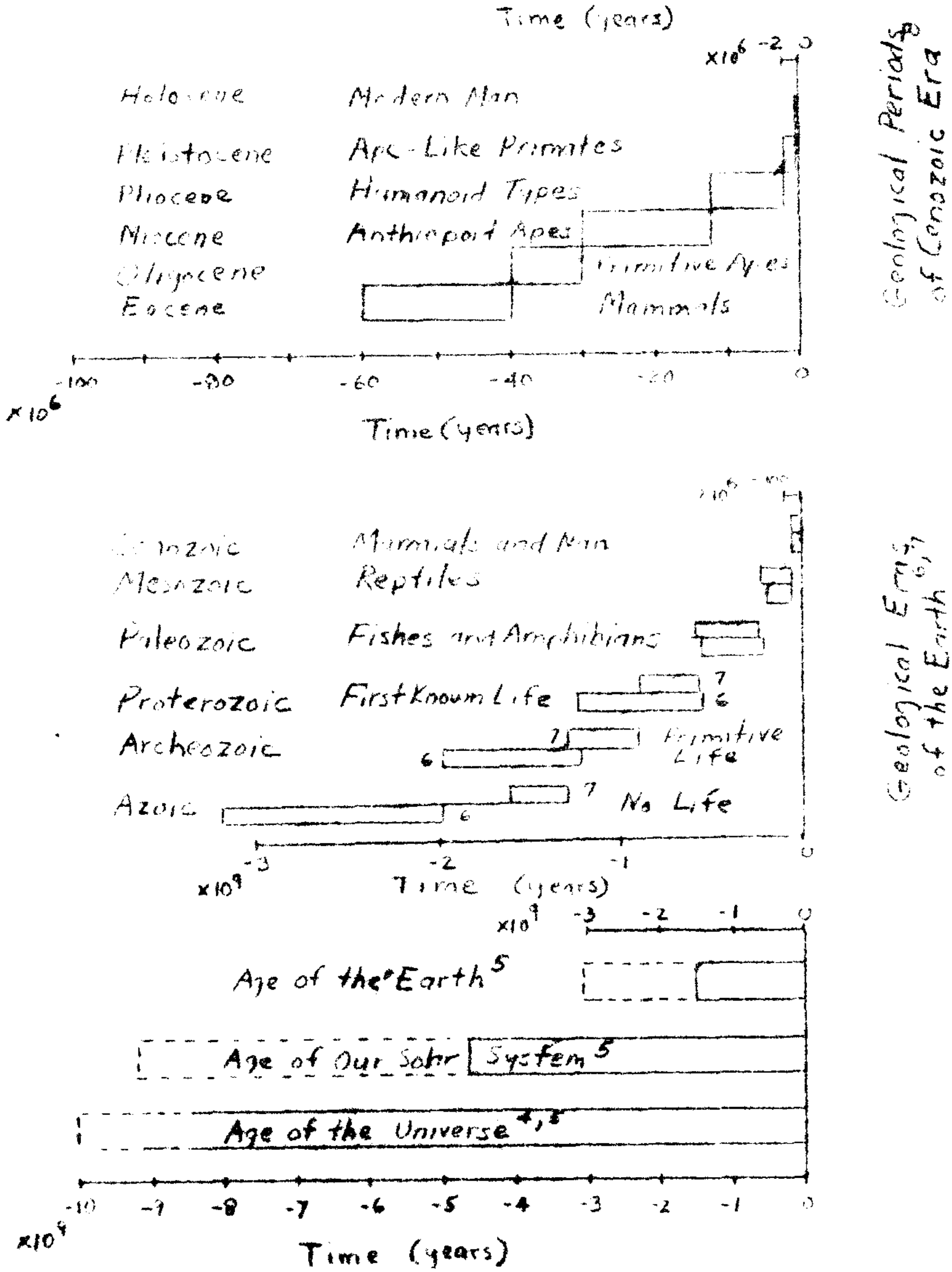
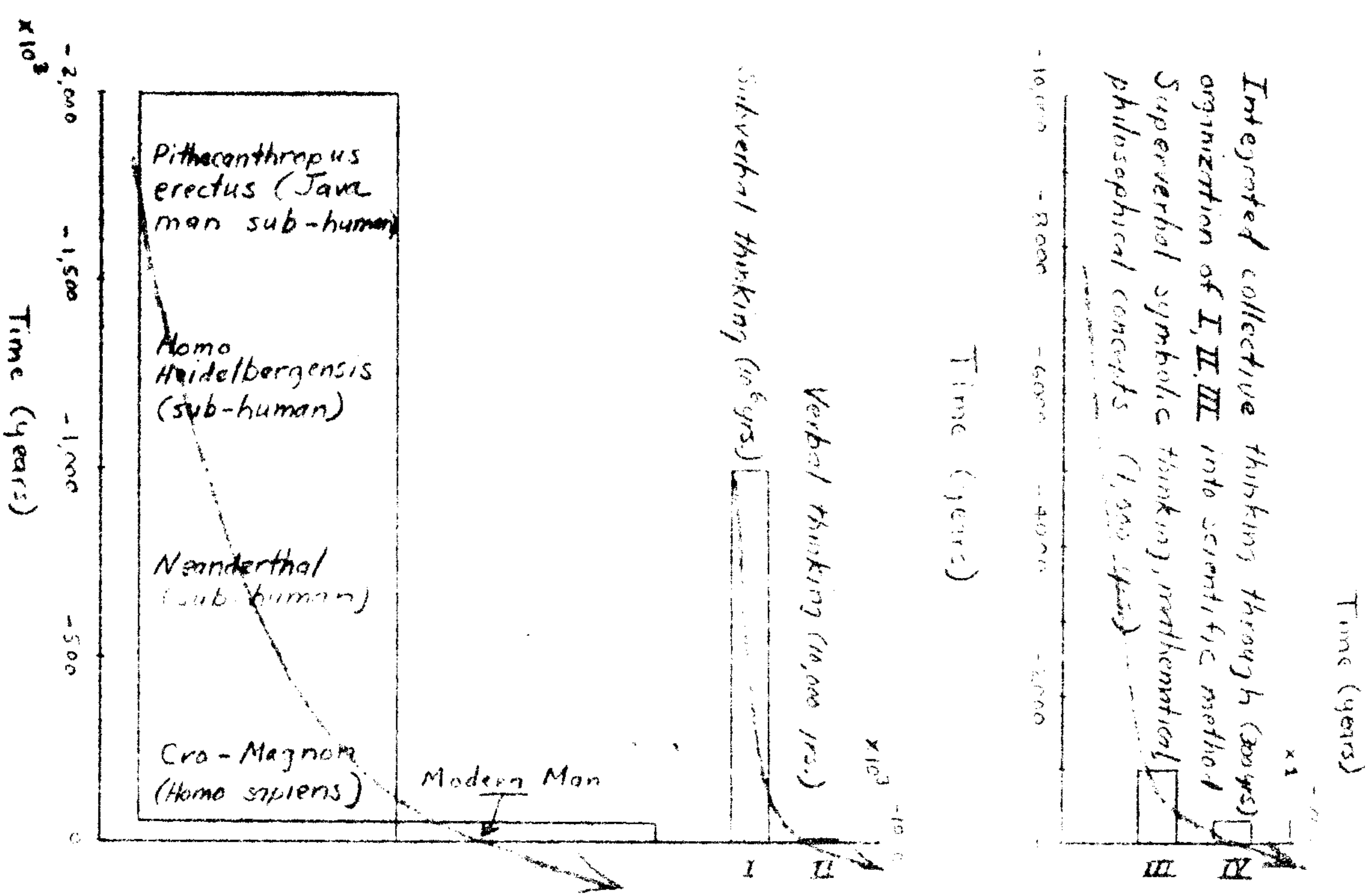


Figure 2 - Historical Perspective (Part One)

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



Development of Man[8]

Evolution of Man's Thinking[9]

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 discovored 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:

$$F = G \frac{m_1 m_2}{r^2} \qquad (1)$$

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 changes and magnetic poles were established as follows:

$$F = C_1 \frac{q_1 q_2}{r^2} \qquad (2)$$

$$F = C_2 \frac{p_1 p_2}{r^2} \qquad (3)$$

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. <u>Maxwell's Equations</u>

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:

$$\text{curl } \bar{H} = \frac{4\pi}{c}\bar{I} + \frac{1}{c}\frac{\partial \bar{D}}{\partial t} \quad (6)$$

$$\text{curl } \bar{E} = -\frac{1}{c}\frac{\partial \bar{B}}{\partial t} \quad (7)$$

$$\text{div } \bar{D} = 4\pi\rho \quad (8)$$

$$\text{div } \bar{B} = 0 \quad (9)$$

In 1865 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:

$$\frac{\partial^2 E_Y}{\partial t^2} = c^2 \frac{\partial^2 E_Y}{\partial x^2} \quad (10)$$

From the general equation for plane waves

$$E_y = f(x - vt) \quad (11)$$

he obtained:

$$\frac{\partial^2 E_Y}{\partial t^2} = v^2 \frac{\partial^2 E_Y}{\partial x^2} \quad (12)$$

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]