A FRAMEWORK FOR THE EXAMINATION OF THEORIES OF ELECTRICITY: IMPLICATIONS FOR POST-SECONDARY ELECTRICAL ENGINEERING TECHNOLOGY EDUCATION.

By

Jana Marie Jilek

A Thesis

submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

Faculty of Education

The University of Manitoba

Winnipeg

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION

A FRAMEWORK FOR THE EXAMINATION OF THEORIES OF ELECTRICITY: IMPLICATIONS FOR POST-SECONDARY ELECTRICAL ENGINEERING TECHNOLOGY EDUCATION

BY

Jana Marie Jilek

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

DOCTOR OF PHILOSOPHY

ABSTRACT

Contrary to what many textbooks and modern-day classroom presentations claim, the evolution of our current concepts of electricity did not follow a neat straight-forward path. The twists and turns taken often resulted in terminology and analogies that are frequently misleading to students. For this reason, we need to understand what the misconceptions and blind alleys were in the evolution of the science of electricity; when and why the electrical engineering schools were established; how the developing electrical industries influenced the curricula of the engineering education, and, finally, what exactly the concepts were found imbedded in the theories of electricity. Through exploration of all these factors we will be able to see more clearly the similarities and the differences between science and engineering approaches to the theories of electricity. Such an exploration will also enable teachers to clarify to the students the models we all accept, and facilitate the building of more easily workable conceptions of electricity.

This dissertation examines the history of the ideas and assumptions that underlie our present theories of electricity and the way these theories are perceived, understood, and taught in electrical engineering technology programs. The investigation focuses on the concepts and mental models of electricity that students acquire in their introductory electric circuits courses. These include the idea of electric charge, electric current, electric potential, electric field, and examines the use of complex numbers and phasors in the analysis of alternating current circuits as they are taught in first year electric circuits courses.

ACKNOWLEDGEMENT

I wish to thank Dr. Art Stinner for his guidance and assistance during my work on this dissertation.

TABLE OF CONTENTS

List of Figures

Chapter 1

INTRODUCTION

1.1 Status of Teaching about Electricity

During the past twenty years, teachers of physics at all levels have been gradually employing strategies designed to guide students from their initial preconceptions towards understanding of the presently accepted theories. They put emphasis on conceptual understanding of the scientific theories and understanding the nature of science rather than simply presenting "the right theory" (Pan-Canadian Protocol; Brouwer, "Towards a More Conceptual Way"). The teaching strategies range from including the history of development of scientific theories in teaching physics (Niaz, "From Cathode Rays"; Niaz and Rodriguez, "The Oil Drop Experiment"; Stinner, "Context, Stories and History") to designing the physics curriculum around a large-context problem (Klassen, "A Theoretical Framework"; Stinner, " Physics and the Dambusters"). These approaches solve some of the difficulties students frequently encounter and that would otherwise be seldom directly addressed. Teaching science at the post-secondary level, however, and especially teaching theories of electricity to students in electrical engineering technology programs, presents its own specific problems.

The problems encountered when explaining electrical phenomena come from several sources. First, the quantities we use to define electricity, such as electric potential or resistance are very abstract. Students acquire some of their concepts of electricity in high school physics classes where the use of analogies is thought to improve students understanding of theories of electricity (Stocklmayer and Treagust, "A historical analysis of electric currents in textbooks"). Moreover, many textbooks used in postsecondary programs employ analogies in an attempt to bring electricity closer to students' everyday experiences (Boylestad, 36-37). The problem is that the limitations of the analogies are not always made sufficiently clear and students tend to hold to their concepts well past their usefulness. Students then try to fit any new data to their existing ideas, rather than adjust their ideas to the new data. Students are often unwilling to change their everyday conceptions because these are familiar and well known to them through experience. An example of such an analogy is the comparison of a flow of water with a flow of electric current. Water flowing in a pipe is something that can be seen and touched, while the new model of electric current as a form of energy transfer is abstract, often meaningless to students, and outside of students' experience. The harm in keeping the analogies to aid the learning of concepts is in forming wrong conclusions – wrong in a sense that predicted outcomes do not correspond to observations. For example, students who take the analogy of water flow as electric current literally don't understand why the current stops when the conductor is cut. As everyone knows, when a pipe is cut the water keeps flowing out of the pipe. For students of electrical technology, who have to make a clear distinction between open and short circuits early in their studies, the water analogy causes more confusion than it aids in the understanding of the behaviour of electric circuits.

Next, the gaps and inconsistencies in physics and engineering theories are seldom explicitly stated. Furthermore, the unknowns are obscured by a huge amount of detailed information. For example, when teaching about electricity as a flow of electrons, students learn the mass of the electron, the charge of the electron, and how to calculate its drift velocity. All such detailed information creates the impression that scientists know well what electrons are, and are able to directly observe them. The description of electric current as a flow of electrons causes problems later, when students must develop the concept of alternating current. They frequently ask: Do the electrons flow back and forth? If students do not satisfactorily resolve this question, they later struggle to understand high frequency currents and phenomena such as "skin effect" and "radiation losses".

There is also confusion about what is understood to be a conceptual understanding of electricity. Even instructors are often uncertain about the nature of electricity and impart this uncertainty to their students (Mulhall et alii, "A Perspective on the Resolution of Confusion in the Teaching of Electricity"). In these cases, better knowledge of history of electricity theories can be a valuable tool in understanding and conveying to the students that vocabulary so highly charged with sensory imagery was derived from the models and theories of electricity held at certain times, not necessarily from any objective data or facts.

Finally, models and theories are often presented as unquestionable facts. In mechanics, a model is usually thought of as a simplification of a more complex object. A structure of a bridge with variable loading due to traffic and winds may be modeled by a beam with a periodically changing load at specific points. An electrical device, such as a motor or a battery, may be modeled as a connection of lumped linear elements producing the same output at the device terminals under specified conditions. In fact, the model is "a black box" and we instruct students not to worry about what is inside as long as on the outside the black box displays the same behaviour as the actual device.

To compound the difficulties, theories and models are often presented in a symbolic form, such as a mathematical equation, that is incomprehensible to students, especially since the limitations of the equation are seldom discussed. To the students then, the mathematical model becomes "a formula", an often meaningless cluster of letters and numbers. A good example of a "simple law" being difficult when expressed mathematically is given by Eugene P. Wigner's[1] discussion of Newton's law of gravitation:

> First, the law ... is simple only to the mathematician, not to common sense or to non-mathematically minded freshmen; second, it is a conditional law of very limited scope. It explains nothing about the earth, which attracts Galileo's rocks, or about the circular form of moon's orbit, or about the planets of the sun. The explanation of these initial conditions is left to the geologist and the astronomer, and they have a hard time with them ("The Unreasonable Effectiveness of Mathematics in the Natural Sciences" 531).

[1]Eugen P. Wigner received a Nobel prize for physics in 1963 for his contributions to the theory of the atomic nucleus.

There are many such "simple laws" in all branches of physics. In the electric circuits theory, the "simplest law" is the Ohm's law. The Ohm's law expresses a relationship between three abstract quantities: voltage, current, and resistance. It is introduced to the students almost at the beginning of the course, when they have very vague ideas about what voltage, current and resistance may be, and it does not explain anything about any of the three quantities, nor about electricity or electric charges.

The need of technology students to learn skills that will enable them to use mathematical relationships to predict the behaviour of devices and systems is hampered by presenting mathematics as an entity separate from science and technology. This practice results in students not relating what they learn in mathematics to the physical world. When faced with a mixture of science and mathematics courses in technology programs, students seldom realize that mathematics, scientific theories, and engineering theories are human inventions that were developed as the need arose. Ideas were often transferred from one field to another, and thus we have the same mathematical description fitting different phenomena in science or technology. For example, expression $y = A \sin \omega t$ can be used to describe either an observable or an unobservable quantity: it can be a position of a point on a sinusoidal curve, a position of a mass oscillating on a spring on a frictionless surface, a statement describing variations of an electromotive force, or a statement describing changing conditions of magnetic flux.

Although many researchers investigate teaching and learning of electricity theories at all school levels, they seldom look at the conditions that make teaching electrical engineering technology courses different from teaching general science. The intent of this dissertation is to examine the impact of the development of the electricity theories and of the electrical industry on theories of electricity and on the way these theories are presented in electrical engineering technology courses. The study focuses on the concepts and mental models of electricity that students acquire in their introductory electric circuits courses; more specifically the ideas of electric current, electric potential, electric field, and the methodology of calculations of alternating current circuits using complex numbers and phasors.

1.2 Research Questions

I have approached the topic of teaching electricity theories in electric circuits courses from a historical perspective. I have traced the development of theories of electricity and electrical industry and their influence on teaching electric circuits theories. My point of view has led me to formulate my two main questions:

- What are the ideas, conditions, and assumptions that determined how theories of electricity are perceived, understood, and taught in introductory electrical engineering technology courses?

- How can we improve the clarity of presentation of theories and methodologies of electric circuits to students of introductory courses in electrical engineering technology programs?

1.3 Assumptions

Based on literature that I will review in chapter 2, I have formed two assumptions. Acknowledgement of these is important for the understanding of my thesis. One assumption is that there are inconsistencies in the theories of electricity. The second assumption is that engineers and technologists approach scientific theories differently from physicists.

The inconsistencies in the theories of electricity are traceable to their historical development. The difference in understanding and use of electricity theories by physicists and engineers stems from the difference of purpose found in science and technology as well as from the difference in their development. As far as the difference of purpose is concerned, physicists and engineers do not have the same objectives even though they both use mathematics as an analytical tool to investigate the physical world. Physicists use mathematical relationships to devise conceptual models of natural phenomena. For that purpose, they simplify and idealize the phenomena by concentrating on only a few aspects or properties and neglect all other influences. On the other hand, engineers and technologists use mathematics to model devices that eventually will be built and are expected to work, often under adverse conditions. Therefore, engineers and technologists must include all possible influences in their design.

We also have to consider the difference in developments of science and engineering theories. According to Thomas Kuhn, development of scientific theories is a non-cumulative process (The Structure of Scientific Revolution 95-96). Kuhn categorized all scientific activities as one of two types: normal science or revolutionary science. Scientists practicing normal science use the existing theories to solve problems. They all work within a paradigm that they all accept, and do not question the correctness of the paradigm. Repeated failures of a theory that is a part of the paradigm to solve significant problems eventually cause the foundations of the theory to be questioned. The process of development of a new theory then goes through a transition from normal science to revolutionary science. During revolutionary change, a new theory competes with an existing theory for acceptance. When the new theory replaces the old one, the older paradigm is replaced in whole or in part by a new and incompatible paradigm.

We do not see such revolutionary changes in the development of engineering theories; engineering theories seem to be at least partly cumulative. The change of a science paradigm and the acceptance of a new science theory may stimulate formulations of new engineering models, theories and methodologies, but they do not necessarily cause rejection of the existing ones. I emphasize that this is a personal opinion based on years of practice. I don't mean to say that engineering theories do not get discarded; some do, but it is done on some other basis than just an incompatible science paradigm. What that basis exactly is could be a topic for another investigation.

It should be also highlighted that there is a lack of agreement on what characteristics a good theory should have. In The Essential Tension (321-325), Thomas Kuhn argues that a good scientific theory has five characteristics. It should be accurate; meaning that predictions derived from the theory should agree with experiments and observations. Second, it should be consistent with other current theories. Third, it should be broad in scope, encompassing more than the phenomena it was originally intended to explain. Fourth, a good science theory should be simple. Fifth, it should be fruitful and open up new areas of research. Of these five characteristics, the first characteristic applies to a good engineering theory, and it applies with a great emphasis: a good engineering theory must be accurate. Predictions obtained by using the theory must agree with experiments and observations, i.e. the designed device or process must work as expected. The fourth requirement, that the theory be simple, is desirable and if the theory will lead to simplified methodology, then this requirement will cause rejection of the more complex theory.

The rest of the requirements are irrelevant for theories taught in engineering. These theories are not always consistent; field theory, force-at-a-distance theory, and electricity as a fluid theory are all presented side by side with equal emphasis, and all are successfully used in design. They do not have to be broad in scope; an explanation of one particular phenomenon and a usefulness of the theory for design of one type of device will justify its acceptance. Neither will the lack of fruitfulness of a theory as defined by

Kuhn cause a rejection of methods based on that theory even if another more fruitful theory exists.

1.4 Definitions of Scientific and Technical Terms Relevant to this Thesis

1.4.1 Terms Used by Electricity Theories

The elusiveness of an exact meaning of terms used by electricity theories is best illustrated by presenting several definitions from different sources.

Electric Charge

The strength of a particle's electric interaction with objects around it depends on its electric charge, which can be either positive or negative (Halliday et alii, Fundamentals of Physics 648).

Charge: An electrical property of matter that exists because of an excess or a deficiency of electrons. Charge can be either positive or negative (Floyd, Principles of Electric Circuits 68)

Electric Current

When charge moves through a material, we say that an electric current exists in the material (Halliday et alii, Fundamentals of Physics 639).

The rate of flow of charge in a conductor is called the current (Boylestad et alii, Circuit Analysis, p.25).

Electric Potential

Electric potential is a property of the electric field itself, whether or not a charged object has been placed in it (Halliday et alii, Fundamentals of Physics 710).

Potential: The voltage at a point with respect to another point in the electrical system. Typically the reference point is ground, which is at zero potential (Boylestad et alii, Circuit Analysis, p.28).

Electromagnetic Field

The electromagnetic field is that part of space which contains and surrounds bodies in electric or magnetic condition (Maxwell, The Scientific Papers 527).

If, in a given region of space, we find that an electrical force acts on a charged particle, we say that an electrical field exists in that region (Arons, Development of Concepts of Physics 542).

The electric field is a *vector field*: it consists of a distribution of *vectors*, one for each point in the region around a charged object, such as charged rod. In principle, we define the electric field by placing a positive charge q_0, called a *test charge*, at some point near the charged object, such as point P in Fig. 24-1a. We then measure the electrostatic force **F** that acts on the test charge. The electric field **E** at point P due to the charged object is defined as

$$\mathbf{E} = \frac{\mathbf{F}}{q} \qquad \text{(electric field)}$$

(Halliday et alii, <u>Fundamentals of Physics</u> 654).

1.4.2 Technical Terms

Ferranti Effect

On lightly loaded or unloaded high voltage transmission lines the voltage at the load end of the line can become considerably higher than the voltage at the source end. This is called the Ferranti effect. The reason is the interaction between the inductance and capacitance of the line.

Open Circuit

Open circuit are two points or terminals that are not connected by any element. They may be at different potentials, but there is no electric current flowing between them.

Radiation Losses

Radiation losses are the losses of energy in the form of electromagnetic waves during the transfer of energy by a transmission line.

Short Circuit

Short circuit is a very low resistance or zero resistance direct connection between two points of an electric circuit. There is electric current flowing between the two points, but the points are at the same potential.

Skin Effect

At high frequencies, the current distribution through the cross-sectional area of the conductor is not uniform. Current density is higher near the surface (skin) of the conductor and lower at the center. The consequence of skin effect is that the resistance of the conductor increases with the frequency.

1.5 Significance of the Study

This dissertation will contribute to meeting the need for greater clarity in presenting electrical engineering theories. The specific problems of teaching science and engineering theories in electrical engineering technology programs have not been investigated in the past. My research will concentrate on the scientific and engineering theories used for solutions of electric circuits problems. The results of these investigations will be useful to instructors of electrical engineering technology courses who want to improve students' understanding of the nature and origins of engineering theories and models of electricity.

1.6 Overview of the Method

The theoretical framework of this thesis is based on historical research. Historical research involves careful reading and critical examination of sources, selection of the relevant materials, and interpretation of past ideas, beliefs, events, and societal structures. Data for this thesis was collected from primary as well as secondary sources that include contemporary textbooks, books on the history of technology and science, scientific journals, oral histories collected by The Institute of Electrical and Electronic Engineers (IEEE), old textbooks on electrical engineering, electrical engineering trade journals, and information from the websites of The Smithsonian Institute and The IEEE.

The research for this thesis resulted in the synthesis of existing documented developments of theories of electricity, technology, electrical industry, and engineering technology education, and in the application of the new insights to teaching electric circuits theories and methodologies in electrical engineering technology courses.

1.7 Organization of the Dissertation

The research questions, the research method, and the overview of the study are given in the introductory **chapter 1**.

In **chapter 2**, I review the existing relevant literature. The review ranges from research work on teaching physics at high schools to investigations of teaching at college and university introductory courses in physics and engineering.

The practical use of electricity started in the nineteenth century. The beginning and expansion of the electrical industry up to the early twentieth century are recounted in **chapter 3**. The state of technology at that time was an important factor in developing engineering theories and methodologies that have been successfully used in engineering design up to now. I limit my research of the history of the electrical industry to the early twentieth century since the theories taught in electric circuits courses, which are the focus of this dissertation, were developed at this time.

The need of the emerging electrical industry for a skilled work force led to the establishment of electrical engineering education at the end of the nineteenth century. The story of its founding and growth is necessary for understanding the curricula of today's electrical engineering programs and I review it in **chapter 4**.

The development of the early theories of electricity is outlined in **chapter 5**. Our predecessors attempted to find explanations for electric effects by using analogies of familiar and successful theories in other fields, such as heat, fluids, and gravitation. They disputed each other's theories, made modifications and alterations to accommodate newly observed phenomena, and often discarded theories and models that were no longer viable in the context of the science of their time. However, in many cases the terminology survived the theories and its continued use is a source of confusion to students.

In **chapter 6**, I answer my first research question by exploring the fundamental assumptions and ideas on which the theories of electricity are based and that were formulated during the nineteenth century. These are the analogy between the theories of heat and fluids and electricity, the concept of a field, an electric potential, and electric current. The nineteenth century was the period when the science of electricity underwent a transformation from a qualitative science to a discipline that is so quantitative that in the minds of many people electrical engineering and mathematics became almost synonymous. The amount of mathematics, however, became a drawback for the engineering profession. Thus, many practising engineers searched for more easily accessible methodologies and models. How this problem was resolved and how the resulting methods for solving alternating current circuits were developed is also described in this chapter.

The curricula of all electrical engineering and electrical engineering technology programs have a course on the electric circuits theory as one of their fundamental courses. In **chapter 7**, I discuss the content of a typical electric circuits course and the teaching methods frequently employed by instructors and encouraged by electric circuits textbooks. Finally, I answer my second research question by proposing a curriculum matrix and offering several suggestions that would reduce the usual difficulties students have with building their concepts of electricity.

Chapter 8 summarizes the content of this dissertation and suggests areas for future research.

1.8 Limitations of the Dissertation

This dissertation examines the history of the ideas and assumptions underlying our present theories of electricity, and the way these theories are perceived, understood, and taught in electrical engineering technology programs. The investigation focuses on the concepts and mental models of electricity students study in their introductory electric circuits courses. These include the idea of electric current, electric potential, electric field, and the methodology of calculations of alternating current circuits taught in first year electric circuits courses using complex numbers and phasors.

I focus on the theories taught in two to three-year electrical engineering technology programs. However, since the four year electrical engineering curricula historically precede the shorter programs, and since there is a considerable overlap in the theories taught in introductory courses in both types of programs, I find it necessary at times to discuss both types of programs jointly or switch back and forth between them.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

In chapter 1, I introduced some of the difficulties students experience when attempting to build conceptual understanding of electricity. In this chapter, I will review research in science education which gave me the initial ideas on which I built my research. The papers included in the first part of the chapter examine the development of students' conceptions in science. The investigations are not directly related to teaching electricity theories, however, they present a line of reasoning that I found relevant to the topic of my thesis. The middle part of the chapter reviews research in teaching electricity theories in secondary and post-secondary programs. The last part of the chapter includes studies that I found difficult to include in either of the first two parts. Such are the investigation concerning the function of theories in engineering design, the examination of the difference between scientists' and science teachers' perceptions of scientific theories and the categorization of scientific theories by a well known philosopher of science.

2.2 Research Promoting Learners' Conceptual Development

Physics theories are generally expressed through mathematical models that use quantitative variables. The symbolic language used in mathematical expressions results in difficulties for students: they need to understand the symbols and the relationships between the symbols. The semiotic process in interpreting mathematical models used in physics is the main concern of De Lozano, Ragout and Cardenas in their paper "Some Learning Problems Concerning the Use of Symbolic Language in Physics". In the view of these authors, the interpretation of the model is dependent on the language used to name and describe the variables. At the introductory college level, students are expected and should be able to use mathematics as symbolic expressions of concepts. De Lozano et alii refer to the well known excerpt from Galileo's *Assayer*:

> Philosophy is written in this vast book, which continuously lies upon before our eyes (I mean the universe). But it cannot be understood unless you have first learned to understand the language and recognise characters in which it is written. It is written in the language of mathematics, and the characters are triangles, circles, and other geometrical figures. Without such means, it is impossible for us humans to understand a word of it, and to be without them is to wander around in vain through a dark labyrinth.[2]

[2] translated by George MacDonald Ross, October, 3, 2005.
http://www.philosophy.leeds.ac.uk/GMR/hmp/texts/modern/galileo/assayer.html#a24

The point De Lozano et alii make is that scientific language has its rules. Unfortunately, these rules are often not explicitly stated. The meaning of words such as “force”, “energy”, and “work” used in the formal science or technology classroom is not the same as when used in every day language. It is important to understand the specific meanings of terms used in science and engineering and their relationship to the physical world. If the differences in the use of the words in everyday English and in physics are not explicitly pointed out, students tend to use these terms in their non-scientific connotation. This presents a barrier to the process of constructing concepts in science and engineering theories.

Cotignola, Bordogna, Punte, and Cappannini in “Difficulties in Learning Thermodynamic Concepts” examine the terminology that was formulated for earlier models of heat and that is still used in present thermodynamic theories. In order to explain why I consider this paper important for my research, I have to briefly review the history of thermodynamics.

The notion of heat as a subtle, imponderable fluid persisted from ancient Greece to the eighteenth century. During the seventeenth century, natural philosophers (Newton, Boyle, and Hooke) suggested that heat is due to the motion of particles inside the bodies. This theory of heat as a fluid continued through the eighteenth and well into the nineteenth century in the form of the caloric theory. According to the caloric theory, the temperature of a body was associated with the density or tension of the free caloric fluid held by it. In some conditions, such as in a change of state, the temperature of a body did not change though it seemed that heat was flowing into it. Joseph Black (1728-1799) tried to explain this finding by proposing that the caloric fluid could be inside matter. It could be either in the interior of the material particles, where the thermometer could not detect it (this form of heat was called "latent heat"), or in the space between the particles, where it could go from the body to the thermometer (this form was called sensitive heat) (Cotignola et alii. 282). The caloric theory of heat was a very successful and useful theory and although it was later discarded, the term latent heat is still used in most textbooks. Cotignola et alii show that the use of terms like "heat capacity" and "latent heat" reinforce the heat fluid concepts in the minds of students. Cotignola et alii's ideas are important for this dissertation, because thermodynamic theories were used to develop theories of electricity, and one of the early concepts of electricity was the concept of electric fluid. For example the term "electric current" strengthens the model of electricity as a flow of a material substance.

Another point Cotignola et alii make is the inconsistent use of the terms "heat", "thermal energy", "heat capacity", and "internal energy". They are concerned that these terms are misinterpreted by students and make them believe that bodies contain heat. Cotignola et alii trace the inconsistencies to the evolution of thermodynamics: for example, heat was defined as a substance in the eighteenth century, a wave in the early nineteenth century, a form of energy in the second half of the nineteenth century, and a form of energy transfer today.

Niaz et alii in "Arguments, Contradictions, Resistances, and Conceptual Change in Students' Understanding of Atomic Structure" suggest the importance of being aware of the historical development of scientific theories for a meaningful learning of science. In this experimental study of students' conceptual change at post-secondary level courses, Niaz et alii followed two groups of university students' understanding of the nature of science in the context of atomic theory development. The experimental group was taught the evolution of atomic theory via class discussions after lectures. The control group was taught the same topic via standard lectures. The class discussion provided an opportunity for the experimental students to think and reflect on the plausibility of new conceptions of atoms. Most of the students in the control class believed that science should be concerned only with hard observable facts and that subjective interpretations are not within the science domain. The experimental class of students that participated in the class discussion showed more understanding of the historical development of the atomic theories, and were more willing to speculate about the presented theories.

One of the fundamental concepts in science and in engineering is the concept of energy. Ebenezer's research group strongly believed that it is valuable to systematically explore students' conceptions and incorporate these into curriculum. Then students will be able to see their own competing theories and contrast these with scientific theories. Students will be in a better position to distinguish between the language that they use and the scientific language. Furthermore, students will experience conceptual empathy when teachers parallel learners' conceptions with the scientific knowledge development. When students' conceptions are explored and exposed, then they are in a better position to learn science from a historical inquiry or conceptual change perspective. Based on these beliefs, Ebenezer and Fraser ("First Year Chemical Engineering Students Conceptions of Energy") and Liu, Ebenezer, and Fraser ("Structural Characteristics of University Engineering Students' Conceptions of Energy") investigated first year engineering students' conceptions of energy. In the first study, the chemical engineering students witnessed demonstrations of making solutions of ionic compounds, followed by interviews probing into their conception of energy in solution processes. It was found that students did not have, what the authors called "a unified framework explaining the processes". The second study used a new class of first year chemical engineering students to further probe into students' conceptions of energy. Students were asked to list the ten most important words associated with energy, and describe how their selected words relate to energy. The students' responses were then used to develop concept maps. By studying and comparing structures of the concept maps, it was concluded that students understood the concept of energy conservation, but that they were not yet able to use their knowledge to explain what happens during the solution-making process.

2.3 Research Promoting Conceptual Development of Electricity Theories

In the previous section I have discussed research into teaching concepts of scientific theories such as atomic structure and energy, and students' understanding of terminology used by scientists. These topics are important to any investigation into the pedagogy of teaching science in general. However, this dissertation is about teaching theories of electricity and therefore research into students' conceptions of electricity is much more directly applicable. The first of the four papers that I have chosen for their relevance is the study "Mental Models of Electricity" by Borges and Gilbert. The authors interviewed secondary school students, technical school students, science teachers, engineers, and electricians on topics taken from electric circuits theory. From the results of the interviews, Borges and Gilbert identified four mental models of electricity: electricity as flow, electricity as opposing currents, electricity as moving charges, and electricity as a field phenomenon.

In the model of "electricity as flow", electric current or electricity is perceived as a material substance supplied by a battery and flowing through the circuit. When presented with a circuit consisting of a light bulb, a switch, and a battery and being asked what caused the light bulb to light up, students for the most part identified only the need for the light bulb to be connected to the battery, even if it was by only one wire. The practitioners emphasized the rules for making electricity flow; for example, in order to light a light bulb, it must be connected to the battery and the circuit must be closed.

The research subjects who did not study electricity described electricity as positive and negative currents separately travelling along the two connecting wires from the battery to the light bulb and being used by the light bulb to produce light and heat. This is the conception to which the authors referred as "the model of electricity as opposing currents". In this model it is implicit that the electric current in the circuit is not conserved.

The model of "electricity as moving charges" was held by third year technical school students, by some engineers, and by some technicians. This model is the idea that electric current is a flow of electrons moving through the conductor. The battery supplies energy to the particles to keep the charges moving through the circuit. Since the light bulb responds immediately to the closing of the switch, the interviewees believed that the electrons move with the speed of light.

The research subjects that held the model of "electricity as a field phenomenon" described electric current as motion of particles due to the electric field that is established by the battery in the conductor. This view was held by many physics teachers and by several technical school students. Most of the engineers accepted what the authors classified as a version of the field model. In this version, the speed of electrons was acknowledged to be very low but the speed of the transfer of energy was deemed to be very high. The behaviour of the circuit was described in terms of a potential difference that causes a flow of something that cannot be more precisely specified, and was understood in terms of energy transformation.

Borges' study showed that there is "a possible pattern of progression" from the simple models (i.e., the earlier theory) towards more elaborate and abstract models (i.e., the more recent theory) as the level of instruction on electricity increases. However, a person can have varying ways of explaining electricity, depending on the question that is asked. The authors concluded that there is an advantage to learning the more complex theories since the subjects holding the more abstract models coped better with practical aspects of electricity; for example, they were able to connect the circuit correctly.

Even more pertinent than the above study is the research reported by Viennot and Rainson on students' difficulties with identifying cause and effect in their paper titled "Design and Evaluation of a Research-Based Teaching Sequence: The Superposition of Electric Field." The authors' hypothesis was that the content of what is being taught and the teaching method are closely interrelated and cannot be separated. In these authors' view, it is necessary to analyze the content before the teaching method is decided.

> The body of knowledge on which scholars agree at a given time could be regarded as a landscape which can be lit from different angles, observed from different perspectives and traveled by different paths. There is a wide choice, therefore a need for a decision, ... in order to define the teaching sequence.(1)

Furthermore, Viennot and Rainson did not expect the presently accepted scientific explanations to emerge from classroom debates; they suggested that "views of science need to be carefully introduced" (2) and "the teaching-learning process should therefore take place in a context of motivated and guided constructive effort"(2). In their study, the authors investigated such motivated and guided constructive efforts in the concept building of "superposition of static electric fields". They stated the principle of superposition as:

> Any point charge creates an electric field at any point in space according to Coulomb's law. This field is independent of the presence or absence of other charges, and of the nature of the environment. The electric field existing at a point is the vectorial sum of electric fields created at this point by all the existing charges. (3)

Viennot and Rainson distributed questionnaires about "static electric fields" to 1837 students in France, Sweden, and Algeria. Students' academic levels ranged from grade 11 to the final year of university. From these questionnaires, the authors identified two main problems: 1. students had difficulty accepting the existence of electric field in a medium other than air when charges did not move; and 2. the majority of students were not able to use the superposition principle if the field was due to combination of point charges and charged bodies. Viennot and Rainson report that in spite of the seeming simplicity of the principle, students have "tendencies to ignore a cause if no effect is visible, associate a cause with only one effect, and consider only one cause for a given effect." (3)

Mulhall, McKittrick, and Gunstone summarize the research on teaching electricity in secondary schools and introductory undergraduate courses in "A Perspective on the Resolution of Confusion in the Teaching of Electricity. The authors present the teachers' and students' perception that concepts of electricity are highly abstract and difficult. Their review of existing research (up to 2001) helps to reveal that the science of electricity includes several theories which are mutually incompatible. They give an example using the notion of "electric current" that is alternately described as electric charges in motion, or as something that transfers energy from one place to another.

The second point Mulhall et alii make is that teachers at all levels find it problematic to try to present the science of electricity as one all-encompassing theory:

> … we now have a good knowledge of the range and nature of models/analogies/metaphors used by students, teachers (school and university), engineers and those working with electricity in practical context…. However, questions such as, "what models/analogies/metaphors?" "when?" "at what levels?" "why (i.e., with what pedagogical justification)"? remain, at least in terms of detail, unconsidered (580).

Mulhall et alii conclude that "teachers are uncertain of the concepts to be taught and of their own understanding of these concepts", and further, that "text books are confused in their presentation of concepts", and, finally, that there is "a lack of consistency in the detail of intended learning outcomes" (577).

In their paper "A Historical Analysis of Electric Currents in Textbooks", Stocklmayer and Treagust briefly discuss Faraday's experiments and his rejection of the electric fluid theories in favour of his ideas of electric fields and lines of force. Stocklmayer and Treagust then continue their line of reasoning by describing Maxwell's use of analogies in the development of the mathematical analysis of Faraday's lines of force, and by contrasting Faraday's and Maxwell's theories with the theories of electrical fluids. Finally, they review the treatments of transmission of electricity along a wire as presented by textbooks from 1891 to 1991. Their findings show that the presentation of electric current in secondary school science textbooks changed very little during the investigated period and essentially has adhered to the fluid theories of the early nineteenth century, prior to Faraday. While in the textbooks written in the 1890s both Du Fay's two fluid theory and Franklin's one fluid theory are somewhat tentatively described, in the textbooks published in the second half of the twentieth century the fluid theories of electricity, mutated into a theory of flow of electrons, are presented as an indisputable scientific fact. Textbooks of elementary physics do not discuss field theories of electric current at all. Stoklmayer et alii interpret this as representation of the dilemma first voiced by Shipstone in "A Study of Children's Understanding of Electricity in Simple D.C. Circuits": Should children be taught the scientific model of electricity or is an understanding of how to use electricity in their daily lives sufficient? Shipstone's question is analogous to one of the issues addressed by this research – the problem of effective use of superseded scientific theories in engineering design methodologies.

2.4 Other Research Relevant to this Dissertation

Apparent in the studies of Borges and Gilbert and Viennot and Rainson is the difference in conception building by students of different academic levels and varying practical background, although the researchers do not explicitly point this out. This issue and the issue of different understanding of scientific theories by scientists and engineers are addressed by Henry Petroski, a professor of civil engineering and history at Duke

University. According to Petroski, the fundamental difference between science and engineering is best illustrated in the approach taken to the study of the environment. While engineers strive to change their environment, scientists are primarily concerned with understanding the universe as it is. Petroski describes engineering as "a fundamental human process that has been practiced from the earliest days of civilization" (Invention by Design 2). The complex computational methods used by engineers help them to analyze ideas, but the ideas themselves come from the basic human desire to change the environment. However, engineering methodologies that focus on guiding towards successful design without discussing how the design may fail leave out an important aspect of the process. Petroski argues that in spite of powerful computational methods and analysis, many designs result in failure. Historical case studies of failed designs are a very effective way of avoiding future debacles and therefore should be part of the engineering curriculum. Although Petroski's main concerns lay in civil engineering, his conclusion on historical studies of failure is valid for any engineering discipline, since all engineering disciplines employ a trial and error approach to design and tend to interpolate from existing designs to a much larger or to a much smaller scale.

The differences in perception of a scientific theory by high school teachers and by scientists are explored by Deng in "The Distinction Between Key Ideas in Teaching School Physics and Key Ideas in the Discipline of Physics". Deng gives several examples of the dissimilarity of key ideas in school physics and in the discipline of physics; the most simple of these being the speed of light. According to Deng, at the high school level, the speed of light is presented by posing two questions: "How fast can light travel?" and "How was the speed of light measured in the past?" For a physicist, the speed of light is a given physical constant, with little reference as to how it was measured. Deng builds his ideas on John Dewey's distinction between the psychological and the logical, and on the theory of "referential realism" proposed by the British philosopher of science Rom Harré. In How We Think and Experience and Education, Dewey saw two distinct aspects in every study or subject, one for scientists and one for teachers. According to Dewey, scientists perceive a given science subject as a body of truth that can be used to make new discoveries. Dewey calls this the logical aspect of experience. The psychological aspect of the given subject matter is experienced by teachers who are not concerned with making new discoveries but view the science subject as a stage of development of science.

In Varieties of Realism, Rom Harré defends "modest realism" which he defines as an acknowledgement of our perception of the natural world as its "genuine disclosure". Rom Harré distinguishes three types of theories in science and each type he associates with a domain of referents called "realm". According to Harré, type 1 theories are used to explain observable phenomena and predict outcomes. The referents of type 1 theories belong to Realm 1. These are quantities that can be actually experienced by the observer. A typical type 1 theory is classical kinematics in which different types of motion are precisely described by the concepts of displacement, velocity, and acceleration. Type 2 theories use unobservable quantities to explain observable phenomena. Harré gives as examples of type 2 theories the plate tectonic theory and the bacterial theory of disease. Deng's examples are the representation of light as electromagnetic radiation and an explanation of the interference pattern of light. In general, type 2 theories involve a representation of a physical system which, at the time of the formulation of the theory, had not yet been observed. The referents of type 2 theories belong to Realm 2. These are quantities that could be experienced by an observer (Varieties of Realism, 71). Harré also defines type 3 theories which I will not discuss here since they are not relevant to this thesis. Harré believes that realism has a different form in each "realm" and that for each "realm" its individual philosophy of science should be developed. At the same time, he acknowledges that the boundaries between the three "realms" are "ill defined" (237) and change with technological development.

Using examples from theories of light, Deng shows that high school teachers tend to use Type 1 theories and relate the theories to students experience, interests, and knowledge background. High school teachers "reconnect with the historic and psychological processes through which scientists developed the subject matter" (Deng, 263). On the other hand, key ideas in the intellectual discipline of physics tend to be Type 2 and Type 3 theories which usually are the latest forms of scientists' understanding of the subject matter. Harré's classification of theories will be useful in examining theories of electricity, which are mostly type 2 theories. For instance, unobservable quantities such as electric charges or electric fields are used to describe observable phenomena: heat, motion, or light. However, for many students as well as for many teachers, the quantities explaining the phenomena are what they consider observable quantities – electric current and electric potential - that are measured by instruments. The object of this dissertation is the examination of the teaching of theories and methodologies of electric circuits, which are mostly Type 2 theories.

Alan H. Cromer is a physics professor at Northeastern University, Boston, with a strong interest in high school physics education. Cromer is one of an increasing number of contemporary science educators who critically examine constructivist theories of learning. In his assessment of teaching in secondary and post-secondary schools, Cromer criticizes the insistence of constructivist researchers that students use their own experience in building their understanding of phenomena. Cromer's objections are that students usually do not have much experience; do not notice details of the phenomena investigated unless the details are pointed out to them; and do not have a theoretical framework that would enable them to organize their observations. Cromer also presents suggestions on developing curricula that advance students' understanding in a methodical manner. For the purposes of this research, the important aspect of Cromer's view is that he makes a distinction between scientists' and science educators' understanding of science. Although Cromer is writing about teaching science students, his ideas can be used as a starting point for exploration of teaching engineering courses. In contrast to the constructivism of many researchers in secondary education that I reviewed in the previous sections, Cromer in Connected Knowledge (27) advocates the need for a theoretical framework as the necessary pre-requisite for teaching science in introductory college physics courses. Surprisingly, Cromer's theoretical framework is similar in nature to the constructivist teaching strategies of Viennot and Rainson. Cromer's statement, "Science requires a theoretical structure prior to experimentation and measurement, since without a theory it isn't possible to extract from the multitude of factors present in every situation those that are relevant" and Viennot and Rainson's view "We think that views of science need to be carefully introduced, in a top-down process among others, and that they cannot all just come out of debates between pupils presented with appropriate tasks" (2), both call for essentially the same approach in presenting science. In their view, it is necessary to present the theory and then do experiments and measurements that will confirm it.

2.5 Summary

Several important conclusions can be drawn from the above literature review. First, language and the consistency of terminology are important to conceptual development. This position was stated by De Lozano et alii who looked at the vocabulary of mechanics and how it differs from everyday language and by Cotignola et alii who examined the language of thermodynamic theories and the use of terms taken from earlier theories. De Lozano's and Cotignola's research are important for this dissertation because the issues they investigated have clear parallels in the theories of electricity. The concept of electric current in the theories of electricity is analogous to heat flow in thermodynamics. These terms were introduced when heat flow and electric current were believed to be a flow of a material fluid. The second conclusion they made was that in lay language, words like "energy", "work", or "force" have different meanings than when used in thermodynamics. This is also true in theories of electricity.

Next, we gained insight from the foregoing literature review into how scientific theories are employed by many diverse users for a wide range of purposes. Students learning science, educators teaching science, scientists doing research, engineers designing equipment, all employ the same theories. However, they each have a different perspective. The difference in the perceptions of physics theories by physics teachers and by scientists is discussed by Deng. Another researcher who makes the distinction between scientists and science educators' understanding of science is Cromer. While both Deng and Cromer examine teaching of physics theories in general, Borges and Gilbert focus on the modeling of electric circuits. They contrast the understanding of electricity by secondary school students, technical school students, science teachers, engineers, and electricians. Their conclusion is that the specific model of an electric circuit a person will use is greatly influenced by his or her past experiences. Viennot and Rainson, while not directly studying the differences in perception of scientific theories by various professionals, also acknowledge that scientific theories are a body of knowledge "which can be lit from different angles, observed from different perspectives and traveled by different paths" (1). The issue of different view of scientific theories by engineers and by scientists is addressed by Petroski, who sees the fundamental difference between science and engineering in the approach each takes to the study of the environment.

Based on the reviewed research, we can assert that teachers' conceptions of scientific theories play an important role in students' conception building. Mulhall et alii found that "teachers are uncertain of the concepts to be taught and of their own understanding of these concepts" (577) and that their lack of confidence compromises students' conceptual development. Teachers' conceptions, however, are not always uncertain. Teachers also may hold conceptions that are well developed and influenced by their understanding of the nature of science. In some instances, constructivist and realist positions come to the same conclusions, although they will use different terminology, as is the case of Viennot and Raison and Cromer. In this case, constructivists and realists all agree that appropriate teacher intervention is necessary if students are to develop conceptions corresponding to generally accepted scientific theories.

Finally, the reviewed research deals with students' preconceptions and conceptual development. There are not many enquiries into teaching a body of knowledge that has to be eventually used by students for a practical purpose, i.e., the design and troubleshooting of equipment and systems. Many phenomena are practically impossible to demonstrate at college laboratories, or even at university laboratories in a way that make the ideas accessible to students. In spite of that, teaching a body of knowledge in technology programs must go beyond teaching concepts or guiding students to build their own individual concepts. At the end, students must accommodate theories and models in such a way that they are able to use methods accepted by industry and which are regarded as standard. The challenge is how to do that.

In the next chapter I will review the development of electrical industry in the nineteenth century. The story of its founding and growth is necessary for understanding of the curricula of today's electrical engineering programs, because the need of the emerging electrical industry for skilled work force led to the establishment of electrical engineering education at that time. (Rosenberg[3], Academic Physics and the Origins of Electrical Engineering in America 66-67).

[3] Robert Rosenberg is an electrical engineer and a historian of electrical engineering with the Institute of Electrical and Electronics Engineers.

Chapter 3

DEVELOPMENT OF ELECTRICAL INDUSTRY IN THE NINETEENTH CENTURY

3.1 Introduction

Electrical engineering programs were first established at the end of the nineteenth century with the goal of providing a skilled work force for the then emerging electrical industry (Rosenberg). The prevailing concepts of electricity and the state of technology at that time were important factors in determining the contents of the electrical engineering courses and in developing models, theories, and methodologies that became part of the curriculum of all electrical circuits courses up to the present time.

3.2 Early Electrical Industries

Up to the end of the eighteenth century, the electricity used in all experiments was produced by rubbing a suitable material such as sulphur, glass or rubber. Experiments with frictional electricity helped to categorize materials as conductors and insulators, found that objects could be electrified by conduction or electrostatic induction, and had shown that electricity has thermal and light effects. All these electrical experiments were of great interest to the experimenters; however, they had no impact on society. The nature of electrical experiments was fundamentally changed by two discoveries. The first discovery was Alessandro Volta's (1745-1827) invention of a steady source of electricity, the electric battery in 1800. The second discovery occurred twenty years later when Hans Christian Oersted (1777-1851) noticed that electric current in a copper wire exerts a force on a magnetic needle.

Volta's invention transformed electricity from being an interesting field of study with no practical use to a valuable source of power. The invention of the electric battery started the steep rise in the number of inventions and innovations that marked the electrical industry of the nineteenth century. The electric battery was very quickly commercialized and became the first step in the development of the electrical industry that in the initial years had three major branches: electrolysis and electroplating, telegraph, and electric lights.

Electrolysis was the first industrial application of electricity. Just a few weeks after Volta's presentation to the Royal Society, William Nicholson (1753-1815), an English inventor and naturalist, and Anthony Carlisle (1768-1840), an English surgeon, also built the electric battery and used it to pass electric current through water and decompose it into hydrogen and oxygen. This triggered a race: What other common substances can be broken up into their elements by electric current? Who can build the biggest battery? Large batteries consisting of large number of interconnecting cells were built in many laboratories, including a battery built by Humphry Davy (1778-1829) for the Royal Society in London in 1807. Davy's battery was constructed from 250 metal plates, and he used it for separating potassium from potash, calcium from lime, and sodium, barium, and strontium from other compounds by electrolysis.

Volta's type of battery uses a chemical reaction to separate electrons and positive ions, and as the zinc in the battery gets used up, the electric current weakens and eventually stops. That means that a battery must be replaced by a new one after it is discharged, and therefore it should be relatively inexpensive. There have been many different electric batteries developed since then, using different materials and also varying in the amount of current they can develop and the length of time they can keep delivering it.

3.3 Telegraphy

The telegraph was one of the important technological consequences of the invention of the battery and the discovery of a relationship between electricity and magnetism. Since the earliest recorded times, people wished for a way of transmitting messages over long distances and devised various systems to achieve it, the earliest being signal fires, drums, carrier pigeons and so on. At the end of the eighteenth century, Claude Chappe (1763-1805) developed a semaphore telegraph. This telegraph consisted of towers spaced within the line of sight of a telescope. The towers were manned by operators who worked semaphores located on top of the towers. For example the telegraph between Paris and Toulon, a distance of 475 miles, had 120 towers and it took ten to twelve minutes to transmit a message (Kirby et alii, 336-337; Finch, 32).

At the beginning of the nineteenth century, the availability of sustained electrical current and the discovery of electromagnetic induction brought about the idea of electrical telegraph. In 1820, Ampère suggested using a separate electric circuit for each letter. It took around ten years to develop telegraphs based on Ampère's idea, but they never became practical.[4] Charles Wheatstone (1802-1875) and William Fothergill Cooke (1806-1879) introduced their telegraph in 1837. They used six wires for the transmission of a message. The first commercial line they built was one mile long and later in 1839 it was extended to 18 ½ miles.[5] In the United States, Joseph Henry experimented with the idea of activating a magnet at the far end of a mile long electric circuit and described his experiments in 1831. Independently of Wheatstone and Cooke, Samuel Morse (1791-1872) used the results of Henry's experiments in his invention of a telegraph that he introduced also in 1837. In 1843 Morse succeeded in getting a grant from the U.S. government to build a telegraph line from Baltimore to Washington. Initially, Morse hoped to sell his line to the U.S. Congress, but that hope did not materialize. Eventually the line became part of the Western Union Telegraph company organized by Ezra Cornell (1807-1874). By 1862, there were 15,000 miles of telegraph lines in Britain, 80,000 miles in Europe, and 48,000 miles in United States (Derry and Williams, A Short History of Technology 627)

---

[4] These ere telegraphs designed by William Ritchie in 1830 and Paul von Schilling-Cannstadt in 1832.
[5] On New Years Day in 1845 the telegraph got a huge amount of publicity by being an instrument in apprehending a murderer. A man took a train from London to Slough where he poisoned a woman and boarded a train back to London. The victim realized that she was poisoned and began to scream. Her screams alerted the neighbours who saw the man leaving his victim's house. The description of the murderer was immediately wired to London. The railroad detective trailed the murderer to his home and next day the police arrested him (Kirby et alii, 338-339)

Up to this time, the telegraph lines were built by "trial and error", which means that scientific theories were not used for the design of the lines. That changed after the first attempt to install transatlantic cable in 1857/58 resulted in a disheartening and very expensive failure. The breakdown of the line just after two weeks of operation prompted the involvement of William Thomson (Lord Kelvin, 1824-1907) in the next transatlantic cable installation. This was probably one of the first introductions of mathematical analysis into what was essentially an electrical engineering design. I will discuss it further in chapter 6.6

3.4 Electric Light and Power

In 1810 Humphry Davy used his large battery to create an electric arc. This inspired the idea of using electricity for light. However, even the largest batteries were not capable of supplying the electric arc with a sufficient amount of electricity for the required time. Practical arc lights were developed only after the invention of the dynamo, a machine that produced electricity by using Faraday's discovery of interaction between the magnetic and electric effects. After the invention of the dynamo by Zenobe Theophile Gramme in 1870, the electric arc lights were widely used for outdoor applications approximately up to the end of the nineteenth century. In the last decade of their use they were gradually replaced by incandescent lights.

Electric lights brought electricity into streets and homes and made the general public daily aware of electric power. They also created the necessity of building electric transmission lines in order to bring the electric power to the lights. For example Edison's famous system at Pearl Street in New York consisted of the dynamo, transmission lines that he had installed under the streets of New York, the light bulbs, and switches.

Although Maxwell's equations apply to electric generators and motors, the invention of electric machines preceded Maxwell's equations. The development of devices that could convert mechanical power into electrical power – the electric generators – followed directly from Faraday's discovery of electromagnetic induction. The electric generators produced a periodically variable electric current which was at the first half of the nineteenth century considered unusable for any practical applications.[6] Both the scientists and the industry were accustomed to a unidirectional electric current provided by the electric discharges and by electric batteries. To counteract this perceived problem, electric generators were fitted with mechanical commutators that switched the flow of current through the load. It was only towards the end of the nineteenth century when Nicola Tesla (1856-1943) invented the alternating current motor (1888) and George Westinghouse (1846-1914) bought the American patent rights for the transformer that the alternating current became the main means of transmission and distribution of electric power. Ever larger electric generators combined with transmission lines were then able to deliver huge amounts of power to locations where no other power could be practically made available in sufficiently large amounts, such as to geographically isolated mines.

[6] It should be noted that the first alternating current generators produced very distorted voltage waveforms, not the clean single frequency sinusoidal voltages to which we are accustomed now.

Contrary to the generally accepted myth, Thomas Edison (1847-1931) did not introduce electric lights and electricity distribution to North America. He was preceded by Charles Brush (1849-1929), an inventor from Cleveland. Brush installed electric arc lights of his own design, supplied by a direct current generator that he also improved at the Telegraph Supply Company where he worked in 1878. In 1879, Brush convinced the Cleveland City Council to allow him to illuminate the city square and the surrounding streets. The first central electric station opened in 1879 and was operated by the California Electric Company of San Francisco. The plant used equipment supplied by Brush. The electricity was used to supply 22 electric arc lights and was distributed by direct current lines. By 1880, there were stations licensed by Brush operating in New York, Philadelphia, Boston, Cleveland, and many other cities. However, the best known direct current distribution system was Edison's, operated from the Pearl Street Station in New York, starting in 1882. Edison's system was a 3-wire 220/110 V [7]. It supplied a load of incandescent lamps with a total power of 30 kW. Similar electric power distribution companies were opening in practically every city in North America, supplying not only lights, but also newly improved direct current motors. Direct current systems seemed to be well established.

In Europe, however, alternating current transmission was preferred. One of the first systems was installed in London, another one in Italy in early 1880's. Both were designed by Gaulard and Gibbs. Their success spurred the development of alternating

[7] Some references give 250V/125V

current transmission in the United States. The main proponent of alternating current transmission was Westinghouse who bought the patents covering the alternating current systems and put into operation an alternating current system in Great Barrington, followed by systems in Pittsburgh and Buffalo.

The alternating current distribution was fiercely opposed by Edison. His strong opposition was not based on engineering or scientific reasons, but on economics. Edison invested large amounts of money in the installation of underground direct current distribution lines and was not willing to abandon his investments. Edison's company had laid copper lines embedded in concrete under many New York streets in anticipation of future expansion, and was thus financially committed to direct current distribution. Both sides, Westinghouse and Edison, claimed and advertised that the competitor's system had a high incidence of fires, injuries and fatalities. During 1887-88, Edison escalated the fight by paying street children to catch dogs and cats (25c a head) and using alternating current to electrocute the animals in front of an audience. This he called "Westinghousing". To really prove his point, Edison electrocuted larger animals as well, several calves, and even a horse. Eventually, Edison hired Professor Harold P. Brown with whose help he arranged a contract with Sing Sing prison to use an electric chair for executions. The first execution was on August 6, 1890, of William Kemmler. The generator used for this purpose had to be, of course, an alternating current generator made by Westinghouse. Since Edison could not buy it directly from the Westinghouse Company, he bought a used Westinghouse-made generator through a broker.

The alternating current vs. direct current dispute became a topic of discussion in several state legislatures, where Edison testified about the dangers of alternating currents. In spite of all Edison's efforts, the trend began to turn towards alternating current systems. The openings of silver mines in Colorado were a further boost for alternating current transmission. The mines were usually located a long distance away from any source of power. The distance was too large for a direct current distribution, but an alternating current was successfully used to transmit power from remote hydroelectric stations to the mines. The systems were isolated; there were no standards, so the frequency used for the generation varied. They were usually governed by factors such as the application for which the power was used, the speed at which the generator could be driven, or the manufacturing capabilities. The most commonly used frequencies were 16 2/3 Hz, 25 Hz, 30 Hz, 40 Hz, 50 Hz, 60 Hz, 66 2/3 Hz, 83 1/3 Hz, 125 Hz and 133 1/3 Hz. The seemingly odd fractional frequencies came from the fact that in the nineteenth century the frequency was expressed in alternations per minute, rather than cycles per second, which is the older name for Hz. Benjamin Lamme (1864-1924), a long time engineer with Westinghouse, gives an example of a Westinghouse-made single phase alternator that had 8 poles, was run at a speed of 2000 rpm and generated voltages with 16,000 alternations per minute, which is equal to 133 1/3 Hz (Lamme, Electrical Engineering Papers 570). [8] The Thomson-Houston company manufactured generators that had a frequency of 15,000 alternations per minute or 125 Hz.

---

[8] Lamme seems to be implying that this generator was made sometime between 1886 and 1889.

The generators in the above examples were used to supply single phase circuits for electric lights. Transformers were already used for the distribution and that was probably the reason for the relatively high frequency. A need for lower frequency came with the use of directly coupled generators; their speed had to be much lower and a higher frequency would require a very high number of poles. Again Lamme gives an example: a generator driven at 80 rpm would have to have 200 poles to produce 133 1/3 Hz, which would have been practically impossible to manufacture at that time. In general, lower frequencies were considered unsuitable for transformers, because they require larger cores than higher frequency transformers. The existing 125 Hz and 133 1/3 Hz frequencies were too high for the new directly coupled generators. The Westinghouse Company came up with a compromise of 60 Hz.

The induction motor, invented by Tesla in 1888 and improved by the Westinghouse Company over the next five years, needed a polyphase distribution. Even before bringing the motor to the market, the Westinghouse Company decided to build polyphase systems at the lower 60 Hz frequency and use them for the lights, with the hope they would be later used for the motors as well. They introduced their first polyphase machine at the Chicago World Fair in 1893. This was a two phase generator with the currents displaced by 90 degrees and each phase operated separately. The first three phase system, a precursor to our modern three phase distribution systems, was probably the transmission line from Lauffen to Frankfurt in 1891, operated at 30 kV. This line to supply power to the Frankfurt Electro-technical Exhibition was built as a joint venture by the German company Allgemeine Elektrizitats Gesellschaft (AEG) and a Swiss company Maschinenfabrik Oerlikon.

In 1889 a decision was made to develop a hydroelectric station at Niagara Falls. An international commission to study the options was appointed and headed by Sir William Thompson, who was knighted as Lord Kelvin in 1866 for his contributions to the success of the transatlantic telegraph cable. The Niagara Falls station and the power line to Buffalo were built in 1895. The station had three two-phase twelve-pole generators capable of delivering 15 000 hp (11.2 kW) of power, rotating at 250 rpm and generating 2200 V. The combination of speed and number of poles resulted in a frequency of 25 Hz.[9] Another curiosity of the Niagara Falls-Buffalo system was the interconnection from the two phase generators to the three phase transmission line accomplished by the Scott connection of transformers.[10]

The 25 Hz frequency became a standard in North America. As late as the 1960s, the 25 Hz frequency was used in large parts of Ontario and in some smaller areas it is still used. In most of the North America, 60 Hz, the standard accepted by Westinghouse, was used.

It is now often said that the alternating current distribution prevailed because of its ability to transform easily to higher voltages and thus more easily and more

---

[9] $\text{frequency} = \frac{p}{2} \times \text{revolutions per sec ond}$

[10] Charles F. Scott (1864-1944) was electrical engineer employed by Westinghouse. While there he assisted Nicola Tesla with development of the ac motor. Later Scott became a professor and head of the Electrical Engineering at the Sheffield Scientific School at Yale University.

economically transmit larger amounts of power over larger distances. This may be partially true, but it is not the whole story. For example a textbook by Alfred Still, Electric Power Transmission, published as late as 1919, describes high voltage (100 kV) d.c. transmission over a distance of 124 miles in France. This is what Alfred Still says about the choice of the system:

> On this continent, it is usual to transmit electric power by means of three phase alternating currents, the periodicity being 25 or 60 cycles per second. In Europe the Thury system of continuous current transmission at high voltages has met with success; it has much to recommend it, and there appears to be no reason why it should not meet with equal success on this continent; but it is probable that three phase transmission, at pressures even higher than those now in use, will hold its own for a considerable time to come. (37)

Clearly, the impossibility of transformation was not an insurmountable deterrent. At the time this was written, an alternating current transmission at 150 kV in USA from Big Creek to Los Angeles was already in operation. The high voltage alternating current transmission eventually took over, but in the 1960s direct current transmission regained acceptance for very long transmission lines.

3.5 Summary

The time of the beginning and the expansion of the electric power industry was a period during which the processes of invention and improvement of electrical systems and devices changed from an empirical approach of trial and error to using mathematical and scientific models. As both science and technology began to rely on mathematics, the relationship between them started to change. Although the use of scientific theories and mathematical models in engineering design did not remove the necessity of design by trial and error, it made possible predictions of the behaviour of objects and equipment under changing conditions before the equipment was actually built and tested.

Many of the important technological inventions in the nineteenth century were a direct result of applications of science. For example, within thirty years, Faraday's discovery of magnetic induction led to the invention of the electric dynamo and electric motor, and over the next thirty years, to the construction of large power stations and extensive power grids for transmission of electric power. Faraday's work also led to Maxwell's theoretical work on electromagnetic fields and Hertz' experiments with electromagnetic radiation. Hertz' experiments later inspired Marconi's invention of wireless transmission.

Another sign of a new relationship between the science of electricity and electrical technology came with a new organization of research. An example of the new systematic approach is the developmental work of Edison's company on the incandescent light bulb. Edison organized his employees into groups so that each worked on a separate part of the invention. In the case of the light bulb, there were three groups; one group worked on developing the filament; another on finding the right gas with which to surround the filament; and still another group was developing the process for sealing the glass containers. Each group was staffed by different workers who possessed different skills. Under conditions like these, it became very unlikely that new science discoveries or new technological inventions would be made by an unschooled person working on his/her own. By the beginning of the twentieth century, electrical science and electrical technology were institutionalized. The rise of research laboratories created the prototype of a scientist as a person with a technical education, engaged in systematic, methodological research. It also contributed to the myth of science providing the theoretical foundation for technology.

Out of many of the large-scale research laboratories that were associated with the electrical industry came many new technological inventions as well as contributions to a fundamental science. Thus in General Electric laboratories, Charles Steinmetz developed extensive new theories about hysteresis of magnetic materials between 1890 and 1910; R.A. Fessenden accomplished broadcasting of speech and music by air in 1906; Lee de Forest invented triode vacuum tube in 1907; and E.H. Armstrong conceived positive feedback and frequency modulation in 1914.

By the end of the nineteenth century it became apparent that the workers in the electrical industry needed not only the practical know-how of their trade, but also a good knowledge of mathematics and physics. The "right proportion" of the theoretical knowledge and the "hands-on" design experience have been the topics of debates within electrical engineering community since that time (Owens, "Electro-technical Education"; Lamme, Electrical Engineering Papers; Ballantyne, "EE Programs"). The story of the founding of electrical engineering education and the role of the electrical industry in its establishment and growth is described in the next chapter.

Chapter 4

DEVELOPMENT OF ELECTRICAL ENGINEERING EDUCATION

4.1 Introduction

Organization and curriculum of Electrical Engineering Education in North America were influenced by three factors. First of all, there was the tradition of existing schools that taught civil or mechanical engineering as a profession; the earliest of these were the schools of civil engineering established in France in the eighteenth century. The second influence was the practice of regular series of public lectures on mathematics and sciences organized for interested tradesmen in Great Britain by various institutions. The third factor was the application of new discoveries of physics into the processes of design and invention. This stimulated introduction of new methods in research and in engineering, which in turn created a need for a better educated work force.

4.2 French and British Roots of Electrical Engineering Education

According to Kirby et alii, engineering as a profession emerged in the seventeenth century in France (327). The earliest engineers engaged in what we now call civil engineering. While practicing their profession, the French civil engineers came to recognize that structures designed by using principles of statics were more economical and performed better than structures designed by using experience alone. With this recognition came a need for science and technical education as a prerequisite for the practice. The first non-military (i.e., civilian) school for instruction in engineering was École des Ponts et Chaussées (School of Bridges and Highways) established in France in 1747. During the French Revolution École des Ponts et Chaussées, as well as other later established schools, ceased to function. In 1794 it was replaced by the École Polytechnique, and later by other schools such as École d'Arts et Metiers and the re-established École des Ponts et Chaussées. These schools based their programs on teaching the basic sciences: mathematics, mechanics, hydraulics, statics, and chemistry. (Finch, 32)

In Great Britain, by the end of the 18th century, increasingly complex machinery used by British industry demanded better educated workers. However, the activity that we now call engineering was not taught at British universities or any other school in Britain. British universities taught mainly the classics and mathematics. Any science courses, if they were taught at all, were devoted to Newton's *Principia* and allowed little criticism.[11] However, many professional and political societies[12] that were formed at that time had adult education as at least part of their platform. Thomas Kelly traces the beginnings of popular science education in Britain to the Spitalfields Mathematical Society, a group of weavers and manual workers formed in 1717 that met regularly to

[11] For example, Thomas Young's theories on the wave nature of light were much better accepted in France than in Britain.
[12] Some of the societies were Society for the Diffusion of Useful Knowledge, Corresponding Society, Brotherly Society of Birmingham, and many others, including the beginning trade unions.

study mathematics and experimental science (George Birbeck. Pioneer of Adult Education 66)

Desire to communicate scientific knowledge to the general public and to use science for practical inventions led to the establishment of the Royal Institution in London in 1799 by two individuals. One was Benjamin Thompson, also known as Count Rumford, and the second person was Joseph Banks, who was at that time the president of the Royal Society. The Royal Institution continued the Royal Society tradition of public lectures and experiments presented by well-known scientists, such as Humphry Davy, who was engaged by Count Rumford soon after the inception of the Royal Institution. Another activity of the Royal Institution was an attempt of Count Rumford to educate mechanics in mathematics, drawing, and other useful skills in a program that included lodgings and work in the Royal Institution's workshops (Kelly, George Birbeck 68)

Dissatisfaction with the state of education at Britain also led to the establishment of the Mechanics' Institute in Glasgow by Dr. George Birkbeck (1776-1841) in 1821. Dr. George Birkbeck was a physician and a professor of Natural Philosophy at Andersons Institute. The lectures of the Mechanics Institute were enormously popular due to a general public wish for education and an ambition felt by many workers to improve their living conditions as well as a very strong popular interest in science.

The Mechanic's Institute was a result of what were to be a few free Saturday lectures on "the mechanical arts" given by Dr. Birkbeck around 1800 to working tradesmen asking questions about equipment with which they worked. By the fourth lecture, the attendance had increased to around 500 people and the lectures became a regular feature (Kelly 31). In 1804 Dr. Birkbeck moved to London and in 1824 became one of the founders of The Mechanics' Institute there. The Mechanics' Institutes in Glasgow and London were soon followed by Mechanics' Institutes in Liverpool, Manchester, Huddersfield, Leeds, and Halifax. All these were the locations of the newly expanding British textile industry. The Mechanics' Institutes were intended to give evening instructions to working men on the principles underlying the technologies used by the industries that employed them. This additional education enabled the workers to use the machinery more effectively. By 1870, it was widely recognized that improved education of workers was essential to the British industry and the British government appointed a Royal Commission to examine the possibilities of technical education. The result was the founding of colleges in industrial towns, often financed by the industry. The colleges were usually associated with the Mechanics' Institutes or with medical schools. Examples are Newcastle Royal College of Science founded in 1871 to provide a trained work force for the mining industry, and Yorkshire College in Leeds for the textile industry (Armytage 231). The first technical training provided by a university in Britain was by the Chair of Applied Mechanism and Applied Mechanics, established in Cambridge in 1875.

4.3 Electrical Engineering Education in the United States

The need for technical education existed also in the United States. As early as 1751, Benjamin Franklin was involved in establishing the Philadelphia Academy that aimed to give a useful and practical education. In 1802, President Thomas Jefferson founded the U.S. Military Academy at West Point. The West Point Academy taught science and mathematics and many of its graduates became engineers after they left the military. In 1824, Rensselaer Polytechnic in New York was established. Yale and Harvard both established schools of science in 1847. In the mid-1800s, Boston was a large center of industry and thus it became the focal point for locating a new type of school – a school that would be equivalent to a university and based on science and its applications to trades. The result of these efforts was the Massachusetts Institute of Technology (MIT), incorporated in 1861. The American Civil War slowed down the preparation to admit the first class, so MIT did not actually open until 1865. The establishment of more colleges in all states was accelerated by the Morrill Act of 1862 that granted federal land to each state for the establishment of colleges that would teach courses related to agriculture and the mechanical arts.[13] By 1863, every state of the Union had an agricultural and mechanical school, and engineering or agricultural courses became an attractive choice for many of the children from the working class or farm background. In the next twenty years the mechanical and civil engineering programs

[13] In 1859 Justin Morrill, a Senator from Vermont, introduced a bill for 'An Act donating Public Lands to the several States and Territories which may provide Colleges for the Benefit of Agriculture and the Mechanic Arts.' The bill became law in 1862. The Morrill Act allowed colleges to sell or lease the land in order to obtain funds to support their programs.

became well established and a strong influence on the programs of the new discipline of electrical engineering.

An interesting historical review of the establishment of electrical engineering education in United States is found in Robert A. Rosenberg's Ph.D. dissertation Academic Physics and the Origins of Electrical Engineering in America. Rosenberg identifies the rapidly developing electrical industry as the main impetus towards formalizing engineering education. Electrical engineering, more than any other engineering discipline, was able to exploit the existing scientific theories for its practical purposes. Since physicists were the chief investigators of the new electrical sciences, physicists became the first professors of electrical engineering. Rosenberg argues that this is the reason why electrical engineering programs have a very strong core consisting of physics courses. Electrical engineering professors were also the first professors with strong ties to the industry.

Supporting Rosenberg's argument is the example of the evolution of an electrical engineering curriculum at MIT. Here, the electrical engineering courses were introduced in 1882 by the Physics Department and were given by that department for twenty years till 1902. Fred Hapgood in Up the infinite corridor recounts the history of MIT and reports on the importance of physicists in the initial half century of MIT existence. In Hapgood's view, the program at MIT was centered on industry and its needs. When the first electrical engineering programs were established, distribution of electric power by the alternating current was the new field in electrical engineering. Therefore, the study of the alternating current electric circuits was an important part, maybe even the most important part, of the electrical engineering curriculum. In engineering education it meant an emphasis on electrical machinery and the practical aspects of engineering as is shown in Hapgood's description of the Dynamo Lab at MIT at the end of the nineteenth century:

> This was a large room, 80 feet long and 20 feet high, with great round metal structures the size of small cars – motors, generators, transformers – sitting on spring-loaded pallets or beds of jacks designed to prevent their vibrations from tearing up the floor. A 10-ton crane with an enclosed cab hung from the ceiling, and loops and twists of inch-thick cables and power jacks the size of belaying pins and arrays of circuit breakers ran along the walls. The equipment dollies were big as golf carts. The ozone in the air suggested enough electrical power to fry an entire high school like a strip of bacon (64-65).

Cornell University was founded approximately at the same time as MIT (chartered in 1865, actually opened 1868), and started the second electrical engineering program in United States just a year after MIT (1883). Its funds came from two sources, the Morrill Act and Ezra Cornell (1807–1874), one of the founders of Cornell University. The second founder was Andrew Dickson White, who became the first president of Cornell. Ezra Cornell was an inventor and a businessman who cooperated with Samuel Morse and built the telegraph lines used by Morse's telegraph company and later unified the telegraph system in the United States into the Western Union Company. The main difference between MIT and Cornell University was the basic premise – while MIT was to be a technical school, at Cornell University classical studies, science, and technical studies were to have equal weight and support.

The first electrical engineering programs were established along lines parallel with the liberal arts programs and therefore they had the same four-year duration (Ryder, "The Way It Was" 42). It should be noted that in France, Germany, and most of Europe the liberal arts programs lasted five years and similarly the electrical engineering programs were also of five-year duration.

The high demand for electrical engineers by the fast developing electrical industry propelled the creation of more electrical engineering programs. According to Ronald R. Kline, a historian of electrical engineering, by 1897 electrical engineering was taught at thirty colleges in United States ("Origins of the Issues" 38-39). Kline quotes an 1899 survey of 18 schools that showed that the programs were of four-year duration and they all had five common elements: 1. electrical theory and practice (often referred to as electrical engineering fundamentals); 2. science and mathematics; 3. mechanics and other "engineering sciences"; 4. drawing and shopwork (the practical aspects of engineering); and language and economics (39). The proportion of each type of course changed over the years. In 1899 the electrical engineering fundamentals were direct current and alternating current circuit theories and electrical machines. New subjects were added to the electrical engineering fundamentals as the new areas of electrical engineering were developed, most notably electronics after World War I, electromagnetic fields after World War II, quantum electronics and solid state electronic in the 1950s, computer hardware and software courses in the 1960s and 1970s, and computer systems and networks in the 1990s. The introduction of all these courses necessitated more physics and mathematics in engineering curricula, often at the expense of the humanities, until language and economics courses were almost completely eliminated in some programs.[14]

In John D. Ryder's view[15], the need for electrical engineering education began with the acceptance of alternating current for electrical distribution in 1890s ("The Way It Was" 39-43). This was followed by a period of stagnation, approximately between 1900 and 1930, when there were no major changes in the electrical engineering curricula. At this time, the idea of what constitutes electrical engineering fundamentals was established; the fundamentals being models and methods of calculations for direct current and alternating current circuits, transmission lines, and electric machines. During these years we see the beginnings of the tension between demands for more practical training from industry (i.e. description of equipment and guidelines for calculations) and the need felt by the many electrical engineering departments to provide better training in the fundamentals of science and mathematics. John D. Ryder gave a description of program at Ohio State University in the mid 1920s when he studied there:

> Our curriculum treated currents and voltages at direct current, and treated alternating currents at 60 cycles per second.... The ac circuits course was considered very "tough" and was used to screen out the less competent students. The third year brought the first machinery courses, which

[14] In recent years economics, management and technical writing courses are making their way back into the electrical engineering curricula.
[15] John D. Ryder was a professor of electrical engineering at several U.S. universities between 1941 and 1972

> continued through the final year. These were descriptive in nature and covered electrical machine design, power plants, transmission, illumination, and street railways. A heat-power course in mechanical engineering covered steam engines and boilers. Mechanics courses covered moments of inertia, columns, trusses, and treatment of timber, concrete, and mild steel as engineering materials. Almost no thermodynamics was taught to electrical engineers; one professor said it was considered too difficult ("The Way It Was" 40).

John D. Ryder points out that his education was not all that relevant to what he eventually did as an engineer. His engineering work was mostly in what we would now call instrumentation – so he did not work with concrete or timber trusses, nor did he work with sinusoidal electric currents.

> Since the early 1900s the engineering colleges' philosophy has changed. They now realize that they are training students in the use of their minds, rather than in the use of their hands and tools as in the "stagnant years".[16] We have also learned that the difference in the exact curriculum from place to place makes very little difference in the ultimate success of our graduates, within very broad limits ("The Way It Was" 43).

Although some of electrical engineering education roots can be traced to the mechanical engineering education that preceded it, the difference in approach to the training of electrical engineers is illustrated by John D. Ryder's observation:

[16] meaning the period 1900 to 1930

> In most of 1930s I was the only electrical engineer in a company staffed with mechanical engineers. I learned that we attacked problems differently – I wanted to solve them theoretically on a pad of paper, the mechanical engineers wanted to go to the shop to see the problem equipment. That this was the result of differing educational pattern in college was confirmed later by psychologist. After all, an electrical engineer did not go to see an electron ("The Way It Was" 41).

Frederick E. Terman who was a graduate student at MIT between 1920 and 1925, and later taught at Stanford Electrical Engineering Department for forty years, describes how during his time at the Stanford Electrical Engineering Department, the main area of research gradually changed from electric power transmission and high voltage to radio-engineering and electronics. In 1926, the Stanford high voltage lab was the largest lab in the United States for transmission line research and its professors certainly had a great influence on the structure and content of engineering courses in North America. (IEEE. Oral Histories <http://www.ieee.org/>).

There is concern within the engineering community about the quality of education future engineers and technologists receive. The most often asked question is what should be the proportion of science and mathematics in engineering courses to the "hands-on" design experience. As was shown by Rosenberg (Academic Physics), the first professors of electrical engineering were physicists. It is partly due to this heritage, that the electrical engineering courses have such a high content of physics and mathematics. On the other hand, the electrical industry that potentially employs the future engineers frequently calls for "a more practical education". In 1892, in a lecture at an American Institute of Electrical Engineers (AIEE)[17] meeting, R. B. Owens, a professor of electrical engineering at the University of Nebraska speculated about the purpose of engineering programs:

> … I take it that a technical school is primarily a place for preparation of men who expect to earn their living as engineers. It is not a school of general culture, nor is it a school of abstract science. It is a device to save time, and teaches the applications of pure science to industrial purposes ("Electro-technical Education" 467).

Professor Owens then goes on to outline what ought to be taught at a college in an electrical engineering program. In the first two years students should learn technical drawing, mathematics, chemistry, physics, some German and French; later,

> when electrical engineering is taken up in earnest *(meaning during second and third year of the program)*, the student should have such a command of physical and chemical facts and methods, and be such a master of mathematical analysis as to leave him free to discuss engineering problems without the necessity of first acquiring the facts and methods he may wish to make use of ("Electro-technical Education" 469).

Owens then continued to list what else the future engineers should be taught: modern geometry, differential and integral calculus, differential equations, maybe quaternions or spherical harmonics.

---

[17] AIEE was a predecessor of IEEE

Benjamin Lamme, a chief engineer at Westinghouse Electric from 1903 to 1924, who established a training program and spent a considerable part of his time training electrical engineers at Westinghouse, also promoted the "fundamentals":

> Coming to the technical training of the students, experience indicates that too much specialization is a mistake. He (*i.e. the student*) gets enough of that in after years. What is needed is a good, broad training in fundamental principles. In engineering matters, a thorough grasp of such fundamentals is worth more than anything else (Electrical Engineering Papers 758).

Lamme illustrated his ideas by giving an example:

> Three electrical engineers, familiar with induction motor design, are given some new problem regarding the action of an induction motor. One of them immediately thinks of a "circle diagram"; the second thinks of a mathematical formula; the third thinks of flux distribution and conductors cutting them at certain speed, etc. Assuming equal mathematical skills for these three men, the one with the physical conceptions of the conductors cutting fluxes has a broader means for attacking the problem than either of the others can be said to have. He can tackle a new condition with better chance of success, as he goes back to the fundamental principles of the apparatus. He thus may create, confidently, new formulae and diagrams to meet new conditions and problems (Electrical Engineering Papers 759).

More recently, in November 1984, the Institute of Electrical and Electronic Engineers dedicated one issue of its journal Spectrum to electrical engineering education. In an article titled "EE Programs", Joseph Ballantyne, then vice president for research at Cornell University, quoted results of a survey of engineering alumni that Cornell distributed in 1980. The survey asked the alumni which courses in their engineering studies were the most valuable in their practice. The most frequent answer was "freshman and sophomore physics and mathematics." Again, this underlined the importance of the "fundamentals" in engineering programs as the essential tools for solving problems the students will encounter as practicing technologists and engineers.

As the consequence of new technological developments resulting from new physics theories after World War 2, the electrical engineering education became more theoretical and out of necessity the more practical aspects of the electrical engineering programs were dropped. This left an open space for the creation of new programs that would maintain the emphasis on the practical aspects of engineering. Thus the electrical engineering technology programs emerged in the United States and in Canada in 1960s. The intention of the technology programs was to provide personnel who are knowledgeable about the practice of engineering rather than engineering theories. The length of the programs varies from two to four years in the United States and from two to three years in Canada. The promotional points for electrical technology programs are the shorter duration, lower cost and more "hands on" experience. However, there is a certain amount of overlap between engineering degree programs and an engineering technology diploma or degree.

The cooperation of the electrical engineering schools with industry and with private inventors began early. As a result of an invitation to use their laboratories extended by MIT to "professional physicists, and others engaged in conducting physical investigations of any kind", Alexander Graham Bell used MIT laboratories from 1874 to 1875 while working on his invention of the telephone (Wildes and Lindgren, <u>A Century of Electrical Engineering</u> 24). The University of Pennsylvania cooperated with Thomas A. Edison beginning in 1878. There was an arrangement between General Electric and the Union College of Schenectady: Charles Proteus Steinmetz, while being paid as the chief electrical engineer for General Electric also served as the head of the electrical engineering department at Union College, Schenectady, NY, from 1903 to 1913 (Wildes and Lindgren, <u>A Century of Electrical Engineering</u> 40).

4.4 Engineering Education in Canada

Engineering education in Canada started in the form of short-term courses on civil engineering and surveying given by post-secondary colleges. The first (most likely) was a three-month course of lectures on engineering given by McMahon Cregan, a prominent railroad engineer, in 1854, under the auspices of King's College in New Brunswick. It was followed by a one-year course on civil engineering and surveying in 1859. In Quebec, McGill University started a two-year diploma program in 1857. However, it had to discontinue the program in 1863 due to lack of interest. The program was reinstated in

1871 (Harris, A History of Higher Education in Canada 73). At about the same time, the Ontario government set up a commission whose purpose was to recommend a format for technical education in Ontario. The commissioners visited a number of institutions in the United States and finally wrote a report in which they recommended the establishment of a school of technology completely separate from any university. Based on that recommendation, a School of Technology was established in 1872 in Toronto. Initially, it offered evening classes in mechanics, drawing, natural philosophy and chemistry and it charged no fees to its students. By 1878, the school changed its name to the School of Practical Science, developed three-year diploma programs in civil, mechanical, and mining engineering, and relocated to the University of Toronto campus. In 1884, it began to award a degree of Civil Engineer to graduates of its three-year program.

In Quebec, the provincial government also supported the establishment of technology education. Initially, it asked Université Laval to create engineering programs and offered some funding that Laval refused. As an alternative, in 1873, the Quebec government founded a school of technology called L'Ecole de sciences appliqués in Montreal. Similar to the school in Ontario, this school also offered three-year diploma programs. In 1875 it was renamed to L'Ecole polytechnique, and in 1887 it was affiliated with Université Laval.

In the meantime, McGill University re-established its technology courses in 1871, this time as a three-year program and started to award the degree of Bachelor of Applied Science. By 1890, engineering programs lasting either three or four years were also offered at King's College at Windsor, the University of Ottawa, King's College in New Brunswick, Dalhousie University, and at the Royal Military College at Kingston.

Electrical engineering departments at Canadian Universities were established considerably later. For example, at McGill University, an electrical engineering program was started in 1939 and at the University of Ottawa as late as 1956. [18] Presently, the engineering curricula at Canadian Universities are similar to those in universities in the United States.

4.5 Summary

Debates about what constitutes a good electrical engineering education arose almost simultaneously with the establishment of the first electrical engineering programs at the end of the nineteenth century. How much theory, i.e. basic science and mathematics should be taught? How much time should be spent on "hands-on experience"? Employers, then and now, complain about new engineers not being ready for their future jobs. As early as 1902, the members of the American Institute of Electrical Engineers (AIEE) met to debate measures to be taken to improve the ability of graduate engineers to apply theory to practical problems. (Kline, "Origins of the Issues" 38). In 1956 the Engineers' Council for Professional Development (ECPD), the predecessor of the Accreditation Board for Engineering and Technology (ABET) set

[18] At present, there does not appear to be a systematic history of electrical engineering education in Canada and it could be a topic of another thesis.

requirements for a four-year engineering program in the United States that included engineering analysis, design and systems (half a year), engineering sciences (one year), basic science and mathematics (one year), humanities and social studies (half year to one year) (Kline, "Origins of the Issues" 43).

According to Rosenberg, the overall design of engineering courses in North America has not changed much since the end of the nineteenth century when the first electrical engineering programs were established, even though new trends in engineering often resulted in new engineering courses, and although there was an occasional experimentation in the length of the programs. Another point of contention at universities and colleges is whether future engineers and technologists should learn their mathematics and science from engineers or from mathematicians and physicists. This debate also started at the time the first engineering schools were established. Yet the fundamental difference in the conceptions of engineering and scientific theories is seldom, if ever, explicitly stated.

Chapter 5

DEVELOPMENT OF THE EARLY THEORIES OF ELECTRICITY

5.1 Introduction

The literature review in chapter 2 gives us an idea that the theories of electricity use terminology rooted in its early concepts. However, this is not explained in contemporary textbooks used for electric circuits courses, for example the widely used textbooks by Boylestad et allii or by Floyd. These textbooks use mathematical models without providing an explicit connection to actual devices or phenomena. A clearer perception of the relationship between the models and the phenomena, and better comprehension of the terminology can be gained by understanding the development of the theories.

5.2 From Antiquity to the Renaissance

Electrical and magnetic phenomena have been well known since antiquity. As natural philosophy and later the sciences developed, theories of causes of electrical and magnetic effects underwent many changes. The initial progress was rather slow compared for example to the development of ideas about motion, perhaps because the known electric effects of materials were considered quaintly interesting but without any practical applications. Philosophically consistent with Aristotelian science, the early electrical theories assumed existence of an intervening medium that transferred the electrical force from a piece of amber electrified by friction to the small objects such as bits of straw or paper and caused them to move. Although the magnetic effect was observable on different types of materials such as magnetite and iron, its action looked similar to the electrical effect and therefore the same theory was used to explain it. The early theory formulated by Plutarch c. A.D. 100, assumed that the intervening medium was air. Plutarch's theory was not challenged until A. D. 1600 by William Gilbert in his book "De magnete" (On the magnet). "De magnete" was a thorough review of the state of knowledge of magnetism and electricity at that time. Magnets were very important to English seamen who were making long voyages across oceans. The magnetic compass was an old and well-known instrument that could save ships from being lost at sea.[19] The mystery of magnets produced many myths about lodestone (magnetic iron ore) and magnetized iron and very little in the way of understanding whether the myths could be confirmed. Gilbert tested many of these myths, such as whether garlic demagnetizes the compass needle. He hypothesized that the Earth is a magnet and he ground a sphere out of lodestone and showed that the pattern of orientation of the compass needle around his model is the same as around the Earth. He was also the first investigator to make a clear distinction between magnetic and electric effects and to notice that amber is not the only material that displays electrical properties. In accordance with the scientific theories of his time, he needed a substance responsible for the electric effects. Gilbert explained the electric attraction by hypothesizing the existence of a material effluvium that binds and carries the moving objects. From antiquity to the renaissance, the philosophers of nature

[19] Whittaker writes that the earliest reference to compass is in 1186, and that is not treated as a new device. However, compass was not known by ancient Greeks.

asked primarily the question of "why" a phenomenon occurs. Gradually during the second half of the17th century, the thrust of enquiry into natural phenomena changed to investigating the phenomena themselves – the primary question became "how" the phenomena can be described. This is already partly apparent in Gilbert's experiments designed to compare the strength of the magnetic force under varying conditions. The need for quantification of magnetic force led Gilbert to invent an instrument called the versarium. The versarium was a detecting instrument, not truly a measuring instrument; it could confirm that an object was electrified, but it could not determine the amount of the electric effluvium that was activated by rubbing.

5.3 Theories of Electricity in the Seventeenth Century

Gilbert's and Plutarch's theories, although incompatible, lived side by side for large part of the 17th century. They were in agreement on the fundamental need for a medium for transmission of the force. Similarly, René Descartes (1596-1650) assumed that all space is filled by a medium which he called ether. Descartes assumed this medium to be imperceptible to our senses and exerting direct forces on bodies in space; the direct forces being pressure and impact force.[20] The problem of natural philosophers of that time was to account for forces that seemingly are not by a direct contact, such as magnetic force. Descartes' ether consisted of particles that were continually in motion. However, there was no empty space between the particles. They moved into space that

[20] The idea that force can act only directly comes from Aristotle.

was vacated by other particles. This type of motion of particles created vortices. Descartes' theory of magnetism proposed that there is a vortex of fluid around a magnet. The fluid enters the magnet at one pole and exits at the other pole. The fluid acts on iron because the molecules of iron present special resistance to the fluid. Descartes was not particularly worried about the agreement of theories and experiments. He went a step further and asserted that physics can be derived from a priori principles. In this he departed from ideas of Tycho Brahe, Galileo, Kepler and followed Aristotelian philosophers of the Middle Ages. Pierre Gassendi (1592-1655), a priest and a professor at the College de France, re-introduced the atomic theory of the Universe – that the universe consists of particles that are moving in otherwise empty space. Later concepts of ether were something between Descartes' and Gassendi's ideas. The ether filled all space, but its particles did not oppose motion of matter through the ether, so the space could be treated as a vacuum (Whittaker 1). The notion of ether became important in the nineteenth century in the development of the electromagnetic field theory.

Around 1675, Robert Boyle (1627 - 1691) tested the air hypothesis of electric effects by using the then newly invented vacuum pump. Boyle found that electrical attraction exists in a vacuum as well, rejected the displaced air theory, and concluded that it must be the direct contact with the effluvium that is the cause of the electrical attraction. Boyle's experiments did not convince adherents of the air theory. They argued that the vacuum pump does not remove all air, which, incidentally, was a correct assertion.

5.4 Theories of Electricity in the Eighteenth Century

Since its inception in 1660, the Royal Society of London organized weekly experimental demonstrations. In the early 1700s, the presenter of the experiments Francis Hauksbee (1687 - 1763) searched for large scale easily observable effects and chose for his demonstrations the phenomenon of barometric light. This phenomenon occurs in the space above the mercury in a barometric tube when the tube is shaken. As mercury is splashed on the walls of the tube and runs down the glass walls, intermittent flashes of light appear. In a barometric tube, the flashes are weak and not always reproducible. Francis Hauksbee devised experiments that eliminated the barometric tube, and indeed the vacuum, and produced a spectacular display of light. He intuitively guessed that the light display is due to the friction between the glass and the little drops of mercury. From here he progressed to use materials other than mercury and glass, rubbed them together in partial vacuum and observed them to produce flashes of light.

A new phenomenon in the now growing field of electricity was discovered by Stephen Gray (1667 - 1736). Stephen Gray did a large number of experiments in which he demonstrated that the ability of electrics to attract small objects (he called it the attractive virtue) can be transferred to some materials through a direct contact and carried a significant distance. An interesting aspect of Gray's experiments is that he used materials such as cork, thread, and wood to conduct the "attractive virtue". We know now these materials as non-conducting. Could it be that the coincidence of high humidity of British weather aided his experimentations? Gray's results meant that the effluvium produced by rubbing existed apart from the electrified body itself. From that came the idea that electricity is a fluid and that it is one of the basic elements of the universe (Whittaker, 42).

Stephen Gray's experiments inspired Charles Du Fay (1698-1739) in France. Charles Du Fay was methodical. He started his investigations with a review of the work done before him and proceeded to list the questions he wanted to investigate: Can all bodies be made electric by rubbing, and is electricity a common property of matter? Can all bodies receive the electric virtue, either by contact or by close approach of an excited electric? Which bodies stop, and which facilitate the transmission of the virtue? Which bodies are most strongly attracted by an excited electric? What is the relationship between the repulsive and attractive virtues? Are they connected or totally independent? Is the strength of electricity augmented or diminished by a void, compressed air, elevated temperature, etc.? What is the relation between electricity and the faculty of producing light, which is common to most electric bodies, and what can be inferred from this relation?

Charles Du Fay repeated many of Gray's experiments. He found that all materials, except metals and soft objects, can be made electric by rubbing, and concluded that electricity is a property of matter. As many experimenters before him, he noticed that rubbed electrics not only attract small objects, but sometimes repel them; however, unlike the other investigators, he did not dismiss this effect and concluded that there are two kinds of electricities: vitreous, gained by rubbing glass, animal hair, etc., and resinous, gained by rubbing amber, copal, silk and many other materials. Based on his tests, Du

Fay built up his theory: bodies that are not electrified have equal amounts of both electricities. If both bodies possess the same type of electricity, they will repel each other; if one body possesses vitreous electricity and the other one resinous electricity, they will attract each other. Finally, he found that metals and wet objects conduct electricity; on the other hand materials that make good electrics such as amber or glass do not conduct electricity.

Around the middle of the 18th century, the interest in electricity spread from England and France to the rest of Western Europe. Almost simultaneously, at Kammin in Pomerania, Ewald Georg von Kleist (c.1700-1748), and at Leyden in Holland, Pieter Van Musschenbroeck (1692-1761), invented, or, to be more precise, stumbled on, a new device. The device came to be called the "Leyden Jar". Musschenbroeck's intention was to store the electric virtue in a container. For this purpose, he used a glass jar half filled with water. A metal wire was inserted into the water and the other end of the wire was brought in contact with the frictional electrical machine. The jar was held in the palm of the hand by the experimenter while the contact was made. The experiment was described by Pieter van Musschenbroeck:

> Suddenly I received in my right hand a shock of such violence that my whole body was shaken as by a lightning stroke. The vessel, although of glass, was not fractured, nor was the hand displaced by the commotion; but the arm and body were affected in a manner more terrible than I can well express. In a word, I thought I was done for (Benjamin, History of Electricity 519).

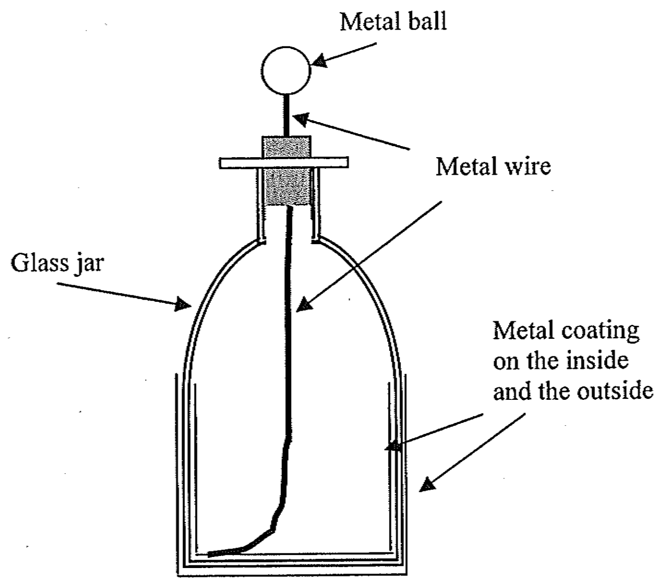


Figure 1 Leyden Jar – A Leyden Jar is a device that early experimenters used to store electricity. It was also referred to as a 'condenser' because electricity was thought to be a fluid that was condensed in the jar.

Leyden Jar is a glass jar that is coated inside and outside with metal. The inner metal coating is connected to a metal wire that passes through cork that is sealing the jar closed. The wire ends in a metal ball. The outer coating is usually connected to the ground. The Leyden Jar is charged by bringing the metal ball into contact with a generator of static electricity.

The Leyden Jar was capable of storing the electric virtue for several days, and delivering powerful shocks when a person held the jar and at the same time touched the wire inserted in the jar. It was later improved by adding conducting layers to the inside and outside of the jar, and eventually it was recognized that it does not need to be in the shape of a jar to store electricity, and that it can be filled by the electric fluid from either side.

The post-Gilbert investigators of electric effects also strove to describe quantitatively what they found, without speculations on underlying metaphysics. However, still partially under the Aristotelian influence, they were unable to accept a force at a distance and had to fill the space with a substance they now called ether. The manifestations of electric properties of electrified objects were then described in terms of the transfer of the electric virtue through ether from one object to another. The trend towards quantitative description of electricity brought along a need for suitable measuring instruments. In 1754, Gilbert's versarium was followed by John Canton's (1718-1772) invention of an instrument that was sensitive to the amount of electricity. Canton's instrument was based on two like-charge pith balls suspended by threads. Canton's instrument was later standardized by Alessandro Volta (1745-1827), and in 1787 further redesigned by Abraham Bennet (1750 -1799)[21] to become the gold leaf electroscope used in physics classrooms to this day.

At the end of the eighteenth century, there were still very few uses for electricity. It was mysterious and it had eye-catching effects that made the science of electricity a popular entertainment. The popular interest drove the race for the inventions of ever-larger electrostatic machines that could generate and store large amounts of electric fluid, and quickly release it with spectacular visual effects. The indisputable physical effects of the invisible electric force and the lightning-like electric discharges drew large audiences to public demonstrations given by travelling lecturers, and kept up the interest of philosophers of nature.

[21]Pounder, <http://www.electrostatics.org/newsletters/NL-161.htm>

The experiments with electricity caught the attention of Benjamin Franklin (1706-1790) in the North American colonies. Franklin repeated many experiments that were already well known to English and French electricians - he started his experimenting with rubbing a glass tube. However, his conclusions were very different from the accepted theories. Franklin concluded that when two substances are rubbed together, there is no electricity created by the friction, one substance looses some electricity, and the other receives it; therefore there is only one kind of electricity, not two, as was assumed by Du Fay. One substance therefore is positively electrified, the other negatively. Franklin also experimented with the Leyden Jar, and again he maintained that the electricity appearing on the conductors inside and outside of the jar is in equal quantities and of opposite signs. One conductor has an excess, the other lack of the electric fluid. (Franklin, "Letters to Peter Collinson"). Through his experiments with the Leyden Jar, Franklin came to recognize that lightning is electrical in nature. To prove his point, he devised his legendary experiment sending a kite into storm clouds to gather electricity and he succeeded in charging a Leyden Jar by conducting the electricity from the cloud through the wet kite string tied to a metal key.

The results of the investigations into electricity during the eighteenth century were two incompatible theories. Charles Du Fay (1698-1739) proposed that there are two types of electricity, vitreous and resinous, and that all electrically neutral materials possess both electricities in equal amounts. Materials become electrified when part of one type of electricity is removed. Benjamin Franklin (1706-1790) proposed a rival theory. Franklin believed that there is only one type of electricity that he called electric fluid. In

Franklin's theory, the "electricised" objects had either a surplus or a shortage of the electric fluid. Benjamin Franklin imagined electricity as an elastic fluid consisting of particles that could permeate matter. In Franklin's assumption the electric fluid, which is equivalent to Du Fay's vitreous electricity, was positive. Du Fay's resinous electricity was equivalent to a deficiency of Franklin's electric fluid. Du Fay's and Franklin's theories coexisted throughout the second half of the 18th century and all of the 19th century. Each theory had its prominent adherents. In fact, although we now reject the notion of electric fluid, the imagery of fluid and flow remains in our terminology of electric circuits.

The effluvium was discredited by Franz Ulrich Theodor Aepinus (1724-1802), a follower of Franklin and a member of the Berlin Academy of Sciences. He built on Franklin's observation that glass is impermeable to the electric fluid and extended it to all non-conducting materials including air. Aepinus built a version of a Leyden Jar with air as the insulating layer. Using Franklin's observation that electric properties of a charged body do not change even when the air was blown away, Aepinus concluded that the electric fluid is confined to thin layers on the surfaces of charged bodies. This being the case, the attraction or repulsion must be due to an action at a distance. The next step was to find how this force varies with distance. The electrical fluid theory served as a pattern for development of one magnetic fluid theory also by Aepinus (1759). He theorized that magnetic poles are the places where magnetic fluid is present in amounts that are either more or less than the normal quantity. Permanent magnets had the magnetic fluid entangled in their pores so that it was difficult to displace (Whittaker, 57). Later, a two magnetic fluid theory was proposed by Anton Brugmans (1732-89) and Johan Wilcke (1732-96). The magnetic fluids were called boreal and austral and had properties analogous to the vitreous and resinous electricity.

Franklin's theory of one electric fluid raised a question of amounts of the electric fluid or electric charge transferred between objects. It was also observed that the attractive or repulsive forces vary in strength. Establishing the relation between the force and the charges and the distance between the charges became the quest of the scientists following Du Fay and Franklin. Newton's work on gravitational force gave rise to an assumption that the electrical force may be described by a similar law. That is, it was expected that the force between two charges will be inversely proportional to the square of their distance and directly proportional to the product of their "electrical masses". Joseph Priestly (1733-1804) was probably the first to make this reasoning. At Franklin's request, he repeated his experiment with a cork ball inserted into a hollow charged metal vessel. When the cork ball experienced no force, Priestly deduced that the form of the law governing the force must be the same as the gravitational law.

> May we not infer from this experiment that the attraction of electricity is subject to the same laws with that of gravitation, and is therefore according to the squares of the distances; since it is easily demonstrated that were the earth in the form of a shell, a body in the inside of it would not be attracted to one side more than another? (Priestly, The History and Present State of Electricity, with Original Experiments qtd. in Whittaker, 53).

A French engineer Charles Augustin Coulomb (1736-1806) as many scientists of his time believed that the electric force is defined by the inverse square law and he set out to confirm it. Coulomb was in a good position to attempt measurements of small electrical forces. Previous to his confirmation of what we now know as the Coulomb law, Coulomb designed a torsional balance capable of detecting very small forces, that he used to measure variations in the earth's magnetic field. Coulomb made his measurements of the separation between two charged pith balls in terms of degrees of twist needed for his torsional balance to balance the electric force. Besides confirming the inverse square law, he found that the electric force is proportional to the amount of electricity present on the charged pith balls. However, he had no way of measuring the amount of electricity, nor any way of determining the constant of proportionality. A consequence of Coulomb's confirmation of the inverse square law was a general belief in and acceptance of action at a distance.

5.5 Sustained Electric Current

In 1800, Alessandro Volta presented to the Royal Society his invention of a steady source of electricity, the electric battery. The electric battery consisted of alternate plates of copper and zinc, separated by paper soaked in brine. When an electroscope was connected to either plate, it indicated an accumulation of charge. With electrostatic sources of charge, the electric effects were short-lived when the charged object was connected by a conductor to the ground. Using Volta's electric battery, the electric effects persisted and the electric battery was capable of supplying electricity for some time.

In the early 1800s, the terminology used by scientists was varied and vague. Terms used included voltaic excitation, electric virtue, voltaic current, galvanism, and electric fluid. For example, Volta described his battery as an apparatus "for the endless circulation of electric fluid." (Bordeau, Volts to Hertz *44*). Furthermore, the experimenters had no precise instruments to quantify the effects of electricity. The only instrument available to Volta was an electroscope, which had only limited use in comparing the strengths of electric cells formed by various combinations of metals, or gauging changes in strength due to various connections of individual cells. However, Volta found that his sense of touch (and pain) allowed him a better understanding of changes in the strength of his batteries:

> .... I can obtain a small pricking or slight shock in one or two articulations of a finger immersed in the water bason, by touching, with the plate grasped in the other hand, the fourth or even third pair of metallic pieces. By touching then the fifth, the sixth, and the rest in succession till I come to the last, which forms the head of the column, it is curious to observe how the shocks gradually increase in force. But this force is such, that I receive from a column formed of twenty pairs of pieces (not more) shocks which affect the whole

> finger with considerable pain if it be immersed alone in the water of the bason… (Dibner, Alessandro Volta 114).

Henry Cavendish (1731-1810) used the same measuring method when he tried to find a relationship between various conductors and the amount of electricity they will conduct. Cavendish used Leyden Jars as the source of electricity, and discharged them through glass tubes containing a salt solution. The glass tubes were of varied lengths and diameters. Cavendish completed the discharge circuit by closing it with his hands and by measuring the intensity of the shock he received. This he called the degree of electrification.

Humphry Davy (1778-1829) and Peter Barlow (1776-1862) in England and A. Becquerel (1788-1878) in France used batteries as the source of electricity in their investigations of conduction by wires made of various metals. In their work they used terms such as "intensity of electricity, quantity of electricity, tension, or excitation force" often interchangeably and without clearly defined meaning. However, in experiments conducted during the early 1800s, three quantities that characterized the "galvanic" circuits began to emerge. These were tension, current flow, and resistance. There were no clear definitions of what each of them meant and there was uncertainty as to whether the electricity flows along surfaces or whether it is conducted through the bodies. Naturally, questions were also asked about the amounts of electricity in the experiments. It bears repeating that the instruments used at this time were not very precise. The amount of electric charge was measured by the gold leaf electroscope; the magnetic needle galvanometers were used to measure electric current.

Important in tracing the developments of quantification of electric sciences are the results obtained, on separate occasions, by Davy, Barlow, and Becquerel. Davy concluded that wires of the same material that have the same ratio of length to their cross-sectional area cause the same amount of current intensity. Barlow was looking for a relationship between the dimensions of a wire, i.e. wire length and diameter, and current intensity. His conclusion was that for wires of the same length, the current intensity increases with the diameter of the wire. Becquerel found that wires made of the same material and that have the same ratio of length to cross-section also have the same conductivity.

One difficulty with batteries was that they were not a sufficiently steady source to enable establishing relationships between the amount of electric fluid in the circuit and the strength of the source. A source that kept the potential difference constant was found by Thomas Seebeck (1770-1831) in 1822 when he heated a junction of two dissimilar metals and produced a difference in electric potentials. This thermoelectric cell was the source used by Georg Ohm (1787-1854) to establish the relationship between potential difference, electric current and the circuit resistance. Ohm's model for his work was Fourier's analysis of thermal circuits. In Ohm's model, the difference of potentials was analogous to the difference in temperatures, and the electric current was analogous to heat. The resulting relationship between electric current, voltage, and resistance is called

Ohm's law. Ohm's law is the foundation of the electric circuits theory. The equations $Q = C\cdot(T_2 - T_1)$ for thermodynamics[22] and $I = \frac{1}{R}(V_2 - V_1)$ for electricity[23] have the same form. I will return to Ohm's work in chapter 6.3.

5.6 Early Theories of Electromagnetism

In A History of the Sciences, Stephen Mason (1962) attributes the search for a single power that is the cause of all force effects in nature, such as light, electricity, magnetism, chemical forces, gravity, etc., to German philosophers of nature Immanuel Kant (1724-1804) and Georg Wilhelm Friedrich Hegel (1770-1831), who postulated the existence of the universal world spirit as interconnecting all forces of nature (349-362). The universal world spirit philosophy led to investigations of possible connections between the various effects such as heat and electricity, chemical reactions and heat, chemical reactions and electricity, light and heat, mechanical motion and heat and also electricity and magnetism. In 1820, Hans Christian Oersted (1777-1851) demonstrated the magnetic effect of electric current in a straight wire. All accounts of this event comment on the serendipity of his observation. Oersted, during his lecture demonstration in April 1820, connected a metal wire to a battery and noticed that a compass needle located close to the wire moved. When the wire was disconnected from the battery, the needle returned to its original position. Oersted repeated the experiment later in a controlled setting, and in July of the same year he published his results. Oersted also

---

[22] Q is the amount of heat; C is heat capacity (characteristic of the material); $T_2 - T_1$ is the difference of temperatures

[23] I is the electric current; R is the resistance (characteristic of the material); $V_2 - V_1$ is the difference of potentials.

noticed that the force changed its direction as the magnet was moved around the conductor in a circle. Oersted's observation conflicted with Newtonian physicists in France and England who believed that all forces are push-pull type along a straight line connecting the two bodies. André Marie Ampère (1775-1836), also in 1820, found that in order to obtain a push-pull type of force along a straight line, the electric current must be carried by a circular loop of wire. A circular current loop thus behaves like a bar magnet. Based on this evidence, Ampère concluded (in 1825) that magnetic effect must be due to the circular electric currents in particles of magnetic materials. This theory is still taught in physics and electrical engineering classes today.

Oersted's discovery of the behaviour of a magnetic needle in the magnetic field produced by electric current provided the mechanism for the measurement of the electric current. The same year, Ampère had shown that the magnetic effect is proportional to the current that creates it, and used a moving magnetic needle to build an instrument to measure the electric current – the galvanometer. The early galvanometer was a compass placed inside of a coil of wire. These instruments were called "tangent" galvanometers because the tangent of the angle of deflection of the needle was proportional to the strength of the current in the coil.

Ampère's design was improved by several experimenters. One of them was the British physicist William Sturgeon (1783-1850), who in 1825 redesigned the instrument. Sturgeon's design was more versatile: current could be routed to flow both above and below the needle. If the current flowed in a loop, the magnetic effect was doubled; if the currents in the two wires were in the same direction, their magnetic effect on the needle would cancel out.

The terminology Ampère used differed from the one used by Volta. Ampère talked of the "tension" that existed between the terminals of a battery. He also spoke of the "intensity" of electric current and noted that conductors present a "resistance" that limits the current flow. Ampère was the first investigator that differentiated between the electric tension of the battery and the intensity of electric current; most investigators made no clear distinction between the two quantities. The two electrical phenomena then known were classified as distinct: the term "electricity" applied to what we now call electrostatics and the effect of sustained electricity produced by batteries was called "galvanism". There was uncertainty about the relationships of the two electrical phenomena and magnetism.

5.7 Summary

The theories of electrical behaviour of materials underwent many changes over time. The initial development was rather slow, compared, for example, to the development of ideas about motion, perhaps because the known electric effects were considered quaintly interesting, but without practical applications.

The initial theories assumed existence of a medium, "an electric effluent", that would cause movement of objects towards electrified bodies by a direct contact. This notion carried into the eighteenth century, when it underwent significant changes. The investigators of electricity began to concentrate on the description of what they saw and did not speculate on underlying mechanisms of the phenomena. Yet they were unable to divorce themselves from the need to imagine some substance responsible for the effects. This substance they called "electric virtue", and the manifestations of properties of electrified bodies were thought to be due to transfers of the electric virtue from one object to another. The work of the experimenters of the first half of the eighteenth century culminated in the theory of two kinds of electricities – vitreous and resinous. It was believed that all bodies have both electricities in equal amounts and become electrified when part of one type of electricity is removed. In the second half of the eighteenth century, a rival theory was proposed. This theory held that there is only one type of electric fluid and that electrified bodies have either a surplus or a shortage of electric fluid.

During the nineteenth century, each of the theories had its prominent adherents. In fact, although we now reject the notion of electric fluids, both theories are still with us in modified forms. Our present view is that every substance consists of atoms and in every atom there are two types of particles that carry opposite electric charges: negative electrons and positive protons.[24] A substance that does not display electric behaviour has both types of particles present in equal amounts. The transfer of charge is due to the excitation of negative particles. With the exception of the sign and the quantum character

[24] More on the more recent theories is in the next chapter

of the negative charges, this is essentially Franklin's hypothesis. However, movable positive particles, ions, can be created in some substances such as gases and solutions by the removal of electrons from atoms or molecules. The charge can then be transferred by motions both of the ions and of the electrons in opposite directions, which is close to Du Fay's two-fluid theory.

The early concept of electric current as a flow of an electric fluid was the central idea in developing and teaching the methodology of analysis of direct current circuits. Naturally, the theories of electricity are not limited to the electric current and the development of science and technological applications of electricity did not stop in the nineteenth century. The theories of electricity that were developed in the second half of the nineteenth century and the early twentieth century and those that are relevant to this dissertation are discussed in the next chapter.

Chapter 6

SCIENCE AND ENGINEERING THEORIES OF ELECTRICITY

6.1 Introduction

Theories of electricity are closely tied to theories of heat. During the nineteenth century, when many of the theories of electricity were developed, a number of similarities between heat and electricity were noted. Both heat and electricity could be created by friction; both could cause combustion; both could be transferred between bodies by contact; good conductors of heat were also known as good conductors of electricity. The early theories of electricity (the fluid theories of Franklin and Du Fay and the field theory of Faraday), as well as the theories of heat, did not use action at a distance to explain the observed effects.

However, there were also some obvious differences between heat and electricity. Most notably, static electricity was known to be distributed only on the surfaces of bodies, while heat was distributed through the volumes of the bodies. Another important difference was that the presence of electric charge did not cause an increase in temperature. Additionally, as the theories of electricity developed, many investigators began to accept the idea of action at a distance for electricity but not for heat.

In order to explain observable effects such as the occurrences of heat, light, or motion of objects, theories of electricity introduce abstract quantities of electric charge, lines of force, electric field, magnetic field, potential, and electric current. The main difficulty in understanding these concepts is their intangibility. When studying mechanics, students can directly see the displacement, velocity, and acceleration of a moving object. They have a workable concept of force from their everyday life. However, the concepts of the electrical quantities, the building blocks of the electricity theories, seem vague and uncertain. What then, are the ideas that led to making use of such hard to define and hard to understand terms, and how were they merged with the theories of heat? Furthermore, how were the theories of electricity incorporated into the models and methodologies taught in electric circuits courses?

6.2 What Are Electric Current and Electric Charge?

Early investigators of electricity believed that objects will not exert force on each other without some form of direct contact. For this reason, their theories proposed invisible effluvia or electric fluids as the carriers of electric forces (the developments of these ideas are described in chapter 5). Such theories, based on a direct contact, lasted until the middle of the eighteenth century. The word "charge" in connection with electricity was first used by Benjamin Franklin in the late 1740s. For instance, in his letter to Peter Collinson Franklin writes:

> To charge a bottle commodiously through the coating, place it on a glass stand; form a communication from the prime conductor to the coating, and

> another from the hook to the wall or floor. When it is charged, remove the latter communication… (letter dated 1748, 198)

Franklin's use of the word "charge" was similar to the way we use it today. For example, a very widely used introductory physics textbook by Halliday, Resnick, and Walker explains:

> … we first charge a glass rod by rubbing one end with silk. At points of contact between the rod and the silk, tiny amounts of charge are transferred from one to the other, slightly upsetting the electrical neutrality of each (637).

Although the use of the word "charge" is similar, the concepts are different: Franklin saw an invisible fluid being drawn from, or being introduced into, the object being charged, while Halliday et alii see minuscule particles gathering on the surface of the object or leaving its surface.

In the early 1800s, with Volta's invention of the battery, a new electric theory called galvanism emerged. At this time, scientists still referred to the electrical effects as a flow of electric fluid. Volta himself, when announcing his invention to the Royal Society in March of 1800, talked of "disturbances" (Arons, Development of Concepts of Physics 510), and later, Volta described his battery as an apparatus "for the endless circulation of electric fluid" (Bordeau, From Volts to Hertz 44). The conceptual change from electric fluid to electric particles had its origin in the first technological application of Volta's electric battery for the electrolysis of water. The first decomposition of water was done three years before Volta's invention of the battery. In 1797, George Pearson, an English physician, passed discharge from a battery of Leyden Jars through water and decomposed it into hydrogen and oxygen. He also passed the discharge from a battery of Leyden Jars through a mixture of oxygen and hydrogen and produced water (Dunsheath, A History of Electrical Power Engineering 34). The decomposition of water into hydrogen and oxygen brought forth a number of theories trying to explain how hydrogen and oxygen are released and transported to the opposite electrodes. Many investigators assumed that the decomposition is accomplished by some means of transferring an electrical quantity from one molecule to another. As one of the many investigators of electrolysis, Michael Faraday devoted a large amount of time to studying the passage of electricity through liquids and gases, and from him we have our terminology: he called the assumed charged particles moving through the liquid "ions", and the electrodes he called "cathode" and "anode". One of the later theories, suggested by the Swiss scientist Rudolph Clausius (1822-1888) in 1857, proposed that atoms of hydrogen and oxygen acquire opposite electric charges and travel to opposite electrodes.[25] The opposite motion of the charged particles (ions), according to Clausius, constituted the galvanic current. Exactly when the term "current" started to be used consistently is difficult to trace. It began to appear in the works of Davy, Barlow, and others. For example Faraday, who used the term electric current quite consistently, wrote:

> Whether there are two fluids or one, or any fluid of electricity, or such a thing as may rightly be called a current, I do not know; still, there are well-established electric conditions and effects which the words "static", "dynamic", and "current" are generally employed to express; and with this

[25] hydrogen travels to the cathode. At this time, the assumption still was that the cathode is positive.

> reservation they express them as well as any other (qtd. in Arons, Development of Concepts of Physics 513).

The sustained flow of electricity in the early 1800s attracted many new researchers. In The Development of Physical Thought, Loeb and Adams likened the situation to a century later when radioactivity and cathode ray tubes created similar levels of interest (367). One of many investigators of the new electrical phenomenon was Hans Christian Oersted (1777-1851). Oersted "understood the galvanic current as a propagating alternation of decompositions and recompositions of the two electricities, and made this *electric conflict* the source of heat, light, and possibly magnetism" (Darrigol, 4).[26] Oersted made these observations about the interaction of electricity and magnetism:

1. The electric conflict acts on magnetic poles.
2. The electric conflict is not confined within the conductor, but also acts in the vicinity of the conductor.
3. The electric conflict forms a vortex around the wire (Darrigol, 5).

In 1821, André-Marie Ampère became interested in Oersted's experiments. He accepted Oersted's idea that the cause of electric current is the process of composition and decomposition of two electric fluids, vitreous and resinous, that starts at the battery and propagates along the conductor, and devised an experiment that showed that electric

[26] Oersted used 20 Cu-Zn cells filled with sulfo-nitric mixture and had the wire turned red to ensure the "electric conflict" is strong

current flowed through a battery and formed a closed circuit, and that intensity of the flow was the same in all parts of the circuit.

By 1831, when Faraday wrote his Experimental Researches in Electricity, he used the term "electric current" in the same sense we use now. It was also known that there are several different sources of electric current. There is the chemical reaction of Volta's battery, the magnetic field line variations within a closed conductive loop, and the temperature difference at junctions of some metals.

By the middle of the nineteenth century, the idea that electricity may be a flow of discrete particles rather than a fluid was proposed by many researchers for various reasons. In 1845, a professor at the University of Leipzig, Gustav Theodor Fechner, (1801-1887), put forward the idea that electric current is a stream of electric charges: vitreous charges moving in one direction and the resinous charges in the opposite direction; both charges being equal in magnitude and number. Wilhelm Weber (1804-1890), who was at that time also at the University of Leipzig, provided mathematical proof that this assumption leads to the law of induction of electric current. Later, in 1871, Weber developed a theory of magnetism based on a model of an electric charge orbiting a fixed electric charge of an opposite sign.[27]

Hermann von Helmholtz (1821-1894), originally a medical doctor, was also one of the scientists who believed that electricity consists of discrete particles: In 1881, while a professor of physics at Berlin, he wrote:

[27] this model resurfaced in the early twentieth century as the Rutherford-Bohr model of an atom.

> If we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid concluding that electricity also, positive as well as negative, is divided into definite elementary portions, which behave like atoms of electricity (Darrigol, 273).

Another path that led to a theory using electrically charged particles as carriers of electricity was the study of electrical discharges in gases. In 1821, Humphry Davy noticed that an electric arc between two carbon poles is deflected when a magnet is placed close to it. The phenomenon was not further investigated until the improvements in the design of the air pump in 1855 enabled the building of vacuum tubes and the study of electric discharges in vacuum. Then, a similar deflection of the glow as seen for the electric arc earlier was observed by several researchers during discharges in the vacuum tube. For example, in 1860, Julius Plücker (1860), in 1869, W. Hittorf (1869), and in 1876, Eugen Goldstein (1876) noticed this phenomenon. Goldstein introduced a new term for the observed glow: he called it the "cathode rays". For the remaining part of the nineteenth century, the question "what are the cathode rays" attracted a large amount of attention. William Crookes (1832-1919) thought the cathode rays to be streams of molecules of residual air, with resinous charge. The observed light, according to Crookes, was due to collisions of molecules and molecules striking the glass of the tube. [28] Crookes also determined that the electricity was flowing from the negative electrode (cathode) towards the positive electrode (anode) by inserting a piece of metal inside the tube and showing that it cast a shadow on the anode side.

[28] There were also other theories explaining the cathode rays: Hertz, for example, maintained that the observed glow is a disturbance of the ether.

In the early 1880s, J.J. Thomson initially thought that the discharge in a cathode ray tube is a consequence of the decomposition of gas molecules into atoms and the recombination of atoms back into molecules. In 1893, J.J. Thomson had a 50-ft long discharge tube built and used it to measure the velocity of the discharge. He found that it was of the same order as the velocity of the light. That was too high a velocity for the discharge to be due to moving ions. More evidence that the discharge could not be a stream of ions came from Hertz. In 1892, he found that cathode rays can pass through thin sheets of metal. Thomson believed that the cathode rays could be deflected by magnets because they were a flow of electric particles. But, because of their high speed and their ability to pass through metal foil, they had to be much smaller than charged atoms (ions). That led Thomson to conclude the particles that he called corpuscles were parts of atoms; Thompson then proposed that atoms were clouds of these tiny particles. Consequently, he set out to measure the charge-to-mass ratio and in 1897 he measured a ratio that was about 2000 times larger than the charge-to-mass ratio of the hydrogen ion. Thomson continued to call these subatomic particles corpuscles – we now know them as electrons.

However, if atoms were built of electrons, they also had to contain a positive charge since on the outside they were electrically neutral. This assumption was strongly supported by observations done by Goldstein in 1876 and 1886, and by Wilhelm Wien (1864-1928) in 1907. Goldstein, while experimenting with cathode rays, noticed weaker rays that could be deflected by electrostatic fields towards the negative pole. Wien used deflection potentials of up to 30 000 V and measured the charge-to-mass ratio of particles in these rays and concluded that they must be hydrogen ions. This was later (in 1907) confirmed by J.J. Thomson.

Thus, in our present theories we talk about electrically charged bodies when they exhibit electrical forces on other electrically charged bodies. We say that the electric charge is the result of the presence or absence of particles we call electrons and protons that carry negative and positive charge, respectively. We also teach that electric current is a flow of these charges.

> If we are to say that an electric current passes through a given surface, there must be a net flow of charge through that surface. (Halliday et alii, Fundamentals of Physics 766).

Students learn exactly how much of the electric charge electrons and protons have, what their mass is, how they move, and how to calculate their drift velocity. The volume of information about the particles makes the particles very real, so real, that students are very surprised when they find out that electrons and protons cannot be observed directly. Students find it amazing that all this information was constructed by observing relatively large objects to move under the influence of electric forces, or by seeing invisible rays leaving a visible trace, rather than observing the elementary particles directly.

6.3 The Influence of Thermodynamics

The publication of The Analytic Theory of Heat by Joseph Fourier (1768-1830) in 1822 motivated many researchers of electricity to take a different approach in their investigations. Fourier based his theory on differential equations that described the radiation of heat from a heated element into the surrounding area. Avoiding speculations about the nature of the phenomenon, Fourier concentrated on the description of "how" heat propagates. Fourier opened his Analytical Theory of Heat with these words:

> Primary causes are unknown to us; but are subject to simple and constant laws, which may be discovered by observation, the study of them being the object of natural philosophy.
>
> Heat, like gravity, penetrates every substance of the universe, its rays occupy all parts of space. The object of our work is to set forth the mathematical laws which this element obeys.

The fundamental relationship for solving electric circuits was found by analogy to heat. Georg Ohm used the analogy when investigating the relationship between what he called "electroscopic force", electric current density and electrical conductivity of pieces of conducting materials. Ohm used Fourier's idea that the amount of heat transferred along a piece of material is the product of the thermal conductivity of the material and the difference of temperatures at the two ends:

$Q = \mathrm{K}\,(T_2 - T_1)$ where Q is the amount of heat
K is the thermal conductivity
$T_2 - T_1$ is the difference in temperatures.

In Ohm's model, the gradient of the electroscopic force at the terminals of the electric battery was analogous to the difference in temperatures, the electric current density was analogous to the amount of heat, and the electrical conductivity was analogous to the thermal conductivity. Ohm expected the relationship to be:

$$\text{electric current density} = \text{conductivity} \times \text{the gradient of the electroscopic force}$$

Again, using Fourier's ideas of how heat transfer occurs, Ohm developed a theory that stipulated that the electricity in a conductor is transferred from one particle to the next in an amount that is proportional to the electrical force between the particles. At each moment, each particle receives exactly the same amount of electricity as it sends out. From this Ohm deduced that a cross-section through a conductor receives the same amount of electricity as it sends out and therefore the flow of electricity is the same through the conductor. Ohm used his measurements to devise an equation:

$$X = \frac{a}{b+x}$$

where X is the reading of the torsion head (divisions)
x is the length of the wire (inches)
a is a constant dependent on the temperature difference of the thermoelectric element
b is a constant that represents the resistance of the reference wire to the electric flow

In the above relationship X is proportional to the electrical flow, a is proportional to the tension, and the term $1/(b+x)$ is proportional to the conductivity. For his particular set up, Ohm calculated a = 7285 and b = 20.25. These results were published in February 1826. Ohm's conclusion was that the electric current density was proportional to the gradient of the electroscopic force.

In his next paper dated April 1826, Ohm gives equation

$$S = k\,\omega\,\frac{a}{\ell}$$

where S is the current intensity
a is the electric tension applied to the wire
ω is the cross-sectional area of the wire
l is the length of the wire (inches)
k is the conductibility of the material of the wire

Ohm stated that

> The force of the current is as the sum of all the tensions, and
> inversely as the entire length of the circuit

We are more familiar with today's version of Ohm's law. Current intensity symbol is I, electric tension is the difference of potentials V, and resistance of the wire is R:

$$I = \frac{V}{R}$$

Comparing the two formulas we get expression corresponding to our present concept of resistance

$$R = \frac{1}{k}\frac{\ell}{\omega}$$

Using our modern notation, the resistance is defined as:

$$R = \rho\frac{\ell}{A}$$

where ρ is the resistivity of the material
l is the length of the wire
A is the cross-sectional area of the wire

Important points shown by Ohm's work were:

1. Electric current passing through a wire is the same at any cross-sectional area of the circuit
2. Electric current is directly proportional to the potential difference applied to the circuit
3. Electric current is directly proportional to the cross-sectional area of the wire
4. Electric current is inversely proportional to the length of the wire
5. Within conductor, electricity is transferred from particle to particle. Each conducting material is characterized by a unique property called specific conductivity
6. When the conductor is uniform, the potential falls uniformly from its highest value at the positive pole to its lowest value at the negative pole.

Ohm described his complete theory of electricity in his book Die galvanische Kette, mathematisch bearbeitet (1827). In many physics textbooks' vignettes Ohm is often described as an experimenter without much theoretical background and his process of arriving at the relationship as a process of induction – he did the measurements first and then found the mathematical relationship. Closer examination shows that Ohm was really looking for a confirmation of his theoretical concept. Ohm considered mathematical background necessary for an understanding of his theory and in this respect he encountered a heavy opposition from many German physicists.

The quantities Fourier defined for heat, such as conduction and flux passing through a surface, are used in all present theories of electricity. Electricity theories, just like Fourier's theory, deal with the transfer of some quantity (electric charge, heat) and both define the transfer as a flow. In both, the flow is produced by a driving force, and in both the driving force is described by a gradient of some quantity: a temperature gradient is the driving force for a heat flow; a gradient of potential (called an electric field) is the driving force for the flow of electric charges. The flow per unit area and per unit time is defined as a flux and is directly proportional to the driving force. Thus

$$J_q = -K_t \frac{\partial T}{\partial x} \qquad \text{Fourier's theory}$$

$$J_e = -K_e \frac{\partial V}{\partial x} \qquad \text{Ohm's law}$$

The proportionality constants K_t and K_e are the thermal conductivity and the electric conductivity, respectively. Both constants depend on the material properties of the conductor. J_e is the electric current (i.e. the electric charge per unit time). In each case the flux multiplied by the area it crosses and to which it is perpendicular, and by the time, will yield the quantity that is being transferred – heat or electric charge.

$$Q = J{\cdot}A{\cdot}t$$

The Analytic Theory of Heat influenced later researchers into electric and magnetic effects, most notably William Thomson and J.C. Maxwell (1831-1879). Maxwell in his paper "On Faraday's Lines of Force" describes the equivalence between heat and electricity:

> The laws of the conduction of heat in uniform media appear at first sight among the most different in their physical relations from those relating to attractions. The quantities which enter into them are *temperature, flow of heat, conductivity.* The word force is foreign to the subject. Yet we find that the mathematical laws of the uniform motion of heat in homogeneous

> media are identical in form with those of attractions varying inversely as the square of the distance. We have only to substitute *source of heat* for *centre of attraction, flow of heat* for *accelerating effect of attraction* at any point, and *temperature* for *potential*, and the solution of a problem in attraction is transformed into that of a problem in heat (The Scientific Papers 157).

Both, Thomson and Maxwell used the analogies to develop farther Michael Faraday's idea of a field.

6.4 The Concept of Field and Potential

In electrostatics, the concept of electric potential is usually presented after the concept of electric field and often in the terms of the electric field. However, historically, potential was defined by Simeon Denis Poisson (1781-1840) in 1812 before the idea of fields was conceived. Poisson supported Coulomb's theory of action-at-a-distance and Du Fay's two-electric-fluids theory. In a paper to the French Academy in 1812 he advanced the science of electricity by using calculus to determine the distribution of electricity in the surface layer of a charged conductor. Poisson adapted the mathematical development of the theory of gravitation by Lagrange (1736-1813), specifically the function V that Lagrange used to express distribution of density of attractive matter. Poisson used it to express the density of another source of force, the electric charge.

$$\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}=-4\pi\rho$$

where ρ is the density of the attractive quantity, in our case the density of the electric charge. Today we use more abbreviated symbolism and express the equation above as

$$\nabla^2 V = -4\pi\rho$$

Several years later (1824) Poisson applied the same method to magnetism.[29] In 1828, George Green (1793-1841) generalized Poisson's mathematical derivations. He also gave the function the name that we use today, the electric potential.

The concept of field is presented in every contemporary physic textbook. The simplest description, and easiest to understand, was given by Maxwell in the introduction of his paper "A Dynamical Theory of Electromagnetic Field":

> The electromagnetic field is that part of space which contains and surrounds bodies in electric or magnetic condition (The Scientific Papers 527).

Later books are more specific in linking the field to its force effects:

> If, in a given region of space, we find that an electrical force acts on a charged particle, we say that an electrical field exists in that region (Arons, Development of Concepts of Physics 542).

The very widely used textbook by Halliday, Resnick, and Walker is very precise and, to an average student, probably very difficult to comprehend since so many of the terms it uses are words the students very recently acquired and very likely have not yet assimilated:

---

[29] Coulomb and Poisson's theories were in the spirit of Laplace's mathematics that dominated French science of that time. The goal of Laplace was to reduce all physical phenomena to forces acting on particles, similar to Newton's gravitational theory.

The electric field is a *vector field*: it consists of a distribution of *vectors*, one for each point in the region around a charged object, such as charged rod. In principle, we define the electric field by placing a positive charge q_0, called a *test charge*, at some point near the charged object, such as point P in Fig. 24-1a. We then measure the electrostatic force **F** that acts on the test charge. The electric field **E** at point P due to the charged object is defined as

$$\mathbf{E} = \frac{\mathbf{F}}{q} \qquad \text{(electric field)}$$

(Fundamentals of Physics 654)

The idea of a field was first proposed by Michael Faraday (Experimental Researches in Electricity 281). Faraday knew that magnets could induce magnetism in iron objects, static electric charge could be induced on bodies located near charged objects, and that there are forces acting on magnets near wires carrying electric currents, the forces being circular in character. In the fundamental scientific dispute of the time, whether matter is particular or continuous, Faraday was firmly on the side of the continuous matter, believing that matter is present everywhere, there is no space unoccupied by matter, and forces can act only by a direct action through this ever present continuous matter which he called "ether". Based on these convictions, Faraday created visual models of lines of electric and magnetic fields spreading through the ether. The idea of lines of force filling the space around the current carrying conductor came from another well known effect: the arrangements of iron filings under the influence of magnets. Faraday saw the density of the field lines as proportional to the strength of the field. The number of lines through a particular area we call now electric or magnetic flux.

Faraday also noticed that galvanic current is induced in a coil of wire adjacent to another coil of wire that carries electricity, but that the induced currents are of only a short duration when the primary current is started or stopped (Faraday, The Discovery of Induced Electric Currents vol. II, 9). There obviously was a complex law governing induction due to a galvanic current and Faraday wanted to find what the law was. Faraday discovered that the link between magnetism and electricity is the time dependent variation of the magnetic flux. The induced electricity in a closed circuit is proportional to the rate of change of the number of magnetic field lines enclosed by the circuit. In the nineteenth century, mathematics was widely used to describe thermodynamic theories and flow of fluid theories.

James Clerk Maxwell (1831-79) used the familiar patterns of fluid movement to visualize Faraday's lines of force like tubes carrying incompressible fluid.

> If we consider these curves not as mere lines, but as fine tubes of variable sections carrying an incompressible fluid … (The Scientific Papers of James Clerk Maxwell 158)

He imagined very complex physical models that helped him to create in his mind the invisible fields. An important part of Maxwell's model was the concept of ether. Maxwell, just like Faraday, was uncomfortable with action at a distance and needed an elastic medium to transfer the forces. From his model, Maxwell developed equations relating changes in the electric and magnetic fields with respect to the three spatial coordinates and time. He found that his equations described transverse waves that behaved just like waves of light and propagated at the speed of light. Maxwell's equations have a very large scope. They describe the properties of all types of radiation such as light, gamma rays, or radio waves, as well as the transmission of electric currents in conductors. They are the fundamental operating principles of devices as diverse as radar, radio, fiber optics and electrical machines.

In Faraday's time, the prevalent model of any type of force was that of an action-at-a-distance, which was successfully used by Coulomb to confirm the inverse square law for electrified objects, and by Ampère to develop theories of attraction between current carrying wires. The difference of the two views, i.e. the field concept and the action-at-a-distance concept, is highlighted by Maxwell:

> Faraday, in his mind's eye, saw lines of force traversing all space where the mathematicians saw centres of force attracting at a distance: Faraday saw a medium where they saw nothing but distance: Faraday sought the seat of the phenomena in real actions going on in the medium, they were satisfied that they had found it in a power of action at a distance impressed on the electric fluids (qtd. in Pocovi and Finley).

William Thomson drew analogies between Faraday's lines of force in electrostatic fields and Fourier's flow of heat. He pointed out that the electric lines are perpendicular to the equipotential surfaces, just as the heat flow is perpendicular to the isothermal surfaces. By using the method outlined by Fourier, Thomson showed that the electric force outside of a closed surface is proportional to the surface charge density and perpendicular to the surface. This was already proven by Coulomb by using the action-at-a-distance. [30]

Thomson also made the connection between the abstract mathematical potential of Green and Faraday's tension or power. Thomson's definition of the potential (1853) was:

> The potential at any point in the neighbourhood of within an electrified body, is the quantity of work that would be required to bring a unit of positive electricity from an infinite distance to that point, if the given distribution of electricity were maintained unaltered (Darrigol Electrodynamics from Ampere to Einstein 120).

Faraday's expression of his induction law was qualitative:

> If a terminated wire moves so as to cut a magnetic curve, a power is called into action which tends to urge an electric current through it (Darrigol Electrodynamics from Ampere to Einstein 36).

Approximately twenty years after Faraday did his experiments, due to the large amount of newly acquired knowledge, the terminology of electricity and magnetism changed.

Maxwell wrote about an induced electromotive force instead of "the power called into action". Thus, for Maxwell, "the induced electromotive force around a circuit was

[30] According to Darrigol (114), Thomson did this at the age of seventeen, just before he went toCambridge.

equal to the decrease of the surface integral of magnetic force across any surface bounded by the circuit."

$$emf = -\oint_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S}$$

There were other changes in terminology. For example Faraday used the term "electric intensity" while Maxwell used "tension" and "quantity", and later talked about "the strength of electric current".

In a paper titled "A Dynamical Theory of the Electromagnetic Field" dated 1864, Maxwell summarized what was known about electricity at that time, unified the various approaches, and derived his field theory. This is how Maxwell described his equations:

> In order to bring these results within the power of symbolic calculation, I then express them in the form of the General Equations of the Electromagnetic Field. These equations express-
>
> (A) The relation between electric displacement, true conduction, and the total current, compounded of both.
>
> (B) The relation between the lines of magnetic force and the inductive coefficients of a circuit, as already deduced from the laws of induction.
>
> (C) The relation between the strength of a current and its magnetic effects, according to the electromagnetic system of measurements.
>
> (D) The value of the electromotive force in a body, as arising from the motion of the body in the field, the alteration of the field itself, and the variation of electric potential from one part of the field to another.

(E) The relation between electric displacement, and the electromotive force which produces it.

(F) The relation between an electric current, and the electromotive force which produces it.

(G) The relation between the amount of free electricity at any point, and the electric displacements in the neighbourhood.

(H) The relation between the increase or diminution of free electricity and the electric currents in the neighbourhood.

(Maxwell, The Scientific Papers, 534).

There are twenty of these equations in all, involving twenty variable quantities. One of the results of Maxwell's analysis was the conclusion that the disturbances in electric and magnetic fields produce electromagnetic waves that travel with speed $v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ which was close to the experimentally measured speed of light.[31] Maxwell then concluded that light must be an electromagnetic wave. He completed and published his electromagnetic theory in Treatise on Electromagnetic Theory in 1873.

We now describe the electromagnetic field as consisting of two vectors at all points in space, the electric field vector and the magnetic field vector. These two vectors are perpendicular to each other and rotate with the same angular speed. The planes in which they rotate are each moving in a direction normal to the plane of rotation. The

[31] The values for the velocity of light were $3.15 \cdot 10^8$m/s measured by Fizeau in 1849 and $2.98 \cdot 10^8$m/s measured by Foucault in 1862. Maxwell's value was $3.1 \cdot 10^8$m/s. (Arons, Development of Concepts of Physics 253).

equations developed by Maxwell describe the time rates of change of the electric and magnetic fields with respect to the three spatial coordinates. The equations are a set of four partial differential equations. The four equations have the same form. The right hand side quantities are the rate of change of densities of the source of the field of force, while the left hand side quantities are the space and time variations of the forces. The equations are as follows:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

The first equation asserts that a changing magnetic field $\frac{\partial \mathbf{B}}{\partial t}$ produces an electric field **E**. For example, when a bar magnet is moved through a closed loop of wire, it will generate a flow of electric current in the wire. The second equation states that changes in an electric field $\frac{\partial \mathbf{E}}{\partial t}$ produce magnetic field **B**. The term $\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$ is called displacement current density. It was introduced by Maxwell to account for the symmetry of the electromagnetic effect. Since magnetic field can also be produced by electric current, the second equation is often written in a form that includes the current: $\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$. The third equation states that charge density is the source of the electric field, while the fourth equation declares that magnetic flux is always found in closed loops and does not converge to one point.

The vector description of electromagnetic fields as described above was not known in Maxwell's time and took some time to develop. Many of the quantities that were defined for the electrical phenomena by mathematicians and physicists had not only a magnitude, but also a direction in space. Thus in the second half of the nineteenth century, there was an increasing need for a mathematical treatment of quantities that would in a concise form include both the magnitude and the direction.

6.5 Mathematical Description of Space

Two ideas led to the creation of a mathematical description of the three-dimensional space. One was the concept of parallelograms of velocities and forces. The use of parallelograms was known for a long time: Archimedes and Hero of Alexandria used parallelograms to add velocities. Similar parallelograms for the addition of forces were used during the sixteenth and seventeenth centuries (Crowe, A History of Vector Analysis 2). The idea of a parallelogram was further developed into a geometrical representation of complex numbers. Credit for the development of complex numbers goes to six men who, at different times, independently arrived at the complex number notation: Caspar Wessel (1797), Jean Robert Argand (1806), Abbé Buée (1806), C. V. Mourey (1828), John Warren (1828), and Carl Friedrich Gauss (1831). It was Gauss' publication in 1831 that made the geometrical representation of complex numbers known to scientists and mathematicians. However, the earliest was Wessel (1745-1818), a Norwegian surveyor. Wessel presented his work in 1797 to the Royal Academy of Denmark, but it went unnoticed until 1897. Wessel outlined his intention in creating the complex number system:

> This present attempt deals with the question, how we may represent direction analytically; that is, how shall we express right lines so that in a single equation involving one unknown line and others known, both the length and the direction of the unknown line may be expressed (qtd. in Crowe, A History of Vector Analysis 6).

Wessel proceeded to define the addition of two lines in a plane and the addition of more than two lines in three dimensions. He then introduced the product of two lines and from his definition of the product, he deduced the meaning of $\sqrt{-1}$.

> Let +1 designate the positive rectilinear unit and +ε a certain other unit perpendicular to the positive unit and having the same origin; then the direction of angle of +1 will be equal to 0°, that of -1 to 180°, that of +ε to 90° and that of -ε to -90° or 270°. By the rule that the direction angle of the product shall equal the sum of the angles of the factors, we have: (+1)(+1)=+1; (+1)(-1)=-1; (-1)(-1)=+1; (+1)(+ε)=+ε; (+1)(-ε)=-ε; (-1)(+ε)=-ε; (-1)(-ε)=+ε; (+ε)(+ε)=-1; (+ε)(-ε)=+1; (-ε)(-ε)=-1.
>
> From this it is seen, that ε is equal to $\sqrt{-1}$; and the divergence of the product is determined such that not any of the common rules of operations are contravened (Crowe, A History of Vector Analysis 7).

Wessel continued that a straight line in a plane can now be represented by a + εb, and he gave the rules for addition, multiplication, division, and raising to powers. From here, he proceeded to develop three-dimensional analysis by setting up three axes in space that are mutually perpendicular and that he used to describe a point in space by

$x + \eta y + \varepsilon z$, where $\eta\,\eta = \varepsilon\varepsilon = -1$.

The next important step in the three dimensional mathematical representation was done by W. R. Hamilton (1805-1865), who developed the algebra of quaternions in 1843 (Crowe, A History of Vector Analysis 10). [32] Hamilton's algebra of quaternions was widely disputed, for example Gauss opposed it. For the history of theories of electricity, its importance rests in the fact that it was accepted by Maxwell and used in his Treatise on Electromagnetic Theory, and that it was the means by which Hamilton conceived the terms "scalar" and "vector".[33] Maxwell in "On the Mathematical Classification of Physical Quantities" made further distinction between "force vectors" which he referred to a unit length and "flux vectors" which he referred to a unit area.[34] Maxwell created the connection between electricity theories and the use of vectors for calculations. Maxwell's use of vectors led to the development of vector calculus, as we know it, by J. Willard Gibbs and Oliver Heaviside. Both Heaviside and Gibbs were inspired by Maxwell. Although they worked independently, their systems are practically identical. Heaviside continued to expand on Maxwell's electromagnetic theory and, by using the vector

---

[32] Quaternions are complex numbers in four dimensions in the form w+ix+jy+kz where w, x, y, and z are real numbers and i, j, and k are unit vectors equal to $\sqrt{-1}$

[33] In Hamilton's writings, scalar denotes the real part of the quaternion notation, while vector is the complex part.

[34] Crowe, Michael J. (1967), *A History of Vector Analysis*, p.131

calculus, reduced Maxwell's twenty equations to the four equations that are the foundation of contemporary electromagnetic theory.

The introduction of vector calculus into the theories of electricity brought new complexity into what used to be a mostly qualitative science. Many of the inventors and electricians who worked with the telegraph lines and the dynamos had very little formal education in mathematics and sciences, mostly because it was not widely available. There arose a need to communicate in an easy-to-understand-way the insights that were gained by using the mathematics and to develop practical methods and models. Of the people who developed the models used in design, the most prominent was Charles Steinmetz who was the chief engineer for General Electric for many years around 1900.

6.6 From Scientific Theories of Electricity to Electrical Engineering

In civil and mechanical engineering, trial and error are essential parts of design, and scientific theories often follow technological inventions. Examples are the construction of bridges and the invention of the steam engine. In these cases, the scientific theories were later used to analyze, improve, and further develop the original designs. The situation in electrical engineering, however, was quite different. From the beginning, the technology and the science were intertwined; often the scientific theory came before the technology. In the research into electrical phenomena, the nineteenth century started with the discovery of a sustained source of electricity by Alessandro Volta that was closely followed by industrial applications in what later became the electro-chemical industry. From this point on, just about each new discovery in the field of electricity had an early application in the industry. The most notable were the applications of Faraday's work in electromagnetic induction: the telegraph and the invention of dynamo. By the second half of the nineteenth century, the electrical industry was booming and attracting many new inventors and investors. However, many of these people had very little training in mathematics and the sciences, since the electrical engineering education programs were not yet developed, and the new inventors and electricians[35] were hampered by the difficulty of obtaining the newly discovered information in a manner they could understand. There was also a proliferation of diverse practices and a lack of standards, both, in telegraphy and in the generation and utilization of electric power for lights and motors.

A transition from the "trial and error" approach of many inventors to the use of fundamental science was William Thomson's involvement in the installation of the transatlantic telegraph line between America and the Great Britain. The first transatlantic cable was laid in 1857/58, with many problems encountered during its installation. It functioned for only several weeks. Since the British government was financially involved in the project, it set up a committee in 1859 to investigate the failure. The committee produced an extensive report on submarine cables; among many other pieces of information,[36] the report summarizes submarine cable installations at that time. Out of the total of 11 364 miles of submarine cables that had been installed, only 3000 miles were

---

[35] At this time, the term 'electrician' included anyone who worked in any of the electrical industries.
[36] The report had over 500 pages.

actually working. The committee also reported that the conductivity of the copper used in the cable varied from 40% to 90% of the standard they set up and that this was one of the reasons for the cable failure. Other cited reasons were poor manufacturing practices, insufficient care when handling and laying the cable, and not being aware of the electrical theory of signal transmission (Dunsheath, A History of Electrical Power Engineering 215-220).

William Thompson (later Lord Kelvin) became interested in the problems connected with signaling via submarine cables in 1854. He started with Faraday's assessment that a submarine cable acts as a Leyden Jar in which the gutta percha insulation functions as the glass, the copper wire inside the insulation as the inner lining of the jar, and the salt water as the outside coating. He further defined $C \cdot \frac{\partial V}{\partial t}$ as a rate of accumulation of electric charge on an element of wire dx as equal to the decrease in of the electric current in this element $-\frac{\partial i}{\partial x}$, i.e.

$$C \cdot \frac{\partial V}{\partial t} = -\frac{\partial i}{\partial x}$$

Using Ohm's law, the change in potential $-\frac{\partial V}{\partial x} = Ri$. Combining the two equations gave Thomson[37]

$$RC\frac{\partial V}{\partial t} = \frac{\partial^2 V}{\partial x^2}$$

---

[37] In these equations V as the electric potential distance x from one terminal, i is the electric current, C is the capacitance per unit length, and R is the resistance per unit length.

This equation has the same form as the equation for propagation of heat as found by Fourier. The solution to this equation shows that the delay of the signal is proportional to the square of the length of the cable. Using the equation, Thomson was able predict the performance of the cable and recommend improvements to the submarine cable that minimized the delay.

When the second transatlantic cable was being laid, W. Thomson became involved in quality control of the cable manufacture as well as the actual laying of the cable. He designed precise instruments with which he could check the cable resistance and the characteristics of the insulation. He also designed instruments that enabled the control of the cable laying process. Successful completion of the project demonstrated that science can advance practical design, and that there is a need for precise measurements and for standard units for the electrical quantities.

Before the transatlantic cable, there were other, shorter submarine cables laid[38], and there also existed an extensive network of over-land telegraph lines. Testing and troubleshooting of the telegraph network was becoming increasingly difficult since the electric tension was still determined by the number of series connected electric cells, and resistance was referred to in terms of standard wire. The standard wires were different in different locations. Many researchers used their own standards and telegraph companies had their own standards as well. In Germany, the standard for resistance was one mile of No. 8 iron wire, in Britain it was one mile of No. 16 copper wire, in France, which was

[38] Cable from Dover to Calais was laid in 1850; a few years later there were cables between Denmark and Sweden and in the Mediterranean Sea.

on metric units, the standard was one kilometre of iron wire four millimetres in diameter. The difficulty of this situation was illustrated by James Clerk Maxwell who wrote in his Treatise on Electricity and Magnetism:

> In the present state of electrical science, determination of the electrical resistance may be considered as the cardinal operation in electricity, in the same sense that the determination of weight is the cardinal operation in chemistry (465).

Of the three quantities that characterize the "galvanic" circuits, i.e. tension, current flow, and resistance, resistance was the first electrical quantity for which the unit was standardized. When Ohm did his research on the electrical properties of conductors, neither the units nor the terminology for the electroscopic force[39], current and resistance had yet been defined. Ohm described the resistance of wires in terms of the dimensions of the wire samples and of the materials from which the wires were made. He gauged the electric tension by measuring the temperature difference of his thermoelectric cells. Ohm had to set arbitrary standards against which he compared his results, and constants in his formulas were dependent on his particular set up. Unless Ohm's experiments were exactly copied, it was difficult to compare them to the results of other investigators.

In response to the concerns of both industry and academic researchers, in 1861 the British Association for the Advancement of Science (BAAS, founded in 1831) appointed a Committee of Electrical Standards of Resistance headed by William Thomson (1824-1907) and James Clerk Maxwell. The Committee based its work on two

[39] later called tension, and later yet potential difference or voltage

theories: one was Ohm's concept of resistance and Ohm's law, the other was Gauss' and Weber's observation that all electric and magnetic quantities can be expressed in terms of three fundamental quantities - length, mass, and time. [40]

The Committee for Electrical Standards had as one objective for its units that they must be convenient for use in telegraphy. Therefore, the Committee decided to use centimeter, gram, and second as the fundamental units (the CGS system of units). In general, it is possible to develop a system of electrical units by starting with Coulomb's equation for electric charges or by starting with equations that link electric current, magnetic field and force[41]. Both methods were used, and thus the BAAS Committee arrived at two sets of units. The resulting electromagnetic and electrostatic units were sometimes referred to as absolute or theoretical units because they had not been determined by any practical standards. It should be stressed that they were not identical. There was not only a conversion factor involved; they also differed in their relationship to the fundamental quantities of mass, length, and time. In the table below is comparison of the dimensions of the two systems.

[40] Appendix B

[41] Originally, the electromagnetic units were developed from Coulomb's equation for magnetic poles

$$F = \frac{m^2}{r^2}$$

Quantity using Maxwell's terminology	**Today's terminology**	**Dimensions in electrostatic system**	**Dimensions in electromagnetic system**
Quantity of electricity	Charge	$L^{3/2}M^{1/2}T^{-1}$	$L^{1/2}M^{1/2}$
Quantity of magnetism	Magnetic pole strength	$L^{1/2}M^{1/2}$	$L^{3/2}M^{1/2}T^{-1}$
Electric current	Electric current	$L^{3/2}M^{1/2}T^{-2}$	$L^{1/2}M^{1/2}T^{-1}$
Line-integral of electromotive intensity	Voltage	$L^{1/2}M^{1/2}T^{-1}$	$L^{3/2}M^{1/2}T^{-2}$
Resistance	Resistance	TL^{-1}	LT^{-1}

Eventually, the electromagnetic units became more widely utilized and were used as the basis for practical engineering units. The British Association prepared electrical standards for resistance made of three different metals, platinum, platinum-iridium alloy and gold-silver alloy. The standards were for a practical unit of resistance, which was equal to 10^9 of the em resistance unit. The new unit for resistance was initially called the "unit of 1862", but later a more simple name was decided on – one Ohmad, which was later abbreviated to one ohm.

The units called volts, amperes, and ohms were developed to satisfy the practical needs of the electrical industry. They were initially meant to be integral multipliers of corresponding electromagnetic units (em):

1 volt = 10^8 em units of potential difference
1 ampere = 10^{-1} em units of electric current
1 ohm = 10^9 em units of resistance

From the initial efforts of the BAAS Committee up to the present time, there have been numerous changes and adjustments to the electrical units. The largest change was in the conversion to the MKSA system and making ampere one of the fundamental units along with meter, kilogram, and second. Thus, the practical units defined by the BAAS Committee are not exactly the units we use today. They may differ by up to 0.05% from present units of the SI system.

Maxwell also outlined the second problem faced by the electrical industry of its time – the need of

> ....diffusing among practical men a degree of accurate knowledge which is likely to conduce to the general scientific progress of the whole engineering profession (A Treatise on Electricity and Magnetism p. viii).

He continued to describe what he considered to be the difficulty in the dissemination of the available knowledge:

> There are several treatises in which electrical and magnetic phenomena are described in popular way. These, however, are not what is wanted by those who have been brought face to face with quantities to be measured....
>
> There is also a considerable mass of mathematical memoirs which are of great importance in electrical science, but they lie concealed in the bulky Transactions of learned societies; they do not form a connected system; they are of very unequal merit, and they are for the most part beyond the comprehension of any but professed mathematicians (viii).

The preference for alternating current for power distribution in the 1890s further contributed to confusion and misconceptions about the theoretical background of electrical engineering. For instance, George Prescott, a superintendent and chief electrician for several telegraph companies in the United States during the 1880s and 1890s,[42] wrote in an article published in the Transactions of American Institute of Electrical Engineers (AIEE) in 1888: "it is a well known fact that alternating currents do not follow Ohm's law, and nobody knows what law they follow" (qtd. in Kline, Steinmetz, Engineer and Socialist 20). In fact, Maxwell showed in his Treatise on Electricity and Magnetism fifteen years earlier that alternating currents follow the Ohms law, however, his work was not sufficiently well known by the practicing electricians of the 1880s and 1890s. In the Treatise, Maxwell used exponential functions as a part of the analysis of an induction bridge[43] that was invented by Maxwell and Fleeming Jenkin, a British telegrapher. In 1879, Johann Victor Wietlisbach (a graduate student of Hermann von Helmholtz) improved the induction bridge by replacing a battery and current interrupter with an ac source, and connecting a capacitor as well as an inductor in the bridge. Wietlisbach solved for the currents in the bridge by solving four simultaneous differential equations by assuming the solution to be in the form of a trigonometric function. Trigonometric functions can be expressed by Euler's identity using exponential

[42] also author of several books on telegraph, telephone, electric light and dynamos

[43] Bridge circuits were an important method of measurement of transmission line parameters. Many of the researchers in electricity used bridge circuits and made improvements to the basic bridge originally used for measurements by Charles Wheatstone. A description of some of the basic connections for bridges together with a brief history is in Appendix C.

functions with a complex exponent.[44] This was used extensively by Lord Rayleigh (J. W. Strutt) in acoustics, optics, hydrodynamics, and for mechanical vibrations. Helmholtz and Wietlisbach were the first physicists to apply it to electric circuits.

A solution for a series RLC circuit[45] was presented by Bedell and Crehore at the General Meeting of the American Institute of Electrical Engineers in June of 1892 ("Derivation and Discussion of the General Solution for the Current Flowing in a Circuit Containing Resistance, Self-Induction and Capacity, with any Impressed Electromotive Force", Transaction of the AIEE 9: 303- 374). In this paper of 71 pages, the authors derive the solution and discuss its implications to a topic that we now expect the students to understand after two to four hours of lectures. The derivation starts from energy considerations

$$ei\,dt = Ri^2dt + Li\frac{di}{dt}dt + \frac{idt\int idt}{C}$$

where on the left-hand side of the equation, eidt is the total energy supplied to the circuit during time dt. The three terms on the right-hand side of the equation represent how the energy is spent. Ri^2dt is used in heating the resistor, $Li\frac{di}{dt}dt$ is used to create the magnetic field surrounding the inductor, and $\frac{idt\int idt}{C}$ is used to charge the capacitor.

They then manipulate the above equation into a more convenient form:

[44] i.e. the solution has a form $Ae^{j\omega t}$. When substituted into the differential equation, exponential terms in the differential equation cancel out and the result is an algebraic equation relating voltage and current through a complex number **V**=**I**(R+jX) The complex number was called impedance in 1886 by Oliver Heaviside.
[45] resistance, inductance, capacitance

$$\frac{d^2i}{dt^2}+\frac{R}{L}\frac{di}{dt}+\frac{i}{LC}=\frac{1}{L}\frac{de}{dt}$$

Bedell and Crehore provide solutions for four cases of the impressed emf (i.e. the nature of e in the above equations)

Case I. $e=0$

Case II. $e=\text{constant}$

Case III. $e=E\sin\omega t$

Case IV. $e=\sum_{E,b,\theta} E\sin(b\omega t+\theta)$

Since we are most interested in the solution for sinusoidally varying currents, I will look at the third solution. It is given as

$$i=\frac{ER\omega^2}{R^2\omega^2+\left(\frac{1}{C}-L\omega^2\right)^2}\sin\omega t+\frac{E\omega\left(\frac{1}{C}-L\omega^2\right)}{R^2\omega^2+\left(\frac{1}{C}-L\omega^2\right)^2}\cos\omega t+c_1e^{-\frac{t}{T_1}}+c_2e^{-\frac{t}{T_2}}$$

The authors also give the form of solution that displays the phase shift between the current and the voltage.

$$i=\frac{E}{\sqrt{R^2+\left(\frac{1}{C\omega}-L\omega\right)^2}}\sin\left\{\omega t+\tan^{-1}\left(\frac{1}{CR\omega}-\frac{L\omega}{R}\right)\right\}+c_1e^{-\frac{t}{T_1}}+c_2e^{-\frac{t}{T_2}}$$

In the discussion of the solution they point out that after the exponential terms become negligibly small, the solution is a simple harmonic function that either lags behind or advances ahead of the impressed emf. They make the observation that if the sine part of the expression is unity, the maximum value of the current is

$$I = \frac{E}{\sqrt{R^2 + \left(\frac{1}{C\omega} - L\omega\right)^2}}$$

and from an analogy to Ohms law, the expression $\sqrt{R^2 + \left(\frac{1}{C\omega} - L\omega\right)^2}$ is "of the nature of a resistance". Bedell and Crehore call this the apparent resistance and suggest the name of "impediment". They also show that

$$\text{effective current} = \frac{\text{effective emf}}{\text{impediment}}$$

In 1891, Sebastian Ziani de Ferranti, a pioneer of high voltage transmission in Britain, recorded a rise in voltage from 8 500V to 10 000V at the end of a five mile long cable from Deptford to London. This phenomenon was called the "Ferranti effect". The reason for the voltage rise was then very puzzling and widely investigated.[46] Practising electrical engineers needed some way of analyzing high voltage transmission lines, as well as some methods to work out the appropriate size of the wires for the coils of the generators and motors. It was possible to do some of these calculations by using Maxwell's theory or by the method outlined above. However, both methods required the skill to solve differential equations and became extremely cumbersome if more complex circuits were used, for example, two or three phase circuits. Kline in Steinmetz cites a survey of eighteen electrical engineering curricula in the United States in 1899 published in the Proceedings of the Society for the Promotion of Engineering Education, vol. 7, according to which there were only four schools that required a course in differential

[46] On lightly loaded or unloaded high voltage transmission lines the voltage at the load end of the line can become considerably higher than the voltage at the generator end.This is called the Ferranti effect. We know now that the reason is the interaction between the inductance and capacitance of the line.

equations (MIT, Armour Institute, California, and Ohio State). Thus, in the 1890s, finding easier methods for calculations of line impedance (i.e. what Bedell and Crehore called impediment) was viewed with some urgency.

In 1880s Thomas Blakesley[47] (1847-1929) wrote several articles on the theory of alternating current (a.c.) circuits in which he used graphical methods. Blakesley pictured sinusoidal voltages and currents in electric circuits as vectors rotating at the same frequency as the voltage impressed on the circuit. His method did not provide complete solutions of the circuits like solutions using Maxwell's equations, i.e. the transient surge of the electric current as well as the condition when the surge dies out and a steady state is reached.[48] Blakesley's method gave only the steady state solutions, but since electrical engineers were interested only in the steady state most of the time, Blakesley's graphical method was preferred. There were other advantages to using Blakesley's method. Many electrical engineers were trained as civil or mechanical engineers and to them the graphical methods were more familiar. The vector diagrams provided an easy visualization of the relationship between magnitudes and phase shifts of voltages and currents in circuits.

---

[47] Thomas Blakesley was a lecturer in science and mathematics at the Royal Naval College, and later a professor of electrical engineering at the University of Birmingham (Kline, Steinmetz 38).

[48] Blakesley's method was not embraced by all electrical engineers. R. B. Owens, a professor of electrical engineering at the University of Nebraska, had this comment: "… to attempt to analyze the action of alternating current apparatus without the use of differential equations, is, to say the least of it, no very easy task. We admit the value of geometrical methods and especially as expressing in convenient form the result of algebraic analysis. Indeed, in the hands of Mr. Kapp, Mr. Blakesley and a few others, they have been used with excellent analytic effect, but their general weakness, as compared with modern methods, is too well known to need comment" (Owens, "Electro-technical Education" Transactions of the AIEE IX: 469-470).

By 1893, only one year after Bedell's and Crehore's paper, A. E. Kennelly, an electrician working for Edison, used the term impedance for the combination of resistance and what he called inductance-speed and capacity speed reciprocal[49] in his paper "Impedance", presented to the AIEE. However, Kennelly was not the first to introduce the term impedance. The priority goes to Oliver Heaviside who used it for the combination of resistance and inductive reactance. In his paper, Kennelly solved the puzzling problem of the Ferranti effect. Kennelly defines the impedance as the geometrical or vector sum of its resistive and reactive components, and gives examples of the impedance triangles. One example is shown in Figure 2:

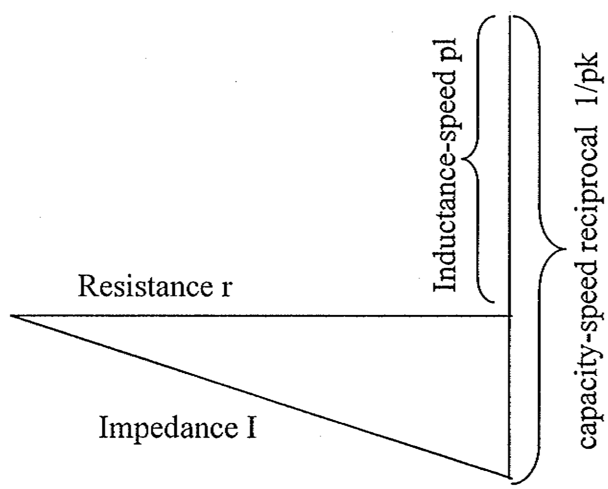


Figure 2 – Example of Impedance Triangle

This diagram is reproduced exactly as Kennelly presented it in his paper. The graphics and notation differ from our standards. Most notably, there are no lines shown to indicate what we now call the real and imaginary axes.

[49] modern terms are inductive reactance and capacitive reactance.

Kennelly points out that impedance defined this way enables the use of Ohm's law and Kirchhoff's laws in ac circuits. He also uses $\sqrt{-1}$ to express the reactive components:

> Any combination of resistances, non-ferric inductances, and capacities, carrying harmonically alternating currents, may be treated by the rules of unvarying currents, if the inductances are considered as resistances of the form pl $\sqrt{-1}$, and the capacities as resistances of the form $-\frac{1}{kp}\sqrt{-1}$, the algebraic operations being then performed according to the laws controlling "complex quantities" ("Impedance" 10:186).

A large part of Kennelly's paper is spent on tables and graphs giving multiplying factors for impedance of transmission lines for a range of wire spacing and a range of frequencies. The intent of these is to give practising engineers an easy way of determining the impedance of transmission lines without the necessity of engaging in complicated calculations requiring calculus. Kennelly concluded his paper with these words:

> .... the paper has been written with the endeavour to point out that the difficulties which at present enshroud the use and the working theory of alternating currents are largely fictitious.
>
> .... although alternating currents are so difficult when studied accurately and absolutely, the working theory of alternating currents can be made as simple as the working theory of continuous currents. I am firmly impressed with the belief – a belief which I trust I may be able to

> communicate – that the most convincing way of proving that this difficulty which has hitherto surrounded the alternating current and its distribution, can be eliminated and removed is, by the development of the notion of impedance (216).

Charles P. Steinmetz, at that time an electrical engineer working for General Electric, responded to Kennelly's paper by describing his own use of complex numbers to find voltage drop and current on ac transmission lines. Steinmetz expanded his theory in a book Theory and Calculation of Alternating Current Phenomena that he published four years later (1897). An even more complete review of Steinmetz' method is in a collection of his lectures from between 1915 and 1920, when Steinmetz was a professor of electrical engineering at the Union College. In these lectures he fully developed the use of complex numbers not only for the impedance, but also for the voltages and currents, and he made a full use of voltage and current phasor diagrams the way we know them today.

6.7 Phasors and Alternating Electric Currents

The calculation of the response of an electric circuit to a sinusoidal voltage input is one of the basic methods that electrical engineering students learn in the introductory circuits courses. One reason for this is that the most widely available electricity is generated and distributed by power utilities as sinusoidal currents and voltages; another reason is that the response of electric circuits to any voltages of any other waveform can be found by finding their response to sinusoidal inputs. In the previous section (8.6) I have discussed how Kennelly used Maxwell's equations to find complex impedance of a simple series electric circuit. Kennely used a very straightforward method; nevertheless the resulting differential equations would be very awkward to solve for electric networks with many variously interconnected components. Kennelly's method was later expanded by Steinmetz to what we now call phasors. Phasors are complex number representations of time-varying sinusoidal quantities. In the case of electric circuits these quantities are voltage and electric current.

The widely available alternating current (a.c.) voltage supplied by power utilities all over the world is generated by rotating an electromagnet inside copper wire coils. In principle, the same effect can be achieved by rotating a copper wire coil inside a uniform magnetic field; this way of generating ac voltage is usually more easily understood by students and therefore is used for the explanation. The magnitude of the generated voltage at any instant depends on the strength of the magnetic field, the area enclosed by the rotating coil, the speed at which the coil is rotated and the position of the coil with respect to the direction of the magnetic field.

$$e = NBA\omega \sin \omega t$$

where N is the number of turns of the coil, B is the magnetic field, A is the area enclosed by the rotating coil, and ω is the angular velocity of the coil.

Nature of Sinusoidal Alternating Waveform

To understand how electromotive force (i.e. voltage) at the terminals of an alternating current generator is produced, consider the diagram in Figure 3:

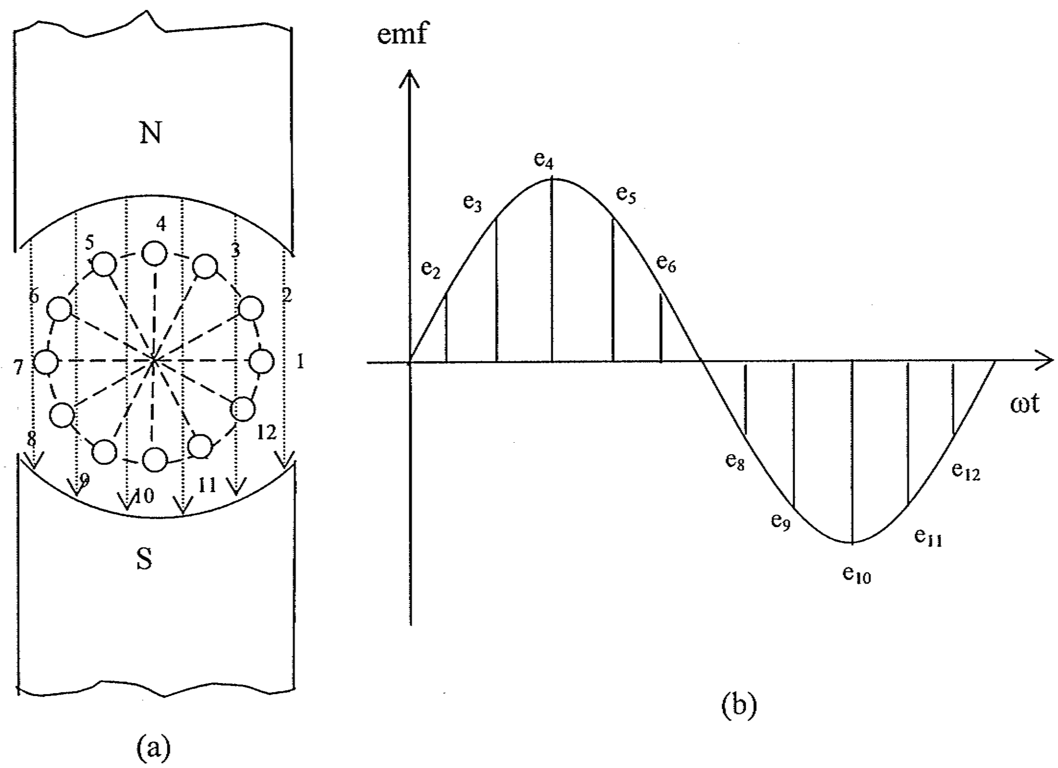


Figure 3 Graph of Alternating Emf Produced by a Single Phase Generator

The diagram in Figure 3 (a) shows 12 positions of one side of the rotating coil, spaced 30° apart. The instantaneous electromotive force (i.e. the emf or terminal voltage) induced in the coil is plotted in Figure 3 (b). The horizontal axis of the plot (b) is labelled in degrees, which may be considered equivalent to units of time, since the coil rotates with a constant angular velocity ω. The vertical axis shows the induced electromotive force.

When the rotating coil is in position 1, the sides of coil in which the emf is induced move parallel to the lines of the magnetic field; as a result no magnetic field lines are cut and no emf is generated. When the coil reaches position 2, it cuts magnetic field lines and an emf is induced in the coil. The vertical line e_2 in part (b) of the diagram represents the instantaneous emf induced in the coil when passing at a constant angular velocity through position 2. Similarly, $e_3, e_4, e_5, \ldots$ through e_{12} represent the instantaneous induced emfs as the coil passes through the corresponding positions. When the coil passes through position 4, it cuts through the magnetic field lines at right angle and therefore cuts through the largest number of lines per degree of position change. Consequently the emf is the largest at this point. As the coil continues to move towards position 5, the number of magnetic field lines it cuts in the same period of time decreases to 0 and therefore the emf also diminishes to 0.

As soon as the coil passes position 5, it cuts through the magnetic field lines from the opposite direction and the resulting emf changes polarity. This induced emf continues to increase in the negative direction until it peaks as the coil passes through position 10; then it decreases to 0 as the coil passes through position 1. The result of the rotation of the coil with a constant angular velocity is an emf that varies sinusoidally with time.

Representation of a Sinusoid Waveform by a Phasor

Tracing the relationship between the position of a rotating coil and an induced emf in a generator relates the rotational motion of the coil and the sinusoidal waveform of the induced emf.

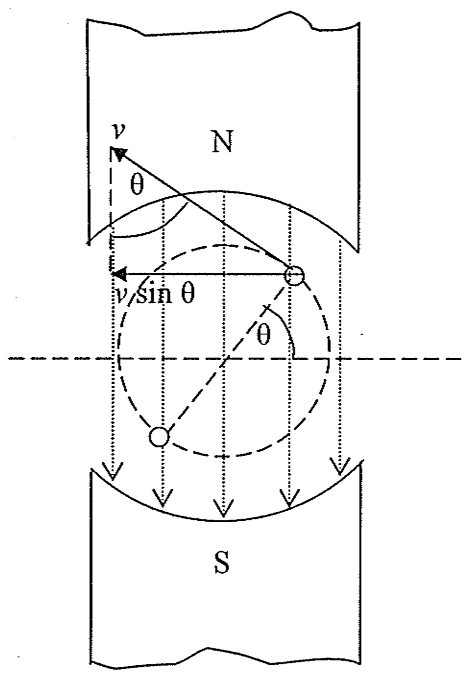


Figure 4 Velocity Components of One Side of a Coil Rotating in a Uniform Magnetic Field

The generated emf is proportional to the component of the velocity that is perpendicular to the magnetic flux

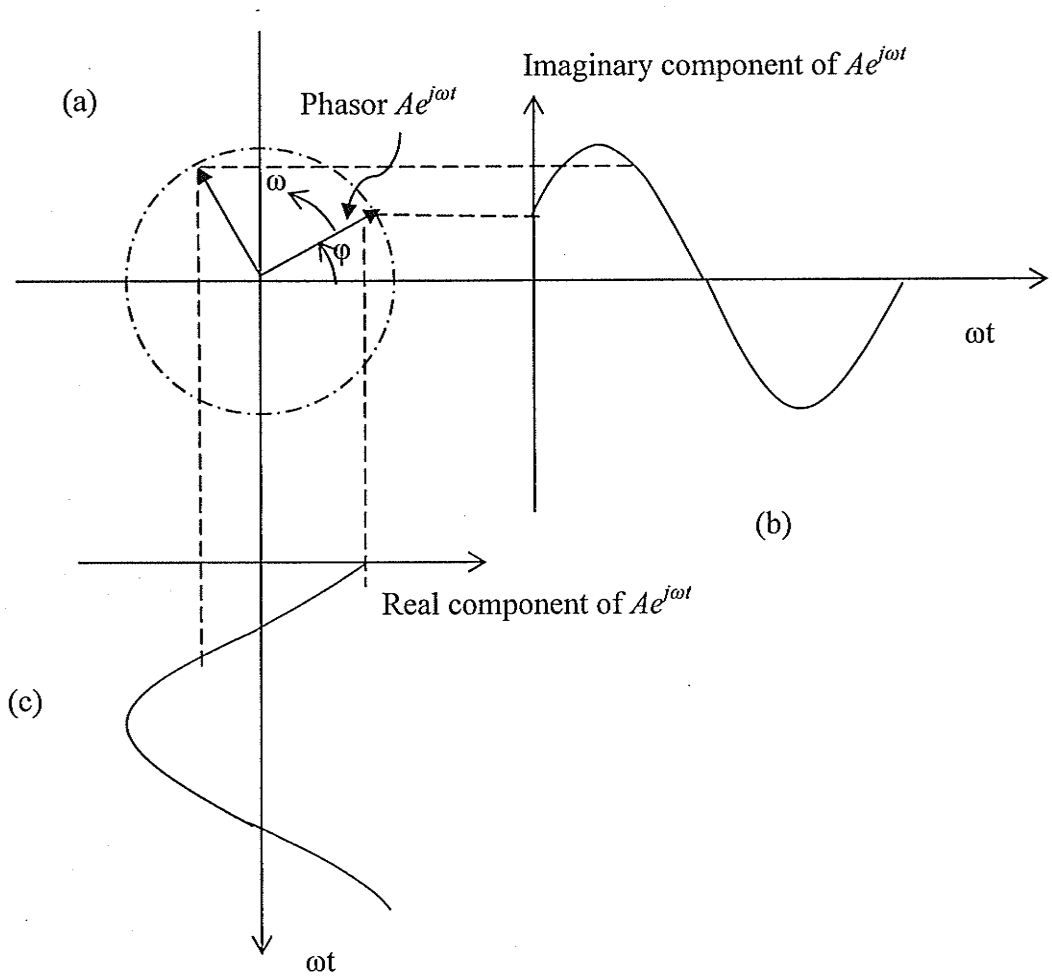


Figure 5 Representation of the Rotating Phasor $Ae^{j\omega t}$.

(a) $Ae^{j\omega t}$ can be considered to be a vector rotating counterclockwise with a constant angular velocity ω.
(b) Real component of $Ae^{j\omega t}$ versus time
(c) Imaginary component of $Ae^{j\omega t}$ versus time

We will rotate a vector in a complex plane with a constant angular velocity and plot its real and imaginary components as functions of angle of the vector with the positive real axis as shown in Figure 5. The initial position of the vector at time t

= 0 is angle φ. Then the imaginary component of the vector is $A_m\sin(\omega t+\varphi)$ and the real component is $A_m\cos(\omega t+\varphi)$. The vector **A** is

$$\mathbf{A} = A_m \cos(\omega t + \varphi) + jA_m \sin(\omega t + \varphi)$$

Using the exponential notation for the vector, we can write it as

$$\mathbf{A} = A_m e^{j(\omega t+\varphi)} = A_m e^{j\varphi} e^{j\omega t}$$

In the above equation,

$$A_m e^{j\varphi}$$

is a complex number that encodes the magnitude and the initial phase angle of the rotating vector A. We call this complex number a phasor. It is understood, although not always explicitly said, that the phasor represents a rotating vector that rotates at a single constant frequency. In electrical engineering, the notation for the phasor is simplified to

$$A\angle\varphi$$

Other conventions in electrical engineering are to use the root-mean-square value of the sinusoidal waveform as the magnitude of the phasor representation, and to specify the angle in degrees rather than radians.

A sinusoidal waveform e of angular frequency ω can be generally expressed as a function of time by using either the cosine function or the sine function:

$$e(t) = E_m\cos(\omega t+\varphi) \quad \text{or} \quad e(t) = E_m\sin(\omega t+\varphi)$$

where E_m, ω, and φ are real constants called the amplitude, the angular frequency, and the phase of the sinusoidal waveform, respectively. However, in electrical engineering it is more customary to use the cosine function. Thus we can write that

$$e = \mathbf{Re}(Ae^{j\varphi}e^{j\omega})$$

Since the angular velocity is constant, the instantaneous value of the emf at any instant is given by the maximum value it can attain (i.e. by the amplitude) and by the position of the coil which corresponds to the phase. This leads to representing the sinusoid as a complex number

$$\mathbf{E} = E_m e^{j\omega t}$$

It must be pointed out that the phasor notation suppresses information about the frequency. The assumption is that all the quantities present in the circuit have the same frequency. Thus the phasor analysis gives solutions only for the steady state, and all sources at the same frequency.[50]

6.8 Summary

In this chapter, I reviewed the development of terms "electric charge" and "electric current". The meaning of the word "charge" changed from the initial sense, as it was understood by Franklin of "filling an object with the electric fluid", to our present understanding of charge as the "presence or absence of particles we call electrons and

[50] Example of using phasors is in Appendix D

protons". "Electric current" became part of the terminology of theories of electricity at the beginning of the nineteenth century, as a consequence of Volta's invention of the electric battery. The initial adoption of the term was consistent with the idea of electric fluid, but as early as 1820 Oersted believed the electric current to be a "propagating alternation of decompositions and recompositions of the two electricities" (Darrigol, 5). The thermodynamic theory advanced by Fourier was compatible with the idea of "electric current" as a flow of material substance and was instrumental in deriving Ohm's law, one of the fundamental laws of electric circuits.

At the present time the concept of "potential" and the concept of "field" are closely related and often the electric potential is defined in terms of the electric field. Historically, "potential" was one of the concepts brought into the theories of electricity from another scientific theory, this time from the theory of gravitation. The concept of field was proposed independently of the concept of "potential". The connection between the electric field and the electric potential was pointed out by William Thomson approximately twenty years later.

The theories of electricity as they existed in the middle of the nineteenth century were assembled and united by Maxwell. Maxwell's mathematical description of electric and magnetic fields, although not widely known by the practicing electricians of his time, had enormous consequences for developments in the electrical industry and in scientific theories. They also became the starting point of engineering analysis of alternating current circuits at the end of the nineteenth century. The case of the use of complex algebra for the solution of electric circuits illustrates the difference between electrical engineering and electro-physics at that time.

Engineers and physicists derived two different mathematical techniques to analyze ac circuits: the engineers' priority was to analyze the power lines, for the physicists it was the impedance bridge. They also derived their methods from different intellectual traditions: engineering graphical analysis versus differential equations. The former was common to branches of engineering knowledge like the strength of materials and statics in civil engineering, which Edwin Layton has called "engineering sciences" ("Mirror-Image Twins" 562-580) . Steinmetz' papers answered the immediate needs and pressures the engineers faced at the moment, while Kelvin and Maxwell, although equally very practically oriented, presented theories that were developed from the viewpoint of mathematical physics. Even Kelvin's work on the submarine cable was done from the viewpoint of a scientist – his concern was not to simplify his theory to make it usable to the practicing engineer for a variety of similar tasks, but rather to apply his science to a specific problem. On the other hand, Steinmetz' papers are examples of the translation of information from science to technology. The ac circuit techniques developed by physicists and engineers solved the same type of problems. However, practicing engineers at the turn of the century were better able to understand and use the Steinmetz' method.

Chapter 7

IMPLICATIONS FOR POST-SECONDARY INTRODUCTORY ELECTRIC CIRCUITS COURSES

7.1 Introduction

In the previous two chapters, I have researched the history of the development of science and engineering theories of electricity. This helps us to understand our present inconsistencies in the theories we teach, and the sometimes misleading terminology we employ. Using the example of the analysis of alternating current electric circuits, I have illustrated the difference in approach to the same problem by physicists and by engineers at the end of the nineteenth century. The engineers' need for an "easy to use" method applicable to a wide range of problems led to the definition of complex impedance and phasor analysis of alternating current circuits.

In the first part of this chapter I will examine the characteristics that determine the difference in approach of engineers and of physicists to the theories of electricity. In the second part, I will describe a typical curriculum of electric circuits courses, the methods of analysis for alternating current circuits taught in electric circuits courses, and the prevalent teaching practices as they are reflected in textbooks. I consider terminology a very important factor in concept development and therefore I will focus on it in the third section of this chapter. In the last section, I will reiterate the difficulties students and instructors experience with the electric circuits curriculum and suggest remedies.

Finally, I will outline a curriculum matrix that would, if fully developed, help instructors to relate concepts and methods of electric circuits taught in electric circuits courses with the knowledge and know-how needed by engineering technologists in their practice.

7.2 Characteristics of Engineering Knowledge

In his book Steinmetz, Engineer and Socialist, Ronald Kline[51] examines the transformation of Charles Steinmetz from a physicist to an engineer at the end of the nineteenth century (20). To show his point, Kline summarizes what, in his opinion, is important in engineering design and what engineers of Steinmetz' era used from the scientific theories in their design. I consider Kline's points valid for the engineering design of any time. Kline defines seven parts of the body of knowledge that make up electrical engineering: (1) mathematical theories of electrical equipment; (2) elementary principles of physics, chemistry, and mechanical engineering; (3) mathematical techniques; (4) empirical data on materials and machines; (5) design rules of thumb; (6) design equations; and (7) technical skills.

[51] Ronald Kline is an engineer and a historian of science. He is also a director of the IEEE Center for the History of Electrical Engineering.

Kline then relates what each of the above points entails when applied to a design of a dynamo, which was one of the major achievements of electrical engineers of the second half of the nineteenth century. Thus, in the case of a dynamo, the equations relating the input variables of the dynamo to its output variables are the mathematical theories of the equipment; Ohm's law and the theory of dynamics are the elementary science principles used in the design of the dynamo; graphical analysis is the mathematical technique; resistance of conductors and the efficiency of various dynamos are the empirical data; simple proportions between machine dimensions and how much power it produces are the rules of thumb; formulas that relate machine dimensions to variables in the equations of the dynamo are the design equations; and, finally, the know-how of winding the coils are the technical skills.

> Steinmetz and other electrical engineers applied all seven components of this knowledge to design and build electrical apparatus, rather then simply applying physics directly to these tasks, as the applied model of the relationship between science and technology would suggest. Since theories of devices were expressed in mathematics and often drew heavily on science, it was quite appropriate that Steinmetz's first contribution to electrical engineering knowledge were theories of the electrical circuit and the transformer (Kline, Steinmetz 21).

Engineering theories emulate the pattern of scientific theories, yet they differ significantly from scientific theories. Many of the abstract concepts used by engineering theories are different from those found in science. The idea of replacing the real continuous conductors of transmission lines and electric devices by a connection of lumped electric circuit components – resistors, inductors, and capacitors - is an example of such a concept in electrical engineering. Using these models, engineers then calculate values such as voltage regulation or efficiency, both of which are abstract engineering terms not used in scientific theories. The actual devices themselves do not behave exactly like the models. The models are simplified versions of the actual equipment, and it is understood that there is an error introduced by using the models. Similarly, the conditions under which the models are said to operate are assumptions, often representing "the worst case" – that is the conditions of operation most likely to cause a failure. What constitutes the worst case condition is tempered by the designer's experience and judgement. Thus the calculations can never completely replace tests on the real devices. It is also important to keep in mind that unforeseen events, and therefore failures, will occur, and a good design will plan for first, second, or even a third contingency, depending on the possible consequences of a failure. Henry Petroski, whose ideas on engineering design I discussed in chapter 2, acknowledges the impossibility of a perfect design and puts very high emphasis on the need to learn from past failures:

> All meaningful improvements in analytical and computational capabilities are at heart improvements in our ability to anticipate and predict failure. Every engineering calculation is really a failure calculation, for a calculated quantity has meaning for engineering only when it is compared with a value representing a design constraint or failure criterion of some kind (Design Paradigms 121-122).

It is quite common that the appearance of a new technical problem is due to factors that were not previously considered important. These usually rise to prominence because a previously well working design was used at slightly different conditions. For instance, increasing transmission line voltages led to larger electric arcs during the opening of lines under load, and eventual breaker failures that in turn necessitated the investigation of new media for the extinguishing of arc and design of different types of breakers. Another example is the recent (August 2003) power blackout in Ontario and the eastern United States. The interconnections of power networks give more flexibility for power transmission, but the mammoth networks thus created are untested and relatively small problems can lead to unforeseen disasters.

Kline's seven components of engineering knowledge, together with Petroski's stress on the need to study the failures of past designs, summarize the content of engineering work and thus outline one possible aim of engineering education. Kline's and Petroski's lines of reasoning put in perspective the main focus of my thesis, which relates directly to what and how electrical engineering technology students are being taught about electricity in the introductory courses.

7.3 Electric Circuits Course

It should not be surprising that students frequently do not find the study of electricity and its applications easy. They need to accept that in order to understand the real life devices and processes, they need to learn terminology that has almost, but not quite, the same meaning as in other aspects of their lives, and they have to work with abstract models that do not look anything like the actual devices.

An electric circuits course is one of the "fundamentals" of any electrical engineering or electrical engineering technology program. The aim of the circuits course is to give students the tools they will need in more advanced courses to analyze a wide range of devices. Using Kline's description of engineering knowledge, we could say that the "tools" that are taught in electric circuits courses are the mathematical theories of electrical devices and some elementary physics principles. Typically, an electric circuit course begins with a review of fundamental and derived units in the SI system. It then continues with definitions of resistance and examples of resistors, definitions of the basic quantities of electric circuit theories, and analytical methods used for the solutions of direct current electric circuits. Next, capacitors and inductors are introduced, and the response of resistive-capacitive, resistive-inductive, and resistive-capacitive-inductive circuits to switching on or off direct current power supplies. Then, before alternating current circuits are presented, students are taught about complex numbers, vectors, and phasors. This is followed by sinusoidal steady state analysis methods, filters, alternating current power, and three phase circuits.

The purpose of the electric circuit analyses is to find voltages and currents in any branch of any linear electric circuit,[52] provided the sources in the circuit are known.

---

[52] linear circuit contains only passive components resistance, inductance and capacitance that do not vary with apply currents or voltages.

Although the analytical methods taught in this course are based on Ohm's law, the principles of conservation of energy and charge, and the work of scientists like Maxwell and Helmholtz, the physics content is to a considerable degree eliminated. For example, the principles of conservation of energy and charge appear in the form of Kirchhoff's voltage and current laws; students know the conservation principles from physics, but are seldom aware of their connection to Kirchhoff's laws. The result is that electric circuits analysis is treated more like a mathematical discipline. The mathematical techniques the students must learn include complex numbers, vectors and phasors (discussed in chapter 6), solutions of simultaneous linear equations, and solutions of elementary first and second order differential equations.

The teaching of electric circuits theories and methodologies is centered on textbooks and the prevalent teaching style is by transmission. Each chapter starts with definitions of new terms. The definitions are often given by an equation. There is a verbal description of the new method that is being taught, derivations of formulas to be used for solutions of problems, and reasoning as to why the method is valid. This is followed by several solved examples that students are expected to follow to solve questions at the end of each chapter. Students are tested on their ability to reproduce the expected solutions. This is really an example of Thomas Kuhn's observation that students learn to understand the laws by working through many exemplar problems (The Essential Tension, 306).

The main emphasis in electric circuit courses is on problem solving. Typical of this is the list of learning outcomes for chapter 9 in Boylestad's textbook. The textbook promises:

> After completing this chapter you will be able to:
>
> - solve network problems using superposition theorem
> - explain Thévenin's theorem and apply the theorem to network problems
> - state Norton's theorem and apply the theorem to network problems
> - explain the maximum power transfer theorem and its relationship to circuit efficiency
> - solve network problems using Millman's theorem
> - solve network problems using substitution theorem
> - solve network problems using reciprocity theorem (234).

The problems students solve in this chapter are various connections of resistances and direct current sources. However, students often do not know why a particular connection is used in an example, whether any connections are more important than some others, nor why they would need to know quantities they are calculating.

The mathematics that is used for the solutions is also considered difficult by students. Engineering heavily relies on mathematical formulas as a compact way of describing models. However, even though the students have studied trigonometric functions, exponential functions, vectors, matrices, or calculus in mathematics courses, they have difficulty applying this knowledge to electric circuit courses. But it does not end here. The presentation of electric circuits in the circuits courses is highly abstract – mere symbols for resistance connected by straight lines. Thus, students stumble when they have to use methods they learned in circuits courses in a more specialized and more practical course, for example, to apply Thevenin's circuit or phasor diagram to an actual electrical machine. Students neither have a clear picture of where the formulas came from, nor of the exact meaning of the abstract electrical quantities the symbols in the formulas represent. They readily give up on attempts to understand the ideas and instead concentrate on memorizing the formulas and the steps of the solution method. Textbooks and instructors often support this approach by summarizing the solution in numbered steps in a cookbook-like manner. For example the already quoted textbook by Boylestad gives the following instructions for finding Thévenin's network of an alternating current circuit:

1. Remove the portion of the network across which the Thévenin equivalent circuit is to be found.
2. Mark (o, •, and so on) the terminals of the remaining two-terminal network.
3. Calculate $\mathbf{Z}_{Th}$ by first setting all voltage and current sources to zero (short circuit and open circuit, respectively) and then finding the resulting impedance between the two marked terminals.
4. Calculate $\mathbf{E}_{Th}$ by first replacing the voltage and current sources and then finding the open-circuit voltage between the marked terminals.

5. Draw the Thévenin equivalent circuit with the portion of the circuit previously removed replaced between the terminals of the Thévenin equivalent circuit. (243-244)

The problems students are asked to solve are part of what Thomas Kuhn would call exemplars. Kuhn defines exemplars as "concrete problem solutions", either done with "pencil and paper" or as experiments (The Essential Tension 298). Theories are not necessarily directly useable for applications; it is through the development of these selected problems that students learn how theories can be applied and how problems can be solved. By doing exemplars students learn to relate new problems to problems they previously solved. However, defining steps in an overly rigid way hardly fosters understanding of theories that underlay the exemplars. It also makes problematic the adaptation of the methods to problems that are even slightly different.

7.4 Terminology

The majority of papers that deal with teaching electric circuits theories focus on using software to help students visualize the concepts, on suggesting various ways of derivation and mathematical modeling of the theories, or on improving the labs that often accompany the electrical circuits courses (Yoshikawa, "Intelligent tutoring system"; Doering, "Circuit Viz"). In these and in similar papers, as well as in electric circuits textbooks, there seems to be an unspoken assumption that students intuitively understand terms like resistance, voltage, current, and so on.

The importance of terminology to mental models of physical concepts that students construct was established by several researchers, for example De Lozano et alii ("Some Learning Problems"), Cotignola et alii ("Difficulties in Leaning"). The issue of technical vocabulary and how it is established was also addressed by Thomas Kuhn in "Dubbing and Redubbing: The Vulnerability of Rigid Designation". According to Kuhn, vocabulary must be in place before the learning can begin. However, students do not acquire the vocabulary by learning the definitions. In Kuhn's opinion, terms should be introduced by exposure to examples of their use in situations that are descriptive of the terms such as those found in a student laboratory. Exposure to one example of use is not enough to enable the student to use the new term. There must be several examples of use, as well as examples where the new term does not apply. If there are several new inter-related terms involved, it is better if they are learned together. In "Dubbing and Redubbing" Kuhn talks about terminology of Newtonian mechanics (11-16). The vocabulary of Newtonian mechanics has been quite stable for several generations, and there is only one term describing any one quantity, such as "force" or "mass". This is not so in the terminology of electric circuits. We talk of electromotive force, voltage, potential difference, or voltage drop, all of which are measured in volts and essentially mean the difference between potentials of two points. Yet we expect students to understand the terms in terminology of electricity from a single definition, often written as a formula. The use of formulas for definitions leads to yet another difficulty. Sometime the same or similar symbol is used for different quantities. Examples are the use of "*W*" for "work" and "W" for a unit of power "Watt"; or use of "*v*" and "*V*" for "velocity" and "voltage". Students unfamiliar with the terminology and often not used to symbolic and mathematical representations just can't assimilate what they are expected to learn. This was documented by Guisasola et alii ("The Evolution of the Concept of Capacitance"; "Difficulty in Learning"), Pocovi and Finley ("Lines of Force"), Shipstone("A Study of Students' Understanding"), and Viennot and Rainson ("Design and Evaluation").

An example of a definition of a quantity by a formula is the introduction of the concept of capacitance. For instance, in Circuit Analysis by R. L. Boylestad, a textbook widely used by many colleges in their electrical engineering technology programs, capacitance is given by definition: "**Capacitance** is a measure of a capacitor's ability to store charge on its plates" (284). Similarly, in Principles of Electric Circuits, T. L. Floyd defines capacitance by saying: "The amount of charge that a capacitor can store per unit voltage across its plates is its **capacitance**, designated by *C*. That is, capacitance is a measure of a capacitor's ability to store charge." (391) In both textbooks, a few lines down, each of these statement is followed by a formula $C= Q/V$. Both textbooks contain good factual information on how various capacitors look and how they are manufactured.

The definition of the capacitance as given in the two examples is dry and hardly engages students' imagination. Additionally, it relies on the assumptions that students already have an understanding of what voltage and charge are. Students do not learn how capacitors were first discovered by a very painful experience of Pieter van

Musschenbroek (the story of the Leyden Jar). They do not learn how the builders of the submarine telegraph cable in the nineteenth century found out about the importance of the capacitance of long transmission lines, and how it was defined by William Thomson when he related the capacitance to the accumulation of charge while solving the problem of delay of the transmitted signal. Nor are students made aware that capacitance is a natural phenomenon that occurs any time there are two or more unequally charged conductors in proximity. Boylestad's and Floyd's textbooks are not exceptions; many other circuit theory textbooks use the same approach, for example Payntner (Introductory Electric Circuits) or Robbins and Miller (Circuits Analysis Theory and Practice).

Another problem with terminology that students encounter is caused by the fact that the vocabulary used for the description of electrical phenomena often comes from earlier theories. As I pointed out in chapter 2 in my reviews of the research done by De Lozano and Cardenas and by Cotignola et alii, terminology is crucial to students' concept building, and terminology that comes from earlier theories supports concepts similar to those that the early investigators of electricity held. Thus when we talk about current or current flow, or about electromotive force, students tend to understand the terms literally. The words current or current flow imply a physical displacement of particles from one location into another location the way liquid would move through a pipe. The term is clearly a leftover from Franklin's and Du Fay's theories when electricity was thought of as a fluid. The term electromotive force (emf) suggests a quantity defined like other forces in physics; something that causes the acceleration of particles that make up the current flow, and that is measured in the same units as other forces that cause acceleration. Neither of these applies to the electromotive force. Students solve problems dealing with electric current, voltage and resistance, or later when alternating voltages and currents are introduced with impedance, with only a vague idea of what each of these terms may mean, especially if actual labs are not part of the course. The recent move towards "virtual labs" is likely to separate the electric circuit course from the "real" electric circuits even more. Thus although the "virtual labs" may improve students' dexterity in performing calculations, they will very likely hamper students' understanding of the electrical phenomena. This is a topic that certainly deserves further investigations.

7.5 Where Do We Go from Here?

Many instructors do their best to explain concepts of electricity clearly and to use demonstrations and laboratory work to make it less abstract. In most cases, however, in the introductory courses such as an electric circuits course, they teach entirely from textbooks. Unless an idea or a concept is described in the textbook chosen for the course, it is very unlikely to be discussed. On the other hand, not everything included in the textbook becomes part of the content of the course. Many textbooks intersperse interesting historical vignettes about important scientists and inventors throughout their content. These are intended to show that the abstract theories and methodologies contained in the textbooks are the results of investigating real phenomena or inventing devices widely used at homes and by the industry. However, the vignettes are often disregarded by the instructors, they definitely are not part of the tests, and therefore students usually skip them. We cannot expect students to read the original papers dealing with the theories they are studying “in which they might discover other ways of regarding the problems discussed in their textbooks”, and “in which they would also meet problems, concepts, and standards of solution that their future professions have long since discarded and replaced” (Kuhn, The Essential Tension 229). They cannot understand the historical texts, partly because the mathematics is beyond what they know (i.e., mathematics of Maxwell and W. Thomson), and partly because the older papers and textbooks use different notation and terminology from what we use now. Thus, electrical engineering technology students are taught the methods of solving electric circuits without being made aware of what led to the development of these methods and what exactly, for example, complex numbers, vectors, and phasors represent. The consequences to the lack of an understanding of these important tools are many. For example phasor diagrams that were initially devised as a helpful visual tool are just another thing to memorize. Students often fail to appreciate the significance of vector diagrams and to relate vector diagrams to the graphs in time domain, or they attempt to use phasor based analysis to transient conditions with very doubtful results.

It must be quite a reasonable assumption that most students decided to study electrical engineering technology because they found the topic of electricity and electrical devices interesting before they enrolled in the program. In spite of that, for many of them, their studies are not progressing well, as is evidenced by the high failure rate in their first “engineering” course – it is close to 50%. There is no question that there is a need for changes in the program and in the teaching methods. The problem is how one teaches theories and methodologies that are abstract (energy, fields, charge), for which the students often have no preconceptions (inductance, phasor, complex impedance) and using models that conflict with "common sense" (equivalent circuits).

There is little doubt that most instructors would agree that the curriculum of introductory courses dealing with electricity, such as the introductory electric circuit course, should be based on a good understanding of the physics theories on which the models, methodologies, and terminology are founded. However, most would probably not include the "obsolete" theories, or familiarity with the historical development of the electricity theories, especially since the electric circuits course is already crowded with so many topics. Nevertheless, comparison of "now" and "then" approaches in explanation of some topics can be revealing. For example the notion of impedance in alternating current circuit is defined using the complex plane and the definition is very brief:

> Now that angle is associated with resistance, inductive reactance, and capacitive reactance, each can be placed on a complex plane diagram, as shown in Fig. 15.19. For any network, the resistance will *always* appear on the positive real axis, the inductive reactance on the positive imaginary axis, and the capacitive reactance on the negative axis.
>
> Any *one or combination* of these elements in an ac circuit defines the *impedance* of the circuit. It is a measure of how much the circuit will *impede,* or hinder, the flow of current through it (Boylestad, Circuit Analysis 555-6).

Compare the above quote with how Steinmetz treats the same topic:

> Since in alternating-current circuits a current *i* through a resistance *r* may produce additional e.m.fs. therein, when applying Ohm's law, $i=e/r$ to alternating-current circuits, *e* is the total e.m.f. resulting from the impressed e.m.f. and all e.m.fs. produced by the current *i* in the circuit.
>
> Such counter e.m.fs. may be due to inductance, as self-inductance, or mutual inductance, to capacity, chemical polarization, etc.
>
> The counter e.m.f. of self-induction, or e.m.f. generated by the magnetic field produced by the alternating current *i*, is represented by a quantity of the same dimensions as resistance, and measured in ohms: reactance *x*. The e.m.f. consumed by reactance *x* is in quadrature with the current, that consumed by resistance *r* in phase with the current (Lectures on Electrical Engineering 98-99).

From here Steinmetz continues to define the complex impedance $\mathbf{Z} = r + jx$.

It is very likely that, at a first glance, many students would prefer the definition by Boylestad for the simple reason that it is shorter and easier to remember, and Steinmetz' explanation, written at around year 1920, is a bit difficult to follow. However, Steinmetz' idea of using the counter electromotive force to explain how the circuit works and how the response of the circuit (i.e. the electric current) is altered by the induced voltages in inductive and capacitive components that oppose the applied alternating voltage could create a longer lasting comprehension than the more mechanical description given by Boylestad and by other contemporary textbooks. For the most part, an electric circuits course teaches methodologies and models used to solve electric circuits and therefore the history of the development of electricity theories may seem irrelevant. We should keep in mind, though, that the methodologies and models are underpinned by scientific theories that developed over time. We have kept using the methods of solving electric circuits for their sheer predictive power, even though the electricity theories have changed. Steven Weinberg (1933), a Nobel Prize winner in physics who also writes on the philosophy of science, expressed an opinion of the long-lasting and short-lived parts of scientific theories that is very pertinent to the topic of teaching science and applies to theories of electricity and engineering models and methodologies as well as to modern physics:

> It is important to keep straight what does and does not change in scientific revolutions, a distinction that is not made in [*The Structure of Scientific Revolutions*]. There is a "hard" part of modern physical theories ("hard" meaning not difficult, but durable, like bones in paleontology or potsherds in archeology) that usually consists of the equations themselves, together with some understandings about what the symbols mean operationally and about the sort of phenomena to which they apply. Then there is a "soft" part; it is the vision of reality that we use to explain to ourselves why the equations work. The soft part does change: we no longer believe in Maxwell's ether, and we know there is more to nature than Newton's particles and forces.
>
> The changes in the soft part of scientific theories also produce changes in our understanding of the conditions under which the hard part is a good

> approximation. But after our theories reach their mature forms their hard part represents permanent accomplishments. ("The New York Review of Books XLV, 15: Oct. 8, 1998: 50)

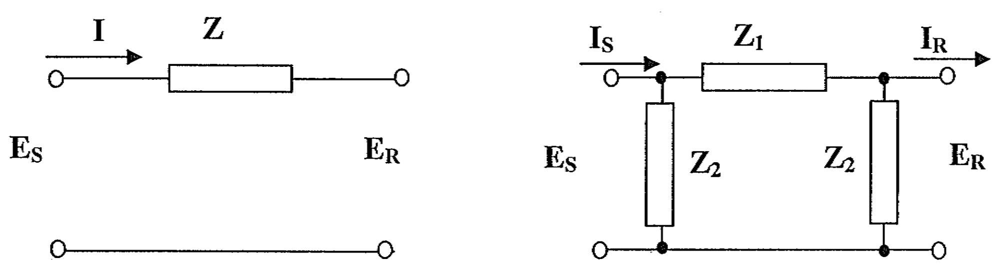
The constructivist methods of teaching permeate middle school and high school science, at least in the curricula. On the other hand, in post secondary science, engineering or engineering technology programs the prevalent type of instruction is by direct transmission and is centered on textbooks. That in itself is not necessarily a problem. Transmission teaching is often maligned; however, it is hard to imagine how else to impart, in the limited time that is given, the amount of knowledge students must acquire, at least to some degree. Students must learn an established body of knowledge and its accompanying terminology. They must practice solving problems, often in a standardized way, and they need frequent feedback on how they do, not only on the final result, but on every step of their solutions. Students must learn how to use the laboratory equipment safely and there is certainly no room here for experimenting with what is safe and what is not so safe. There simply is a need for explanations and instructor intervention.

In the teaching of electric circuits, we could attain better intelligibility by keeping more connections to the theories of physics – by this I mean explanations of how devices work based on physics theories rather than on mathematical models. Many textbooks (and hence instructors) do it quite well for some devices (motors, generators, meters) in more advanced courses. However, devices studied as a part of an electric circuits course, such as filters, are often treated as mathematical equations that relate the input and output variables. For example filters are described by the equation:

$$\mathbf{A_v} = \frac{\mathbf{V_o}}{\mathbf{V_i}}$$

where $\mathbf{V_o}$ is the output voltage,
$\mathbf{V_i}$ is the input voltage,
$\mathbf{A_v}$ is the voltage gain, or also called by the less descriptive name of the transfer function.

We need to stress the limitations of any analogies and models that we use. In the electric circuits courses, models are the mathematical equations that relate the input and output variables and that are usually created with a help of an equivalent circuit. For example a transmission line can have several different pictorial and mathematical models. Two examples are shown in Figure 6.



$\mathbf{E_S = E_R + IZ}$

$\mathbf{E_S = AE_R + BI_R}$
$\mathbf{I_S = CE_R + DI_R}$

where **A, B, C, D** are complex constant depending on $\mathbf{Z_1}$ and $\mathbf{Z_2}$

Figure 6 – Examples of Equivalent Circuits

The important question for students here is when to use which model. It also helps understanding if the students are aware of the similarities of the models, and also the similarities of these models of transmission lines to the models of filters mentioned earlier.

A valuable idea that constructivism brought forward is the importance of the historical development of theories and their dependence on the social and economic conditions. The historical vignettes as they are used in textbooks now are mere decorations, often presented from our vantage point. For example:

> In the early nineteenth century, Georg Simon Ohm, a German physicist, defined several cause-and-effect relationships between the values of current, voltage, and resistance in a circuit. Specifically, he found that current is directly proportional to voltage and inversely proportional to resistance (Paynter, Introductory Electric Circuits 106).

Unfortunately, vignettes like this one give the students distorted picture of what was involved in finding the most fundamental laws in electric circuits. A student reading this probably thinks there is really nothing to it. All Ohm needed was a voltmeter, an ammeter, and a variable power supply. There is no indication of how from very little clues, and starting with practically no equipment, the pioneers of electrical science built a complex structure that enabled the incredible technological developments of the last two hundred years. If a history of science and technology is included in the course, and a case can be certainly made that it would be beneficial, it must be an integral part of the course. From personal experience, I have found that including the narrative of the development of the mathematical description of space, enhanced the otherwise rather dry topic of complex numbers, vectors, and phasors, and if nothing else, kept students asking questions well into their break. To what degree it improved students' comprehension as compared to more traditional explanation could be a topic for another study.

Finally, I would like to suggest a development of a curriculum matrix. The type of matrix I propose differs from the usual curriculum matrices in that it not only relates curricular activities and learning outcomes, but also relates the curricular activities to Kline's seven components of engineering knowledge. This type of curriculum matrix should help the instructors to focus on the concepts and techniques of circuit analysis and answer "why" a particular topic is included and how it relates to the practice of an engineering technologist.

Fully developing a curriculum matrix is a time-consuming task that would take a team of people. Therefore it is not my intention to develop the matrix for the entire course. However, I will give two examples demonstrating how I imagine the matrix. I use two parts of the electric circuits course as examples: the first part is the introduction to electric circuits, and the second part is the introduction to alternating current circuits analysis. The matrix relates items of curriculum and components of engineering knowledge as defined by Kline (Steinmetz, 20). It is important to understand that scientific and engineering theories are only two components of the "engineering knowledge". Although the topics taught in electric circuits are mostly mathematical theories and some elementary physics principles, there are other components of engineering knowledge also present. This is apparent especially in the first example, shown in Appendix D.

The matrix in Appendix D is done for the introductory part of electric circuits course. The rows of the matrix list curricular activities. In this case, these are fundamental and derived units, electricity, and definitions of quantities used by theories of electricity: current, voltage, resistance, and power and energy. The columns of the matrix correspond to the seven components of engineering knowledge, with two more columns added. The second last column gives suggestions of activities that could improve students' concept building, and the last column is for comments on presenting the individual topics in a classroom. While it might seem that this part of the course consists mostly of elementary physics theories, constructing the matrix gives better insight into the content of the course. In this section, students must learn not only the elementary physics theories, but they also use empirical data of various materials (resistivity and inferred temperature), learn symbols of equipment they will later need to draw circuit schematics, use electric meters, and learn some design rules of thumb (conventional current direction, polarity notation)

The matrix in Appendix E is prepared for the part of the course teaching introduction to analysis of alternating current circuits. The organization of the matrix is the same as for Appendix D. The curricular activities are the characteristics of sinusoidal voltages and currents, mathematical descriptions of sinusoidal voltages and currents, mathematical descriptions of sinusoidal voltages and currents with a phase shift, complex numbers, phasors, etc. as you follow the headings of individual rows. The content of this part of the course is highly abstract as it predominantly consists of mathematical techniques. Bringing it "down to earth" by devising projects like building a two-pole generator and using an oscilloscope to display the alternating voltage[53] would very likely make it more understandable and interesting to students that are "hands-on" oriented. Part of the matrix is also my suggestion that the history of the mathematical description of space is discussed prior to teaching complex numbers. Students hear about complex numbers and phasors for the first time in the technology program and they can hardly have any preconceptions except those invoked by the terms "complex" and "imaginary".

Electric circuits courses are expected to give students the theoretical tools they will use in later more advanced courses, and, most likely, in their professional life. Having an organized way of relating each topic of the electric circuits curriculum to knowledge and skills helps development of teaching sequences and planning of the lessons.

7.6 Summary

I used Kline's characterization of engineering knowledge to discuss the important points of engineering design. Kline's ideas and Petroski's thoughts on the nature of engineering both summarize the content of engineering work and thus outline one possible aim of an engineering education. They put in perspective the main focus of my

[53] The voltage will alternate, but unless the magnetic poles have the right shape it will not be sinusoidal. However, this, too, can be a part of the classroom discussion.

thesis, which relates directly to what and how electrical engineering technology students are being taught about electricity in their introductory courses.

Electric circuits course is one of the "fundamentals" of any electrical engineering or electrical engineering technology program. Its aim is to give students the theoretical tools they will need for analysis of a wide range of devices and systems. The presentation of electric circuits is highly abstract and the main emphasis is on problem solving. The problems students solve are various connections of passive components and voltage and current sources, with the goal to calculate voltages and currents in branches of the circuits. Although the analytical methods taught in this course are based on physical principles, the physics content is to a considerable degree eliminated and replaced by mathematical models. The result is that electric circuits analysis is treated more like a mathematical discipline.

The importance of terminology to mental models of physical concepts that students construct was established by several researchers. In this chapter I have discussed Kuhn's ideas about terminology and put them side by side with the treatment of new terms by widely used electric circuits textbooks. While there is no question that students must learn an established body of knowledge and its accompanying terminology, we could attain better intelligibility by keeping more connections to theories of physics – by this I mean explanations of how devices work based on physics theories whenever possible and explicitly pointing out the connections to their mathematical models.

Finally, I have proposed a development of a curriculum matrix. The type of matrix I have in mind differs from the usual curriculum matrices in that it not only relates curricular activities and learning outcomes, but also relates the curricular activities to Kline's seven components of engineering knowledge. This type of curriculum matrix should help the instructors to focus on the concepts and techniques of circuit analysis and answer "why" a particular topic is included and how it relates to the practice of engineering.

Chapter 8

CONCLUSION

8.1 Summary of the Thesis

The objective of this dissertation was to examine the ideas, conditions, and assumptions that determined how theories of electricity are perceived and understood; to look at the ways these ideas are reflected in the teaching of introductory electric circuits courses in electrical engineering technology programs, and consider ways that could improve the clarity of the presentation of theories and methodologies of electric circuits.

I began the examination by reviewing the relevant existing literature. The review ranged from the research work on teaching physics at high schools to the investigations of teaching at college and university introductory courses in physics and engineering. It gave me several important ideas that guided me through this work. One of the ideas was that language and the consistency of terminology are important to conceptual development. The second idea was that teachers' conceptions of scientific theories play an important role in students' conception building, and that when "teachers are uncertain of the concepts to be taught and of their own understanding of these concepts" students' conceptual development is compromised (Mulhall et alii, 577). I also gained insight from the literature review into how scientific theories are employed by many diverse users for a wide range of purposes. Students learning science, educators teaching science, scientists doing research, engineers designing equipment, all employ the same theories. However, they each have a different perspective.

From my work as an engineer, I am aware that engineers and technologists are seldom motivated to be concerned with the philosophical views of the source of their knowledge. They are deeply immersed in the tangible, verifiable world of devices, data, and methodologies and to them, the electricity theories deal with real entities. However, after I taught electrical engineering technology students for several years, I slowly became aware that students are often troubled by inconsistencies they find in theories of electricity. They tend to think of models literally and believe that entities like lines of force or magnetic field lines are physical, although invisible, lines in space. They ask questions like "What do you mean by magnetic field lines? Are they real?" and "What colour are electrons?" As I was trying to answer these and similar questions I began to realize that I need to know more about the origins of the concepts of electricity.

The content of curricula of electrical engineering and, later, of electrical engineering technology programs cannot be well understood without some knowledge of the development of the theories of electricity. Many of the important ideas that we teach now were formed during the nineteenth century, for example the concept of electric current, or the concept of electric and magnetic fields. This was also the time when the science of electricity underwent a transformation from a qualitative science to a discipline that is so quantitative that in the minds of many people electrical engineering and mathematics became almost synonymous. The amount of mathematics, however, became a drawback for the practicing engineers in their every-day work. Thus engineers searched for more practical methodologies and models. The concepts of complex impedance and the use of rotating vectors as mathematical descriptions of voltages and currents in the alternating current circuits became the preferred method of solution. These new techniques were enthusiastically accepted by engineers at the beginning of the twentieth century because they were easier to understand and use in everyday practice than the more rigorous solutions employing differential equations. They certainly have the same advantages for students of electrical engineering technology today. However, we should not overlook that these techniques introduce abstract entities that students find hard to visualize.

The examination of the historical development of the theories corroborated some of the conclusions of other researchers that I have reviewed in chapter 2. Most important of these is the acknowledgement that there are many discontinuities and inconsistencies in the theories of electricity that make it more difficult to teach and to learn. Many students ask relevant questions when they first come to the class, but soon abandon the practice when they find instructor's answers unsatisfying and are pressured into learning algorithms and formulas. We teach by using algorithms and mathematics with the result that student just memorize the steps without understanding what they are doing and how it may apply to actual devices and systems.

This dissertation suggests several strategies that, if implemented, should improve students understanding. They include:

- Give students at least some idea of how and why the methods they are being taught were developed.
- Pay attention to terminology and the way it may at times mislead students' concept building. Especially pay attention to the situations where several different terms are used to describe one quantity.
- Understand and point out the difference of purpose between pure physics and electrical engineering.
- Avoid definitions of quantities by using only formulas. In many cases, a historical narrative of how scientists became aware of the need for a definition of a particular quantity, or how it demonstrated itself, would help students' understanding.
- Relate the mathematical models to real circuits and devices and point out the limitations of the models.

These strategies are included into the samples of the proposed curriculum matrix, shown in Appendices D and E, that relate the curricular activities to the components of engineering knowledge and incorporate historical perspective into teaching the theories and methodologies of electric circuits.

In electric circuits courses, roughly half of the students fail the exams. This fact alone sufficiently demonstrates that there is something amiss with students' understanding of the topics. The strategies suggested by this dissertation link engineering models to both physics theories on which they are based, and to practical problems.

These links will make the students aware of how the models were created and help them to appreciate both the usefulness and the limitations of the models. These are not entirely new suggestions. The literature on teaching physics in secondary schools and in post secondary non-technical programs abounds with ideas similar to these; they just did not yet percolate to electrical engineering technology education.

8.2 Recommendation for Further Research

Frequently throughout the study, topics arose that needed more investigation. First, more work is needed to fully develop the curriculum matrix for all parts of the electric circuits course. This could be connected with a study of the curriculum content. What exactly are the analytical skills the future technologists will need? Some of the methodologies we teach were developed in the time of the slide rule and were intended to simplify tedious hand calculations. There is no reason to keep including these in contemporary courses.

A second area for further research is finding out exactly how much of the physical concepts will be beneficial to introduce this early in an electrical engineering curriculum. Including more physics than the students are able to understand at this time would just lead to more memorization, not understanding. For example, should capacitance be explained by using an electric field concept? Should we introduce electric flux at this point? Would perhaps just a historical perspective be more useful in this introductory course? I believe that practically all the topics that we teach in electric circuits should be examined from this point of view.

Works Consulted

Alioto, Anthony M. A History of Western Science. Englewood Cliffs, N.J.: Prentice Hall, 1993.

Ames, Joseph Sweetman, ed. The Discovery of Induced Electric Currents. vol. II, New York, Cincinnati: American book company, 1900.

Armytage, W.H.G. A Social History of Engineering. Cambridge: MIT Press, 1961.

Arons, Arnold B. Development of Concepts of Physics. Reading, Mass.: Addison-Wesley Publishing Co., 1965.

Barth, Michael. "Electromagnetic Induction Rediscovered Using Original Texts." Science & Education 9 (2000): 375-387.

Bedell, Frederick, and Albert C. Crehore. "Derivation and Discussion of the General Solution for the Current Flowing in a Circuit Containing Resistance, Self-Induction and Capacity, with any Impressed Electromotive Force." Transaction of the AIEE 9 (1892): 303- 374.

Benjamin, Park. History of Electricity, New York: John Wiley & Sons, 1898. reprint New York: Arno Press, 1975

Bettencourt, Antonio. "On What It Means to Understand Science." Second International HPS & ST Proceedings. Queen's University, Kingston, Ontario, May 11-15, 1992.

Blanco, R., and M. Niaz. “Baroque Tower on a Gothic Base: A Lakatosian Reconstruction of Students’ and Teachers’ Understanding of Structure of Atom.” Science & Education 7 (1998): 327-360.

Bloor, David. Knowledge and Social Imagery. University of Chicago Press, 1976.

Bowen, James. A History of Western Education:The Modern West Europe and the New World. Vol. 3. London: Routledge, 2003.

Boylestad, Robert L., et al. Circuit Analysis, 3rd Can. Ed. Toronto: Pearson Prentice Hall, 2003.

Bordeau, Sanford, P. From Volts to Hertz. Minneapolis, Minn.: Burgess Publishing Co., 1982.

Borges, A. T., and J. K. Gilbert. “Mental Models of Electricity.” International Journal of Science Education. 21.1 (1999): 95-117.

Brouwer, W. “Towards a More Conceptual Way of Teaching Physics.” Physics in Canada. Jan/Feb. 1995: 55-61.

Burke, James. The Knowledge Web: From Electronic Agents to Stonehenge and Back – and Other Journeys through Knowledge. New York: Simon & Schuster Books, 1999.

Bybee, Roger W., ed. Science, Technology, Society. Yearbook of the National Science Teachers Association. Washington, DC: National Science Teachers Association, 1985.

Cardwell, D. S. L. Turning Points in Western Technology. New York: Science History Publications, 1972.

Clark, John A. Physics of Today. Boston: Houghton Mifflin, 1940.

Cobern, W. and C. Loving. "In Defence of Realism: It Really is Common Sense." Proceedings the Sixth International History, Philosophy and Science Teaching Conference." Denver, Colorado, 2001.

Cohen, I. Bernard. The Birth of New Physics. New York: W.W.Norton & Company,1985.

---. Revolution in Science. New York: W.W.Norton & Company, 1985.

Cotignola, M. I., et al. "Difficulties in Learning Thermodynamic Concepts: Are They Linked to the Historical Development of this Field?" Science & Education. 11 (2002): 279-291.

Cromer, Alan H. Connected Knowledge: Science, Philosophy, and Education. Oxford: Oxford University Press, 1997.

Crowe, Michael J. A History of Vector Analysis. Notre Dame: University of Notre Dame Press, 1967.

Crump, Thomas. . A Brief History of Science as Seen Through the Development of Scientific Instruments. London: Constable & Robinson, 2002.

Curd, M. and J. A. Cover, eds. Philosophy of Science: the Central Issues. London; New York: W.W.Norton & Co., 1998.

Darrigol, Olivier. Electrodynamics from Ampere to Einstein. Oxford: Oxford University Press, 2000.

De Lonzano, Silvia Ragout and Marta Cardenas. "Some Learning Problems Concerning the Use of Symbolic Language in Physics." Science and Education. 11 (2002): 589-599.

Deng, Zongyi. "The Distinction Between Key Ideas in Teaching School Physics and Key Ideas in the Discipline of Physics." Science and Education. 85 (2001): 263-278.

Derry, T.K. and I. W. Williams. A Short History of Technology. New York: Oxford University Press, 1960.

Desmond, Kevin. A Timetable of Inventions and Discoveries. New York: M. Evans, 1986.

de Vries, Marc. "The History of Industrial Research Laboratories as a Resource for Teaching About Science-Technology Relationships." Research in Science Education. 31 (2001): 15-28.

Dewey, John. How We Think. Boston, New York: D. C. Heath and Co., 1933.

---. Experience and education, New York: The Macmillan Co., 1938.

Dibner, Bern. Alessandro Volta and the Electric Battery. New York: Franklin Watts, 1964.

Doering, E. R. "Circuit Viz: a New Method for Visualizing the Dynamic Behavior of Electric Circuits." IEEE Transactions on Education. 39.3 (1996): 297-303.

Dunsheath, Percy. A History of Electrical Power Engineering. Boston: The MIT Press, 1962.

Ebenezer, Jazlin V. and Duncan M. Fraser. "First Year Chemical Engineering Students Conceptions of Energy in Solution Processes: Phenomenographic Categories for Common Knowledge Construction." Science Education. 85.5 (2001): 509-535.

Faraday, M. Experimental Researches in Electricity. London, J.M. Dent & Sons, ltd.; New York, E.P. Dutton & Co., 1912.

Faulkenberry, Luces M. and Walter Coffer. Electrical Power Distribution and Transmission. Englewood Cliffs, N.J.: Prentice Hall, 1996.

Finch, J. K. Engineering and Western Civilization. New York: McGraw-Hill, 1951.

Floyd, Thomas L. Principles of Electric Circuits. 7th ed., Englewood Cliffs, N.J.: Prentice Hall, 2003.

Franklin, Benjamin. "Letters to Peter Collinson" The Pennsylvania State University. October 3, 2005. <http://www.libraries.psu.edu/do/digitalbookshelf/30396027/30396027_part_40.pdf>

Fourier, Joseph. Analytical Theory of Heat. Trans. A. Freeman, New York: Dover Publishers, 1955.

Furio, C., et al. "Learning the Electric Field Concepts as Oriented Research Activity." Science Education. 87 (2003): 640-662.

Galileo Galilei. Assayer. Trans. George MacDonald Ross. October 3, 2005. <http://www.philosophy.leeds.ac.uk/GMR/hmp/texts/modern/galileo/assayer.html#a24>

Gardner, Paul L. "The Representation of Science-Technology Relationships in Canadian Physics Textbooks." International Journal of Science Education. 21.3 (1999): 329-347.

Glasersfeld, E. v. "Cognition, Construction of Knowledge, and Teaching." Synthese. 80.1 (1989): 121-140.

Grattan-Guiness, I. Joseph Fourier 1768-1830. Boston: The MIT Press, 1972.

Greenslade, Thomas B. Instruments for Natural Philosophy. October 3, 2005 <http://physics.kenyon.edu/EarlyApparatus/Electrical_Measurements/Sturgeons_Galvanometer/Sturgeons_Galvanometer.html>

Guisasola, Jenaro, et al. "The Evolution of the Concept of Capacitance throughout the Development of the Electric Theory and the Understanding of Its Meaning by University Students." Science & Education, 11 (2002): 247-261.

Guisasola, Jenaro, Jose L. Zubimendi and Jose M Almudi. "Difficulties in Learning the Introductory Magnetic Field Theory in the First Years of University." Science Education. 88 (2004): 443-464.

Habakkuk, H.J. American and British Technology in the 19th Century. Cambridge: Cambridge University Press, 1962.

Hacking, Ian. Representing and Intervening: Introductory Topics in the Philosophy of Natural Science. Cambridge; New York: Cambridge University Press, 1983.

Hacking, Ian. "Experimentation and Scientific Realism." Philosophy of science: the central issues. Eds. M. Curd, and J. A. Cover. London; New York: W.W.Norton & Co., 1998.

Halliday, David, and Robert Resnick. Fundamentals of Physics. New York: John Wiley & Sons, 1968.

Halliday, David, Robert Resnick, and Jearl Walker. Fundamentals of Physics. New York: John Wiley & Sons, 1993.

Hapgood, Fred. Up the Infinite Corridor: MIT and the Technical Imagination. Reading, Mass.: Addison-Wesley Publishing, 1993.

Harré, Rom. Matter and Method. London: Macmillan & Co., 1964.

---. The Principles of Scientific Thinking. The University of Chicago Press, 1970.

---. ed. Scientific thought 1900-1960. Oxford : Clarendon Press, 1969.

---. Varieties of Realism. Oxford: Basil Blackwell, 1986.

Harré, R., J. L. Aronson, and E. C. Way. Realism Rescued: How Scientific Progress is Possible. London: Duckworth & Co., 1995.

Harris, N.C., E. M. Hemmerling, and A. J. Mallman. Physics, Principles and Application. New York: McGraw-Hill, 1990.

Harris, Robin S. A History of Higher Education in Canada 1663-1960. University of Toronto Press, 1976.

Hayt, William H. Engineering Electromagnetics. 2nd. Ed. New York: McGraw Hill, 1967.

Heering, Peter. "On Coulomb's Inverse Square Law." American Journal of Physics. 60.11: 1992.

Hempel, C. G. Fundamentals of Concept Formation in Empirical Science. University of Chicago Press, 1956.

Hestenes, David, and Malcolm Wells. "A Modeling Method for High School Physics Instruction." American Journal of Physics. 63.7 (1994): 606-619.

Hodson, Derek. "Philosophy of Science and Science Curriculum." Journal of Philosophy of Education. 20 (1986): 241-251

Institute of Electrical and Electronics Engineers. Oral Histories. October 3, 2005 <http://www.ieee.org/>

Jenkins, John. Sparkmuseum. October 3, 2005 <http://www.sparkmuseum.com/GALV.HTM>

Johnson, Don H. "Origins of the Equivalent Circuit Concept: The Voltage Source Equivalent." Proceedings of the IEEE. 91.9 (2003): 636-640.

Kelly, T. George Birkbeck. Pioneer of Adult Education. Liverpool: Liverpool University Press, 1957.

Kennelly, A. E. "Impedance." Transaction of the AIEE. 10 (1893): 175-216.

Kipnis, Nahum "Scientific Controversies in Teaching Science: The Case of Volta." Science and Education, 10(2001): 33-49.

Kirby, R. S. et alii. Engineering in History. New York: McGraw-Hill, 1956.

Klassen, S. A Theoretical Framework for the Incorporation of History of Science in Education. Ph.D. dissertation. The University of Manitoba, 2002.

Klee, Robert. Introduction to the Philosophy of Science. Oxford University Press, 1997.

Kline, Ronald R. "Origins of the Issues." IEEE Spectrum, Nov. 1984, 38-43.

---. Steinmetz, Engineer and Socialist. Baltimore: The Johns Hopkins University Press, 1992.

Kowalski, Ludwik. "A Short History of the SI Units in Electricity. " The Physics Teacher. 1986.

Kuhn, Thomas S. The Essential Tension. The University of Chicago Press, 1977.

---. The Structure of Scientific Revolution. 3rd ed. The University of Chicago Press, 1996.

---. "On Learning Physics." Science and Education. Jan. 2000: 11-19.

Lamme, Benjamin G. Electrical Engineering Papers. East Pittsburgh, Pa., Westinghouse Electric & Mfg. Co., 1919.

Layton Edwin T. "Mirror-Image Twins: The communities of Science and Technology in Nineteenth-Century America" Technology and Culture. 12 (1971): 562-580.

Liu, Xiufeng. "Structural characteristics of students' conceptions of natural phenomena." Research in science and technological education. 16.2 (1998): 177-193.

Liu, Xiufeng, Jazlin Ebenezer and Duncan M. Fraser. "Structural Characteristics of University Engineering Students' Conceptions of Energy." Journal of Research in Science Teaching. 39.5 (2002): 423-441.

Loeb, L. B. and A. S. Adams, The Development of Physical Thought. New York: John Wiley & Sons, 1933.

MacLaren, Malcolm. The Rise of the Electrical Industry During the Nineteenth Century. Princeton University Press, 1943

Mason, Stephen F. A History of the Sciences. New York : Collier Books, 1962.

Matthews, Michael R. Science Teaching: The Role of History and Philosophy of Science. New York: Routledge, 1994

---. Constructivism in Science and Mathematics Education. October 3, 2005 <http://wwwcsi.unian.it/educa/inglese/matthews.html>

Maxwell, James Clerk. A Treatise on Electricity and Magnetism. 3rd ed. New York: Dover Publications, 1954.

---. The Scientific Papers. ed. W.D. Niven, New York: Dover Publications, 1952

McClellan, James E. and Harold Dorn. Science and Technology in World History. Baltimore: The John Hopkins University Press, 1999.

Mulhall, P., B. McKittrick, and R. Gunstone. "A Perspective on the Resolution of Confusion in the Teaching of Electricity." Research in Science Education. 31 (2001): 575-587.

National Research Council. Science Teaching Reconsidered. Washington, D.C.: National Academy Press, 1997.

Negru, John. The Electric Century. Montreal: The Canadian Electrical Association, 1990.

Niaz, Mansoor. "From Cathode Rays to Alpha Particles to Quantum of Action: A Rational Reconstruction of Structure of the Atom and Its Implications for Chemistry Textbooks." Science Education. 82 (1998): 527-552.

Niaz, Mansoor, et alii. "Arguments, Contradictions, Resistances, and Conceptual Change in Students' Understanding of Atomic Structure." Science Education. 86 (2002): 505-525.

Niaz, Mansoor and Maria Rodriguez. "The Oil Drop Experiment: Do Chemistry Textbooks Refer to Its Controversial Nature?" Science & Education. 14 (2005): 43-57.

Nigim, K.A. and R. R. DeLyser. "Using MathCad in Understanding the Induction Motor Characteristics." IEEE Transactions on Education. 44.2 (2001): 165-169

Owens, R. B. "Electro-technical Education." Transactions of the AIEE. IX (1892): 462-475.

Pan-Canadian Protocol for Collaboration on School Curriculum. Toronto, Ont.: Council of Ministers of Education, Canada, 1998.

Paynter, Robert T. Introductory Electric Circuits. Upper Saddle River, N.J.: Prentice Hall, 1999.

Petroski, Henry. To Engineer is Human: The role of Failure in Successful Design. St. Martins's Press, 1985.

---. Design Paradigms. Cambridge University Press, 1994.

---. Invention by Design. Harvard University Press, 1996

Pocovi, M. Cecilia and Fred Finley. "Lines of Force: Faraday's and Student's Views." Science and Education. 11 (2002): 459-474.

---. "Historical Evolution of the Field View and Textbook Accounts" Science & Education. 12 (2003): 387-396.

Posner, G. J., et al. "Accommodation of Scientific Conception: Toward a Theory of Conceptual Change." Science Education. 66, (1982): 211-227.

Pursell, Carroll W. Technology in America, Boston: The MIT Press, 1990.

Pounder, Colin. "A Derbyshire Electrician -- Abraham Bennet." Electrostatics Newsletter, October 3, 2005, <http://www.electrostatics.org/newsletters/NL-161.htm>

Rhodes, Richard. Visions of Technology: A Century of Vital Debate about Machines, Systems, and the Human World. New York: Simon & Schuster, 1999.

Robbins, A. & Miller, W. Circuit Analysis Theory and Practice, 2nd ed., Albany, N.Y.; Toronto, Ont.: Delmar, 2000.

Rosenberg, Robert. "The Origins of EE Education: a Matter of Degree." IEEE Spectrum. Nov. 1984: 60-68.

---. Academic Physics and the Origins of Electrical Engineering in America. Ph.D. dissertation, Baltimore: The John Hopkins University, 1990.

Ryder, John D. "The Way It Was." IEEE Spectrum. Nov. 1984: 39-43.

Sears F. W., M. W. Zemanski, and H. D. Young. College Physics. 7th ed., Reading, Mass.: Addison-Wesley

Shipman, Harry L., et al. "Changes in Students Views of Religion and Science in a College Astronomy Course." Science Education. 86 (2002): 526-547.

Shipstone, D. M. "A Study of Students' Understanding of Electricity in Five European Countries". International Journal of Science Education. 10.3 (1988): 303-316.

---. "A Study of Children's Understanding of Electricity in Simple D.C. Circuits." European Journal of Science Education. 6 (1984): 185-198.

Silver, Brian L. The Ascent of Science. New York: Oxford University Press, 1998.

Steinmetz, Charles P. Lectures on Electrical Engineering. vol.I. New York: Dover Publications, 1971

Still, Alfred. Electric Power Transmission. 2nd ed. New York; London: McGraw-Hill, 1919.

Stinner, Arthur. "Physics and the Dambusters." Physics Education, 24 (1989): 260-268.

---. "Providing a Contextual Base and a Theoretical Structure to Guide the Teaching of High School Physics." Physics Education. 29 (1994): 375-381.

---. "Science Textbooks: Their Present Role and Future Form." Learning Science in the Schools: Research Reforming Practice. eds. S. M. Glynn, S. M.and R. Duit, 1995.

Stinner, A., et al. "Context, Stories and History in the Science Classroom." Science and Education 12.7 (2003): 617 – 643.

Stinner, A., and H. Williams. Teaching Science in the Secondary School. Winnipeg: University of Manitoba, 1993.

Stocklmayer, Susan M., and David F. Treagust. "A Historical Analysis of Electric Currents in Textbooks: a Century of Influence on Physics Education." Science and Education. 3 (1993): 131-54.

Suplee, Curt. Milestones of Science. Washington, D.C.: National Geographic, 2000.

Teichmann, Jürgen, Wolfgang Schreier, and Michael Segre. Experimente die Geschichte machten. Bayerischer Schulbuch-Verlag, 1995.

University of St Andrews, Scotland, School of Mathematics and Statistics. Max Karl Ernst Ludwig Planck. October 3, 2005 <http://www-gap.dcs.st-and.ac.uk/~history/Mathematicians/Planck.html>.

Van Fraassen, Bas. The Scientific Image. Oxford: Clarendon Press, 1980.

Van Melsen, Andrew G. Science and Technology, Pittsburg: DuQuesne University Press, 1961.

Vemulapalli, G. Krishna, and Henry C. Byerly. "Carl Hempel's Philosophy of Science: How to Avoid Epistemic Discontinuity and Pedagogical Pitfalls." Science and Education. 13 (2004): 85-98.

Viard, J. and F. Khantine-Langlois. "The Concept of Electrical Resistance: How Cassirer's Philosophy, and the Early Developments of Electric Circuit Theory, Allow a Better Understanding of Students' Learning Difficulties." Science and Education. 10 (2001): 267-286.

Viennot, L. and S. Rainson, S. "Design and Evaluation of a Research-Based Teaching Sequence: the Superposition of Electric Field." International Journal of Science Education. 21.1 (1999): 1-16

Volta, Alessandro. "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds." Philosophical Magazine Sept, 1800. Dec. 1, 2005. <http://dbhs.wvusd.k12.ca.us/webdocs/Chem-History/Volta-1800.html>

Weinberg, Steven. "Review of Kuhn's Work" New York Review of Books XLV, 15: Oct. 8, 1998.

Whittaker, Edmund. A History of the Theories of Aether and Electricity. London, New York: Thomas Nelson and Sons Ltd., 1951.

Wildes, K.L. and N. A. Lindgren. A Century of Electrical Engineering and Computer Science at MIT, 1882-1982. Boston: MIT, 1986.

Williams, Trevor I. A Short History of Twentieth Century Technology. Oxford University Press, 1982.

Wigner, Eugene P. "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." The World Treasury of Physics, Astronomy, and Mathematics. Ed. Timothy Ferris. Boston: Little, Brown and Co., 1991.

Yoshikawa, A., Shintani, M., Ohba, Y. "Intelligent tutoring system for electric circuit exercising." IEEE Transactions on Education. 35.3 (1992): 222-225.

Zorpette, Glenn. "EE programs." IEEE Spectrum. Nov. 1984: 44-54.

Appendix A

DETERMINATION OF MAGNETIC FIELD OF EARTH

Gauss' and Weber's observation that all electric and magnetic quantities can be expressed in terms of length, mass, and time are based on their measurements of the magnetic field of Earth. In their measurements they used Coulomb's definition of force between the magnetic poles of two magnets that Coulomb assumed to have the same form as the force between two electric charges, or the Newton's gravitational law, i.e. to be proportional to the inverse of square of the distance.

$$f = \text{constant} \cdot \frac{mm'}{r^2}$$

m and m' are magnetic strengths of the poles
r is the distance between the poles.

The constant in the above equation depends on the medium and on the unit system. For simplicity, we will set it to 1. Gauss and Weber defined the magnetic field H due to an isolated north or south pole of magnetic strength m also similarly to the definition of an electric field, i.e. as the ratio of the force and the quantity causing the force:

$$\text{magnetic field} = \frac{\text{magnetic force}}{\text{strength of the magnetic pole}}$$

Using symbolic notation, the magnetic field of one pole of a magnet is:

$$H = \frac{f}{m'} = \frac{m}{r^2} \quad \therefore \quad f = m'H$$

Every magnet has two opposite poles of equal strength, thus the magnetic field at a point A that is distance d from the center of a bar magnet of length l is the sum of fields due to the north pole and to the south pole of the magnet. The sign of the North magnetic pole is arbitrarily chosen as positive.

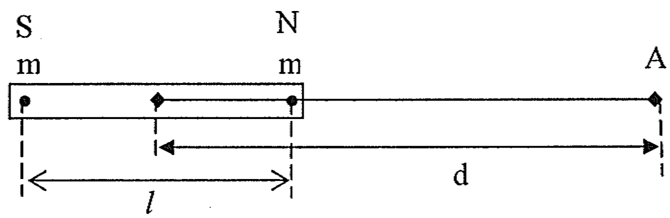


Figure A1 Magnetic Field of a Bar Magnet

$$H_{magnet} = H_N + H_S = \frac{m}{\left(d - \frac{\ell}{2}\right)^2} - \frac{m}{\left(d + \frac{\ell}{2}\right)^2}$$

After some algebraic manipulation the magnetic field of the magnet is given by the equation:

$$H_{magnet} = \frac{2\ell dm}{\left(d^2 - \frac{\ell^2}{4}\right)^2}$$

If l is much smaller than d, then the $l^2/4$ term can be neglected and the magnetic field can be approximated by:

$$H_{magnet} = \frac{2\ell m}{d^3}$$

The product "l·m" is constant for any magnet, as long as the strength of the magnet does not change and is called the magnetic moment of the magnet. It is usually denoted by M.

$$H_{magnet} = \frac{2M}{d^3}$$

Originally, when Gauss did his work, it was impossible to directly measure magnetic field or a magnetic moment of a magnet. Gauss' method used the fact that magnetic field of earth is practically uniform. He devised two measurements that gave him two relationships (i.e. two equations) between the magnetic moment M of a reference magnet, and the uniform magnetic field H of earth.

Measurement 1

In the first measurement, Gauss obtained the ratio of the magnetic moment M to the magnetic field of Earth H

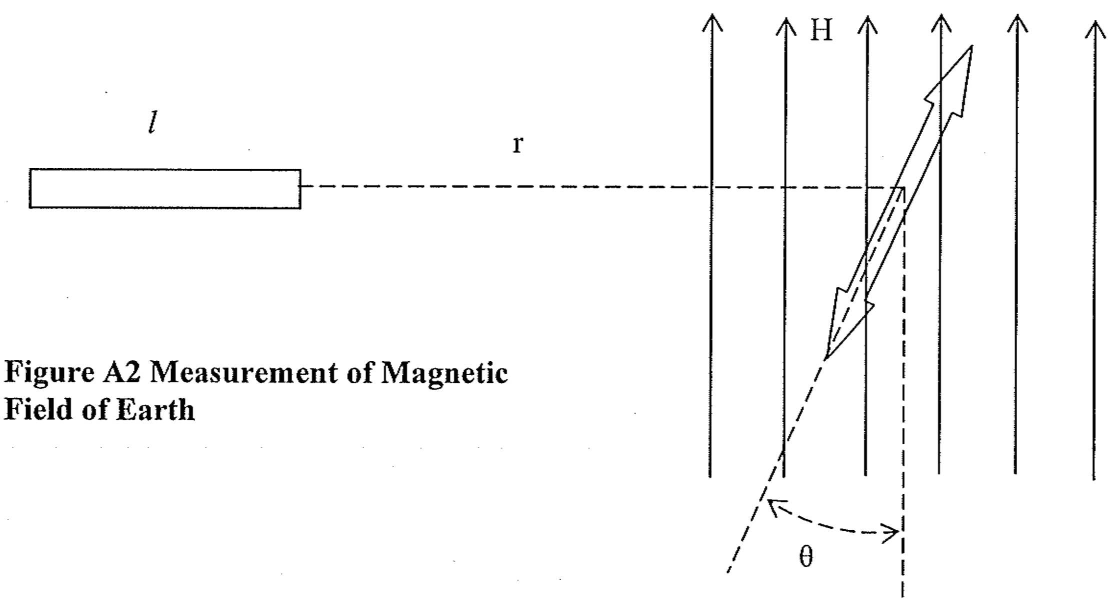


Figure A2 Measurement of Magnetic Field of Earth

Gauss and Weber placed a reference bar magnet perpendicularly to the Earth magnetic field H and it was held stationary. The magnet has a magnetic moment that is not known and that we will call "M". Then a compass needle of length "*l*" was placed distance "r" from the reference magnet. In this configuration, two torques acted on the compass needle – one torque τ_M was due to the reference magnet, the other torque τ_H was due to the earth magnetic field. Both, τ_M and τ_H vary with angle θ so that the compass needle will come to rest when $\tau_M = \tau_H$.

$$\text{Torque } \tau_M = 2 \cdot f_M \cdot \frac{1}{2} \cdot \ell' \cdot \cos\theta = f_M \cdot \ell' \cdot \cos\theta = \frac{2Mm'}{r^3} \cdot \ell' \cdot \cos\theta = \frac{2M}{r^3} \cdot M' \cdot \cos\theta$$

$$\text{since } f_M = \frac{2Mm'}{r^3} \quad \text{and} \quad M' = m' \cdot \ell$$

$$\text{Torque } \tau_H = 2 \cdot f_H \cdot \frac{1}{2} \cdot \ell' \cdot \sin\theta = H \cdot m' \cdot \ell' \cdot \sin\theta = H \cdot M' \cdot \sin\theta$$

Since $\tau_M = \tau_H$, we get

$$\frac{2M}{r^3} \cdot M' \cdot \cos\theta = H \cdot M' \cdot \sin\theta \quad \therefore \quad \frac{M}{H} = \frac{1}{2} \cdot r^3 \cdot \tan\theta$$

Measurement 2:

In this measurement, Gauss and Weber suspended the reference magnet by a fine fibre in the earth magnetic field so that it could rotate about a vertical axis through its center. The magnet settled in an equilibrium position parallel to earth magnetic field. Now they twisted the magnet from its equilibrium position by a small angle α (less than 10 degrees). The torque that returned the magnet to its equilibrium was

$$\tau = HM \sin\alpha$$

For small angles, sin α ≈ α and therefore $M \cdot H = \frac{\tau}{\alpha}$

The suspended bar magnet is a torsional pendulum. The equation relating the magnitude of the torque acting on the pendulum and its angular displacement is

$$\tau = \kappa\alpha$$

Ratio τ/α is the torque constant κ for oscillatory motion of a torsion pendulum. Therefore, Gauss and Weber measured the period of oscillations, and from this measurement calculated the torque constant κ and from it the product of M and H.

$$T = 2\pi\sqrt{\frac{I}{\kappa}} = 2\pi\sqrt{\frac{I}{MH}} \qquad \therefore \qquad MH = \frac{4\pi^2 I}{T^2}$$

"I" in the above equation is the moment if inertia of the bar magnet that can be found by separate measurements in which the torque is known.

When Gauss and Weber combined this result with the expression for the ratio M/H, they were able to calculate the magnetic moment of the bar magnet M and the Earth magnetic field H.

$$M = \sqrt{\frac{2\pi^2 I}{T^2} r^3 \tan\theta} \qquad and \qquad H = \sqrt{\frac{8\pi^2 I}{T^2 r^3 \tan\theta}}$$

Appendix B

BALANCE BRIDGES

The rapid growth of electric networks (telegraphic, telephone, distribution) during the second half of the nineteenth century required accurate knowledge of circuit parameters – resistance, inductance and capacitance. The use of bridge over any other method of measurement of circuit parameters has the advantage of requiring only a simple measuring device – a galvanometer – that needs to be only capable to detect the presence or absence of electric current.

The bridge connection was first used to measure resistances by Charles Wheatstone in 1843. Maxwell succinctly described Wheatstone's bridge as an arrangement in which "six conductors connects four points". The circuit is shown in Figure A1 . In this figure, R_1 is the resistance to be measured R_2 is an adjustable calibrated resistance (rheostat), and R_3 and R_4 are known resistance of equal value. There is a source of electromotive force E, usually a battery, connected between two opposing points A and C. The electric current between the two other opposing points B and D is measured by a galvanometer. When the points B and D are at the same potential, there is no current flowing through the galvanometer. This happens when the value of R_2 is adjusted to match the value of R_1. Werner von Siemens (1816-1892), a German inventor and entrepreneur, increased the sensitivity of the bridge making resistors R_3 and R_4 also adjustable. The zero current through the galvanometer is then achieved when the ratios of the resistances are equal.

$$\frac{R_1}{R_2} = \frac{R_4}{R_3}$$

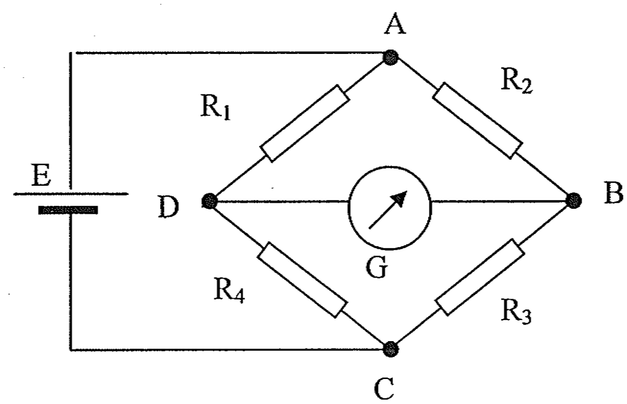


Figure B1 Wheatstone Bridge for Measuring Conductor Resistance to Direct Current

Since the Wheatstone bridge provided a convenient and accurate method to measure resistance, there were efforts soon made to adapt the bridge to measure inductances or capacitances. In a paper *Dynamical Theory of the Electromagnetic Field* (1865) Maxwell introduced a method of measuring self-inductance of a coil using a bridge balanced under steady state conditions. This means that in the Figure B2

$$\frac{R_1}{R_2} = \frac{R_4}{R_3}$$

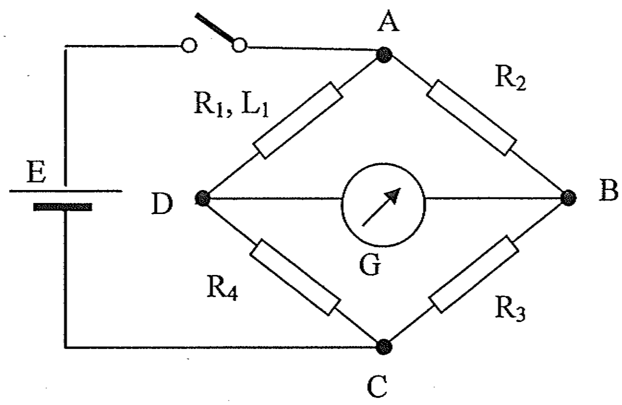


Figure B2 Maxwell's Method for Measuring Self-Inductance of a Coil

On closing or opening the switch, a voltage equal to

$$e_L = -L\frac{di}{dt}$$

is induced in branch AD of the circuit, this disturbs the balance of the circuit and there will be current flowing through the galvanometer. If the deflection of the galvanometer is calibrated, the self-inductance of the coil can be calculated.

The next step in the development of bridge methods for measurements of inductance is to modify the above connection to find balanced condition when the self-inductance is measured. This is done by inserting an adjustable calibrated inductor into the branch AB as shown in Figure B3.

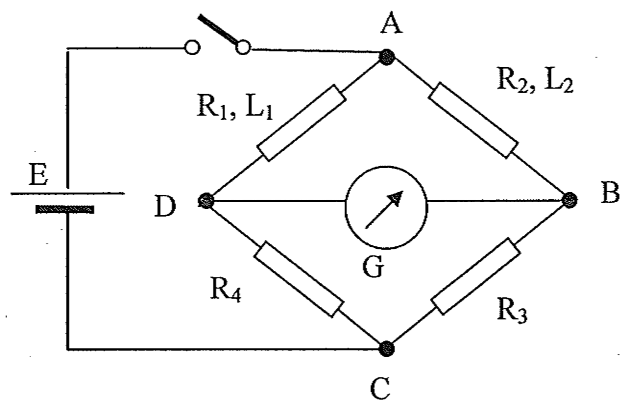


Figure B3 Induction Balance Bridge

Now when the switch is opened or closed, the transient voltage due to L_2 will balance the transient voltage due to L_1 when L_2 is adjusted to equal L_1.

The alternating current bridge is attributed to Max Wien (1866-1938), a professor of physics at the Technical University of Danzig, and later at Jena. Wien used a voltage supply with a steady frequency. Initially, in 1891, this voltage supply consisted of a vibrating wire making and breaking the primary current to an induction coil. The secondary current from the induction coil was used to supply the bridge circuit. Later, in an effort to provide a sinusoidal waveform source for his bridge circuit, Wien used a small alternator. The sinusoidal voltage supply has the advantage of measuring the values of inductance or capacitance under similar conditions as occur in practice. Wien's bridge uses capacitors in two of its branches. Today this connection is best known in its application as a sine wave oscillator.

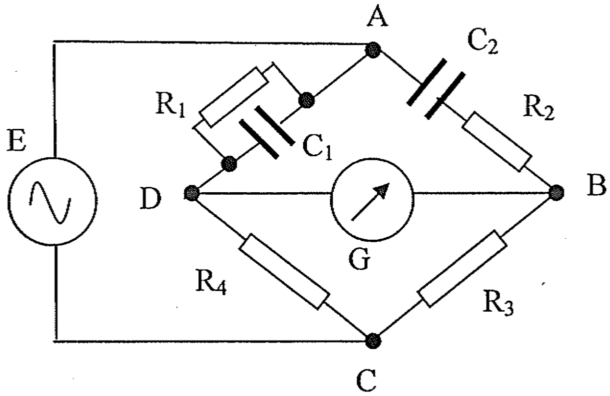


Figure B4 Wien's Bridge for Measuring Capacitance

A bridge connection that is often referred to as Maxwell's bridge contains an inductor in one of the branches and a capacitor in the opposite branch. There are resistors in the remaining two branches. (Figure B5). Maxwell's bridge is used to measure unknown inductance using calibrated resistance and capacitance.

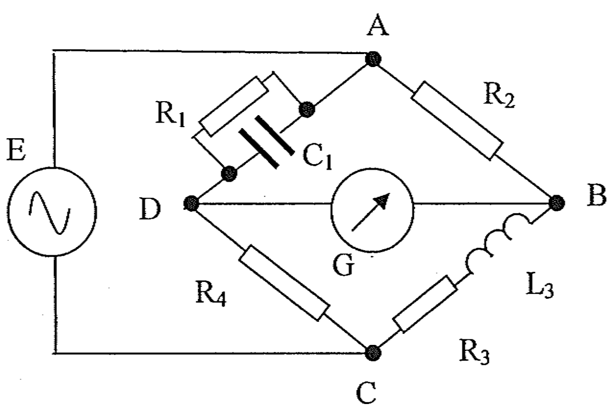


Figure B5 Maxwell's Bridge for Measuring of Inductance

The a.c. bridges are usually analyzed by using the complex impedances. A generalized connection of an a.c. bridge is shown in Figure B6

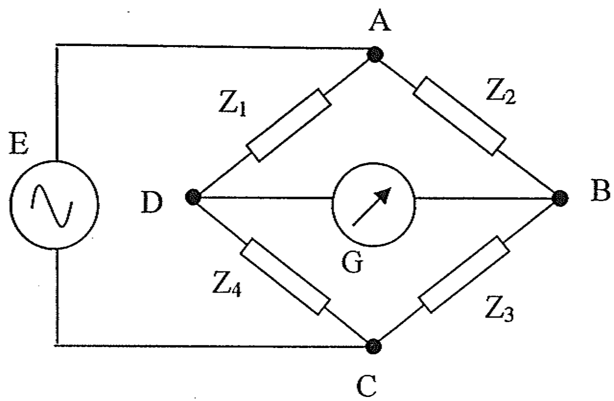


Figure B6 A.C. Impedance Bridge

Similarly as for the d.c. bridge, there is no current flowing through branch BD if the potentials at B and D are equal. From this condition we get that

$$\frac{Z_1}{Z_2} = \frac{Z_4}{Z_3}$$

For example in the case of the Maxwell's bridge, the individual impedances are

$$Z_1 = \frac{1}{\frac{1}{R_1} + j\omega C_1}$$
$$Z_2 = R_2$$
$$Z_3 = R_3 + j\omega L_3$$
$$Z_4 = R_4$$

Substituting for the impedances into the condition for the balanced bridge,

$$Z_3 = \frac{Z_2 Z_4}{Z_1}$$

$$R_3 + j\omega L_3 = \left(\frac{1}{R_1} + j\omega C_1\right) R_2 R_4$$

$$R_3 + j\omega L_3 = \frac{R_2 R_4}{R_1} + j\omega C_1 R_2 R_4$$

Therefore the resistance of the unknown coil is

$$R_3 = \frac{R_2 R_4}{R_1}$$

and the inductance of the unknown coil is

$$L_3 = C_1 R_2 R_4$$

Appendix C

ELECTRIC CIRCUIT CALCULATION USING PHASORS AND COMPLEX IMPEDANCES

C1. Circuit with a Resistance

Resistance is considered to be constant for a fixed frequency and temperature, which means that at any instant, the current is proportional to the applied voltage. This is the Ohm's law.

$$i_R = \frac{v_R}{\mathrm{R}} = \frac{V_m \sin(\omega t + \phi)}{\mathrm{R}} = \frac{V_m}{\mathrm{R}} \sin(\omega t + \phi) = I_m \sin(\omega t + \phi)$$

In time domain, the voltage and current are represented by a sine curve. The voltage and current are in phase.

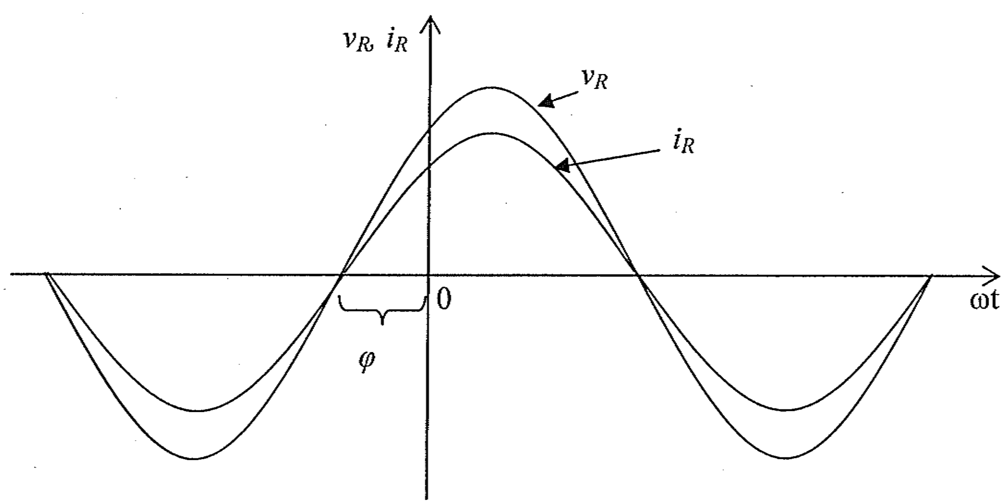


Figure C1 Voltage and Current in a Resistive A.C. Circuit

Using phasor notation the above relationship is written as[54]

$$\mathbf{I}_R = \frac{\mathbf{V}_R}{R} = \frac{V\angle\phi}{R} = I\angle\phi$$

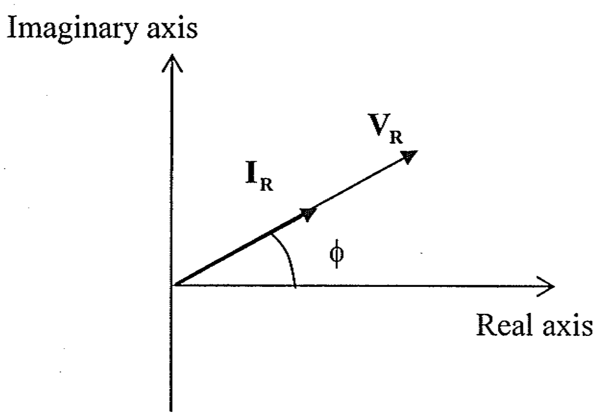


Figure C2 Phasor Representation of Voltage and Current in a Resistive A.C. Circuit

The ratio between the voltage and current phasors of a resistive circuit is the circuit resistance.

$$R = \frac{\mathbf{V}_R}{\mathbf{I}_R}$$

C2. Circuit with an Inductance

The voltage across an inductance is proportional to the rate of change of current through the inductance:

$$v_L = L\frac{di_L}{dt}$$

[54] for more explanation refer to 8.7 of this dissertation.

For a sinusoidal current

$i_L = I_m \sin(\omega t + \phi)$

Therefore

$v_L = L\dfrac{d}{dt}(I_m \sin(\omega t + \phi)) = L\omega I_m \cos(\omega t + \phi) = \omega L I_m \sin(\omega t + \phi + 90°)$

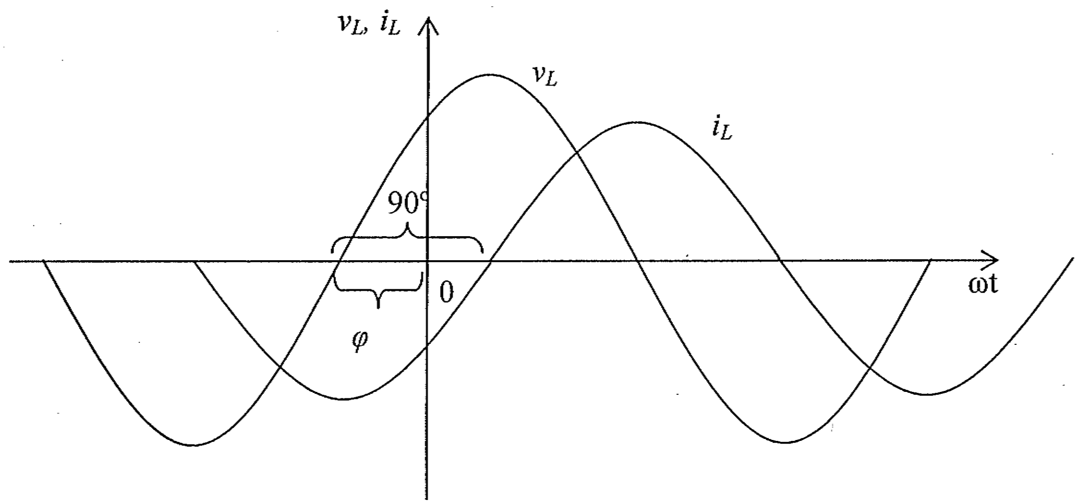


Figure C3 Voltage and Current in an Inductive A.C. Circuit

Using phasor notation the above relationship is written as

$\mathbf{V_L} = j\omega L\mathbf{I_L} = jX_L\mathbf{I_L}$

The factor "j" comes from the 90° phase shift between the voltage and the current in an inductive circuit. X_L is the inductive reactance

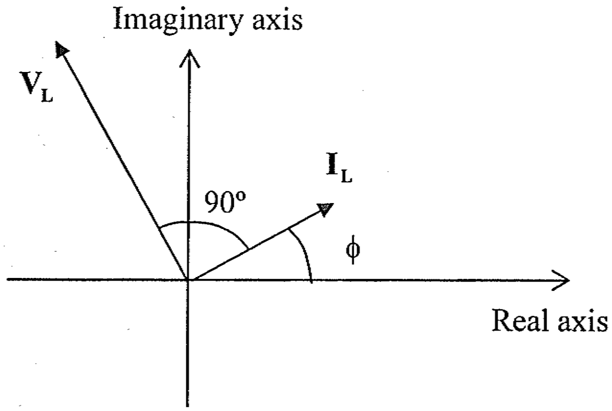


Figure C4 Phasor Representation of Voltage and Current in an Inductive A.C. Circuit

The ratio between the voltage and current phasors of an inductive circuit is the circuit impedance. Since there is no resistance in the circuit, the impedance has no real component.

$$\mathbf{Z} = \frac{\mathbf{V}_L}{\mathbf{I}_L} = j\omega L = jX_L$$

C3. Circuit with a Capacitance

Current through a capacitor is proportional to the rate of change of voltage across the capacitor

$$i_C = C\frac{dv_C}{dt}$$

For a sinusoidal voltage

$$v_C = V_m \sin(\omega t + \phi)$$

Therefore

$$i_C = C\frac{d}{dt}(V_m \sin(\omega t + \phi)) = C\omega V_m \cos(\omega t + \phi) = \omega C V_m \sin(\omega t + \phi + 90°)$$

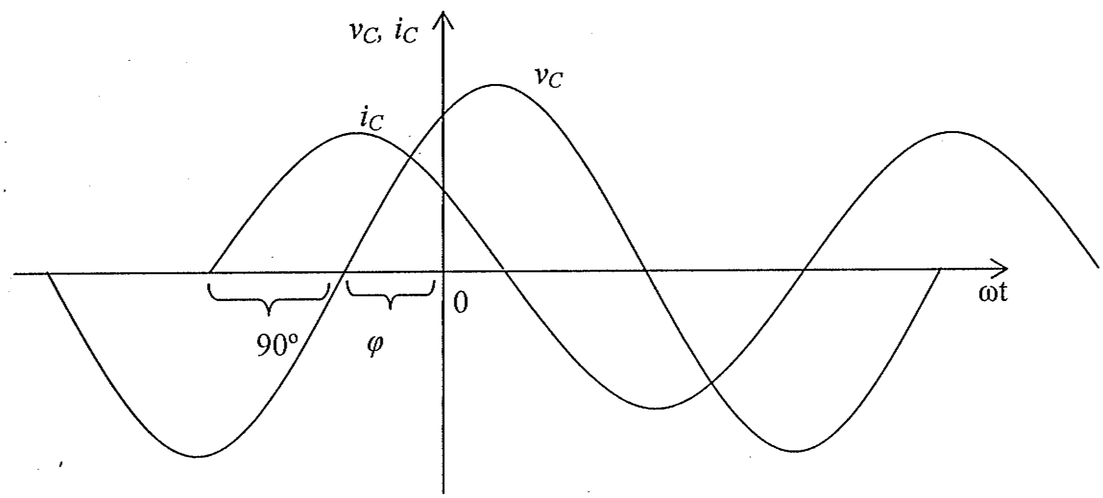


Figure C5 Voltage and Current in a Capacitive A.C. Circuit

Using phasor notation the above relationship is written as

$$\mathbf{I}_C = j\omega C\mathbf{V}_C$$

Similarly to the inductive circuit, the factor "j" comes from the 90° phase shift between the voltage and the current in an inductive circuit. This time the current leads the voltage as is apparent in the time domain graphs. X_C is the capacitive reactance.

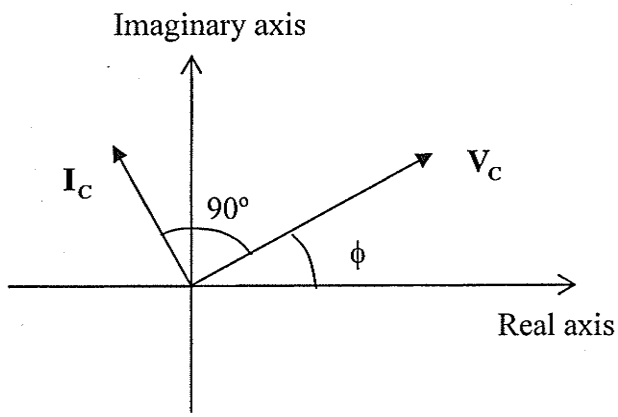


Figure C6 Phasor Representation of Voltage and Current in a Capacitive A.C. Circuit

The ratio between the voltage and current phasors of a capacitive circuit is the circuit impedance. Since there is no resistance in the circuit, the impedance has no real component.

$$\mathbf{Z} = \frac{\mathbf{V}_C}{\mathbf{I}_C} = -\mathrm{j}\frac{1}{\omega C} = -\mathrm{j}X_C$$

C4. Analysis of Series RLC Circuit Using Phasors and Complex Impedance

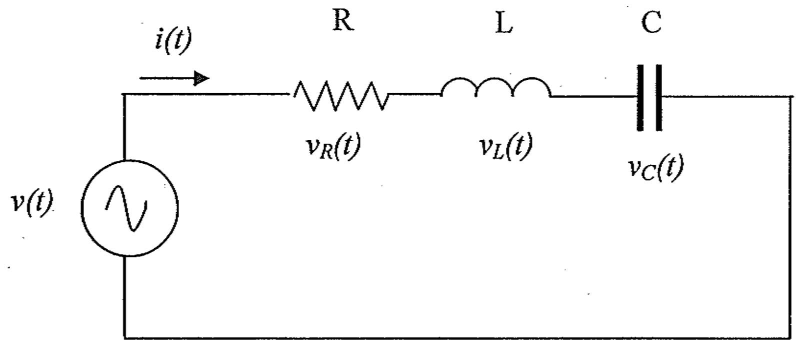


Figure C7 Series RLC Circuit

Impedance of the circuit is the ratio of the voltage phasor to the current phasor:

$$\mathbf{Z}=\frac{\mathbf{V}}{\mathbf{I}}=\frac{\mathbf{V}_R+\mathbf{V}_L+\mathbf{V}_C}{\mathbf{I}}=\frac{R\mathbf{I}+j\omega L\mathbf{I}+\frac{1}{j\omega C}\mathbf{I}}{\mathbf{I}}=R+j\omega L+\frac{1}{j\omega C}=R+j\left(\omega L-\frac{1}{\omega C}\right)$$

The impedance diagram of Figure C8 shows the components of the impedance of the circuit in the complex plane:

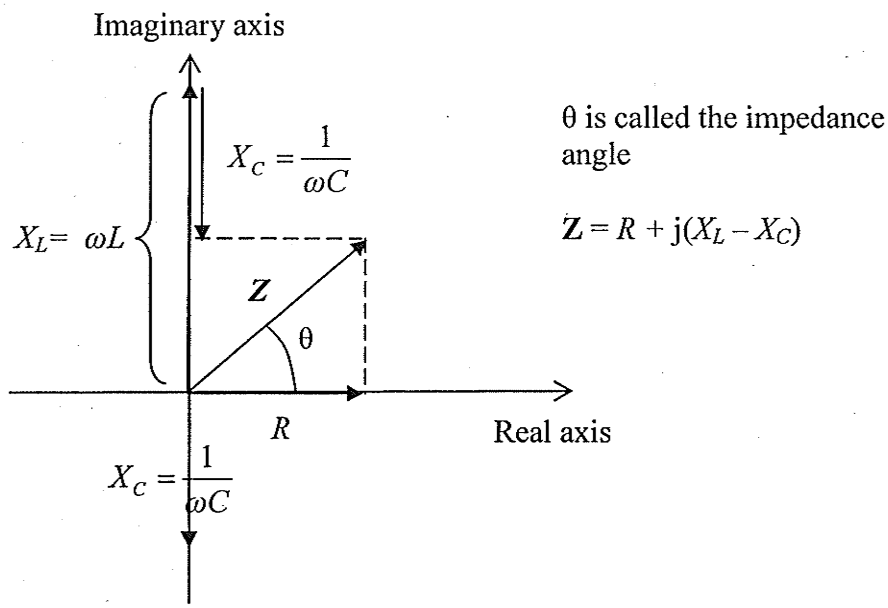


Figure C8 Impedance Diagram of a Series RLC Circuit

In order to draw the phasor diagram, one of the quantities must be chosen as the reference, i.e. its angle is assigned to be 0°. For a series circuit, the reference is usually the voltage, since the voltage is the applied, and therefore the known quantity.

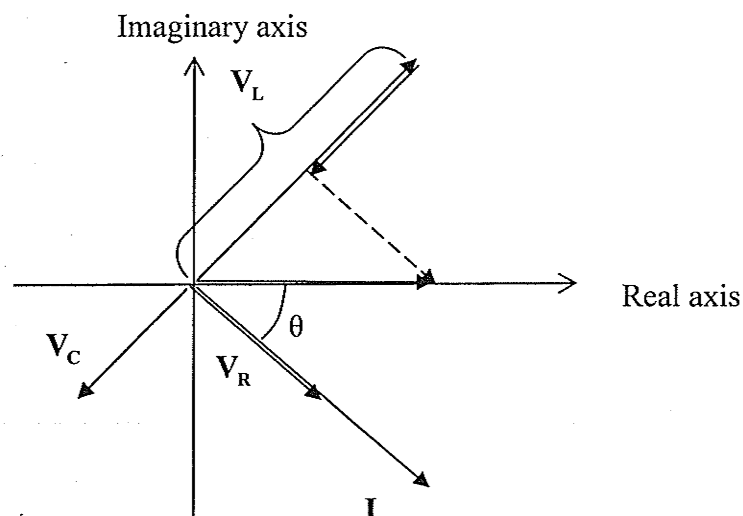


Figure C9 Phasor Diagram of Voltages and Current in a Series A.C. Circuit

Apendix D

Curriculum Matrix: Introduction to Electric Circuits

		Items of engineering knowledge							Suggested activities to aid concept building	Comments
		Mathematical theories of electrical equipment	Elementary principles of physics and chemistry	Mathematical techniques	Empirical data on materials and machines	Design rules of thumb	Design equations	Technical skills		
Curricular activity	Fundamental and derived units		·SI Units: m, kg, s	·Operations with powers of ten ·Significant digits and rounding off			·Engineering prefixes		·Why SI units? What was used before them?	Electrical units should be introduced later with the corresponding topics.
	Electricity	·Use of symbols	·Atomic structure ·Coulomb's law ·Elementary charge						·What is electric charge?	A story of development of the concept of charge should precede the atomic structure theory
	Current	·Ideal current sources	·Definition of current		·Harmful effects of electric current ·Safety considerations	·Conventional current direction		·Use of ammeter	·What is electric current?	Discuss: Is electric current a circulation of charges around the circuit? What is a drift velocity? How fast electricity travel?
	Voltage	·Ideal voltage sources	·Electric Field ·Potential energy ·Potential difference		·Breakdown voltage ·Batteries ·Grounding	·Polarity notation		·Use of voltmeter	·Concept of a field versus concept of a force-at-a-distance	Discuss the terminology: voltage, potential, potential difference, electromotive force.

	Resistance		·Conductors and insulators ·Definition of resistance ·Definition of conductance ·Temperature effects ·Ohm's law		·Tables of resistivity of various materials ·Tables of temperature intercepts of various materials ·types of resistors	·Inferred absolute temperature ·resistor colour coding		·Use of ohmmeter	·What did Ohm actually do? ·What equipment did he use? ·What is 1 ohm?	
	Power and energy	·Power losses ·Efficiency	·What is power? ·What is energy?					·Use of Wattmeters ·Use of Watthourmeters		

Apendix E

Curriculum Matrix: Introduction to Analysis of Alternating Current Circuits

		Items of engineering knowledge								
		Mathematical theories of electrical equipment	**Elementary principles of physics and chemistry**	**Mathematical techniques**	**Empirical data on materials and machines**	**Design rules of thumb**	**Design equations**	**Technical skills**	**Suggested activities to aid concept building**	**Comments**
Curricular activity	**Characteristics of sinusoidal voltages and currents**			·Sketch a sinusoidal waveform ·Identify cycle, period, positive and negative half cycles, maximum value				·Build a two pole generator ·Use an oscilloscope to display sinusoidal voltage	·Relate sinusoidal wave to a two pole generator	
Curricular activity	**Mathematical description of sinusoidal voltages and currents**			·Write the equations for sinusoidal voltages and currents ·Calculate frequency, instantaneous value, average value, effective value					·Understand the relationship between frequency and angular speed of a two pole generator ·Define effective value in terms of direct current	

	Mathematical description of phase shifted sinusoidal voltages and currents			·Write the equations ·Find phase angle of the sinusoidal function					·Associate the phase angle with rotor position of a two pole generator	
	Complex numbers			·Polar and rectangular forms ·Complex number operations					·Why do we need complex numbers? ·Mathematical description of space ·The meaning of "j".	
	Phasors			Sketch phasors for sinusoidal voltages and currents in a complex plane ·Write phasor representation for sinusoidal voltages and currents ·Add, subtract, multiply and divide phasors						Discuss the reasons for using phasors rather than the time domain descriptions. Discuss the steps in development of complex numbers, vectors, and phasors. Discuss the conditions for which the phasor analysis is valid (steady state, single frequency)
	Response of single R, L, and C components to sinusoidal voltages and currents			·Write the equations for sinusoidal voltages and currents in time domain for circuits with one passive component. ·Sketch the voltage and current waveforms ·Write the phasor expressions.						
	Response of RLC circuits to sinusoidal voltages and currents			·Write the equations for sinusoidal voltages and currents in time domain. ·Sketch the voltage and current waveforms ·Write the phasor expressions.						

	Complex Impedance	·Define impedance of a resistive circuit ·Define impedance of a purely reactive circuit. ·Inductive and capacitive reactance vs frequency ·Define impedance of an RLC circuit.		·Draw impedance diagram in a complex plane. ·Calculate impedance of a resistive circuit ·Calculate impedance of a purely reactive circuit. ·Calculate impedance of an RLC circuit.						