STUDENT LEARNING OF THE CONCEPTS OF CAPACITANCE, INDUCTANCE, AND ELECTROMAGNETISM

BY

LESLIE COWAN

In partial fulfilment of the requirements of the Ph.D. degree, University of Surrey, 1987
SUMMARY

This study, influenced by an interest in the history of electricity, explores the problems which many students experience in understanding the phenomena of capacitance, inductance, and electromagnetism related to motors and generators.

Interviews were conducted with school pupils, vocational students at technical colleges, and university/polytechnic students in their first two terms of degree courses. Interviewees were encouraged to speak of their difficulties encountered during electrical studies. The conversation was guided towards a prepared framework of questions, supplemented by a number of drawings and diagrams, which were used to probe the students' familiarity with the phenomena and concepts associated with them. The interviews were tape-recorded, and analysed with a view to determining the reasons for the learners' difficulties.

Following an introduction commenting on the need for this research, there is a chapter concerned with the pioneers whose discoveries laid the foundations for capacitive and inductive knowledge. Then follows a chapter which considers some of the principal writings of the distinguished early electricians and electrical educators, with a survey of important textbooks for the three classes of learners. The next chapters give extracts from the interviews, and discuss the data obtained.

An important conclusion is that the majority of students of electricity fall into two distinct categories: "Visualizers" and "Mathematics", and that difficulties can arise when the needs of each are not well served by the instruction received or the textbooks used. Misunderstandings at an early stage of electrical education can be carried forward to higher education.

In the final chapter recommendations are made for improving the opportunities which could be given to both "Visualizers" and "Mathematics" to master the electrical fundamentals - these include the study of neglected historical texts, and the repetition of pioneers' original experiments.
ACKNOWLEDGMENT

I wish to thank Dr. John Gilbert for his numerous valuable suggestions, and his helpful advice given to me during the course of this research programme.
Forty-five years ago, when I was struggling to grasp the fundamental principles of electrical engineering, in order to facilitate experiments which I was conducting with sound amplification, I experienced particular difficulty in following the treatment of capacitance and inductance in the Physics textbooks to which I had access. Innocently believing that older youths (who were trainee electrical mechanics) would be possessed of the understanding which escaped me, I made inquiry about the physical basis for some of the component functions. I was disappointed: those about to enter the electrical industry had not gained a confident mastery of the basic principles.

In the interval of time there have been greatly expanded opportunities for technical education, and a plethora of electrical textbooks and electrical hobby magazines, yet most of the difficulties which I and others experienced in the past with capacitive and inductive concepts continue to perplex a considerable proportion of students.

I determined to research the reasons for the difficulties encountered by these contemporary learners, and to seek ways of ameliorating them.
CONTENTS

Preface

CHAPTER ONE

Introduction 1
Student Problems Which Invite Research 8

CHAPTER TWO

Early Electricians 15

CHAPTER THREE

Textbooks Which Have Served Students of Electricity 78

CHAPTER FOUR

The Interviews 169

CHAPTER FIVE

Discussion: The Interviews 357

CHAPTER SIX

Recommendations Based on Research Findings 382

Table of Interviews 432
Notes 433
Bibliography 443
CHAPTER ONE

STUDENT PROBLEMS WHICH INVITE RESEARCH

Introduction

1.1 Previous Research in this Field 7
1.2 Research Method: Interviews 8
1.3 Knowledge of Basic Principles 12
1.4 Textbook Use 12
1.5 Possible Changes and Improvements 13
1.6 The Value of Historical Texts 14
CHAPTER ONE

STUDENT PROBLEMS WHICH INVITE RESEARCH

Introduction

For a number of years before undertaking this research programme I had been aware that a considerable proportion of students who begin the study of electricity experience difficulties in grasping the basic principles, and that these unresolved difficulties may remain troublesome to them for long periods of time. I had discussed these matters with school teachers, vocational instructors, and those who received freshmen into university and polytechnic degree courses. Almost all agreed that a large proportion of learners suffered from problems and misunderstandings associated with the fundamental electrical properties, principally those of capacitance, inductance, and electromagnetism related to motors and generators. As my interests in sound recording and reproduction brought me into contact with manufacturers of electrical equipment, I was able to learn the opinions of industrial employers who accepted vocational trainees. They frequently commented on their new recruits' weaknesses in the same areas of electrical education.

When it became possible for me to undertake an extended research programme concerning student learning problems, I decided to investigate the reasons why so many learners experienced these difficulties with electrical fundamentals. I visited a large number of schools, technical institutions, industrial training groups and university and polytechnic first year Engineering and Physics students
to hear what problems they had experienced. As a result of these conversations I received confirmation that the electrical phenomena, mentioned by the teachers and employers as specially troublesome, were in fact those which the students found hardest to master. My informal talks suggested that capacitive and inductive phenomena continued to be sources of anxiety to a considerable proportion of those who had been successful in gaining entrance to university/polytechnic degree courses in Electrical Engineering, and that those at an earlier stage of their electrical education were often struggling uncomfortably to come to terms with these concepts.

In the course of my conversations with students (and their teachers) at different levels of study, it became apparent that they had little knowledge of the achievements of the great electrical pioneers of the past, and that in consequence they were unaware of the significance of their researches in relation to the fundamental principles being studied. As a historian I felt that this absence of information was disappointing, and that the opportunity for providing the students with interest, encouragement, and inspiration was being neglected. This was particularly so in connection with practical work in the laboratory, and only very rarely did the experiments recall those historical discoveries upon which so much of modern electrical practice depends.

The students at technical colleges following vocational courses appeared to suffer from very much the same problems with capacitance and inductance as the school pupils, and in view of the current widespread interest in computers and digital systems, I wondered if the teachers were sufficiently emphasizing the importance of the basic principles, and whether the beginners on most courses were skimping the traditional electrical fundamentals in their hurry to
reach "more interesting" computer-associated studies. Moreover, because of the tendency in many schools and technical institutions to start the learners off upon a "systems approach" (that is, a "black-box" or modular approach), I questioned if the pupils were receiving sufficient instruction and getting the opportunities for personal experience in the investigation of basic principles through the use of discrete components. These thoughts were further stimulated by the comment of the chief training officer of a large electrical laboratory, seeking the explanation for the disappointing performance of his latest trainees, who said:

"The interest in the software side of computing seems to have taken over, to the detriment of fundamentals."

Other discussions with works managers at domestic electrical equipment companies, and the engineers in charge of the Research and Development sections of audio manufacturers, confirmed that there was cause for concern about the uncertain grasp that many of the trainees had of these fundamental properties. One blunt manager of a well-known Midlands audio amplifier company exclaimed:

"There's a mighty lot wrong with the training they (the technical college youths) get now. When I show them simple circuits they can't make head nor tail of them. Don't they teach them basics? I want people who know about components, not the sort who can take little blocks and plug them into place."

Another considered opinion came from the recruiting officer of a major national company who said:

"Academically able recruits are always welcome, but they also need to know how circuits work, and be able to sit down at the bench and sort out problems by means of the multimeter and oscilloscope. We still require our trainees to have a good basic knowledge of electrical fundamentals."

The engineers responsible for industrial training within factories and the instructors on Maintenance courses agree that,
despite the financial rewards for properly qualified technicians, they are finding it increasingly difficult to obtain from the technical colleges those who have a sound understanding of basic electrical phenomena and a confidence in the handling of discrete components. The skilled and versatile electrical mechanic is in danger of dying out. This scarcity situation was outlined in a feature article in the journal *Studio Sound* under the title "Who Will Fix It?" It concluded:

"Skilled maintenance personnel will continue to command a premium with today's digital technology in many locations. One studio owner commented while cradling his four year-old daughter on his lap, 'I used to think I wanted to send her to college. Now I think if she can fix boards and decks she'll make more money than she could as a doctor or lawyer.'"

Another expression of discontent with the electrical education in this country was made by Dr. John Scarborough, the Managing Director of a Lancashire telecommunications firm, in an article which appeared in *Technology Week* who wrote:

"A critical factor in securing our growth is the recruitment of both electronics design and development engineers and technically qualified sales engineers. We have been actively recruiting for over 12 months, but still have vacancies in both categories. Advertisements have elicited a poor response. Recent graduates of our universities and polytechnics often appear to regard the bench and the soldering iron as museum pieces, and their knowledge of fundamental electronic circuitry principles is deplorably lacking. Their practical and revenue-earning value to a small company like ours is negligible in the short term. It seems absurd that after three or more years at university, we should then have to provide a basic training in electronics in order to gain a useful employee."

My conversations with students and their teachers on various Higher Education courses indicated that many had reached this stage with a rather shaky knowledge of electrical fundamentals. Some admitted that they had been successful in A-level work largely through a facility in the application of formulae and much practice in the technique of answering examination questions, rather than through a thorough understanding of the concepts involved in electricity and electronics.
My inquiries about capacitive and inductive phenomena and the principles of electromagnetism related to motors and generators revealed that a considerable proportion of the students were concerned about their own deficient knowledge, and anticipated further embarrassment as courses progressed. These preliminary conversations suggested that for many the school studies had largely consisted of rote-learning, or the acceptance of given information, without personal inquiry, experiment, or further thought, and that the pressures of examination requirements, as much as personal indolence, were implicated in this inadequate preparation.

During visits to speak with students in the university and polytechnic laboratories, I was particularly struck by the fact that so few of the freshmen were enjoying their practical work, and I considered that this was linked to the astonishing fact that many on the benches appeared to have little understanding of the circuits with which they were working.

As a result of these early inquiries I resolved to investigate the reasons why so many learners experience difficulties and problems with the fundamental principles of electricity and concentrate my attention upon the three areas which appeared to present severe difficulties to a considerable proportion of the learners: the concepts of capacitance, inductance, and electromagnetism related to motors and generators, and their practical applications. By extensive interviews with school pupils, vocational trainees, and first-term university/polytechnic students on Physics and Engineering degree courses, I hoped to identify the most common difficulties which the learners had with the selected principles, and to trace the source of such difficulties. My preliminary inquiries had suggested that some contributory factors might be unsuitable textbook presentations and illustrations (and their influence upon the
teachers using them); the speed of dealing with fundamental principles; the teachers' own familiarity with the material; and the insufficiency of the practical work in the laboratory - but I had every reason to suppose that much else would be discovered in the course of the research programme.
Surprisingly, there appears to be no record of any research in the area of student learning problems directly associated with the concepts of inductance and capacitance; however, valuable work has been done in the related field of schoolchildren and young persons' concepts of current, voltage, and resistance in simple (usually d.c.) circuits. Principal among these are investigations concerning students' understanding of the concept "Potential" by Gilbert (1977)\(^3\); the students' use and understanding of particular words in physics, including "Electric Current", using the Interview-about-Instances method of investigation, by Osborne and Gilbert (1979)\(^4\); children's models of current flow in d.c. circuits, Osborne (1981)\(^5\) and (1982)\(^6\); and the understanding of current, voltage and resistance in d.c. circuits, Shipstone (1982)\(^7\); secondary students' understanding of energy, Brook and Driver (1984)\(^8\); and elementary electricity, Black (1985)\(^9\).

These researchers found evidence of much misunderstanding, confusion, or personal interpretation within an "alternative framework" which was in conflict with the concepts required for the students' advancement in electrical studies. That result gave good reason to expect that students of the more complex phenomena associated with capacitance, inductance, and the electromagnetic properties of generators and motors would experience similar or more serious misunderstandings.
1.2

The Principal Research Questions Addressed in this Study

The primary purpose of this inquiry was to gain greater knowledge of the learners' problems in mastering the principles of capacitance, inductance, and electromagnetism related to motors and generators; and, to that end the study addressed especially these research questions:

a) Why did many students experience difficulties in understanding the essential electrical features of the capacitor and inductor, and the physical conditions governing their operation and functions in circuits? Similarly, why were many learners uncertain of the principles of electromagnetism in its application to motors and generators?

b) Were these fundamental principles receiving sufficient attention during the early stages of electrical studies.

c) Were the learners given sufficient practical experience of capacitive and inductive circuits, and the operation of motors and generators in the laboratory?

d) Were the learners successfully resolving their problems and difficulties, and in this were they receiving sufficient support from their teachers?

e) Were there problems particular to the vocational students preparing for industrial work?

f) Was there a relation between electrical hobby activity and performance on the learners' courses of study?

g) Were the textbooks used satisfactory to the learners' needs?

h) Could a knowledge of the electrical pioneers' researches and historical texts be of value to present-day learners?
i) Could the inquiry discover new factors which could assist or detract from the learners' electrical studies?

j) Were the learners' critical of the content of their courses; of their methods of instruction; or of the laboratory procedures? What recommendations could they make to improve their chances of success and satisfaction in study?
1.3

Research Method: Interviews

My principal means of obtaining data was through an extended private interview with the three classes of learners, during which I explored the difficulties which they had in understanding the concepts of capacitance and inductance, and electromagnetism associated with motors and generators. The school pupils were preparing for A-level examinations; the vocational students were those attending technical institutions, principally preparing for Technical Education Certificates; and the university/polytechnic students were first and second-term undergraduates reading for Physics or Engineering degrees.

The interviews began with an extended conversation in a relaxed atmosphere designed to persuade the students to speak without restraint concerning personal difficulties in mastering electrical fundamentals, followed by a tape-recorded semi-structured interview where conversation was guided towards a prepared body of questions which were supplemented by a number of drawings and diagrams shown for the purpose of exploring the student's conceptions of capacitance, inductance, and electromagnetism related to motors and generators.

Every effort was made to put the student at ease by the exhibition of a genuinely sympathetic interest, and the person was encouraged to recall memories of problems or difficulties encountered during the early stages of electrical studies (and, subsequently up to the time of the conversation) which might relate to the area of investigation, and to learn as much as possible of the student's attitude to current studies: classwork, laboratory practicals, and textbook use.
In almost all cases, I was able to win the student's confidence and obtain a frank account of problems experienced, and to discover something of the methods which the student used to overcome them.
PARTICULAR AREAS OF INQUIRY

Knowledge of Basic Principles  The Value of Practical Work  Hobbies

I was particularly interested to learn of the students' degree of familiarity with the basic theoretical principles, as well as to obtain information on their acquaintance with the formulae which mathematically describe the electrical phenomena. Similarly, I wished to hear from the students the estimate of value which they put upon the practical work undertaken in the laboratory, and to know whether they thought the balance of emphasis and time given to practicals and theoretical work was correct. Independently, I obtained - whenever cooperation was granted - the opinions of teachers and demonstrators on the same subjects.

Another object of inquiry during the interviews was to learn if the school pupils and vocational trainees made a hobby of constructing electrical recreational equipment, and if they felt that this was advantageous to their studies. Associated with this was a wish to discover what use was made of the electrical hobby magazines by the two groups of learners.

Textbook Use

An important area of inquiry was concerned with the textbooks used by each of the three categories of students. It was hoped to
learn which texts were favoured by the students, and by their teachers, and how far the presentation affected the ease of study and understanding. It was believed that it might be possible to refer some student difficulties to the use or neglect of the recommended books, so inquiries were made about the use of textbooks for private reading to supplement classroom and laboratory instruction. In addition, the potential of appropriate graphic illustrations to clarify theoretical principles was investigated.

1. 6

During the interviews particular note was taken of the students' criticism and comment on classroom and laboratory activity, with a view to determine if there was a pattern of discontent which marked each category of student, or the different levels of electrical instruction. All the interviewees were encouraged to make recommendations for change and improvement which could be applied to their own courses, based on their study experiences.

The purpose of such inquiry was in large part to determine what possible actions might be taken by the teachers, in addition to their present efforts, to assist the learners to overcome the problems and difficulties which the research programme might reveal, and to gather information which might suggest classroom or laboratory procedures which might contribute to improving the students' performance in their required work at different educational institutions, and render their theoretical or practical work more rewarding to themselves and their teachers.
The Value of Historical Texts

My discussions with teachers revealed that they (and in consequence their pupils) were almost wholly unaware of the sequence of discoveries in electrical research conducted by the late 18th and 19th century pioneers, and that they were ignorant of the original scientific papers, reports, and early books through which they communicated their discoveries to fellow scientists and interested amateurs - and subsequently to the technicians who were drawn into the electrical industries.

I was interested to learn whether some of these publications could be of value to present-day teachers and students, and I suspected that the comparative simplicity of the explanations of recently discovered electrical fundamentals had been overlaid with a complexity in the modern introductory texts which contributes little to the students' mastery of these fundamentals. I therefore undertook a comprehensive study of the pioneers' published work, paying particular attention to their texts (and others inspired by their research), with a view to identifying what portions of the writing and graphic illustrations could be of value to modern students; and, with the purpose of noting how the original material had been adapted and presented in currently favoured electrical textbooks.

Thus there follows a survey of the discoveries of the pioneers' researches in capacitance, inductance, and electromagnetism related to motors and generators, and the results which they published, and the electrical texts which developed from the new knowledge.
## CHAPTER TWO

### EARLY ELECTRICIANS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Early Electrical Research</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>Volta and the Electric Pile</td>
<td>19</td>
</tr>
<tr>
<td>2.3</td>
<td>Hans Christian Oersted</td>
<td>22</td>
</tr>
<tr>
<td>2.4</td>
<td>The Interaction of Electricity and Magnetism</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>Arago's Researches</td>
<td>25</td>
</tr>
<tr>
<td>2.6</td>
<td>Ampère's Research</td>
<td>25</td>
</tr>
<tr>
<td>2.7</td>
<td>The Discovery of the Solenoid</td>
<td>26</td>
</tr>
<tr>
<td>2.8</td>
<td>Ohm's Law of 1827</td>
<td>26</td>
</tr>
<tr>
<td>2.9</td>
<td>Joseph Henry</td>
<td>28</td>
</tr>
<tr>
<td>2.10</td>
<td>Henry's Electromagnets</td>
<td>30</td>
</tr>
<tr>
<td>2.11</td>
<td>Henry Discovers Impedence Matching</td>
<td>31</td>
</tr>
<tr>
<td>2.12</td>
<td>Henry's Electric Motor</td>
<td>32</td>
</tr>
<tr>
<td>2.13</td>
<td>Henry's Experiments with Induction</td>
<td>34</td>
</tr>
<tr>
<td>2.14</td>
<td>Henry's Experiments with Self-Induction</td>
<td>35</td>
</tr>
<tr>
<td>2.15</td>
<td>Experiments with Transformers</td>
<td>36</td>
</tr>
<tr>
<td>2.16</td>
<td>Experiments with Oscillators</td>
<td>37</td>
</tr>
<tr>
<td>2.17</td>
<td>Michael Faraday</td>
<td>39</td>
</tr>
<tr>
<td>2.18</td>
<td>Electromagnetic Rotation</td>
<td>41</td>
</tr>
<tr>
<td>2.19</td>
<td>The Transformer, Magnetic Induction, The Generator</td>
<td>43</td>
</tr>
<tr>
<td>2.20</td>
<td>Self-Induction: Faraday's Analysis</td>
<td>47</td>
</tr>
<tr>
<td>2.21</td>
<td>Specific Inductive Capacity</td>
<td>48</td>
</tr>
</tbody>
</table>
2.1 Early Electrical Research

In the 18th century electrical studies were often undertaken by enthusiastic amateurs who followed personal interests and predilections. If they believed that they had obtained significant results, they proudly communicated these findings to the small number of widely dispersed natural philosophers whom they knew would appreciate their ingenuity and perseverance in gathering new knowledge of the world. Sometimes they were men of comfortable means with sufficient resources to indulge their intellectual curiosity in the physical world around them; of these, the most notable pioneers were Benjamin Franklin in America, and Henry Cavendish in England. They undoubtedly accomplished much to advance the body of electrical and magnetic knowledge at a time when so much remained to be investigated, yet their discoveries were hesitantly and slowly incorporated into European scientific thought. Franklin's researches were not built upon by the generation which followed him, so electrical experimentation remained neglected in America until the work of Joseph Henry. There were also difficulties of communication: Franklin was at a great distance, and his novel ideas relating atmospheric electricity to phenomena of electrostatic laboratory machines called for discussion and clarification which was denied to the Italian, French, German, and English natural philosophers. The research findings of Cavendish which might have been such a
vigorously stimulated to his scientific contemporaries, were withheld from publication by that perfectionist, and the mathematical relations drawn from his researches on electrostatic charges reached few of the receptive minds of his time.

The limited number of 18th century natural philosophers who were professionals working within the universities were persons of scholarly disposition who had been drawn to the physical sciences because these offered an opportunity to exercise their delight and fluency in mathematical manipulation, and they had behind them the long tradition of the medieval Quadrivium (arithmetic, music, geometry, and astronomy). They tended to be "general practitioners" expending their energy in the unspecialized natural philosophy of the time, which ranged through optics, chemistry and physics. Magnetism and electricity were studied independently, though most thinkers felt that there was a close connection. That dichotomy was reinforced by the authoritative opinion of Charles Augustin Coulomb (1736-1806), whose 1785 experiments with the attraction and repulsion of electrified bodies not only provided the scientific world with the first reliable mathematical formulae governing such bodies, but also left it with the conviction that magnetic and electrical phenomena were utterly distinct.

The electrical pioneers of the later 18th and early 19th centuries were deeply interested in the metaphysical theories of their time, for these speculations on the wider issues of space, time and matter, seemed to offer guidance in extracting some certainties from their investigation of the puzzling properties of electricity and magnetism.

Among the writers on metaphysics, none gained more respect than Immanuel Kant (1724-1804), notwithstanding the fact that he had much
to say on scientific matters which was based on abstract reasoning rather than practical experiment. From their study of his work they understood him to predict that systematic research would lead to a revelation of the unity of such natural forces as light, electricity, and magnetism; and, that he urged upon his readers an acceptance of the principle that the human mind is gifted with the faculty of apprehending an ordered system of laws in the physical world; the philosopher trained to effectively apply that faculty should gradually unfold the nature of an underlying basic force (Grundkräfte). So, a continually increasing body of reliable scientific knowledge, and ultimately, elucidation of the Grundkräfte, appeared to be guaranteed to the properly directed energies of the natural philosopher who accepted the ideas which Kant promulgated in the Critique of Pure Reason (1781). To natural philosophers teased by the mysteries of electricity and magnetism, there was a great deal of encouragement to be had from a system of metaphysics which taught that human intuition was specially atuned to receive truths about the real world associated with their laboratory experiments.

They were particularly interested in Kant's personal interpretation of matter and space, for he rejected Newton's corpuscular theory and his centrally acting forces at a distance. By Kant's theory, matter is a continuous quantity consisting of moving forces of attraction and repulsion, and he accepts the existence of an aether which fills all space, interpenetrates all matter, and possesses a spontaneous and perpetual motion. Kant's forces sufficiently resembled the familiar behavior of magnets, and his aether could be associated with the supposed "imponderable fluids" of electricity.
These were intriguing concepts designed to stimulate the adventurous among the natural philosophers. Yet comparatively little of lasting worth was accomplished by these early electricians before 1800. To the modern individual it may appear incomprehensible that these researchers of undoubted intellect and conscientiousness should have made such slow progress, but they were struggling to understand the behavior of new and complex phenomena with the most primitive of tools. Their magnetic materials were naturally occurring ores or needles which had been stroked with loadstones, and their apparatus was without astatic neutralization of the earth's magnetic field. Electrical research was dependent on the mechanically operated influence machines or the brief discharges of Leiden Jars, and in the absence of a source of continuous electromotive force, controlled measured and repeatable experiments were frustratingly difficult. Moreover, they were attempting to establish fundamental electrical and magnetic laws before the properties of voltage, current, resistance, flux density, permeability, and reluctance had been identified, and before there were any received units by which to measure and compare quantities.
It was the momentous invention of the "electric pile" which revolutionized the state of electrical research. This was the achievement of Alessandro Guiseppe Volta (1745-1827), who held the chair of natural philosophy at the university of Pavia for forty years. This painstaking experimentalist was known from youth as a person with a special ability to call forth imaginative devices to further his studies, and had invented a useful charge-building instrument, the Electrophore, early in his professional career. According to the memories of his pupils, Volta's teaching, in contrast to that of other academic natural philosophers, was marked by the absence of mathematical reasoning, and was centred upon practical experiments often employing inexpensive, simple instruments of his own devising. He can be recognized as a "Visualizer" rather than a "Mathematic". His rivals sneered at the minimum use which he made of mathematics in his lectures, and noted how he avoided those divisions of Physics which demanded a rigorous mathematical approach. In the 1790's, when attacked by Barletti on this account, although deeply respected by his students and admired by his colleagues for his brilliance, he was nevertheless obliged to justify his personal, very effective educational methods to his superiors.

This was the very time when he learned of the "discovery" of Luigi Galvani, and determined to observe for himself the alleged "animal electricity". He quickly found that Galvani was mistaken, and his own research convinced him that the electric charges arose from the contact of dissimilar metals, and that frogs' legs were quite unnecessary for their production. In the course of multiple
controlled and recorded experiments extending over a number of years, he established which metals produced the strongest electrical charges. For the most part, his experiments required no more than simple arithmetic proportions, involving comparisons of the effects of charges built up in different Leiden Jars, and the comparative strengths of current obtained from a variety of dissimilar metals, separated by brine-soaked cardboard. His most sensitive instrument was nothing other than a straw electroscope, and he never worked to a measured accuracy greater than a single degree of the compass.

Volta did not undertake the establishment of a theory which summarized the effects of electrical phenomena in mathematical formulae. That he left to the professed mathematicians, Ohm, Lenz, and Ampère, who, provided with a source of controlled current electricity, were afterwards able to experiment and theorize in the numerical mode which was natural to them.

When satisfied that his "electric pile" had been proved and was ready for the scientific community, Volta communicated the results of his experiments and the design of his invention to Sir Joseph Banks, the President of the Royal Society at London, in a letter of the 20th March, 1800. This was published in the most prestigious scientific journal of the day, the Philosophical Magazine under the title: "On the electricity excited by the mere contact of conducting substances of different kinds." It is a descriptive, qualitative account of the invention and its application, and measurements are used only in the very simplest sense.

Volta could scarcely have foreseen the quantity and intensity of the research which followed directly from this new source of electromotive force. In the succeeding thirty years almost all the British and European natural philosophers introduced the "Electric Pile" (or its variation, the "Crown of Cups") into their
laboratories, and with its aid a plethora of new discoveries and theories emerged which marked the transition from the age of electrical ignorance to the age of electrical science. Within twenty years Oersted was able to establish proof of the long-supposed relationship of electricity and magnetism.
Hans Christian Oersted

Hans Christian Oersted (1777-1851) was predisposed to believe that careful investigation could elucidate the connection between electricity and magnetism, for he was both an ingenious practical experimenter and a devoted student of Kant's metaphysics. According to his understanding of Kant's metaphysical theory, all experience to which the human senses react and the human reason can comprehend is ultimately dependent on attractive and repulsive forces. Oersted accepted that heat, light, electricity, and magnetism - those preoccupations of the natural philosophers - were all modifications of the Grundkräfte, and conversion of one force to another was held as more than just a possibility, rather a constant challenge. Oersted himself had dared to anticipate this as early as 1812 in his publication, Researches on the Identity of Electricity and Chemistry.

Oersted accepted the "Two Fluid" theory of electricity with its attendant conflict of Positive and Negative electricity in current-carrying circuits, and his experiments with his electric piles had familiarized him with the heat and light which very thin metal wires developed when connected to their terminals. He argued that magnetic forces might also be caused by "electric conflicts", and because of the interchangeability of forces, a sufficiently powerful electric current might demonstrate qualities similar to those possessed by magnets.

He had, in common with Michael Faraday, a wonderful ability to conceive "in his mind's eye" novel experiments and arrangements
of laboratory equipment which could clearly demonstrate particular effects for the greater understanding of his students or the interested public attending his lectures. In his teaching, like Volta, he sought explanations and demonstrations of the most direct and simple sort, avoiding complex mathematical presentation, and deliberately set out to popularize natural philosophy by building upon the familiar ordinary experiences of his students, rather than adopt an abstract mathematical approach. Both his extraordinary popularity with his students, and the remarkable extent of Danish scientific education testify to the effectiveness of his programme of imaginative experiments, which was strongly in contrast to the emphatic mathematical approach of most of his European academic contemporaries.

In the winter of 1819 Oersted was in the process of demonstrating the ability of a voltaic pile to heat a wire red-hot, when he observed that each time his assistant made or broke the connection, there was a deflection of a compass needle lying below the wire. He subsequently confirmed, by experiment, that he had indeed discovered the interaction of electricity and magnetism, and that current-carrying wire was surrounded by a circular magnetic force. He appreciated the great significance of the phenomenon, and on July 20th, 1820 sent to scientific acquaintances throughout Europe a paper in Latin: *Circa Effectum Conflictum Electrici In Acum Magneticam* which sparked off the new and wonderful study of electrodynamics. It was this paper which Michael Faraday read a few months later in an English translation: "Experiments on the effect of a current of electricity on the magnetic needle."
The Interaction of Electricity and Magnetism

Oersted's paper is a plain account of his equipment and the results obtained: it contains no mathematical analysis, nor theory related to the phenomena observed. The words used in description of the primary effects are characteristic of his mechanical, non-mathematical language:

"Let the straight part of the wire be placed horizontally above the magnetic needle, properly suspended, and parallel to it. If necessary, the uniting wire is bent so as to assume a proper position for the experiment. Things being in this state, the needle will be moved, and the end of it next the negative side of the battery will go westward.

If the distance of the uniting wire does not exceed three-quarters of an inch from the needle, the declination of the needle makes an angle of about 45°. If the distance is increased, the angle diminishes proportionally. The declination likewise varies with the power of the battery."

Oersted's publication excited the brightest scientists of the time to further their researches, and men like Arago and Ampère immediately set to work with enthusiasm to explore the phenomena, with the result that they soon produced a body of theory expressed in rigorous mathematics, which satisfied their instinct for precision, consistency, and predictive measurement.

Among those who partook of the excitement of the new discovery was the astronomer Dominique François Arago (1786-1853) who witnessed the verification of Oersted's experimental results at Geneva, and on returning to Paris, repeated Oersted's experiments and continued research in his own laboratory in the company with his friend, Ampère. Within a few months he could advise the scientific world that he had found it possible to magnetize iron by winding it in current-carrying wire.
2.5

Arago's Researches

In 1825 Arago was honoured by the award of the Royal Society's Copley medal for his work on the phenomenon of Magnetic Rotation, now known as "Arago's Disk". He had shown that it was possible for a rotating copper disk to deflect a magnetized needle supported above it—a action which Faraday was later to explain in terms of his theory of induction. In addition to these discoveries, Arago may have made his greatest contribution to the development of electrical science by inspiring Ampère to concentrate his keen mind and impetuous energy upon the investigation of electrodynamic problems.

2.6

Ampère's Research

Before the end of 1820 André Marie Ampère (1775-1836) was able to demonstrate that two parallel current-carrying wires in close proximity could attract or repulse each other, according to the direction of their currents: attracting when in the same direction, and repulsing when in opposite directions. Ampère, a wonderfully gifted mathematician who was deeply imbued with the traditions of Physics, was presented with what appeared to be a conflict with the Newtonian theory which only acknowledged central acting forces, and conflicted equally with the teaching of Coulomb that electricity and magnetism could not interact. His response was to interpret the phenomena in a way which denied the existence of one of these properties. According to Ampère, the magnetism exhibited by Oersted's experiments was but a particular aspect of the behavior of the "two fluid" electricity in motion, related to the "conflict" of positive-going fluid in one direction, and negative-going fluid in the other direction; and, he explained the qualities of the permanent magnet by assuming that the magnet possessed internal circuits of electrical currents.
Ampère was primarily a mathematical physicist, and his chosen model was one which would allow an analysis likely to produce equations for the transmission of the forces in which he was interested. When the resulting calculations satisfied him, he was not disposed to further investigate in exhaustive fashion any apparent inconsistencies or unsolved problems in the physical nature of the experimental situation - as Faraday consistently did.

Ampère's elaborate mathematical theory of electrodynamics was ultimately based on the principle that electric currents circulated around each molecule within metal substances. His theory was received with enthusiasm by the skilled mathematicians among the natural philosophers who admired its elegance, but it was regarded with some reservation, even skepticism, by those who were substantially empirical researchers - like Faraday - and some, believed there was scant evidence from the physical world to justify the complex theory.

2.7
The Discovery of the Solenoid

Ampère's seven-year study of electrical science was crowned by the discovery that a length of wire, when wound into a helix, produced a great multiplication of the magnetic effects, and that it developed pronounced North and South poles at its ends. This simple device, which he named a "solenoid", was to provide Joseph Henry and Faraday with an invaluable tool for their subsequent research and invention.

2.8
Ohm's Law

Studies to further the knowledge of electrical phenomena were pursued with vigour in Germany in the years immediately after Oersted's discovery. Notable among the successful workers was George Ohm (1787-1854) whose carefully organized experiments and very precise measurements
allowed him to frame the vitally important law named after him, to the effect that the current in a (d.c.) circuit is directly proportional to the electromotive force, and inversely proportional to the resistance of that circuit. That the scientific men of the world should fail to appreciate his 1827 law for some 20 years afterwards is one of the mysteries of history. His paper clarified the properties of current, electromotive force, and resistance, which were only half-understood by his contemporaries. It seems to be the case that the concepts - which modern schoolchildren learn early in their Physics classes - were then curiously strange and difficult to grasp, both in their theory and laboratory practice. As a result of the paucity of reference to Ohm's laws in the scientific journals, both Henry and Faraday in their formative years of electrical studies remained innocent of formulae which could have advanced their research, and might have modified the purely qualitative approach which they used.
The hunger for knowledge of electricity and magnetism was considerable among the amateur scientific societies of America, and it has been recorded that the person who was to be the most distinguished electrician of his country, Joseph Henry (1797-1878), was in youth stimulated to advance his study of the subject through participation in the meetings of the two local societies at Albany. Henry, in his history of self-education, and firm commitment to working men’s educational improvement groups, is closely comparable to Michael Faraday in his similar activities, some ten years earlier in Britain.

Henry possessed a number of other personal and professional characteristics which were similar to those of Faraday: like him he was of a naturally serious disposition, and was deeply influenced by a quiet and personal religious faith. Both were convinced that their systematic research could reveal a divine design in the organization of natural forces. Both were modest persons dedicated to the betterment of human life by scientific investigation, and both resisted the temptation to grow rich by commercializing their discoveries. Henry, too, was familiar with only a little of the mathematical knowledge of his time, and being a man who instinctively interpreted electrical phenomena according to the known behavior of mechanical things, sought no deep study of mathematics. Although accurate when working within his limitations - he did briefly serve as a surveyor - he never used anything other than simple arithmetic calculations in his experimentation and scientific papers.

In early youth, inspired by the chance reading of a popular introduction to contemporary science, Henry determined to gain an
an entrance to that profession. He then lived at Albany, a small
town in New Jersey, which lacked the educational facilities of
larger cities, but it was a place where there was a strong drive
towards self-improvement through education. Henry attended
several night-school classes and busied himself in the activities
of the local amateur scientific societies. His eagerness to learn
brought him into contact with one of the town's leading intellectuals,
Dr. Beck, who engaged him to assist with the chemical experiments
which he demonstrated before the interested townsfolk. By 1826,
Henry had so won the esteem of Dr. Beck, that he was appointed to
an academic post at Albany College. The title sounded grand:
"Professor of Mathematics and Natural Philosophy", but in truth
it was greatly misleading: Albany College was a small secondary
school with only four teachers, and the "mathematics" consisted
in the rudiments of arithmetic, and the "natural philosophy" was
in fact simple chemical experimentation.

From youth Henry was fascinated by electricity and magnetism,
however, his provincial location isolated him from contact with
the major developments which were taking place across the Atlantic,
and that disadvantage was a severe impediment in his years of
apprenticeship and his early professional work. He was, in effect,
a self-educated man of science, and a born experimenter who persis-
ted with his researches often in ignorance of what was being done
elsewhere along the same lines, and not infrequently learning of
the European progress from the scientific journals which reached
him belatedly. He began his work guided by the textbooks which
were already somewhat out of date, like those of Abbe Nollet and
Joseph Priestley. He knew also of the experiments which Benjamin
Franklin conducted at Philadelphia, and had the benefit of inheriting
the tendency of the American natural philosophers to accept Franklin's "Single Fluid" theory of electricity, which avoided the complications and the inconsistencies of C.F. Dufay's "Two Fluid" theory which outside America was generally held in approval.

In the same year that he received his teaching appointment, Henry learned of the wonderful invention of William Sturgeon (1783-1850), the iron-cored electromagnet. He examined a specimen at New York and immediately began experiments to modify it. He was so successful in his efforts that by October 1827 he was able to read a paper before the local science society, the Albany Institute, on his redesigned electromagnet, and to demonstrate that he had transformed it from an ingenious scientific curiosity to a practical machine with an immediate application in Industry. However, he did not publish his paper until 1831, for with Henry it was a habit to withhold the printed reports while he refined and perfected his experimental methods and the results obtained. This procrastination more than once resulted in other researchers being credited with prior discovery of phenomena which he had pioneered.

**Henry's Electromagnets**

What Henry had done was to bend a soft iron bar of \( \frac{1}{4} \) inch diameter into a horseshoe shape, then he had obtained thin copper wire (of the type which was run through conduits to operate bells in large domestic establishments) and insulated the wire with strips of silk cut from his wife's petticoat. The wire was then wound into 400 turns around the horseshoe. (That insulated wire replaced Sturgeon's few widely-spaced turns around a varnished iron core.) The wire was then attached to plates of copper and zinc suspended in troughs of saline solution or acid.
Henry's purpose, he wrote, was to "create the greatest lifting power with the least expense of galvanism". His electromagnet was the first multi-turn, multi-layer electromagnet, and was immensely more powerful than any magnet had ever been before. In summarizing his results, Henry displays that his approach is very much that of a qualitative investigator who does not examine relationships in a mathematical manner:

"The experiments conclusively proved that a great development of magnetism could be effected by a very small galvanic element, and also that the power of the coil was materially increased by multiplying the number of wires, without increasing the length of each. ... The effect appears to depend in some degree on the number of turns, which is much increased by using a number of small wires."

It is clear that Henry's research did not follow from abstract mathematical reasoning; it is much more likely that his experiments were the practical applications of visualized situations within a mechanical context. When the experiments were carried out he was quick to observe general relationships and essential connections, but he does not introduce comparative measurements of specific lengths of wire, nor correlate readings given by his "galvanometer" as an instinctive "Mathematic" would have done.

2.11

**Henry Discovers Impedence Matching**

Henry seems to have been the first person to have experimented with series and parallel circuits. He used both forms of wiring when connecting batteries, and in the windings of his electromagnets, and he recognized the different effects that these arrangements could provide. (The modern terms "series" and "parallel" had not then been coined, but Henry described his batteries connected in
series as the "intensity" arrangement, and those in parallel as the "quantity" arrangement. Those terms remained in use for the next thirty years.) In addition, Henry identified the need for matching impedences (though, in his case he was dealing with resistance in direct currents): he pointed out that to get the maximum power transferred it was necessary to connect a "quantity" battery to a "quantity-wound" electromagnet. Henry's discovery of the properties of series and parallel, and the desirability of impedance matching were major scientific achievements. It is the more wonderful when it is remembered that Henry had not even any regular units of measurement - certainly no electrical units for potential and current, and it is highly unlikely that he had any understanding of Ohm's laws, which were little known outside Europe (and originally presented in a mathematical form which Henry would not have comprehended.)

2.12

Henry's Electric Motor

The exact chronology of Henry's experiments and discoveries is difficult to establish, for unlike Faraday, he did not keep careful laboratory notebooks, and his published papers usually refer to work which was considerably in the past. In 1831 Henry published a description of the first electric motor. This anticipated by a few months what Faraday was doing at the British Institution - neither man knew of the other's activity at the time. Henry's electric motor used electromagnets with a reciprocal action and incorporated his invention of the Commutator,
which was to be an essential component in subsequent industrial
d.c. generators and motors. Like his improved electromagnet,
Henry's electric motor was quickly given a practical application
in industry. By 1834 Thomas Davenport of Brandon had built his
own version of Henry's reciprocating electro-magnetic motor, and
in the same year, Thomas Edmundson of Baltimore announced a modifi-
cation which allowed the machine to perform a rotary motion.
The great potential of the electric motor was appreciated and
a large number of engineers applied their skills to improving
its efficiency. The contemporary position is summed-up by J.P.
Joule, who wrote in 1839:

"The improved plan by Professor Henry of raising the
magnetic action of soft iron, has developed a new and
inexhaustible source of force which appears easily
and extensively available as a mechanical agent; and
it is to the ingenious American philosopher that we
are indebted for the first form of a working model of
an engine upon the principal of reciprocating polarity
of soft iron by an electro-dynamic agent." 12

Working in isolation in Albany, Henry did not learn of
Faraday's 1831 experiments and discovery of electromagnetic induct-
ion until 1832, and that information came to him not through the
advice of fellow scientists, but through the pages of the popular
journal, The Library of Useful Knowledge, (Issue No. 117). As he
had spent several years conducting tests with electromagnets, and
had observed inductive effects when two or more of his electro-
magnets were in close proximity, he was considerably upset to
learn that Faraday had preceded him in writing a report on this
phenomenon. He quickly prepared an article for publication in
America which would give an account of his own research along
parallel lines to Faraday's. It appeared in the July issue of
The American Journal of Science. 13
2.13

**Henry's Experiments with Induction**

In his article Henry describes the use of his extremely powerful electromagnet capable of lifting 600-700 lbs., and how he had carried out an experiment whereby, across the poles of this electromagnet was placed a soft iron armature wound round with thin varnished-copper wire, the ends of which were connected to a galvanometer. When the electromagnet was energized by contact with the terminals of the battery, the secondary circuit in the armature caused the galvanometer needle to deflect. He summarizes the experiment:

"The experiment illustrates most strikingly the reciprocating action of the principles of electricity and magnetism, if indeed it does not establish their absolute identity. In the first place, magnetism is developed in the soft iron of the galvanometer magnet by the action of currents of electricity from the battery; and, secondly, a separate bar of iron, rendered magnetic by contact with the poles of the magnet, induces in its turn currents of electricity in the helix which surrounds it. We have thus, as it were, electricity converted into magnetism and this magnetism again into electricity." 14

Henry had demonstrated mutual induction as Faraday had done, but he had used separate iron cores, not the single ring-core employed some months earlier in England, and he was primarily interested in electromagnetic effects brought about in two static coils, while Faraday had, in addition, investigated the inductive effects of the moving magnet. Henry and Faraday, without doubt, working in total ignorance of each other's research, had between them laid the foundations of electrical engineering.
At the end of the 1832 paper Henry wrote of another of his major discoveries, almost unwillingly because he had then not had the opportunity to exhaustively analyse the phenomenon: it was what he called "extra current", which modern terminology calls electromagnetic self-induction, a property which was to become of fundamental importance to future communications, power supply, radio transmission and reception, and innumerable other electrical engineering operations. Again, Henry's own words demonstrate that he offers only a qualitative description without further mathematical analysis of the interplay of the materials, the dimensions, the alternatives, and the effects:

"I have made several other experiments in relation to the same subject, but which more important duties will not permit me to verify in time for this paper. I may, however, mention one fact which I have not seen noticed in any work, and which appears to me to belong to the same class of phenomena as those before described; it is this: when a small battery is moderately excited by diluted acid, and its poles, which should be terminated by cups of mercury, are connected by a copper wire not more than a foot in length, no spark is perceived when the connection is either formed or broken; but if a wire of 30 or 40 feet long be used instead of the short wire, though no spark will be perceived when the connection is made, yet when it is broken by drawing one end of the wire from its cup of mercury, a vivid spark is produced.

... The effect appears somewhat increased by coiling the wire into a helix; it seems also to depend in some measure on the length and thickness of the wire. I can account for this phenomenon only by supposing the long wire to become charged with electricity, which by its reaction on itself projects a spark when the connection is broken."

In November 1832 Henry was invited to fill the Chair of Natural Philosophy at the College of New Jersey (later to become Princeton
University), and he accepted it. Despite heavy administrative duties, inventions and discoveries continued to come from his laboratory during the next few years. Among the most important of these was the 1835 electromagnetic relay. In that device a low powered electromagnet could be activated from a distance, and by attracting a second electromagnet, could complete the circuit of high power.

In the same year, 1835, Henry published the first account of that very important arrangement, the non-inductive winding. Once more, his description is non-mathematical:

(After describing strips of insulated copper, nearly an inch wide, and coiled into a spiral) ... "One of these ribbons was next doubled into two equal strands, and then rolled into a double spiral with the point of doubling at the centre. By this arrangement the electricity, in passing other spirals, would move in opposite directions in each contiguous spiral, and it was supposed that in this case the opposite actions which might be produced would neutralize each other. The result was in accordance with the anticipation; the double spiral gave no spark whatever, while the other ribbon coiled into a single spiral produced as before a long snap." 18

In 1836, during a sabbatical leave of absence, Henry travelled to the continent of Europe and to Britain, where he met and joined in experiments in the laboratories of William Sturgeon, Charles Wheatstone and Michael Faraday. At London Faraday invited him to lecture at the Royal Institution on "The Mathematical Aspect of his Work". The embarrassed Henry, who had nothing to offer on that subject, declined, saying that: "He had come to learn, not to instruct."

2.15

Experiments with Transformers

Henry's extremely important transformer studies were brought
before the American scientists in his paper read at the American Philosophical Society in 1838. This paper explained that by adjusting the number of turns on the primary and secondary coils, it was possible to step-up and step-down voltage. He summarized the results:

"It established the fact that an 'Intensity' current can induce one of 'Quantity', and, by the preceding experiment, the converse has also been shown, that a 'Quantity' current can induce one of 'Intensity'."  

He also reported on the findings of his investigation of the screening of coils, and recommended the avoidance of solid iron in the construction of transformers to cut down Eddy currents - he recommended bundles of wire for cores - and anticipated the modern laminations.

2.16 Experiments with Oscillators

Henry investigated the important electrical phenomenon of oscillation of currents, and related these to the discharge of Leiden Jars in another non-mathematical paper, read before the American Philosophical Society in 1842. Henry concludes:

"The discharge, whatever may be its nature, is not correctly represented (employing for simplicity the theory of Franklin) by the single transfer of an imponderable fluid from one side of the jar to the other; the phenomena require us to admit the existence of a principal discharge in one direction, and then several reflex actions backward and forward, each more feeble than the preceding, until the equilibrium is obtained."

It was William Thomson (later Lord Kelvin) who undertook the mathematical analysis and provided the formulae for calculating
oscillation, and showed that their periods, intensities, and damping were related to their capacity, self-inductance and resistance. 22

Henry was also an early pioneer in wireless telegraphy, and experimented with signals in the form of discharges from Leiden Jars passed through inductors, and received at a distance of many yards by other inductors attached to galvanometers. Moreover, Henry understood the basic nature of the electromagnetic waves he was employing, and in that he anticipated James Clark Maxwell's first studies by about 12 years. In a paper given in 1851 before the American Association for the Advancement of Science, he explained:

"... (they) are propagated wave-fashion. (these inductive effects)extend to a surprising distance; and, as they are the result of currents in alternating directions, they must produce in surrounding space a series of plus and minus motions, analogous to, if not identical, with the undulations." 23

Joseph Henry's activities as an electrical researcher virtually came to an end with his appointment, at the age of 49, as Secretary to the Smithsonian Institute at Washington. 24 Although the rest of his life was spent as an administrator, he can be credited with the fine accomplishment of having introduced Physics as a serious study to the American universities. Revered in his own country, Henry was not given adequate recognition abroad. 25 Appreciation of his pioneering work only came posthumously with the publication of his collected papers, issued as Scientific Writings of Joseph Henry, by the Smithsonian Institute, Washington, in 1886.
Michael Faraday

The person who carried out the most extended and comprehensive early 19th century researches on Electricity and Magnetism, and who must be credited with some of the most momentous discoveries of his time was Michael Faraday (1791-1867). He had the benefit of very little formal education. His brief schooling provided him only with what he himself described as "the rudiments of reading, writing and arithmetic" before the poverty of his family obliged him to be put to work when still a young child. However, it was his good fortune to become the messenger-boy to a bookseller/bookbinder who recognized his exceptional thirst for knowledge when he observed the boy avidly reading the books and journals which he carried; and who, in kindness gifted an apprenticeship without premium.

Because of his extreme modesty and reticence, we can learn little about his boyhood from Faraday himself, but the documents gathered by his principal biographers, and the considerable body of his personal notes, diaries, and letters to close friends supply a clear picture of his personal characteristics. Above all things, there is an insatiable desire to learn what was not already known of the physical nature of the world; this is the principal motive governing his dedication to a life of methodically planned research. In all his studies he was extraordinarily persevering, and in his practical experiments unusually patient and confident - within the restricting bounds of modesty - that properly organized investigation would unravel fundamental laws of nature.

One of the striking features of his personal notes, laboratory records, and communications with young contemporaries, is his pre-occupation
with mechanical effects, observed or anticipated, and the absence of mathematical involvement. In later periods of his life he did not alter this approach. His numerous scientific papers contain scarcely any reference to mathematical relationships - in place of those he gives vivid graphic descriptions of his experiments, findings, and speculations. Faraday's work built upon what was already discovered by predecessors such as Oersted, and Davy, and like them he believed that careful laboratory research might provide the key to a great universal principle which somehow governed and connected the vital forces represented by electricity magnetism, light, and gravity. However, Faraday had neither the training nor the inclination to attempt a unification of the great forces by means of mathematical theory. For him physical experiment was paramount. From Faraday's laboratory notebooks giving the record of the August 1831 "Experiments on the Production of Electricity from Magnetism", it is certain that while in almost every instance he was testing some theory which he had formed, there was no mathematical basis; instead, there was a graphic picture of what he expects to happen based on some mechanical action or analogy.

The popular notion of Faraday making chance, but vitally important electrical discoveries, during 30 days isolated research in 1831, is quite absurd and misleading. His interest and involvement in electrical studies dates back to his youthful experience as laboratory assistant to Sir Humphrey Davy, and his personal notes prove how conscientiously he applied himself and kept abreast of the current electrical knowledge of his time. During his "apprenticeship years" with Davy he was active in assisting in those novel and exciting
electrical experiments which the voltaic pile allowed - previously impossible when such activities were limited to the laboriously produced charge obtained from the electrophorus or the friction machines. Thus Faraday was one of the first persons in England to take part in experiments concerned with the magnetization of iron and steel by electrical currents.

During Faraday's time with Davy he was reading widely in all the scientific literature available, and, by his own account, conducting such personal experiment as his meagre funds allowed. His book-lists show that electrical studies took a prominent place in his self-education. He was therefore well-prepared to seize the opportunity for advancement when in 1821 he was asked to write a long article on electricity and magnetism for the Annals of Philosophy. It appeared under the title, "A Historical Sketch of Electricity and Magnetism".

2.18

**Electromagnetic Rotation**

As a conscientious practical worker he carried out almost all the experiments of Oersted, Arago and Ampère about which he wrote. As early as December 1821 Faraday had discovered the new phenomenon of Electro-magnetic Rotation. (Where he showed that a wire, into which he had made a crank shape, lightly suspended and connected to the terminals of a batter, would respond by moving towards or away from a magnet held nearby.) In this discovery he had succeeded where the more experienced researchers on the Continent, as well as Davy and Dr. Wollaston, had failed. Faraday had used an electric current to do mechanical work - in fact created the first primitive electric motor. Moreover he had taken one step towards his ambition of achieving a convertibility of natural forces.
Although Faraday had begun electrical research in the 1820's, it had to be in time stolen from intense laboratory investigations concerning the hardness of steel, the manufacture of optical glass, the diffusion of gases, and the decomposition products of oils (during the latter he had discovered Benzol). In his notebooks for 1824 and 1825 there are references to experiments to test for possible evidence of induction (using a magnet brought close to a current-carrying circuit in which was included a galvanometer). But he had to report that in this he was unsuccessful.\[^{28}\] The reason was that his galvanometer was not sufficiently sensitive. When he returned to this experiment ten years later, he had better equipment and identified the effect he had attempted to find.

During 1825 Faraday read Ampère's "Magnetic Theory of Electric Dynamic Phenomena," but he found that he could not cope with the mathematical presentation. His letter to Ampère of 17th November, 1825 survives. He wrote: "With regard to your theory, it so soon becomes mathematical that it quickly gets beyond my reach." Nevertheless, Faraday was to repeat Ampère's experiments and was to interpret the results in a manner very different from Ampère's mathematical analysis of the hypothetical molecular activities which the French scientist had made the basis of all electrical phenomena.

Extreme conscientiousness in all undertakings was another of Faraday's characteristics, and being truly committed to the primary function of the Royal Institute (which was to make scientific knowledge available to the uninformed public), he devoted a vast amount of energy and time to improving its floundering finances. It was largely the revenue from subscription to his popular lectures, and the fees paid by commercial organizations for his chemical analysis which secured the Royal Institute's stability. However, these labours diverted
concentrate his attention upon electrical problems. Thereafter, he was, at intervals, to continue studying the subject to the end of his career. The measure of his industry may be gathered from the fact that his laboratory notebooks contain the extraordinary number of 15,997 methodically recorded experiments.\(^{29}\)

In August 1831 Faraday began a series of electromagnetic experiments which established his reputation as one of the very greatest scientists of his age, and which were to be presented to the Royal Society under the generic title of *Experimental Researches in Electricity*. His first electrical experiments of 1831 are noted in his laboratory book at the 29th August as "Experiments on the production of electricity from magnetism, etc."

2.19

The Transformer, Magnetic Induction and the Generator

Faraday had a ring, 6 inches in external circumference, fabricated from \(\frac{7}{8}\)" thick soft iron, then he wound a primary coil on one side of the ring and attached it to a battery; a closed secondary coil was wound on the opposite side of the ring and was arranged to pass over a magnetized needle. At the make or break of the battery terminals he obtained an induced current which resulted in deflection of the needle. He had made what was, in effect, a battery-powered transformer. By the 24th September he had achieved the first induction of a current by the use of a moving permanent magnet, described in his own words: "Hence here distinct conversion of magnetism into electricity." By the 17th October he could obtain the same results by moving a bar magnet into the end of a helix of wire attached to his galvanometer, thereby showing that electromagnetic
induction could be obtained by the relative motion of a conductor in a magnetic field, or, as expressed by Faraday: "Therefore a wave of electricity was so produced from mere approximation of a magnet and not from its formation in situ." By the 28th October, he could triumphantly record: "Made a copper disk turn round between poles of the great horseshoe magnet of the Royal Society. The axis and edge of the disk were connected with a galvanometer. The needle moved as the disk turned." He had created the first electric generator.50

In these researches Faraday can be observed as an experimenter of quite exceptional imagination and resourcefulness, and viewed as a visual planner mechanically organizing his experiments and interpreting the effects in a manner foreign to the natural mathematician. The strength of the visual conception can be noted in his comments on the disk rotating between the poles of the electromagnet, where he wrote of the copper disk cutting "magnetic curves" (later to be called "lines of force"), and adds:

"By magnetic curves I mean lines of magnetic force which would be depicted by iron filings 31 surrounding a permanent magnet or an electromagnet."

Faraday's interest in this pictorial device, and his lifelong fascination with the theory of Lines of Force, are strong indications of his natural tendency towards "visual pictures" of scientific phenomena.

We may observe Faraday as the non-mathematical researcher even more closely in his second paper, "Magneto-electric Induction", summarizing his recent experiments reported to the Royal Society on the 12th January, 1832, when he said:
"These results tended to prove that the currents produced by magneto-electric induction in bodies is proportional to their conducting power. That they are exactly proportional to and altogether dependent upon the conducting power, is, I think proved by the perfect neutrality displayed when two metals or other substances, as acid, water, etc., are opposed to each other in their action: the feeble current which tends to be produced in the worse conductor, but has its transmission favoured in the better conductor, and the stronger current tends to form in the latter has its intensity diminished by the obstruction of the former; and the force of generation and obstruction are so perfectly balanced as to neutralize each other exactly. Now as obstruction is inversely as the conducting power, the tendency to generate a current must be directly as that power to produce this perfect equilibrium."

In this case, as in many others, Faraday offers a generalization rather than a precise mathematical expression, which would have presented a law in the form of a formula.

With the same phenomena before him, Ohm was able to offer a simple, but vitally important formula: $I = \frac{E}{R}$

Had Faraday drawn mathematical conclusion from his experiments, other researchers would have taken more notice, and he would almost certainly have advanced electrical science more quickly in its progress. Nevertheless, Faraday had introduced to the scientific world a range of new and wonderful discoveries, and the Royal Society honoured him with their Copley Medal in recognition of his achievement.

For the following two years Faraday was preoccupied with an investigation into the effects of electricity in the decomposition of different substances. The results of this research were incorporated into three papers which he read before the Royal Society. In that of January 9th 1834, he suggested the use of a number of new scientific terms which subsequently were adopted in electrical engineering and physics. They included: Electrode, Electrolyte, Electrolysis, Anode, and Cathode.
In the Autumn of 1834 Faraday returned with intense energy to the study of induction which he had initiated in his first two "Experimental Researches in Electricity." With apparatus designed and constructed to his own specifications, he explored inductive effects obtainable with single and double coils of different lengths and materials, made sensible by shock, sparks, and galvanometer deflection. A very instructive entry in his laboratory notebooks for 14th November, 1834 reads:

"Now I begin to see light. The phenomenon of increased spark is merely a case of the induction of electric currents. If a current be established in a wire, and another wire forming a complete circuit be placed parallel to it, at the moment the current in the first is stopped, it induces a current in the same direction in the second; it is then showing but a feeble spark. But if the second be away, it induces a current in itself on wire in the same direction, producing a stronger spark. The strong spark in the current when alone is therefore the equivalent of the current it can produce in a neighboring wire when in company."

A full account of the experiments and the results obtained and his interpretation of the phenomena observed, was given in his 9th series of 'Experimental Researches in Electricity,' entitled "On the Influence by Induction of an Electric Current on itself – and on the Inductive Action of Electric Currents Generally."
2.20

Self-Induction

The essence of the paper concerns a circuit diagram and the experiments he was able to carry out with that arrangement of components:

```
\[ \text{Diagram:} \]
```

In Faraday's words:

"'Z' and 'C' represent the Zinc and Copper plates of the electro-motor, (in modern terminology, 'Battery')) 'G' and 'E' the cups of Mercury where contact is made or broken; 'A' and 'B' the terminations of 'D', the long wire, the Helix or the electromagnet, used to complete the circuit; 'N' and 'P' are the cross wires, which can either be brought into contact at 'X', or else having a galvanometer or an electrolyzing apparatus interposed there.

... The most instructive set of results was obtained, however, when the galvanometer was introduced at 'X'. Using an electromagnet at 'D', and continuing contact, a current was then indicated by the deflection, proceeding from 'P' to 'N' in the direction of the arrow; the cross wire serving to carry one part of the electricity excited by the electro-motor, and that part of the arrangement marked 'ABD', the other and far greater part, as indicated by the arrows. The magnet needle was then forced back, by pins applied upon opposite sides of its two extremities, to its natural position when uninfluenced by a current; after which, contact being broken at 'G' or 'E', it was deflected strongly in the opposite direction; thus showing, in accordance with the chemical effects ((in an earlier experiment)) that the "Extra-current" followed a course in the cross wires contrary to that indicated by the arrow, i.e.: contrary to the one produced by the direct action of the electro-motor.

The case, therefore of the bright spark and the shock on Disjunction may now be stated thus: If a current be established in a wire and another wire forming a complete circuit, be placed parallel to the first, at the moment the current is stopped it induces a current in the same direction in the second, the first
exhibiting then but a feeble spark; but if the second wire be away, disjunction of the first wire induces a current on itself in the same direction, producing a strong spark. The strong spark in the single long wire or Helix, at the moment of disjunction, is therefore the equivalent of the current which would be produced in a neighbouring wire if such a second current were permitted."

2.21

**Specific Inductive Capacity**

Faraday's laboratory notebooks of 1836 and 1837 provide a wonderful insight into the thoroughness with which he investigated the nature of Capacitance and measured specific inductive capacities. There is no doubt that he had a particular faculty for picturing in his mind the types of apparatus which could advance his inquiries, and for designing suitable laboratory apparatus to carry out those experiments. By December 23rd 1836 he can describe the new research instrument which he has constructed: a pair of unequal concentric copper vessels, the smaller within the larger, isolated from each other, but with the facility for charging the inner sphere; air-tight, but fitted with a stop-cock which could be attached to an air-pump, and used to extract all the air, or to fill with gases or liquids, which in Faraday's words:

"The inductive apparatus described is evidently a Leiden Phial, with the advantage, however, of having the Dielectric or insulating medium changed at pleasure."

With this instrument, used in conjunction with a Coulomb Torsion Electrometer to measure electrostatic charges on the inner sphere, he carried out a large number of pioneering experiments which he summarized for the Royal Society in his 11th series...
of "Experimental Researches in Electricity", read on the 21st December, 1837.

In this paper, On Induction, Faraday offered a theory on the nature of electricity which was in direct conflict with that held by eminent electricians of his time, like Coulomb and Poission and Ampère, and, consequently almost all his audience. They believed that electricity was a fluid (or two fluids, one positive and the other negative) separate from matter; whereas Faraday's research had convinced him that they were wrong, and that all electrical effects were formed from and connected with matter itself.

2.22

**Capacitive Experiments**

Interpreting "Induction" in the widest sense - to effect some electrical phenomenon upon a body without physical connection - he builds his case based upon extensive experiments. Referring to his specially designed equipment he says:

"At present I believe ordinary induction in all cases to be an action of contiguous particles consisting of a species of polarity, instead of being an action of either particles or masses at sensible distances; and if this be true, the distinction and establishment of such a truth must be of the greatest consequence to our further progress in the investigation of the nature of electric forces.

Inductive effects are produced by electricity, not currents, but in its statical state, and this induction is exerted in lines of force which, although in many experiments they may be straight, are here curved more or less according to circumstances. I use the term "Lines of Inductive Force" merely as a temporary conventional mode of expressing the direction of the power in cases of induction; and in the experiments with the hemispheres, it is curious how, when certain lines have terminated on the under surface and edge of the metal, those which were before lateral to them expand and open out from each other, some bending round and terminating their action on the upper surface of the hemisphere, and others meeting, as it were, above in their progress outward, uniting their forces to give an increased charge to the carrier ball, at an increased
distance from the source of power and influencing each other so as to cause a second flexure in the contrary direction from the first one. All this appears to me to prove that the whole action is one of contiguous particles, related to each other, not merely in lines which they may be conceived to form through the dielectric, between the Inductive and the Inducteous surfaces, but in other lateral directions also. It is this which gives an effect equivalent to a lateral repulsion or expansion in the lines of force which I have spoken of, and enables induction to "turn a corner". The power, instead of being like that of gravity, which causes particles to act on each other through straight lines, whatever other particles may be between them, is more analogous to that of a series of magnet needles, or to the condition of the particles considered as forming the whole of a straight or curved magnet. So that whatever way I view it, and with great suspicion of the influence of favourite notions over myself, I can not perceive how ordinary theory applied to explain induction can be a correct representation of that great natural principle of electrical action."

Faraday then explains that he adopted the "Capacity for allowing or causing inductive action" of air as '1', and that by experiment he had found that Shell-lac measured '1.5'. He introduces the term "Specific Inductive Capacity", and gives other figures: Specific Inductive Capacity of flint glass is 1.38, and sulphur is 1.62; and that he had found that, in the case of gases, "All had the same power of, or capacity for, sustaining induction through them."

2.23

The Action of the Capacitor

Summarizing his observations (with respect to what we now call capacitors), Faraday says:

"The direct inductive force, which may be conceived to be exerted in lines between the two limiting and charged conducting surfaces, is accompanied by a lateral or transverse force equivalent to a Dilation or Repulsion of these representative lines; or, the attractive force which exists among particles of the Dielectric in the direction of the Induction is accompanied by a repulsive or diverging force in the transverse direction."

Faraday's friend and colleague, Dr. Tyndall commented on
his model: "Faraday visualizes with the utmost clearness the state of his contiguous particles; one after another they become charged, each succeeding particle depending for its charge upon its predecessor."  

Faraday the "Visualizer"

Faraday's exposition is very much that of a "Visualizer": he models in mechanical and physical terms, without the introduction of any mathematical expressions (other than simple ratios). His explanation of the nature of electricity is highly picturesque: it is a Strain, transmitted from particle to particle in close proximity, or when that is not possible, the result is a polar stress, recognized as Induction.

Faraday's theory was respectfully received, but not warmly welcomed by his contemporaries. Most of them could not sufficiently accommodate themselves to the challenge to prevailing electrical theory. Most felt ill at ease with Faraday's non-mathematical approach, and few of them were prepared to investigate further the nature of his Lines of Force. One of the exceptional persons was the young William Thomson (later Lord Kelvin), who did seriously consider the nature of Faraday's lines of force, and in an early piece of scientific writing, he demonstrated that the lines of force could be employed in the development of a mathematical theory of electrostatic action. However, a detailed application of Faraday's research results had to wait for the great work of James Clerk Maxwell.
William Thomson (1824-1907), later Lord Kelvin, is a fine example of a natural "Mathematic": from an early age he demonstrated an exceptional talent for arithmetic, geometry and algebra, and his eagerness to advance himself as rapidly as possible in his mathematical studies astonished even the academics among whom he lived. His father, Professor of Mathematics at Glasgow University, early recognized William's remarkable abilities and arranged for him to have every educational opportunity, allowing him to join the university classes at the age of ten. From that time he absorbed all the information which was available to the students of Natural Philosophy, Pure Mathematics, and Astronomy.

Although he won all the prizes which were open to him, he did not graduate at Glasgow university, because graduate status would have prejudiced his admission to Cambridge university, where his father had arranged for him to continue mathematical studies under those who were regarded as the most stimulating teachers of their time. The memories of his fellow students and teachers at Cambridge, and the evidence of his first mathematical essays, provide an unmistakably clear picture of a wonderfully talented person who loved mathematical involvement above all else, and who found an outlet for his creative energy in applying mathematical principles to the contemporary developments in Physics.

While in his final year at Cambridge his father was actively engaging support for his ambition to have his son appointed at Glasgow university in place of the aged professor of Natural Philosophy. When he learned that some of those who had the power
of election favoured the new-fangled Continental notion that a professor of Natural Philosophy should not only teach the mathematical theory of his subject, but should have some experience of practical laboratory work, he advised William to gain an entry into a Physics laboratory. That he was able to do in Paris, in the Spring of 1845, when he volunteered assistance to Professor Regnault, at the College De France. There he learned of the deep respect in which Michael Faraday was held, and that knowledge reinforced his already considerable interest in the electrical work done by Faraday - which had first been drawn to his attention some years before by one of his teachers at Glasgow university, David Thomson, who was a nephew of Michael Faraday. He immediately set about studying his Experimental Researches in Electricity. Contact with physical research was the catalyst which set William Thomson on his lifelong application of mathematics to electrical studies. Something of his sophisticated approach to the common phenomena of electricity may be gathered from an entry in his diary for 8th April, 1845:

"Today in the laboratory I got the idea, which gives the mechanical effect necessary to produce any given amount of free electricity, on a conducting or non-conducting body. If $M$ is any electrical element, $V$ the potential of the whole system upon it, the mechanical effect necessary to produce the distribution is $\mathbf{V} \cdot \mathbf{M}$. If the body be conducting this $\exp$ becomes $vM$. This enables us to find the attraction or repulsion of two influencing spheres without double integrals. Also the theorem of Gauss that $\mathbf{V} \cdot \mathbf{M}$ is a minim. when $v$ is const., shows how the double int which occurs when we wish to express the action directly, may be transferred into the diff. co. of a simple int taken with reference to the dist between two spheres. This has confirmed my resolution to commence experimental researches, if ever I make any, with an investigation of the absolute force of statical electricity. As yet each experimenter has only compared intensities between Dev of their electrometer. They must be measured by Pounds on the square inch, or by "Atmospheres". Also the standard must be the greatest intensity which can be retained by air of given density."
It was his enthusiasm for electrical studies which greatly impressed the French physicists and caused him to be invited to contribute an article on the subject to the 10th volume of the Journal De Mathematiques. Thomson wrote to his father that the purpose of the article would be, "To explain the phenomena of ordinary electricity observed by Faraday, and supposed to put objections fatal to the mathematical theory (of Coulomb)."

That article was expanded into a paper "On the Electric Laws of Statical Electricity", which was read before the British Association at Cambridge on June 23, 1845, when Faraday was present. The youthful Thomson, in awe of the revered Coulomb, suggested that he could not be in error, and proceeded to offer a solution to the problem of calculating the mutual attraction between two spherical conductors. He gives the law:

"The mechanical value of the distribution of electricity on a group of insulated conductors may be easily shown to be equal to half the sum of the products obtained by multiplying the potential within it."

He calculates the attractive forces for the case of two equal concentric spheres at four different distances and suggests that the difference between Faraday's results and the expectation from Coulomb's laws were due to the inadequacy of the measuring instruments. He also drew attention to the need for the establishment of a standard for "electrical intensity" which could be used by all engaged in experimental research.

2.26

Interpretation of Faraday's Theories

Following the talk, William Thomson was introduced to Faraday. It was the beginning of a fruitful exchange of correspondence, and visits. Shortly after their first meeting Thomson wrote to Faraday
that he was revising his British Association paper for publication in the Cambridge and Dublin Mathematical Journal, and said:

"A principal object is to show that in all ultimate results relative to the distribution, and to attraction or repulsion, it agrees identically with a complete theory based on your views. ... It was from the connection with mathematical theory of heat that I was first able to perceive the relation which lines of inductive action have to mathematical theories."

Under the inspiration of Faraday's writings, the younger scientist was to produce a series of important papers which gave mathematical form to Faraday's experimental results.

In 1846 William Thomson was appointed to the Chair of Natural Philosophy at Glasgow university at the age of 22. Even at that very moment, when pressed by the responsibilities of his new undertaking and planning a physical laboratory for himself and his students, his mind was filled with the potential application of mathematics to problems in Physics. He wrote in his diary for 31st October, 1846:

"I have this evening (in the middle of my work finishing an introductory lecture) after thinking on Faraday's discovery of the effects of magnetism on transparent bodies and polarized light, been recurring to my idea (which occurred to me in the May term) which I had to give up, about magnetism and electricity being capable of representation by the straining of an elastic solid constituted in a peculiar way. I THINK the following must be true:

If particles along a closed curve of any form be displaced equal small distance along the curve, the displacement produced, at any pt. of the medium, can be represented in some way by means of the diff.coeffs of the solid angle whose vertex is the pt. and base the closed curve. This solid L is the potential due to the action of a volt current, circulating in the closed curve, as is known.

Then a bar magnet would be represented by an axis turned round in the elastic solid so as to drag points of the solid round
along with it, etc. ... I am not at all sure of anything I have written just now, but want to get it out of my head, as I have no time to spare during the session."

In 1849, in his paper read before the Royal Society, Thomson once more applies his mathematical insights to the interpretation of Faraday's discoveries of the previous four years; the interaction of magnetism and polarized light, and the properties of diamagnetic repulsion observed in Bismuth (and lead, tin, copper, and some 50 other substances investigated by Faraday.) His purpose was to offer in rigorous mathematical form a theory of magnetism "freed from unnecessary hypothetical assumptions" - that is, to dismiss the outmoded "One/Two Fluid" theories to which many contemporaries still gave their allegiance. In an extension to the paper he dealt with the concept of magnetic inductive capacity in the material, an important scientific innovation.

Thomson's papers not only won for him great respect for his mathematical genius, but they redirected the serious attention of contemporary scientists back to Faraday's fundamental research reports. Those who were accustomed to associate physical phenomena with mathematical expressions found a new sympathy with Faraday's studies when interpreted according to Thomson's clever ideas. Moreover, Thomson smoothed the way for further confirmatory experiments by urging the adoption of "absolute units" in the investigation of electromotive forces (already introduced on the Continent by Wilhelm Weber). Thomson recommended the use of the British measures, the Foot, Grain, and Second for the fundamental units of length, mass, and time.

The rapidity of Thomson's development as a mathematical analyst of the puzzling electrical phenomena of his time is evidenced by
the brilliant insights which he offered in his paper "On Transient Electric Currents" of 1853. By mathematical calculation, Thomson had discovered that there is a critical relationship in a capacitive circuit involving a Leiden Jar where capacity in the circuit was equal to four times the coefficient of self-induction divided by the square of the resistance. If the capacity was less than this, the discharge was an oscillating one; if the capacity was greater than this, the discharge was non-oscillating. Thomson suggested that by using a large self-inductance and small resistance, it would be possible to produce large oscillatory discharges. This was the paper which laid the foundations of the theory subsequently studied and developed by Hertz and Lodge, and ultimately, was to contribute to wireless telegraphy.
James Clerk Maxwell

Of all the intellectuals who admired Faraday's writing on electromagnetic theory, none was more deeply impressed than James Clerk Maxwell (1831-1879), and it was he, above all others, who brought numerical precision and mathematical development to Faraday's experimental results.

Information which has been preserved in the contemporary biography of his friend, Lewis Campbell, describes a natural aptitude for scientific inquiry and a supreme curiosity about the qualities and functions of all things in his environment. From boyhood he demonstrated an analytic disposition governed by an orderly mind, a passion for all that was mathematical and a desire to use his calculating powers to further his knowledge of physics. He enjoyed a number of privileges which contributed to his rapid scientific advancement: in particular, his father was a keen amateur natural philosopher with good contacts among the Edinburgh scientific circles; and, recognizing his son's talents, he missed no opportunity of introducing him to practicing scientists who could judge for themselves the boy's great potential and offer assistance and advice in guiding his education. Among those with whom he had a family friendship was William Thomson, who gave both help and encouragement in his scientific studies.

Maxwell the "Mathematic"

Maxwell is a person who, to some extent, partakes of both the "Visualizer" and the "Mathematic" characteristics - but there can be no doubt that his instincts and strongest tendencies were
towards the "Mathematic." At first sight it does not appear so: from adolescence he was frequently engaged in physical model-making, and his earliest scientific paper, written at the age of 15, was a novel mechanical method of drawing oval curves. His later adolescence was a time when he was much pre-occupied with experiments on light and colour and was engaged in the use of various models and home-constructed pieces of apparatus; later still, there were physical models relating to heat distribution; and ultimately there was the mechanical model for his 1861/2 paper "On the Physical Lines of Force", which demonstrated the principles of his theory of electromagnetism.

While he had a penchant for diagrams, geometric figures and mechanical models, those were rarely the sophisticated results of a visual designer, and it is clear from comments in his important electromagnetic papers of 1861/2 and 1864, that he himself did not hold them in high esteem. The value seems to have been in the initial stimulating effect they brought to bear on his mathematical processes, and the aid they provided in explaining his complex ideas to others; moreover, the records of his conversations, his notes, and personal letters, throw strongly into relief the fact that his fundamental method was intensely mathematical, and he rapidly withdrew himself from the initial starting-point of those models.

As William Thomson had done nine years before him, James Clerk Maxwell read a university course in Scotland, then without graduating, moved to Cambridge university where he studied for another degree in Mathematics; and, like Thomson, he distinguished himself by excellence, and was groomed for immediate advancement.
Soon after gaining his B.A. at Cambridge, Maxwell inquired of William Thomson what advice he could offer "several of us here who wish to attack electricity." What should they read, and in what order? Thomson must have recommended Faraday’s Experimental Researches in Electricity, for shortly afterwards Maxwell wrote to his father that he was deeply immersed in that work. We know from Maxwell’s introduction to his Treatise that he became so enthralled that he "resolved to read no mathematics on the subject until he had read Faraday." 44

2.29

Maxwell Studies Faraday

While it may seem curious to some that such a highly mathematical mind should be drawn to the non-mathematical writings of Faraday, Maxwell makes it perfectly clear that he understood and sympathized with a method so remote from his own, and even typifies Faraday as an experimenter who did his best work by avoiding the methods of the mathematician. Much later in life, when he was able to crystallize the results of his research into a treatise for students, Maxwell wrote: 45

"The method which Faraday employed in his researches consisted in a constant appeal to experiment as a means of testing the truth of his ideas, and a constant cultivation of ideas under the direct influence of experiment. In his published researches we find these ideas expressed in language which is all the better fitted for a nascent science, because it is somewhat alien from the style of physicists who have been accustomed to establish mathematical forms of thought"

and a few pages later, he continues:

"It was perhaps for the advantage of science that Faraday,
though thoroughly conscious of the fundamental forms of space, time, and force, was not a professed mathematician. He was not tempted to enter into the many interesting researches in pure mathematics which his discoveries would have suggested if they had been exhibited in mathematical form, and he did not feel called upon either to force his results into a shape acceptable to the mathematical taste of the time, or to express them in a form which mathematicians might attack. He was thus left at leisure to do his proper work to coordinate his ideas with his facts, and to express them in natural, untechnical language."

2.30

Maxwell Develops Faraday's Ideas Mathematically

Accepting an aether theory (as did so many of his contemporaries) and the laws of Newton, Maxwell set himself the task of developing Faraday's ideas into a complete theory of electromagnetism, expressed in mathematical terms. This he did in the course of writing three important papers, and the subsequent publication of his Treatise on Electricity and Magnetism in 1873. For the purpose of expanding Faraday's ideas Maxwell employed various analogies between different branches of Physics, following the example of William Thomson, who had compared electrical phenomena with those of heat. In his speculations about the physical nature of electricity, Maxwell was daring and highly individual in applying mathematical procedures to extend the hypotheses as far as calculation would allow. As he explained in the opening section of his 1855 paper which he read before the Cambridge Philosophical Society there were no comprehensive electrical theories available, and the
literature which existed was unsatisfactory. What was required, he wrote was

"A simplification and reduction of the results of previous investigations to a form in which the mind can grasp them. The result of this simplification may take the form of a purely mathematical formula or of a physical hypothesis. In the first case we entirely lose sight of the phenomena to be explained; and though we may trace out the connections of given laws, we can never obtain more extended views of the connections of the subject. If, on the other hand, we adopt a physical hypothesis, we see the phenomena only through a medium, and are liable to that blindness to facts and rashness in assumption which partial explanation encourages."

What was needed, he believed was a comprehensive theory applicable to the whole range of electrical interests of his time: electrostatic studies, electromagnetism, permanent magnets, magnetism of induction, and the study of varying currents.

As a young mathematician writing for the attention of other mathematicians and scientists, Maxwell, about to introduce a rather extreme physical analogy, felt that he should justify his method and wrote:

"In order to obtain physical ideas without adopting a physical theory we must make ourselves familiar with the existence of physical analogies. By a physical analogy I mean that partial similarity between the laws of one science and those of another which makes each of them illustrate the other. Thus all the mathematical sciences are founded on relations between physical laws and laws of numbers, so that the aim of exact science is to reduce the problems of nature to the determination of quantities by operations with numbers. 47

In this paper, by means of analogy Maxwell analysed Mathematically
two matters which were particularly important in Faraday's writings: the distribution of lines of force, and the hypothetical strain between electrical components which he called the "Electrotomic State".

In connection with the lines of force, Maxwell wished to advance beyond the descriptive picture of a pattern of lines surrounding a magnet or current-carrying wire, because that can only provide "the direction of the force, but we should still require some method of indicating the intensity of the force at any point." Maxwell's alternative method was to "consider these curves not as mere lines, but as fine tubes of variable section carrying incompressible fluid." Then, knowing the direction and magnitude of the velocity of the imaginary fluid it would be possible to calculate the direction and magnitude of the force at any point within the field.

Maxwell is careful to insist that his model is remote from practical observation:

"It is not even a hypothetical fluid introduced to explain the phenomena. It is merely a collection of imaginary properties which may be employed for establishing certain theorems in pure mathematics in a way more intelligible to many minds and more applicable to physical problems than that in which algebraic symbols alone are used."

Maxwell tells us that the imponderable fluid, which possesses no inertia, flows in uniform motion through a resisting medium, and that the resistance is proportional to the fluid's velocity, and explains that the velocity of the imaginary fluid due to a source "S" at a distance r varies inversely as $r^2$. Maxwell's own words summarize the essentials of the paper better than any of the commentators:
Let us see what will be the effect of substituting such a source for every particle of positive electricity. The velocity due to each source will be proportional to the attraction due to the corresponding particle, and the resultant velocity due to all the sources would be proportional to the resultant attractions of all the particles. Now we may find the resultant pressure at any point by adding the pressures due to the given sources, and therefore we may find the resultant velocity in a given direction from the rate of decrease of pressure in that direction, and this will be proportional to the resultant attraction of the particles resolved in that direction.

Since the resultant attraction in the electrical problem is proportional to the decrease of pressure in the imaginary problem, and since we may select any values for the constants in the imaginary problem, we may assume that the resultant attraction in any direction is numerically equal to the decrease of pressure in that direction, OR

\[ X = -\frac{dp}{dx} \]

by this assumption we find that if \( V \) be the potential

\[ dV = Xdx + Ydy + Zdz = -dp \]

OR, since at an infinite distance \( V=0 \) and \( p=0 \), \( V = -p \) in the electrical problem we have

\[
v = -\frac{\sum_{r} dm}{r}
\]

in the fluid

\[
p = \sum_{r} \left( \frac{k}{4\pi \gamma r} \right)
\]

therefore, \( S = \frac{4\pi \gamma}{k} dm \)

If \( k \) be supposed very great, the amount of fluid produced by each source in order to keep up the pressure will be very small.

The potential of any system of electricity on itself will be

\[
\sum (pdm) = \frac{k}{4\pi \gamma}, \quad \sum (pS) = \frac{k}{4\pi \gamma} \, W
\]
If \( \sum (pdm) \), \( \sum (p'dm') \) be two systems of electrical particles, and \( p, p' \) be the potentials due to them respectively, then by equation No. 32 (given earlier in the paper)

\[
\sum (pdm') = \frac{k}{4\pi} \sum (p'S') = \frac{k}{4\pi} \sum (p'S) = \sum (p'dm)
\]

or the potential of the first system on the second is equal to that of the second system on the first.

So that in the ordinary electrical problems the analogy in fluid motion is of this kind:

\[
V = -p, \quad X = \frac{dp}{dx} = kv, \quad \text{and} \quad \text{dm} = \frac{k}{4\pi} S,
\]

whole potential of a system = \(-\sum V \text{dm} = \frac{k}{4\pi} W\),

where \( W \) is the work done by the fluid in overcoming resistance.

The lines of force are the unit tubes of fluid motion, and they may be estimated numerically by those tubes.

In the second part of the paper Maxwell examines the Electrotonic State, continues with some commentary, then he gives the equations he has derived and provides some calculated examples. In his section, "Summary of the Theory of the Electrotonic State" he writes:

"We may conceive of the electrotonic state at any point of space as a quantity determinate in magnitude and direction, and we may represent the electrotonic condition of a portion of space by any mechanical system which has at every point some quantity, which may be
a velocity, a displacement, or a force, whose direction and magnitude correspond to those of the supposed electrotonic state. This representation involves no physical theory, it is only a kind of artificial notation. In analytical investigations we made use of the three components of the electrotonic state, and call them electrotonic functions. We take the resolved portion of the electrotonic intensity at every point of a closed curve, and find by integration what we may call the entire electrotonic intensity round the curve.

As an example, Maxwell takes a "sphere of diamagnetic or paramagnetic matter introduced into an electric coil" and continues:

"Let us find the electrotonic functions due to this electromagnet. It will be in the form

\[
\begin{align*}
\lambda_0 &= \lambda, \\
\beta_0 &= \omega z, \\
\gamma_0 &= -\omega y
\end{align*}
\]

where \( \omega \) is some function of \( r \). Where there is no electric currents, we must have \( a_2, b_2, c_2 \) each \( = 0 \), and this implies

\[
\frac{d}{dr} \left( 3\omega + r \frac{d\omega}{dr} \right) = 0
\]

the solution of which is

\[
\omega = C_1 + \frac{C_2}{r^2}
\]

Maxwell sent off-prints of his 1855/6 papers read before the Cambridge Philosophical society to Michael Faraday, and received the encouraging reply:

"I received your paper and thank you very much for it. I do not say I venture to thank you for what you have said about lines of force, because I know you have done it for the interests of philosophical truth; but you
must suppose it is a work grateful to me, and gives me much encouragement to think on. I was at first almost frightened when I saw such mathematical force brought to bear upon the subject, and then wondered to see that the subject could stand it so well. I send by this post another paper to you; I wonder what you will say to it. I hope, however, that bold as the thoughts may be, you may perhaps find reason to bear with them. I hope this summer to make some more experiments on the time of magnetic action, or rather on the time required for the assumption of the electrotonic state, round a wire carrying a current, that may help the subject on. The time must probably be as the time of light; but the greatness of the result, if affirmative, makes me not despair."

Faraday then sent to Maxwell information about his current investigations, and an exchange of letters and research papers between the two scientists was established.

The enormous difference between the natural mental inclinations of the two great scientists is exposed in a passage in a letter from Faraday to Maxwell of 13th November, 1857:

"... There is one thing I would be glad to ask you. When a mathematician engaged in investigation of physical actions and results has arrived at his conclusions, may they not be expressed in common language as fully, clearly, and definitely as in mathematical formulae? If so, would it not be a great boon to such as I to express them so? - Translating them out of their hieroglyphics, that we also might work upon them by experiment. I think it must be so, because I have always found that you could convey to me a perfectly clear idea of your conclusions, which though they may give me no full understanding of the steps of your processes, give me the results neither above nor below the truth, and so clear in character that I can think and work from them. If this be possible, would it not be a good thing if mathematicians, working on these subjects, were to give us the results in this popular, useful stage, as well as in that which is their own and proper to them?"

Notwithstanding the gulf which separated them in their approaches to the subject of electromagnetism, Maxwell held
Faraday's pioneering research in the greatest respect and appreciated its practical value. He wrote to a friend in 1858:

"My students ... about 1/4 in number, form a voluntary class and continue their studies. ... We have taken magnetism, and electricity, static and current, and now are at electromagnetism and Ampere's laws. I intend to make Faraday's book the backbone of all the rest, as he himself is the nucleus of everything electrical since 1830."

Some very interesting and illustrative comments having reference to Maxwell's exceedingly important papers of 1861/2 are afforded by the letter Maxwell wrote to Faraday on 19th October, 1861:

"I have lately been studying the theory of static electric induction, and have endeavoured to form a mechanical concept of the part played by the particles of air, glass, or other dielectric in the electric field, the final result of which is the attraction and repulsion of 'charged' bodies.

The conception I have hit on has led, when worked out mathematically, to some very interesting results, capable of testing my theory, and exhibiting numerical relations between optical, electric, and electromagnetic phenomena, which I hope soon to verify more completely. When I began to study electricity mathematically, I avoided all the old traditions about force acting at a distance, and after reading your papers as a first step to right thinking, I read the others, interpreting as I went on, but never allowing myself to explain anything by these forces. It is because I put off reading about electricity until I could do it without prejudice that I think I have been able to get hold of some of your ideas, such as the electrotonic state, action of contiguous parts etc., and my chief object in writing to you is to ascertain if I have got the same ideas which led you to see your way to do things, or whether I have no right to call my notions by your names."

The period 1860-65, when Maxwell was Professor of Natural Philosophy and Astronomy at Kings College, London, was distinguished by the production of his most important papers. In addition to his 1860
paper "On the Theory of Colours" given before the Royal Society - which won for him the Rumford Medal - it was also the time when he was experimenting with the measurement of the capacity of capacitors and the nature of their discharges, and the characteristics of dielectrics. That work was to be of the greatest value to him when he edited and annotated the research notes of Henry Cavendish, published in 1879. These were the years when he wrote his very important papers, "On the Physical Lines of Force" (1861/2) and "On the Dynamical Theory of the Electromagnetic Field." (1864)

Maxwell realized that the scientific world needed a unified theory of electric and magnetic behavior such that it would be possible to predict electromagnetic action in space and time under particular conditions. It was to be his great achievement that he produced such a theory. His mathematical exposition is complex, nevertheless he could summarize in a set of equations the numerous patterns of electromagnetic behavior essentially in terms of the electric field $E$ and the magnetic field $H$. His theory provided the mathematical basis for the concept of fields, which was to exert such a powerful influence on so many branches of Physics.

When writing "On the Physical Lines of Force" Maxwell wished to accommodate the time occupied by electromagnetic induction as Faraday's contiguous particles acted upon each other. He found that these particles in the aether possessed both elasticity and mass, and he incorporated these characteristics in a mechanical model. But his natural and instinctive approach was that of the "Mathematic" and his chosen model is most inelegant and open to critical comment and truly an unsatisfactory introduction to a subtle theory.
Dr. K.I.L MacDonald has written:

"What is often important when dealing with forces (or for that matter any other problem in science) is to have some adequate "picture" or way of thinking visually about the behavior, to help one in predicting how those forces will act in a given situation. Today this picture usually becomes more valuable the closer one is involved with experimental work, but sometimes the modern theorist is critical of trying to visualize how forces act in nature, and he may say that if we can express the behavior mathematically that is the best (and all) that we can do."

The model which Maxwell offers is a contrivance so curious as to be grotesque and of such an impractical nature as to make any engineer wince.

Mechanical Model of the Electromagnetic Field

from Maxwell's "Treatise on Electricity and Magnetism

Pierre Duhem has observed: "We thought we were entering the tranquil and neatly ordered abode of reason, but we find ourselves in a factory."

Perhaps Maxwell considered that his model would serve as a substantial aid towards the understanding of the non-professional mathematicians, but for him it must have been lightly valued as a transitory step towards the mathematical expressions.
Faraday had suggested that there must be a tension along the lines of force in diamagnetic media, now Maxwell constructed a mechanical model which incorporated these elements, and introduced a type of "ball-bearing" between the vortices, to suggest current, arranged in such a way that it is possible for contiguous surfaces of particles and vortices to have the same motion. In Maxwell's words:

"When the electrical particles move out of place, they constitute an electric current. The particles move from one vortex to the next while current is flowing. In making the transition, they may jump around and cause an energy loss which appears as heat, but while they are rotating in place there is supposed to be no slippage between the particles and the vortices, and no loss of energy. Thus it remains possible to maintain a magnetic field indefinitely."

Another characteristic of his model is that in a dielectric the electrical particles can not move, therefore there is no current. The total displacement ($D$) is directly proportional to the force acting on the balls. The constant of proportionality is analogous to the specific inductive capacity ($\xi$) of the medium ($D = \xi E$). The energy of the electric field is equal to the work done in distorting the particles, so is the force exerted by the vortices multiplied by the distance the material is displaced (which is proportional to $ED + \xi E^2$).

When an external force is exerted upon particles, they distort so that they press against each other and the contiguous vortice. The force of one ball upon another is supposed to represent electrical force due to charge.

In truth, the attempt at maintaining similarities with the crude mechanical model must be a severe constraint on Maxwell. In obtaining his equations he follows the development of three basic assumptions: that the vortices provide purely magnetic effects;
that the electrical balls provide relations between current and magnetism, and latent elasticity of the electrical balls accounts for the electrostatic effects.

By equation Maxwell was able to show that wave motion (in the form of changing magnetic and electric fields) could propagate itself freely in space without damping, the waves radiating out from their starting point. He was able to predict the speed of electromagnetic waves travelling in space, which was found to be practically the same as the speed of light. As the rays of the sun can propagate through empty space to reach the earth, so Maxwell could identify light as a form of electromagnetic radiation.

In his 1864 paper, "A Dynamical Theory of the Electromagnetic Field", Maxwell expanded upon the theory given in the earlier papers, and divorced himself from the restrictions of his mechanical model. He characterized new properties belonging to electromagnetic waves, such as the fact that they are all transverse (rather than longitudinal) and he was able to calculate the energy of the electric and magnetic components of the electromagnetic wave.

Further, he could account for the behavior of polarized light in crystals, which corresponded with the prevailing theories of light.

In the introduction to "A Dynamical Theory of the Magnetic field", he says:

"The most obvious mechanical phenomenon in electrical and magnetic experiments is the mutual action by which bodies in certain states set each other in motion while still at a sensible distance from each other. The first step, therefore, in reducing these phenomena into scientific form, is to ascertain the magnitude and direction of the force acting between the bodies, and when it was found that this force depends in a certain way upon the relative position of the bodies and on their electric or magnetic condition, it seems at first sight natural to explain the facts by assuming the existence of something either at rest or in motion in each body, constituting its electrical or magnetic state, and capable of acting at a distance according to mathematical laws."
The theory I propose may be called a theory of the Electromagnetic Field, because it has to do with space in the neighbourhood of the electric or magnetic bodies, and it may be called a Dynamical theory because it assumes that in that space there is a matter in motion, by which the observed electromagnetic phenomena are produced."

Maxwell introduces twenty equations, involving twenty variable quantities. Thereafter, he expresses in terms of these quantities:

"The intrinsic energy of the electromagnetic field has dependence partly on its magnetic and partly on its electric polarization at every point. From this I determine the mechanical effect acting, first on a moveable conductor carrying an electric current; secondly, on a magnetic pole; thirdly on an electrified body. The last result, namely the mechanical effect acting on an electrified body, gives rise to an independent method of electrical measurement founded on its electrostatic effects."

Next he shows how to calculate the electrostatic capacity of a capacitor, and the specific inductive capacity of a dialectric.

Maxwell applies the general equations to the case of a magnetic disturbance propagated through a non-conducting field, and shows that the only disturbances which can so propagate are those which are transverse in the direction of propagation, and that the velocity of propagation is the velocity "v", found from experiments, such as those of Weber, which expresses the number of electrostatic units of electricity which are contained in one electromagnetic unit.

Maxwell is very emphatic with regard to his references to energy - at the end of Part Three of the paper, he writes:

"In speaking of the energy of the field, however, I wish to be understood literally. All energy is the same as mechanical energy, whether it exists in the form of motion or in that of elasticity, or in any other form. The energy in the electromagnetic phenomena is mechanical energy. The only question is, where does it reside? On the old authorities it resides in the electrified bodies, conducting circuits, and magnets, in the form of an unknown quantity called potential energy, or
the power of producing certain effects at a distance. On our theory it resides in the electromagnetic field, in the space surrounding the electrified and magnetic bodies, which may be described without hypothesis as magnetic polarization and electric polarization, or, according to a very probable hypothesis, as the motion and strain of one and the same medium."

Later Maxwell investigates "the properties of the electromagnetic field, deduced from electromagnetic phenomena alone, which are sufficient to explain the propagation of light through the same substance." He concludes that the "agreement of the results seems to show that light and magnetism are affectations of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws."

The theory which Maxwell developed in his three major papers on electromagnetism were further refined and expanded in his great textbook, "A Treatise on Electricity and Magnetism," published in 1873. It was primarily from this textbook that the scientific world learned to respect the equations which became universally known as "Maxwell's Equations." Unfortunately, James Clerk Maxwell died at the age of 48 in 1879, and did not live to see the confirmation of his prediction relating to artificially induced electromagnetic radiations. In 1887 Heinrich Hertz carried out experiments with a high-voltage spark discharge via a pair of plates, and was able to receive the electromagnetic radiations by means of a metal detector ring.
SUMMARY

Thus we can observe the slow and uncertain progress of electrical studies during the 18th century as amateur Natural Philosophers pursue their own personal interests, and a few academics seek new knowledge which might link together natural forces. With Volta's discovery of electrical charges associated with dissimilar metals in contact, and his invention of the "Electric Pile", the way was prepared for an acceleration of inventive activity, when outstanding scientific brains struggled to analyse complex phenomena in ill-equipped laboratories.

Oersted's experiments identified the interaction of electricity and magnetism, and his 1820 announcement to the European men of science, set them to examine the properties of the magnetic field which surrounds the current-carrying wire. Soon mathematical physicists like Ampère and Ohm applied numerical logic to the observed behavior and provided equations and formulae to relate voltage, current, and resistance, to guide the next generation of researchers.

In America, Henry first working in ignorance of the contemporary research of Faraday, experiments in the late 1820's with a primitive electric motor, develops the iron-cored electromagnet, and identifies the functions of series and parallel circuits. He then lays the foundation for transformer studies, investigates self-inductance and the phenomenon of current oscillation and pioneers electrical télégraphy. Like Faraday, Henry is a "Visualizer" who conducts and interprets his experiments in a non-mathematical manner.
Faraday's electrical studies correspond in many respects with those of Henry, but are more extended in time and variety; building upon knowledge of his predecessors, he continuously explores the properties of electromagnetic phenomena from 1831, as recorded in his *Experimental Researches in Electricity*. He makes major contributions in the study of the transformer, the generator, and the behavior of the solenoid. Applying his theories on Lines of Force he explores the phenomena of capacitance and inductance. His theories attract the attention of great mathematicians, the first of which was William Thomson (Lord Kelvin) who was inspired to incorporate them in his first mathematical theory of electromagnetic action (1846), and subsequently returned to them in 1853 when offering the first mathematical expressions governing the oscillation of current in coils.

Faraday's Lines of Force were also used as a starting point by Maxwell, who brought numerical exactness to Faraday's graphic analogies associated with the properties of capacitance and inductance. Maxwell, the outstanding "Mathematic", progresses in his papers of 1855/6 and 1861/2 and 1864 towards a unified theory of electrical and magnetic phenomena; but the fullest expression of it is given in his *Treatise on Electricity and Magnetism* (1873), where with his set of equations, he is able to summarise electromagnetic behavior in terms of the electric field \( E \) and the magnetic field \( H \), and provide the mathematical basis for the concept of fields.

In the course of three generations of study, electricity and magnetism had advanced from an amateur preoccupation to a sophisticated scientific discipline. A number of the earlier
pioneers had been "Visualizers" and non-mathematical in their approach, but from the middle of the 19th century the leading electrical figures were fluent mathematicians whose complex theories could not have been developed without abstract analysis of the quantities of the physical world. These pioneers, by their writing, made it possible for a great many others with varying degrees of interest, both "Visualizers" and "Mathematics", to learn of the new science.
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>The Early Electrical Textbooks</td>
<td>78</td>
</tr>
<tr>
<td>3.2</td>
<td>Maxwell's Treatise on Electricity and Magnetism</td>
<td>85</td>
</tr>
<tr>
<td>3.3</td>
<td>Maxwell's Elementary Treatise on Electricity</td>
<td>90</td>
</tr>
<tr>
<td>3.4</td>
<td>S.P. Thompson's Elementary Lessons in Electricity and Magnetism</td>
<td>95</td>
</tr>
<tr>
<td>3.5</td>
<td>J.A. Fleming's Short Lectures to Electrical Artisans</td>
<td>102</td>
</tr>
<tr>
<td>3.6</td>
<td>Professor Jamieson's Elementary Manual of Electricity and Magnetism</td>
<td>106</td>
</tr>
<tr>
<td>3.7</td>
<td>Professor Jamieson's Practical Elementary Manual of Magnetism and Electricity</td>
<td>107</td>
</tr>
<tr>
<td>3.8</td>
<td>Philip Atkinson's Elements of Dynamic Electricity and Magnetism</td>
<td>109</td>
</tr>
<tr>
<td>3.9</td>
<td>Popular Expositions</td>
<td>111</td>
</tr>
<tr>
<td>3.10</td>
<td>Oliver Lodge's The Modern Views of Electricity</td>
<td>111</td>
</tr>
<tr>
<td>3.11</td>
<td>Amédée Guillemen's Electricity and Magnetism</td>
<td>114</td>
</tr>
<tr>
<td>3.12</td>
<td>Higher Education Textbooks</td>
<td>117</td>
</tr>
<tr>
<td>3.13</td>
<td>Alfred Daniel's Textbook of the Principles of Physics</td>
<td>117</td>
</tr>
<tr>
<td>3.14</td>
<td>R.T. Glasebrook and W.N. Shaw's Practical Physics</td>
<td>118</td>
</tr>
<tr>
<td>3.15</td>
<td>M. Joubert's Traité Élémentaire D'Électricité</td>
<td>119</td>
</tr>
<tr>
<td>3.16</td>
<td>Textbooks which treat of A.C. Electricity</td>
<td>121</td>
</tr>
<tr>
<td>3.17</td>
<td>J.A. Fleming's The Alternate Current Transformer</td>
<td>122</td>
</tr>
<tr>
<td>3.18</td>
<td>S.P. Thompson's Dynamo Electric Machinery</td>
<td>124</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.19</td>
<td>Texts for Amateurs and Technicians</td>
<td>128</td>
</tr>
<tr>
<td>3.20</td>
<td>Advanced Technical Books</td>
<td>132</td>
</tr>
<tr>
<td>3.21</td>
<td>W.H. Timbie's <em>Elements of Electricity for Technical Students</em></td>
<td>134</td>
</tr>
<tr>
<td>3.22</td>
<td>Textbooks for Wireless Constructors</td>
<td>137</td>
</tr>
<tr>
<td>3.23</td>
<td>Harmsworth's <em>Wireless Encyclopedia</em></td>
<td>138</td>
</tr>
<tr>
<td>3.24</td>
<td>The Foundations of Wireless</td>
<td>141</td>
</tr>
<tr>
<td>3.25</td>
<td>H. Cotton's <em>Basic Technical Electricity</em></td>
<td>142</td>
</tr>
<tr>
<td>3.26</td>
<td>A.E. Clayton and H.J. Shelley's <em>Elementary Electrical Engineering</em></td>
<td>143</td>
</tr>
<tr>
<td>3.27</td>
<td>New York Institution of Technology: Programmed Courses in Electricity</td>
<td>144</td>
</tr>
<tr>
<td>3.28</td>
<td>M. Nelkon's <em>Electricity and Magnetism</em></td>
<td>145</td>
</tr>
<tr>
<td>3.29</td>
<td>Tom Duncan's <em>Physics: A Textbook for A-Level Students</em></td>
<td>147</td>
</tr>
<tr>
<td>3.30</td>
<td>M. Nelkon's <em>Advanced Level Magnetism and Electricity and Fundamentals of Physics</em></td>
<td>149</td>
</tr>
<tr>
<td>3.31</td>
<td>The Nuffield Advanced Physics Course</td>
<td>151</td>
</tr>
<tr>
<td>3.32</td>
<td>Electrical Hobby Magazines</td>
<td>155</td>
</tr>
<tr>
<td>3.33</td>
<td>Frank Linsley's <em>Introduction to Electrical Science</em></td>
<td>157</td>
</tr>
<tr>
<td>3.34</td>
<td>Roger Hamilton's <em>Electrical Principles for Technicians</em></td>
<td>158</td>
</tr>
<tr>
<td>3.35</td>
<td>Bleaney and Bleaney's <em>Electricity and Magnetism</em></td>
<td>160</td>
</tr>
<tr>
<td>3.36</td>
<td>W.J. Duffin's <em>Electricity and Magnetism</em></td>
<td>162</td>
</tr>
</tbody>
</table>
CHAPTER THREE

TEXTBOOKS WHICH HAVE SERVED STUDENTS OF ELECTRICITY

3.1

Early Electrical Textbooks

For more than a generation following Faraday's greatest researches there were few textbooks available to the students of electricity whether amateur or academic, and as those students were limited in number, there was little inducement to the publishers to cater for their needs. The "Professional" electricians were at first mostly associated with the few universities and technical institutions where there was an appreciation of the advantages to be gained by encouraging this line of scientific research; but, when telegraphy became commercially viable in the 1860's, and electric lighting reached the stage of practical application in the 1870's there appeared an increasing number of vocational electricians to be educated.

The serious amateurs and the academics kept abreast of electrical developments through the papers read before the Royal Society, and the reports of the British Association for the Advancement of Science, and those of the British Institution, supplemented by the few journals which recorded the work of foreign, principally Continental European scientists. Periodicals such as The American Journal of Science, Scientific American, Nature, and Van Nostrand's Magazine, were widely read; and from 1861, most important of all, The Electrician, that valuable weekly
publication which carried the current news of all that was most exciting from the laboratories and studies of workers world-wide, and on the pages of which eminent British electrical theorists like William Thomson, James Clerk Maxwell, and latterly, Oliver Heaviside propounded their views.

By the middle of the 1860s publishers realized there was a market for elementary surveys of electrical science. A few were printed and proved the strength of the demand for information in this rapidly expanding field, and encouraged the production of more scholarly works primarily directed towards the students attending educational institutions, and those who had ambition to enter them.

In an age when self-improvement was a passion with many, and education beyond the elementary stage was deemed to be the key to progress in the world, those introductory books were warmly welcomed by those who could not benefit from the mathematical presentations in the academic journals, and provided a stepping stone to more advanced texts.

One pioneering work of an elementary nature, dating from 1862 and highly esteemed in its time, was A Treatise on the Principles of Electrical Accumulation by F.C. Webb. It is primarily concerned with electrostatic phenomena, couched in easily understandable language and employing the minimum of mathematics, with sufficient illustrations to clarify the topics under discussion. It was a work which brought together a good deal of what was known about the subject at the time, and one which was characterized by a missionary educational zeal.

The author writes in his preface of one of his intentions:
"The precision with which Professor Ohm's laws of the voltaic circuit coincide with, and account for all the various effects which arise from an alteration in the size of plates, amount of resistance, etc., in a voltaic circuit, is already generally admitted and the equations are given in most foreign works on the electrical telegraphy. In the few modern works which we possess in England, on voltaic electricity, it is to be regretted, however, that Ohm's formulae, so important in their bearing on many telegraphic problems, do not often appear, and in these few exceptions they are not considered with that detail which their comprehensive nature and importance merit."

The Author gives an account of some of the principal research results of Faraday, and De La Rive and Sir W. Snow Harris, and comments on their discoveries. He deals with the charging of condensers by means of electrical machines, and describes the different types of Leyden Jars available to the researcher, and their capacities, and the means of discharging them, and he gives mathematical calculations illustrating their charge and discharge. He writes of numerous experiments with condensers, and explains the measurements which can be taken with the electroscope. While Faraday's electrical researches underpin the greater part of his work, there is much that is personal in comment, and strong inducement is given to the student to experiment for himself, and he offers some theorizing about then little-understood phenomena, such as the nature of the earth's power of distributing charge.

In 1867 Henry M. Noad, Lecturer in Chemistry at St. George's Hospital, offered to vocational students a thoroughly sound and interesting work called The Student's Textbook of Electricity. The author acknowledges his great debt to Faraday's Experimental Researches in Electricity, and the assistance he has received from the writing of William Thomson, Fleeming Jenkin, and other electrical educators, but the presentation and commentary are his own. In addition to dealing with frictional electricity, the
chemical effects of currents from batteries, and electrostatic induction, he gives much attention to the condenser in the form of Leyden Jars and tells of experiments which were carried out by Faraday and other scientists, and he fires the students' imagination with accounts of the awesome power possessed by large batteries of Leyden Jars, which in their discharging can melt iron, tear apart blocks of wood, and magnetize steel bars, etc.

Bearing in mind the needs of his readers, he describes the uses to which Voltaic electricity may be put, details Ohm's law and its applications, and explains the utility of Wheatstone's Bridge. His sections on electro-magnetism are designed to encourage practical applications: not only does he tell of Faraday's experiments, but writes on "electro-magnetic engines", and comments on the prospects of using the "prodigious force of electro-magnets and their power of annulling or reversing in an instant, which might seem to justify the hope of their affording a motive power as energetic and more economical than even steam."
But he doubts if there will ever be "magnetic engines" providing a cheap or efficient source of power because batteries employ zinc and acid and copper which are more expensive than coal.

Noad describes various magneto-generators based on Faraday's and Henry's researches, and the degree of success in obtaining continuous current from these machines. He tells of the work of Pixii and Saxton, and of the displays at the 1862 International Exhibition of the applications of "magneto-electricity" to the production of light. The students are given an account of the nature of induction coils and their uses to produce high voltages for research purposes. He describes Ruhmkorff's improvements,
and the students are encouraged to speculate on the applications
of the instrument, and he gives some account of the experiments
whereby remarkable coloured effects could be obtained by discharge
through various gases.

Noad's textbook is up-to-date with the current applications
of electricity, and instances its use to drive looms in the cotton
industry, engraving instruments in the workshop, electric thermometers
in the laboratory, and clocks in the home. The qualities of the
textbook are such that it is easy to understand why it achieved
its considerable reputation.

A year after Noad published his textbook for students, he
issued a book on the inductor, specifically aimed at the amateur
electrician who wished to construct his own equipment and carry out
research and experiment with it. This was The Inductorium (or
"Induction Coil, being a popular exposition of the electrical
principles on which it is constructed, with the description of a
series of beautiful and instructive experiments illustrative of
the phenomena of the induced current.")

Following a sketch of the research results of Oersted, Ampère
and Faraday, and experiments of Joseph Henry, he describes the
theory of the inductor, and explains the nature of the "extra
current" (back-EMF). He then shows the practical uses of inductors
as applied to the "dynamo-magneto machines" of Wheatstone and Siemens.
He gives an account of the construction of induction coils suitable
for amateurs, and describes numerous experiments employing the
discharges of the coil through glass containers exhausted of air
and filled with various gases or chemicals.

Noad's textbook enjoyed considerable popularity, partly on
account of the quality of the writing, and partly because he had
the foresight to arrange with a London instrument-maker to provide "kits" with which to carry out the experiments which he prescribed.

An excellent, comprehensive, although compact textbook for beginning university students and technicians was published by Fleeming Jenkin, Professor of Engineering in the University of Edinburgh, in 1873. In his preface he explains that he had "long known that an elementary treatise on electricity and magnetism was much needed ... because the electrical science of the mathematicians is so dissimilar from that of the practical electricians that it had been quite impossible to give students any sufficient, or even approximately sufficient textbook."

With the aid of 1/3 line illustrations, Fleeming Jenkin describes and comments upon the electrical phenomena which he considers it essential for electrical students to understand. Employing, for the most part arithmetic and simple algebraic expressions, he describes the principal electrostatic conditions, clearly showing the relationships between charge and potential and capacity, and discusses the measurements employed in assessing electrostatic forces. In his section on magnetism he explains the nature of magnetic fields and electromagnets, and the measurement of electromagnetic induction, and shows how these phenomena are of practical importance in telegraphy. His section on currents is particularly interesting and instructive by means of a number of simple experiments, pictorially recorded, to demonstrate various phenomena associated with current flow and the interaction of certain magnetic effects.

Substantial coverage is given to the theory of the condenser, and he compares the charging of the Leyden Jar by electrostatic
induction with that given by voltaic batteries, and explains how a comparative estimate of the capacities of different condensers may be made by "relative throws of the galvanometer." He describes, and illustrates with simple drawings, the various arrangements of apparatus whereby experiments may be carried out, and shows that the capacity of the condenser is:

\[ S = \frac{Q}{i} \]

See: Notes, No. 1.

With an abundant use of diagrams to assist the student's understanding, he shows that when the distance between two condensers is diminished the capacity of the condenser is increased; likewise, by increasing the size of the opposing plates and diminishing the distance between them, there is an increase in the quantity which the condenser will store when raised to a given potential. He explains that: "The coefficient by which the capacity of an air condenser must be multiplied in order to give the capacity of the same condenser when another dielectric is substituted for air is constant for each substance, and is called the "Specific Inductive Capacity" of the dielectric. It is a quantity of much importance in telegraphy. It has been approximately determined for a few substances." And he offers the students a "table of numbers" for their guidance.

A small section of the book is devoted to the basic principles of the "Electro-magnetic Engine" which was then beginning to become a practical, rather than a laboratory interest. His students must have an understanding of the nature of electromagnetic induction observed when moving a conductor across lines of magnetic force, and he writes:
"The work done on the conductor is found by observation to be represented by an increment or diminution in the current flowing through that conductor; now the work done by a current is by definition equal to $EQ = EQt$, where $E$ = the electromotive force acting between the ends of the conductor.

If a unit length of the conductor be moved a distance $L$ across the lines of magnetic force in a field of intensity $H$, the work done will be $L = CHL$, hence, as the work done by the current must be equal to the work expended in moving the conductor, we have $EQt = CHL$, or $E = HL$. Now $L$ is the velocity with which the conductor is moving, so that the electromotive force per unit length is equal to the intensity of the magnetic field multiplied into the velocity of motion."

The technicians are assisted by a long section on telegraphic apparatus which comprehensively covers the basic principles and uses. The instruments of measurement are described, explained, and clearly illustrated, and calculations are given which are applicable to practical situations.

The textbook was immediately recognized as sound, and was widely used. Its continuing value was attested by researchers of the next generation who recommended it to their own students.

3.2.

Maxwell's "Treatise on Electricity and Magnetism"

Indisputably, one of the very greatest of the early electrical educational texts was James Clerk Maxwell's Treatise on Electricity and Magnetism published in 1873. It was written over a number of years, principally during the interval between his retiring from the chair at King's College, London, in 1865 and his appointment as first Professor of Experimental Physics at Cambridge. The Treatise is acknowledged by all but a tiny cavilling minority to be a magnificent pioneering achievement, drawing together almost all
the existing electromagnetic knowledge of the time, interpreted, and analyzed, and extended by a prodigious intellect. But in many respects it was not a satisfactory text for the readers. Maxwell set it before his Cambridge students and they found it dismaying difficult. Following generations, notwithstanding the greater familiarity with many of the underlying concepts, have found it no less difficult. In part, the reason is that Maxwell pitched the work at such a high scholastic level that scarcely any one other than his own peers could feel comfortable in following it; in part it was written as an exploratory exercise probing the furthest reaches of electrical knowledge.

C.W. F. Everitt, writing on the Treatise has summarized the position:

"Most readers come to it expecting a systematic exposition of the author's ideas which makes further reference to earlier writings unnecessary. It is a mistake. In later conversation he remarked that the aim of the Treatise was not to expound his theories finally to the world, but to educate himself by presenting a view of a stage he had reached. He gave the Treatise a loose-knit structure, organized on historical and experimental rather than deductive lines. Ideas are exhibited at different phases of growth in different places: different sections are delivered independently, with gaps, inconsistences, and even flat contradictions in arguments. It is a studio, rather than a finished work of art. The studio, being Maxwell's, is tidily arranged; and once one has grasped what is going on it is wonderfully instructive to watch the artist at work; but any one who finds himself there unawares is courting bewilderment, the more so if he overlooks Maxwell's advice to read the four parts of the Treatise in parallel rather than in sequence."

While in the broadest sense the subject of capacitance and inductance infuse the whole of the Treatise, several sections are devoted to specific aspects of each phenomenon. In the early passages of the first of the two volumes some consideration is
given to capacity in a conductor, the nature of condensers, specific inductive capacity, and disruptive discharges, without extensive comment; but, when he turns to the mathematical theories of electricity, and begins to apply these to "electrical work and energy in a system of conductors" he offers real difficulties. To follow him adequately the student needs a working knowledge of G. Green's *Essay on the Application of Mathematics to Electricity and Magnetism*, Poisson's *Theory of Electricity*, and William Thomson's writing on displacement and potential of points in the electric field. When he introduces the properties of the dielectric he gives six different expressions for the energy of the electric field, all rather complex. By unexpected contrast, Maxwell could sometimes be remarkably clear even to those without advanced mathematical experience: in that section titled "Electric Accumulators and the Measurement of Capacitance" there is a simple account of the nature of condensers then currently in use in electrical research. He describes the failings of the common varieties and the measuring instruments, and the improved versions of the instruments designed by William Thomson.

At Chapter 10 his subject is "Conduction in Dielectrics", it provides an example of the complications to which students may be led by the subtle curiosity of an ingenious mathematical mind. Because none of the dielectrics are perfect, some conduction does take place under the influence of an EMF, so he studies the state of a medium in which induction and conduction are going on at the same time. After working 12 equations he finds it necessary to account for a "residual charge", and proceeds to consider the situation where the dielectric "formed of a conglomeration of small
pieces of different simple media" which possess this property - and, in doing so produces a further 31 equations. The phenomenon of "electric absorbtion" and residual discharge lead him on to consider the actual case of the telegraph cable, each portion of which is in effect a condenser, and to the Fourier equations used to investigate the analogous behavior of heat. Then, to relieve the burdened student, Maxwell rounds off his chapter with a non-mathematical mechanical model of the properties of the dielectric.

Mechanical Illustration of the Properties of a Dielectric

From Maxwell's "Treatise on Electricity and Magnetism

The model has five tubes of equal section, four vertical and one horizontal, having the lower half filled with mercury and the upper with water; a small tube with a stop-cock connects the lower part of the model, and a piston is made to slide in the horizontal tube. By discussing the motion of the water or mercury, and the movement of the piston, Maxwell is able to describe most of the phenomena of the condenser: the charge and discharge being represented by the motion of the piston, and the electric potential being represented by the fluid pressure.
In the section concerned with induction of electric currents, Maxwell gives some of the historical background to the study of induction, including a brief summary of the discoveries of Oersted, Faraday, and Ampère. He gives a concise statement without mathematics of the necessary conditions for induction between two circuits; and, as an aid to remembering the directional relationships, he offers the Ampère "Le Bonhomme" visualization; then, typically, wishing to delve further, he suggests a model of the earth around which is a quadrant arch of metal, pivoted at the North Pole, which the student may well find confusing. Thereafter he exhaustively examines the laws of inductive electric currents in fixed circuits, related to another of his semi-pictorial drawings. Finally, without mathematics, he outlines the experiments of Faraday, Lenz, and Helmholtz, and William Thomson in an admirable manner.

In the ninth chapter of the second volume of the Treatise Maxwell gives his general equations of the electromagnetic field, now universally known as "Maxwell's Equations" and part of the higher education of all studying Physics. In the 11th chapter his subject is "Energy and Stress in the Electromagnetic Field" where he introduces the principle of electromotive forces which govern all the forms of the motor and generator. Once again the mathematical analysis is so extensive and subtle that it is unlikely that it was fully appreciated by many of his students, other than the specially gifted.

In the 14th chapter of the second book, coils are examined for self-induction and mutual-induction, and related to mathematical equations given by Gauss and Lord Rayleigh. He returns to these again in the 17th chapter of the second volume when he describes the important experimental technique with the "Maxwell Bridge" for determining the self-induction of a coil, and the comparison of the self-induction of two coils.
It was not only Maxwell's student readers who had difficulty in following his reasoning, and accepting his theories; some of the leading physicists of the time could not understand, or at least accept, portions of his Treatise, including Heinrich Hertz, who felt that there was a major inconsistency in the expressed views on the nature of charge and electric current, and Maxwell's displacement theory; similarly, William Thomson (Lord Kelvin) for many years was unable to accept Maxwell's theory of the nature of electromagnetic waves. Maxwell, recognizing that part of the trouble was that changes of mind in the course of writing had introduced unnoticed inconsistencies and contradictions which might lead to misunderstandings, and opportunities to those who sought to find fault. From his day to ours, there have been writers who delighted in exposing minor mathematical or literary slips, and thereby found opportunity to offer scorn towards Maxwell's intellectual masterpiece.

3.3

Maxwell's "Elementary Treatise on Electricity"

Maxwell soon discovered that his Treatise was well beyond the powers of the majority of his students, and he made a considerable attempt to simplify many of the sections in a body of lecture notes which he used during classes, and he had it in mind to publish these as a separate book for those who were not "professed mathematicians", or insufficiently prepared to work directly from the Treatise. Unfortunately, his numerous commitments towards the end of his life, and his ill-health, prevented that project from being realized.
After his death, William Garnett decided that he would assemble the notes, and he published them under the title *Elementary Treatise on Electricity* in 1881. Garnett considered the manuscript to be sufficiently advanced up to Chapter 8, and thereafter he provided a further five chapters drawn from Maxwell's notes associated with the text where possible, but principally by taking portions from the major *Treatise*. There were many at the time—and later—who felt that Maxwell had been done no great service by the publication. Had he lived the book would certainly have had the benefit of his own revision in the earlier parts, and there would have been a great deal of simplification of those sections taken from the scholarly *Treatise*.

A fragment of the Preface which Maxwell was preparing has survived, and that explains his intentions for the elementary book. He writes:

"The aim of the following treatise is different from that of my larger *Treatise on Electricity and Magnetism*. In the larger *Treatise* the reader is supposed to be familiar with higher mathematical methods which are not used in this book, and his studies are so directed as to give him the power of dealing mathematically with the various phenomena of the science. In this smaller book I have endeavored to present, in as compact a form as I can, those phenomena which appear to throw light on the theory of electricity, and to use them, each in its place, for the development of electrical ideas in the mind of the reader.

In the larger *Treatise* I sometimes made use of methods which I do not think best in themselves, but without which students can not follow the investigations of founders of mathematical theory of electricity. I have since become more convinced of the superiority of the methods akin to those of Faraday, and have therefore adopted them from the first."

In the first two chapters of the *Elementary Treatise* Maxwell is principally concerned with electrostatics, and much of the text
is given in the form of experiments - some are classical experiments of Faraday and other pioneers - which we may believe were conducted by his students in the laboratory under his supervision. The results are summarized and difficulties and significant facts drawn from observation are recorded. His third chapter, on "Electrical Work and Energy" introduces progressively more algebraic expressions, but even the non-mathematical student can follow the greater part of his argument because he gives verbal descriptions of the principal equations. To assist with the understanding of the concept of "Electrical Work" he introduces the "Indicator Diagram" which was first used by James Watt for measuring the work done by a steam engine.

Chapter Five is a commentary on Faraday's ideas on induction translated into mathematical expressions; however, to clarify the position for his non-mathematical readers, Maxwell comments on the relations of the electrical phenomena by means of physical analogies. He introduces the analogy between electrostatic phenomena and those of the uniform conductor of heat in solid bodies, which was first pointed out by William Thomson in 1842.

In Chapter Six, Maxwell gives a commentary on electromotive force and continues with an analysis of the nature of Potential, working with numerous algebraic equations, then he summarises:

"The numerical value of the potential at a given point due to a unit of electricity at a given distance is the reciprocal of the number expressing that distance. If a charge is e, then potential is at a distance Z, e/Z."

Maxwell deals with the mathematical properties of Leyden Jars: he deduces expressions from Coulomb and other early researcher's
results, then describes the application of William Thomson's measurements with his "Attracted Disk Electrometer". He writes of the difficulties of studying equipotential surfaces and explains: "I have drawn several diagrams of equipotential surfaces and lines of force, so that the student may make himself familiar with the forms of these lines ... I am anxious that these diagrams may be studied as illustrations of the language of Faraday in speaking of "lines of force", "the forces of electrified bodies", etc. There is no contradiction between Faraday's views and the mathematical result of the old theories, but on the contrary, the idea of lines of force throws great light on these results, and seems to afford the means of rising by a continuous process from the somewhat rigid conception of the old theories to notions which may be capable of greater expansion, so as to provide for room for the increase of our knowledge by future researches."

In a very short section entitled "On Electrostatic Capacity", some of Maxwell's notes are offered relating to early forms of condensers, and he gives the algebraic expressions for the charges on the plates in the simplest cases. Then he compares the charges on the inner and outer coatings of the Leyden Jar, which has one side connected with earth. Finally, he gives William Thomson's method of verifying the existence of a determinate relation between the capacity of four condensers (the Wheatstone Bridge method), commenting on the mathematical relationships.

Maxwell's *Elementary Treatise on Electricity* was undoubtedly useful to those students who were unable to cope with the complexities of the larger *Treatise*, and provided them with technical information which previously was only available by delving deeply into engineering reference books like *Spons Dictionary of Engineering*.
Maxwell's drawing of Lines of Force
and Equipotential Surfaces

from *Elementary Treatise on Electricity*
S.P. Thompson's "Elementary Lessons in Electricity and Magnetism"

Maxwell's work had a stimulating effect upon academic authors, focusing their attention on some of the requirements to assist the growing number of engineering students attending colleges of higher education, and freshmen reading university science courses. One such author who was deeply indebted to Maxwell's example was Silvanus P. Thompson, who in 1881 produced the first of his numerous acclaimed electrical engineering textbooks under the title of *Elementary Lessons in Electricity and Magnetism.*

The 1880's was a time of rapid expansion in the field of electrical engineering: national and international telegraphy was thriving with intensive development by commercial and government agencies; the newly developed telephones were being enthusiastically adopted; generators, especially those adapted for the supply of electric lighting, both arc and incandescent, were being manufactured in large numbers. In industry all kinds of electrical research was progressing apace to exploit the new technology. The prospects for advancement in this new industry naturally attracted a large number of young people interested in gaining some electrical educational background, which they obtained principally in evening classes. What they needed most of all was a suitable textbook adapted to their educational level. This was admirably supplied by Silvanus P. Thompson.

Having distinguished himself as a very young man in the external examinations of London University in Physics and Chemistry, Silvanus P. Thompson was appointed as the first lecturer in Physics at the University College, Bristol. He was a dedicated teacher, and an
enthusiastic lecturer who had the gift of putting over ideas clearly and simply to those beginning the study of electricity. On the basis of his experience during the first years of his teaching, when the hunger for basic electrical knowledge was gathering, he prepared a scheme for a university level textbook but the publishers, MacMillan, would not have his book on the grounds that his reputation as a university teacher was not yet established. However, they accepted his alternative suggestion, a school textbook on electricity and magnetism. This was published in 1881, as *Elementary Lessons in Electricity and Magnetism.* It was instantly recognized for its high worth; was reprinted twice almost immediately, and 16 times in the succeeding 12 years, and thereafter continued to be intensively read long after the last edition, at the time of the first World War.

As the preface clearly indicates, Silvanus P. Thompson had others in mind beyond the schoolchildren: his book is for the electrical technician, the interested amateur, and those who wished to progress to more advanced electrical studies. He writes:

"A scientific knowledge of various kinds of electrical apparatus the reader will require to operate, or with which his business is connected, is of the highest importance. There is also a class of liberally educated persons who desire to extend their knowledge of electrical principles, but have not the time or patience to follow the intricacies of mathematical formulae, especially in the abbreviated form usual in the books referred to. A third class of student is those who intend to become electrical engineers, to whom a thorough knowledge of elementary physical electrical principles is important as a preparation for more intensive mathematical courses."
The text is exceptionally clear, uses only the simplest of mathematics, and is practically orientated. The principal areas treated are the essential facts in the history of electrical research; induction and the generation of current; condensers and measurement of capacity; the units employed in electrical measurement; the motor; the generator and its industrial uses (particularly the provision of electric lighting); electric welding; electric telegraphy; the telephone and the submarine cable. The work is illustrated with 120 drawings and explanatory diagrams of instruments, experiments, industrial apparatus, and equipment related to generators, motors, telegraphy and telephones.

Thompson's book is particularly easy to follow and understand in those sections dealing with capacitance and inductance. Before considering practical capacitors, he introduces the basic laws of electrostatics, and shows how electrical quantities are measured in fundamental units (centimetre, gramme, second), the unit of force, the dyne; and the meaning of potential, and how the earth may be regarded as being at zero potential. He gives Faraday's experiments with the charging of spheres, and offers a simple definition of capacity: "The electrostatic capacity of a condenser is measured by the quantity of electricity which must be imparted to it in order to raise its potential from zero to unity", and he explains how the physical size of the sphere can influence its electrical capacity. He discusses the methods of indicating the presence and measuring the charges on the condenser, and briefly offers the theory of the Leyden Jar and tells of experiments of Cavendish (which Maxwell had recently published).
Thompson stressed the need for a practical understanding of the nature of capacitance, instancing the case of the submarine cables which possess significant capacitance which may retard the signal. He offers formulae for calculating capacitance of condensers and explains why the energy of the discharge is equal to \( \frac{Q^2}{2C} \).

In the matter of self-inductance, an area fraught with difficulties for the beginner, Thompson gives a simple explanation:

"Suppose a coil to possess 'S' spirals, and that it generates a magnetic flux through those spirals of 'N' lines, when the current is turned on, then turning the current on will have the same effect as if a magnet of 'N' lines were suddenly plunged into the coil; and turning the current off will have the same effect as if the magnet were suddenly withdrawn. The current induced by plunging the magnet into the coil is an inverse current tending to push it out; while that induced by withdrawing the magnet is a direct current tending to attract it back. It follows that the self-induced electromotive force on turning the current on will tend to oppose the current, and prevent it growing as quickly as it would otherwise, while that induced on stopping the current will tend to help the current to continue flowing."

He shows that the energy of the magnetic field surrounding the current is equal to \( \frac{1}{2}LC^2 \)

\[ \text{(L = the total amount of cutting lines by the circuit when a current of one ampere is suddenly turned on or off.)} \]

He tells of Von Helmholtz investigating mathematically the effect of self-induction upon the strength of current, and that he had deduced important equations to express the relation between the inductance of a circuit and the time required to establish current at full strength, and his conclusion that self-induced electromotive force will depend upon the rate at which the current is changing. He explains that the time-constant is the time required by the current to rise to a certain fraction, 0.634 of its final value.
Thompson is equally clear and direct in his treatment of mutual inductance, a subject on which there was little theoretical or mathematical guidance to the students at the time. He shows by example that the magnetic flux due to the current 'C' in a primary coil of 10 units will be:

\[ N \text{ (number of lines of force)} = \frac{4\pi C S}{10Z} \]
\[ Z = \text{reluctance of the magnetic circuit} \]
\[ S = \text{the spiral} \]

The total amount of cutting magnetic lines by the coil \( S_2 \), when the current is turned on or off, will be:

\[ S_2N = \frac{4\pi C S_1 S_2}{10Z} \]

Hence the induction in the secondary circuit due to the turning on or off of 10 amps will be \( \frac{4\pi C S_1 S_2}{Z} \) and if the current in the primary is varied at the rate of \( \frac{dC}{dt} \), the electromotive force \( E_2 \) thereby induced in the secondary will be \( E = -M \frac{dC}{dt} \), where \( E \) will be in volts, if \( M \) is expressed in Henrys, \( C \) in amps, and \( t \) in seconds.

Silvanus P. Thompson, who was specially drawn to a study of generators through his enthusiasm for their applications in providing illumination, writes particularly well on their nature and use. Having described the dynamo as a machine for converting mechanical power into electrical power by the operation of producing relative motion between magnet and conductor, he offers a compact historical account from Faraday's first primitive magneto-electric machine, to the mid-century improved armatures designed by Werner, Siemens; the substitution of the electromagnet for the
steel field-magnets introduced by Wild; and on to the application of the highly effective method of using the current generated in the armature to excite the field magnets. 8

Thompson is exceedingly helpful to the student when treating "alternate currents" - then a little discussed subject because most electrical equipment was DC operated. He simply and clearly explains:

"Alternating currents do not always keep step with the alternating voltages impressed upon the circuit. If there is inductance in the circuit, the currents will lag; if there is capacity in the circuit, the currents will lead in phase."

For prospective engineers he impresses a fundamental matter:

"Inductance has this effect of importance: it produces a reaction on the electromotive force - choking the current down. While the current is increasing in strength the reactive effect of inductance continues to prevent it rising."

He includes good diagrams and illustrations to explain the functions of the dynamo; he also treats concisely and clearly the nature and uses of alternating current motors, and gives a sound account of the basic principles of the transformer and its applications to distributing current to distant locations for the purpose of electric lighting.

In the following sections of his textbook, Thompson gives numerous examples of the uses of capacitance and inductance in contemporary equipment such as the telegraph and telephone, and circuits designed to produce oscillating currents and electromagnetic waves. He makes reference to James Clerk Maxwell's new and advanced theories, and the researches of Hertz.
Silvanus P. Thompson's textbook has a very important place in electrical education history. It was the first choice of many teachers in day schools and evening institutes, and for two generations was the subject of warm commendation from many distinguished electrical researchers, including Ambrose Fleming, Sir Oliver Lodge, and Sir Ernest Rutherford.
Under the circumstances where a basic electrical knowledge was a requirement for a growing number of students, both authors and publishers were encouraged to produce introductory textbooks. Very many were produced in the early and middle years of 1880's, though few have any special distinction in presentation, arrangement, or illustration - the majority simply repeating or rearranging what others had written. However a number of distinguished electricians, who had already established a reputation by research or educational writing, applied their skills to assisting the young vocational engineers. Among them was J. Ambrose Fleming, who in 1886 published *Short Lectures to Electrical Artisans*: being a course of experimental lectures delivered to a practical audience. This was the revised text of a series of talks given before the pupils and workmen at the Comton Works, Chelmsford.

The lectures, which range widely over the subjects of magnetism and electromagnetism and their industrial applications, are given with a minimum of mathematics, but with the appropriate theory described in words and referred to equipment and instruments which the young technicians would be familiar with. The book is provided with good diagrams and numerous aids to memory. While there is no doubt that Fleming has new ideas to offer in the discussion of basic theory and can provide an interesting text for his readers, it is clear that he has borrowed considerably from Silvanus P. Thompson's *Elementary Lessons in Electricity and Magnetism* of five years before.
Fleming's chapter on magnetism is particularly helpful. He outlines the nature of lines of magnetic force; the measurement of magnetic fields; permeability and susceptibility and saturation. His diagrams display curves which explain the relationship of magnetic permeability to magnetic induction in c.g.s. units in the case of soft iron; and thereby considerably assist his simple exposition. One notable diagram and its accompanying commentary is that known as "Fleming's Right-hand Rule", which has since established itself as a classic aid to memory used by generations of engineers in training, to recall the direction of the current induced in a conductor when moved so as to cut the lines of force and alter the amount of magnetic induction passing through a circuit.

Diagram of J.A. Fleming's "Right-hand Rule", illustrated in "Short Lectures to Electrical Artisans"

Fleming also introduces his "Left-hand Rule" for motors.
It is a text in which Fleming, who was not particularly known for his simplicity of expression, has been at pains to adapt his language to a specialized young audience. One instance of this is his fairly extended account of the interaction of the coils of a transformer. He also offers clear analogies in the matter of self-induction which were likely to be remembered by his vocational audience and readers:

"We may put the matter another way. The current moving in a wire behaves just like a heavy fly-wheel being set in motion. You can not start a heavy wheel full speed, or at once, because of its inertia, and you can not stop one running suddenly. The similar behavior of current has won for this property the name of electrical inertia, which term is sometimes used instead of self-induction ... a magnetic field can not be brought into being, so to speak, immediately. The circular lines of magnetic force round a straight current do not spring into existence suddenly when the current begins, but expand outward, gradually, like the widening ripples when a stone is dropped onto still water, and when the current ceases, these lines collapse gradually again onto the wire and do not disappear instantaneously in the place where they are. The curious thing is that the collapsing back of the lines of magnetic force onto the wire may, for a moment, give rise to an electrical "push" or electromotive force greater than the steady force which maintained the current, and this sudden driving force of electricity in the wire at that instant when the circuit is broken, causes the bright spark seen whenever a strong current is interrupted."

Fleming explains to his young technicians that the action of self-induction hinders the sudden rise and fall of current strength in a wire, hence in circuits with large self-inductance it is not possible to make very sudden changes in the strength of current flowing in it, and it is this which hinders telephonic transmission of speech in long coils of wire.

In the section where he deals with electromagnetism, Fleming discusses the method of utilizing electromagnets efficiently, and
the different types of electromagnets used in dynamos of different kinds. Here his illustrations are particularly good and include cross-sections of various magnets used in dynamos. Some of his drawings are a mixture of pictorial representations and circuit diagram; that is, he uses some symbols for components such as resistors, and inductors, merged with drawings of mechanical elements.

His treatment of induction coils includes their uses as instruments designed to create large sparks from the terminals of secondary coils, which was a matter of particular interest at the time in the laboratories and workshops of the industry. He also deals with inductors used as transformers for the alteration of voltages for various industrial purposes. He emphasises the growing importance of this once neglected area of electrical engineering:

"Induction coils formerly found their application only in scientific research and experiments, but they have recently, with modifications, become important practical appliances in electric lighting. By their use we can convert our large current of low electromotive force into small currents of high electromotive force, and so convey the electricity at a lowest cost of conductor."

He explains that the cost of copper used for large currents is expensive.

In his sections dealing with the instruments which vocational workers can use to measure electrical quantities, he avoids all complications which could arise from an academic discussion of units, and explains very simply what the scientists understand by voltage, current, resistance, work, and Joule, and how these are related to electric motors which the students use. Similarly, he offers a very plain explanation of the principles of the electric motor, taking care to refer his commentary to such machines as the technicians will be familiar with, and supporting his text with sectional drawings.
The value of this text to the particular audience to which it was directed was acknowledged by its continued sale and by the second edition published in 1898.

3.6

Jamieson's "Elementary Manual of Electricity and Magnetism"

Another prominent educationalist who wrote for those making their first acquaintance with electrical principles was Professor Andrew Jamieson, of the Glasgow and West of Scotland Technical College, an influential teacher, a prolific writer on technical subjects, and energetic editor of a large number of electrical educational publications. His *Elementary Manual of Electricity and Magnetism*, first published in 1889, was specially arranged for use by students preparing for the government Science and Art Department's examinations.

This text, which was based on years of practical experience with vocational students, was a simple exposition of the essential features of electromagnetism, assisted by numerous line drawings, a large number of practical experiments, and various aids to memory in the form of ingenious diagrams. Professor Jamieson devised hand and finger rules comparable to Fleming's, which were of assistance to the beginner, and his elementary textbook gives drawings to demonstrate the applications of these rules. The most frequently employed was his "Right-hand Rule" for testing the direction of the magnetic force due to a known direction of current, or for the direction of current when the direction of magnetic force was known; and his extension of the "Right-hand Rule" to solenoids, whereby given the direction of the current
in the solenoid, it is possible to find the North or South poles of the solenoid — or vice versa.

3.7

A Practical Elementary Manual of Magnetism and Electricity

Professor Jamieson's textbook was widely used and frequently reprinted and revised, but his greatest success came with the more advanced practical textbook published at the same time, under the title of A Practical Elementary Manual of Magnetism and Electricity, intended for the young engineering students. It contains basically the same material on a rather higher standard, and laid out in the form of a progressively intensifying lecture course. He examines all the fundamental principles which the young engineer of the time was required to be acquainted with, and offers numerous drawings and diagrams of his own devising, supplemented by carefully chosen specimen questions and answers. By reconstructing the classical experiments of Ampère and Faraday and Ohm and Lenz, and some of those of William Thomson in connection with the measurement of inductance, and relating these to the current dynamos and generators and their uses, he provided his students with a very sound preparation for more advanced future studies.

Few other textbook writers of his time made such excellent use of drawings to simplify the direction of electrical currents in transformers, and his aids to memory were genuinely useful and more easily followed than most offered in other manuals. Professor Jamieson's deservedly popular work continued to be revised in nine editions up to 1918.
Andrew Jamieson's Hand and Finger Rules for determining direction of the magnetic field, and for learning of the direction of currents passing through windings.

TESTING FOR THE DIRECTION OF THE MAGNETIC FIELD DUE TO THE KNOWN DIRECTION OF CURRENT IN A STRAIGHT WIRE, OR PIECE TANGENT TO THE PATH OF THE CURRENT.

Rule 1.—If you know the direction of the current in the winding, then by placing your right hand, as shown, the thumb points in the direction of the N-pole of the solenoid or spiral.

Rule 2.—Ascertain the N-pole of the spiral or solenoid by means of a compass-needle, then by placing your right hand on the solenoid (as shown by the figure) so that the outstretched thumb points in the direction of the N-pole (or where the magnetic lines of force leave the coils), the fingers will point in the direction of the current passing through the windings.

from A Practical Elementary Manual of Magnetism and Electricity (1889)
Philip Atkinson's "Elements of Dynamic Electricity and Magnetism"

The vocational students weak in mathematics found a text specially disposed to their requirements in The Elements of Dynamic Electricity and Magnetism by Philip Atkinson, published in 1891. He had realized that many of the young students were gaining too little from other textbooks. He explains in his preface:

"Previous to the last decade the demand for electrical books was confined chiefly to scientific investigators versed in the higher mathematics, and the authors of such books were electricians of the same class, who recognized the importance of mathematical accuracy in treating electrical phenomena. Hence mathematical formulae became a prominent feature of such books, but the various electrical industries to which the recent unprecedented electrical development has given rise, has given employment to a numerous class of persons to whom mathematical books are almost unintelligible, and yet to whom a scientific knowledge of various kinds of electrical apparatus which they require to operate, or with which their business is connected, is of the highest importance. There is also a class of liberally educated persons who desire to extend their knowledge of electrical principles, but have not the time or patience to follow the intricacies of mathematical formulae, especially in the abbreviated form usual in the books referred to."

Atkinson's text is a minimum mathematics exposition, straightforward in presentation, and practically orientated. He gives the historical account of the fundamental experiments and subsequent applications to industrial uses, and treats of electrical measurement, the units employed and the instruments regularly used in his time. In addition to dynamos and motors, he treats of electrolysis in theory and industrial practice. The relations of electricity to heating, including thermopiles and electric welding; and he covers the production of illumination by arc
lighting and incandescent lamps, and explains the distribution of current, and the series and parallel lighting circuits employed in his time. He writes interestingly also of the electric telegraphs, both manual and automatic; submarine cables for the transmission of telegraphy, and of the printing telegraph machines, and multiplex telegraphy; and of the telephone's early history and current use. His text is readable and self-explanatory to the beginning student, and the illustrations employed are clear and helpful.
"Popular" Expositions

The rapidly increasing curiosity of the general public with regard to the nature of electricity was catered for by many popular publications; most of them were of a superficial nature, but a number were genuinely educational and designed with care to appeal to thinking people who had no professional involvement or desire for a technical qualification. One of the most unusual in its approach is that of Oliver J. Lodge, The Modern Views of Electricity, published in 1889. A contemporary advertisement explains the novel features:

"The object of this work is to explain without technicalities, and to illustrate as far as possible by mechanical models and analogies, the position of thinkers on electrical subjects at the present time. It deals particularly with the view of electrical theory which is specially associated with the names of Clerk Maxwell, and Sir William Thomson. It aims, as far as possible, to explain what is known of the nature of electricity but entirely without the use of mathematics."

Oliver Lodge's "The Modern Views of Electricity"

The principal sections of Oliver Lodge's book are concerned with fundamental notions; the dielectric; charge and induction; metallic and electrolytic conduction. Lodge's analysis of the action of the condenser by means of graphic diagrams is unique and ingenious.
He places much emphasis on the study of these diagrams, and makes out a strong case in his text for the use of those, as opposed to the conventional representations. He writes:

"To illustrate the phenomena of charge, I will now call your attention to these diagrams - which less completely but more simply than hydraulic illustrations, serve to make the nature of the phenomena manifest."

Lodge's mechanical model of the condenser is characteristic of the manner by which he draws an analogy with vital electrical functions.

A cord is supported on pulleys and a number of beads are firmly attached to the cord, so that they can move with it; elastic threads are attached to the beads, and a weight drives the pulleys, and a clamp is used to stop the motion of the cord. The cord represents electricity flowing in a closed circuit; the weight represents a battery supplying electromotive force;
the beads represent the particles of an insulating substance; the elastics connected with the beads allow the equivalent of electric displacement, but can spring back to their original positions when the electromotive force is removed. The specific inductive capacity of the dielectric is represented by the stretchability of those elastic threads: the stiffer the threads are to pull out, the less is the inductive capacity of the medium. Clamping the cord corresponds to making the resistance of the circuit infinite. The dynamic action of the model is that when a given EMF is applied, or the weight operates, a definite displacement of the beads is produced. One side of the model gets more cord than the other, and that represents positive charge; the other side gets less cord, and it is negatively charged. If the applied EMF exceeds a certain limit, the strain is such that the elastics break, equivalent to the dielectric being ruptured.

Oliver Lodge also offers an ingenious mechanical model to represent induction. It is clearly based upon Maxwell's mechanical model of induction.\(^1\) The purpose of his model is to show how an induced current rises and then gradually dies away. For this he attempts to demonstrate how a magnetic field excited in any manner spreads itself into and through conducting media.

---

\(^1\) From "Modern Views of Electricity"
He represents the conducting medium as a square of wheels, imperfectly geared together and capable of slip. An electromotive force, represented by a rack attached to cogs causes the wheels within the inductor to move. The outer layers of wheels inside begin to rotate, but there is delay before they are in full motion. For the inner layer the delay is greater, and so on — ultimately, the motion penetrates and everything is in a steady state. The periphery of the wheels, moving in the direction opposite to that of the wheels in contact with the rack, suggest the opposite induced current excited at the "make" in the conductor near a growing current, or an increasing magnetic field. The penetration of the motion deeper and deeper, and the gradual dying away of all slip illustrate the induced current rising and gradually dying away, becoming nil as soon as the magnetic field (the rotation) has penetrated to the interior of the conductor.

It is certainly a curious model, and one can only wonder whether it contributed to a clarification of the difficult concept, or introduced new questions. However, other sections of Oliver Lodge's book deal with conduction in wires and electrolytic actions, telegraphy and telephones, and measuring equipment, and are described and explained with admirable clarity.

3.11
Amédee Guillemin's "Electricity and Magnetism"

Another book of popular appeal which deserves considerable respect is Electricity and Magnetism by Amédee Guillemin, which was translated from the French, and revised and edited by Silvanus
P. Thompson, in 1891. Although this is certainly an introductory work and largely non-mathematical, it is a comprehensive survey of electrical phenomena, the research which investigated it, and the industrial applications of that research. It is almost encyclopedic in its treatment, and has the benefit of 600 illustrations. Amédeé Guillemin was a prolific writer on the sciences from the early 1870's and, although primarily concerned with arousing popular enthusiasm for astronomy, he had been well-known in Britain since 1872, when Mrs. Norman Lockyer had translated his book *The Forces of Nature*.

After introducing the laws of attraction and repulsion and the concept of charge, Guillemin gives some historical information on "electric machines" and their early use with Leyden Jars and the early experiments with them. Unusually, he deals with Franklin's various experiments, such as those which relate to sparks on discharging the condenser, and he gives some account of how Franklin anticipated uses to which condensers could be put in a domestic situation. He explains the measurement of capacitance, and the instruments developed for that purpose. His treatment of self- and mutual-inductance is by way of an account of the pioneering experiments of Faraday, in which he refers to the "Extra current" (back EMF) quite briefly, then he explains the basic function of the transformer through a description of the Ruhmkorff coil. His sections on the dynamo and the generator are at once simple and interesting in their gradual unfolding of the applications of fundamental principles. These sections have the benefit of Silvanus P. Thompson's editorial work in bringing them up-to-date. One of the very interesting features of this book is that he shows how some of Nature's
electrical phenomena, like the Aurora Borealis, St. Elmo's Fire, thunder and lightning, etc., can be explained by scientists applying their knowledge of inductance and capacitance.
During the 1880's and early 1890's the physics students at university and other institutions of advanced education were provided with a number of textbooks which were pitched at a higher level of mathematical ability; these, overtly - and occasionally covertly, made abundant use of the writings and research results of William Thomson and James Clerk Maxwell, and knowledge obtained from the published papers of Continental researchers such as Helmholtz and Hertz. Most of these textbooks had their origin in the relatively recently established laboratories attached to the universities and institutions of higher education, and they grew out of specific courses organized or supervised by the writers.

Alfred Daniel's "Textbook of the Principles of Physics"

In 1884 Professor Alfred Daniel, of Glasgow University, published his *Textbook of the Principles of Physics* which was specifically designed to provide a solid background for those entering upon medical or scientific courses. The author acknowledges his deep debt to William Thomson and Professor Tait of Cambridge, and the sections on electricity and magnetism show a considerable dependence on their writings. The treatment is highly mathematical, the exposition rather densely packed, dull, and scarcely likely to motivate the young reader, who in all probability would be dismayed at the prospect of working through a vast compendium of scientific knowledge.
Another university laboratory-developed textbook is the 1883 *Practical Physics* by R.T. Glazebrook and W.N. Shaw, demonstrators at the Clarendon Laboratory, Cambridge. The writers indicate in their preface that the book was intended to give assistance to the students and teachers in physical laboratories, and was offered because they felt the absence of any book covering the same ground. The work is primarily a description of experiments where a high priority is given to methods of exact measurement in the course of which they hope to illustrate the more important principles of their subject. It is a textbook better suited to those who are already fairly advanced in mathematics and with some knowledge of laboratory procedures. The impression given is that the writing is primarily directed to the attention of the teacher rather than the student. The authors comment that: "For the most part they have not attempted explanations of principles, but have trusted to the ordinary physical textbooks to supply the theoretical parts necessary for understanding the subject." However, in their sections dealing with electricity, they have borrowed extensively from Maxwell's explanations and commentary in his *Elementary Treatise on Electricity*. Their textbook covers much the same ground, but has more concentration upon units of measurement which were then the subject of great interest at the Cavendish Laboratory. The student reader requires considerable knowledge of algebra and trigonometry to benefit fully from their experiments and commentary, particularly where they deal with measurements of electromotive force and
electro-chemical measurements on the resistance of conductors, and the absolute measurement of electrical resistance.

Their treatment of the nature and measurement of capacitance is rather brief, most of it taken from Maxwell's larger Treatise, although they offer a rather more elaborate treatment of the comparison of capacities, employing the Maxwell arrangement of the Wheatstone Bridge (nulling) method. The authors make little concession towards the student's need for visualization, and the illustrations are few.

3.15

M. Joubert's "Traité Élémentaire D'Électricité"

Another first year university-level textbook is M. Joubert's Traité Élémentaire D'Électricité, translated into English and adapted to British students' requirements by G.C. Foster, Professor of Physics, University College, London, and E. Atkinson, former Professor of Experimental Science in the Staff College, which was published in 1892. The English academics felt that the French text was not sufficiently rigorous, for they wrote: "In the use of mathematical reasoning we have allowed ourselves a little more freedom than was used by M. Joubert." To get the best from the book it was necessary for the student to have a fair command of algebra, trigonometry, and have a fluency in handling logarithms. Basically, the text is an extensive compilation of the published material of distinguished researchers and writers, and the 552 pages have an appropriately large number of illustrations. There are many acknowledged borrowings from Faraday, Maxwell, and William Thomson. The
section on capacity treats, in considerable depth, the capacity of the electric field; the capacity of tubes of force mathematically examined; specimens of calculations of capacity in special cases such as coaxial cylinders, and a variety of different types of condensers. There is also mathematical analysis of the influence of different types of dielectrics, and the nature of charge and discharge in condensers.

The section on induction describes and calculates the characteristics of induction currents; examines Lenz's Law; electromotive force; the coefficient of self-induction; and electromotive force due to self-induction. The principles are then applied to particular circuits related to industrial equipment. There is treatment of electrical oscillation and an account of the experiments of Oliver Lodge and Hertz with oscillators during their work with radio transmission of electrical waves.

The textbook was popular in academic circles, and went through three editions, the last in 1909. Each was kept up-to-date with current research and experimentation and the practical applications of principles, so that there is the inclusion of such subjects as cathode tubes and Röntgen Rays.
During the 1880's engineers and industrialists became convinced that a major requirement was the centralized source of electrical power, and that for reasons of economy and electrical efficiency in distribution, A.C. installations would have to replace those operating on D.C. Mechanically and electrically efficient A.C. generators were developed by Siemens, Ferranti, General Electric, and other progressive companies in Britain, Europe, and America. By the use of steam or water as prime movers, and powerful high-voltage A.C. generators, it was possible to distribute electricity over long distances to transformers at factories or town centres where the voltage could be reduced to a level suitable for illumination of arc or incandescent lights, or to power industrial motors.

Once begun, the developments were so rapid that many of the technicians and teachers were embarrassed by their lack of understanding of the theory and practice of the new A.C. technology which had appeared among them. They were familiar with D.C. circuits in generators and motors, but A.C. behavior appeared to be extremely complicated by comparison. Some guide was urgently required. This was to be provided by J. Ambrose Fleming, Professor of Engineering at the University College, London, who in 1889 produced his two-volume work *The Alternate Current Transformer*. According to the understanding of his time, the word "transformer" was interpreted more loosely than in modern times, and encompasses coils, windings, and every form of inductor, and every circuit where inductance features significantly, including the propagation of electromagnetic waves.
Professor Fleming explains in his preface:

"The practical employment of periodic currents and their inductive transformation is becoming so important that it seemed probable that a service would be rendered to those dealing with these matters by placing together the main outlines of the theory of the application of current induction ... the desire of the author has been to collect out of the technical journals and specialized transactions of societies the contributions of various writers who have especially added matter to our knowledge of this department."

The work is more exhaustive in analysis of alternating currents than any previous text, and the author does not hesitate to use fairly advanced mathematics, nevertheless, the material is accessible to most levels of technical and academic students by reason of the numerous verbal descriptions of the more involved theoretical sections, and the inclusion of 250 specially prepared diagrams, drawings, instrumental and mechanical illustrations in support of the text. Fleming explains that A.C. circuits are not really new to the reader's subject, but were employed by the early researchers like Faraday and Ampère and Arago, and others, and calls upon their experiments to explain the concept of the field of electromagnetic force. By description and diagrams he gradually builds up an understanding of the electromotive force of induction and employs graphic means to represent the variation of coefficient of induction. His section on the theory of periodic currents explains Fourier's theorem; the analysis of complex periodic motion; derived sine curves; and various graphic representations of periodic currents. When dealing with self-induction and mutual-induction, Fleming gives the historical background, including the researches of Joseph Henry, to explain the theory of the induction coil. He covers the use of iron cores, and clarifies the effect of saturation and magnetic hysteresis, and also writes on efficiency of the transformer.
In his sections on electromagnetic theory Fleming offers the reader a commentary and interpretation of Maxwell's theories, including the displacement current, and the production of electromagnetic waves. Fleming deals thoroughly with the practical circuits which contain inductors and capacitors, and describes the resonant electric circuits. His text was completely up-to-date with the research of his time, and includes description and commentary on Hertz' researches on electric oscillatory induction, and the propagation of electromagnetic waves by both Hertz and Lodge, and he gives an account of the uses of the Wheatstone Bridge to investigate self-induction of copper conductors undertaken by Lord Rayleigh.

At all times Fleming keeps in mind the practical application of the information which he offers, and attempts to tie-in the new information with the background knowledge which his readers may already possess. For instance, he refers to applications of condensers to telegraphy circuits, explaining that in telegraphy the self-induction of the relay is an obstacle to the production of rapid changes of current strength through the relay; however, if the terminals of the relay are connected to a suitable condenser, the effect of self-induction of the relay will be lessened. Again, in examining the behavior of condensers he offers very clear graphic representations of the charge and discharge of condensers through large and small resistances, and similarly supplies excellent illustrations of the LC circuit which can produce controlled oscillations for different purposes. His treatment of oscillatory circuits leads on to the contemporary research which was experimenting with various circuits for the propagation and reception of electromagnetic waves, and he deals with the instruments which were then used to measure them.
Fleming treats thoroughly the industrial applications of inductive devices: he gives comprehensive coverage to transformers for supply of current for lighting purposes, and describes successful large-scale centralized installations such as the Westinghouse Electric Lighting Company in America, and the London Electric Supply Corporation (Ferranti), and the Metropolitan Electric Lighting Company of London. He describes and illustrates these power stations, and provides many explanatory diagrams, photographs, and drawings, together with circuit diagrams and practical details of the construction of transformers.

The quality and value of The Alternating Current Transformer was immediately recognized and acknowledged. Silvanus P. Thompson, reviewing the work in The Electrician, (the most respected electrical journal of the time) wrote:

"It would be difficult to pick out from the electrical literature of the past ten years any work which marks, as emphatically as does Dr. Fleming's book, the manner in which the practical problems of the day have compelled electrical engineers to advance their knowledge of the theoretical science ... it is a book which the electrical engineer of the present and future alike will read."

3.18 S.P. Thompson's "Dynamo Electric Machinery"

In 1882 Silvanus P. Thompson, who had earned for himself a remarkable reputation as an enthusiastic technical educator, was invited to give the Cantor Lectures before the Royal Society; he chose for his subject "Dynamo Electric Machinery." The lectures were enthusiastically received, and published in the Journal of the Royal Society of Arts; however, the demand for the valuable
information which they contained was so great that they were reprinted in The Electrician. The author was encouraged to expand the writing into a textbook. This he did, and published in 1884 under the same title. It was a great success, and was quickly translated into many foreign languages. The work was subsequently revised on numerous edition which kept abreast of technical developments. The strength of approval and admiration that was felt for this textbook was summarized by the reviewer of the 2nd edition writing in the Electrical Engineer:

"An exceedingly clear, simple, and logical statement of the essentials of a complex subject. If Professor Thompson had done nothing else, this invaluable book would serve as his enduring monument."

Dynamo Electric Machinery is a comprehensive textbook with 230 excellent illustrations which fully justified the author's aim, which was, in his own words: "To make the work a manual for students of electrical technology, for whom no textbook of this branch of science has hitherto been available." Those who worked through it were bound to gain a thorough grounding in the basic principles of the subject, and an acquaintance with the equipment of the day, and the best practices in working with it.

Silvanus P. Thompson expounds the principle of the dynamo and the laws relating to the production of current with admirable clarity, accompanying his text with diagrams of the cutting of the lines of force which are particularly easy to associate with the real conditions. The illustrations, often in the form of his own excellent drawings, are particularly useful in that section of his work dealing with the mechanism and design of the dynamo,
where he offers a straightforward but thorough account of the different types of armature, and a variety of windings, and the functions of the commutator and brushes. There is also a fine account of the induction of coils in the rotating armature, complemented by graphs of the curves of induction and the curves of potential. The theoretical principles are related to notable contemporary dynamos, such as the Siemens and the Gramme, which are treated to comprehensive descriptions of the mechanical and electrical features, and suitably illustrated. In a most skillful manner he keeps the theoretical and practical considerations well balanced - as the instance where he explains the difficulty of designing machines where the undesired effects of self-inductance must be minimized.

While many sections may be understood without difficulty by those technicians who were unversed in mathematics, the author also introduces a substantial section dealing with the algebraic theory of the dynamo, giving expressions for the electromotive force, the current, and the principal types, and the average electromotive force induced in a coil rotating in a uniform magnetic field; and he makes comparison between the magnetic field due to permanent magnets of steel and the magnetic field due to field magnets excited by the current from an independent source. There is also a mathematical analysis of the changing electromotive force when the coil passes through different degrees of rotation with respect to the field magnets.

For those better able to understand and appreciate visual representation, Silvanus P. Thompson offers a fine section on the geometric theory of the dynamo, and he introduces characteristic curves. These Characteristic curves offer graphic comment on the performance of different types of dynamos in current use, comparing
magneto and separately-excited machines.

In his section "The Dynamo as a Motor", he gives an historical account of research and achievement in this area where the potential for future development was little appreciated. He gives description of the various types of motors which his students should know about, and quotes examples of their uses in industry, such as the driving of lathes, heavy machinery, electric lifts, and electric fans. As in the case of the dynamo, he gives the theory of the electric motor and the mathematical expressions related to the efficiency of motors, and on a technical level, he tutors the readers in the essential features of maintenance, control, and testing.

The pleasant, easy style carries the reader along, feature after feature retaining his interest, with a gradual accumulation of fact, description, and theory, building up the necessary knowledge. Without doubt Silvanus P. Thompson had a remarkable gift for communicating technical material in an attractive form of language. His Dynamo Electric Machinery quickly became a classic text, was translated into many languages, and ran through nine editions, each larger than the last, and each provided with better and fuller illustrations which kept pace with the accelerating developments in dynamo electric machinery.

In 1885 Silvanus P. Thompson was invited to become the Principal of the Finsbury Technical College at the early age of 34. He was to hold the appointment for the rest of his life. His teaching of electricity attracted great numbers of students, and through them and his textbooks, his educational influence was exceedingly great. Latterly, he succeeded to every honour which was open to an electrical educator, including that of President of the Institution of Electrical Engineers.
By the early years of the 20th century the most exciting area of research and development was that of radio telegraphy. Among the authors who catered for those seeking knowledge in this field was J. Ambrose Fleming, the inventor of the diode valve used for detection of electromagnetic waves. As early as 1906 he had produced a comprehensive study of the subject called *Principles of Electromagnetic Wave Telegraphy and Telephony*, which he intended for electrical engineering students and practical operators. It provided one of the standard textbooks for the increasing number of amateurs who were taking an interest in radio in the years leading up to the first World War. During the war the military authorities understood the immense value of reliable radio communications, and made provision for the training of large numbers of operators and technicians, and encouraged intensive research. It was under these conditions that J. Ambrose Fleming revised and modernized his textbook which was reissued in 1916 as *An Elementary Manual of Radio Telegraphy and Radio Telephony*.

Unfortunately Fleming's writing became progressively more complex and mathematically abstract as the years passed, and as he got more and more involved in radio research and commercial developments. *An Elementary Manual of Radio Telegraphy and Radio Telephony* is concerned with much that was then of current interest and presents information which practical students required, but it is pitched on a level a good deal
higher than that of the majority of the readers for which it was intended. However, for those who could cope with the text there were adequate rewards.

Amongst the newer material which he offered were sections on electrical oscillations, both undamped and damped; the nature of high frequency inductance; resonance; condensers for radio telegraphy; and circuits for transmission and reception. Fleming gives information on the types of transformers in use, and circuits for spark discharges producing electromagnetic waves, including those of his own design and those by Wien and Peukert. He also deals with the nature of electromagnetic waves, giving a sketch of Maxwell's theory and an account of the practical applications of radio waves using contemporary equipment, including his thermionic diode valves.

The real difficulty is that what Fleming regards as an "elementary" mathematical exposition of theoretical matters is often something of extreme difficulty to beginners, and apparently neither he nor his editors appreciated the great gulf that existed between author and the bulk of the expected readers. Only the most determined elementary students and practical operators would continue with the book after such an example as his introduction to aerial wires, on page 27, where he tells how to calculate the capacity of a wire, mentioning that: "The whole potential \( V \) of the wire is given by

\[
V = 4\pi Pr \int_0^r \frac{dx}{\sqrt{x^2 + r^2}} = 4\pi Pr \left\{ \log_e \left( \frac{1}{2} + \sqrt{\frac{1}{2} + \frac{i}{4}} \right) - \log_e r \right\}
\]
Hence, if the length of the wire is large compared with its diameter, its capacity present is given by

\[ C + \frac{i}{2 \log_e \frac{i}{r}} \]

using ordinary logarithms and microfarads, this becomes

\[ C = \frac{i}{4.6052 \times 900000 \times \log_{10} 2 \frac{i}{d}} \]

In contrast to the emphatic mathematical approach used by Fleming, there was another textbook available to the vocational student in H.E. Penrose's *Magnetism and Electricity for Home Study* (1918), which seeks to minimize the use of mathematics and depends more upon establishing visual identifications of specific functions of components and circuit arrangements. The author was an experienced instructor at the Marconi Marine Communications Company, who during the first World War was responsible for training Royal Navy and Royal Flying Corps personnel in radio telegraphy. Because it is a text intended for self-study without supervision, the author has gone far to remove anticipated difficulties. Perhaps expecting criticism from academic reviewers, he justifies his approach in the preface:

"In departing from the orthodox methods adopted in standard textbooks, the author in no wise wishes to despise those methods; indeed, the ultimate object is to encourage the large body of students who need a stimulated enthusiasm to overcome a genuine dislike of mathematical reasoning ... if a severe demand has been made upon the "electron theory", it must be remembered that these lessons are
intended to present facts vividly to aid the non-mathematical mind in following the truths expressed in standard works."

The text covers all the fundamental principles which the students and technicians would be expected to understand, but a special feature of the text is that numerous aids for the vocation-al student have been introduced which other authors did not consider necessary. Important names and concepts, laws and formulae, are written first in bold type (not italics - which are scarcely noticed by many students). There are many analogies with mechanics, hydraulics, and phenomena drawn from practical experience. Chapter headings are in the form of the principal subject matter to be treated, and the experimental apparatus to be used; there are summaries of sections of the text, and frequent reviews of the principles already propounded; and, there are many explanations offered in terms of electron activity, visualized in a simple manner for the student's ease of understanding electrical principles. Although progression is gradual, the amount of material covered in 315 pages is considerable, and much up-to-date early 20th century electrical knowledge is given. The author acknowledges that some of his descriptions are simplifications, but the purpose is: "To enable the student to form mental images of the various happenings in and around the electrical circuit."

Penrose's Magnetism and Electricity for Home Study is a text of considerable merit, attractive and useful to the student, and in every respect fulfilling the best intentions of the author.
An interesting textbook for first year university students was the 1910 text written by seven American college professors under the title of *A Textbook of Physics*, edited by A. Wilmer Duff. It contains admirable chapters on electricity and magnetism by Arthur W. Goodspeed, Professor of Physics, University of Pennsylvania, and on electromagnetic induction by Albert B. Carman, Professor of Physics, University of Illinois. Both provide concise, clear expositions which bring together a great deal of contemporary knowledge, well-organized within a compact space, and illustrated by well-chosen drawings conveniently located at exactly the right portion of text. There is more historical information than usual in such a textbook and it is presented in a manner interesting to the student. Many of the explanations are offered in the form of analogies to other areas of Physics including hydrostatics, and heat. The section on electrostatics anticipates many of the problems which the students find in understanding the nature of charge and the relationships of capacity and voltage. There is an easily understood section on the function of the dielectric and the basic principles are related to practical condensers, both by historical account of the fundamentals discovered by pioneering researchers and the purposes to which these theoretical principles have been applied in modern machinery and instruments. Particularly clear drawings and diagrams are used to illustrate the comments on experiments, and there is guidance given in using measuring equipment.

The chapter on induction is equally commendable. Numerous line drawings clarify the concepts of magnetic fields, and the currents...
in transformers (a frequent area of misunderstandings among students); and the electromechanical conditions governing generators and motors. An added attraction for the student is the way in which the author has drawn him into the circumstances of historical research, as when self-induction is followed through the experiments of Faraday, and on to Helmholtz with his 1851 deduction of the equation

\[ I = \frac{E}{R}\left(1 - \frac{R}{L}t\right) \]

showing the law of the growth of currents in inductive circuits.

There are also numerous experiments related which could be repeated in the laboratory, using the Wheatstone Bridge and following a simplified account of Maxwell's own procedures. The advantages of A.C. as opposed to D.C. is explained, particularly with reference to the subject of power transmission, and the effects of inductance in A.C. circuits is explored through the use of graphs which demonstrate the lag of the current.

The section on electromagnetic waves is introduced through a clear account of oscillation in a LC circuit. Again, the historical background is applied to enliven the study of basic principles. The researches of Henry and William Thomson, and Feddersen are given, accompanied by interesting photographs showing oscillatory discharges. Thereafter Hertz' investigations are described and an account given of the then contemporary and exciting transmission and detection of "electric waves."

Among the first year college texts in Physics, this is a work of outstanding quality in terms of content and presentation. It was extensively used and was revised in a second edition.
W.H. Timbie's "Elements of Electricity for Technical Students"

A textbook which by its various editions deeply influenced students over more than 50 years was W.H. Timbie’s *Elements of Electricity for Technical Students*. First published in 1911, when the author was a young instructor at the Pratt Institute, Brooklyn, New York, subsequent reprints and revisions were produced throughout the years when the author was a venerated Professor of Electrical Engineering at Massachusetts Institute of Technology.  

To quote the author's preface:

"The textbook is designed primarily to meet the needs of young men who desire an occupation connected with the electrical or allied industries. Such young men need a thorough grounding in the fundamental principles of electrical theory and measurement. They usually have neither the time nor the previous preparation for acquiring this knowledge through advanced or mathematical treatises. They need their information in a directly usable form. After acquiring the words of a law, they need above all to know what the law means in a practical sense. Thus they need extended drill in applying the same underlying principle to the many diversified problems of the electrical industry."

Throughout the text Timbie follows an arrangement whereby he first offers a brief definition or discussion of his subject, followed immediately by a number of simple problems intended to allow the student to "make the sense of the matter his own, in his own language and manner of thought ... and to cultivate in him some degree of alertness and initiative in applying his knowledge."

At the close of each chapter there is a number of more advanced problems in which the author is at pains to apply the information
contained in the text to real situations, rather than abstract theory. A large number of diagrams of unusual clarity provide an exact and memorable visualization of the conditions of the problems. The author deliberately avoids overburdening the student in the early stages, providing only the facts and principles which he felt the technical student needed to know, and know well. The core material is primarily concerned with the principles of D.C. and A.C. generation, distribution, and the utilization in light and power. While the textbook was intended especially for technical students, and demanded of the reader only a knowledge of arithmetic and simple algebra, progression through the text did afford a substantial groundwork for more advanced work in electrical theory and practice, such as might be met with at university level.

Following a solid chapter on magnetism and equations relating to magnetic forces, he offers a very well illustrated account of electromagnetism, applying the theory to practical motors, and generators, and their uses in such applications as hoists, and the distribution of energy. Interesting individual chapters on the generator and the motor provide further theory and applications to particular conditions which the student will meet in practice, as opposed to the idealized theoretical conditions, drawing his attention to factors which would contribute to diminished efficiency. He details the action within the armature and the magnetization of the core, and the losses involved in generation and eddy current losses.

In the chapter dealing with induction Timbie progressively builds on the fundamental principles; deals with Lenz's law, and examines transformers, and the inductive properties of circuits
and explains the calculations used in the computation of inductance. Then he gives a clear account of the effects of inductance in practical circuits employed in transmission lines and oscillating circuits. An equally interesting chapter on capacitance provides the background history, the mechanical nature, and the applications of capacitors, and acquaints the student with dielectric strength, and provides the means of estimating capacity and its measurement by instruments. To maintain practical interest, the author show numerous applications of theory to practice, particularly in the areas of submarine cables; cables laid in metal sheaves which related importantly to telegraphy and telephony at the time of publication; and the capacity of aerial lines, and the practical tests applied to them; and the uses of condensers to absorb energy in the starting and stopping of heavy motors. All his problems and mathematical solutions are clear and thoroughly relevant to the text. The summaries at the end of each chapter are particularly good with short paragraphs emphasizing the most important points, using large capitals to highlight vital matters.

The quality of the text was quickly appreciated. The publishers were delighted to boast that sales exceeded those of any other comparable work. Each new edition was kept abreast of the times, describing and illustrating each advance in electrical technology.

W. H. Timbie's Elements of Electricity for Technical Students is an admirable introduction to the subject of electrical engineering and must be regarded as one of the classic texts in the history of electrical education.
The late 19th and early 20th century researches upon the transmission and detection of radio waves were put to practical applications with remarkable speed. An awareness of the great potential of this new form of communication spurred on some of the most brilliant minds in America, Europe, and Britain to design equipment which was not subject to the limitations of line telegraphy. In 1892 Edourd Branley invented his metal-filing detector. Three years later Guglielmo Marconi demonstrated his practical radio transmission with an oscillatory spark discharger, and reception with a simple raised aerial. In 1900 Marconi patented his invention of the tuned circuit of capacitor and inductor. In 1904 J. Ambrose Fleming, following the discovery of the "Edison Effect" \(^{(17)}\) invented the diode thermionic valve for detection, which was in turn improved by Lee Forest in 1906, who added a third electrode and thereby produced the triode valve, which provided the first reliable means of amplification of an electrical signal. The many requirements of the First World War accelerated further technical progress and introduced thousands of people to a new area of interest through technical training. For many the involvement in war-time communications was carried forward into a peacetime hobby - a hobby which was pursued with great enthusiasm.

Years before the official start of broadcasting by regular stations in America (1920) and the British Broadcasting Company in England (1922), there was intense activity by private constructors of radio equipment, encompassing the whole range of skills from those who built the simplest crystal-sets to the operators of
powerful long-range transmitters. The circumstance of numerous persons with knowledge and experience existed to support a radio manufacturing industry, and an expertise to run broadcasting services when these were established.

The BBC programmes aroused such unprecedented enthusiasm, that by the end of the first full year of broadcasting 492,000 receiving licences had been issued. Among these was a very considerable proportion of amateur practical constructors of radio receiving equipment, and to cater for them specialized educational publications quickly became available. One of the most ambitious, educationally sound, and influential projects was the preparation of Harmsworth's *Wireless Encyclopedia*, which was issued from 1923 in 24 monthly parts. This was designed to be read and studied, rather than used as a source of reference only. Under the consultative editorship of Sir Oliver Lodge, a galaxy of outstanding authorities provided special articles and extended essays on subjects of importance to radio amateurs. Among the contributors were J. Ambrose Fleming, Sir Edward Appleton, B.P. Eckersley (the chief BBC engineer), and J.H.T. Roberts, of the Cavendish Laboratory, Cambridge. The subjects examined represent virtually the whole range of electrical knowledge available at the time, compressed into 2,271 pages with the addition of 5,000 illustrations.

3.23

Harmsworth's "Wireless Encyclopedia"

A feature of the *Wireless Encyclopedia* of greatest importance is a series of extended essays, by the distinguished writers concerned with fundamental principles. J. Ambrose Fleming writes on
"Wireless Theory for Amateurs" in which he gives a concise and helpful introduction to the functions of the capacitor and inductor, showing how their relationships are fundamental to the means of transmission and reception, and explaining how a circuit requires to be tuned, adjusting the values of capacity and inductance to obtain a particular natural frequency of oscillation for transmission; and how the aerial similarly requires to be tuned to the same frequency. With unusual clarity he explains the nature of high frequency oscillations which form the carrier waves, and how the sound required to be broadcast is applied to modify the amplitude of the carrier waves; and finally how the receiving circuit is energized and able to decode the original studio sound.

A comparable extended essay by J.H. T. Roberts on "Electricity: characteristics and modes of action" discusses electron theory, electrical fields, and the nature of electric charge and potential. The writing emphasizes the functions of the capacitor and inductor, using clever photographs to show experiments such as the magnetic effects of current-carrying coils, and annotated drawings to explain the principles of the Oscillatory discharge of a capacitor; and the principles of measuring instruments.

Sir Oliver Lodge writes on the meaning of electrostatic capacity and its necessary associations with radio work. He explains the essential relationships of inductance and capacity in aerials, and shows how to calculate the capacity of different types, including single-wire aerials, as used by Marconi in his early experiments, when he suspended a vertical wire from a high post - in effect, a condenser with the wire forming one plate and the earth forming the other, with air as the dielectric. He also comments, explains, and calculates appropriately for parallel wires, and frame aerials.
Drawings from Harmsworth's Wireless Encyclopedia:
accompanying J.H.T. Roberts' article, "Electricity"

Fig. 15. On the left is shown the first stage in the series of oscillations following the discharge of a condenser. Lines of electric force are shown across the plates of the charged condenser, with no current in circuit. The condition is shown graphically in the diagram above.

Fig. 16. Terminals are connected and the condenser is accordingly discharged. No lines of force are indicated between condenser plates, the charge being in motion as current. Lines of force due to current are shown all round the circuit. One quarter of an oscillation period has now elapsed, as shown in the diagram above.

Fig. 17. The charge has run back into the condenser, charging it the opposite way round. There is no current in circuit, and no lines of magnetic force. Lines of force are shown in the condenser. This is half an oscillation period. The series is continued on the following page.
The quality of the writing throughout the Wireless Encyclopedia is so high that it compares favourably with much of the textbook writing intended for the professional in training. It is probably true to write that no other work intended for the amateur enthusiast ever surpassed this pioneering work in usefulness or interest. Not surprisingly, the three volumes have become the prized possession amongst radio constructors who appreciate vintage radios and the history of electrical engineering.

3.24

"The Foundations of Wireless"

Another relatively early text for radio amateur enthusiasts which won for itself a special reputation for quality and usefulness is the book which first appeared in 1936 under the title of The Foundations of Wireless by A.L.M. Sowerby. This book has continued in numerous editions and revisions up to the present time, though the later editions were substantially modified by M.G. Scroggie, and the work is now known as The Foundations of Wireless and Electronics.

This introduction to radio principles is basically non-mathematical in treatment, but employs the usual algebraic formulae. Its special qualities are the isolation of the really important elements of the subject which the amateur must know and understand thoroughly, and crystal-clear explanations and commentaries associated with carefully chosen and accurately located illustrations. The various editions have all stressed the importance of the tuned circuit; the uses of valves (and later, solid state devices); the principles of design in radio circuits; and the nature of amplification which aims
at avoiding distortion; and the means of providing power supplies to radio circuits.

Generations of technical students and enthusiastic amateurs have received a good grounding from this textbook which continues to be deservedly popular after 50 years.

3.25

H. Cotton's "Basic Technical Electricity"

For students following vocational courses in day and technical schools, the Professor of Electrical Engineering at University College, Nottingham, H. Cotton, prepared an appropriate text, *Basic Technical Electricity*, published in 1949. This was one of a series of works concerned with industrial applications of electricity, the purpose was to offer a training in the fundamentals which the technical student could utilize in his later work, rather than to prepare for any particular examination. The book was concerned with essential principles, practical measurements, and test instruments and such circuits as they would meet in industry. The text required only a basic mathematical equipment, and was editorially tailored to the vocabulary and interests of those with a modest educational background. A fault was that there were too few illustrations (only 74 line illustrations and six photographs of machinery in the earlier editions.)

The work proved popular with the students and teachers, and was frequently reprinted, the third edition appearing in 1960 in an m.k.s. form which took into account modern developments in components and instrumentation.
For those technical students who were more ambitious, and capable of more advanced work, there were the editions of Elementary Electrical Engineering, by A.E. Clayton and H.J. Shelley, both lecturers in Electrical Engineering at Victoria University. Their work, first published in 1927, could be used by those who had a familiarity with higher mathematics, and for many years this text was recommended by numerous technical institutions in preparing their students for diplomas in Electrical Engineering at the Ordinary standard. The work offered a thorough grounding in D.C. and A.C. circuits, transformers, measurement, the distribution of power, electrical lighting, and small electric motors. A great deal of technical material was covered in a somewhat dry, uninspiring manner. It appeared to be favoured by the teachers rather than the students, though the latter were well served by the provision of numerous questions and answers designed to test whether they had absorbed the information offered in the text. There were numerous reprints and editions, the 5th in 1966, each more densely packed with technical information which kept abreast of new devices such as solid state components, and the modern circuits which employed them.
New York Institute of Technology: Programmed Texts

A most interesting text for American university and college entry students was prepared by the staff of the Electrical Technology Department of the New York Institute of Technology, between 1958 and 1964. This is in the form of a linear programmed text, Programmed Course in Basic Electricity. This text is one of three which were developed after extensive discussions with the Electronics Industries Association of America, and a group of major companies employing large numbers of those trained in electricity and electronics.

The course is organized in a sequence of very small interrelated steps which take the student forward from the most elementary concepts and mathematical procedures to moderately advanced levels of understanding. An essential and important element in this course is the large number of small drawings which assist and guide the student learning. The sections on capacitors and inductors are both admirably clear and sound: in the case of capacitors, the student is first introduced to the concept of capacitance and the symbols used for different types of components; then charging and discharging and the function of the dielectric is illustrated in a series of small diagrams; thereafter the student is exercised in the factors which govern capacitance, the units and the calculations. Later, phase relationships and capacitors under A.C. conditions and capacitive reactance is examined, and finally, energy losses in a capacitor and capacitor voltage ratings are introduced.

Inductance is similarly treated in a large number of small steps. Initially the magnetic field around a current-carrying conductor is shown through diagrams, then solenoids are introduced
and Fleming's Hand Rules, followed by Lenz's law; and diagrams explain the induction of a coil by current changes. Thereafter simple transformer theory is given and calculations for self- and mutual-inductance. Small distinct drawings explain the dependence of induced EMF on the angle of cutting, and this is followed by induction related to generators. The section closes with inductance and voltage phase relationships and inductive reactance.

The student who conscientiously works through these programmed sequences would undoubtedly gain a basic understanding of the concepts of inductance and capacitance, and would be well prepared to do more advanced work. He/she is able to check his own progress by undertaking questions on the theory given and by calculating problems - the answers being given at the end of the book. 19

3.28

M. Nelkon's "Electricity and Magnetism"

During the 1940's and 1950's, M. Nelkon, Head of the Science Department, William Ellis School, London, published a number of school texts on Physics and Electricity which set a high standard for other authors to emulate. His Electricity and Magnetism, first published in 1948, was regarded with particular respect by teachers and pupils as it passed through many editions. The text deals with the classical principles of electricity and magnetism to the General Certificate of Education scholarship level, offering a thorough grounding in the concepts central to electrostatics,
magnetism, and A.C./D.C. circuit theory. It was also one of the first texts to recognize that schoolchildren should have the chance to learn something of the physical principles of valves, and valve circuits, which up till then had been an area exclusive to the vocational students. An excellent feature of the book was the inclusion of 381 illustrations. Both students and teachers appreciated the inclusion of many numerically-worked examples taken from the examining boards, and the guidance given in the handling of units and symbols included in equations, and the assistance in applying numerical values.

In the chapter concerned with condensers and electrostatic instruments, the author presents all the necessary information in a straightforward manner often anticipating student difficulties, and treating the subject with such thoroughness that those who followed the text would feel confidence in tackling any of the examination questions on the subject. Included in the treatment is the comparison of capacitors by ballistic galvanometers, the circumstances governing capacitance, and relative permittivity. Different types of capacitor, mica, paper, variable air, and electrolytic are introduced and their utilization given. The measurement of capacitance is examined through the use of various instruments, including the gold-leaf electroscope, the quadrant electrometer, and the electrostatic voltmeter.

The author's chapter on electromagnetic induction is comparable in its thoroughness, although much information is given in a compact space. Good diagrams accompany text explanations of the magnitude of induced EMF; Lenz's law for the direction of induced EMF; and worked examples applying the formulae firmly fix the principles in the reader's understanding. Descriptions of experiments with the primary and secondary coils make use of information
already gained, and are supported by excellent diagrams.
Transformer theory is given and related to both audio and radio frequency transformers. The growth and decay of current in an LR series circuit is examined, as is the energy stored in the magnetic field of a coil. Thereafter, the principles which have been expounded are applied to the nature of the simple generator and to the electric motor.

A grounding is also given in A.C. theory with sound passages dealing with phase differences, lagging and leading, and A.C. currents treated as vector quantities. The variation of $X_C$ and $\phi$ and $C$, and the variation of $X_L$ with $\omega$ and $L$. The student is also given basic information of series, parallel, and resonant circuits.

The popularity of Nelkon's text was to some extent challenged by one or two authors who used a lighter style which was thought by some teachers more appropriate to the contemporary schoolchildren.

3.29

Tom Duncan's "Physics: A Textbook for A-level Students"

One text in particular was, and remains, highly favoured, Tom Duncan's Physics: A Textbook for Advanced Level Students (1981). The more leisured exposition and generous supply of photographs, diagrams, drawings, and various small aids to learning provides an attraction to the latest generation of students preparing for A-level and technical certificates in vocational institutions. While the subject matter covered is much the same as that of rival textbooks, the author has been at pains to bring his material close to the interests of the contemporary learner.

In the pages dealing with capacitance, a few uncomplicated
passages relating to plate capacitors and the dielectric are supported by excellent drawings which help to clarify the concept of the electric field. The worked examples are simple and sufficient to impress the necessary operations. The relevance to the contemporary scene is evoked by use of an analogy between electric and gravitational fields which are then applied to space travel. Good cut-away drawings and photographs of different types of capacitor connect the text with practical components, and drawings are used to show the student experiments which can be carried out on the capacitors, and there are passages dealing with instruments used for capacitance measurement: the electroscope, the D.C amplifier, and the electrometer.

The section on electromagnetic induction makes easier reading than is frequently the case. The historical situation is given, basic principles explained, and the classical experiments of Faraday are illustrated in a series of easily understood drawings. Lenz's law is given and the application related to a number of different situations in generators and motors. The photographs and drawings emphasize the real utility of the fundamental principles previously explained, and the student is given the impression that he has gained an insight into the production and distribution of electric power.

The publisher has been more indulgent than usual in the size, number, and variety of illustrations - though the provision has resulted in the book being exceptionally costly for a soft-bound schoolbook. Discussions with students appear to confirm that the author has anticipated the most common student difficulties.
M. Nelkon has also provided a very suitable textbook for the less academically able or vocational student, in his *Advanced Level Magnetism and Electricity*, first published in 1954. In this text the physical aspects of the topics is kept in the foreground with an emphasis on a very clear presentation of fundamental points especially those which were likely to worry the student with a limited mathematical ability. Again, in this textbook there are numerous examples, fully worked out for the student to follow, from examination papers set by various boards. The treatment of inductance and capacitance is similar to that offered in his *Electricity and Magnetism*, though there is a little less compression of explanation and commentary.

Nelkon also prepared a text suited to the requirements of 'O'-level GCE candidates in his *Fundamentals of Physics* (1967) which was widely accepted as a solid and reliable book. His careful selection of those parts of scientific knowledge essential to the syllabus, presented in short sections with an easy progression from one level of difficulty to the next, won for this book a wide acceptance in the schools comparable to that enjoyed by the more advanced texts. The adaption which he made in *C.S.E. Physics* (1975) to cover the C.S.E. examinations of the principal boards, proved to be particularly popular, meriting frequent reprints, and three revisions, each brought in line
with contemporary advances in scientific knowledge and the needs of teachers and pupils.

**C.S.E. Physics** offers the younger or less able pupil an informal approach, inviting involvement in the unfolding of the mysteries of electricity by the inclusion of much reference to things electrical with which they may have some knowledge and experience. Most sections have an historical introduction, then short paragraphs giving basic theory lead on to simple experiments described in the text, and illustrated with drawings which are particularly easy to understand by the addition of coloured direction lines. A large number of these illustrations merge with the text and are supplemented by photographs of modern devices, and instruments which make use of the principles described. The fundamentals of magnetism and electromagnetism are provided and closely connected with such common domestic equipment as electric bells and the telephone. At the end of each short section there is a most useful summary of the principles covered, which in turn is followed by a practical section which allows the laboratory work to build upon the theory previously outlined. In addition, there are ample exercises laid out in the form of revision, and these are provided with full answers and explanations at the end of the textbook.

Chapters of the textbook examine the motor and the dynamo. Each is provided with exceptionally clear drawings, and those concerned with the motor are designed to show the physical motions as well as the principles of action, and progressively move from the theoretical to the practical motor. It is then shown through photographs and other illustrations how the moving coil principle is applied to numerous instruments.
Electromagnetic induction is largely explained through the analysis of the dynamo. Some of the basic principles being carried forward from Faraday's experiments to the student's personal experience of the cycle dynamo. An elementary account is given of A.C. conditions and a number of almost self-explanatory small drawings introduce the action of the primary and secondary coils of the transformer. The principles of the transformer are associated with the transmission of electrical power and the grid system. C.S.E. Physics by these means holds the pupils' attention and coaxes him/her forward in easy stages, and constantly displays the relevance of the theoretical principles being studied.

3.31

The Nuffield Advanced Physics Course

During the later 1960's and early 1970's a great deal of thought and discussion was directed towards alternate ways of teaching and learning in science. At school level one of the boldest and most interesting undertakings was the preparation of the Nuffield Advanced Physics course, led by the Joint Organizers, P.J. Black, University of Birmingham, and Jon Ogborn, Worcester College of Education, with a team of teachers from a number of schools and colleges of technology. In this course a good deal of emphasis was placed upon the students learning by themselves by practical experiments, guided by carefully prepared textbooks and notes. There was a deliberate design intention to avoid theoretical remoteness, and to offer fundamental principles which might be useful for the present
and the future. The presentation and the materials were designed to stimulate scientific interest and thoughtfulness among the learners. The theory and experiments were intended to illustrate the important ways in which discoveries in Physics have affected human life in modern times. The organizers intended that the students should enjoy their progression in scientific studies, and gain satisfaction from a growing understanding of the fundamental principles and the practical applications, and the intellectual stimulus of problem-solving in the case of electricity and electronics when dealing with components grouped to form circuits of practical application.

Those sections dealing with capacitance and inductance involve the student in more practical experimentation than would normally be offered on a traditional course. It also involved rather more use of equipment - much of it being designed specifically for the Nuffield Advanced Physics Course - than was commonly used in most schools. In studying the charging and discharging of capacitors the students are expected to measure with appropriate equipment the charges on the capacitor when particular electromotive force is applied through batteries; to note the potential difference across the capacitor and resistors, and the current through the resistor; the rate at which the charge on the capacitor is increased or decreased; and by personal experiment the student is expected to gain an understanding of the nature of time constants in RC circuits, examining the wave forms on an oscilloscope, and by carrying out their own measurements. Through numerous experiments with capacitors in A.C. circuits the student can follow by means of the oscilloscope the variation of the current and voltage for
a capacitor through a full A.C. cycle. Similarly, the difficulties which students often have in understanding capacitive reaction can be minimized.

The course programme allows the students to see how RC circuits are used in various electronic devices, and the student is taken on to the study of operational amplifiers where the use is made of circuits containing resistors and capacitors, so that they quickly feel that they have been gathering information which is not just theoretical, but which has an immediate practical application, and one concerned with items which are impinging on their own environment.

In the section on inductance, the student similarly learns primarily by what the inductors do, rather than by traditional theory lying behind their operation. Again, with the assistance of the oscilloscope, the behavior of the inductor is examined and the student is taken through experiments which show the relationship of current and voltage and energy flow through an inductive circuit. Similarly, phase differences in an LR circuit are examined and the students are offered an introduction to impedance. He/she also works through experiments with oscillations in a parallel LC circuit, and advances to experiments with radio fundamentals using tuned circuits.

There are similar extensive experiments whereby the student may gather the fundamental principles and mechanical actions of the motor and generator, aided by specially-written textbooks into which the numerous drawings and diagrams are a vital and integral part. Much of the written text serving not only to explain and comment on the material to be studied, but to encourage the students to apply the principles to the practical experimentation.
The evidence which has accumulated from the experience of teachers and students working with the Nuffield Advanced Physics Course is that it has been highly stimulating, and has met a weakness which did exist on some courses where too little practical work was carried out by the students themselves. The students have expressed enthusiasm for the practical involvement, and both teachers and students have been warm in praise for the handbooks prepared by the course writers.
The very active amateur body of constructors of radio and electrical equipment diminished greatly during the late 1950's and 1960's due to the easy availability of low cost ready-built items of radio, audio, and electronic test equipment. However, in the 1970's there was a burst of renewed interest among the amateurs: the mass-production of solid state components provided the home constructor with low cost, easily handled, space-saving components, and the opportunity to undertake circuit designs for audio and radio which were impractical at an earlier time. Magazines, such as the Radio Constructor, Everyday Electronics, and Hobby Electronics flourished for a number of years, providing a new generation of amateurs with circuits and constructional designs for a range of useful and entertaining devices, and kept the largely youthful readers abreast of the rapid developments in electronics.

Because there was a real demand, and because it was very much in their own interests, Everyday Electronics ran, almost every year, a series of instructional courses (usually in 12 parts) which introduced the newcomer to electricity and electronics fundamentals. By specifying the use of solderless breadboards and mass-produced transistors, diodes, resistors, and small capacitors, the publishers were able to design their own courses with the minimum of expense to the readers.
In these courses the mathematical content was limited almost to simple arithmetic, and the use of formulae was restricted, and the instruction depended very much upon pictorial representations, layouts which could be imitated with ease, simplified drawings, and photographic details. Once the basic principles were explained, the readers were encouraged to apply what they had learned to practical circuits. When the nature of capacitance was outlined and the functions of capacitors in such situations as coupling, filtering, and isolation had been given, the reader was invited to begin the construction of small devices in which these components could be utilized. Similarly, in the case of inductance, the readers were instructed in their role as key components in oscillators, and tuned circuits, then presented with situations where they could be so employed.

While by conventional standards the mastery of electrical theory was somewhat neglected, the conscientious reader could be enabled very quickly to apply new-found knowledge to the production of items of test equipment, practical amplifiers, and a variety of musical and entertainment devices - and, hopefully, to be infected with an enthusiasm to continue in the hobby of electrical and electronic constructions.
For vocational students a large number of books have been provided to assist those following courses in preparation for "City and Guilds" and later, "Technical Education Courses". The majority tend to be repetitious in their statements of principles and in the illustrations employed. Books for vocational students require to possess special qualities to tempt the readers into a pattern of regular use: all teachers at technical schools know that the majority of beginning students have an inbuilt resistance to studying from textbooks.

Frank Linsley's "Introduction to Electrical Science"

One author with a particular appreciation of the difficulty is Frank Linsley, whose Introduction to Electrical Science, first published in 1974, is written in an informal, conversational manner designed to coax the student into cooperation.

In this book a number of student difficulties have been anticipated, and every effort has been made to produce an interesting and attractive book. This short work is largely descriptive, rather than mathematical, but the calculations presented are carefully worked step by step in numerous examples. Fundamental principles are laid out succinctly, numerous drawings of simple circuits are given and commented upon, and many practical points which the vocational student will meet are explained in a direct
and simple manner. Capacitance, is treated rather slightly, but electromagnetism and induced EMF is examined more thoroughly. Induced EMF is considered through the rotating magnet generator, assisted by self-explanatory drawings; Faraday's laws and the essentials of magnetic flux linkage are explained, and transformers introduced by expanding on the principles already given. The calculation of secondary EMF for a given p.d. applied to the primary is offered in round figures, and there is a simple statement relating to power ratings.

Throughout Frank Linsley's book there is a regular emphasis upon practical applications of electrical principles tending to persuade the student that what has been studied has an immediate and permanent usefulness in his intended profession.

3.34

Roger Hamilton's "Electrical Principles for Technicians"

For the more advanced vocational student, Roger Hamilton, of Wolverhampton Polytechnic, has provided Electrical Principles for Technicians (1980), primarily designed to cover the T.E.C. syllabus, "Electrical Principles, Levels 2 and 3". This book contains excellent chapters dealing with capacitance, and the magnetic field, and electromagnetic induction. The student is first introduced to the concept of the electric charge and field, illustrated by the traditional Maxwell drawings, then there is a clarification of potential and the electric field strength which prepares the student for the study of capacitance; then, a series of circuit drawings lead the student through the theory of series and
parallel arrangements, and prepare for an analysis of the parallel plate capacitor and the dielectric and the energy stored in a capacitor. Equipped with this theoretical foundation the student is taken on to worked examples involving real capacitors, and introduced to paper, mica, ceramic, air, and electrolytic capacitors which will be met with in vocational situations.

In the section dealing with electromagnetic induction, the vocational student is made specially aware of the importance of this property which is of such importance to his understanding and handling of motors, generators and transformers. Worked examples and line drawings illustrating the principles are especially clear and direct in their application to real-world conditions. Self- and mutual-inductance are explained and discussed in a straightforward manner and each is related to other engineering fundamentals, such as transformers, motors, and generators, discussed elsewhere in the text. A series of worked examples, questions, and tests is used to build the students' confidence in the principles expounded.

The important principles relating to A.C. circuits which the vocational student will meet in practice are thoroughly examined, and there is a firm grounding in sine waves, and their additions, R.M.S. values, and phasors, all illustrated by numerous worked examples and diagrams. Other equally sound chapters dealing with the transformer, generators, and motors, guide the student thoroughly in important concepts and practical applications within the electrical engineering field.

Electrical Principles for Technicians is a reliable companion to vocational readers' studies and a solid foundation for any further more advanced work which may be undertaken.
Bleaney and Bleaney's "Electricity and Magnetism"

At university level Physics, a textbook held in high esteem by colleges which place great emphasis on mathematical expertise is *Electricity and Magnetism* (3rd edition, 1983), by B.I. Bleaney, Fellow of St. Hugh's College, Oxford, and B. Bleaney, Professor of Experimental Philosophy, University of Oxford. The textbook first appeared in 1957, and has undergone various reprints and two subsequent editions. It is intended to cater for undergraduate Physics students, but has some chapters which can be used during the early part of a graduate course. The fundamental theory of capacitance and inductance is included in the first eight chapters which the authors describe as "at an elementary level".

The concept of capacitance and the nature of the capacitor is preceded by a number of sections concerned with electrostatics, where the treatment is rigorously mathematical, though the shape of the exposition follows the historical researches of Coulomb, Faraday, and Maxwell. Having outlined the electrical nature of matter, Coulomb's law and fundamental definitions are given; electric field and potential are considered, definitions of electric field and potential are given, lines of force are discussed and illustrated with Maxwellian drawings, then the student is introduced to Gauss's theorem. Thereafter electric dipoles are examined and numerous equations derived; then follows a consideration of the dielectric and the concept of polarization is discussed.
Gauss's theorem is applied to dielectrics, and equations are derived for electric displacement. There is a discussion of the vector quantities, electric displacement $D$, and there is consideration of boundary conditions at the surface between two dielectrics, and illustrated by two line drawings. The potential energy in a system of charges and charged conductors is reviewed, and expressions are given for the total energy in such a system; finally, stresses in dielectric media are examined and expressed in terms of the Maxwell Stress Tensor, illustrated by line drawings.

In the chapter dealing with "Electromagnetic Induction and Varying Currents" reference is made to Faraday's experiments and the results are summarized in two laws and the sine of the e.m.f. is given by Lenz' law. An equation is given for self-induction and the circumstances of magnetic induction from one coil to another is introduced; a formula is derived for mutual-inductance (Neumann's formula), and an equation given for the circumstance where the flux through two coils is changing; the practical transformer is referred to, and the coefficient of coupling is explained. Calculations of the magnitude of inductance is illustrated for a number of different shapes of coil; long, solinoid, two coaxial coils, and a pair of coaxial cylinders, illustrated by line drawings. There is a discussion of transient currents and circuits containing inductance and resistance, and capacitance, accompanied by a number of simple circuits, and an examination of the operation of a battery charging a capacitor; and a consideration of the discharge of a capacitor through resistance and inductance, accompanied by
two drawings comparing an oscillatory discharge with non-oscillatory discharge. The magnetic energy and mechanical forces in an inductive circuit are described, and equations are derived for various circuits and different circumstances. Some of the principles obtained from a study of inductance are applied to measuring instruments; galvanometers, ammeters, and voltmeters, and the wattmeter.

The treatment in all these sections is rigorously mathematical, and although the authors consider their presentation to be at "an elementary level", discussion with those to whom the text was recommended indicate that many find the writing unattractive and difficult to follow; on the other hand, those with a confident fluency in mathematics consider the style pleasing in its compression and directness.

3.36

W.J. Duffin's "Electricity and Magnetism"

Another textbook much used and liked by undergraduates reading Physics is W.J. Duffin's Electricity and Magnetism, first published in 1965, and subsequently issued in revised editions. The author writes in his preface:

"The text particularly emphasizes the experimental basis, the development of concepts, and the reasons for introducing them, as well as the formation of general laws and their application to specific problems."

The writing is specifically designed to engage the student's attention and sympathy, rather than provide a detailed exposition. The earlier chapters take into account the possible gaps in the
knowledge of those who have come direct from A-level preparatory work. The treatment is such that it can benefit Engineering students as well as those reading Physics. There are many excellent features which assist the student by clearly laying out the nature of the matters to be studied, and the author's aims for each section. There are also useful summaries of important results to be derived from the chapter to be read, and recommendations for further reading. An interesting addition is a set of commentaries on the material of each chapter, which in the author's words has the purpose of showing "That the subject is still alive and well, and to counteract the feeling, often engendered by a textbook, that the elementary classical Physics is closed to further argument and discussion."

The chapter on "Capacitance and Electric Energy" applies a good deal of the information which the students received from earlier sections dealing with the electric field and electric potential, and the forms of Gauss's law, and that is used to investigate practical conditions. The concept of capacitance is introduced and discussed, and definitions offered, and the proportionality of $Q$ and $V$ explained; ideal and real capacitors are examined in text and with drawings, and the subject of distributed capacitance is related to coaxial cables. Methods of calculating capacitors in series and parallel are given, and a simple network of capacitors analysed; the theory of the dielectric in its different forms in real conditions is examined; and, thereafter different types and their functions in circuits are introduced, and finally stray capacitance and screening are explained. There is no doubt that considerable pains have been expended to avoid unnecessary complications in deriving the equations, so that the students with only
a moderate background in mathematics can progress with the text.

The chapter on "Electromagnetic Induction" is particularly interesting in its exposition, and is rendered easier to understand by the numerous clear drawings. A section explaining Faraday's experiments in succinct form is followed by a study of electromotance, assisted by numerous small drawings showing induced electromotance in a moving conductor, and flux cutting and flux linking in the motion of a rigid circuit. Other sections deal with the transformer and show the relationship of the concepts already gained. In short, direct passages the student is introduced to the concept and definition of self-inductance and the calculations of its values. Similarly, mutual-inductance is treated through various examples which most students can follow with relative ease.

Each section ends with problems for the student to solve, which are designed to reinforce the knowledge gained or to check the accuracy of the information memorized. The arrangement is such that each chapter is almost in the form of a revision upon what has previously been studied.

Discussions with those students who used the text indicate that this is one of the most popular books among first and second year undergraduates reading Physics or Engineering.
SUMMARY

In the middle of the 19th century the new science of electricity attracted the interest and curiosity of many who had not taken any part in the pioneering work, and the publishers soon realized there was a market for introductory texts. The earliest of these were written by academics like F.C. Webb, H. Noad, and F. Jenkin, who provided elementary overviews of the principal fundamentals known to them: electrostatics, capacitance, and induction. All the authors, without exception owed a great debt to Michael Faraday, not only for his research findings, but for the example he had given in the orderly presentation adopted in his *Experimental Researches in Electricity*.

The textbook writers were equally in debt to James Clerk Maxwell for the mathematical interpretation and expansion of Faraday's pioneering experiments given in his *Treatise on Electricity and Magnetism*: it was a rich fund of electromagnetic theory from which they could extract material suitable to the different levels of student requirement. Maxwell's *Treatise*, probing and extending all the electromagnetic knowledge of his time, is one of the greatest intellectual achievements of the 19th century, but it is useful only to those possessed of a fluency in higher mathematics. The posthumous simplified version of his text, published as *An Elementary Treatise on Electricity*, was also important through the stimulation it gave to academic authors who wished to reach out to the non-specialist readers. One such author, Silvanus P. Thompson, produced his masterly introductory text, *Elementary Lessons in Electricity and Magnetism* in 1881, and it enjoyed international popularity and merited respect for the next two generations.
Because the rapidly expanding electrical industry required appropriately instructed technicians, academics like J. Ambrose Fleming, and Andrew Jamieson provided them with texts of a non-mathematical type, where the emphasis was upon diagrams and illustrations, and the clarification of the new and complicated concepts. Both authors concentrated much attention upon providing the technicians with aids to memory.

These writers and others recognized that Higher Education students required to be well-grounded in mathematics to maintain and advance the progress in electrical knowledge. They wrote for their own students, and subsequently had published for others, technically advanced works which expounded theory and practice of the electromagnetic equipment which was becoming ever more important. Towards the end of the century, in England, S.P. Thompson's *Dynamo Electric Machinery* (1884) became a classic text for the engineers studying generators and motors, and at the beginning of this century, in America, the *Textbook of Physics*, edited by A.W. Duff (1910), and W.H. Timbie's *Elements of Electricity for Technical Students* (1911) held a similar respected position.

With the advent of radio communication, texts were required to guide the large and enthusiastic body of amateur constructors. They were well served by expertly written works such as Harmsworth's *Wireless Encyclopedia* (1923) edited by Sir Oliver Lodge, and A.L.M. Sowerby's *Foundations of Wireless* (1936).

The present day radio, audio, and electronic equipment constructors are guided and advised by monthly journals like *Everyday Electronics*, and *Hobby Electronics* which contain valuable instructional courses designed for those without higher mathematical
knowledge, where the dependence is largely upon pictorial representations to simplify fundamental principles.

During the last forty years the school pupils have had many electrical texts written specifically for those preparing for admission to Higher Education courses, but in all probability none have been more favourably received by the teaching profession than the works of M. Nelkon, whose 1948 *Electricity and Magnetism* became a bench-mark for other authors. More recently, works written in a persuasive, lighter style, which aim at presenting the essential information in a manner attractive to the contemporary pupils have sprung into popularity, like Tom Duncan's *A Textbook for Advanced Level Students* (1981). These, and alternative approaches, like the texts to accompany the Nuffield Advanced Physics Course have been produced with the intention of stimulating pupils in scientific thought, and encouraging them to more personal exploration of practical circuits than is usual with traditional courses.

A similar shift away from formerly favoured texts may be observed at the university/polytechnic first year level. Both Engineering and Physics freshmen express in conversation, and demonstrate by their choice of books on their shelves, that they seek works which aim to engage the students personal interest, such as W.J. Duffin's *Electricity and Magnetism*, where the emphasis is not primarily on the submission to an extreme severity of mathematical discipline, but where the reader is given explanations why particular concepts are introduced at particular locations, and the reader is gradually made aware that he is progressing in knowledge through the application of previously treated subject matter. It is worthy of notice that such books are now referring to the continuity of historical research in electricity.
In the course of the history of more than 100 years of electrical education textbooks, a few authors stand out for the quality of their expositions and their very great influence upon contemporary readers and subsequent writers. Silvanus P. Thompson is certainly one of these, and he is followed by Fleming, Lodge, Jamieson, and Timbie. Their work offered the example and laid the foundations for the range of excellent contemporary texts which are available to the pupils at school, the vocational trainees at technical college, and the university students - all of whom can today benefit from more numerous and better quality illustrations than were ever offered before.
CHAPTER FOUR

THE INTERVIEWS

4.1 The Interviews 169
4.2 Pilot Study 170
4.3 Three Categories of Students 173
4.4 The Interview Procedure 176
4.5 "Visualizers" and "Mathematics" 186
4.6 Extracts from Interviews: School Pupils 189
4.7 Electrical Hobbies and School Work 190
4.8 Discussion: Hobbies and School Work 195
4.9 Problems and their Solutions 197
4.10 Discussion: School Pupils' Problems 200
4.11 School Pupils: "Visualizer" or "Mathematic" 202
4.12 "Visualizers" 202
4.13 Discussion: "Visualizers" 208
4.14 "Mathematics" 211
4.15 Discussion: "Mathematics" 216
4.16 School Pupils' use of Textbooks 220
4.17 Discussion: Use of Textbooks 222
4.18 Practical Work 223
4.19 Discussion: Practical Work 228
4.20 Capacitors and Capacitance 230
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.41 Interviews with University/Polytechnic Students</td>
<td>278</td>
</tr>
<tr>
<td>4.42 Memories of Theoretical Studies at School</td>
<td>281</td>
</tr>
<tr>
<td>4.43 The Treatment of Electromagnetism</td>
<td>282</td>
</tr>
<tr>
<td>4.44 Particular Difficulties at &quot;All Girls&quot; schools</td>
<td>283</td>
</tr>
<tr>
<td>4.45 Unqualified Physics Teachers</td>
<td>284</td>
</tr>
<tr>
<td>4.46 &quot;Visualizers&quot;</td>
<td>285</td>
</tr>
<tr>
<td>4.47 Difficulties with Inductance</td>
<td>285</td>
</tr>
<tr>
<td>4.48 Practical Work</td>
<td>287</td>
</tr>
<tr>
<td>4.49 The Need for More A.C. Experience</td>
<td>288</td>
</tr>
<tr>
<td>4.50 Criticism of the Academic Approach</td>
<td>289</td>
</tr>
<tr>
<td>4.51 The Need for a &quot;Revision Course&quot;</td>
<td>290</td>
</tr>
<tr>
<td>4.52 Meeting Difficulties</td>
<td>292</td>
</tr>
<tr>
<td>4.53 &quot;Visualizer/Mathemetic&quot; in Higher Education</td>
<td>295</td>
</tr>
<tr>
<td>4.54 Dislike of Practicals</td>
<td>298</td>
</tr>
<tr>
<td>4.55 The Student &quot;Visualizers&quot;</td>
<td>302</td>
</tr>
<tr>
<td>4.56 The Uses of &quot;Mental Pictures&quot;</td>
<td>304</td>
</tr>
<tr>
<td>4.57 Problems with Inductance</td>
<td>305</td>
</tr>
<tr>
<td>4.58 &quot;Visualizers&quot; and Textbook Illustrations</td>
<td>306</td>
</tr>
<tr>
<td>4.59 &quot;Visualizers&quot; and Practical Hobbies</td>
<td>308</td>
</tr>
<tr>
<td>4.60 Higher Education Students' Understanding of Capacitance</td>
<td>312</td>
</tr>
</tbody>
</table>
4.61 Capacitive Reactance
4.62 Higher Education Students' Knowledge of Inductance
4.63 Students' Understanding of the Transformer
4.64 Reluctance to Speak about Inductance
4.65 The Principles of the Motor and Generator
4.66 Higher Education Students' and Textbooks
4.67 Higher Education Students: Hobby Magazines
4.68 The Experience of Practical Work
4.69 Difficulties with Circuit Diagrams
4.70 Criticism of Laboratory Practice
4.71 Guidance Required in the Interpretation of Circuit Diagrams
4.72 The Need for an Introductory Course
4.73 Demonstration and Instruction Required: Motors and Generators
4.74 Criticism of Excessive Theory and Abstract Mathematics
4.75 Criticism of Tutorials
Discussions with students and with teachers at universities, polytechnics, technical colleges and schools have provided good reason to believe that many who begin the study of electricity experience difficulties in mastering some of the fundamental principles, and this is particularly so in the case of the phenomena of capacitance, inductance, and electromagnetism related to generators and motors.

During numerous talks with training officers and works managers in the electrical and engineering industries, a recurring topic was a complaint that the new recruits display serious weakness in their understanding of fundamental principles. Although this matter has seldom received publicity, it must be regarded as worthy of concern, for the employers are obliged to spend much time in providing revision and instruction.

Conversation with many students of electrical subjects have convinced me that a significant proportion of those who have passed far beyond the elementary stage of their studies of electricity and electronics do not have confidence in their own understanding of various basic principles; and, failure to grasp these can introduce difficulties at their future occupation, whether that be the instruction of others, practical work with electrical equipment, or industrial supervision.

My research programme has aimed at gaining information on the nature of students' difficulties, and to learn if these may be connected with the strategies used by teachers to explain and comment on these principles; or the students' lack of personal interest in the basic electrical properties, or the methods employed by learners to clarify difficulties;
or the student's experience of practical work in the laboratories; or inadequacies of the textbook presentation (including methods of explanation and graphic illustrations); or whether there are other factors which might interfere with the students' ability to form a clear understanding of the concepts involved. If these questions could receive satisfactory answers as a result of the research programme, then I hoped I would be able to make recommendations which could ameliorate the students' difficulties.

Exploratory talks were held with teachers of Physics and electrical technology at different levels, from elementary school Science to university degree work in Engineering and Physics; but the principal source of helpful information was the students themselves, especially those who had quite recently completed their formal programme of studies which qualified them for Higher Education courses.

Pilot Study

4.2 A pilot study was undertaken which was in the form of meetings with teachers in charge of university, polytechnic, and Further Education courses in Oxford, followed by interviews with 18 of their students. During the interviews I encouraged the students to recall those portions of their earlier work which had caused them problems and anxiety, or required particular personal attention. The discussions and interviews confirmed that the subjects chosen for investigation were indeed those which caused difficulty and some continuing anxiety beyond the preliminary stages.

The pilot study revealed that there was no doubt that some of the students were experiencing difficulties with textbook use, practical work in the laboratories and classroom instruction which were unknown to their own teachers. Further, it suggested that the students could be persuaded to speak without restraint about their difficulties with the study of capacitance, inductance, and electromagnetism, and the
degree of success which they had in overcoming these difficulties, only when they were convinced, in the course of a fairly lengthy conversation, of the genuine sympathy of the inquirer. Such conditions can best be met by extended informal conversation in a relaxed atmosphere; it was therefore decided that the interviews would be held, whenever possible, in the students' own rooms or recreational quarters.

The Research Interviews

In the course of a programme of interviews which extended over four years from 1982 until 1985, three categories of students discussed their problems and learning experiences with me. These were: school pupils preparing for A-level examinations; vocational students at technical institutions; and first year Physics and Engineering degree students at university and polytechnic. At all school and vocational interviews there was prior consultation with the teachers, and at university with the lecturers or tutors (whenever they were prepared to meet me), so that I had the benefit of their experienced comments on regularly occurring problems, student misunderstandings, the knowledge of the examination board requirements, and other matters which can affect student performance. Subsequently, I was introduced by them to their students so that any possible suspicions of my intentions might be disarmed. Although each category of interview required a slightly different approach governed by the student's age and prior electrical education, the nature of all was similar, being a semi-structured interview substantially centred on a core of prepared questions and topics.
The pilot study had revealed that there was much dissatisfaction felt by students at all levels of study concerning the nature of the theoretical and practical presentation of their courses; so, during the four-year programme of interviews, those who took part were asked to give recommendations for changes which, in their opinion, would improve the methods of instruction, or the content of the courses, or the laboratory procedures, and each was encouraged to make critical comment on the textbook explanations and the graphic illustrations.
THREE CATEGORIES OF STUDENTS

School Pupils

4.3 Research was conducted at a number of Oxfordshire schools preparing the 5th and 6th form Science classes for the Oxford and Cambridge entrance examinations, and the GCE examinations (several of them making use of the Nuffield Advanced Physics course, in whole or part). 30 Pupils were interviewed, selected by the Science teachers to represent the range of ability, some of whom were known to have had difficulties with the electrical portion of their Physics studies. During the interview a core of selected topics and questions was introduced to coax the learners to speak freely about their knowledge of capacitance and inductance. The schools included Comprehensives, Oxford College linked, and Independent public schools.

Vocational Students

I received cooperation from a number of the lecturers attached to Further Education colleges in Oxfordshire, and I was given access to their classes and practicals in the laboratory, where I had discussions and subsequent interviews with 20 1st and 2nd year day-release students following the 3 year Technical Education Course (TEC), the majority of whom are engaged in electrical equipment servicing or were working in the light electrical engineering industries. I have also had the cooperation of the staff of the North Oxfordshire Technical College at Banbury, and those of the Abingdon Further Education College. I attended the classes and the laboratory meetings, and interviewed 20 students representative of a varying range of ability.
The pilot study had revealed that it was not unusual for these students to take an irresponsible attitude to arrangements made, and to fail to honour appointments for interviews. In an effort to put the forward-planned meetings on a secure foundation, each volunteer was sent a written confirmation with the time, date, and location of the interview, and it was made clear that a fee of £1 was to be paid as recompense for the person's time. This proved to be effective as a reminder and an incentive to keep the appointments.

At Oxford all the colleges were notified of my research project: permission was sought from the Heads of all colleges to allow me to invite 1st year students reading for degrees in Physics and Engineering Science to meet me for discussion. All but two gave such permission, and several appeared personally interested and sympathetic with the undertaking. Unfortunately, there was little interest or support from the tutors. The few who were willing to meet me were cooperative and prepared to discuss the student difficulties, and provided samples of their "hand-outs" and student test-papers.

A large number of students volunteered to meet me. Most appointments were in response to notices posted on the student notice-boards, but many came through introductions from those who had already been interviewed; others, who had heard of the research programme, came forward independently—not a few of whom expressed appreciation that some one was showing sympathetic interest in matters which had been a source of anxiety to them. Visits to talk with the students engaged in practical work at the Clarendon Laboratories resulted in a series of interviews, and similarly, visits to speak with 1st year students at the Engineering Science buildings brought numerous volunteers.
The friendly interest of the Professor of Engineering at the University of Reading resulted in introductions to members of staff, and the opportunity to meet first year Engineering and second year Electrical Engineering students in the laboratories, and there arrange for interviews. Similarly, the cooperation of the Electrical Engineering staff at the University of Surrey gave me the facilities to talk with students in the laboratories and obtain a series of interviews.

I have had numerous meetings with my former colleagues at the Oxford Polytechnic, both in the Engineering and Science departments, and I have been able to spend time in the laboratories gaining the acquaintance of the students and subsequently interviewing many of them. Laboratory discussions were held with over 350 university/polytechnic students, and extended interviews were subsequently carried out with 90 of these.
The semi-structured interview permitted a considerable degree of freedom with regard to the particular questions asked and the order in which they were put, although a central core of topics was always included. The early stage of the meeting usually provided sufficient information on the person's familiarity with the subject to allow an approach in conversational inquiry at the appropriate level of electrical experience. The interviews were private: the school pupils met me in their empty classrooms, and the vacational students usually talked with me in a side-room adjoining their laboratory. In the case of the university/polytechnic students, whenever it could be arranged, the interviews were held in the privacy of the student's rooms. A firm assurance was given that whatever they might tell me would be treated as confidential, and that nothing of it would ever be quoted in a manner which could identify the speaker. (A few laboratory partners requested joint interviews, and these were accommodated; and, exceptionally, a small circle of friends arranged a group interview.)

With the permission of the student, a tape-recording was made of the interview which followed the introductory section. Because the pilot study had shown that the appearance of a fairly large tape-recorder and microphone tended to evoke self-consciousness or reticence among some students, the practice was adopted of putting both machine and microphone out of sight.
The interview was effectively split into two parts: during the first part - extending to 20 minutes or more - the aim was to win the student's trust, and put him or her at ease. It was explained that the primary purpose of the research was to gain greater knowledge of the learner's problems. Although each conversation was necessarily different and dependent to a great extent on the student's background, there was much encouragement to speak of personal interests, educational experiences, successes and disappointments in their studies. Whenever the conversation touched upon any memory of difficulty in following classroom instruction or laboratory work, or textbook use, such matters were picked out for closer scrutiny. The second part of the interview generally lasted 30 minutes, and here the conversation was guided towards the prepared framework of questions, supplemented by a number of drawings and diagrams, which were used to explore the student's familiarity with the phenomena, and confidence in discussing the concepts associated with capacitance and inductance, and electromagnetism related to generators and motors.

The interviewee was asked when and where his/her first study of electricity began, and encouraged to reminisce about any portion of the early studies remembered as troublesome. If specific areas of difficulty were mentioned, these were queried, to learn if the student associated these with class teaching, or textbook reading. Thereafter, the student was asked what strategy was employed to overcome such difficulties. If preference had not been already expressed, it was inquired if the solution to the problem was sought first from the teacher, or textbook or fellow student; and, if the information was not volunteered, the reason for the order of preference. Particular interest was taken in the students' use of textbooks, and comments were solicited on the usefulness for personal study, reference facility, and clarity of explanation, and guidance from drawings, photographs, and diagrams.
The student was asked to speak of the relationship of the classroom teaching to practical work in the laboratory, both in earlier and current courses, and encouraged to comment personally on the division of time and attention and the importance which practical work took in that person's learning experience. Quite frequently some reference to laboratory experiment led to a discussion on the application of electrical components, and then the interviewee was asked about his familiarity with them, especially capacitors and inductors.

The student was then asked, "How does a capacitor work?" and school pupils were shown a line drawing:

![Line drawing of a capacitor]

Thereafter, depending on the accuracy or comprehensiveness of the answer, there were questions on the essential features of the component, and the nature of the dielectric and other physical conditions which govern its operation. At some point Capacitance was mentioned, and then the student was asked: "Can you tell me something about the quality of a capacitor which we call its "Capacitance?" The student's understanding
of d.c. and a.c. applications was questioned, as well as familiarity with the units of measurement, and the formulae which relate capacitance, voltage, and charge.

The students were asked what size of capacitors they were familiar with, and there was usually some discussion about the reasons why they were unlikely to have had experience of a one Farad capacitor. Some questions on charge storage usually followed.

The school pupils were shown:

![Diagram](image1)

and

![Diagram](image2)

and were asked to give a commentary on how the charge builds up on the capacitor, and drawn to see if they had knowledge of time constants, and asked to compare the conditions of d.c. and a.c. connected to the capacitor. Most students were asked about phase relationships of voltage and current, and about capacitive reactance. The interviewee was then asked to speak about the practical uses of capacitors.
The inductor was then considered. The advanced students were asked: "Tell me something about your experience with inductors?", and the school pupils were shown the drawing:

and asked: "What happens when the switch is closed?" When some reference is made to magnetic field, the interviewee was asked to relate that to the current, and asked about the length of its duration. If the person referred to the growing or collapsing magnetic field, there were questions on the result of that.

There usually followed some conversation leading to the subject of back-e.m.f., and knowledge of this was drawn by requesting some commentary on "what happens?" If the person was able to do so, he/she was encouraged to offer an understanding of the term "Inductance."

The student was shown the drawing:
and asked if he could indicate which is the North and which the South pole, and by what process the decision was reached. The person was asked what would be the effect of replacing the battery with an a.c. generator, and (unless it had already been mentioned) was asked about time constants, and the more advanced students were asked to speak of phase relationships of voltage and current, and asked about the formula for inductive reactance. The subject of mutual inductance was mentioned and inquiries made if the transformer had been studied.

The drawings were shown:

![Diagram of magnetic field and coil connections.]

The interviewee was asked: "How is the secondary coil affected when the switch is closed?" According to the reply, the student was encouraged to speak of Lenz' law, the polarities, and what happens when the current reaches maximum.

A drawing of the collapsing field was then shown and the interviewee was asked: "What is the effect upon the secondary coil?"
If the answer did not introduce current direction, inquiry was made about this, and an explanation sought. Then the student was asked to speak of the uses to which inductors are put.

The interviewees were asked about reading circuit diagrams: how they approached this, and whether they had had any instruction in doing so.

The school pupils were shown the drawing:

![Circuit Diagram](image_url)

and asked if they could recognize the components, and then asked what function they served. They were asked to attempt to identify the nature of the circuit and to give a commentary on the flow of signal.
The vocational and university/polytechnic 1st year degree students were shown the circuit diagram, and the same questions were put:

Each student was asked if they constructed any circuits out of personal interest (such as amplifiers, radios, etc.) and if they read any of the electronic magazines, such as Wireless World, Radio and Electronics World, Everyday Electronics, Hobby Electronics, etc. Finally, each was asked what changes - given an ideal situation, he or she would make in the instruction received, and what each might like to learn that he/she had not been taught.
Analysis of Interview Data

The tape-recording of each interview (and the written notes taken during discussions) were carefully reviewed, and what were regarded as significant comments or answers by the interviewee were isolated for consideration, and interpreted partly in the light of the person's history of study given during the initial informal discussion, and partly by knowledge of similar patterns of learning experiences gathered from the interviewee's peers.

If the person had indicated the characteristics of a "Visualizer" or "Mathematic", his conversation and answers were checked to see if there was any evidence that his tendency influenced to any marked degree his choice of reading matter, or his response to the different types of classroom and laboratory instruction offered, or his procedures applied in private study.

Particular attention was paid to problems encountered in understanding the fundamental properties of capacitance, inductance, and electromagnetism related to generators and motors, for the purpose of deciding whether or not these could be due to inadequate theoretical background, or the inability to relate theoretical knowledge to the practical conditions in the laboratory. Similarly, careful note was taken of particular difficulties experienced by the three categories of interviewees; school pupils, vocational trainees, and university/polytechnic students. The data was examined for information concerning the individuals realization that problems existed, and the measure of importance they attached to these matters, and it was observed what action was taken to attempt to resolve them;
and, in the case of successful outcome, what share could be attributed to individual effort, the teacher's assistance, and helpful textbook presentation in words, examples, or diagrams.

The interviewee's extra-mural electrical recreations were noted and, whenever these could be related to course work, the person's observations on possible benefits were compared with the comments of others of comparable experience.

The person's critical comments on the educational content of his course, and the manner of instruction in both classroom and laboratory were carefully analysed to learn what was commonly approved or complained about, and suggestions were extracted for future improvement.

The data was examined for particulars of student experience which might lead to the discovery of previously unsuspected reasons for learners' difficulties in mastering the electrical fundamentals considered in this inquiry.
Quite early in the research programme it became apparent through the interviewees choice of examples and description of study habits, that they had a bias towards either a mathematical orientation, or a bias towards a graphic orientation in their electrical studies. The first class of student will tend to base his study and understanding of electrical fundamentals upon mathematical formulae which relate to the measurable phenomena associated with components and circuits. Although he may have at some time examined the physical action models of capacitance and inductance, he relies upon mathematical description, and immediately thinks of the formula $C = \frac{Q}{V}$ or the formula $E = N(\frac{\Delta Q}{T})$ volts. These students I have identified as "Mathematics" in this research.

The second class of student will tend to base his study on a visualization, or mental graphic representation of the physical functions of components or combination of components in a circuit. Such a person when considering the action of a capacitor will summon up a mental picture of two plates being charged, and indulge a more or less clear impression of an accumulation of electrons "stored". Similarly, in the case of the phenomenon of inductance, this type of student tends to picture the current flow, and associate magnetic field, cutting the conductor itself, and visualizes a surge of induced e.m.f. These students I have identified as "Visualizers".
Each class is influenced by his natural tendency when studying textbooks, following class teaching, or reading circuit diagrams in practical work. The "Visualizer" may be intimidated by explanations of principles expressed in concise mathematical presentation, but he encounters fewer difficulties in mastering fundamental principles when offered a variety of illustrations which represent the actions of currents and the effects of voltages. He tends to read the circuits as groupings of components which have particular physical functions which can be clearly visualized, and he may have difficulties when attempting to comprehend situations where there is a complex time element, such as may not be easily translated into separate images, e.g. oscillating or capacitive reactive circuits. On the other hand, the "Mathematic" student will happily follow textbook discussions and blackboard talk with the minimum of diagram aid, and will read his circuit primarily in terms of the measurable characteristics of component groupings, and be guided by the formulas which govern those particular arrangements.

The information obtained from my research programme indicates that the "Visualizer" students outnumber the "Mathematic" students at the Secondary Education level, and that in Tertiary Education the highest proportion of "Visualizers" is to be found among the Engineering degree students. Discussion with first year university tutors confirms this observation.

During the interviews the "Visualizers" constantly stressed the need to "see" or "imagine in the mind" physical actions, or recall to their memories diagrams or images from the oscilloscope; the "Mathematics" were less explicit and descriptive, usually limiting their comments to expressions of deep interest in the mathematics, and taking the attitude that their methods were so natural (to them) and so superior that no alternative approach was worthy of much discussion.
During the interviews considerable attention was focused on these contrasting classes, and the bearing which their characteristics had on the student's study techniques and reactions to the teaching received, and the appropriateness of their textbooks to cater for their distinct tendencies.
School Pupils

4.6 My knowledge of current youthful hobbies, and discussion with those preparing for A-level examinations gave good reason to believe that a substantial proportion of school pupils had electrical interests, and some practical construction experience which was unconnected with their formal studies in Physics. One of my first questions, therefore, was directed to learning when they had first come into contact with electrical interests, and to inquire if this was a hobby activity, and whether or not it had a beneficial influence upon the school work which they were required to do in both classroom and laboratory. The information supplied indicates that even more of the pupils than I had believed had some experience of kit-building or interconnecting of prepared modules. These undertakings varied greatly in their educational qualities, but even those which provided slight theoretical insights to the electrical operations tended to stimulate an interest in more serious activities when the kits, or modules were treated with more than superficial attention.

The following extracts from interviews give some exchanges of conversation which provide information on introductory electrical experience, and are characteristic of the range of answers given by many pupils to this question.
Electrical Hobbies and Influence on School-work

Extract No. 1

("Phil", a 6th form boy, who had family encouragement.)

Interviewer: Can you tell me if you had any electrical hobbies before your school Physics course?

Student: Two or three years ago, I started off making crystal radios with my grand-dad.

I. Did that lead on to anything else?
S. Well, I got interested in electronics.
I. And you made up other things?
S. Yes, I built several short-wave radios.
I. Would you say that the radio building at home has helped you with your present A-level studies?
S. Yes ... but there is very little electronics involved, just the basics of transistors.
I. Do you continue to do practical work for yourself as a hobby?
S. Yes. I've just done a "Robyton" attachment for my computer.

Another 6th form boy, "Magnus", had been given an electronics construction set some two years before, and had subsequently gained a considerable degree of interest and experience of working with components. I asked:

Extract No. 2

I. And did you use it much?
S. I enjoyed myself making things for myself. I built a few things.
I. Would you consider that such work with an electronic construction set has helped you in your electrical studies here?
S. I'd say it depends on the kit: I'd say if it was all laid out on a plate, you probably gain little. I adapted a bit. If you have to think about it yourself and work out values and so on, then it's good. If it's all explained, there's a tendency not to think about it.

"Tim", a pupil in the lower 6th form at an Oxford College-linked school, told me he had been imitative of the hobby activities of an older brother, and that for about 5 years he had "dabbled" in circuit building.
Extract No. 3

S. Electronics is my main hobby: making things.
I. What do you make?
S. Simple radios, and power supplies, and various small things.
I. Can you tell me something about the beginnings of your electrical hobby?
S. I used to buy *Everday Electronics* every month. They had a basic electronics course. I did some of the experiments - when I had the components. But I didn't actually go out and buy all the parts necessary for the complete course. I think that some of the circuits covered are very useful for basic principles, but the course wasn't much use if you wanted to have something finished - something in a box for use afterwards, and say: "Look what I have finished."

I. Did you continue to buy *Everday Electronics* when the basic electronics course ended?
S. Yes, but after a couple of years I began to realize that the circuits were being repeated.
I. Would you say that the study of those magazine circuits helped you with your school work here?
S. In some of the circuits, yes. They gave block diagrams. Most people haven't seen the circuit before, and if you split into small blocks, then you can examine each block separately. You find that you can take it in easier.

I. Quite often people at school will say to me that they are very interested in electronics, yet they don't construct things. Can you say why that's so?
S. I'm not really sure. I think you have to have a certain ... you have to be inclined in a certain way. I don't build things specifically for a task, I don't build them to be useful. Certain things I build, then I see if they work. If they do, I'm pleased. If not, I take them apart and do something else.

"Martin", a fellow pupil in the same class as "Tim", had some two years before been gifted an educational electronic construction set, but he had not persisted with experiments with it, and did not believe that it had contributed much to his studies, but acknowledged that the practical manipulation had some value.

Extract No. 4

S. I had the "Radionic" kit. I made up some things from that; they were quite interesting.
I. Did the circuits work when made up?
S. 75% of the time they did.

I. When they didn't work, how did you go about finding out what was wrong?
S. There was a faults list. The way they set their board out - it was rather complicated - they had printed circuit boards, and you had to look very carefully to see ... I think it could have been laid out better.

I. Would you say that such building with the "Radionic" kit has contributed to your understanding of the electrical work you do here?
S. Well, no ... well, I think it lets you appreciate it with a sort of "hands on" feeling. The usual way is "hands off" - theoretical. So, you can actually see things.

"Rupert", a 6th form pupil, who was following the Nuffield Advanced Physics course, told me that he had earlier done some simple circuit building before his present studies. Recent laboratory work had reminded him of pleasant memories, and he was stimulated to further personal practical experiment.

**Extract No. 5**

I. Can you remember any of the circuits you built from components?
S. I built a "Flip-flop" and a small transistor radio.

I. Where did you get the circuit design from?
S. It was from a book of some sort.

I. Was it a hobby publication?
S. ... there's one book I've got, called *Electronics*, I can't remember the author - a Penguin book, I think ...

I. Can you say why you didn't continue with the electrical constructions?
S. Well, my hobby is now computers. But ... we've just done transistor amplification in Physics. I find it quite interesting. I was thinking about making an amplifier myself.

I. Could you do your private work here in the laboratory?
S. I have my own soldering iron and solder, and things like that. So I can do it here.
A few pupils who had started early upon hobby electrical work at home were able to acquire considerable experience of circuits before reaching the A-level preparation stage. This could result in a superior attitude towards their colleagues, and an arrogant, unjustified opinion concerning their own level of knowledge.

One 6th form boy, "Edmund", a pupil at a private school, came from a family with professional association with electrical engineering, and had had several years kit-building experience before the A-levels.

Extract No. 6

S. The others haven't done as much construction, but they've covered most of the same - well, all the same basic electricity work.

(Asked about his own early constructions, he replied:)

S. They were "Radionics", pre-mounted components. I made things like small amplifiers, oscillators, systems ...  

I. Did you follow circuit diagrams?

S. Yes.

I. Would you say that the kit-building made the understanding of circuit diagrams easier for you?

S. Yes - but I think I had already always understood it, anyway.

The possibility of making an easy transition from educational amusement with a kit to A-level preparation was brought out by "Pat", a 6th form pupil, who had been gifted a "Radio Shack" electronic experiment kit.

Extract No. 7

I. Can you tell me when you first started those electrical experiments?

S. I think it was in the 4th year - I had been bought an "Electronic Lab" kit.

I. Did the "Electronic Lab" kit kindle an interest in electronics?
S. I think so, because after only a few minutes of effort you could see something positive as a result.

I. Did that home construction help with your electrical studies here?

S. I think so. When I had built a few things I had used plenty of components. I think I was fairly familiar with them as practical devices. The practical work with them made it really more meaningful.

The temptation to use an educational electronic kit for purely personal amusement was indicated by one pupil, when replying to the question, "Was experience with it a useful introduction to A-level laboratory work?"

**Extract No. 8**

S. Well, I don't think so. I mean, I enjoyed myself making things, but it was very much like putting a jig-saw together.

I. Were there not discrete components and a circuit diagram?

S. There were circuit diagrams, and I looked at them, but I didn't make much of them. With the kit it was more like intelligent playing about

Another 6th form boy, who spoke of being familiar with common components from an early age because of his father's professional involvement with electronics, was weak on theoretical knowledge.

**Extract No. 9**

I knew how to put electrical components together, and I had an interest in it, but capacitors and inductors ... well, it has taken me a long time to really understand them.
DISCUSSION

Electrical Hobbies and Schoolwork

Some of the pupils had been introduced to electrical constructions at home by older relatives, and by their example and guidance had been started upon a hobby which was relevant to an important area of their school Physics. Interview Extract No. 1 relates to the development of a hobby which had its origin in the practical skill of a grandfather, who, in all probability, had himself in his youth built the type of crystal set which he introduced to my pupil. The satisfaction obtained from building a simple crystal set is well-known to all who have undertaken this project as a first exercise of practical electrical construction, and not infrequently other more sophisticated radio receivers are built to gratify the interest and curiosity aroused by the construction. This was the case with "Phil" who developed an interest in the short wave bands, and constructed appropriate radios for the reception of distant signals, and thereafter moved on to other branches of electronics, including his current enthusiasm for computers.

The enjoyment obtained from practical home constructions of even the simplest nature is the motivation for the youngster to exert himself in carrying out the educational experiments intended to be undertaken with the prepared kits, and it is the spur to dare to undertake the more advanced projects involved in building units from circuit diagrams published by the hobby magazines. This is clearly indicated by "Magnus" in Extract No. 2, who "adapted a bit" and gained useful experience which he carried forward to school work. Without doubt, there is a fascination involved in building practical
working electrical systems from discrete components which is difficult
to convey to those who have not had that experience: that fascination
was known to "Tim" who in Extract No. 3 explained: "I don't build things
specifically and for a task, I don't build them to be useful. Certain
things I build, then see if they work. If they do I am pleased. If not,
I take them apart and do something else."

The initial interest created by first home efforts is sometimes
couraged by more experienced acquaintances, but from the earliest days
of amateur electric constructions the commercial publications have been
highly influential. "Tim" was one of the pupils who recognized the
value of the beginners' magazine "Everyday Electronics" and took advantage
of the "Basic Electricity" courses which that publication has run at
regular intervals during the last ten years. He acknowledged that: "Some
of the circuits covered are very useful for basic principles" and realized
that their method of explaining theoretical diagrams by simplifying into
"blocks" of essential circuit elements was an aid to understanding his
school work.

Even those pupils who did not persevere in using their educational
construction sets, like "Rupert", appreciated that the handling of
components provided a useful introduction and could be the means of
directing attention towards other associated electrical activities
such as computer projects. While some of the more advanced pupils
preferred not to dwell on their early experiences in using kits, most
admitted that they had assisted in following circuit diagrams, and
provided a means of gaining confidence in recognizing and handling
discrete components. This was typified by "Pat", who, after he had
built a few constructions had used "plenty of components" and become
fairly familiar with them as practical devices.
Problems and their Solution

4.9 A question was put to all interviewees: "Do you remember any particular difficulties in your electrical studies?" This deliberately loose generalizing language was used to avoid trespassing on the more specific questions on capacitance and inductance to be put at a later stage of the interview. However, by no means all were prepared to vocalize any such memories, and in many cases the existence of troublesome difficulties was made plain at a later stage of the meeting. Characteristically, many minimized known difficulties, then spoke more freely of them later. Not infrequently an honest and forthcoming answer would indicate how difficult some of the fundamental principles are to the young learner.

When a recognized difficulty was mentioned, it was inquired what strategy was adopted to clarify it, and to whom the person looked for assistance. It was noted how rarely the pupil would go directly to his teacher with a problem.

A 6th form boy at a private school, "George", was willing to be cooperative in answer to this question:

**Extract No. 10**

I. I wonder if you can remember any particular difficulty at an earlier stage of your course?

S. Yes ... I don't know whether it's my fault or not, but I've always found it a bit difficult to accept something that is new, therefore it takes me quite a long time to accept some simple rules, or facts, or even in some cases, what you would call common sense ideas.

I. Could you give me an example?
S. Well ... like current going through a battery and wires and so on. Even now, I'm not absolutely confident that I know what's going on.

I. If you find yourself with something you can't understand, do you go to ask the master, or do you talk with other boys, or what?

S. Well, when I have a problem I always try to think about it, to sort it out myself, and, I'm afraid in 9 out of 10 cases, it doesn't work. Then I'll try and look through the books that I like.

I. Could you tell me which they are?

S. One is Nelkon and Parker, and there are two I can't remember, but I have found them useful. But if I still can't find any clues, then I ask some one else, one of my study mates, and if I still can't understand, then as a last resort, I go to the masters.

A 6th form boy, following the Nuffield Advanced Physics course, "Magnus", could not think of any specific difficulties he had had during his electrical studies, explaining that, "My major problem is with Mechanics."

But he was prepared to speak about solving his problems:

Extract No. 11

S. I'm fairly lucky. I don't actually find it too difficult. There are one or two of us doing it together ... probably we do have problems

I. Tell me, when you have a problem, do you go to a friend, or a textbook, or the teacher?

S. What I do usually is leave it overnight, and think about it. If I still can't manage it, then, yes, I look through the Physics books. If that doesn't work, probably I'll come and ask Tony (the technician) - he's usually around. If he can't manage it, I go up to the library.

Several pupils were not prepared to identify current electrical problems, but would recall those of the past, and explain how they overcame difficulties. A 5th form boy, "Julian" following a Nuffield course at
Extract No. 12

S. When I was about 14 or so I had difficulty discovering the difference between voltage and current. It took a long time to grasp it. They were both measurements and I didn't really know much else. Eventually, it clicked. They used analogies with water ... I think I then realized what the problem was.

I. Now, when you have a difficulty in understanding some part of your course, what do you do: do you ask your friends, or your teacher, or look for the solution in textbooks?

S. Generally I'd say ... I'd talk to some of the others. I think that would help.

I. And if it didn't?

S. ... I suppose I'd look at the books.
Problems And Their Solution

4.10 In the matter of coping with electrical study problems the interviewees several times expressed their determination to face the intellectual challenge and overcome it without assistance, if possible. "George" and "Magnus" (Extracts. Nos. 10 and 11) both gave the impression of taking considerable pride in not flinching from difficulties presented during their courses. Characteristic of the attitude of many pupils, they preferred not to discuss the problem with their colleagues until they had first attempted to gain clarification from the books they had to hand (usually few in number). Most pupils preferred not to speak about a learning problem - through embarrassment or fear of being thought "slow-witted" or less capable than their peers; but, if there was some reason to believe that someone else shared the same problem, then it could be openly discussed. Close friends and study-mates were those with whom discussion might first be made, and if no solution followed, then a superior authority was to be consulted.

Two points of interest arise from these exchanges. The first is that very few pupils take their problems directly and immediately to their teachers. None of the pupils gave me to understand that they doubted the teacher's ability to assist them, so their reluctance to approach the teacher is more probably due to the desire not to reveal their "ignorance." With some there may have been a feeling of guilt that they had not paid sufficient attention during classwork, but most entertained adolescent embarrassment because they had not readily grasped some concept or mathematical procedure. All who spoke to me of their problems were prepared to put themselves to considerable inconvenience before approaching their own teachers. This diffidence on the part of the pupils was certainly not fully appreciated by the teachers with whom I conversed.
The second point is that the school libraries are not used effectively by most of the pupils. While it is not to be expected that those at school will have developed the same ability to work efficiently on their researches as older students, it became plain to me, through listening to the pupils descriptions of their activities in the library, that they often do not seek assistance of the more experienced persons in locating those books most appropriate to their needs. Their accounts suggest that their ill-organized library investigations were frequently unsuccessful, and it was at that moment that they approached their teacher: if the matter seemed to them sufficiently important to risk "losing face."
In conversation and interview several of the school pupils indicated that a graphic or visualizing approach was essential to their study and understanding of electrical properties - and this was particularly so in the case of capacitive and inductive phenomena. Three of the interviewees could be identified as pronounced "Visualizers", and these were well aware of their own tendencies; nevertheless, as the matter had never been discussed with them, none had ever given any consideration to the significance of his methods and inclinations in comparison with colleagues. Others indicated by their conversation that they entertained a bias towards the "Visualizer" approach.

A sixth form pupil, "George", who had spoken of problems experienced at different stages of his electrical studies, clearly identified himself as a person who relied heavily upon mental pictures. After he had said that he was a slow learner, and a person who found considerable difficulty in understanding the fundamentals of electricity, he was encouraged to be more explicit:

Extract No. 13

I. Can you tell me a little more which might suggest the reason for your difficulty in understanding?

S. I think the reasons are partly personal - I have to form a picture of what is going on.

I. Yes, I am interested in this.

S. I like to think of pictures of current and so on, but it's
difficult. And, so ... I mean, the masters certainly try very hard
to explain it to us, but - I don't know if it is true of other people -
but I often need to visualize exactly what is going on - say, the electrons
in the circuit.

Later in the interview he implied that his visualizing approach
was not well matched with the textbooks which he used. He had been
asked if the texts "explained things in a way that makes matter clear
to you" and he had replied:

Extract No. 14

S. I would say No - because ... well, Nelkon and Parker is a
very good book, but there is so much there that it doesn't always
explain clearly - except in mathematics, then it does describe in
detail. Otherwise - it may not be so for any one else- but I think that
it doesn't explain in a way that I really understand. I think that
what is said in the textbook doesn't often link up with the problems
I have.

Another pupil in the same form, "Edmund", who had had some
considerable experience of hobby electronics, was proud of his ability
to interpret circuit diagrams with fluency. When asked to offer an
opinion why others often found considerable difficulty in this reading,
he replied:

Extract No. 15

S. I think that some people wouldn't straight away follow circuit
diagrams and the splitting of currents. I can think where things go.
I. Do you mean that you can visualize current or signal flow?
S. Yes, I can.

At another time during the interview, when he was referring to
the charging of a capacitor, he offered a strong graphic description:

Extract No. 16

S. There is a high initial current, then it slows down. So it is
being stored somewhere - you're charging.
I. When you say 'charging' what do you mean? how do you think of it?

S. The easiest way to visualize it would be a circular tank with a rubber diaphragm - using the water analogy - water is pumped in, the battery being the pump. You are initially having a large amount of water flowing in, then as the pressure rises, it stops flowing in.

Although mathematic expertise and strong tendencies towards the "Visualizer" characteristics can be found in combination, the majority of those who favoured the mental visualization procedures were not very fluent mathematicians. This was noted among the school pupils, where several who spoke of experiencing difficulties with the mathematical requirements of their Physics courses, appeared to take considerable comfort in the fact that they could sometimes obtain a working acquaintance with certain principles by exploiting mechanical analogies or mnemonics.

One lower 6th form pupil, "Martin" told me that he was experiencing such difficulty with the mathematical side of his course that he had been obliged to get assistance from a tutor; when shown a simple inductive circuit he felt perfectly confident that he understood the fundamental principles of the current, voltage and magnetic flux based on a memorization of a textbook illustration:

*Extract No. 17*

I. I am interested to know how you think of what happens when we complete this circuit by throwing the switch?

S. Well, what happens ... OK ... Well, the way I think about it is, that you are supposed to think of electrons moving, therefore the current moves the other way, then there is the generation of a field, a magnetic field. I use the "right-hand grasp" - it is very visual. I mean, you actually have to follow it round, and make sure that it is going to go down that way. Therefore the current will be up in the centre.

I. When you think of a field growing, what in fact comes to your mind?

S. Little lines - I don't think there is going to be a force field gravitational or magnetic, or whatever: it's little lines.

I. So in your case it is done in a graphic sense?

S. Absolutely.
This boy was particularly observant and appreciative of the graphic design features of a favourite electrical textbook, *A-Level Physics*, by Rober Muncaster (1981), and said:

**Extract No. 18**

"I like the shading - and the impact of some of the diagrams. I like the diagrams to be large. A useful thing, is the way they set out their equations: if there is any kind of variable they put on a little aside, that this equation comes from, say 'See page 17' or so, or they give you definitions."

A fifth form pupil, "Rupert", somewhat uncertain of his mathematical ability found difficulty in relating formulas to component functions and obtained much assistance from mental imagery. Asked if he could remember if capacitance had caused him trouble during his studies, he replied:

**Extract No. 19**

S. It has. I didn't understand it the first time it was explained to me - it was a matter of keeping on reading in the book about it.

I. Are you able to tell me a little about where the difficulty lay?

S. I ... once I started thinking of electrons moving, and building up on one plate, and being sort of drawn away from the other, I think that clarified it a lot. Whereas just saying: "the charge on something" is less easy to understand.

I. Are you the sort of person who likes to picture things in your mind?

S. Very much. I like to know that an electron is moving along somewhere rather than depend on an equation. I'm quite happy with mathematical formulas as well, so long as I can know what is taking place inside.
Ascription of Tendency

The grounds for my ascription as either "Visualizer" or "Mathematic" were drawn principally from the interviews, where an account of an approach to electrical studies might refer to the need for pictorial aids; or, reveal a history of success in mathematics. Other indications were contained in volunteered comments on the type of textbooks or classroom/laboratory teaching preferred, and in the emphasis placed on graphic imagery or formulae when speaking of learning experiences. While not all those interviewed could be categorized with certainty, it was frequently the case that a clear tendency was revealed in the course of the semi-structured interview. On some occasions an individual's bias was apparent during the earlier (non-recorded) preliminary conversations. (It should be mentioned that I consciously attempted to avoid settling any ascription until the full interview had been concluded.)

When the person was a strong "Mathematic" or a strong "Visualizer", their offered comments and direct answers quickly provided information which corresponded with the particular pattern of preferences which I had noted in others of their category. In the case of those less pronounced in their tendencies, my grounds for ascription accumulated in the course of the interview, when I noted repeated references to pictorial illustrations, or memories of visual observations of circuits or demonstrations, or details of personal constructional experience. Sometimes I had been alerted by the speakers examples, calling forth component operation diagrams which had been useful; or the application of Fleming's finger rules; or reference to electrical circuits where power currents or signal paths
had been fixed in the memory. By encouraging the learners to
speak of their problems and the methods they employed to solve
them, I obtained a considerable body of information about the
persons study habits which might link that individual with one
or other tendency. Not infrequently their comments on classroom
or laboratory presentations gave further indications of their
bias which could confirm the ascription.

Although few if any had given the matter specific thought,
some pupils were aware that they had a disposition to form mental
imagery in the course of their electrical studies; they may have
particularly active pictorial imaginations, or possess gifts of
draghtsmanship which can be frequently associated with the play
of visual forms in the mind. If the early application of graphic
imagery has eased the course of initial electrical studies, it is
likely that this approach will be continued as the investigation
of circuits becomes more complicated. A minority of those class-
ified as "Visualizers" would speak of weakness in mathematics,
and there is some reason to believe that they consciously applied
a pictorial approach to their electrical work to compensate for
difficulties experienced in following abstract mathematical theory.
"Visualizers"

George, can be classified as a pronounced "Visualizer." In Extract No. 12, he explicitly tells of his need to form mental images to aid his understanding of the electrical fundamentals: "I have to form a picture of what is going on." Some of his difficulties in the classroom were due to that requirement not being gratified. He acknowledged that the teachers exerted much effort to clarify what seemed obscure to the pupils, yet he felt sure that their approach, and that of the textbooks, did not suit his personal needs.

From the school pupils point of view, most of the Physics teachers in the schools are exceedingly knowledgeable in the electrical principles they are attempting to convey to those in class. Whether or not this is the case, it can be difficult for some, especially if new to the profession, to believe that a straightforward mathematical presentation could present problems to intelligent youngsters. The desire for mathematical rigor and the old tradition that it is an undesirable weakness to simplify, may also contribute to an academic approach. The Physics teacher's natural inclination may be towards the "Mathematic" tendency, and many are probably quite unaware of the discomfort felt by the pronounced "Visualizers" among their pupils. Such pupils would benefit from a stronger emphasis being placed on explanations which detail physical processes of the dynamic functions of components and electrical properties.
In extract No. 14, "George" vocalized his dissatisfaction with his recommended textbook (long held in high regard by the majority of school Physics teachers): "It doesn't always explain clearly - except in mathematics, then it does describe in detail ... but I think that it doesn't explain in a way that I really understand." To a person like "George", of strong visualizing tendencies, the mathematical proofs and "intricacies" of mathematical explanation appear frustrating and alien, and there is good reason to believe that such learners can react with dismay, and may lose heart and not persist in trying to obtain a full understanding of the principles being presented.

Some of the pupils with pronounced visualizing tendencies, such as "Edmund", have gained confidence through practicing methods natural to them. He was more assured in reading circuit diagrams than others in his class, and could visualize "The splitting of currents" (Extract No. 15) and could "Think where things go," and his interest and enthusiasm for the subject had motivated him to seek out literature which offered explanations suited to his own tendencies. His knowledge of theory was buttressed by highly visual mechanical analogies like that which he used to describe the charging capacitor in extract No. 16.

In the study of inductors the "Visualizers" receive much assistance from Fleming's two "hand-rules". Several of the pupils automatically began to position their fingers when asked about the action of a simple inductive circuit. "Martin", identified as a "Visualizer", typified the situation when he said (Extract No.17) ... "I use the 'Right-hand grasp' - it is very visual. I mean, you actually have to follow it round, and make sure that it is going to go down that way." Both "Martin" and his colleague, "Rupert" held in their minds vivid memories of the introductory graphic models of electron movement and lines of force. For them those were not images to assist the transfer of thought to mathematical formulae, but ever-present graphic representations.
As "Rupert" said (Extract No. 19) in connection with capacitive charging: ... "Once I started thinking of electrons moving, and building up on one plate, and being sort of drawn away from the other, I think that clarified a lot. Whereas just saying, "The charge on something' is less easy to understand." And later: "I like to know that an electron is moving along somewhere, rather than depend on an equation."
4.14 During the research programme the data obtained from the three categories of interviewees provided evidence that those with a pronounced "Mathematic" tendency were very much a minority in each category. Of the relatively small number of school pupils interviewed, one boy demonstrated by his answers and attitude that his natural inclination was that of a pronounced "Mathematic", and a second, though less intensely so, was clearly characterized by "Mathematic" tendencies. Both were 6th form candidates for approaching A-level examinations.

The pronounced "Mathematic" among the school pupils had (or affected) a considerable superiority towards practical electrical work, and particularly the simple laboratory measurements, calculations, and experimental operations which related to the theoretical expositions of classroom or textbook.

When asked: "Have you made a hobby of constructing anything electrical?" he replied: "No, I don't want to." The following exchange continued:

Extract No. 20

I. Don't you like the practical side?
S. I'd say the things we do in the lab are waste of time.
I. Can you tell me a little more about that?
S. Well ... what we do in the lab just follows from theory: like potential drops around a circuit, and ... energy stored in capacitors, and the rest. When you know the formula you can calculate it all without wasting time in the lab.
I. So you are attracted to the theory of electricity, but not to the practical side. Tell me, is that because you are interested in the mathematics of electricity?

S. I like all the maths. in Physics. I'm more advanced than other people. The maths. in practicals - it's trivial.

The boy felt that his mathematical prowess raised him above the mechanical operations of his colleagues in the laboratory. It was suggested to him:

Extract No. 21

I. Well, perhaps you could find it more interesting to tackle work that your colleagues haven't yet reached. Have you done inductive and capacitive reactance?

S. I've done plenty of that on my own.

I. On your own?

S. My father got me three or four Physics books and I've done most of the A-level questions in them.

I. So you get a particular pleasure from the mathematical side of Physics.

S. Yes.

I. I presume that you are a good mathematician ...

S. I'm always first in class

I. What do you propose to do after A-levels?

S. I'll do a Physics degree

When it was mentioned that a Physics degree course would involve some electrical practicals the boy did not respond. In view of the fact that he was familiar with the type of A-level question where a calculation is applied to a circuit containing capacitors, I inquired about his approach to such a question, to learn if his method was purely mathematical.
Extract No. 22

I. I am interested to know how you approach a typical A-level question on capacitors, such as when you are given a circuit diagram showing two capacitors, marked with different capacitances, in series with a potential maintained across them by a battery of known voltage; and you are asked to calculate the potential difference across each.

Do you think of the physical nature of the currents, or what takes place in the capacitors, or is it entirely a mathematical procedure?

S. I would take the values given and calculate the potentials straight away.

This tendency to consider components merely as elements of a mathematical exercise appeared to pervade all the electrical study he had done, and largely to blind him to any interest in applications in the physical world. I asked him:

Extract No. 23

I. When reading about inductance and capacitance have you not been interested to know of the practical applications of such components?

S. I think I know something of what they do ... I haven't much interest in all that.

 Asked for recommendations for assisting others in the electrical studies which he found so simple, the following exchange took place:

Extract No. 24

I. Could you make any recommendations for assisting others in this study?

S. Do more maths.

I. Apart from that, what else?

S. Most of my class don't bother with anything but their notes, I'd say they should read more.
I. Like the extra Physics books you have?
S. Yes
I. Do you remember the names of those which you have?
S. Our textbook is Nelkon and Parker, but my dad got me *Essentials of Higher Physics* (Mary Webster, 1978), and *Advanced Level Physical Science* (D.J. Powney and B.J. Stokes, 1977)

The disinclination to share the interests which other boys took in the non-mathematical associations of electrical studies was, to a lesser extent, also characteristic of the second pupil of the "Mathematic" tendency. He, "Ronny", when asked if he had made a hobby of building electrical devices replied:

*Extract No. 25*

S. No. I've never been very interested in that.
I. Can you tell me which A-level board examination you are preparing for?
S. The Nuffield.
I. There is a good deal of construction, or at least unit-building and experiment in their programme. How do you feel about that?
S. It's all right ... I don't like it as much as some of the others.

When encouraged to expand upon this absence of interest, there was a suggestion of irritation at the slowness of his colleagues:

*Extract No. 26*

S. It takes a lot of time ... you don't get very far.
I. What about the challenge of finding out by experiment?
S. I think I find out more in class, or by reading.
I. Don't you like to put the theory from your reading into practice in the laboratory?
S. Well, I think the theory is more interesting than doing experiments at practicals.

This boy depended heavily upon formulae for his understanding of component functions. When shown a diagram of the capacitor discharge circuit, he was asked:

**Extract No. 27**

I. And when the capacitor is fully charged, how do you think of it then?

S. It has stored energy equal to $\frac{1}{2}QV$

I. Yes. Do formulas come easily to your mind?

S. I like equations - I'm quite good at maths.

To learn if, like so many of his colleagues, he had any mental picture of an accumulation of electrons, I asked:

**Extract No. 28**

I. Do you think of the charged capacitor in any other way?

S. Well ... it's a quantity of charge stored. It's equal to the capacitance times voltage, $Q = CV$

Like the other "Mathematic" school pupil, he gave the impression of having little interest in the practical application of the components he had studied, except when there was a strong mathematical association. This was characterized by the exchange:

**Extract No. 29**

I. I wonder if you remember any of the uses made of transformers?

S. We've done problems using the Turns Ratio: you can step up or down voltage with a transformer.
DISCUSSION

"Mathematics"

In the course of the research programme the number of persons identified in this class was few but their characteristics were remarkably alike. Notable during their conversation was the extreme enthusiasm for mathematical reasoning and calculation, and the dismissal of suggestions of interest in practical work. The strong "Mathematics" have taken a pleasure in the precision of mathematical calculation for many years, and by the time of their preparation for A-level examinations, they delight in the conciseness of formulae, which for them is a sufficient summary of electrical phenomena. They are impatient with information which is more slowly acquired from practical observation and experiment. They feel that the mathematical side of their electrical studies is intellectual; but the practical side is manual, and less worthy of their attention. Both the school pupils of a strong bias had consciously distanced themselves from the practical application of their electrical studies, and believed they had lost nothing in doing so.

The school pupil "Mathematics" possessed characteristics common to other strong "Mathematics" interviewed at university and polytechnic in that they prided themselves on their abilities, and were conscious that their superior techniques received the approbation of their teachers. Their offered opinions and answers to inquiries demonstrated their dislike of mechanical manipulation of electrical components, and a preference for abstract reading. They remember formulae easily, and are rather condescending in reference to graphic illustrations elucidating electrical component functions.
The Pupil, "Murdoch", who showed himself during interview to typify the pronounced "Mathematic", was impatient for more advanced studies than his colleagues were engaged in, and apparently unappreciative of the value of practical work in the laboratory. He gave me to understand that the intellectual part of his course was pleasing, but any laboratory activity was, for him demeaning. "Murdoch" was genuinely interested in electrical theory because of the pleasure which mathematical reasoning and mathematical challenges connected with electrical studies could provide. He had read more than his colleagues and he felt he could gain nothing by manipulating components in the laboratory, and believed that "it was a waste of time" (Extract No. 20). The laboratory measurements he regarded with contempt: "The maths in practicals - it is trivial." It is interesting that he knew that he had progressed beyond his fellows in part through personal effort, and could make the recommendation to others that they should extend their reading beyond the notes issued to them.

Another boy of "Mathematic" tendencies, "Ronny", was less extreme in his attitude; he, however, also scorned the hobby side of electrical activities. For him electricity and electronics were an intellectual pursuit, and the practical work necessary to carry out the Nuffield course requirements was to be tolerated, rather than enjoyed. Whereas many of his colleagues might find a pleasure in exploring the effects of different circuit arrangements by physically handling the units, "Ronny" as a "Mathematic", was content to think of the circuits and component functions as mental abstractions.

Characteristically he was familiar with the appropriate formulae, and had those relating to capacitor energy and charge
storage readily to hand (Extracts Nos. 27 and 28). He was also
typical of the "Mathematic" in caring little for the applications
of electrical components and circuits; and, although he had un-
doubtedly read more than his classmates, the practical uses had
not registered strongly in his memory, except where there was a
numerical association. Since it is the custom for contemporary
textbook authors to seek the attention of the majority of young
readers by photographs and illustrations relating to the applic-
atations of components and simple circuits, it may be that the
"Mathematic", less amenable to visual material, simply ignores
these textbook features.

It is desirable that the teacher attempt to counter the
prejudiced attitude of the extreme "Mathematic", and try to
persuade them to adopt a more tolerant and flexible attitude.
One way of reaching their attention is through the historical
facts which can be made interesting to most young learners. The
tendency of the strong "Mathematic" to scorn practical electrical
applications and non-mathematical activities might be restrained
if they were made aware of the alternative non-mathematical
approaches of major electrical pioneers like Volta, Henry, and
Faraday. If as part of their class work, their teacher could
offer for reading and consideration extracts from some of the
pioneers' papers which made known for the first time new fundamen-
tal electrical discoveries, even the most extreme of the "Mathematics"
might be persuaded to reconsider their tendency towards a condescend-
ing attitude to the physical, qualitative, visualizing approach to
electrical studies. Both "Visualizers" and "Mathematics" could be
interested in such topics as Faraday's speculation on the nature of
the lines of force between charged bodies. The "Visualizers"
among the pupils are likely to be particularly interested in the manner in which Faraday's philosophical concept was given diagrammatic form by Maxwell in the drawings he included in the *Elementary Treatise on Electricity*; and the "Mathematic" would be pleased by Maxwell's confident translation of Faraday's ideas into mathematical reasoning. Even the strongest of the "Mathematics" would appreciate the fact that Maxwell's mathematic equations could not have been formulated without the ideas having been originated at an earlier stage in a non-mathematical manner.

If the young "Mathematic" were persuaded to look into some of the papers of Maxwell and William Thomson, they might find themselves drawn to a more tolerant attitude when they learned of the respect which those distinguished mathematicians held for the non-mathematic, practical researcher, Faraday. Those pupils who took pride in their facility in calculation and facility in applying mathematical expressions might experience a rewarding progression in their electrical studies if they followed the interpretation of Faraday's theory on the Lines of Force offered by Maxwell in the fourth section of his *Elementary Treatise on Electricity*, (The Electric Field), and the fifth section (Faraday's Lines of Induction). In all probability, the more advanced of the "Mathematics" would appreciate William Thomson's youthful paper of 1846 "On the Mathematical Theory of Electricity in Equilibrium" (*Cambridge and Dublin Mathematical Journal* November, 1846).
School Pupils Use of Textbooks

Some of the pupils did appreciate the value of the books, both those 'officially recommended' and those which they discovered for themselves, and made such reading part of their programme of study. One 6th form boy at an Oxford college-linked school, "Phil", spoke of making regular use of textbooks, and compared different examples in the school library, and of his realization that their contents could usefully supplement the information gained in the classroom. Although identified as having "Mathematic" bias, he was particularly interested in obtaining alternative examples of diagrams.

Extract No. 30

I. Are there any which you particularly like or dislike?
S. Yes. The Muncaster one is extremely good.
I. What is good about it?
S. The lay-out. The diagrams are very good. It is shaded, not just straight lines. The diagrams are easy to understand.
I. And are there books which you can criticise in regard to the diagrams?
S. Yes. We have two textbooks, one of them most of us don't like. I can't remember what it's called, but there aren't that many diagrams - it's mainly text. The diagrams are small, and they're not 3-dimensional or shaded.
Those pupils who had adopted the habit of reading regularly for themselves in the textbooks without specific instructions to do so, undoubtedly obtained a firmer framework of electrical knowledge, and experienced fewer problems in understanding the fundamentals; moreover, when they did meet such problems they had confidence in their own ability to extract the desired explanation. I was interested to learn if such students could offer suggestions for improvements to the textbooks they used, in line with their own immediate requirements.

A sixth form boy, "Tim", a pupil at an Oxford college-linked school, was asked:

Extract No. 31

I. I am interested to gather comments on possible improvements, could you suggest what would assist you?

S. It sounds funny, but - I think maybe some colour. Maybe different colours in diagrams. I don't mean that it has to be in full colour, only different colours. Say red and blue, rather than just plain black and white pictures: like they have in Scientific American.

"Magnus" at a private school, believed that much of his information on electricity and electronics was the result of his own textbook reading:
Extract No. 32

I. Is textbook study something which you take to easily?

S. Yes. I don't mind taking up a textbook and reading it. It takes me a little time to get new ideas, like when I first came across FETS. Once I got it, I found it very easy. The explanations vary, but on the whole they tend to say not very much in a lot of words.

Although many of the pupils interviewed preferred to be independent of the teacher, when faced with the need for information only a few reported satisfaction in their unguided researches in the textbooks. A characteristic account was given by a 5th year pupil at a private school, "Willie", who had just begun the study of transistors and realized that he was confused about their mode of action:

Extract No. 33

"I first of all went to a book, but actually, it wasn't much good. Then - I'm doing a Nuffield course - I got it from the notes. We're given files of notes, and within two or three days I understood transistors.

DISCUSSION

Use of Textbooks

4.17 Pupils did not make full use of textbooks which could assist them. Not many spoke of regularly studying from them, and there was evidence of a decided reluctance to prepare each topic from the recommended or approved text. It would seem that some of the well-established and respected textbooks are "tolerated" by pupils rather than appreciated for their qualities. They are consulted by direction, or when assistance with difficulties is not readily obtained elsewhere. The habits and skills involved in abstracting information from textbooks are not much cultivated by the majority of those I talked with. Several times the pupils confided to me that they found it difficult to obtain the information they sought from the texts read.
The value of practical work in the laboratory was better appreciated by those pupils who had made a hobby of electrical constructions. Their background experience allowed them to undertake experiments and to follow demonstrations with greater confidence knowing that they understood the functions of the components used, and they usually had some knowledge of the simpler measuring instruments which allowed them to use the laboratory equipment more easily. Among their peers, those with hobby experience were regarded with considerable respect, and that allowed them to enjoy a feeling of superior achievement. I got the impression that their desire to retain this initial advantage encouraged them in a full commitment to the practical work.

One 6th form boy, "Tim", attending an Oxford college-linked school, who was preparing for the Oxford and Cambridge examination, had had several years electrical construction experience. He was critical of the limited opportunities given for personal experiment. The more advanced experimental work at his laboratory was demonstrated by the teacher, and that he regarded as unsatisfactory:

**Extract No. 34**

S. Mr. ... does a couple of experiments for us, and of course the class crowds round him - let's say it is about five feet away, and you can't quite see it, or feel it. It is better to have a circuit and do it yourself.

I. How would you arrange things?
I. Are you then suggesting that each important theoretical principle involved should be done as a "hands-on" experiment?

S. Yes.

I. Do you use oscilloscopes in your laboratory?

S. Yes.

I. And have they helped you to grasp troublesome principles?

S. Yes. We used it in Phase Shift experiments. We've done a series of experiments. Each week a different experiment. In one you try to make a circle on the oscilloscope to show a 90 degree shift. It's quite useful then, because you can see the circuit performing and by changing a slight amount of capacitance ... Oscilloscopes are great. I'd like to have one.

Another 6th form boy at the same school, "Phil", who had had several years experience of electrical hobby constructions, felt that his colleagues suffered from having too little practical experience, and that the time-tables for Physics at his school should allow a larger proportion of practicals. (Two periods out of seven per week) He spoke of assisting fellow pupils with their difficulties in coping with the experiments in the laboratory.

Extract No. 35

S. The thing that most people seem to get wrong is the wiring up of circuits in practicals. They get problems with that.

I. What are the problems?

S. They join the wires in the wrong places.

I. Do you know why they make those mistakes?

S. It's not following the diagram. We've not actually ever been taught how to wire a circuit. That would be a good thing to have in a practical.

By contrast, a private school pupil, "Willie", who had no electrical hobby background, felt that he attended too many practicals, and that
they were undertaken with an inadequate theoretical preparation. He also saw the need for a teacher's summary, and explanatory commentary at greater length on the laboratory experiments. He was asked, in connection with his course work:

Extract No. 36

I. Do you find it balanced? Theory as compared with practical work?
S. I ... I've been thinking this out: and quite honestly, I think the weakness is that we do too many practicals. You can end up doing a practical, and after getting results, the right results, not understanding what you've done.
I. It's interesting. What has gone wrong? Could you tell me?
S. I believe it goes back to the basics, and how it works, what you're doing. You should read it up before.
I. Before the practicals?
S. Yes. Read it before, and after it analyse the answers. Whereas, usually, as periods are set out, after you've finished your practical, by the time you've finished your practical, it's the end of the lesson. I would much prefer to have it all explained?
I. Explained?
S. Explained after the practical. I think you have to be given a chance to try and work out your own ideas - what's happening, during the practical.

This boy had an interesting suggestion for a project in his laboratory meetings which would contribute materially to his and his colleagues' understanding of practical electrical studies:

Extract No. 37

S. I think it might be a good idea if we had a circuit diagram, quite large, with different components in it, and say, over a two or three week period we study every piece, find out what it does, and eventually work
I. Have you a particular circuit in mind?

S. Nothing in particular. I think it would give me a clearer view of what circuits are like, and how to build circuits, and how to treat the individual pieces.

A 6th form boy, "Nichol", who was preparing for the Oxford and Cambridge board's A-level examination, was drawn to electrical circuits because of his interest in electronic music. He had very little experience of electrical constructions, and that was using prepared modules requiring only interconnection. He wished his laboratory periods to provide more instruction on the manner in which components functioned within circuits. He had some difficulty with both capacitors and inductors, and although he felt he had grasped the theoretical principles, he was aware that what he had learned was quite remote from practical applications; however, he was enthusiastic about one extended project he had recently been involved with in the laboratory:

Extract No. 38

S. Some of the things in class were exactly right, I'd say.

I. Such as?

S. We did a basic study of the components of a radio - broadcasting and receiving system, and I found that incredibly interesting. We got the modulation, and the beat frequency, and the carrier-wave, and other things.

I. And this brought the use of the components home forcefully?

S. Yes, the components of the system, capacitors and what not had been totally isolated; when we talked about capacitors we just proved how the charge goes and everything, but they weren't in real circuits. Then with the radio circuit, it was the first time on the A-level course, we got an actual circuit.

This teacher-guided analysis of a superhetrodyne radio circuit
had without doubt provided the pupil and his colleagues with a genuine
insight into applications of the simple components they had previously
studied, and was more memorable than anything previously learned in
class. This particular pupil was sorry that the length and timetable
of his course could not allow repetitions of this project, and expressed
the opinion that it would be highly desirable for theoretical studies
to be immediately followed by some demonstration of practical applica-
tion in the laboratory.
With the exception of those of strong "Mathematic" tendencies, and one pupil who believed he was taking part in too many unproductive laboratory meetings, those interviewed recognized the value of the practical work, and the weight of opinion was that they would benefit from more of it. Demonstrations by teachers or technicians were not popular, although it was understood that restrictions on time and equipment sometimes made this necessary. Both those with a background of construction experience and the absolute beginners had a strong inclination to handle circuits and to discover personally, and there are good grounds for believing that they did wish to use the laboratory time to confirm the knowledge which they had acquired theoretically in the classroom or from reading.

Unfortunately the financial restraints on school spending severely limit the number of more costly items of equipment available for pupil use; nevertheless, it is easy to sympathise with "Tim" who was critical of the more advanced experiments being always performed by the teacher: ...

"The class crowds round him, ... and you can't quite see it or feel it." (Extract No. 34)

All but one of the schools visited used an oscilloscope in demonstrations. This was much appreciated by the pupils, who undoubtedly carried from such experiments a more memorable impression than any static representation would permit. Those of strongest "Visual" tendencies probably are most gratified by the oscilloscope demonstrations, but others certainly benefit by the excitement of this dynamic presentation. The enthusiasm of "Tim" comes across clearly in Extract No. 35 when he talked of the phase shift experiments which were rendered meaningful when he saw them physically shown on the cathode ray tube.
The importance of adequate explanation of what was to be undertaken in the practicals, and of appropriate supervision, was brought out in the conversation with "Willie" in Extract No. 36. For those like himself, who had little or no electrical hobby background, it was difficult to get the best out of experiments when relying on a personal, and rather shakey theoretical knowledge. He was sufficiently thoughtful to have analysed his own difficulties, and to have recognized that many laboratory experiments are in the form of observation and measurement which, if conscientiously carried out, can produce "the right results" but which are of little worth because the theory upon which they are based is not thoroughly understood.

Although "Willie" spoke of "too many practicals", what he implied was that there were too many practicals which were not advantageous to him personally. His call for more instruction or guidance in preparation for the experiments is worthy of notice, as is his wish for a final commentary by the teacher concerning what was acheived by the laboratory experiments.

One regular comment from the pupils was that they wished to have more instruction on the components' functions within the circuits (as opposed to the abstract theoretical considerations.) The interest and curiosity of pupils is stimulated by working models, and their own desire to have an authorative commentary on them is clearly brought out in the request for an extended examination of a particular circuit (Extract No. 37), and the enthusiasm of "Nichol", when speaking about the analysis of the superhet radio (Extract No. 38): "We had a basic study of the components of a radio - broadcasting and receiving system - and I found that incredibly interesting. We got the modulation and the beat frequency, and the carrier wave, and other things."
4.20

The pronounced "Mathematics" among the pupils expressed innocent astonishment that anyone could find difficulty in understanding the principles of capacitor theory. Both the private school pupil "Murdoch" and the university college-linked school pupil "Ronny" associated a fully charged capacitor with the formula for the stored energy, \( \frac{1}{2} QV \), and were familiar with the three forms of the relationships of \( Q \), \( C \) and \( V \). Their reading had provided them with an acquaintance with the factors which affect capacitance in the diagramatic models exhibited in the textbooks, and they appreciated the importance of the dielectric material, largely from having worked through mathematical problems concerned with these variables. They, too, found difficulty in extending the concept of capacitance beyond the circuit component.

**Extract No. 39**

I. You will remember that very often the textbooks use the word "Capacitance" - when you read that word, what immediately comes to mind?

S. I'd say it's the measurement of the component in Farads.

I. Yes, and you know the formula?

S. \( C = \frac{Q}{V} \)

One 6th form pupil, "Phil" preparing for the Oxford and Cambridge entrance examination, had a decided "Mathematic" bias, and was quite confident that he understood the meaning of capacitance:
I. Can you tell me what you understand as the meaning of the word "Capacitance"?

S. Well, it's its ability to store charge. If it's a large one, it will be able to store more.

I. And how about the formula relating to capacitance?

S. C equals Q/V

The majority of pupils had greater difficulty in expressing in words what they understood by the term. By no means untypical was the comment of a thoughtful 5th form boy who had spoken of his electrical reading:

A colleague of his, who had considerable experience in electrical constructions, clearly demonstrated that he associated the word with the components he was accustomed to handle in his practical work:

I. Now the term "Capacitance" is much used in textbooks and circuit descriptions: can you tell me how you think of it, and what it means to you?

S. It's a sort of measurement of the permittivity of an insulator, the width of an insulator, and the area of the plates - the larger the capacitance, the larger the capacitor.

The charge and discharge of the capacitor was frequently considered in the sense of "energy storage". One private school pupil in the 6th form,
who had been identified as being in the "Visualizer" category, on being shown the simple circuit of the battery connected with a switch, resistor, and capacitor, in series, was asked: "What will happen when we close the switch", replied:

Extract No. 43

S. Well, my immediate answer would be that the current will flow from the positive through the meter and resistor, and then it will reach the capacitor. I think I'm right in saying that the capacitor will be charged.

I. And that means what?

S. That some energy is being stored.

I. Could we take that a little further: what does "energy is being stored" mean to you?

S. ... well, I think it means potential energy.

A little later he was asked about the discharging of the capacitor:

Extract No. 44

I. Let's look at this circuit again: suppose we have charged the capacitor fully, then we proceed to discharge it by opening the switch. Can you give some account of what happens?

S. I would say that it is taking away the energy stored inside.

I. I wonder if you could describe what takes place in the circuit.

S. Isn't it that electrons flow away from the capacitor?

I. And where do they flow to?

S. To the battery.

Like many others who were weak on the phenomena associated with the charging and discharging of capacitors, this pupil had remembered the generalizing description, but made no mention of the voltage building up across the capacitor, nor of the property, capacitance. When asked what the term "Capacitance" meant to him, he replied in some confusion:

"Capacitance is Q over ... No. ... Q equals C over the potential difference"
A tendency noted among many pupils was the apparent contentment with a vague, generalizing concept of "charge", without any reference to the factors affecting capacitance, which was used to describe or explain the processes of capacitor charging and discharging. One instance of this, characteristic of numerous other examples, was the response of a fifth form private school pupil when questioned about a simple capacitive circuit:

Extract No. 45

I. Let us look at some components. Here is a small circuit with a capacitor. If we add a battery to the terminals, could you describe what happens?

S. We would charge up one plate, and that is inducing a charge on the other plate of the opposite charge - pushing the original charge, the same quantity, through on the other side.

Those pupils who had experience of constructing circuits as a hobby did possess a clearer knowledge of the factors affecting charge storage, and had a better grasp of the abstract concept "Capacitance", but rarely did they mention any units or refer to any mathematical expression. An example is the conversation with a 6th form boy, an identified "Visualizer" who had done much kit building.

Extract No. 46

(Following a reference to the types of capacitors he had used in projects)

I. They have one thing in common - can you comment?

S. It is to store charge.

I. Yes. Let's consider the amount of charge stored. What decides the amount that a device of this sort can hold?
Those with less constructional experience often demonstrated a considerable vagueness about the nature of charging and discharging the capacitor beyond the simplified electron flow descriptions offered by the textbooks as an introductory model of the physical situation. An example of this was given by "Nichol", preparing for the Nuffield Advanced Physics examination, who exhibited a "Visualizer" bias. When shown the simple capacitive circuit and asked: "Could you tell me something of what happens when we connect a battery to these terminals, he replied:

Extract No. 47

I. Can you tell me something about the current in this circuit?

S. Well, the capacitor will charge up ... charge is flowing onto the capacitor, therefore it will flow through the ammeter, and once it has become charged, the current will stop flowing.

I. Why does it stop flowing?

S. Because the two plates have opposite charges, and there is a field built up on the negative plate which opposes.

I. Opposes what?

S. Any more charge.

I. How do you think of this phenomenon "charge"?

S. I think of it as something moving onto it.

I. Something?

S. Electrons.

The same pupil had a limited and rather uncertain understanding of concept "Capacitance" and its mathematical relationships. Asked how he would explain "Capacitance", he replied:
In terms of a parallel plate capacity, you relate it to the area of the plates, and the distance between them.

Yes. Can you go on?

A lot of people say it is the ability to store charge. It is in effect the ratio of the voltage applied to the charge. There is a formula for it.

Do you remember it?

.... I did know it ...

That's all right; it doesn't matter.

"Ronny", a 6th form college-linked school pupil, of "Mathematic" bias, knew of the mathematical relationships, and spoke with confidence in commenting on the diagram of the capacitor being charged:

If we close the switch, how would you describe the result?

The capacitor will be charged: positive charge on one side and negative charge on the other, they will equal the battery e.m.f.

Does that happen instantaneously?

Not instantaneously - the time it takes depends on the capacitance and the resistance. There is an exponential variation until the capacitor is fully charged.

Can you tell me a little more about that?

Well, there's a time constant formula, $T = RC$ That's how long it takes to charge to 63% of the e.m.f.

Only one of those not observed to have a distinct "Mathematic" tendency spoke of the Time Constant curve, and his reference was that of a confused memory of carrying out an experiment to plot the curve:

(Following conversation about the capacitor's ability to store charge)
I. Can you remember anything relating to a measure of the capacitor's charge?

S. ?

I. Don't worry: I was thinking about the Time Constant.

S. Oh. I know. I've done it.

"Willie" was asked:

Extract No. 52

I. Now if we look between the plates, does the space serve any purpose?

S. It serves the purpose of acting as a thing for the charge to attract ... it's like a window ... I find it hard to explain.

I. Don't worry, just try.

S. It's a sort of resistor. It causes physical resistance to charge.

Another pupil, a non-constructor, was rather confused, and was familiar only with the insulating property of the dielectric:

Extract No. 53

I. There is a space between our plates ...

S. The dielectric.

I. Yes, can you tell me anything about it?

S. It's an insulating material.

I. Yes, and has it any other property?

S. Is it to control the flow of electric charge from the negative to the positive? There are things like permittivity of different materials which will allow - I think - if I remember correctly, charge to go through a certain thickness.
DISCUSSION

Capacitors and Capacitance

4.21 Although only a few of those school pupils interviewed referred to having experienced memorable difficulties in studying the nature of capacitance, there can be no doubt that many were aware that they had only an uncertain understanding of the concept. Most of the pupils could associate the phenomenon of capacitance only with the circuit component, the capacitor, scarcely giving consideration to examples of capacitance existing between other separated conductors in other circumstances. In part this may be because the pupils' attention had been primarily directed towards the important functions of the capacitor in the simple circuits offered in the textbook introductions to the phenomenon, and the practice of the teachers in explaining the principles by means of the conveniently considered capacitance of the component; by tacit consent it being understood that the multiplicity of examples of distributed capacitance in wires, and localized capacitance in almost all electrical circuits could be studied at a later, more advanced stage.

Only a small number of the pupils appeared to be able to describe mathematically the behavior of capacitors in circuits. Most believed that they understood the component's essential function of storing charge, but few expressed with any clarity the underlying principles, beyond the fact that the charge would increase until the plates equalled that of the source, which in their experience was almost always a dry battery. Only a small number appreciated the factors governing the capacitance of particular components.

It was somewhat surprising that so few pupils could recall the basic formula for capacitance. All the school textbooks stress the
equation in its various forms, and the A-level examination questions frequently require its use.

One of the interesting points which emerged from the exchanges with the school pupils is that they very frequently confuse the terms "Capacitor" and "Capacitance", using the term for the component when the phenomenon was intended. An example of this is given in Extract No. 41, where "Willie" asked what he understood by "Capacitance" replied: "I'd treat it almost like a battery. It's holding charge. It's difficult..

Even the "Mathematic", Phil, who had the advantage of wider textbook reading, when asked for the "meaning of the word Capacitance" replied: "Well, it's its ability to store charge" and certainly intended that to apply to the component, because he goes on to add, "If it is a large one, it will store more."

An unexpectedly large number of pupils exhibited a vagueness about the process of charging and discharging of the capacitor by means of a battery, despite the attention given to this in the textbooks, and the standard laboratory demonstrations. This is characterized by "George" in Extracts Nos. 43 and 44. He, and other pupils, did not refer to the voltage across the capacitor, nor consider the interrelationships of the factors affecting capacitance. While the more experienced hobby constructors did show some appreciation of these factors, they were rather imprecise and seldom referred to quantities of units or gave any examples from their circuit building experience.

It was observed that only the "Mathematics" among the school pupils showed an awareness of the significance of the Time Constant curves in charging and discharging of capacitors. Although they exhibited little interest in the practical importance of these phenomena, they had memorized the mathematics (Extract No. 49).
Among school pupils there was a good deal of misunderstanding about the nature of the dielectric and its functions, and, apparently, few of them had learned, or remembered the relevance of the specific dielectric constant. Those who did were pupils with more practical experience of electrical circuit building. Characteristic misunderstandings were expressed by pupils in Extracts. Nos. 52 and 53.

It was expected that there would be difficulties and misunderstandings among the school pupils in comparing the capacitor's behavior under D.C. and A.C. conditions; however, none of those interviewed expressed any doubt or hesitation in this matter, which in the past was known to disturb the beginner. Full credit must be given to the modern textbooks which no longer carry the misleading statement to the effect that a capacitor will block D.C. but allow the passage of A.C.

As many pupils possess a most restricted concept of capacitance, associating it primarily or wholly with the component, the capacitor, with which they have become familiar, it is desirable to counter this misunderstanding by providing some knowledge which will allow them to consider capacitance in a much wider context than the common circuit component.

One way in which the pupils could obtain a clearer understanding of the nature of capacitance is for them to learn something of the historical situation where pioneers progressively unravelled the mysteries of the phenomenon. Even a slight acquaintance with the records of Faraday's experiments given in his "Laboratory Notebooks" and reported to the Royal Society, would alert them to the fact that he was exploring capacitive effects which always exist between a charged body isolated from other bodies (or from the earth), and
that other researchers, like Ampère, were studying capacitive conditions arising from currents of electricity in complete conducting circuits.

If, with the assistance of comments and gloss from their teachers, the pupils read something of Faraday's "Laboratory Notebooks" of 1836 and 1837, or the official account given to the Royal Society in the 11th series of "Experimental Researches" (December, 1837), they could scarcely avoid being caught up in the excitement of the story of the unfolding of one of Nature's secrets, and they might share in Faraday's speculation on the qualities of the "Lines of Force", while he carried out his experiments with plate and spherical capacitors. On reading of the special apparatus which he designed and had constructed to accommodate his experiments, the electrical properties which might previously have been associated only with the memorized formulae, would, in all probability, become much more interesting; and, an equation like \( C = \frac{Q}{V} \) would certainly become more meaningful.

Those students who found difficulty in appreciating the functions of the dielectric could quickly gain a better understanding of those properties as they learned of the experiments which Faraday carried out on the "Specific inductive capacity" (dielectric constant), carefully recording the measurements obtained from materials such as glass, sulphur, and a variety of gases, to compare with air.
Those school pupils who demonstrated that they were fairly competent in their electrical knowledge were asked briefly about capacitive reactance. It wasn't expected that they would have more than the basic information of the phenomenon required by the GCE boards. The two pronounced "Mathematics" were familiar with the formula, but others who acknowledged an acquaintance with the phenomenon were, at best typified by the response of a 6th form Oxford college-linked school pupil, "Phil", with a considerable "Mathematic" bias, who gave this exchange:

**Extract No. 54**

I. Have you studied capacitive reactance?

S. Yes, we have.

I. Would you prefer to think of the formula, than think of what happens physically to the capacitor under conditions of reactance?

S. Yes. I'd rather just use the formula. Well ... as long as I understood - if I thought about it - how it would work.

I. Suppose some one just beginning the subject should inquire of you, could you describe capacitive reactance?

S. I'd say it was resistance to the flow of a.c.

A lower 6th form pupil "Tim" associated reactance with unresolved difficulties in fairly recent studies, and believed that his problems
would be alleviated if he could master the appropriate equations:

**Extract No. 54a**

S. We did them a couple of months ago, and I haven't come round to revising them yet. But I think I'll have to spend quite a while doing that.

I. You are in a good position to tell me of difficulties you experienced.

S. It is mostly the idea of reactance in capacitance, and how inductance affects reactance as well. It is all held in a number of equations. I tried to memorize them by repeating over and over again.

During the course of the interview the pupils were asked about the types of capacitor with which they were acquainted, and asked to speak of the practical uses to which capacitors were put. The nine who could be identified as regular hobby constructors had experience of the most commonly used types of components specified for low voltage projects. The non-constructors rarely volunteered information on any type other than the fixed parallel plate air-dielectric capacitor; and, while they knew that the component's unit was the Farad, they seldom could remember having handled any particular capacitor whose measurement could be given in micro- or pico-farads.

The constructors were familiar with a limited range of applications, but the non-constructors demonstrated an extreme paucity of examples, indicating that they had remembered little of the information offered in the current textbooks.

A 5th form Comprehensive school pupil who had a little experience of kit-building, could mention the air-spaced variable capacitor he had used in the tuned-circuit of an A.M. radio receiver, and had used ceramic and polyester capacitors in a simple amplifier circuit. However, he could not readily think of other applications of the component. One 6th form
pupil with considerable experience of kit-building, "Edmund", when asked what capacitor uses came to mind, replied: "I've used them in an oscillator. I've used them in smoothing power-supplies in an audio-amplifier."

Another colleague of his, with less hobby experience answered:

**Extract No. 55**

I. I wonder if you can think of any uses of capacitors which come readily to mind?
S. A power supply
I. Yes, what did it do there?
S. Well, immediately after rectification, you'd have it to smooth most of the peak.
I. What is it about the capacitor that does the smoothing?
S. It's the timing - it discharges through a resistance.

A fifth form university college-linked school pupil with a little hobby experience replied to the same question: "I immediately associate them with flashing lights." Puzzled, I inquired: "Flashing lights?" and he explained: "Disco flashing lights," which indicated that his knowledge of basic electrical theory allowed him to interpret the peculiar illumination of his favourite recreation.
INDUCTANCE

4.23

Not infrequently the pupils had a basic knowledge of the principles of the effects of the magnetic field around a current-carrying conductor under d.c. conditions, but seemed unwilling to comment freely on even the simplest inductive circuits shown to them, as though uncertain of talking about matters which they only partly remembered. The students had learned of Time Constants in their classes, yet these and the formula were not referred to. The resistance to discussion may be observed in the stilted replies of "Phil", of "Mathematic" tendency, who had experience of electrical constructions, and who had more theoretical knowledge than many of his colleagues.

Extract No. 56

I. Could I jog your memory a little with this drawing: a battery, a knife switch, and a coil of wire. When we close the switch various things happen. Could you summarize them?

S. You get the current flowing and it sets up a magnetic field. That builds up, and when it is at a maximum it stays constant, until you release the switch.

I. Could you say a little more?

S. The magnetic field cuts the wire of the coil.

I. Yes, then what?

S. You've got the field going in that direction and the current ... 90 degrees to it, so you get a force on the wire.

I. And the result of that?

S. Back e.m.f.
He was asked what he understood when he read of the term "Inductance", and his reply was: "Energy stored in the magnetic field". Asked if he had done any school experiments with transformers, he said:

Extract No. 57

S. Very little.
I. In the case of mutual inductance, have you examined the currents flowing in the two coils?
S. I haven't thought about it.
I. I wonder if you have studied Inductive Reactance?
S. Yes. It's 2\(\pi fL\)

A fifth form pupil, Rupert", who was in the "Visualizer" category, believed that he had a reasonable grasp of d.c. inductive circuits, but was just beginning the study of a.c. circuits, was prepared to admit that he had some problems:

Extract No. 58

S. I have had a certain amount of difficulty. But it was right at the beginning. I think that once it was clarified in class by the master, it became fairly easy.
I. Here is an inductive circuit. I wonder how you might explain to a younger boy what happens?
S. Well, I would say that it was the building up and breaking down of a magnetic field around the coil, or inside the coil.
I. And in physical terms, what happens?
S. It tries to maintain the status quo. It fights any change.
I. I wonder if you have studied mutual inductance?
S. Yes, fairly recently.
I. Have you had any problems with it?
S. ... I can't think just now.
While all but a number of the fifth year pupils told me that they had 'covered' transformers, there was a determined opposition to inquiries about their function. Even one of the pronounced "Mathematics", Ronny, who had spoken of this theoretical electrical studies as being too simple to retain his full interest, was not forthcoming:

Extract No. 59

I. Have you studied transformers?
S. We've done a little with them.
I. Here is a drawing of two coils, separated but effectively a transformer. When the primary is connected to an electric current, what would you say of the secondary?
S. A voltage will be induced.
I. Yes. Now suppose you know the direction of the primary current, can you say what the direction of the secondary current will be?
S. I could work it out ... I'd have to think about it ...

Practical experiments were found helpful by a number of pupils to whom the theory of inductive behavior was difficult to accept in the abstract. A clear example of this was the 5th form Comprehensive school pupil, "Colin", who related his knowledge of the inductive fundamentals to impressions made on him during laboratory work:

Extract No. 60

I. In this drawing we have a battery, a coil of wire, and a switch. If we close the switch, can you comment on what happens?
S. Current travels along the wire.
I. Yes, please go on.
S. You get electromagnetism ... we've done some experiments with iron filings.
I. Here is another drawing: do you recognize what's happening?

S. Yes. It's the lines cutting the coil.

I. Would you like to comment on what happens here?

S. Well, we were taught this with coils ... we went on to think of the back e.m.f.

I. Did you have any problems with back e.m.f.?

S. Yes. It did strike me as a bit odd.

I. And how did you make sense of it?

S. I don't know if I ever actually made it out - it obviously happens; I've come to accept it. But, we did one experiment where we used an electric motor, and we turned it by hand; then completing a circuit, we found how much harder it was to turn, so it seems likely that there is such a thing as back e.m.f.

Current directions in inductors, while difficult to rationalize was made meaningful to several of the pupils by the graphic models of Fleming's rules. One lower-sixth form pupil, "Martin", at a university college-linked school, identified as a "Visualizer", told me of his difficulty in studying induction, and of his dependence on visualizing aids:

Extract No. 61

I. Can you remember what it was about inductors which caused problems?

S. I think the fact that any current was produced at all. Why on earth would it produce current, quite apart from it being proportional to the change of cutting - I'd wonder why it should happen in the first place. It's rather advanced.

I. Here is a small drawing of an inductive circuit. I am interested to know how you think of what happens when we complete this circuit by throwing the switch.

S. Well, what happens - OK - well, the way I think about it is, that you are supposed to think of electrons moving, therefore the current moves the other way, then there is the generation of a field, a magnetic field. I use the "right-hand grasp" - it's very visual. I mean - you actually have to follow it round, and make sure that it's going to go down that way. Therefore the current will be up in the centre.
When encouraged to continue with his commentary, he was able to expand somewhat:

I. Could you go on a little with your commentary?

S. Well, if you use the "Right-hand Grasp" rule, as we have been taught to do, they will eventually all line up the one way as you go round this coil. And if you assume that they are going the one way, you are going to have the magnetic field going the way which the arrows eventually pointing to.

I. And can you say what happens then?

S. Yes. This front of wire is going to be cut by the lines, then there is back e.m.f. isn't there? Our teacher explained that back e.m.f. always resists any change.

During the course of many interviews the pupils were asked what types of inductors they knew, and what were the uses to which inductors were put. The response was disappointingly meagre, and almost limited to the experimental coils and electromagnets and transformers. The electrical constructors were familiar with the inductors used in tuned-circuits of radio receivers, and some referred to inductive aerials which could change the electromagnetic waves into signals, but none of them referred to their use in coupling circuits. It was noted that no student instanced the motor or generator as examples of inductive applications, notwithstanding the fact that all the current school textbooks deal clearly with these. Similarly, although these textbooks explain the operation of relays and telephone ear-pieces, no pupil mentioned them.
DISCUSSION

Inductors and Inductance

4.24 It was often difficult to obtain a satisfactory impression of the school pupils' understanding of inductance under both d.c. and a.c. conditions: this was due to the considerable reluctance of many of the pupils to offer much discussion on the subject. Without doubt this component's functions caused them particular trouble in their studies, and practical work with inductors was slight. Many of the pupils referred to the need to revise their knowledge of inductance formulae, or stated that they were still in the process of learning about inductive behaviour (as was indeed the case, for the interviews could not be limited to the final portions of their courses.) An impression was obtained, through informal conversations with the less mathematically able, that the whole area of induction was regarded with some degree of anxiety, and that it was reputed to be "complicated", and the consensus of opinion among the pupils was that, if possible, inductive questions were to be avoided during tests and examinations.

The phenomenon of back e.m.f. troubled many of the pupils, but there was little indication that clarification was sought on this undoubtedly difficult concept from either the textbooks or the teacher. It is interesting that in Extract No. 56, the boy of "Mathematic" tendency, "Phil", when summarizing the result of energizing the coil ("You get the current flowing and it sets up a magnetic field. That builds up, and when it is at a maximum it stays constant, until you release the switch.") does not mention back e.m.f. and its existence was only drawn from him after further questioning. The important effect of the opposition to the changing magnitude of the current, so heavily
stressed by the textbooks, appeared not to have been easily remembered.

It was noted that although all the textbooks make a point of comparing and contrasting inductor and capacitor operation, both as an aid to memory and to impress on the reader their individual characteristics, scarcely any of the pupils appeared to have this information available for discussion. Few thought fit to mention and comment on the storage of electrical energy, except in a superficial manner. One who did, was the boy with a strong "Visualizing" tendency, quoted in Extract No. 17, who had been impressed by the mechanical analogy of induction.

The importance of different physical demonstrations of inductive behavior was brought out in the interviews with several pupils, particularly "Colin" (Extract No. 60) who had resisted the acceptance of the idea of back e.m.f. until the compelling comparison of the incomplete and complete motor circuit. Equally, the extreme usefulness of Fleming's "hand-rules" for the learner with "Visualizing" tendency was stressed by the account of "Martin" in his attempt to comprehend the complexities of the inductor, (Extract No. 61).

One rather surprising result of the discussions about simple inductive d.c. circuits was that none of the pupils appeared to be familiar with the fact that on breaking the circuit, it is possible to observe momentarily a higher voltage than the original source of the e.m.f. This favourite demonstration of the past was apparently not seen, or remembered, by those interviewed. As the phenomenon is mentioned in current school texts, it is probable that the pupils did not notice it if they read the chapter, or their teachers did not draw their attention to it during class or laboratory meetings. Some referred to the opposition to change, and realized that the back e.m.f. would appear with the falling current as well as the rising current, but none spoke of sparking or high voltage.
Many students would be assisted in understanding the concept of inductance if they were introduced to some historical account of the experiments which Henry and Faraday and others conducted in the course of their research into the phenomena associated with the production of inductive currents by means of moving magnets; the rapid making and breaking of battery-powered circuits; and the effects of alternating currents. For the students to know something of the historical sequence of events, where the earliest researchers were slowly unravelling the basic facts about inductance, would certainly be interesting to very many, and it would provide different perspectives to their learning problems. Moreover, their own studies might take on a new interest if they felt an empathy with the efforts of Faraday, Lenz, and Maxwell. Instead of memorizing formulae as abstract entities, or associating the phenomenon of inductance with laboratory experiments remote from practical life, the pupils could imagine the exciting experiences of Joseph Henry, working in Albany around the year 1830, observing unexpected induced currents in unpowered electromagnets brought into the proximity of other operating electromagnets. Similarly, they could be drawn into the drama of Faraday's mutual inductive experiments in London at almost the same time, when he obtained induced currents in a secondary coil whenever the primary opposite it made or broke contact with its battery terminal.

Some of the problems associated with understanding the principles of back-e.m.f. could be removed, and much of the pupils' anxiety about its mysterious properties could be diminished, if they made acquaintance with the accounts of Henry's successful inquiries into
what was then known as "extra current" - the phenomenon which he and Faraday investigated (again at almost the same moment in time), primarily through the production of sparks on breaking the circuit of an energized coil.

Easily assimilated information on these experiments is available in such a book as The Discovery of Induced Electromagnetic Induction (1900) by J.S. Ames. Teachers who appreciate the inspirational benefits which the pupils can receive from these historical researches, could select for class reading suitable excerpts at appropriate stages of the course of instruction.
During the research programme one of the points which emerged from conversation with technicians, engineers, and works managers, was the absence of any form of instruction in systematic circuit diagram reading. Almost always the individual had gained the skill through trial and error in practical work, or by imitating the methods of more experienced acquaintances or colleagues. Most of those with whom I spoke regretted that they had not had the advantage of guidance in this accomplishment so vital to the engineer, technician, teacher, or individual seriously concerned with electrical work. I was, therefore, most interested to learn if the contemporary courses for pupils and students offered training in circuit diagram reading. All the interviewees were asked about this, unless the information had been given in earlier informal conversation. All school pupils denied having had any training in circuit diagram reading - other than the initial introduction to the most common electrical component symbols drawn on the blackboard in class, or directed to their attention by required reading in study notes or textbooks.

Typical of the interview exchanges on this subject was that with a lower 6th form boy who was a keen electrical constructor:

**Extract No. 62**

I. Were you ever instructed in reading circuit diagrams?

S. No. Because I have done electronics for a hobby for 5 years or so I've got used to it. But we've only recently done more up to date components.
Another pupil of considerable kit building experience, an identified "Visualizer", "Edmund", explained:

Extract No. 63

S. I got basic instruction in the manuals. I followed from there and worked out sections at a time.

I. Many people, relatively new to electricity, find circuit diagrams confusing. Can you suggest why that is?

S. I think it is very difficult to transfer a flat two-dimensional object into being a three-dimensional system.

I. And would you say that is the case even when the individual components are recognized and understood?

S. Well, I usually think of small sections which I recognize from what I have read in the past.

It was inquired of one lower 6th form pupil, "Martin", who was introduced to electrical activities through a home construction kit, if he considered that that had been an aid to his school work.

Extract No. 64

I. Did the use of that kit help you to read circuit diagrams?

S. Not really, because the way they set their board out. It was rather complicated, and they had different printed circuit boards, and you had to look very carefully to see things. I think it could have been laid out better. Here in the laboratory you have to draw a diagram, and if you don't you usually wire it up wrong.

All the hobby constructors, and most of the others were able to interpret the circuit diagram of the crystal set. A fifth form boy with little practical experience, in his comments was characteristic of many others:

Extract No. 65

I. How would you begin to read this?

S. Well, first of all, I'd take the aerial and the earth. They are the most noticeable things. I'd look at the capacitor - I'd treat that as a variable resistor ... and I think that is a diode, and that - that is headphones.
I. You have picked out all the components. Now what would you say to yourself?

S. I'd say it's a radio.

Another fifth form boy at a Comprehensive school, "Trevor", who was working towards the Nuffield Advanced Physics examination, on being shown the drawing said:

Extract No. 66

S. Some sort of radio?

I. Yes. It's the primitive radio, a crystal set. Can you tell me a little about how we hear the sound at the headphones?

S. There is a surge of waves and it comes down the aerial.

I. Could you give me the signal path from there?

S. The waves flow round the circuit until it reaches the headphones. The wave passes through this thing.

I. Do you recognize it?

S. It's a diode?

I. And do you remember what it does?

S. It stops current one way.
At two of the five schools where pupils were interviewed the Nuffield Advanced Physics Course was taught in preparation for A-level examinations. I was interested to have the opinions of those engaged on this programme as to whether they found it stimulating, particularly with regard to the emphasis on personal experiment and discovery in the laboratory, and whether they felt that the student handbooks provided them with the supporting theory in a form which they could easily understand and apply effectively. While bearing in mind that the young people had little scope for comparison with the traditional courses and that their electrical education was still at an early stage, the answers given to my inquiries suggested that they appreciated the innovations of the Nuffield Advanced Physics course, and that they felt it was serving them well.

A fifth form boy at a private school, "Willie", who had earlier spoken in appreciation of his class notes (based on the Nuffield handbooks) felt that the notes provided very satisfactory explanations of a theoretical problem he had encountered recently. I inquired if the problem had been resolved "Through reading alone, or by doing the Nuffield experiments?" He replied: "By reading and by experiment. I like to see what the textbook says. But by experiment I find a lot." His criticism was that he felt that his course required too much time to be spent in the laboratory, and that the experimental work needed
a good deal of teacher's commentary during or after it (Extract No. 36).

A 6th form boy, "Magnus", felt that some extra mathematical preparation was desirable. He also believed that his colleagues did not always take full advantage of the Nuffield printed material. I gathered that in his opinion it wasn't read with focused attention and that the theory was not sufficiently considered during the associated laboratory work.

Extract No. 67

I. I expect you have formed some opinions about your course. Is there anything which you could draw to my attention?

S. Well, with the course we are doing at the moment, the Nuffield Course, more could be made of what is exactly in the modules for a start - a lot of people seem just to put it together and write down what happens. They don't actually know how it happens.

I. Please go on.

S. Well, it depends on the person doing the course. If the person is inspired to do the work he probably should add to his notes. That's the area to be worked on - obviously that is left to the person. You can look up the maths out of class - you can't do the practical out of class. You can make notes during prep. in the library.

I. In your experience would you say that the balance of practical and theoretical is right?

S. I think I would put slightly more emphasis on the more mathematical side. I don't think it is far off. It helps you think in the right way. I think that is fairly essential.

4.27 In the majority of school interviews there was some discussion about the considerable range of electrical hobby magazines which are available to the young reader at magazine shops and school libraries. A surprisingly small number of pupils spoke of reading them with any regularity. Clearly many had not examined them at all, others assumed, after a quick glance at some issue, that they had no relevance to their own electrical studies, or that they would be of interest only to those who were already fairly advanced electrical constructors. If there was any encouragement from teachers to make use of these publications, this did not come across during the interviews.
Several of the interviewees who had adopted electrical construction as a hobby did make use of the magazines, and acknowledged that they could offer support and assistance on the school courses. One 6th form boy at a university college-linked school, who told me that electronics projects were his main hobby, said:

Extract No. 68

S. Yes. I used to boy Everyday Electronics every month - but after a couple of years I began to realize that the circuits were being repeated. Now I borrow books from the library.

I. Would you say that the study of such magazine circuits helped with the school work here?

S. In some of the circuits, yes. They gave you block diagrams. Most people haven't seen the circuit before, and if you split it into small blocks, then you can examine each block separately, and you find you can take it in easier.

Others offered a variety of reasons for not investigating the electrical magazines. One fifth form pupil at a private school, who had spoken of his appreciation of the value of reading, mentioned his increasing interest in electronics, and referred to the lethargy of his colleagues when we had this exchange:

Extract No. 69

I. I am interested to know if you read any of the electronic magazines?

S. No. I can't say I do.

I. Yet you are interested in the subject?

S. It's a financial problem.

I. Perhaps you could borrow them - say from your library?

S. I suppose I could.
Another boy in the same class was asked: "Do you read any of the electrical magazines, like *Wireless World*" replied, "I used to buy it. I haven't while I've been here. Mind you, I read other people's electrical magazines."

One or two of those who had originally taken the beginners' magazine, *Everyday Electronics*, and followed its articles, had quite quickly dispensed with it as they progressed in their A-level studies. One pupil, "Nichol", who had progressed moderately in his electrical skills, explained the matter:

**Extract No 70**

S. I read *Practical Electronics* sometimes, but I find that I am more interested in what they offer to build. It depends on how hard they are.

I. *Practical Electronics* projects tend to be pretty advanced. Do you know *Everyday Electronics*, where they offer projects which are easier?

S. Yes. I know. Although I'm not really an expert, I think *Everyday Electronics* things are simple.

4.28 A number of the pupils who gave the impression that they would be willing to respond freely were asked what modifications or improvements they could suggest to their own courses. The most frequent recommendation was a wish for more laboratory instruction directed towards explaining the functions within real circuits of components which they studied largely on a theoretical level. This request was summarized by the 6th form boy with limited practical experience, who asked for an extended component and circuit analysis to "Find out what it does and eventually to work out how the whole thing works" (Extract No. 37)

Transistor operation was a recurring problem with those who had entered upon electronics. There were frequent exchanges similar to the pupil working on the Nuffield Advanced Physics course:
Extract No. 71

I. Just a last question: if conditions were ideal and you could suit yourself and could alter your course, what would you change?

S. Well, I'm not too keen on light ... I think I'd see that replaced by a lot more of electronics.

I. What part of it?

S. A lot more discussion of how components fit into circuits. I'd like more of transistor circuits.

Among the suggestions were strong calls for more "Visual" or "Graphic" aids: one 5th form boy, "Rupert" who was identified as a strong "Visualizer", made out a case for dynamic demonstrations:

Extract No. 72

I. Looking back over your own experience in learning about electricity and electronics, can you make any recommendations for improvement?

S. Well, if I could bring in my hobby - I think that computer animation would help a lot. Say, by showing electrons along a wire and into components, so that people could actually believe that they were there. Our Physics master has attempted to write programs on his spectrum computer. He was trying to illustrate how the holes and electron moved in transistors. He had a slight problem with his graphics. If I had something like that when studying reactance, it would have been easier for me. I have never quite understood what it is, but I am willing to accept it as a sort of idea to help with the mathematics of it.
4.29

A notable difference between the vocational students and the school pupils is that the former feel a need to transfer theoretical knowledge quickly into practical experience. Most of those who talked with me at the technical colleges appreciated the importance of classroom instruction, and the considerable efforts of the teachers to convey the fundamentals clearly and without unnecessary complications; but they all expressed in various forms their strong inclination to work over the theoretical descriptions in material circuits at the workshop bench.

An example of this feeling was given by a first year trainee technician, "Leo" when talking of the problems he had encountered earlier on his course:

4.30

Extract No. 76

S. Well, the main thing is - when the teacher explains what a circuit does, or a component does - is seeing the uses of it. You know, you see different components, and when you add the two together you get something totally different to what you expect - then you understand.

I. Can you give me an example?

S. Yes. You know when you talk about capacitor storing energy and charging up and that - it's not until you put it with a resistor that you see what use is the time constant. You don't realize what use it was until you put it with the resistor.

He explained why inductance was to him something of a mystery:

S. Inductance doesn't mean a lot to me - not as much as capacitance.

I. Are you able to say why you learned less about inductance?
S. Well, what we have been doing so far has been in class: we haven't come to any practical uses of it. We have just been learning about what happens to current and voltage, and impedance. But we never sort of see what they do and why.

I. So the practical work is very important to you in learning and remembering?

S. Oh, definitely. I should think so. In class you sort of sit back and sometimes you don't understand, but when you actually see it and that in practicals ...

A little later in the interview he said:

"It's a lot more interesting when you actually see it and actually do it. It's a lot better than sitting and watching it on the board. You can do the practical first and then you can get really interested, and you can get to know what happens. Sometimes the theory can be really deep and go on for a long time, and that, and by the time you've got to the end, you are so dazzled that you have forgotten what's happened before.

A colleague of "Leo", had similar feelings on this matter. "Brian" said:

Extract No. 77

S. You sort of listen and go away thinking you understand, then you look back at it and you find that you still can't understand. It hasn't really sunk in. But doing something yourself makes it stand out. It's much better than watching it on the board. You can do that all day, but actually building something, it stands out in your memory.

A small group of students from the same class, when talking to me informally, instanced their current study of transistor amplifier circuits: they found the lectures "boring," but the actual building of the same circuit was "exciting." They agreed that they all preferred, given the choice, to learn from the instructor at the bench, and believed that "the learning is quicker."

The difficulty, which many of the "Visualizers" have in coping with the traditional teaching of electrical principles was brought out by "Duncan" who found a particular difficulty with inductance:
S. I think the main thing with inductance is that they talk about it in class as if you could imagine the flux, and it's OK if you can stick into your mind where there is flux there is inductance – but I can't see it. I like mechanical things, like an engine with pistons going in and out, moving up and down. But with this coil I can't see anything.

I. Have you been able to get any help from the books in the library?

S. To be quite honest, I go to the library and ... to me, personally, I don't think the books teach you much. I need a person to actually demonstrate and say, "Look, this is it," and to experiment. Just to show that that is it.
The Transfer of Theoretical Principles into Practice

The success which the vocational students have in obtaining clarification of basic principles through the immediate application of them in practical circuits suggests a useful method of assisting school pupils and others who have difficulty in absorbing the information from the regular class teaching. To a limited degree a similar approach is employed by some teachers who use and adapt elements of the Nuffield Advanced Physics course, but most teachers regard any simplification of the traditional rigour as undesirably weakness. The experience of the vocational students does indicate that a proportion of those following academic courses might benefit by the immediate transfer of the classroom theory to practical circuit projects.

The vocational students' need to know of the practical application "in real life" conditions, of the theoretical matters explained at the blackboard. For most this means handling or constructing circuits incorporating those phenomena. This need is clearly brought out in Extract No. 76 where "Leo" was waiting to learn what inductance "can do, and why." For the vocational student understanding of electrical phenomena is closely connected with personal experience of circuits observed at the work bench, and vivid memory of basic principles is gained by the satisfaction of examining or constructing the appropriate circuits, rather than through intellectual investigation.

For those of strong "Visualizer" tendency, like "Duncan" (Extract No.78), inductance as a phenomenon is almost meaningless without visual demonstration, preferably with the accompaniment of an instructor's commentary.
during the course of carefully designed practical experiment. For such persons the full comprehension of the phenomena of capacitance and inductance and their importance, is likely to be obtained most effectively through a combination of personal experiment and authoritative commentary linking theory with experiment. For such students the graphic confirmation offered by the oscilloscope, with its dynamic images, is especially valuable.

The vocational students obtained both satisfaction and pleasure in building their circuits illustrating fundamental principles, and it is worthy of note that they believed that they learned most effectively while engaged in such pleasurable activities. There is perhaps a lesson to be learned here which is applicable to school laboratory work: that the practicals do not require to be the vehicle for applying exact measurement to confirm mathematical theory, but can be a means of pleasurable reinforcement of basic theory.
An important difference between school pupils and the vocational students of similar age is that the vocational students are not usually required to read up their subject in the textbooks. Their theoretical knowledge is supplied by the teachers in the classroom and supplemented by hand-outs intended for reference. Most of the teachers acknowledge the fact that few of their students have the experience, natural inclination, or literary skills which would allow them to research their own studies in the textbooks. Although in recent years a range of publications have appeared specifically to cater for the Technical Education Certificates, none of the teachers I spoke with appear to have directed their students to them; instead, they prefer to give blackboard instruction, notes, and hand-outs on selected topics which experience has shown require particular study and revision.

While some of the youths I interviewed and talked with do make use of the library facilities at their colleges, the majority gave me to understand that they were averse to personal reading for information or clarification. By comparison with the school pupils, a notable contrast in their attitude towards learning was that they felt little or none of the guilt or embarrassment experienced by the school pupils when they encountered difficulties in comprehending any of the fundamental topics, instead of seeking assistance from their fellow pupils, or consulting the textbooks, their immediate action was to go to their instructors with their problems, and frequently seek the practical application of the principle and inquire in what way that related to the matter which was causing them the difficulty. Their teachers, knowing this tendency, exert considerable pains to accommodate this approach and devise practical
projects which incorporate the principles which their students must master to carry out their future industrial or service duties.

An example of this was given to me by a trainee technician approaching the end of the 1st year of his college course, who had previously experienced difficulty in understanding the function of a transistor.

Extract No. 79

S. I'm designing this electrical circuit which has photo-electric resistors and switches, and as it is broken it operates a solenoid which makes a ramp move upward to push something off a conveyor belt. We use two transistors in it, and a few resistors. We're working on it. I can see how a transistor works better now, as I am doing this. It is easier than the theory. You don't really remember it until you actually see that's happening here. We got an oscilloscope, and then we saw what was needed, and things like that.

4.33 Some of the technical students did dip into electronic magazines, but few of them did this with any regularity, because as one youth put it: "I find them a bit heavy." Some of the interviewees had taken construction projects from Hobby Electronics or Everyday Electronics, relying on their more advanced work-shop colleagues for any necessary assistance. The majority of the technical students displayed a degree of nervousness in discussing the books or magazine articles which could promote their studies; their attitude was summarized by one youth who confided to me: "Textbooks! I don't like to use them because I find them confusing. If I've a problem I go to the teacher and ask about it. It's difficult, you know, to understand a textbook."
An exchange with a second term day-release boy, "Brian" at a technical college is characteristic of many:

Extract No. 80

(He had expressed a disinclination to consult the textbooks)

I. Can you tell me a little why you find it so?

S. Well, in some of the electronic books there is ... you get a different sort of language. Some people call things by different names: that's what I find confusing.

(The illustrations were more meaningful)

I. Are not the illustrations and diagrams helpful to you?

S. They are. Sometimes you can see it immediately. But sometimes, I look at it, and I can't sort of picture it. But when I can see it, then they're a real help, you know. They are better than the writing."

A second year service engineer who acknowledged that in the past he had experienced difficulties in understanding the action of the capacitor commented:

Extract No. 81

S. It's difficult to know how to say it ... they are not as straightforward as other things like resistors, where it is simple to understand because there are other similar things in everyday life.

I. Were you not able to get some help from the books?

S. They are helpful in some ways, but they get extremely mathematical and it can be very heavy going, and difficult to get the information out. I tend to learn by experience of what they do rather than learn from the books what they can do. You start using them and learn by experience. For me practice is a lot better than theory. Projects are a lot more helpful - being here, and actually making circuits.

A second year technician, "Duncan" offered me his reasons for avoiding textbook use whenever possible:

Extract No. 82

S. Oh, the textbooks, well, it's quite complex: first you open a textbook, but they write the way the author thinks is right, but it's
not right for me - my way of learning. It's like a professor teaching in a primary school: he would never make it.

Again, it takes so long. For example, I want to find a definition of something, but in the book I can't find it, and I am referred back to something else, and I find I have to start at the beginning to understand a diagram at page 217. Oh - I just give up.
DISCUSSION

Vocational Students' Use of Textbooks

One point which emerged regarding the technical students attempts to consult textbooks in the library is that several of them complained that it involved "so much time." Clearly many had done the minimum of reading during their school days, and found it difficult to concentrate on the written word, and they read slowly and with conscious effort. Regarding the clarification of difficulties and their reluctance to read in the library, two or three youths explained to me: "It's quicker to learn from the teacher at the bench."

Discussions with technical college librarians convince me that they are well aware of the reluctance of the day-release and elementary students to take advantage of their facilities. They seem to have accepted the position that only the more advanced or older students will read anything beyond the teachers' theory-notes or laboratory experiment descriptions, and are resigned to the fact that those textbooks written especially to acquaint the new technical students with the fundamental principles of electricity and electronics, will rarely be read by any but the second or third year students seeking revision material.

It is important that the vocational students should be made aware of the existence of the newer publications written for the Technical Education Courses, and that attempts be made to overcome their anxieties and disinclinations by gentle conditioning in the form of group readings in the relevant sections of these specially prepared texts, such as those published by Pitman, Granada Technical Books, John Murray, and the Oxford University Press, to accompany specified T.E.C. modules.
All the technical college students could easily read the crystal set diagram, and most of those who were approaching the end of their third term could offer a satisfactory commentary on the two transistor amplifier. It is interesting that their regular handling of practical circuits allowed them to approach both circuits in a methodical manner approved by electrical technicians, so that in the course of following signal paths and noting currents and component groupings, they found recognizable blocks of units which allowed them to identify the system as a whole.

A characteristic example of the trainee technician approach to circuit diagram reading was given by a first year student, "Ernest"

Extract No. 83

S. I work from one end, going through everything - normally, I go from positive to the earth or negative end. I'd follow it round, and when I got to each component, I'd see where the current went, and follow through the different branches.

I. In this case could you take your path through this (crystal set)?

S. I'd come down through this variable inductance, - it's connected to a variable capacitor, which is connected to the positive end of the diode, which is connected to this headphones, then it comes back to the other end of the variable capacitor, and that's the end of the circuit.

I. And are you able to say what sort of circuit it is?

S. Yes. It's a radio circuit.
And later:

I. Here we have a more complicated diagram. Where would you begin?

S. I'd take it from the supply.

I. And from there?

S. I'd go to that capacitor and see where it was connected - it's in parallel with this, and its blocking ... then, I'd come to the bottom here and see the connections with the emitters of the transistors ... they are amplifiers?

I. You are right. Could you continue?

S. It's blocked again here, so I'd come round to the top, here, then - another amplifier: I'd look for the load.

I. Good. I see how you go about the reading.
DISCUSSION

Circuit Diagram Reading

4.36 In the activity of circuit diagram reading the technical college students were more confident and more fluent than the school pupils of the same age. This was not the result of any formal instruction, for none of the vocational students had received any such systematic training in circuit diagram reading as part of their college courses. The day-release students had acquired their acquaintance with common arrangements of components from their workshop experience, and their attendance at the bench beside skilled electrical servicemen. Those in the early stages of full-time technical college training had built up their degree of familiarity with diagrams in part from the analysis of practical circuits given by their instructors, and in part from the practice of drawing out the theoretical circuits of all projects which they undertook to build.

The ability of the vocational students and the confidence which it allows them in approaching new electrical diagrams, sets an example of what might be achieved in the schools if some systematic instruction in this skill were to be given. The necessary amount of extra effort on the part of the teachers would be modest, yet the benefits to their pupils would be considerable. The evidence of what the vocational students can accomplish in this activity within a few months and with relatively little difficulty is impressive. With the advantage of an organized programme of instruction, the school pupils could equal or exceed these achievements.
MOTORS AND GENERATORS

4.37 Of those few who had studied something of the theory and practice of generators and motors, only one was prepared to talk about his studies, the others withdrew to an embarrassed silence after indicating that they had some little acquaintance with the subject but that they required a good deal of revision on matters which they had failed to grasp. A characteristic exchange was that with "Danny":

Extract No. 84

I. Are you able to explain the operation of a motor?

S. Well, I'd try, but I can't say I'd succeed. I'd say that generally it's quite complicated. I have so many notes on different sorts of motors, sometimes I don't know which is which, and I still don't understand all of it.

"Sidney", however, was rather more forthcoming:

Extract No. 85

S. Motors ... it's been on the course, but I don't fully understand them. They are not my favourite subject.

I. Can you say what it is about motors which prevent you getting to understand them?

S. The main difficulty is the people who have been teaching. The person who taught us motors wasn't a very good lecturer, and I don't get on very well with him.

I. If you were asked by a new student to explain how a motor works, what would you say?
S. Well, there is the field magnets which creates the electromagnetic field and the current flowing in the armature - this is the tricky bit - I won't say react with it ... but it's a force produced by Fleming's Left Hand Rule to move the electrons in the armature in a certain direction. I suppose I have always taken it for granted really. Here I don't really understand it. It's very abstract from real life.

I. Have you had any help from dismantling or assembling a motor?

S. No. I can't say I have. But I'd say it would be a good idea if you'd done some theory behind it, then actually looked at the motor to see what was happening in the motor.
None of the vocational students interviewed gave evidence of having strong "Mathematic" tendencies. However, the vocational students' numerous graphic references were particularly noted during discussions about capacitors and their functions. Again and again they made such statements as: "I try to picture how it stores this charge." One impetuous youngster burst out with: "Capacitance! But what is it? I mean, you can't see it. Or at least I don't know it. If you put something across there to measure it, I say: 'I still can't see it.'" But another colleague who felt more confident that he did understand the nature and function of the capacitor explained: "All that build up of electrons on one side of the thing: I've got a little picture of all that."

The "Visualizer" characteristics were also indicated by the vocational students' greater dependence on the drawings and diagrams reproduced from classroom blackboards, and upon those illustrated hand-outs supplied by the instructors. Moreover, there is no doubt that they tended to respect the theoretical circuit diagram a good deal more than their age group following academic courses at school.

The instructors have learned from experience how important graphic aids are to their students, and they take great pains to convey by models and analogies much that would be treated mathematically elsewhere. During my attendance at classes I have been impressed by the skill and patience of the instructors whose own blackboard illustrations must supply the graphic images for students who will rarely extract them for themselves from the textbooks.
from the textbooks.

DISCUSSION

Mathematics and Visualizers

4.39 It was not expected that many, if any, "Mathematic" students would be found among the vocations, because few of the students enrolled for technical courses had distinguished themselves by academic inclination at school, and the vocational programme tended to minimize the exploitation of mathematical expertise. On the other hand, many of those who spoke with me indicated a pronounced bias towards the "Visualizer" characteristics. Their conversation was marked by frequent use of figures of speech relating to "seeing" and "looking" relating to phenomena associated with the fundamental principles of electricity. Their need for visual confirmation of the occurrences predicted by theory was made plain by the importance which they attached to the practical work at the bench, and their pleasure in handling measuring instruments, and viewing the oscilloscope images. Since they read little, the evidence of their experiments and the memory of what they observed, took the place of the authoritative commentary of the textbooks.

DISCUSSION

Generators and Motors

4.40 It was not possible to obtain the desired data on the vocational students' understanding of generators and motors because only four of those interviewed had followed a course which included more than a superficial treatment of this once emphasized topic in electrical training. I gathered from the instructors that in order to meet the current demands of employers it was necessary to give electronic circuits a priority during the first year courses.
INTERVIEWS WITH UNIVERSITY/POLYTECHNIC STUDENTS

4.41 Those who volunteered to speak with me represent a wide spectrum of the first year Engineering and Physics students. They included many who were experiencing difficulties with their electrical studies, but the majority were coping satisfactorily, but felt that they had useful comments to make on their past experiences. A considerable number of those who had been interviewed by me persuaded their boy/girl friends, or laboratory partner to meet me, and a not inconsiderable number contacted me because they were pleased to know that some one - for the first time, to the best of their knowledge - was taking an interest in learning of the problems within their subject area.

Most of those interviewed were in the first or second terms of their first year, and memories of their school courses remained fresh, but they had been long enough in Higher Education to know what level of work was required from them, and to form reasonably balanced judgements on the effectiveness of the theoretical and practical electrical instruction received in preparation for A-level examinations. Some, who knew that they were weak in electrical knowledge had avoided such questions in the A-level examinations, and believed that they would be able to continue to avoid such matters during their further study. They discovered that they were mistaken. Some attempted to "catch-up" by reading the textbooks recommended for the Engineering or Physics degree courses, and had discovered, with a certain amount of alarm, that these texts assume a solid prior foundation. Others had found the pressure of work did not allow the opportunity to revise slowly and carefully, and consequently experienced
difficulty in allocating their time and energies. Several spoke of feeling "rushed along" by the intensity of the required course work; some talked of using A-level texts to revise what they had previously neglected; and a larger number projected undertaking intensive revision "during the vacation."

Many were sharply critical of more than the textual content of their books: they were aware of deficiencies in the illustrations, in the examples, and in the design presentation. This is particularly true of the "Visualizers". It is clear that these factors are more important to them than the majority of educators suppose, and their predilections undoubtedly affect their choice and usage of textbooks. At the beginning of their university/polytechnic degree courses the students can look back upon their experiences with the school textbooks and consider how well they were served, either directly through their own study, or through the intermediary gloss supplied by their teachers.

Many of the first year students told me that they had gained the impression that instructors and tutors were impatient with those who exhibited any lack of fluency in handling "basic principles." Students spoke of having forgotten some of the Physics they had studied during the interval between sitting the examinations and beginning their university/polytechnic course, and some hoped for an introductory review which might accommodate any memory losses suffered on newly-acquired information. For most, no such revision course was offered in the first week or two. A considerable number of students complained of the great emphasis placed upon mathematical expertise and calculation, particularly at those institutions with a long academic tradition. It was felt to distance their electrical studies from the practical applications, and their own personal interests.

Many of the Engineering students reported that they suffered from inadequate experience of practical work, and had to undertake much rapid
adjustment, often embarrassing, at the very beginning of their laboratory visits. Those who had done hobby activities in electrical construction were placed at a considerable advantage, for even a small amount of practice in circuit building provided confidence, and knowledge of components which other non-building students lacked.

A number of the girls interviewed complained of ill-equipped laboratories at school, and of little encouragement from teachers or fellow A-level candidates. (However, some had subsequently learned of recent improvements at their schools, where the senior staff were beginning to appreciate the need for sufficient practical experience in properly equipped laboratories to complement the theoretical A-level studies.)

A considerable proportion of students in the first or second terms of their degree courses criticized their school courses for treating inductance and capacitance in an "isolating manner" whereby the theory was not sufficiently, if at all, related to practical experiments in the laboratory. The majority of the interviewees complained that the teaching scarcely touched upon the components' functions in common electrical circuits, or electrical apparatus which the pupils would be familiar with. Only a small number of students spoke of receiving a "basic electronics" course to acquaint them with transistors and associated circuits. The Engineering and Physics degree students were expected to possess, or quickly acquire, a knowledge of these solid state devices, a requirement which presented considerable difficulty to many students fresh from school. Interviewees told me of serious problems they had experienced in familiarizing themselves, largely by textbook study, with the operation of these devices and their interaction with other circuit elements such as capacitors, resistances, diodes, and inductances.
Memories of Theoretical Studies at School

The university/polytechnic students were asked to think back to their school electrical studies and comment on them as a foundation for the work which they were engaged upon. While a considerable proportion felt that their preparation had been sound, or at least adequate, and they knew something of the difficulties under which their Science teachers laboured to provide the A-level instruction, there were many who voiced complaint on the grounds that the theoretical coverage was superficial; the tuition was designed primarily to push as many as possible through the A-level examinations; and, that certain areas of contemporary importance (like Electronics) were omitted, and that practical work in the laboratory was minimal. Of these, many discovered that there was a great gulf between their school knowledge and the standard required of them in the first term of degree courses. As one youth beginning his engineering studies put it: "At school there was virtually no electronics, only a little E.M., and what there was of it was simple stuff. When I came here I had to mug up a lot - and quickly!"

Some of those who considered their school preparation unsatisfactory were frank in telling me that they blamed themselves for not being more conscientious in carrying out the reading and classwork assigned to them. Those who had taken no interest in hobby electrical constructions regreted it, and looked back with envy upon their colleagues who had that advantage. "Harris", a student who had encountered considerable initial difficulty in coping with the requirements of his Engineering Science degree course, told me:
Extract No. 86

"It always seemed to me that those people who had electrical sets and were interested in it, were good at it, and the teachers to some extent catered for them. Those people were reading electrical magazines and had their own home kits and little sets, and made wirelesses. It seemed that for them it was absolutely easy, so they wanted to rush on all the time and do those various things. For the other people, it was all, 'Electricity, Oh. dear, I can't understand that very well because it hasn't been explained.' I always felt I was left behind. I didn't know the steps up to whatever we were doing at that moment. I sort of gathered the basic steps by the time we were actually being taught the more advanced steps - so I always thought I was on unequal terms with other people."

4.43

The Treatment of Electromagnetism

Several students felt that their teachers had treated electromagnetism in an unsatisfactory abstract manner whereby the theory was kept remote from all practical matters. This was particularly troublesome to those who were not biased towards a mathematical approach, and hankered after some solid visual references. One girl, entering upon her Physics degree studies, said: "Electricity, I wasn't able to do much with it. In other things, you can understand what's going on, like gases, and things, you can see them. With electricity it was different."

"Bessy", a colleague of the previous speaker, pointed to the failing of the remote academic approach in being depressing of personal interest and inquiry:

Extract No. 87

S. When we were introduced to capacitance at school, it didn't make much sense.

I. How did you clarify it?

S. By reading textbooks, and by the teacher going over it.
I. How did the teacher help?

S. He gave us the equations to use. Quite honestly, it was equations and that is all we knew - what we had to use in the examination at the end.

I. Did you not inquire into the functions and uses of the capacitor?

S. No, I didn't.

4.44

Particular Difficulties at "All Girls" Schools

A few of those who had early difficulties on their degree courses were girls who had attended "all-girls" schools where there was little encouragement to study the sciences, insufficient equipment, inexperienced teachers, and a lack of peer support. A student reading for an engineering degree, "Milly", told me of her near-isolation among her classmates, and of her determination to pursue her ambition, despite difficulties with electromagnetism:

Extract No. 88

S. There was so much of it that it was hard to grasp.

I. Such as?

S. Well, even with Faraday's law - when you had the flux going through the system, how much it would cut at one time. I couldn't understand that, and the teacher couldn't explain it. I think the teacher was trying to simplify it far too much, because people couldn't cope with the maths. It was simplified in the wrong way.

I. Did the textbooks help?

S. Well, to a relative extent. It is difficult to gather facts from a book.

I. Did you talk about it to your class-mates?

S. I don't think anybody else had the interest, or would have been worried by it. The other girls - I went to an "all-girls" school - well, to be honest, the number of girls really interested in Physics was small.
Unqualified Physics Teachers

Some of the girls realized that their teachers were not comfortable in teaching electricity, and that the subject had not been part of that teacher's professional training and they were not giving tuition from choice or personal interest, but were meeting the urgent needs of the head teacher, ill-supplied with qualified Physics graduates. One girl, confiding to me that A.C. theory was a "big problem", said it was mainly because the teacher didn't like electrical studies, and had little knowledge of transistors in particular. The teacher's disinclination was sensed by the pupils, and they suffered as a result. The teacher did what she could, and her pupil, hankering after a place on a scientific course at university, did what she regarded as the expedient thing: "What I did was to read and pick up bits by which to answer questions that I thought would be set in the exam., not really understanding what I should be understanding."

Something of the danger of acquiring a dislocated, partial acquaintance with basic principles at school was forcibly impressed on one interviewee, who told me of her embarrassment at discovering her ignorance of the fundamental principles governing common components, when she volunteered for some practical experience at a Ferranti electrical laboratory:

"When I went there it was the first time I really understood silly things, like if you have an extremely high frequency in a capacitor, it short-circuits. That's the sort of thing which wasn't taught at school - really basic concepts."
"Visualizers"

Students who were of a strongly practical tendency and those who were inclined towards habits of visualization, spoke of other school-time difficulties in mastering the principles of capacitors. They believed it was due to inadequate explanation given in the class, and the absence of guidance with regard to the functions and practical applications of the components which were examined in isolation from associated circuits. Some found that there was a considerable amount of remedial study which they had to undertake on entry to degree level work.

A Physics student, "Amanda", told me:

Extract No. 89

"I had problems in actually seeing what was physically happening. When you can see it, it becomes easy, but it is very difficult to understand when you can't you can see from the meter that the negative charge has moved up to one plate and the positive goes to the other plate, but when you go into more detail with capacitors it's difficult to see what's going on. I always found it difficult to understand capacitors, what they are for, because most things which actually are useful can be seen - but we weren't told what capacitors are used for. I have had a lot of problems with electricity, and I have had to do quite a lot of detailed work with my tutor. That has made things a bit easier."

4.47

Difficulties with Inductance

The same student was unsure of her understanding of the nature of inductance; yet she had not, up to that time, revised this fundamental, and had even turned in a test-paper which included inductive calculation. I asked how that could be, and received the reply:

"I had it just by rote, really. Most of the problems that we had to do were like series circuits and parallel circuits
and what happens is all just mathematics. You just use "L" and forget about physical things."

I asked her what she felt about that, and received the answer:
"Well, I'm not happy about it."

Several first and second term degree students spoke of their struggles to master the principles of inductance. At school the teachers' classroom explanations were often confusing to those who inquired about curious phenomena exhibited by the component, the inductor, and the standard textbooks' commentary appeared to be little appreciated by others who attempted to "read-up" the subject. Several told me that at A-level they were resigned to accepting what they were told, and hoped to clarify the mysteries at a later stage of their Physics studies. In the course of my interviews I met many who had not yet fulfilled that intention.

A Physics student, recently begun upon her course, summarized her problem:

"Yes. I find it confusing: the existence of the back-e.m.f. at the same time as the forward one - the fact that they are balanced. I thought everything would come to a stop. It's difficult to grasp."

"Dennis", a first year Physics student had been troubled by inductive problems in A-level preparation, and continued to be anxious about some considerations of phase which were still unresolved. He told me:

Extract No. 90

S. At school it was LCR circuits which got me. I was confused because of the current being out of phase. That was very difficult to understand.

I. How did you try to make sense of it?

S. I think I probably just accepted it. Well, I managed to work it out in the end. But the thought of voltage hanging around...you've got to imagine energy stored in this thing... I don't know that I can completely understand it now.
Practical

4.48 A considerable proportion of the interviewees believed that their practical work at school had been unsatisfactory. They complained that they later realized that they had received less than was necessary as a preparation for the courses which they presently were engaged upon. I was frequently told that they believed the laboratory work was superficial and not conducive to further their understanding of the theoretical principles dealt with in the classroom. From their accounts, there can be no doubt that in many cases the equipment and facilities were quite inadequate for practical A-level experiments and could not provide sufficient "hands-on" experience to build confidence in using instruments.

One beginning engineering student, "Michael", in reminiscing about his school laboratory said:

Extract No. 91

My major problem was in practicals: I think there was too much given, given all at once. I mean, it was just very confusing. What happens is that you go on to new and harder material and find troubles because you are not sure of things gone before. That's what I found. I got through my exams because they ask for solutions which you can provide by following the equations without knowing much more. That's why a lot of people just use equations and don't bother about understanding what's going on.

Those who had suffered from inadequate opportunities for using laboratory experimental set-ups and instruments quickly discovered that this lack of experience was a hinderance to their initial progress on degree work. One girl said to me: "Lack of practical work was a disadvantage - is still a disadvantage. I am not very good on electronics practicals, on oscilloscopes, and other instruments. I am uncertain with them. Fortunately I get a lot of help from the demonstrators."

All the interviewees were asked to consider what changes they might wish to make on the electrical sections of their school Physics courses (given ideal circumstances and a completely free hand) for the purpose of
making such courses more enjoyable and interesting to the students, and more effective in the provision of a foundation for electrical studies in higher education.

4.49 The recommendations offered repeatedly stressed a desire for a more thorough grounding in a.c. electromagnetic theory, both the basic concepts and the analysis of the circuits with which the phenomena are associated. Several students told me that the information they accumulated was piece-meal, shallow, and very biased towards formulae and calculation techniques to answer typical examination questions, and little of that tied-in with the electrical and electronic world of their daily lives. Various speakers lamented the fact that their courses did not introduce them to Electronics, a subject which the newspapers, magazines, radio and television broadcasts were all stressing, and one which would particularly affect the younger generation.

Those who had prepared for their A-levels at schools where the instruction was abstractedly theoretical, were disturbed to discover the state of ignorance they were in, when they compared their condition with that of their course colleagues. As one recently arrived Physics student put it to me while at work at her bench: "Some people here, when they came into the lab, hadn't a clue what they were doing. They never had seen a resistor or capacitor. It does help to know what the components look like!"

Frequently students who had not taken any hobby interest in electricity remarked that they would change the syllabus to include more practical circuit building, not so much to achieve a fluency in mechanical operations, but to fix in the mind the theoretical knowledge gained in classroom, and to familiarize themselves with the arrangements they knew only from the diagrams on the printed textbook page. One student summarized it in these words: "At school you should start recognizing the building-blocks of electrical circuits."
Among those who experienced difficulties in the earliest stages of their degree studies were a number who were critical of the academic approach to electrical study, at school and university. Discontent was particularly felt by some at colleges strictly under the influence of physicists who believed in infusing their students with an overriding passion for mathematical rigor in all scientific work. The essence of his dissatisfaction was expressed by "John", a second term Physics student, who said that at school he had been an enthusiast for Physics and good at it; but, he remembered that his first weeks at university had been disappointing and he had lost his excited interest because he felt that the electrical studies were used as the vehicle for mathematical exercises, rather than offered as the unfolding of a fascinating branch of science. For persons like himself, "who used mathematics, rather than were mathematicians", the balance was wrong. He had hoped that the practicals in the laboratory would build upon his school experiments, but was dismayed to find that there, too, there was a preoccupation with the exactness of measurement and very much less concern with what was being measured. In commenting on his experiences he deeply wished that the teaching staff would involve the students in what was taking place physically within the circuits:

Extract No. 92

"It would be nice if they could somehow manage to get you to understand and be able to solve problems eventually without just plunging you into the maths at the "deep end" to start with: it doesn't inspire, and its difficult to follow. If the initial emphasis was on what is actually happening, and then perhaps on how to work it out mathematically ... I would have practicals where circuits were analysed, explained, and commented upon, and then the maths applied."

The need for more initial guidance in what was expected of the people
newly arrived at the laboratories, and what they could hope to learn from the practical benchwork, was expressed by a girl who had come to read Physics after attending a school where there had been the minimum direction in the classroom and very little appreciation of the value of practical skills. She said to me: "I think a lot about my school work. We girls didn't like the lab. work. The boys would stay behind to do electronics and things, but the girls never did. They were a lot more mature than the boys, and their interests were outside the school."

4.51 Several students spoke of the need to bridge the gap between school electrical knowledge and practical experience, and that of the university – either by means of an introductory course or by some modification of the lecture programme to accommodate the "freshers." One student said: "When you come here they assume you know all the basics – and, while we have done it, we did it once and we didn't have any practice on it. I certainly never answered a question on amplifiers before. I needed help with fundamentals, right at the beginning."

A second term Engineering student, "Bernard", told me that he had found the first term a trial because of his inadequate preparation. He realized that it was necessary for him to give himself a "crash course in revision", and was successful in that, largely through the assistance of his Engineering colleagues at college, rather than from textbooks, particularly the recommended university textbooks which assumed that the reader already possessed a thorough knowledge of the elementary theory.

Extract No. 93

S. I had to go back to basics again. I had never studied them deeply.
I. Can you think of particular weaknesses?
S. The real basics: capacitors, inductors, right down to the diode.
I. How did you go about it?
S. More talking to others than anything. I bought all the books which were recommended and ploughed through them. For a lot of the time I just got a lot more confused.

I. Why was that?

S. They assume too much. They didn't tell you what you want to know: they don't go through it bit by bit. It all seems jumbled. They say it's basic principles, but they just "throw you in at the deep end."

A friend of the former speaker, "Gladys", also studied Engineering at the same college, suffered problems in extracting information from the textbooks:

Extract No. 94

S. I'm frightened of electrical work, to be truthful. I find it very hard to understand, although I quite like it.

I. What is it that frightens you?

S. Well, if someone goes through a circuit with me - like when we have circuit theory lectures - I can understand it totally when he's doing it. But, as soon as I get a problem, I think, even before I've started, "I'm not going to get this right" because I know I never have in the past. I tend to give up before I've started, because I think they are difficult, and sometimes they are not as hard as I thought. When I was at school I never used the textbooks. We were dictated notes. The textbooks were there to refer to, but I never needed them. So, I found being here, and having to teach myself from the textbooks, it's a bit of a shock."

A girl starting her Physics degree course, believed that some of her difficulties were connected with the "all girls' school" where the teachers had attempted to divert her from her determination to study science. "Rita" said:

Extract No. 95

S. I often got the feeling that I shouldn't be doing Science because I am a girl. I think that was a big part of it then. They tried to prevent me doing the subjects I wanted to do. The teacher tried to talk me out of it. It was fairly strong. The headmistress said: "Have you seriously considered it? Science is all very well, but ... We suggest that you do English, or more History, or ..."

I. But you really wanted to study Physics?

S. Yes. But I also felt that perhaps I couldn't do it - because they said I couldn't.

The majority of those interviewed believed that they had overcome their Higher Education entry difficulties by the second term. However, I
learned of other problems which continued to hinder students' progress subsequently, and these were made the subject of my inquiry.

Coping With Initial Study Difficulties

4.52 I wished to learn the procedures used by students to overcome those problems which arose during the early months of their courses, and to hear what they thought of the various sources of assistance, such as study in the textbooks; consultation with their peers; and the guidance and advice obtainable from their teachers. With few exceptions those interviewed expressed a disinclination to seek assistance from their instructors. They offered a variety of reasons which appeared to be based on considerations of respect for the precious time of the Staff, but which probably had its origin in student lore that such calls upon academic help would not receive the warmth of welcome which the inquirers might desire.

Many favoured, in the first instance, discussions with fellow students, and the examination of their worked examples of similar problems. Most of those who offered a firm opinion in the matter believed they were best served by private study with the textbooks. Consultation with the teaching Staff was rarely mentioned, and then usually as a protection against examination embarrassment, or as a sort of grudging necessity under the pressure of circumstances. "Gerald", who had recently puzzled over some questions relating to electromagnetic waves, confided to me:

Extract No. 96

S. I spend hours looking at textbooks until I find the answer. They do eventually help me. I mean, you can eventually find out what's supposed to be going on - but I find it very time-consuming.

I. Have you approached your tutor about these problems?
S. Well, I have never actually gone to see any tutor about academic work, except at my weekly tutorial; in other words, I have never gone to see him half-way through the week because I can't do something."

An Engineering student, "Louis", who had recently clarified some troublesome inductive phase difficulties preferred to be independent of his instructors. When asked if it was normally his method to work at his problems alone in the library, he replied:

Extract No. 97

"I would always go to the textbook, then I would talk about it with the others - yes, about as often as I would go to the books. I've found it easier to sit down with a textbook: it doesn't get bored. You can sit there and go through it several times, and work it out piece by piece, rather than with a tutor who may have another tutorial coming up and is pressed for time."

In some cases where the difficulties were connected with memories of practical experiments on component behavior, it would be expected that the solution would be sought in the laboratory; however, either from a school-time preoccupation with theory, or prejudice against personal manipulation of the equipment, students would opt for textbook research. A young engineer who had anxieties about her understanding of capacitors in a.c. circuits told me she was going to learn more about them. "How will you go about it" I asked. "It's going to be by reading" she answered. "I think so. Obviously, if I read enough I can get enough different explanations to be able to get a general understanding. It won't be by practicals: they are so boring."

Many of the first year interviewees spoke of seeking the resolution of their problems through the assistance of their colleagues. In part, this appeared to be because in the first months of their Higher Education
they found it exceedingly hard to break themselves into the discipline of personal research. It was also in part due to a difficulty in adjusting to the condition of loneliness necessarily associated with gaining an education primarily through reading. Some spoke of the understanding and cooperation of their colleagues and others stressed the impracticality of postponing inquiries until the weekly tutorial; moreover, that tutorial time was likely to be reserved for the consideration of the written work set during the previous week. "Jane", an Engineering student, told me:

Extract No. 98

"We talk with each other. I'd say that I probably get half my education just by chatting to other people. It's easier in that you can get a good argument with someone, and really thrash some subject out until eventually you can come to a conclusion. Then we both understand it better."

Another Physics student told me of her regular habit: "I usually go to a second-year person, and ask. And I have a look at some of the questions they have done, and some solutions. Then, usually, it is OK."

A colleague of the previous speaker, "Winifred", similarly approached more advanced students:

Extract No. 99

"My friends help me with my work, that is how I do it. I go to them and say, 'This is the question. Can you answer it?' I feel guilty about it, because I do it frequently. It is better than leaving things until the tutorial. I can spend a whole tutorial on one question. Our tutorials are about explaining what went wrong with the tests of last week. I prefer asking friends to searching the books. I find it very difficult to get things out of books. They never answer what you want to know."
By the time the students enter upon their Higher Education, if they have a strong inclination towards the "Mathematic" approach, it is certain to be demonstrated in their attitude towards the course tuition, the laboratory facilities provided, and their choice of textbooks. The most strongly biased "Mathematics", although they have not considered the matter from the point of view of this research inquiry, were aware of their own eccentricity when compared with the large majority of their peers. That knowledge however gave rise to no discomfort, rather a feeling of superiority or satisfaction that they had adopted procedures of study agreeable to them and likely to be effective in academic achievement.

Through experience and practice the mathematical skills, which had come more easily to them than to others, were being constantly sharpened, and the executive satisfaction which they obtained tended to confirm their confidence that their methods were most appropriate for academic progress. The "Mathematic" inclinations do not necessarily rule out any use of "Visualization" - indeed, several of those in this category talked of using some of these characteristics - but those methods were considered appropriate to a preliminary stage of study, or thought of as a less desirable alternative for particular situations. All the "Mathematics" I interviewed were reading for Physics degrees. It is likely that the characteristics which I have identified pre-determined their choice of degree course as much as their personal interest in the subjects offered and the career prospects thereafter.
"Alex", whose school had taught the Nuffield Advanced Physics course, remembered that he had experienced difficulties in grasping the principles of inductance. He had found himself in conflict with the visually emphatic, highly practical nature of that method. He satisfactorily obtained his own solutions by consulting textbooks of his own choice. He told me:

Extract No. 100

"On the Nuffield course they didn't seem to like mathematics too much. They tried to present inductance by analogy. I just found it very difficult. I wanted to know what was happening, even if it is in terms of symbols. I don't think I paid a lot of attention to what was taught on the course. I looked elsewhere in the traditional books."

I asked what place his practical work in the laboratory had had in clarifying the inductive problem. He replied:

"It was quite difficult to relate, experimentally, what was going on with the explanations and the drawings given in the books. If you have equations in front of you which describe a quantity variance, and you take measurements, you can see what's going on, even if it is in an abstract form. But when you try to actually form a picture, it just doesn't work.

So you are the sort of person who is drawn to mathematics behind the physical actions of components and circuits?

Almost always the mathematical side.

In the laboratory are you aware of approaching things from the mathematical point of view rather than the practical?

Well, I think I take a fairly reasonable note of the physical set-up, but I am interested in looking for, ... say, inductances in parallel, or series, or capacitances in series or parallel, because there are opportunities of applying the formulas relating to them. You can say, "that is all right then, here is the equation" and so on. That lets you get on.

I asked the same student about his conception of electrical terms:

Extract No. 101

I am interested to know your opinion about some of the terms commonly found in the textbooks, for instance, "Impedence" - what does it mean to you when you read of an amplifier having a certain impedance?
S. Its voltage across the current.

I. And in a particular situation, like the amplifier?

S. Then I think of the induction and capacitance involved.

I. Do you know whether you generalize the result, or consider each separately?

S. I think of the mathematics of it. I remember, I asked the Physics teacher about phase difficulties - about what was actually happening; but, if he did give me an explanation, I don't think I understood it, except mathematically. So, I just take it mathematically. That means ... I suppose, I can't understand what's going on, what each wave does: consciously. I don't think it's necessary.

I was interested to have this 'Mathematic's' opinion about the place of laboratory work on his course. He said:

Extract No. 102

S. Practical work occupies such a lot of time, and being of a mathematical bent, I would be quite happy to do none. I know, obviously, it is necessary, but it's just my view. I think, frequently, that practical work is the least valuable to me. I prefer to do things on paper: provided I get the right answers. If I am given a set of principles to work with, I am quite happy with those principles, and if I can get the right answers I am quite happy about the answers. But, if I am not too sure about the principles, then, when I meet the answers, then I know I am using them in the right way, but I have to go back into the principles again, and keep at it until I understand.

I. I think I know what you mean: you don't want to confirm the paper result by going to the actual experiments. You do it in your mind.

S. Yes. I think I'd always do that. I'm happy to leave the experimental work to others.

Another Physics student of strong "Mathematic's bias was asked how he would respond to meeting the term "Inductive Reactance" replied:

"Basically mathematically: in terms of complex numbers."

He had studied transformers and found reflective impedance "a little troublesome." I asked if he would know the directions of the various currents of the secondary and primary windings:

S. You mean the back e.m.f.; no, I'd have to sit down and work it out mathematically.

I. Mathematically - not by picturing the directions of currents?

S. Definitely mathematically.
I asked another Physics student, "Jerry", if he thought about the physical function of the capacitor and inductor.

Extract No. 103

S. No. I do it mathematically.
I. Was that how you did it when preparing for A-level?
S. I found I didn't have to know very much. I mean, it's all just intuition really. You are given formulas. I found I didn't really need to know much of what was going on.

I inquired if he found value in the practicals given at his school. His answer was: "I don't think I ever wanted to go into the labs." I presumed that he had no electrical hobby: "Oh, no. But, ... I think it was in my last year they started a club for playing about with components and so on. I wasn't interested." I wondered if there was any tuition which he wished he had had at school. He replied: "The only thing I wish I had learned at school is a lot more formulas. When I came here I didn't know much about electricity."

4.54 A regular characteristic of the "Mathematic" was a repugnance towards physical manipulation and even the thinking of the physical functions of the components. An alternative mathematical approach tends to be used, even when that may prove more complex. When I asked "Gladys", a first year Physics student, how she followed the currents of the transformer, she replied:

Extract No. 104

"With electrical problems I usually try to get down the terms and work things out mathematically, and let the maths explain what's happening - rather than try to work it out. I usually draw the two things, and then I usually use Kirchoff's law. I try to do two equations, and then substitute back to get the sort of reflecting "V". I can usually cope, though sometimes I end up losing contact with what's going on in the actual circuit."

During the course of her reading, what did the term "Capacitive Reactance" mean to her? Her reply was: I think it means what the formula tells me."
"Peter", a pronounced "Mathematic" reading Physics, told me:

Extract No. 105

S. I'd say I'm very much the mathematician. I certainly don't feel I understand a subject very much until I can understand the maths of it.

I. Is this true of your reading: I mean, are you drawn to textbooks which have a strong mathematical bias?

S. Yes. I'd say that's the way I do it. I'd say I don't gain much from practicals, unless I've worked through the theory. It seems a bit moronic to be convinced because something seems to work. At least, working things through is more satisfying intellectually.

I. The theoretical basis of a capacitor's function would doubtless interest you, but does that interest carry over to a curiosity about the physical nature of the function?

S. Do you mean the separation of charge within the metal and the capacitance of different capacitors?

I. Yes, all that relates to the component and its action in a circuit.

S. I do think a bit about components and their actions in circuits. It depends on how difficult the circuit is. If it's some horrible electronic circuit, then I just think of the maths of it.

The "Mathematic's" characteristic aloofness from the handling of real circuits was made plain when I asked:

I. How do you cope with the practical side of your course?

S. Personally I would be quite happy not to have any practicals.

I. None at all?

S. I know it's not a widely held view, but I'm only interested in theory. Obviously, you need to have some practical experience, as I have had, but I think the main point of Physics is the intellectual aspect.
DISCUSSION

The "Mathematics" in particular the strong "Mathematics", volunteered opinions and comments which leave no doubt as to their tendencies. Their conversation is usually marked by quantitative expressions, and they are rather uncomfortable with questions about the physical processes associated with components and circuits, and tend to direct the talk away from laboratory activities or practical electrical applications. The practical work which "Mathematics" must do in Higher Education is carried out without enthusiasm or personal interest, and (as in the case of "Alex", No. 100) they do not respond as well as "Visualizers" to the assistance offered by textbook diagrams and illustrations, but seek an opportunity to apply the formulae, in which they place great confidence.

The "Mathematics" take a delight in solving problems, but very much prefer these to be abstract and intellectual, and are impatient with the manipulation of circuits. They often express a similar impatience with time-consuming laboratory measurement, and tend to dismiss the observations and conclusions which others draw directly from experiment; and, like "Peter" (Extract No. 105), remain unconvinced until they have satisfied themselves intellectually by mastering the mathematical theory.

While "Peter" is a pronounced "Mathematic" and his views and inclinations are of an extreme nature, his attitude towards practical work in the laboratory is in considerable measure shared by others in this category. The "Mathematics" who talked with me all expressed preference to keep practicals as short as possible and to have as
few as possible. Having minority tastes, they exchange ideas on their work with a limited number of others of like interests, and generally like to work on their own, favouring textbooks which others find difficult. They tend to associate the practicalities of the electrical circuits and their real-life uses as a somewhat unsuitable subject for persons of their intellectual nature.

Although in the course of this research the number of students displaying strong "Mathematic" tendencies was small, there was much consistency in the opinions expressed, and so many similarities of procedure described, that there is good reason to accept the likelihood that they are representative of an important class of student in Higher Education. They are in exceedingly strong contrast to the many "Visualizers" who came forward to tell me of their experiences.
Those students who I have denominated "Visualizers" tend to use mental pictures to clarify their scientific studies more than others. Examples of this are given by students applying their habit of visualization to assist in separating the different currents which can flow in transformers, and by others in their methods for reading the circuit diagram of the amplifier which I invited them to examine.

"Visualizers" were interviewed who were reading both Physics and Engineering degree courses, but the majority were Engineers. They quite rapidly identified themselves during interview by the emphasis they placed on Graphic or non-mathematical elements in their work, and often signalled their bias by frequent use, and emphasis, placed on key words or phrases which were specially significant to them; words such as "See in the mind", "Picture", "Visualize." Their inclinations and habits appear to be genuinely natural to them, and there was no evidence that their tendencies were imposed by any form of training - other than that of comfort and convenience in following a method which had been successful in the past. However, as they advanced in the study of Electricity/Electronics, some "Visualizers" encountered the difficulty that some phenomena were so remote from experience that mental picturing becomes exceedingly difficult.

The accounts of the interviewees suggested that inductive phenomena, which are principally observed through instruments or indirect effects, are particularly difficult for the "Visualizer" to comprehend. The "Visualizer" can also find the tendency brings
conflicts—particularly when attempting to resolve problems of understanding fundamental principles—in the company of those fluent in mathematics, or when consulting the recommended textbooks which are rarely adapted to their predilections.

The information gained during the interviews suggests that the strong "Visualizers" take a greater interest in practical work than the majority of their colleagues, and very much more so than those of the "Mathematic" tendency. It was also noted that many of the most successful and enthusiastic hobby constructors were of the "Visualizer" category. A considerable proportion of those who favoured this approach regularly used a visual imagery to clarify electrical problems in some measure, before continuing to a consideration of the mathematics of the subject in hand. As far as it could be learned from the relatively brief interview, most of the visual imagery relating to capacitance and inductance had its origin in the drawings given in the textbooks (or adapted from them by their school teachers), and those were remembered with special precision which simulated three-dimensional effects. For the "Visualizer" pictorial aids are particularly important, and contribute considerably to fixing electrical principles in their memories.

The approach of the "Visualizer" was put simply and directly by "Colin", an Engineering undergraduate who had gathered a considerable experience of circuit construction, having started at an early age by assisting his father in such projects. In the course of conversation about his method of approaching a new and complicated circuit, he said:

Extract No. 106

S. I just sit and work it out

I. Do you attack it in a mathematical manner, or do you follow
out the physical effects in your mind?

S. The second. I definitely do that. I don't just go through the mathematics of it, working out current measurement and formulas. I would do it physically. That's how I learned, by trial and error. I would try to understand how it works.

I. Would you follow signal paths?

S. Yes. I'd imagine points: where the component was and what it was doing. You know, it's quite a good thing to do. You can imagine why you've to fit a transformer there, and why you've to fit a capacitor across it, and so on. That's basically how I learned. Just by imagining what happens, not going into any analytic mathematics. Just thinking of the components and what they do. Then you can put the maths on after that. I think that's the better way to do it.

The value of mental imagery to those less mathematically fluent than some of their colleagues was put to me by "Harris", a Physics student, who had applied this method when coming to grips with A-level inductance.

**Extract No. 107**

"My experience is that people who particularly like maths get on well with electronics. A personal friend of mine who has always been better than me at maths and is doing the course, he is keen on electronics and everything, because he tends to follow through mathematical equations; whereas, I tend to stand back and like to get the grasp of the physical concepts in terms of a picture. He will get to an answer at the bottom and he wouldn't really understand it, but I go from step to step. He gets the answer and he's OK. He loved the formulas and this and that. I think there is a contrast between those people who like to understand everything about what they are doing - like me. I go slowly, but I've got to know exactly what's what and why."

4.56 The Uses of "Mental Pictures"

The translation of physical phenomena into mental pictures had considerably assisted "Jane", a first year Engineering student, when she had studied capacitance at school and was making progress towards mastering the mathematical theory.

**Extract No. 108**

S. Well, eventually I got the hang of it. The sort of picture of what happens, then from that I went on to the mathematics of it.
I used to think of large plates for large capacity - it makes it a lot easier if you can think of a lot of charge on a large plate. I could picture the gathering on the large plates.

She also had difficulty with the principles of inductance at school, and some problems remained:

S. I think the problem came with the electromagnetic fields. How the field set up by the current flowing was changing ... Well, the concept of it changing. Changing, but actually moving, as it were. You have momement over the wire: that didn't seem clear. It still doesn't, really.

I. Could you tell me a little of how you think of the field in relation to the wires?

S. Well, I have to think in terms of the magnetic field being a lot of concentric sorts of rings whirling round the inductor; and, as the current builds up, the field builds up too, and moves out. But if it decreases all the rings move back in. Every time a ring goes in, it cuts the wires.

I. And then?

S. It produces a back e.m.f.

I. Which you understand as what?

S. It tries to maintain the current as it was.

I. Do you imagine back e.m.f. physically doing that - as opposed to thinking of the formulas?

S. Oh, No. I do think of it physically.

Something of the difficulty which "Visualizers" have with the picturing of invisible and intangible electrical phenomena was expressed by an engineering student, "Michael", who had struggled to visualize the dynamic actions of flux around a current-carrying wire:

Extract No. 109

S. I did try to visualize it, but still didn't know what it was.

I. Is it your natural tendency to visualize the physical happenings in the circuit?

S. Yes. Quite certainly. I must say it's pretty disconcerting. It's essentially something that we can't picture properly, yet if we eventually
get things to work with it ... Well, it can help understand the effect, though you can't say exactly what caused it. You can always explain it in mathematical terms.

Some of the limitations of the mental imaging were referred to by "James", a first year Physics student:

Extract No. 110

"Well, I used to have mental pictures. I used to do this an awful lot. But now I've found that the further I go, the more the making of images fails me in that respect. The more things begin to behave as you wouldn't expect them, so I have to rely on formulas. Now I very much rely on formulas. But ... I find the visual approach inevitable - it happens to me."

The "Visualizers" ready access to imagery to separate the transformer currents was explained to me by "John", a Physics student:

Extract No. 111

I. And would you know the direction of each current?
S. Well, it's going to oppose change, which is Lenz' law.
I. Yes, and ...?
S. I could work it out. I could visualize what's going on.
I. You would visualize it?
S. Yes. I'd visualize the opposition and work it out that way. I couldn't think of doing anything else.

4.58

"Visualizers" and Textbook Illustrations

The "Visualizers" need for observable and tactile experiment, and appropriate illustrations in the textbook was expressed by "Andrew", a first year Physics student:

Extract No. 112

S. It isn't my favourite subject, but it isn't that I dislike it.
The ideas, the concepts ... some of them are quite hard. They are telling you what happens to signals, but you just can't picture it at all.

I. You like to picture electrical things, rather than depend on calculations?

S. Yes. I find that if I have seen a thing in an experiment, if I have seen a thing and actually touched it in a practical, and measured it, and plotted it on a graph, then it's much better than if I do a theoretical proof that something should happen. I can grasp it much better. The books are really based on a lot of theoretical models. They give you these proofs, and you just think: "Oh" and then look at the equation at the end and that you are going to have to learn for the exam. I suppose some people find the proofs interesting, but I don't at all. You can be pretty unsure if you don't really understand the formulas you are using.

The fact that book illustrations are of particular importance to "Visualizers" was stressed by "Max", an Engineering first year student, who had found fault with the recommended British textbooks and turned to American publications.

Extract No. 113

I. I would be interested to have a comparison of the illustrations in the British and American books.

S. The Americans are far better at three-dimensionnal drawings.

I. Is that type of illustration important to you?

S. Yes. I think it makes a lot of difference. Having drawings which are very clear, three-dimensionnal.

I. There are students who approach their work from a mathematical analysis, and another sort who use a visualizing and imaging approach. Are you in one of these classes?

S. Oh. I'm very much in the visualizing class. Definitely. I'm very much the sort of "Engineer's Engineer."

The vital visual element in studying electrical matters was strongly put to me by a "Visualizer", Joy, a Physics student:

Extract No. 114

I have to try and understand the actual physical principles involved. I think that half of the understanding of something is actually being able to see it physically, rather than just looking at a sheet of
paper and doing the calculations. That doesn't mean anything to me, really. Well, not as much as being able to explain "why."

I asked if she had ever been taught about the practical applications of inductors.

"No. We've done nothing like that. Things like that haven't been talked about, just the Physics of it. If you could see how it is used, and when it is used, it's bound to help you in understanding. The fact that you see how it's used and what it does and how it works. By the time you get to university they think you have enough background behind you to understand the principles, and you are just using theory to extend those principles. But you still need to see what's happening as much as you need to work out the maths."

4.59 The approach of the engineer who works by practical experience rather than theory was stressed by "Louis":

**Extract No. 115**

S. Because I started experimenting at quite an early age, when my maths was not in any way capable of dealing with that, I had to do it on the physical level. I built up an intuition; and, I can look at a circuit diagram and visualize how it's going to work. Now, if necessary, I can go back and say: "Right, knowing this I can apply the formulas."

I. Would you say this is true of many of your colleagues?

S. Most of them operate in another way, I think - in a mathematical way. I think they deal in a mathematical manner, and I think it often leads them astray.

I. Why does it lead them astray?

S. From what I have said, you can apply maths too much: you can end up not seeing how it actually works, and have no feeling for it. Many of the engineering problems have been caused by people who have taken a rigid mathematical approach to something, and not sat back and looked at it from an engineering viewpoint, and just not used common sense.
DISCUSSION

Strong "Visualizers" when reading for a degree in Physics or Engineering, are made aware of their tendencies by the contrast of their procedures with those of colleagues around them. They (like "Harris", Extract No. 107) hesitate to rely principally on the mathematical formulae, because they feel an urge to "stand back, and like to get the grasp of the physical concepts in terms of a picture."

Moreover, they are deeply interested in the physical process of electrical functions, so that they can not be satisfied to get "an answer at the bottom", but want to "really understand it, and go from step to step". The strong "Visualizer" nevertheless can be an excellent mathematician, and most of them in Higher Education do obtain the benefits which the ordinary application of mathematical formulae and theory can offer.

The "Visualizer", by habit and long practice, generally has a store of electrical imagery to call upon (whether of a static or dynamic nature), and finds it easier to start with the recall of these than to apply mathematical theory. As with "Jane", (Extract No. 108), considering the action of a capacitor, an image comes to mind, and afterwards she turns to the mathematics of the situation.

In the course of their conversations the "Visualizers" often indicate (or tend to confirm) an ascription by their frequent volunteering of graphic models, such as the pictorial descriptions of electromagnetic fields; and, by the emphasis which is placed upon them, it is certain that these are not simply conveniences of speech, but are exceedingly important to the students. The
"Visualizer" feels a need to examine the practical circuit and make his own observations, and is not as easily satisfied by textbook treatment as those without his tendency. Such a condition is strongly expressed by "Andrew", (Extract No. 112).

It would appear to be the case that "Visualizers" can be more flexible and versatile in their approach than the "Mathematic": the circumstances of their environment may apply pressures upon them to modify their tendencies towards a mathematical approach, and many appear to be able to conform. The pressures for change during secondary education may come from the methods recommended or insisted upon by teachers, or even from the need to accept and memorize textbook material for the purpose of passing A-level examinations. There are even greater pressures placed upon the freshmen "Visualizers" who read for Physics degrees (and some Engineering degrees) where a highly-charged mathematical environment progressively obliges them to cultivate a manner of study and thought which is not particularly comfortable. Such a modification of habit or tendency is rarely demanded of the "Mathematic" in Higher Education: most of the teaching he is exposed to is strongly mathematically orientated, and those obligatory activities of a strong graphic nature in the laboratory are not of sufficient length, nor regarded with sufficient importance to force any substantial modification in the "Mathematic's" tendencies.

The interviews gave reason to believe that among Engineering students there is a considerable proportion of "Visualizers" and that they are also found among Physics students in lesser, but significant numbers. These people do have an approach to their work which is at variance with "non-Visualizers" and there can be no doubt that it would be to their advantage if these study
procedures were taken into consideration.

Much of the teaching which is offered to these students appears to be designed primarily for the needs of those who are, to some degree, inclined to a "Mathematic" bias, and similarly, most textbooks present their material in a form which is not attractive to the "Visualizer", and may be in conflict with their tendency to seek out strong pictorial physical "landmarks" which can be committed to the visual memory. It is also evident, from the students' personal accounts, that their tendencies are not understood by their teachers, who if they have learned anything of the "Visualizer's" approach, generally disapprove, and urge the adoption of regular rigorous mathematical methods.
The concept of capacitance is not clearly understood by many of those beginning their Engineering and Physics study at university and polytechnic. During earlier A-level preparation, most of the attention focused on the component, the capacitor, and it would seem that the urgency of covering the syllabus in a manner effective for examination success prevented much consideration of other instances of capacitive behavior. Few of the students have subsequently expanded their knowledge of the phenomenon, and they find it very difficult to believe that capacitance exists elsewhere than with the component with which they are familiar.

Notwithstanding the fact that all the undergraduates reading Physics or Engineering will have learned something of electrostatics - the subject is certainly covered adequately in the standard textbooks - few of them appear to be able to associate that knowledge with the phenomenon of capacitance which they meet in Higher Education courses. Those who acknowledged that they possessed only a hazy notion of the phenomenon of capacitance displayed some embarrassment, so that little progress could be made during the interview after the students had offered their memory of the mathematical formula, and indicated that they proposed to "read it up."

The weak grasp of the subject displayed by "Jane", a first term Engineering student, was shared by several others:

Extract No. 116

I. Has the meaning of the term Capacitance caused you any trouble?
S. Yes. I'd say it did, and it still does. There are complications ...
I. Could you tell me a little of this?

S. Well, obviously, now I just think of it as electrons or holes that accumulate on one or the other plate - on one side it is just electrons. Capacitance is the energy stored there.

I. You mentioned the plates; what about the space between them?

S. Well the dielectric is there. It's relative to air.

I. Is it connected with capacitance?

S. I just know it's insulation. Beyond that, I'm not so clear.

"Herbert", another first term engineer, could associate the phenomenon only with the circuit component:

Extract No. 117

I. Has the concept of capacitance been troublesome?

S. I usually understand what's meant by capacitance when I read the word in the books.

I. Suppose a youngster were to ask you: "What is this thing which the books call 'Capacitance', what would you say?

S. I'm not sure. I'd have to start from basics and build up to the component itself.

I. A single wire forming a complete circuit will have a measure of capacitance. Could you comment?

S. ??

A fairly similar exchange was held with "John", a Physics student:

Extract No. 118

I. ... and the concept of 'capacitance'? 

S. It's the extra charge that has to go on a positive plate for an increased potential of one volt. Once you have got that clear, there's no real problem.

I. Suppose a youngster were to inquire about capacitance associated with a current-carrying wire round a complete circuit?

S. Oh, a single wire. Well, ?? I didn't realize that a single wire would have capacitance.

Some students admitted that they had no memory of every having
considered the matter at all. A typical exchange was with "Milly", reading Engineering Science:

**Extract No. 119**

I. When the textbooks mention the word 'Capacitance' what does it mean to you?

S. I have never really thought about it. I just accepted it.

I. What does it mean to you now?

S. I'd automatically say it was the ratio of charge over voltage.

Not infrequently students showed little sense of curiosity about the phenomenon, and some believed that they had learned nothing about it beyond the condition attached to a particular component. An example of this conviction was given by "Rita", a Physics student: "I don't really remember it ever being explained. It was just a case of: "It's this, and this is what it does."

A different approach was taken by "Louis", an Engineering student with strong practical interests:

**Extract No. 120**

I. Suppose some one asks for an explanation of what the books call 'capacitance', how would you explain it?

S. I think I would have difficulties. I think I'd try to show them - through practical experiment what a capacitor does. I think that's important. From the engineering point of view, what is of prime importance is the understanding of what it does and how to use it.

**Capacitive Reactance**

4.61 Capacitive reactance, as introduced at school, was remembered as a troublesome element of electrical theory by many who were in their first year of Higher Education. Although they may have used the formula in the solution of problems, the physical nature of capacitive reactance was often only partially understood. Together with inductive reactance, the phenomenon could invoke feelings of uncertainty, vagueness, and anxiety, and a reminder of the students' as yet unfulfilled intention of undertaking some revision.
Most of those interviewed spoke of their A-level preparation as dealing with inductive and capacitive reactance together, and, after even a little distance in time, there tended to be some confusion of theory. Those who had not satisfied themselves in clarifying their thoughts on the subject, preferred to avoid a consideration of the physical situation, and relied solely upon formulae. "Milly", reading Engineering, remained in considerable doubt about the practical nature of capacitive reactance, and trusted to her memory of the equation to "get by." She told me:

Extract No. 121

S. I can't remember it very clearly at school. We did it together with inductance. I think I just accepted it. I could cope with the graphic method. Here we use the "J" notation. The thing that bothers me is getting the sign right.

I. If a person were to ask you, could you explain the nature of capacitive reactance?

S. No. I would just write it down - the formula.

"John", a Physics student, who was yet to undertake his intended revision of the subject, expressed a considerable degree of uncertainty:

Extract No. 122

S. Capacitive reactance? Well, I suppose one does have problems with it. One tends to take the attitude that anything that's involved with complex numbers is fairly fishy anyway.

I. Have you had trouble with the Lead/Lag alternatives in capacitive circuits?

S. Interesting ... I wouldn't say it was difficult ... but, it is difficult to see how it would arise from just looking at it - without doing any thinking about it - but, I don't think it's too complex.

I. At university have you used an oscilloscope to examine wave forms and capacitive reactance?

S. I suppose I must have ... I can't think.

I. Do you remember which wave form leads in a capacitive circuit?

S. Well, let me see ... Oh. Which leads and which lags? I can't remember.
One Physics student who had been unable to master the principles of capacitive reactance at school, had afterwards resolved his difficulties during the first few months at university. "Ferdinand" told me:

Extract No. 123

S. It took quite a long while to understand it - up till quite recently. After a while it seemed quite obvious.

I. How were you able to clarify these matters?

S. Through fellow students at college. You know: one gets hold of an idea, then you explain it in all sorts of different ways, until the way that appeals to some one else is reached. So you get to know as much as each other.

An example of a "Visualizer" using a dynamic picture as a memory aid for identifying the priority of phase in a capacitive a.c. circuit was given by "Jane", an Engineering student:

Extract No. 124

S. Well, with a.c. capacitive circuits you've got leading and lagging. That's awkward - trying to memorize those. Well, the way I think of it now is that an inductor is like a buffer to the current: the current goes behind, so the capacitor is opposite to that.

I. When you think of the current, do you think of something moving, or is it the formula that you refer to?

S. Yes. It's real. I think of it moving.

Another use of the mental image to assist the memory was given by "Kenneth", a Physics student of marked "Visualizer" bias:

Extract No. 125

S. It troubled me slightly in the beginning: to know why, and how there could be a lag or lead. I worked out physically what was happening in the inductor and capacitor, then I had no problem after that.

I. Did you use the graphic method, or did you follow book illustrations, or do practical experiments?

S. We did experiments to see it. Also all the same things are shown
in the books. I very quickly built up a picture in my own mind of what's happening physically, but you never quite believe it until you actually see it on the oscilloscope.

The interviews reveal an area of weakness common to university and polytechnic students. In all probability, on account of the school emphasis on theoretical matters and limited practical work, immediately followed by an academic approach where numerical problem solving is so high regarded, many of the interviewees had acquired an unbalanced knowledge of capacitors, which largely isolated them from an understanding of the practical applications of the devices. Very few of the students, other than the experienced circuit constructors, could instance the uses to which these devices are put in the multitude of electrical and electronic circuits which relate to their daily lives.
4.62 The interviews revealed that inductance was a source of much anxiety to those preparing for A-level examinations, and the unpleasant associations were not absent from the minds of many who had reached the second term of their university or polytechnic studies. From the accounts given, it is clear that the school pupils felt that their teachers were often struggling to impart the principles of inductance theory. In some measure this may be because those teachers were attempting a simplification of the fundamentals to ease the learning process for the examination candidates; nevertheless, by omitting some of the theoretical elements they may have delayed the students' consideration of essential principles until an awkward point in their education: the weeks of adjustment to university or polytechnic studies.

It was the students' experience that inductance received less attention than other basic electrical principles, and that a.c. circuit theory was seldom taught with any thoroughness, and the laboratory experiments (to the best of their recollections) were generally in the nature of observed demonstrations, few of which had tied-in closely with their classroom theory. Very few of the students spoke to me of having studied voltage and current wave forms with the oscilloscope. Students confided to me that they were not happy about their grasp of inductance. Few of them, other than the most conscientious and persevering, had studied the subject in the recommended school textbooks. This is unfortunate, because currently favoured textbooks treat the subject with care and offer helpful drawings.
Those who had prepared this area for A-level examination had sometimes acquired such a slight understanding that it was largely forgotten by the time they had reached university or polytechnic, and even the application of Lenz' law had become a vague memory to a considerable number of those interviewed.

The "Visualizers" among the students found much difficulty in registering in their minds the physical operation of phenomena which are so remote from ordinary human experience. The "Mathematics" appeared to be less troubled, possibly because they were content to treat the operations in abstract, and not to inquire too deeply about those functions. Some who had mastered the formulae and had practised examination questions, later recognized that they had much more to investigate. A considerable number of those in their first or second terms at university had not clarified their ideas about induction. They were disappointed to discover no opportunity for revision and that they were expected to have a sound knowledge of "school level work."

For many of the students, inductive theory was a priority on their list of textbook chapters for revision. For some the subject of induction invoked considerable embarrassment during the interview, which prevented any probing in depth into this area of weakness.
An example of the difficult situation which some recently arrived Engineering undergraduates found themselves in was given by "Alex", who had forgotten Lenz's law:

Extract No. 126

S. Inductance, - it was difficult, yes.
I. Are you able to put your finger on the difficulty?
S. I think it was the confusion of the "feed-back" idea: whether it was positive or negative.
I. Yes?
S. Somehow, I didn't believe it. But again, I'm not sure I can quite believe it now. At school, I can honestly say that I didn't really know what was going on most of the time, yet I was able, through working hard, to get a top grade.

A colleague, "Bill", had much the same unresolved problems:

Extract No. 127

"Yes. We have done that quite recently, self-inductance and mutual inductance, but I haven't really studied it: I mean, I haven't really thought about it. I don't remember much from A-level. Inductance, it's a big mystery. But then, so are quite a few of the forces to me."

Charles, a Physics student, had been rather alarmed during the first weeks of his course to realize he knew much less about inductance than many of his fellow students. He told me:

Extract No. 128

S. It's a difficult area. I think it's the one, I suppose, I'm least happy about, and really must attempt to fill out. I don't know if there's any reason why it should be more difficult than capacitance.
I. Suppose a schoolboy should inquire of you: "What is this thing
called inductance", how would you help him?

S. I don't know what it is myself. I'd certainly have to think about it. But as a general concept it's quite difficult. I suppose I'd give him the formula.

"Kitty", an engineering student, had not studied the subject seriously at school, and regretted it because she felt she had lost her opportunity:

Extract No. 129

"I just think of inductance being in the circuit. Inductance is the flux formula, probably because I don't understand the actual physical thinking of it. So, I have to fall back on the formula. I'd like to better understand what's going on above and beyond knowing the formula. At school we tended not to look into books, and at university there never seems time to look around."

Quite frequently in the course of conversation, students would indicate uneasy feelings of conscience with regard to the currents circulating in a secondary winding: generally it had not been thoroughly examined at school, and they anticipated hidden difficulties. When the subject was reached during her interview, "Rita", a first year Physics student, was reluctant to speak on a hateful topic:

Extract No. 130

S. Oh, it's fields again. I don't understand it. I can't visualize it. The effect of fields.

I. How will you get over this difficulty?

S. I'll attempt it through books ... but I don't know ...

Weaknesses in areas of school Physics which had never been adequately treated by personal reading and study, were sources of lingering anxiety to a considerable number of students, to judge by the comments made in the course of interviews with first term undergraduates. The words of "Aline", an Engineering Science student, were similar to those I had heard from
several others.

Extract No. 131

S. "We are going to have E.M. lectures soon. I'm not looking forward to them. I wasn't good at it at school.

I. Do you remember specific areas of difficulty?

S. Inductance, mutual and so on. How to analyse circuits connected into inductance. You know, trying to imagine voltages - it's rather hard to imagine. I have kept my A-level notes on Electromagnetism. The trouble is that it seemed complicated then. I couldn't understand the explanations the teacher gave us.

One of the students who had struggled with the recommended course texts but made little progress in furthering his knowledge of inductance, was "Ronny", an engineering student who had memories of school misunderstandings concerning the phenomenon. He explained:

Extract No. 132

S. It remains a problem. It's the concept: what actually happens inside an inductor. I don't understand it.

I. Have your engineering course textbooks not helped?

S. Well, several times I have looked into textbooks and not been able to understand it. I just lost interest. They seem to sweep round it: they suggest that it's really simple and you should be able to understand it. So it's done in a couple of pages. They've not enough explanation and they've not enough examples, worked examples.

Most of the students who talked with me of their understanding of the term "Inductance" as met in the course of their reading, felt a lack of confidence in interpretation. One young engineer told me plainly: "I certainly never had the hang of it. I couldn't picture what the thing really was. I used to like water comparisons: I don't think that had any connection with inductance."

A Physics student at the same college said: "The idea of fields, and the more fundamental levels of electrical properties, wave propagation and that sort of thing; they still cause me great problems. I can apply the formulas, and quite often get the right answers, but I think there is some physical understanding still lacking."
The Transformer

4.63 The students who felt confident about their knowledge of the theory and operation of the transformer were frequently those who had carried out experiments with them in the laboratory. It was noted that those classified as "Visualizers" benefited most from such practical work. It appeared to enable them to "fix the information" in a pictorial form in the memory, and that image was easily recalled.

An instance of this was given by "Max", a strong "Visualizer", who considered that he had thoroughly mastered all the transformer principles while at school:

Extract No. 133

S. I think I had a fairly strong appreciation of what flux was, and flux intensity, and the idea of actually having a linkage because of that. I could picture that quite easily.

I. Was that because of some textbook illustration?

S. I don't know ... I think partly the way the teacher explained it. I think we had a good A-level teacher. The practicals as well demonstrated it. I think the practicals are very important in that sense. I think it would be very difficult to explain without diagrams, and the actual thing there is much better than diagrams.

By contrast, "Aline", an Engineering student, had little practical experience of transformers and continued to have trouble in visualizing flux linkage:

Extract No. 134

S. It was all rather difficult imagining how that all tied-in with each other, and how you get the results. It's the difficulty of thinking about it in physical terms: to think about the action within the coils.
S. Yes. I think that if they could draw some analogies perhaps people could visualize more easily; then link it in with electromagnetism. Then you could say: "Oh, yes. I see what they mean" If we could analyse what happens before we did the mathematics.

I. Have you ever seen oscilloscope wave forms from a transformer in action?

S. No, but I think that would help.

Students talked with me of having studied transformer phenomena mathematically, and having satisfied their tutors on test problems, yet weeks later, they felt uneasy. Their studies had been very much isolated from the real world of electrical engineering. This was brought out by "Jerry", a Physics student at university:

Extract No. 135

S. Yes, we've done them. Our lecturer was good, and we've a fine tutor. But, ... yes, there still are some problems.

I. Can you follow the directions of the currents in an operating transformer?

S. Well; ... if I mugged it up a little.

I. Have you thought about the applications of the transformer, or of the different types?

S. I can't say I have.

I. In your laboratory the benches are fitted with isolating transformers. Do you know about these?

S. I don't think I have heard anything about them.

Some of the students of "Visualizing" bias felt very strongly that their needs were quite ignored in an educational system where mathematics was stressed so emphatically. One Engineering Science student, "Selina" said:
S. Yes, we've covered transformers, but very very stogily, and mathematically. Nobody has done any sort of hand-waving, which is what I like.

I. You mean applying Fleming's left and right-hand rules?

S. No. When I say hand-waving, I mean some sort of physical explanation of what's going where and what's happening. They go straight into equations.

I. You feel that these physical descriptions are necessary for you?

S. Yes. Very much so. And I have found that, generally - almost always - whenever you ask a question which is really basic to the point that it seems stupid, you are never answered in a simple way. They always send you right back to equations - but you have seen those equations, and you want a different way of thinking about it.

The most despised thing here, it seems to me, is to ask a "stupid question". They seem to think that if some one asks a simple question it is because that person hasn't done any thinking. Actually, I think it's the other way around. The person who asks the questions about basics, is the person who has thought it through and found something which bothers them.
DISCUSSION

Reluctance to Speak about Inductance

During the interviews with first and second term university/polytechnic students it was clear that there was a great reluctance to talk about inductance. I received the impression that many had studied it superficially at school, and associated the phenomenon with the formula and little else beyond a few specimen A-level questions; and, having succeeded in their examination hurdle, they were content to forget about this fundamental property. On several occasions there was an almost exact repetition of the conversation held with a second term Engineering student (who told me he had obtained an "A" grade in his A-level GCE examination):

S. Inductive reactance - we did it briefly at school.
I. How do you remember it: by formula or physical description?
S. I just don't remember it at all.

A colleague of this student was not more forthcoming:

"Inductive reactance? I'm not sure. Isn't it involved in resonant circuits? I've done fewer circuits with inductance than capacitance. I think I've less knowledge of them."

There was a paucity of information regarding the uses of inductors, and apart from the frequent reference to tuned-circuits, there was little knowledge or interest in practical applications. The exchange with a second term university Engineering student was characteristic of many:

S. The uses of inductors? Well, ... transformers.
I. Where have you met transformers?
S. Well, ... I suppose just for transforming voltages from the mains for the computer.
There can be no doubt that many would benefit from a more prolonged study of inductance at school; however, in view of the fact that a considerable proportion of students hesitate to tackle the "complexities" of inductance, it seems best that teachers should attempt to ease the diffident learners' problems by recommending (in addition to the use of the prescribed textbook) students to work through a programmed text on the topic, such as the excellent coverage given in the Basic Electricity course of the New York Institute of Technology (1964), where the numerous characteristics of inductors and inductive phenomena are examined in very small steps, progressively providing a solid foundation of knowledge of inductors under both D.C. and A.C. conditions. Alternatively, they could be asked to read in the public libraries the admirably clear exposition which S.P. Thompson gives in his Elementary Lessons in Electricity (1881, and numerous subsequent editions).

Another means of aiding the learners is to recommend the reading of biographies of those who pioneered the study of inductance. In the course of following the researches and speculations of the first researchers, the essential features of inductance can be understood without the academic pressures of the textbook exposition. Few pupils would find any difficulty in reading The Life and Letters of Faraday (1870) by H.B. Jones or, Joseph Henry (1950) by Thomas Coulson, and almost all would gain much interesting and useful historical information on the fundamental principles governing the phenomenon.
4.65 Approximately half the students who talked with me were experiencing no significant problems in the study of motors and generators. These had been fortunate enough to obtain a sound foundation of electromagnetic theory during their A-level preparation, and were confident that their understanding of fundamental principles would carry them forward successfully on their more advanced work. In almost every case, those who believed that they had a grasp on the theory and functions of the motor and generator had undertaken some construction (or dismantling) of the units in the school laboratory.

Among those satisfied with their understanding on the subject was "Amanda", who said: "Yes, I think I understand motors. Fleming's right-hand law. We built one in practicals. We stuck bits together with Sellotape. It worked. It was the practical of the year!"

Another Engineer who appreciated his school practical model-making was "Max" who told me: "At school we did the theory, then, as part of our course, we made an electric motor in the lab. We wound wire, and put corks on, and so on. That was useful and it was great fun. That electric motor sticks in my mind."

I. Have you stripped-down functioning motors or generators?
S. It's the sort of thing I do at home. I am a compulsive taker-apart.

However, some students had memories of difficulties and confusion in their attempts to grasp the electromagnetic principles of motors and generators, and had not subsequently, studied the textbooks to clarify these.
There was a tendency to harbour anxieties about the "complications" surrounding these units' operation when at school, and thereafter they retained a disinclination to investigate them again, except when urgently required to do so by their course commitments.

One example of this was given by "Jane", who told me:

"It was all right until they told us of the back-e.m.f. in the motor. That really threw us. Because the motor turns the magnetic field produces a current back, or back e.m.f., so it's almost as if the motor is in equilibrium, I suppose, but spinning round. Well, that's how I pictured it. But there's something to do with the difference in the back-e.m.f. and the back ... Oh, it's still a bit hazy."

Some of those who had experienced difficulties in understanding the motor principles had consulted the textbooks and had been disappointed by what they regarded as inadequate explanatory illustrations. "Rhoda" told me:

"They all seemed very complicated, and they didn't seem to have that many illustrations."

I. What were your particular difficulties?

S. Well, things like eddy currents, and stuff like that. You just seem to have to accept that that sort of thing happens in a motor. It's very difficult. I think I switched off when I got to that sort of thing. I thought I would get by without learning it. I could survive on other things."
DISCUSSION

The proportion of students who have not mastered the principles of induction at the start of their Higher Education courses are undoubtedly at a considerable disadvantage: The principles which they have neglected to study will constantly be forced upon their attention during the study of electromagnetism, electronics and power engineering, wave transmission and reception, and much else. The more perceptive of those ill-equipped on entry to their courses realize that they must read deeply in the textbooks. Conversation with those who were active in this provides confirmation that the information is available in the standard school textbooks, and it is to those that they go for study, rather than the first-year university texts which they feel rarely offer sufficient guidance and sufficient space to simple A.C. inductive circuits and their properties.

For those students who recognize their weakness in understanding the principles of motors and generators, it could be very much to their advantage if they were advised to examine a number of alternative textbooks to choose those which offer the "Visualizers" or "Mathematics" the more appropriate expositions. They should not neglect to dip into the older textbooks which can still provide valuable guidance. "Visualizers" might respond best to some revision of theoretical principles gained by reading Sylvanus P. Thompson's *Elementary Lessons in Electricity*, followed by the more advanced exposition in the same author's *Dynamo Electric Machinery* (1884), which has the interesting feature of a good historical summary of the achievements of the pioneers, including Lord Kelvin, Maxwell, and Hertz, and a very sound treatment of the...
Lead/Lag principles which often perplex beginning engineering students. Those of the "Mathematic" tendency would probably feel more comfortable in studying fundamental principles from J.A. Fleming's *The Alternate Current Transformer* (1889).
During the interviews the Physics and Engineering students spoke freely about their use or neglect of the recommended school textbooks. Many of them felt that they had not taken full advantage of those texts. Some had wisely retained their A-level books and had subsequently realized their worth. Not infrequently they expressed a wish that their teachers had firmly specified particular chapters in preparation for theoretical classroom discussion or laboratory experiments. This, however, was a consideration in retrospect, for they acknowledged that the attitude of most of their fellow-pupils had been to avoid anything but obligatory reading. Some spoke of the respected standard textbooks, like Nelkon and Parker being regarded as "hard to read," and even frightening to some who entertained the misconception that they were expected to absorb and become familiar with the book's total contents. Nelkon and Parker's textbooks (the particular edition of their comprehensive texts being rarely remembered by title) were held in particular respect, and continued to prove useful for revision during the first two terms of their Higher Education courses. A minority of those who had used the textbooks complained of the "dryness" of the presentation, and expressed a preference for the more direct, "chatty" style employed by Tom Duncan, or the less demanding works of Roger Muncaster.

Some of the students with a strong "Visualizer" bias expressed a preference for a particular textbook on the strength of the illustrations and the ease of reading the typescript. One student told me: "I got a lot out of Nelkon, but I'm critical of the illustrations." When asked why,
he replied: "Small diagrams, small printing, everything packed into hundreds of pages, far more than you need for A-level...but, it's a nice book to have: I go back to it because I missed this or that in a particular section."

Another book which students mentioned frequently and with approval was Tom Duncan's _Advanced Physics: Fields, Waves and Atoms_ (1983). It was relied upon by a number who had done well in the university entrance examinations, and was regarded as being particularly helpful in its treatment of capacitance. It, too, was still being consulted by students interviewed, some of whom also spoke highly of the same author's _Science for Today and Tomorrow_ (1983).

One Engineering student explained to me her reason for keeping Tom Duncan's books beside her at university: "Some bits are very good. I find it useful now, for basic things. You see, our textbooks seem to be one step ahead - I mean the university ones - they don't tell you the simple things. It's nice to go back to A-level, where he tells you, 'This does this, and that does that' - the others skip over it."

_Electrical Technology_, by Edward Hughes (now in its 5th edition, 1977), a much-recommended text, was well known to all the Engineering students, and held in considerable esteem by them. Some of the newer students expressed the opinion that this book is "too mathematical", and chose to augment or replace it with _Electricity and Magnetism_ by W.J. Duffin (3rd edition, 1980). Duffin was held in equal favour by the first and second term Physics students, who regarded the text as providing a smooth transition from A-level school electromagnetic studies.

I gathered from the interviewees that they seldom commented, critically or otherwise to their tutors on the subject of the textbooks which they used, although it is clear from their conversation
that often they considered that they were not well served by the recommended texts. The complaint of "excessive preoccupation with maths" was not limited to the Engineering students, but was expressed by several Physics undergraduates. Such persons were usually "Visualizers" by my classification.

An example of such comments came from "John", a first term university Physics student:

**Extract No. 136**

S. The textbooks we use are intensely mathematical.

I. Which do you use?

S. I've got three: Bleaney and Bleaney, Lorrain and Corson (*Electromagnetic Fields and Waves*, 2nd edition, 1980, Paul Lorrain and Dale Corson), which is also highly mathematical and very complex, and I have got Duffin, which I think is slightly better. Most people follow the recommended texts, but most also have got Duffin. Another thing: examination questions are very mathematical. The exam. questions are really oriented towards a mathematical textbook. This doesn't suit me. They are sort of asking you to work out something rather than try to explain something.

I. You say "too mathematical", could you expand a little?

S. I find that I generally can do all the mathematics I need, but I fall down on the initial theory. I criticise the use of 'Maxwell's Equations'. I just wanted to know what they are and what they represented, and what they are used for - but I got a complex mathematical approach instead.

"James", a "Visualizer" reading Physics was particularly responsive to textbook illustrations. He commented:

**Extract No. 137**

"Lorrain and Corson's *Electromagnetic Fields and Waves* has very good and helpful illustrations, which remind me of Duncan's books. Whereas pathetic little Duffin here, his illustrations are really terrible. Duffin suffers through his illustrations, and frequently it has little to do with the surrounding text. You shouldn't have to keep swapping backwards and forwards across pages for the appropriate illustrations because the printers can't typeset properly.

Another recently arrived Physics undergraduate explained her personal preference on the grounds of clarity and of ease of reference:
"I use Duffin's *Electricity and Magnetism*: it's good for finding things. It gives things the way you can understand - say, about discharges and things. If they are complicated problems, I often have to use Lorrain and Corson. But I dislike it. I hate it. It jumps in all the proofs. It assumes you are really clever."

"Janice", a first term Physics student, told me that she keeps Tom Duncan's *Advanced Physics* beside her, and consults it from time to time:

**Extract No. 138**

"I like books which have lots of worked examples. Duffin doesn't have those worked examples."

She also consulted Nelkon and Parker, partly on account of the worked examples offered, but also because:

"I understand it. It presents things in an interesting way. I look back to it and think, 'This is pretty familiar.' Bleaney and Bleaney could do with more examples and more pictures. For instance, their explanation of electrostatics is a bit obscure because you can't relate to it. If you learn something, you like to know how it affects the world. It's for that reason that I like Feyneman's lectures." (Lectures on Physics, (1972) Richard P. Feyneman.)
DISCUSSION

The students knew that their electrical education would result from the accumulation of knowledge gained from lectures, personal study and the exchange of information among their colleagues, supplemented by the teachers' prepared-notes and practicals in the laboratory. According to their inclinations, and their response to the instruction offered, they generally applied themselves with particular energy to one of these sources of information. Those of independent habits largely educated themselves through reading in the libraries, and regarded the lectures and laboratory work as secondary activities, which might, if circumstances were favourable, provide useful supplementary knowledge. A substantial proportion of the rest combined the minimum of reading in the recommended texts with a great deal of exchange of technical knowledge among themselves.

A smaller number of practical-minded individuals aimed at gaining most of their knowledge and experience through laboratory experiment, supplemented by technical reading. These people were found at polytechnics and those universities which emphasized a comprehensive technical education, rather than at those institutions where there was a long tradition of academic endeavour.
THE READING OF ELECTRONIC HOBBY MAGAZINES

4.67 Most of the electronic constructors continued to read hobby magazines during their Engineering or Physics courses. Only a few of the other students began reading them during their Higher Education. Among the first group it was generally the case that their maturing tastes led them on to professional, or semi-professional electronic journals, but they retained an interest in the hobby magazines, and from time to time built circuits from their designs. A few of those interviewed told me that they had obtained helpful material related to their studies from the pages of these publications.

"David", a first year Electrical Engineer, told me:

Excerpt No. 139

S. I read quite a few magazines.
I. Which are they?
S. Wireless World, Electrical Engineer, they are quite useful, though some of the concepts are too advanced.
I. Have you taken circuits from them for your own use?
S. Yes, I've made a pre-amplifier and an amplifier.

A few of those who were enthusiastic electrical constructors felt the pressure of work so great as to exclude recreational building of projects during their first two terms at university/polytechnic courses. Nevertheless, they believed this was only a temporary interruption, and intended to return to their hobby and their magazine reading. Most expressed something of the benefit they received from those publications.
"Dennis", beginning a Physics course at university said:

"I used to read *Hobby Electronics* and *Electronics International*. I really used to enjoy reading how these circuits worked, because it was like a secret unfolding."

Those who had recognized the continuing usefulness of hobby magazines were happy to speak about the projects they had built, and to give credit to the sources. "Fred", nearing the end of his first year on a university Engineering course, told me:

**Extract No. 140**

S. I soak up small amounts of information from them.

I. Which do you read?

S. *Practical Electronics* and *Everyday Electronics*. I've made quite a few little things from them, like a Time-controller, and a syren; and, something I could never understand at school, an oscillator.

A number of the constructors told me that their interests had recently turned to the study and operation of home computers, and as a result their magazine projects had mostly been from that large range of publications which now flood the magazine shops. They continued to "dip into" the hobby electronics magazines.

A considerable proportion of the students exhibited indifference to the interest and practical advantages offered by the electrical publications available in their own laboratories. A typical reply to my inquiry if electrical magazines were read, is that given by a first term Physics student: "I haven't yet. They've quite a lot of magazines in the lab. I suppose I might look at them; but I'm very busy at present"
Another student believed that electrical magazines in the laboratory (which he had not examined) would be "too complex" or of value only "to those with that sort of hobby". A few acknowledged that "there might be something useful in them", and resolved to examine them at some unspecified time in the future.
While many students acknowledged that the laboratory experiments were essential to their courses, and of value to them personally in the acquisition of experience gained under conditions of professional supervision, a large proportion of those interviewed gave vent to complaint, ranging from mild dissatisfaction to extreme criticism. They expressed feelings of malcontent on the ground that large amounts of time were spent in carrying out prescribed measurements, tests, and mathematical operations which rewarded them with little new scientific information.

With other students, the principal complaint was that practical work was over-extended in time, and that their powers of concentration had diminished severely before the end of their laboratory session. Some recent arrivals spoke of feeling "under pressure" throughout the whole of their long meetings. Those who had little experience of practical electrical activity entertained much anxiety about their ignorance in handling equipment, and their lack of familiarity with the components, and believed that they were being rushed through experiments without pause for reflection. Others among the inexperienced in electrical circuits told me that they wished very much to have more introductory commentary and explanation of the phenomena involved in experiments. Some
realized that a considerable degree of personal exploration was intended at each stage, but even they expressed a hankering after more guidance than they generally received.

A frequent complaint was that practical experiment was being prescribed in advance of the particular topics being discussed in lectures or tutorials. Some interviewed told me that they would not object to undertaking practicals in an area not yet covered by lectures if they had adequate guidance in preparing some private reading, but that no recommendation to chapter and verse of any textbook was given, and the laboratory notes supplied to them were not theoretical in nature, but limited to the actual manipulation of the instruments and components to be used. In consequence, doing the experiments without advance preparation brought them little benefit in the course of much expenditure of time.

A considerable proportion of both Engineering and Physics students at each institution visited spoke to me of their difficulty in interpreting circuit diagrams. Although all their laboratory experiments, and private reading involve the use of theoretical circuit diagrams, few of the students appeared to possess any fluency in reading them. They themselves were aware of this, and there is evidence that some of the misunderstandings and inefficient learning in the laboratory is due to this lack of skill. One first term student summed it up by pointing to the circuit diagram in front of her and her laboratory partner: "We don't really understand much of what it represents."

The students at each institution consistently commented on the helpfulness of the demonstrators in the laboratory, yet there seemed often to be a reluctance to take advantage of their services, or to seek theoretical information from the tutors. I sensed that much
of dissatisfaction among the complainants was due to an unwillingness to admit, or exhibit, ignorance of basic principles to their instructors. A first year Engineering student tried to express this when talking about an apparent lack of connection between the course theory and practicals:

Extract No. 141

S. We spend quite a lot of time here doing practicals, but they never seem to be ... I don't know ... nobody enjoys the practicals as much as you would expect.

I. Can you say why?

S. Well, the pressure doesn't help. There's always a time limit. You have to rush things a bit. I suppose you don't always know exactly what you are doing. You follow the method laid down.

Some have carried with them unpleasant memories of school practicals and find it very difficult to adjust to the more extended laboratory work at university. One girl in her first term had rejected the practical work almost immediately.

S. It's a complete bore. I'm going to miss out as much as I can.

I. Why do you so dislike it?

S. Well I just don't - it was awful at school, and it's rushed here. I'll just do as little as possible. I'll just write up what's needed, and read what I must. I'll get by.

Another Engineering student who had not had the benefit of prior instruction which pleased him at school, believed that he could gain little from the practical work at university: "I reckon they are a bit silly - they don't serve a great deal of purpose. They don't do me much good. This sudden leap into electronics. None of it means much to me."

4.70

Criticism of Laboratory Practice

Some university students spoke of being thrust into an electronics course without previous experience, other than a few brief introductory statements about the nature of the transistor operation. Those who were
not hobby constructors spoke of their confusion and the considerable
difficulty in gathering the necessary information from the recommended
textbooks. Even the hobbyists felt under excessive pressure, and were
critical of the educational methods employed. One enthusiastic
constructor, "Colin", offered his comments:

Extract No. 1

"I had done a lot of practical work and used a good many
different types of transistors, inductors, capacitors, and so on —
that was a great help. But these first year practicals are a bit
complicated to beginners. To start doing all sorts of networks,
right from the beginning! It might be better to let them work with
transistors, and capacitors, and have a look at voltages across
resistors and so on. You see, the instruction sheets for practicals
really lay it out step by step: they say, "Plug in here" and "Do this",
"Put the oscilloscope over here" - it makes it very mechanical. If
you are careful, you just go through the notes and copy what you see,
and you haven't gained much. It would be better if they left you
with a whole lot of inductors, capacitors, resistors, and an oscilloscope
and just let you try things yourself."

Some of the frustration and disappointment of a first year Physics
student who discovered that his laboratory work was limited to the
mechanical operations of following a set of written instructions, was
given in the description of his laboratory activities:

Extract No. 1

"It was a case of here is a box, and here is an oscilloscope,
get a lot of readings with it. Then, you do graphs and tables, and so on.
There is no reason why it does what it does. I need someone to explain.
I'd like to go into recording after this course, but if I was confronted
with a circuit which might have broken down, I really wouldn't know what
do do. It dawned on me recently. It isn't good enough.

Another first year Physics student complained of her dissatisfaction
with the time-consuming laboratory activities involving seemingly pointless
measuring and writing-up of "non-meaningful experiments", and went on
to say: "I wish we could build an amplifier, and have every single piece explained as we put it in. And, not just have it explained, but have a look at it, and put a signal across it, and see what it looks like on the oscilloscope."

When a considerable proportion of students feel strongly that they are wasting their time in carrying out operations which benefit them little, there is clearly a need for reconsideration of the programme. Student interest, let alone enthusiasm, can not be retained under circumstances where a mechanical following of printed instructions is demanded, and it is difficult to believe that such a method can result in effective learning. I was assured that students do discover for themselves ways of circumventing the burden of obligatory laboratory sessions. There would be no difficulty in confirming the widely-held belief that many of the laboratory "write-ups" are identical.
Those who were not hobby electrical constructors often experienced considerable difficulties and embarrassment quite far into their courses because of awkwardness in reading theoretical circuit diagrams. Scarcely any of these persons realized the need for this skill during their school days, and once they started upon their Physics or Engineering courses they met the situation in a variety of ways. Some attempted to learn something of the circuits by going back to the books formerly used, or to other elementary texts. Others sought help from more advanced students on a regular basis, and some few postponed facing the problem by taking the attitude that they "could scrape along well enough for the present, and would improve later." Some students had made an effort to study diagrams in a systematic manner, and usually, they had been assisted in that by their interest in following the circuits given in the hobby magazines. It would seem that few of the students had talked of this matter, even to their friends, yet they told me that they regretted not having received instruction in this essential skill.

Before showing the circuit diagram of the simple radio, I asked each student if he/she had received any form of instruction in diagram reading. The exchange with "Max", is typical of many:

I. Did any one ever show you a method for reading circuit diagrams?

S. No. Not really. Not in any useful sense. The result is that when I look at a large circuit, or are asked to analyse it, I don't know where to start.
More than one interviewee repeated the memory of one Engineering freshman:

"I used to see a circuit and be very frustrated. I thought this should be easy to work out, but I never, just never could do it."

There were frequent complaints that some lecturers were unaware that their new students found any difficulty in following circuit diagrams. "Rita", a Physics student said to me:

"The lecturers started on Electronics and circuit theory, started on transformers, and I found that they assumed that you knew about them any way, and knew how to read the circuit. I took the notes, and the "hand-outs", but I didn't follow the lectures. I'm trying to understand the circuits by reading something about them in basic books."

Students quite often found that they were being held up in progress because they could not properly understand the diagrams used in the textbooks. "Aline" confided to me:

"I have spent a lot of time trying to understand them. The trouble with a big circuit is that you can't understand it, so you've just got to put in all the maths and the formulas. I can do that, but I don't like to. I can't visualize it doing all these things at once."

A few students who had received some instruction in reading circuits had obtained that independently of their school or university work. A member of their family had trained them in the course of cooperating on some electrical project, or, more rarely, the person finding there was a need, had sought instruction from an electrical engineer. "Amanda", a first year Physics student, a "Visualizer", gave me an instance of this:

Extract No. 144

S. We had some electronics to do and I got panicky of that, and I went to a man I happen to know who is the founder of an electrical company. He set up the circuit for me, and that really helped.

I. He built the circuit physically?
Yes, so that I could see it and understand it. When you have only the diagram, you can't really think of it happening, or even understand it when they talk about it - in the textbooks, I mean.

Only rarely did the students mention having approached their teachers with problems related to circuit diagrams, and they appeared to have received little assistance. "Herbert", a Physics student, said:

Extract No. 145

"I would like to have some sort of course showing how to look at circuits, because I have had difficulties. I've found that when you ask someone here about something, 'What does this circuit mean?', they don't seem to understand that there is a problem: a problem in just looking at the circuit to see what's going on. They seem to think it's very obvious - which it probably is - if you have enough experience."
RECOMMENDATIONS FOR IMPROVEMENT

4.72

Introductory Course

At the end of each interview the student was asked for recommendations for changes or improvements to the courses, assuming the ideal situation where a "free hand" would be given and no financial restrictions applied. The changes should be such as to make their courses pleasanter and more interesting to people of their age, and likely to strengthen the quality of education they aimed for.

Most of those who talked with me had given some prior thought to this matter, though their opinions had been given only to their friends and acquaintances engaged in their own studies. There was one suggestion which was shared by a large proportion of the interviewees, and that was given by students in every category of institution: they wished for some form of introductory course at the start of the first term: a means of providing a transition from school to university levels of study. This is a strongly felt need presently going unsatisfied. The recommendation was put to me firmly by "Joy", reading Physics at University.

Extract No. 146

"I think there is a need of a lot more introduction when you first come up. There is an assumption that you have had adequate preparation at school. The thing is, you come from different schools and you have done it at different boards. It's assumed that you have common knowledge, but some are better off and some are worse off than others. The people who are worse off suffer. A slow introduction is necessary so that you really understand the basics - later, I would want a lot more explanation, and less maths.

Another beginning Physics student said:

"Things are stacked against people who have deficiencies. Those who
haven't quite grasped the principles have to go to a higher level without the benefit from a revision course."

Many of those who wished for an introductory revision course specifically mentioned the need for instruction in Electronics. "We were thrown in at the deep end" said one engineer, "What we spent months over at school was covered in one lecture, then they would go on from there as if every one was able to follow them. What happened was that some just got lost."

The requests for revision were extended to practical work: many of those who had the minimum of laboratory experience allowed to them at school, and had handled few instruments and components, felt strongly that they should be given assistance at the first few weeks. As one student put it to me: "There should be a couple of weeks doing basic things in the labs. But they assume you know it already, and they rush on. The lectures should be synchronized with the practicals.

**Practical Work**

Many of the students' complaints and recommendations related to their laboratory work. At various times it was put to me that often students were not fully aware of the purpose and significance of their experiments, and the more conscientious and thoughtful felt a dissatisfaction in working throughout the year's duration without being able to see the plan and purpose of their activities. Several students said that they would appreciate receiving a calendar of the whole year's work in the laboratory, accompanied by information which cross-linked the experiments with the theoretical material offered in lectures. One student of Physics said:
"I would like to know why we are being given particular experiments, why some things need to be remembered. It really helps if you know what use things can be. It's a problem when you don't see the use of what you are doing, but if you do, it gives you confidence for what's next."

4.73

Demonstration and Instruction Required: Motors and Generators

Several who had little electrical construction experience suggested that they and others would benefit from extended demonstrations accompanied by explanatory commentary. One beginning Engineer, "Belinda", a "Visualizer", gave me an example of what she had in mind. She wished to see a generator dismantled in front of her by an instructor who would give a running commentary as the work progressed:

Extract No. 147

"With something like a generator or dynamo, the diagrams in a textbook are all very well, but they tend to show you part only: some of the components, like the coil moving between the magnets; but then they tend to go on to much more detailed descriptions of what's happening and you can't really follow that very well. I mean you can't entirely imagine all the component parts. I can remember at A-level the teacher went through a rather detailed description of the motor, and I just couldn't follow it."

Another student expressed a comparable recommendation when she said:

"The fact is that I haven't really examined motors and generators in action. It would be interesting to have more practical examinations. The trouble with practicals is that although you are encouraged to think about the theory of it, it's very easy to go through all the practicals without ever
actually working out the theory and seeing where it all ties in with the course work."

A plea for more information about the physical functions was made by "John", a Physics student and a "Visualizer":

Extract No. 148

"I wish the initial emphasis was on what is actually happening, then perhaps they could explain how to work it out mathematically. I'd have practicals where circuits were analysed, explained, and commented upon, then the mathematics applied. For example: there was one problem I was doing last week; now, if they had started off by saying 'The waves are attenuated when it goes into copper ...' but, they didn't start that way. They started off with wave equations."

4.74

Criticism of Excessive Theory and Abstract Mathematics

Students at one university complained frequently about an excess of theoretical discussion and abstract mathematics, and recommended more attention to the practical and "real-life" aspects of their studies. Even the least experienced of the undergraduates felt that what they were being offered was undoubtedly "academic" and remote from the professions which they proposed to enter. One Engineering Science student put it in this way:

"I would like to see more practical emphasis. I feel that it's probably true of all the courses here, the emphasis is very very theoretical, especially in something like Engineering. If you go into Engineering, it is essentially practical. I think it's wrong that we aren't doing more practical work. There is a bias among academic people that you don't get your hands dirty."

Several students suggested a reorganization of their programmes of study so that there was a tighter synchronization of
lectures, practicals, and tutorials. They felt that when 
treating of particular topics, each activity was unnaturally 
isolated by intervals of time. Most realized that teaching 
conditions were far from ideal, and that the numbers of 
students undertaking Science studies presented timetable 
problems which could not easily be resolved. However, some 
changes were suggested to overcome unnecessary obstacles to 
their progress. One Physics undergraduate said:

"I'd try to arrange it so that we had lectures, practicals, 
and tutorials in the right order. I am writing up practicals 
without having had tutorials, and honestly, I don't know what's 
going on. The theory hasn't caught up with the practicals."
Criticism of Tutorials

There were many calls for improved tutorial facilities. Almost all the students appreciated the potential advantages of having the close attention of a teacher, singly or in small groups, but it was felt that tutors were not always truly sympathetic to the learning difficulties which "ordinary people, not those brilliant types" encountered. If conditions could allow it, most students would gladly attend more tutorials than they received, but they would wish those tutorials to be more closely connected with the work they were studying at any given week of their courses. The newer students tended to stand, in some degree, in awe of the tutor, and not to reveal the true state of their difficulties or misunderstandings for fear of being scorned as an ignoramus. Most wished for a measure of informality so that they could be more open with the person who was to guide them through their course. One recent arrival put it:

"The trouble about tutorials is that I don't get the questions answered. If you ask something very simple they don't seem to understand. I do have mental blocks over some simple things. My tutor doesn't seem to understand that. He seems to have forgotten that there can be any difficulty."

At one university there were frequent recommendations for an improved instruction programme in electronics, and the tutorial system was particularly instanced as being unhelpful. A second year Physics student, looking back on the previous year's work told me:
"I got the feeling that our tutors didn't actually know much about electronics themselves. I may be wrong in that, but they didn't seem to. They didn't encourage us at all. The Physics they were interested in was not what we got."

Some considerable proportion of the students felt that much of their tutorial work was designed to assist the processing of students through the machinery of the university system, rather than to assist them to gain the best possible education. One second year Physics student, "Peter" gave me his considered opinion:

Extract No. 149

"All the education I have had so far has been geared to an examination, not towards understanding. Knowing how to answer the questions is what seems to matter, rather than understanding something thoroughly. I would always go for the basic fundamental understanding, and build from that. I think more explanation of Electrical and Magnetic fields is necessary, then afterwards there should be the applications. I would prefer to get a real feeling for what's going on."

Almost all the students who were not electrical hobby constructors experienced some degree of difficulty in reading theoretical circuit diagrams during their first year. Various students, while giving their recommendations for improvements referred to the desirability of obtaining some form of assistance in this skill during the earliest stage of their Engineering or Physics degree studies. Some wish for this to be given during tutorials, others wished it to be built into a laboratory induction course, and others would have preferred the instruction to have been given during their school days. It was acknowledged that with practice fluency does come; but they regretted that in
the absence of any organized training, they were suffering frustration and inconvenience.

One Engineering student, during his first term said:

"You need to know how to read circuits, and then you need to know how to put them together. We just need to know the essential details of the basic circuits - what happens to the input and the output. If you don't know, there is no obvious end to what they give you, and you just "switch off". If you get the simple circuits explained, and you can understand them, you can get on to the more advanced circuits, from the reading point of view."

Numerous other suggestions for changes to the Physics and Engineering courses were offered, but those were principally connected with individual preferences and individual modes of study and had little potential advantage to the main body of interviewees, or were irrelevant to the subject of this inquiry.
### CHAPTER FIVE

**DISCUSSION: INTERVIEWS**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>The Interviews</td>
<td>357</td>
</tr>
<tr>
<td>5.2</td>
<td>The &quot;Mathematic&quot;</td>
<td>359</td>
</tr>
<tr>
<td>5.3</td>
<td>The &quot;Visualizer&quot;</td>
<td>361</td>
</tr>
<tr>
<td>5.4</td>
<td>The Vocational Student &quot;Visualizers&quot;</td>
<td>363</td>
</tr>
<tr>
<td>5.5</td>
<td>The &quot;Visualizers&quot;' need for Graphic Imagery</td>
<td>364</td>
</tr>
<tr>
<td>5.6</td>
<td>Estimate of the Distribution of &quot;Visualizers&quot; and &quot;Mathematics&quot;</td>
<td>366</td>
</tr>
<tr>
<td>5.7</td>
<td>The Concept of Capacitance</td>
<td>368</td>
</tr>
<tr>
<td>5.8</td>
<td>The Vocational Students' Understanding of Capacitance</td>
<td>372</td>
</tr>
<tr>
<td>5.9</td>
<td>The Higher Education Students' Concept of Capacitance</td>
<td>373</td>
</tr>
<tr>
<td>5.10</td>
<td>Capacitive Reactance</td>
<td>374</td>
</tr>
<tr>
<td>5.11</td>
<td>The Concept of Inductance</td>
<td>376</td>
</tr>
<tr>
<td>5.12</td>
<td>The School Pupils' Knowledge of back-e.m.f.</td>
<td>377</td>
</tr>
<tr>
<td>5.13</td>
<td>Experience of Alternating Current</td>
<td>379</td>
</tr>
<tr>
<td>5.14</td>
<td>Vocational Students' Understanding of Inductance</td>
<td>380</td>
</tr>
<tr>
<td>5.15</td>
<td>Higher Education Students' Knowledge of Inductive Principles</td>
<td>380</td>
</tr>
</tbody>
</table>
DISCUSSION

5.1
The Interviews

It was the purpose of the research programme to discover why many persons experience difficulties in the course of their studies of the fundamental principles of Capacitance, Inductance, and Electromagnetism related to motors and generators, and to learn why a considerable proportion of those who had reached the early stages of their Higher Education related to electricity and electronics did not have the confidence in their own understanding of these basic principles. It was hoped that the interviews with school pupils, vocational trainees, and those in the first terms of their degree courses in Physics and Engineering would be able to provide information which would help to explain the weaknesses in electrical knowledge, and direct attention to the reasons for learners' initial and continuing difficulties with the basic principles chosen for investigation. It was conjectured that the learners' problems and difficulties might be connected with such factors as the students' response to modes of instruction received in the classroom; or, the beginners' absence of personal interest in the basic electrical properties; or, the students' uncomfortable experience with practical
work in the laboratory; or, unsuitable strategies in coping with the study of novel phenomena; or, inadequacies of textbook explanation, commentary, and illustration - and it was believed that other obstacles to electrical study might be revealed. When such factors had been identified, it was expected that useful suggestions, based on deductions from the data obtained, and the students' personal recommendations for course improvements, could be given to minimize the student study difficulties.

The interviews with the different categories of learners provided a substantial body of personal opinion and accounts of experience in the study of electrical fundamentals which confirmed that many learning difficulties could be referred back to the classroom and laboratory misunderstandings, and students' use or neglect of the recommended textbooks - all of which will shortly be discussed - but that another factor of great importance influenced their response to instruction offered, and potentially assisted or obstructed their electrical learning at each stage of their education, and that this factor, never previously recognized, deserved careful consideration.

During the interviews it became apparent that students of electricity frequently had what could be identified as a bias towards either a mathematic orientation (the "Mathematic") or a graphic orientation (the "Visualizer"), and that such bias could have a significant influence on the student's attitude to the work required of him/her and his choice of textbooks and strategies of study. In a few cases this bias was very strong indeed. It was found that the "Visualizers" predominated in each category of interviewee, with the exception of those reading Pure Physics.
The "Mathematic"

5.2 Those whom I have classified as "Mathematics" were persons of strong individuality, who, quite early in their school Physics studies discovered that their tastes were not in line with the majority, and took it upon themselves to follow an approach comfortable to their own mathematical inclinations. This usually involved private reading of textbooks which their fellow pupils preferred not to investigate.

A "Mathematic" like "Alex" (Extract Nos. 100-102), who found himself among pupils following the Nuffield Advanced Physics course, was obliged to distance himself from the practical, basically non-mathematical approach, and seek his own instruction in the more rigorous textbooks. While the "Mathematic" does not necessarily scorn graphic illustrations, they do not respond to them with the same interest or enthusiasm which is demonstrated by those of the "Visualizing" bias, and some can dispense with them completely. In the course of conversations with the "Mathematics" their implicit trust in formulae and the consummate importance of equations is brought out unmistakably. Such characteristics are present in the methods described for me by "Jerry" (Extract No. 103) and "Gladys" (Extract No. 104), and govern their whole approach to their electrical studies.

The "Mathematic's" aloofness from the practical functions and applications of electrical circuits predisposes such persons to choose courses at universities of academic tradition, where they are not pressurized to do more than a certain minimum of laboratory work. In the Physics departments of such institutions they find that their superior mathematical skills bring them to the attention and favour of their tutors, although the supervisors of the laboratories are not similarly gratified.
Although the numbers of those with strong "Mathematic" bias are small at school, they form an important class of highly motivated people; like their counterparts, the strong "visualizers", they may not be well served in the educational system if their particular needs are not recognized. The habits of study of the strong "Mathematic" may be shared, in modified form, by others of less intense "Mathematic" tendency. These persons cultivate a great deal of interest in the theoretical side of their electrical studies, and are drawn to textbooks (and classroom expositions) of a more abstractly mathematical nature, which others find "difficult". They usually keep company with those of similar "Mathematic" inclinations, and not infrequently indicate in their conversation a certain condescension to those not as fluent or confident in mathematical expertise. A common characteristic of the "Mathematic" is to favour the mental exercise of theoretical questions over the practical work. At every level of laboratory activity the "Mathematics" find the practical experiments tediously time-consuming, and the numerical recording of data unstimulating, and possibly irritatingly simple. The "Mathematic" can take much pleasure in the application of mathematical expertise to electrical problems, but is rarely more than superficially interested in the real-life uses of the electrical circuits.

Those of the "Mathematic" tendency appear often to be flexible, and with the exception of the extreme "Mathematics", can make good use of the same graphic aids to learning which are more urgently required by the "Visualizers." The "Mathematics" may obtain the benefit of clarification from textbook drawings, and be guided by block and pictorial diagrams to grasp the lay-out of particular
Groupings of components. In conversation with me, "Mathematics" have mentioned instances of borrowing pictorial aids to clarify a concept: one student was enabled to realize the nature of distributed capacitance in a line by imagining a series of separated miniature capacitors strung along it; another found it convenient to visualize, in dynamic form, the physical expansion and contraction of the propagation of electromagnetic waves as given in the textbook illustrations. Nevertheless, the "Mathematics' familiarity with formulae and the mathematical relationships of electrical functions, make them much less dependent on imagery than the "Visualizers". Given the opportunity, such people prefer to apply the intellectual, abstract, non-practical approach. There is usually little pressure on the "Mathematics" to modify their tendencies, for most of the theoretical textbook discussions emphasize a mathematical approach, and, from the accounts of the interviewees, much of the classroom instruction is deeply influenced by the standard textbooks.

The "Visualizer"

5.3 The "Visualizer" demonstrates a bias towards mental imagery which is both strong and consistent throughout their electrical education. There is reason to believe that in the schools there are large numbers of "Visualizers" who could benefit from educational methods adapted to their particular requirements. It is probable that if teachers could identify those among their pupils who are "Visualizers", they could introduce more graphic imagery which would materially assist that class of student who experiences a need to form very many "mental pictures" in the course of building up an understanding of electrical fundamentals. It is clear from
conversations with the interviewees that at present this
requirement is seldom gratified. The emphasis of much
classroom instruction is on theoretical, usually strongly
mathematical presentation which can be uncomfortable for
some "Visualizers" and discouraging to others. Students
of this category who sought assistance from standard text-
books were often disappointed to find less support from
diagrams and other illustrations than they had hoped,
and working with books which were not designed for their
tendency, they found it difficult to extract the required
information. Moreover, the learning aids which are of
the greatest advantage to the "Visualizer", such as
working models representing fundamental electrical prop-
erties, Oscilloscopes, cine- and video-cassette films,
are much under-employed.
It was interesting to note that none of the vocational students appeared to have a "Mathematic" bias, and that most of them indicated "Visualizer" tendencies. Few of those attending technical institutions had done well at mathematics when at school. By direction, and personal inclination, they had moved into an occupation for which they appeared to have aptitude. The vocational electrical courses emphasize the connections between fundamental principles and their application to common functional products, and they concentrate the students' attention and energy upon practical work, rather than urge a high degree of familiarity with mathematical theory. These students' normal mode of instruction, at the serviceman's work-bench and at technical college, is heavily dependent on the principles of observation and imitation of the specialist craftsman, seem well suited to the tendencies of the "Visualizer."
The "Visualizer's" Need for Graphic Images

The "Visualizers" are rewarded by the success of their study habits, so they apply mental imagery as a first step in almost every electrical investigation. This is clearly described by "John" (Extract No. 112), who required visual, tactile, and graphic confirmation of what he had been taught in theory. Their bias frequently guides them to a particular type of heavily illustrated textbook, as in the case of "Max" (Extract No. 113), who favoured the 3-dimensional illustrations often used in American textbooks. Such textbooks are rarely approved or recommended in traditional Higher Education courses. The "Visualizer" may be somewhat suspicious of mathematical formulae or mathematical proofs as offered in the recommended textbooks, or given in theoretical work in the classroom. Some of the "Visualizers" felt strongly that they were exposed to an excess of mathematical preoccupation, and even believed, like "Louis" (Extract No. 115), that their "Visualizer" approach allowed them to avoid errors and impracticalities.

Those students who began to read for Engineering or Physics degrees are confronted with more serious problems than those which they experienced at school. Few of the lectures, and little of the laboratory work, is likely to appeal to their inclination to stress the graphic rather than the mathematical approach to their studies. All have to accommodate themselves considerably when joining those institutions where there is a rigorous mathematical approach to the work. The beginning Engineers among them are only slightly less uncomfortable on account of having larger numbers of similar disposition working together.
The accounts of the interviewees of the "Visualizer" class indicate that as they progress on their Higher Education courses they can develop a flexibility, even a versatile approach, under the exigencies of degree studies in Physics or Engineering. While the "Visualizer" finds it more difficult, he attempts, whenever possible, to call up "mental images" to clarify concepts. However, some of the phenomena are so remote from common experience that it becomes less troublesome to accept the mental shorthand of mathematical formulae for all course work. This is explained by "James" (Extract No. 110), yet it is clear from the comments made to me that their underlying desire is for a graphic form whenever that is obtainable.
The Distribution of "Visualizers" and "Mathematics"

5.6 The research programme was organized to obtain information largely of a qualitative, rather than an quantitative nature, nevertheless, some estimation of the numbers of students possessing an unmistakable "Mathematic" or "Visualizer" tendency was possible. Of the 30 school pupils interviewed, two demonstrated strong "Mathematic" characteristics, and four demonstrated strong "Visualizer" characteristics; of the remainder, the majority appeared to have "Visualizer" tendencies in varying degrees. With the polytechnic and university students reading for Physics and Engineering degrees, there was a higher proportion of "Mathematics" to "Visualizer", which was expected because the entry qualifications had effected a prior selection. Among 50 reading for Physics degrees, five were very strong "Mathematics" and at least another 30 could be classed as "Mathematics" in varying degrees. Strong "Visualizers" were also found studying Physics: two demonstrated pronounced graphic tendencies, but they had learned to accommodate themselves to the mathematical rigour of their courses.

Of the 40 Engineering degree students interviewed, six demonstrated themselves as strong "Visualizers", and a majority of the remainder appeared to share this tendency in varying degrees. No very strong "Mathematic" was identified studying Engineering.

Of the 40 vocational students interviewed, four could be identified as strong "Visualizers". Discussions with the others indicated a bias towards the same approach in most cases. No strong "Mathematic" characteristics were observed among any of the vocational students (and none indicated any mathematical interests.)
This research programme could not undertake an inquiry which might establish whether the "Mathematic" and "Visualizer" tendencies were innate to the individuals who possessed them, or acquired through environmental circumstances. The age and experience of the interviewees were such that their tendencies were already well established, and those tendencies seemed "natural" to them. It is probable that the strongest "Mathematics" and "Visualizers" may have received an inherited gift which accelerated and eased the acquirement of mathematical expertise or visual imagery; and, in many cases the early childhood environment of such persons may have been such as to encourage and reward their endeavours, confirming them in habits of thought which could subsequently be identified as those of a "Mathematic" or "Visualizer".

Those persons of less pronounced tendency could have developed their habits of thought and study under the influence of the teaching they were given; the guidance offered by parents or older members of their family; and experiences of pleasure or dissatisfaction in pursuing mathematical or visual activities at school and at home; and numerous other environmental circumstances upon which it is only possible to speculate. It is clear that the pupils acquired, or first demonstrated, their tendencies quite early in the course of their school education, and that by the time they undertook A-level Science studies, their habits were soundly established.

A research programme could be designed for the purpose of learning how far, if at all, the tendencies of the "Mathematic" and the "Visualizer" are innate, or acquired by environmental influences. I believe that if it were carried out with thoroughness it would produce information of material assistance to educators. Such research would require much statistical data obtained from children in primary schools, and ideally would follow those individual through to the beginning of their secondary education.
In the course of research to identify the reasons for the difficulties which learners have with the study of capacitance, the interviews with school pupils revealed that many of them had a very uncertain grasp of the concept of capacitance; often it was little more than a slight acquaintance with the capacitive circuits given in their classroom notes or the textbook used, so that the phenomenon could not be associated with anything other than the component, the capacitor shown there. Both the school pupils and those newly arrived at university or polytechnic, who reminisced about their studies, agreed that the classroom instruction regarding capacitance had been brief, unemphasized, and very limited in scope. After the basic theory and formulae were offered, and a few calculations made to illustrate the application of the formulae to numerical problem solving, the interviewees could remember little commentary or guidance beyond the simplest laboratory experiments (such as the charging and discharging of the capacitor).

The significance of this fundamental property seems not to have been further considered, and little was said about very important and widespread uses made of capacitors and capacitance. In many cases teachers supplied their pupils with dictated notes or hand-outs, and recommended consultation in an approved textbook. Even when their trust in the conscientiousness of the learners was justified, it is unfortunately true that many young learners do not easily absorb information from the printed page, and tend to ignore or give slight attention to phenomena which is outside their experience.
What many teachers regard as simple principles, may require from the pupils extended consideration. As one schoolboy declared: "I have always found it a bit difficult to answer something that is new, therefore it takes me quite a long time to accept some simple rules or facts."

Many of the learners did not think much about capacitors and capacitance during a long period after they had been introduced to them: in their innocence and ignorance, it did not appear that there was much more to learn about them. The theoretical studies in preparation for A-level examinations could alert them to a realization that they did not thoroughly understand some of the phenomena associated with capacitance. Unfortunately, only a small minority sought information and clarification from their teachers, for numbers of interviewees spoke to me of seeking the solution to their problems in conversations with colleagues, and of dipping somewhat haphazardly into textbooks for the means of resolving confusion.

The majority of the school pupils had much difficulty in understanding the meaning of the term "Capacitance" because their experience of capacitance was restricted to the theory and laboratory observations on the behavior of the common component exhibiting that quality, the capacitor. This is true of both "Mathematics" and "Visualizers". From their responses to my inquiries about "Capacitance", it is clear that many immediately made a mental translation to the term "Capacitor". It is likely that they also do so on meeting a reference to "Capacitance" during such reading as they do.

The electrical hobby constructors had a better understanding
of the basic operations of charging and discharging capacitors. But some appeared to be satisfied with an oversimplified and vague memory of one of the physical analogies, and most had no distinct understanding of the Time Constant Curve. Some of the "Visualizers" had attempted to clarify their ideas by picturing the electron drift which introductory texts had described. Unfortunately, they discovered that it was only partially successful, for none of the contemporary school textbooks follow through with a complete sequence of the operations of charging and discharging, and misunderstandings can easily be acquired as the individual attempts to visualize the dynamic sequence of events.

Not a few of the hobby constructors employed the capacitor in a mechanical way - without thinking much about its function beyond the fact that it was a component of a particular description specified in the circuit diagram. There was a general paucity of information about the nature of different types of dielectrics and their functions, which point to an inadequate knowledge of the interconnected factors which govern the operation of the capacitor. It was disappointing to discover that so many could not recall the basic formulae for capacitance.

The school pupils who were "Mathematics" averred that they had "no difficulties" with capacitors, because it "followed from theory, and when the formulas are known, all the necessary calculations can be obtained"; however, these pupils were persons who disliked, and tried to avoid, practical work and might later experience problems in physical manipulation, choice of suitable components, and the organization of practical circuit arrangements.
It is certainly necessary that many of the pupils be encouraged to extend their knowledge of capacitance beyond their restrictive association with the component, the capacitor. It would assist them to consider the wider occurrence of the phenomenon if they were to learn something of the history of the early electrical pioneers' exploration of this fundamental property, which presented itself in their researches upon direct and alternating currents. Their concepts would be considerably enlarged if they read of Lord Kelvin's early struggles with trans-Atlantic telegraphy, where his efforts were at first bedeviled by the capacitance in the long cables - and how, later, he was able to overcome the capacitive effects by neutralizing them by appropriate quantities of inductance. Both "Visualizers" and "Mathematics" would find material of interest to their individual tendencies, if personally or with the guidance of their teachers, they dipped into a biography such as S.P. Thompson's *Life of William Thompson* (1872). For those extreme "Mathematics" who tend to remain aloof from the practical work, there will be a good example of an outstanding mathematician who did not disdain from becoming deeply involved with the practicalities of physical research.

Those pupils who are weak in their grasp of the principles of charging and discharging of capacitors could be materially assisted by the very clear exposition offered in the electric technicians' book in the "Common Core" series, *Basic Electricity* (1980). The "Visualizer in particular would greatly benefit from the exceptionally bold, simplified diagrams illustrating the Time Constant Curve associated with the charging and discharging of the capacitor.
The Vocational Students' Understanding of Capacitance

5.8 The vocational students demonstrated little uncertainty about capacitance, having grown familiar with a number of its effects in practical circuits. They were often quite fluent in speaking of particular capacitors which had come within their experience, but they had little or no interest in the theory which governed their operation. Their instructors, knowing the reluctance of technical students to become involved in the mathematics of electricity/electronics, adopt the practice of minimizing calculation and simplifying formulae, and are often ingenious in avoiding work which might exceed the modest mathematical ability of their students: they know of the aversion to what one described to me as: "Theory that can be deep and goes on for a long time."

There is a potential problem for those vocational trainees who wish to advance themselves in industry: the more rewarding positions demand greater theoretical and mathematical expertise than many can readily obtain. However, those more conscientious and potentially capable are now being strongly encouraged to persist in their studies through the whole series of progressive Technical Education modules; and those who qualify after three or four years should gain the necessary skills and experience to satisfy the entry requirements of the technical development and research departments of the larger industrial employers.
The Higher Education Students' Concept of Capacitance

5.9 The university/polytechnic students reminisced that their school teachers had treated capacitance (and inductance) in an isolated manner: the exposition of the theory of capacitance was very little related to the practical experiments in the laboratory and even less with the application of capacitance to useful electrical circuits. Most students indicated that they had not been made aware of the extent to which capacitance may enter into practical circuits. The hobby constructors had a better understanding of the situation, but their knowledge was usually linked to the most commonly used power supply and filter circuits. The "Visualizers" believed that the mathematical treatment had not assisted them to understand the significance of the physical component, the capacitor, when that was in active operation. What was missing, they felt, was sufficient commentary explaining in detail the dynamic functions of the component.

A considerable number of those in their first and second terms at university had not revised the basic principles of capacitor functions, and, apparently they knew little more than the mathematical formulae, which they had learned to apply to given numerical quantities for A-level examination purposes. The concept of "Capacitance" was unfamiliar to many beginning students, both Engineering and Physics, like "Herbert" (Extract No. 117) and "John" (Extract No. 118) who continued to rely on evaporating memories of school notes.
Those who entered upon degree courses of study in Engineering and Physics quickly discovered that capacitance was a phenomenon which they were expected to understand thoroughly, and those who carried forward only a limited knowledge of this property, such as a familiarity with the ratio of charge over voltage, could suffer embarrassment. Those who were not hobby constructors often had very little knowledge of the different types of capacitor, and even less about their practical uses. For such people in their first term in Higher Education, it was a common resolve that they would "read-up" capacitors and capacitance "during the vacation".

5.10

Capacitive Reactance

Those students who were prepared to talk about Capacitive Reactance indicated that it had been treated with little emphasis, and had not been revised. Capacitive Reactance was little understood by those beginning their Higher Education, and most could not give any example of the phenomenon. Even when the could, as in the case of "Milly", reading Engineering (Extract No. 121) who had university experience of problems involving capacitive reactance, it was entirely a mathematical problem-solving activity, and her understanding was limited to the memorized formula. Those who had progressed beyond A-level requirements had been obliged to exert themselves considerably to gather the principles of phase difference from the textbooks. Several of those who talked to me of their success in this matter, like the Engineering student "Jane" (Extract No. 124), and the Physics student "Kenneth" (Extract No. 125), were "Visualizers" who put their tendency to picture dynamic situations to good use, and recorded the appearance of oscilloscope wave forms.
As a considerable proportion of the students entering upon their Higher Education studies were weak in their knowledge of capacitive reactance, it seems desirable that the topic be given rather more attention towards the end of their school studies, preferably under the direction of their teachers; or, failing that, they should revise for themselves by private reading. They might choose either one of the older respected texts like W.H. Timbie's *Elements of Electricity for Technical Students* (1911) - which has the advantage that the author went out of his way to be as direct and simple as possible, on account of the ideas being presented were then relatively new and unfamiliar; or, they could consult one of the American textbooks with an abundance of illustrations, such as *Basic Electronics for Engineering Technology* (1981), by N.R. Ekeland.

The interviewees' accounts give good reason to believe that some form of review of capacitance, in theory and practice, is highly desirable in the early days of Engineering and Physics degree students' courses. Such a review could treat of a range of typical capacitors in common use, appropriate to particular power, electromagnetic and electronic circuits. Some revision of capacitive reactance is necessary, and for those who will regularly have to use oscilloscopes in their laboratory work, it is best that the phenomenon be demonstrated with that instrument.
The Concept of Inductance

5.11 The phenomena associated with inductance were frequent sources of misunderstanding among school pupils. While most had a basic acquaintance with the effects of the magnetic field around a current-carrying conductor under d.c. conditions, few could apply that knowledge even to simple inductive circuits. Several of the pupils interviewed indicated that they were nervous of the subject of inductance: among their classmates the subject was reputed to be complicated and difficult to master. For many, their knowledge was based on partly-remembered classroom teaching, or dictated notes. Some of the "Visualizers" who had difficulty in grasping the principles of induction had gained some basic information through memorization of a textbook's pictorial illustration of the relationship of current, voltage, and magnetic flux, which was buttressed by Fleming's hand-rules. Unfortunately, without further acquaintance with mathematical formulae, that knowledge remains an inadequate foundation for Higher Education electrical studies.

The "Mathematics" among the school pupils knew the formulae, but preferred not to be much involved in laboratory experiment which could familiarize them with characteristic inductance circuits. Both "Mathematics" and "Visualizers" were extraordinarily weak on information concerning the common uses of inductors. The more thoughtful among the interviewees were aware that what they had been taught about inductance theory had little connection with practical applications which could come within their experience, and several vocalized the group feeling when they wished they had heard more
about the way that components functioned within circuits, rather than the abstract theoretical considerations.

To many, the memory of their school electrical studies was one of dull activity, designed primarily to equip them with the mathematical means to gain the necessary A-level credits. The weakness in understanding these fundamental principles can continue to obstruct the progress of students like "Dennis" (Extract No. 90) during the first months of Higher Education. The concept of inductance worries many at school, and from the confidences of the students, there seems good reason to believe that it also worries many of the teachers, whose explanations failed to satisfy their pupils. Something of this must be blamed upon the shortage of properly qualified teachers, and the inexperience of those recently qualified.

School Pupils' Understanding of Back-e.m.f.

5.12 There is no doubt that the principles of back e.m.f. troubled many school pupils, though they were reluctant to speak much of this, as were those beginning their Higher Education. A number of the "Visualizers" remembered how difficult it was for them to absorb electromagnetic theory from the classroom talk or the notes which they were given, and they never obtained sufficient practical experience to establish grounds for solid confidence. On the other hand, the "Mathematics" tended to be impatient with the analogies used by teachers to simplify inductive formulae: they did not share the problems of the "Visualizer" colleagues, and their preference was for expressions of concise mathematical symbolism, and they were
perfectly satisfied with the inductive equations, and the academic textbook commentaries, as instanced by "Alex" in Extract No. 100.

Experience of a.c. Electricity

5.13 Many of those new to Engineering and Physics courses looked back upon their school inductive studies with regret because they had not taken full advantage of the instruction and the recommended literature; but more frequently it was because they considered that too little time had been given to the examination of a.c. conditions relating to transformers, reactance, filter circuits, and the operation of motors and generators. Relatively few of those interviewed had more than a modest knowledge of transformer action, and usually they were "Visualizers" like "Max" (Extract No. 133) who had benefitted from sound teaching, and had laboratory experience of working with transformers and had put his natural inclinations to use in separating the various currents flowing in the operating transformer. Alternatively, they were experienced constructors who had employed transformers in particular situations. Few of the students had more than a superficial acquaintance with mutual inductance.

Unfamiliarity with Transformers

Those who had not been given the opportunity of studying the transformer at the work-bench (and particularly those who had not had the wave-forms demonstrated with the oscilloscope), did experience difficulty in following the electrical functions of the transformer
and in connecting that with the electromagnetic theory. This is instanced by the conversation with the Engineering undergraduate, "Aline", a "Visualizer" (Extract No. 134). She was only one of several students who complained of being subjected to the mathematical analysis of the transformer currents when in a state of near-ignorance of the physical structure and applications of the device. It would seem that at both school and university the opportunities for engaging student interest are often lost by treating transformers primarily as a source of mathematical exercises. The failings of that approach were noted in conversation with "Jerry", the Physics undergraduate (Extract No. 135) who had followed and appreciated the academic work, but who did not know of the existence of the Isolating Transformer at his laboratory bench, nor its function.

There is clearly a need for more information on the transformer as a practical instrument. It is desirable that this should be offered towards the end of the school studies. It is preferable that the operation of the transformer be explained and demonstrated in the laboratory, where the principles can be implanted most firmly if the instructor were to call upon a historical account of Henry's discovery: that by adjusting the number of turns on his primary and secondary coils, he could step-up or step-down the voltage; and similarly, it could be pointed out that it was he who introduced the screening of coils.

In the classroom all possible graphic assistance should be obtained from heavily-illustrated texts. Some of the earliest treatments of the transformer still remain unsurpassed in illustrations and diagrams, such as J.A. Fleming's Alternate Current Transformer (1889). But the student is also very well served by a modern lucid and concise account such as is given in Technical Electricity and Electronics (1984) by Buban and Schmitt.
The Vocational Students’ Understanding of Inductance

5.14 The concept of inductance is undoubtedly particularly difficult to the learner on the vocational courses. Because of their characteristic impatience with classroom theory, little is to be gained by much teaching of the subject at the blackboard. They want "to see it, and want to know what it does", and they want a reference to something mechanical which is within their own experience. In their situation, the oscilloscope demonstration of wave-forms is the best tool which the instructor has in communicating the basic principles of this phenomenon. Like most of the school pupils, the vocational students seldom associate inductance with motors and generators, but it is not unreasonable to suppose that their interest in the principles of inductance could be stimulated by the instructors working backwards from the dynamic actions of the motors and generators which are so dependent upon these principles.

The Higher Education Students’ Knowledge of Inductive Principles

5.15 A considerable number of first and second term Engineering and Physics students were uncertain of their mastery of inductive principles. In the course of a brief exchange on the subject it became clear that many scarcely remembered much more than the simplest formulae. In conversation it was frequently indicated to me that at school their consideration of a.c. circuits was rushed and skimmed, and that they had found the teachers’ commentaries confusing, and had not subsequently expanded on the little they had brought from school.
The students' confidence in their understanding of the phenomena was not necessarily linked to success in the A-level examinations, for some of the interviewees spoke of lingering anxieties about inductive principles. Several told me plainly that they had been able to cope with the A-level questions only because they had memorized a routine of formulae application.

The Opinions of Higher Education Students

The Engineering students were frequently of the opinion that electromagnetism required more time and attention at school: they believed that they had not carried sufficient information from school to be able to progress smoothly to the higher level of instruction offered to them at the beginning of their courses. This was particularly true in the case of transformers, motors and generators. Those who were more conscientious than others had tried to use the recommended university/polytechnic texts to supply their deficiencies, but were made painfully aware that those texts assumed a great deal of knowledge which they did not possess.

Many students described inductive phenomena as "difficult", and, in all probability, for that reason they postponed the needful textbook study. The longer they delayed, the greater the anticipated difficulties became in their imagination. Many times students like "Alex" (Extract No. 126) indicated a sense of "confusion" when thinking about inductance, and others, like "Bill" (Extract No. 127) talked of its "mystery". They, and others based their opinions principally on their A-level notes, and had not looked into the
school level textbooks for assistance. The concept of "Inductance" was even less clear than "Capacitance" in the minds of those who could offer me only the mathematical formula.

Some of the beginning students had good reasons for anxiety: they had learned from second-year students that they were expected to be well-grounded in electromagnetic principles at the start of their university Electromagnetic lectures, yet like "Aline" (Extract No. 131), they were quite unsure of the basic inductive principles in which fluency was assumed. Some who had tried to read up the subject for themselves, like "Ronny" (Extract No. 132), had discovered the difficulty of gathering the principles of induction from the recommended books, and had come to the conclusion that a good understanding of the subject involved deep study and time for leisured reflection, conditions which were not likely to be available to them during term-time.

Many university/polytechnic students voiced a wish that their lecturers and tutors would recognize that there were great inequalities in the academic grounding of the newcomers: they called for a "slow introduction to counteract the conditions stacked against people who have deficiencies and have to struggle." Among the topics much mentioned by them as decaying in memory since A-level studies, were inductive principles.
CHAPTER SIX

RECOMMENDATIONS BASED ON RESEARCH FINDINGS

6.1 Recognition of the Two Categories
6.2 School Pupil "Visualizers"
6.3 School Pupil "Mathematics"
6.4 Recognition of the "Visualizers" in Higher Education
6.5 The Need for More Practical Work
6.6 Practical Work on Motors and Generators
6.7 Encouragement to Vocational Students
6.8 Guidance in Preparation for Practical Work
6.9 Instruction in Circuit Diagram Reading
6.10 Encouragement to Follow Electrical Hobbies
6.11 The Reading of Hobby Magazines
6.12 The Resolution of Student Problems
6.13 Vocational Students' Problems
6.14 Prescribed Textbooks
6.15 Textbooks Appropriate to Each Category
6.16 Group Reading for Vocational Students
6.17 The Use of Heavily Illustrated Textbooks
6.18 Textbooks for Degree Students
6.19 Fundamental Principles Require More Attention
6.20 Training Required in Circuit Diagram Reading

Page
382
383
384
385
386
388
389
389
390
391
392
393
394
396
397
397
398
400
403
405
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.21</td>
<td>Revision of Fundamental Principles</td>
<td>406</td>
</tr>
<tr>
<td>6.22</td>
<td>Relating Capacitance to Practical Uses</td>
<td>408</td>
</tr>
<tr>
<td>6.23</td>
<td>Regular Revision of Inductive Circuits</td>
<td>409</td>
</tr>
<tr>
<td>6.24</td>
<td>Back-e.m.f. Should be Related to Motors and Generators.</td>
<td>409</td>
</tr>
<tr>
<td>6.25</td>
<td>Transformer Action Should be Studied with the Oscilloscope</td>
<td>410</td>
</tr>
<tr>
<td>6.26</td>
<td>Relation of Inductors to Practical Uses</td>
<td>411</td>
</tr>
<tr>
<td>6.27</td>
<td>Historical Experiments to Aid Learners</td>
<td>412</td>
</tr>
<tr>
<td>6.28</td>
<td>Prescribed Reading</td>
<td>417</td>
</tr>
<tr>
<td>6.29</td>
<td>Recommendations for Historical Reading</td>
<td>417</td>
</tr>
<tr>
<td>6.30</td>
<td>Overcoming Vocational Students' Reluctance to Reading</td>
<td>419</td>
</tr>
<tr>
<td>6.31</td>
<td>Recommendations for Group Reading</td>
<td>420</td>
</tr>
<tr>
<td>6.32</td>
<td>Introductory Course: Higher Education</td>
<td>422</td>
</tr>
<tr>
<td>6.33</td>
<td>Recommendations for Introductory Courses</td>
<td>422</td>
</tr>
<tr>
<td>6.34</td>
<td>Practical Instructions through Simple Circuits</td>
<td>424</td>
</tr>
<tr>
<td>6.35</td>
<td>Consideration of Solid State Devices</td>
<td>425</td>
</tr>
<tr>
<td>6.36</td>
<td>Reconsideration of Older Textbooks</td>
<td>426</td>
</tr>
<tr>
<td>6.37</td>
<td>Recommendation of Textbooks Specifically for &quot;Visualizers&quot; and &quot;Mathematics&quot;</td>
<td>427</td>
</tr>
</tbody>
</table>
CHAPTER SIX

Recommendations based on Research Findings

6.1 Recognition by the teacher of the two categories of learner can bring advantages to both parties. If, quite early in any course of electrical instruction, the teacher is observant of characteristics which indicate the "Visualizer" or "Mathematic", he can assess to what degree the person's methods of study are influenced by his/her bias towards one or the other classification. The "Visualizer" is particularly attentive and critical of diagrams and illustrations, and considerably less enthusiastic of the mathematical equations. The stronger "Visualizer" soon reveals his bias as he persistently seeks for a physical description of the component actions, and gropes for some analogy which has a reference to visible phenomena within his experience. The teacher who recognizes the habits of the "Visualizer" will not assume that these people are poor mathematicians and simply need more rigorous drill in numerical techniques, but will accept that they do have other non-mathematical tendencies which can be accommodated and put to beneficial use in the course of mastering the fundamental principles of electricity.

The "Visualizers" should be encouraged to draw circuit diagrams of the practical circuits which are illustrative of capacitive and inductive theory - preferably in the laboratory, where they can be constructed from discrete components without delay. With the advantage of the instructor's explanatory commentary linking the theory and the formulae with what they have produced, the "Visualizers" can establish a stronger mental association than is likely to result from the classroom "talk and chalk".
The teacher's awareness of the importance which visual aids have in the "Visualizer's" learning processes could substantially modify the presentation of some topics which can be identified as difficult to transfer from the printed page to the individual's pictorial imagination. Such are the inductive phenomena, and the sympathetic teacher, aware of the special needs of the "Visualizer", might consider beginning this study directly from laboratory experiments, allowing the learner to observe the dynamic phenomena by means of the behavior of the wave-forms on the oscilloscope screen and the multimeter scale.

Acknowledgement of the particular needs of the "Visualizer", and especially those strongly so biased, would result in greater attention being given to the choice of recommended textbooks, and more guidance to students using them. In all probability many teachers would propose reference to several of the more heavily illustrated recent introductory texts, and suggest the study of suitable diagrams from a number of works, while retaining the recommendation of more academic textbooks, with their rigorous mathematical proofs, to the undoubted "Mathematics".

6.2 The school teacher who appreciates the different tendencies of his pupils would be in a good position to guide those uncertain of future educational progress: he might advise the strong "Visualizer" with manipulative skills to consider the prospect of joining a Technical Education Certificate course in Electricity/Electronics at a vocational college; or, he might encourage an academically inclined "Visualizer" to consider the possibility of reading for an Engineering degree at university or polytechnic.
6.3 Similar benefits would result from the recognition and appropriate accommodation of the particular requirements of the "Mathematics". The extreme "Mathematics" are few and easily identified by their superior numerical skills, and their impatience with laboratory work. Their tendencies are almost certainly so well established by the time they reach A-level preparation that it is likely that the teacher's efforts could only achieve a slight modification of attitude and behavior - yet it is worthwhile encouraging greater tolerance of the physical functions of capacitors and inductors and the circuits in which they are used, and these persons should be advised that to scorn laboratory experiment could prejudice their progress in Higher Education.

Those "Mathematics" of less pronounced bias could be encouraged to flex their mathematical skills on formulae-related problems found in textbooks intended for a higher stage of study than their own. If precision equipment is available in the laboratory, their interest in the practical circuits could be sharpened by urging them to use those instruments to compare the measured result with their own calculations, and account for differences which may be found.
Recognition of the "Visualizer" in Higher Education

6.4 If at university/polytechnic level the teachers would acknowledge the existence of "Visualizers" and their tendency "to see in the mind" rather than immediately apply a mathematical approach, then it is almost certain that students' questions concerned with physical conditions associated with inductive and capacitive circuits would receive more patient treatment. Those teachers who recognized the tendencies of the "Visualizer" would not dismiss them as naive and needful only of mathematical revision - which was the experience of some who complained to me that the response to their requests for physical explanations of fundamental principles was to be "sent right back to the equations", although they wanted "a different way of thinking about it." ("Selina")

The university/polytechnic teacher, having become aware of "Visualizer" characteristics would realize that a proportion of his students resist the abstract mathematical presentation of physical electrical occurrences, preferring "to understand how it works, not going into any analytical mathematics." ("Colin")
The Need for More Practical Work

6.5 There was a consensus of opinion among the pupils preparing for A-level examinations that they received too little practical experience designed to acquaint them with electrical fundamentals. Some believed that the experiments rarely stimulated them sufficiently to encourage further personal inquiry, and only rarely did they illuminate obscure, partly-understood theoretical principles relating to capacitance and inductance. The pupils wanted instruction and demonstrations which explained and commented upon the physical processes within components and circuits. Unfortunately, such desires were seldom gratified.

Some of the university students, looking back upon their electrical instruction, complained of it being remotely theoretical and excessively mathematical: like "Bessy" (Extract No. 87). They spoke of too many memorized formulae and equations, which although effective for examination success, did nothing to engage their interest in the study of electricity. Those who were "Visualizers" hankered after an alternative manner of learning about the electrical mysteries, and like "Amanda" (Extract No. 89) and "Michael" (Extract 91) who very much wished that they could "understand what was going on" in the physical sense of knowing more about the fundamental properties of the components and their actions in circuits, and the practical applications of the devices. Those students indicated that they were groping for a graphic or visual reference, and were the type of persons who could benefit from greater contact with practical work in the laboratory.
The slight acquaintance with practical work was a cause of anxiety to a good number of students who had reached Higher Education, and strong regrets were felt whether the weakness resulted from a lack of commitment to laboratory activities, or inadequate school facilities. The failing was particularly embarrassing at the very start of their Physics or Engineering degree courses when it became apparent that their teachers assumed a considerable practical knowledge of components, circuits, and instruments.

In the opinion of a considerable number of students, the attitude of their school teachers was that electrical theory demanded much attention, but that work in the laboratory was an "extra", and that the practical skills could be acquired, or improved, at a later date. "Michael" (Extract No. 91) was one of several who complained of rushed experiments and a programme too concentrated to allow time for reflection. "Bernard" (Extract No. 93) is an example of the student who discovered how inadequate his school practical work had been, and he had had to work very hard to make good the deficiency. The girls, in particular, complained of superficial laboratory work, and many of them studied at schools where the Science department was severely under-staffed and under-equipped, and except in the rare cases where a "school club" had been organized for electrical hobby constructions, there was little opportunity or encouragement to practical electrical constructions.
Practical work on Motors and Generators

6.6 One of the most frequent recommendations was for an early and thorough practical coverage of motors and generators. The "Visualizers" in particular found difficulty in mastering the principles from blackboard drawings or textbook illustrations. A dynamic action is sought. People like "Belinda" (Extract No. 147) spoke for many others when she called for the dismantling (or construction) of a generator by a demonstrator in the laboratory. Properly aided by running commentary, such work on a generator or motor is memorable, and would justify the time and effort involved by the benefits which it can give to novices.

A large number of students felt that they had been denied an essential area of information by not receiving some tuition in basic Electronics at school. On account of the contemporary acceleration in electronic devices and circuits, it certainly should be possible for all Science students, and especially those going forward to study for Physics and Engineering degrees, to receive a basic training in electronic devices and circuits. The polytechnics and universities, however, should acknowledge that there is an area of weakness at present, and provide much more discussion of elementary electronics at the start of their laboratory sessions.
Encouragement to Vocational Students

6.7 As it was with the school pupils, so similarly the vocational students had need of instruction in the practical operation of motors and generators, and the theory which governs them. Although the trainees complained of the difficulty of concentrating on the inductive principles in the classroom, their established interest in mechanical devices could be a means to maneuver them into gaining some familiarity with electromagnetic fundamentals through the examination and analysis of the behavior of motors and generators at the laboratory work-bench.

6.8 One potential source of difficulty and confusion to beginning Higher Education students was frequently singled-out for criticism: that they must often undertake experiments without a sufficiently clear understanding of the purpose of their work. Unfortunately, some instructors in charge of first term practical work assume more knowledge on the part of the students than they possess, and provide too little in the way of explanatory comment. As the student in Extract No. 141 expressed it: "You don't always know exactly what you are going. You follow the method laid down." By contrast, a number of enlightened educators do provide notes to the first and second term students which guide them to the pages of a number of textbooks dealing with the topics to be studied in practicals. The majority of the students would benefit if this practice was universally adopted.
Instruction in Circuit Diagram Reading

6.9 The interviews with first term Physics and Engineering degree students indicate that some of their early course difficulties were related to an inability to read theoretical circuit diagrams accurately and with confidence. At school scarcely any attention is given to the interpretation of circuit diagrams beyond the recognition of the common symbols because the teachers consider that the simple circuit arrangements, incorporating so few components, pose no problems. The problems arise, however, when the complexity of circuits increases dramatically at the next stage of their electrical studies.

As it is necessary for all Physics and Engineering degree students to develop some fluency in reading electrical circuit diagrams, it is highly desirable that this skill should be practised while at school by those who are proposing to go forward to such courses. Once in the Higher Education laboratory, the students can suffer both embarrassment and practical problems if they cannot read their circuit diagrams - as demonstrated by the "fresher" engineer and her laboratory partner who had before them on the bench a circuit diagram which contributed little to their experiment because: "We don't understand much of what it represents."

It is unfortunate that few university/polytechnic teachers appear to acknowledge that there is any difficulty in acquiring the fluency that they expect from their students. It would seem that they have forgotten that once they did not have the facility themselves. The students were in no doubt that it would be much to their advantage if they had received some tuition in circuit diagram reading at school, or immediately on entry to their degree courses.
Encouragement to follow Electrical Hobbies

6.10 The School pupils who were hobby electrical constructors met with fewer difficulties and anxieties in the course of their A-level preparation. In part this can be accounted for by the background of basic knowledge relating to discrete components and their arrangements in the common circuits employed by the kits and experimental sets; equally, it can be attributed to enthusiasm generated by their achievements in producing for themselves even the most elementary working models—a enthusiasm sufficient to carry them through temporary learning problems as they advance in their studies.

The experience of those constructors suggests how desirable it is for teachers to recommend electrical hobby activities to those who appear to be losing interest, or those who begin to fall behind their fellow pupils. The educational advantages, combined with the pride which equipment building can bring, may win over prejudice and distaste born of anxiety, felt by persons like "Harris" (Extract No. 86), who felt that he had to struggle to cope with what others found relatively easy. Although teachers, pressed by numerous commitments and unsatisfactory conditions, may not consider it important to turn their energy to the urging of pupils to these constructions, the students interviewed have been grateful to those school teachers who provided that initial encouragement.
6.11 A valuable ally of school teachers in the electrical education of their pupils is the range of hobby magazines which are designed to appeal to those of limited technical knowledge and modest resources. The hobby magazines encourage the young constructors with attractive articles for manageable circuits; later, many who had benefited from such reading, continue to patronize similar, though more advanced magazines, and extract practical circuits and gather items of useful information while reading for Physics or Engineering degrees.

It is unfortunate that a considerable proportion of school pupils and Higher Education students displayed apathy towards these publications, or expressed only weak dilatory good intentions of investigating their contents.

There is a need for university/polytechnic teachers to exert a positive influence to encourage the use of these magazines - perhaps by displaying articles relevant to current studies, and by discussing them, as they appear in the monthly issues, in class.
The Resolution of Student Problems

6.12 Many of those interviewed volunteered memories of problems encountered while studying electrical fundamentals at school, and one common characteristic was that they hesitated to go directly to their teachers for help. The impression often gained was that they felt the amount of time devoted to the principles of capacitance and inductance was too brief to allow them sufficient acquaintance with the theory and its application; however, they recognized that their A-level preparation was so comprehensive as to oblige the teachers to maintain a speed of presentation which put them somewhat under pressure. Among those who spoke of early learning difficulties were those who were certainly conscientious, but slow in absorbing knowledge (by comparison with their colleagues). By their own accounts, they preferred to seek assistance from their friends, or search the textbooks, rather than take their problems to the teacher. While a measure of self-reliance is desirable, the pupils should be assured that difficulties and problems, which may loom large in their eyes, can be resolved more easily and quickly by seeking the assistance of the teacher - and, that they may be secure in the knowledge that they will not be embarrassed by any suggestion of intellectual incompetence.

As the school pupil can not have extensive experience of private study, it seems desirable for teachers to recommend a regular procedure to follow when study problems arise. It might take the form of first carefully considering the nature of the difficulty to see if it can be removed by checking classroom notes; then attempting to find a treatment of the matter in the approved
Vocational Students' Problems

6.13 The vocational students' attitude to learning problems and their solution has much to commend it to their fellow learners at other institutions: they generally do not entertain feelings of shame or guilt on account of theoretical misunderstandings, but promptly seek assistance from their instructors whenever it is required. It follows naturally from the less formal arrangements of the Technical College method of instruction, where small groups of day-release youths are taught under conditions which correspond closely to the daily supervision and guidance obtained from the more experienced technicians at their places of work.

Whereas the vocational student expects to receive ready and willing assistance whenever it is sought, the university/polytechnic students appear to harbour considerable doubt whether their requests for assistance would be warmly received, believing that they might be scorned for lack of fluency in "basic principles." In some measure they stay aloof when assistance is required, through a misunderstanding that the Staff invariably expect persons at their level of study to work through their difficulties on their own resources. Some clearly do not realize that it is a duty - and a primary aim of all teachers of good will - to offer assistance in study difficulties. Among the university/polytechnic students interviewed, few had taken problems to their tutors at any other
time than the regularly appointed tutorial meeting, even when those problems appeared to them to be urgent.

The indications are that a more open and cooperative attitude should be aimed at between teacher and student in this matter of resolving learning difficulties. The student should know that there is always the opportunity for speedy access to a teacher or tutor to discuss learning problems which might otherwise become inflated beyond a reasonable level of importance.
Prescribed Reading: Textbooks

During discussions with the school pupils' teachers, the opinion was several times offered that many of the learners' problems and difficulties could be avoided if they would only supplement their classroom notes with some conscientious reading in the prescribed or recommended textbooks. However, the pupils do not accept that this is so, and many offered comments in explanation of the meagreness of their reading. They found the respected older texts "dry", unattractive to people of their age, "difficult to follow", and "too complicated" in mathematical presentation. Some who followed their teachers' recommendation discovered that their textbooks were "hard going", and did not persist in the effort, optimistically hoping that the matters under discussion would eventually be clarified in the course of classroom work. It was the "Mathematics" among the pupils who regularly undertook textbook study: to them much of what was read was just an expansion of theoretical principles previously discussed in class, and such material presented little difficulty to them.

Most of the electrical texts approved for school use were written by physicists who were almost certainly "Mathematics", and they present their material with a bias which is natural to themselves. The "Visualizers" find little illustrative material to suit their tastes in the textbooks available to them in the school libraries, and few are sufficiently motivated to search for alternative educational works.
Textbooks Appropriate to each Category

6.15 If teachers recognized the differing requirements of the "Visualizer" and the "Mathematic", then they could guide each to the most appropriate type of instructional text, stimulating the "Mathematic" by directing his/her attention to academic works on the next level of accomplishment; or introducing the "Visualizer" to the few contemporary texts offering numerous explanatory diagrams, or to historical electrical manuals heavily illustrated with mechanical analogy, written for those who had no opportunity to study higher mathematical methods.

Group Reading for Vocational Students

6.16 During discussions with vocational students it emerged that their electrical reading was exceedingly limited. With few exceptions, they consulted textbooks only under compulsion for specific projects. Most did not possess the natural inclination, nor the literary skills necessary to support any sustained reading. What they did read was usually taken from the instructors' hand-outs, and such notes as they took in class or laboratory. One unfortunate result of this is that a strong prejudice may develop against the use of books, and may become self-perpetuating among the technical students. Their teachers are well aware of the extreme resistance that the trainees have to reading any of the introductory electrical engineering texts, and are familiar with their aversion to mathematical expressions. As
one instructor said to me: "If you ask them to do something only a little harder than Ohm's Law, they take fright."

As experience has shown that prescribed reading is thoroughly unpopular and seldom undertaken, most technical college teachers avoid it. However, the prospect of improvement is at hand: in the last few years there have appeared vocational course texts which can hold the attention of many of those who would reject the traditional expositions. The difficulty is to introduce these to the students. Conversations with technical college librarians have convinced me that they have made heroic efforts to break through the students' prejudice that "books are only for the brainy types". The best chance of success is when the technical instructors accompany newly arrived students to the library; and in cooperation with the librarian, spend time talking about a carefully selected, and physically separated, group of textbooks - books which can be of particular value to the course upon which they are entering.

6.17
The Use of Heavily Illustrated Texts

Both the vocational course students and the school pupils who are strong "Visualizers" could be led into a closer acquaintance with electrical theory if they were encouraged to progress through one of the heavily illustrated electrical technology books. If the school or technical college teacher were to set aside a little time each week for class reading and discussion of texts like Basic Electricity in the "Common Core Series", or one of the Babani educational series, such as Elements of Electronics, which are specifically designed through memorable diagrams and uncomplicated
language to make a strong impact on the novice; alternatively, older historical texts could be made the subject of group reading, with the teacher guiding the young students to works which offer friendly, clear commentary upon the fundamental theory which governs so much of their practical occupations. There are many suitable historical texts, but the innovative instructor could scarcely choose better material than is contained in J. Ambrose Fleming's informal talks to electrical trainees, or those sections concerned with capacitance and inductance and generators in Silvanus P. Thompson's first book for the electrical student.
Textbooks for Degree Students

6.18 Few among the Engineering and Physics degree students had ever complained to their tutors about the textbooks which were recommended to them; yet many of them expressed dissatisfaction and disappointment in the use of them. One comment made on several occasions was to the effect that their texts had an excessive preoccupation with mathematics - an observation which probably would come as a surprise to their teachers. However, if university/polytechnic teachers were to acknowledge the existence of the two classes of student, the matter is readily understood: the members of each class progress most smoothly and comfortably when studying from texts which favour their personal inclinations.

The "Mathematicians" have little ground for complaint, because they are well served by a variety of sound electrical treatises which are regularly reprinted and revised. The "Visualizers" find more difficulty in locating texts most helpful to them: the graphically orientated works are not readily accessible, and, as far as I could learn, they are never recommended to the undergraduates. However, such works do exist, and the discussions I have had with many Higher Education "Visualizers" convinces me that these texts might be consulted advantageously by the students if librarians and teachers were able to bring them to their attention. For the visualizers, works of this type, both modern manuals and texts of earlier years, could be truly valuable.
"The "visualizers" who wish a review of electromagnetism could benefit greatly from a perusal of Silvanus P. Thompson's *Dynamo Electric Machinery* (1884) with its comprehensive descriptions and abundance of drawings and graphic illustrations. They would also find a sympathetic writer in W.H. Timbie, whose *Elements of Electricity for Technical Students* contains a multitude of diagrams of exceptional clarity, which guaranteed its use by generations of students at the Massachusetts Institute of Technology. Those who prefer modern texts could take advantage of the New York Institute of Technology's *Programmed Course in Basic Electricity* (1964), an excellently lucid treatment is there offered on the subjects of capacitance and inductance, presented through a very large number of small drawings and diagrams.

Alternatively, the "Visualizers" wish to revise their knowledge of the physical performance of capacitors and inductors could be gratified by studying the first section of *Oscillator Circuits* by Thomas M. Adams (1980), where numerous illustrations examine the behavior of capacitors and inductors within practical circuits by means of an exhaustive analysis of electron currents, which are identified and described in detail. In the author's words: "The circuit diagrams used are more than just abstract drawings of circuit connections - they are concrete "working models" of circuit actions in diagram form."
Such texts are well suited to "Visualizers" on the early stage of their Higher Education programmes, but it is unfortunate that their valuable qualities are not more widely known among those who could benefit from studying them. If there was acknowledgement of the particular bias of "Visualizers" at the Higher Education level, it is likely that such works would be favoured by a considerable number of undergraduates, as well as teachers, who would appreciate the advantages to be gained from the study of material appropriate to particular study habits.
Fundamental Principles Require More Attention

6.19 There are good grounds for recommending that teachers should dwell longer on the fundamental principles than is usual in secondary school courses leading to A-level examinations. The pupils tend to skimp the study of capacitance and inductance, partly because these appear to be preliminary topics to be considered before reaching the interesting electrical functions of groups of components within circuits, and partly because some learners may in error suppose that much of what they require to know about these devices is given by the formulae associated with them.

The more experienced teachers are well aware of the need for the pupils to familiarize themselves with the physical properties, the mathematical expressions, and some of the applications of the capacitors and inductors, but may hesitate to insist that their pupils pause in their eagerness to advance long enough to check their understanding of the concepts of capacitance and inductance. A recognition by school teachers of the two categories of learner, the "Mathematics" and the "Visualizers" would make it possible to offer particular forms of assistance, personally or through textbook reference, which could guide each type of pupil through a more thorough introduction to fundamental principles in the manner most appropriate to the pupil's natural tendencies.
It is highly desirable that those who can be identified as "Mathematics" should be given special encouragement to transfer some of their theoretical interests to practical experience with working circuits, perhaps through the sociable activities of lunch-hour or out-of-school-hours electrical construction clubs. In some cases "Mathematics" may find the classroom work too simple, and may require the stimulus of more advanced problem-solving, which the teacher can supply by recommending alternative, more mathematical textbooks - occasionally those normally used in Higher Education. On the other hand, the "Visualizer" may obtain encouragement and the best conditions for personal study procedures if the teacher directs his attention to a type of textbook which is heavily illustrated with explanatory diagrams (possibly with coloured illustrations), or obtains the opportunity to view School Television Science programmes, or selected Open University introductory electronics films.
Training Required in Circuit Diagram Reading

6.20 All school pupils should be given some training in circuit diagram reading. This could be introduced through the reading and interpretation of the simple circuits which the pupils will have drawn for themselves in the laboratory under supervision, and continued by the examination of textbook circuits. The hobby and amateur constructors' magazines could be very usefully employed to provide both a range of progressively more demanding circuit diagrams and interesting discussion subjects. There is a wealth of suitable material contained in the instructional courses printed in the "Everyday Electronics" magazine which can be presented to the pupils in the classroom, analysed by the teacher, and made the subject of consideration and discussion by the pupils. The practice gained by reading and interpreting these circuit diagrams, chosen to reinforce and expand upon regular classroom work, can only be highly beneficial to all pupils.

Familiarization with electrical magazines has another advantage for the pupils: the "Visualizers" will be able to find diagrammatical and illustrative material to clarify the theoretical principles already studied, and the "Mathematics" may discover in such publications as "Wireless World" and "International Electronics World" an abundance of theoretical articles and much numerical material to stimulate and hold their interest.

If the teachers introduce appropriate electrical magazines as a regular feature of classroom and laboratory meetings, there will be encouragement to the pupils to value these publications for personal reading - reading which must contribute to their electrical education.
Revision of Fundamental Principles

6.21 Because new information obtained in the classroom or laboratory is subject to the frailty of memory, it is important that the characteristics of fundamental properties like capacitance and inductance should be frequently revised. Young pupils seldom recognize this need, so the direction must come from the instructor. In conversation with me, teachers have acknowledged this requirement, but have spoken of the heavy pressure imposed on their time and energy by the quantity and variety of topics which they must teach, and the heavy responsibility of preparing candidates for A-level examinations. Even when it is impractical to undertake periodic comprehensive theoretical reviews, it is worthwhile for teachers to introduce discussion from time to time – apparently offhand, it might appear – designed to review and reinforce earlier studies.

In the case of capacitance, because research has shown that students frequently merge the concept with the component, the teacher should assist the pupils to a clearer distinction by relating capacitance to circuits which do not contain the component, the capacitor. A better understanding of capacitance is likely to result if, in the course of informal conversation, the pupils learn that a capacitance (which “Visualizers” may picture as a physical storage of charge) can form whenever a p.d. exists between two complete conducting circuits.

Likewise, it is desirable that there should be, in the earlier stages of electrical studies, quite frequent exchanges between pupils and teachers concerning the component, the capacitor itself:
particularly those factors which affect its capacitance, such as the area of the plates, the space between them, and the electrical field which can be developed there. Because the learner who is not a hobby constructor may have little experience of the range of dielectrics, it would be helpful to both pupil and teacher to discuss specific dielectric constants. Here the pupils' interest and attention might be captured by reference to historical experiments, such as contributions to electrical science made by the experimental measurements undertaken by Cavendish, Faraday, and Maxwell.

Because the "Visualizers" have much temptation to dwell on pictorial summaries of capacitive functions, it is highly desirable that those who are so identified should be thoroughly "drilled" on the basic formulae for capacitance. These should also be encouraged to cultivate an awareness of the mathematical description of various specific capacitors in terms of the sub-units of the farad. Research has shown that "Visualizers" among the pupils tend to be vague about measurements, even when they understand the basic functions of the capacitor: this suggests that it would be wise for the teachers to insist that they understand the significance of the simple time-constant formula, $T = RC$, and relate that to the $63\%$ of the charging, by battery or other supply. Similarly, it is very desirable that the "Mathematics" should be encouraged to think beyond the formulae, to the underlying physical conditions, which if considered in detail can prove as complex and intellectually satisfying as the equations which govern them.
Relating Capacitors to Practical Uses

6.22 It is recommended that teachers should attempt to convince their pupils that their studies are not abstract exercises with the primary purpose of passing a required examination, but that the fundamental theoretical properties which they study have a real-life relevance. It would be helpful if in the laboratory the pupils could be introduced to a range of typical capacitors in regular use in common circuits, and be shown the operation of those circuits. The pupils appreciation of the nature and functions of the component will be heightened when their attention is drawn to the action of capacitors in familiar equipment in everyday use, such as the suppressors fitted to kitchen and garden tools; electrostatic loudspeakers; and the capacitive microphones attached to their portable tape-recorders.
Regular Revision of Inductive Principles

6.23 The many students who spoke of their lack of confidence in their understanding of the phenomenon of inductance gives support to my belief that school pupils would welcome the revision of inductive theory at intervals throughout their A-level preparation. Because inductive circuits are so numerous, and the principles are inherently more complex than those of capacitance, my recommendation is that regular revision should take the form of a thorough theoretical and practical reconsideration of such circuits as the pupils have reached at that particular time.

Back-e.m.f. Should be Related to Motors and Generators

6.24 As many students do not appreciate that inductance can exist in every situation where there is a changing magnetic field associated with a complete metallic circuit, it is worth stressing that every current-carrying wire must be associated with some measure of inductance. Another fact worth emphasizing is that it takes time for a current to create an observable magnetic field: that, once understood, tends to ease the students' difficulties in appreciating inductive behavior in a.c. circuits.

Conversation with the pupils suggest that they can confuse some of the characteristics of inductance with capacitance. A very satisfactory discriminator would be a memory drill to the effect that an inductor opposes any change in current through a circuit - in contrast with a capacitor which opposes any change in voltage across a circuit.
School pupils generally find difficulty in appreciating the full significance of back e.m.f., even although they may know of the expanding magnetic field cutting the current-carrying wire. It is desirable that they should be encouraged to think of back e.m.f. in operation by means of both theoretical commentary and practical demonstration of its application to motors and generators; and, be given the opportunity to observe the energy storage characteristics of an inductor by witnessing the conditions when a large inductive circuit is suddenly broken, and the energy contained in the coil's magnetic field is converted into a high voltage (and, probably, a spark is seen at the switch).

Transformer Action Should be Studied with the Oscilloscope

6.25 It is also desirable that a little more time should be devoted to the study of transformer action, so that those about to enter upon higher education would have more than just an acquaintance with the "turns ratio". The basic principles of induction related to transformers can be considerably simplified if laboratory demonstration can be arranged with groups of pupils following the oscilloscope wave-forms while the teacher offers a running commentary on the current paths of both primary and secondary coils. For those pupils who are "Visualizers" this is the very best method of creating a clear and lasting impression of mutual inductance. By the same demonstration it is possible to convince the "Mathematic" that visual representations
of electrical phenomena can be a sound means to identify conditions which may also be determined by mathematical formulae.

Relating Inductors to Practical Uses

6.26 I recommend that the theory of inductance be constantly referred to its practical applications, and that in both classroom and laboratory, the electromagnetic operation of motors and generators be related to basic inductive conditions. It is also desirable that the enormous utility of inductive circuits should be stressed by analysing the functions of inductors in familiar equipment, such as car spark-plugs, radio tuned-circuits, power supplies for portable tape-recorders, and the magnetic sound-heads of the same machines.
It is certainly a challenge to teachers to capture and hold the attention of young learners when introducing fundamental electrical properties. It seems best to undertake most of the work on capacitance, inductance, and electromagnetism in the laboratory where there is the prospect of excitement and novelty, and the opportunity for an active involvement not possible in the classroom.

In order to make the greatest impression on the learner, whether school pupil or vocational trainee, it is desirable to call upon some of the historical background relating to the scientific investigation of these phenomena, explaining the circumstances which inspired the great pioneers to investigate these properties, which today may be taken for granted.

The early writers on electricity appreciated the advantages of bringing the achievements of the past to the attention of their students, and they stressed the continuity of experiment. Maxwell did so in his Treatise, and Silvanus P. Thompson had introduced much historical reference into his Elementary Lessons in Electricity. Subsequently, Professor Jamieson had been at pains to refer to the classical experiments of Ampère, Faraday, Ohm, and Lenz in his writing; and in turn, W.H. Timbie included much historical material to keep alive the learner's interest in his Elements of Electricity for Technical Students. The inspirational value of historical accounts was equally understood by influential 20th century educators such as Richard Gregory (Discovery or the Spirit and Service of Science, 1916) and T.P. Nunn (Education: Its Data and First Principles, 1920), both of whom warmly advocated its use.
I suggest that to heighten the learners' curiosity and interest, some of the major experiments carried out by Oersted, Ampere, Faraday, Henry, and others should be repeated in the laboratory before the students. It would be possible to link together a number of these historical experiments which could both demonstrate the development of electrical knowledge, and the continuing importance which these fundamental principles have for modern learners.

It would be advantageous to pupils to witness a demonstration of Oersted's 1820 discovery of the interaction of electricity and magnetism, where a current-carrying wire deflects a compass needle at the make or break of the terminal. They could be advised of the very great significance of the magnetic field created by the current flow, and reminded that basically the same effects observed in Oersted's experiment govern the operation of the volt/amp meters which they will use in many of their own laboratory measurements. Similarly, the magnetic attraction and repulsion which is exerted by the fields around parallel current carrying wires could be shown in repetition of Ampere's discovery (also of 1820), and the point stressed that this principle underlies the electric motor upon which so much of modern life depends.

At a very early stage in the learner's introduction to laboratory procedures the teacher could offer a modern simplification of Ohm's 1827 experiments which conclusively proved the relationships between voltage, current, and resistance; and they could be made aware that not only did Ohm's experiments provide a firm basis for a great deal of research which followed, but is still essential formula for D.C. calculations which they will use.
Few pupils could fail to be impressed by the Faraday discoveries of 1831, and if some of these were demonstrated in the school laboratory with a little historical commentary, it could stimulate the young learner's curiosity and assist the memory of their significance. With very little apparatus the teacher could recreate Faraday's momentous experiment, the induction of current, by plunging a magnetized bar into a coil attached to a meter. The pupils could be told that it is virtually the same action which operates their own cycle dynamo; and that Faraday's experimental research ultimately led to the world-wide generation of electricity.

The pupils might be led to an acquaintance with mutual induction through one of the most important of all electrical experiments, Faraday's Ring/Induction Experiment, where a current is induced in the secondary coil by the magnetic field of the primary, excited by the making or breaking of a battery (or the moving proximity of a magnet). The pupils' attention and interest could be attracted by a repetition of some of the experiments which Henry carried out at about the same time with induction through multiple coils, and with step-up and step-down transformer windings (an arrangement which he invented in 1838).

The principles of self-induction are likely to be more readily absorbed if the learners know something of Faraday's 1834 research with the energy stored in the magnetic field of a coil, and see a demonstration of the sparks and magnetic needle deflections when the current is broken. Those laboratory experiments might be made the more memorable if the teacher were to read appropriate extracts from Faraday's notebooks for November 1834. It would also be possible to give Joseph Henry credit for his independent research on the effects of back-e.m.f. when the name of the unit of inductance is given. His experiments two years before Faraday's may jointly
share the honour of laying the foundations and subsequent developments in power supply, communications, and enumerable electrical engineering operations.

When the pupils are first introduced to the property of capacitance, some of Faraday's experiments of 1836/7 with static electricity using insulated vessels could be repeated; and, in particular the demonstration concerned with the investigation and measurement of specific inductive capacities might go a long way towards illustrating a topic frequently misunderstood by the learners.

The young pupils may well assimilate the principles of series and parallel circuits more easily, if they were explained and demonstrated within the context of Joseph Henry's discoveries of the uses of these circuit arrangements while working on the improvement of the basic electromagnet during the years 1827/30. The demonstration of the difference in attractive force resulting from different circuit arrangements would undoubtedly attract interest. Electromagnetism can have special attractions to the mechanically minded youngster who discovers that its fundamental principles can be studied through the electric motor. There is a good opportunity to capture the pupils' attention by demonstrating the most primitive form of electric motor by repeating Faraday's early electrical experiment of 1821, when he succeeded in rotating a current-carrying wire about the poles of a magnet. The pupils could be also shown how Henry operated an electric motor using two electromagnets with a reciprocal action controlled by his invention, the commutator, which subsequently became an essential component in D.C. motors and generators.
To relate the fundamentals to contemporary interests

Another laboratory activity which could prove valuable for the creation of vivid memories of component functions, and the application of theoretical principles of capacitance and inductance, is the extended analysis of practical apparatus known to the students; such as a consideration of the principles of radio wave transmission and reception by a superhet system (described by "Nichol" in Extract No. 38). I strongly recommend that such laboratory circuit analysis be concerned with equipment which is personally used by the young people. The ubiquitous "Walkman"-type personal tape-player provides an ideal subject. A simplified commentary could focus attention on the capacitors and inductors of the power supplies; the amplifier blocks; the filter circuits; the pre-emphasis oscillator; the inductors which form the tape-heads; and the electromagnetic principles employed in the operation of the loudspeaker or headphones.
Proscribed Reading for particular categories of Students

6.28 Some teachers told me that they know no entirely satisfactory textbook and do not make "prescribed reading" recommendations to their A-level students. However, because there is now a wide range of electrical education texts available, I believe that it is possible to locate suitable sections or chapters from a number of publications which will satisfy the most critical teachers.

I recommend that prescribed reading should be made a regular feature of electrical education: it trains the pupil in independent study, and can introduce him/her to alternative presentations and viewpoints, and may offer suitable explanations to troublesome difficulties. It is my opinion that teachers should frequently read some relevant portions of recommended texts with the students in class, and invite questions for discussion. This can give an excellent opportunity for pupils to bring forward unresolved problems, or seek the clarification of doubtful matters carried forward from earlier classwork or personal study.

Recommendations for Historical Reading

6.29 The teacher who recognizes the categories of "visualizer" and "Mathematic" is better able to direct his students to textbooks of a type most appropriate to their preferences and study habits; and, with the expenditure of a little time he can prepare for such recommendations by becoming familiar with contemporary and historical electrical educational texts which are likely to be attractive to each type of pupil.
The "Mathematic" pupil who has exhausted the exercises and numerical problems of the prescribed reading, might be directed to the excellent chapter on Inductance in the 1910 *Textbook of Physics* edited by A.W. Duff, where there is a clear mathematical exposition of the historical progress of experiments from Faraday to Helmholtz; or, he may be referred to the 1972 *Feynmann Lectures on Physics*, by P. Feynmann.

Similarly, the "Visualizer" may be well served by reading sections of *Electronics for Today and Tomorrow* by Tom Duncan where he can benefit by studying the numerous coloured diagrams. The Teacher who appreciates the advantages which a person of graphic tendencies can obtain from extensively illustrated textbooks, will investigate some of the less widely known textbooks, and will be rewarded by the discovery of several which are specially suited to the tendencies of the "Visualizer". Among the very best of these are Phillip Kogan's *A Secondary Book of Physics* (1964), and *The Cathode Ray Revolution* (1966).

It is very desirable that teachers and school librarians should make the rich and varied range of electrical education texts known to their pupils, and encourage the habit of reading: recommending them to consult these publications in the public libraries, when the works concerned are historical; and, whenever possible, obtaining them for school libraries - by purchase if finances permit - and by interlibrary loans, if they do not.
Notwithstanding the current preoccupation with computer and microprocessor technology, the works managers and training officers in industry have repeatedly told me that when considering the employment of new recruits, what particularly concerns them is the analog area: they are interested in people with a basic knowledge of the fundamentals; who have an understanding of the principles of electromagnetism, and who know about components, and are familiar with the uses of resistors, inductors, capacitors, etc.

At present it would seem that while many of the vocational students in training would reach very satisfactory levels in practical skills, their theoretical background is likely to be below the standard necessary to those who wish to advance with reasonable speed in the world of industrial electrical engineering. This inquiry suggests that the key to improvement in this area is the greater use of the appropriate technical training electrical publications.

Overcoming Vocational Students Reluctance to Read

6.30 It is my recommendation that a major effort be made by both technical college teachers and college librarians to overcome the prejudice of the vocational trainees to the regular use of the library for consultation and extended reading. The books and magazines which are capable of holding their attention exist, but it is not easy to convince the youngsters who have not developed the habit of reading that they can gain much from making their acquaintance.
The sympathetic librarian can help allay the vocational student's anxieties by demonstrating how a subject index can lead him to magazines and articles on subjects of interest to him; and the teachers can similarly locate for him a range of specially-written textbooks which deal with topics of the course work from the visually emphatic, practical, point of view.

Recommendations for Group Reading

6.31 Recognizing that so many of the trainees do not have any higher mathematical skills, teachers can make use of both historical and contemporary works which have been deliberately designed to present electrical fundamentals in the "non-mathematical manner." I recommend that class reading and discussion of these texts should have a place on the timetable. Most teachers feel the necessity of covering the basic electromagnetic theory in the classroom at the blackboard, and of demonstrating its application in the laboratory, but the group examination and discussion of heavily illustrated texts can serve as a reinforcement and review of that work.

Among historical textbooks which could supply valuable information on electromagnetism related to motors and generators, few would serve the vocational students better than Elementary Lessons in Electricity by Silvanus P. Thompson (1895), with its very clear explanatory comments in unassuming language. The considerable numbers of vocational trainees with "Visualizer" bias would certainly learn a good deal about the
fundamental principles from the wealth of diagrams introducing mechanical analogies in Oliver J. Lodge's *The Modern View of Electricity* (1889). Such works could be supplemented by the progressively more mathematical treatments offered in *Basic Electricity and Circuit Concepts* written by the Texas Instruments Learning Centre.

Because there is a large quantity of valuable material contained in the historical texts, a progressive publisher or editor might be persuaded to produce an anthology of writings by the electrical pioneers. It could take the form of reprints of vitally important research papers glossed by a commentary which links the fundamental discoveries with the modern applications; or, alternatively, it could be arranged on the basis of chapters (or portions) on particular phenomena from the textbooks of the pioneer electrical educators. Such an anthology could be usefully employed by both vocational and academic institution teachers, who could read selections in class or laboratory. It would allow them to recreate something of the discoverer's enthusiasm among the youthful learners, and at the same time demonstrate the continuity that exists between fundamental research and contemporary developments.
Introductory Courses in Higher Education

6.32 The university/polytechnic students in their first and second terms of Engineering or Physics degree courses commented much on their early experiences of Higher Education, connecting those with the preparation they had received at school. They offered thoughtful recommendations for changes which might make for a smoother transition from supervised schoolwork to independent studies.

6.33 One frequent and strongly felt need was for an introductory course, at the start of their degree courses; or, for modifications to those programmes which are presently in operation. The benefits which a well-designed introductory course can bring are indisputable, and from the information offered by some of the interviewees, it is clear that had such an induction programme been available to them, it would have made their first few weeks less trying and educationally more rewarding, and would have provided a firmer base from which to progress more quickly, than otherwise would have been the case.

The introductory course should not be just a brief token convention where inspirational addresses are given, but a tightly organized series of classroom and laboratory meetings extending over one or two weeks. The reservation of these periods would not be "stealing" valuable time from the term's allocation, but would enhance the likelihood of effective learning and teaching within
the remaining weeks. Such an introductory course can offer an opportunity for revision of studies not sufficiently examined at school, or half-forgotten in the interval since A-level examination preparation; moreover, it can allow those teaching on the degree courses to present to the new students something of the institution's approach to classroom and laboratory work. Very importantly, from their knowledge of the topics which in the past have caused "freshers" difficulties, the teachers can guide the new students away from misunderstandings and unreliable methods.

Such introductory courses should certainly offer a thorough review of both inductive and capacitive theory, including a.c. reactive phenomena, and should use oscilloscope demonstrations, which are so vital for the "Visualizers". Similarly, the fundamental principles of electromagnetism as related to motors and generators, require to be presented to the "freshers" with an abundance of explanatory diagrams in the classroom, and that theory should be given practical realization in the laboratory by means of running commentary on working models.
Practical Introduction to Simple Circuits

6.34 The teachers and demonstrators, recognizing that some of their new students will be woefully ignorant of components and their electrical and mechanical arrangement in circuits, should patiently undertake some basic practical instruction and introduce their students to an analysis of the simplest circuits, resisting the temptation to dismiss such activities "because they are the proper business of the school teacher."

As some students carry a prejudice against practicals from their schools, and others have never approached the laboratory work with personal enthusiasm, it is desirable for the staff to attempt to convince the newcomers that their practical activities will serve a useful purpose, and that they will profit from them. In large part, that might be achieved by more extended introductory commentary linking the principles of experiments to theory - and to the recognizable practical applications outside the laboratory.

It would be highly advantageous if, on the first visits of the newcomers to the laboratory, a number of simple circuits, of the type later to be met with in experiments, could be built from discrete components in front of the students, accompanied by an explanatory account of the electrical functions which the individual devices perform within the circuit. Such demonstrations might most usefully be repeated at intervals throughout the first term as the circuits under discussion advance in complexity.
Consideration of Solid State Devices

6.35 It is recommended that the introductory course should also consider the basic characteristics of solid state active devices which will be met in forthcoming laboratory experiments, and that the new students, some of whom will never have had any experience of transistors, be guided through a number of simple amplifier and switching circuits.

If university/polytechnic teachers acknowledge the two categories of students, then even those engaged upon lecturing to the first year Physics undergraduates will be able to appreciate that not all their students follow by nature a rigorously mathematical method, and may go a considerable distance to meeting the complaints of many "Visualizers" that the classroom treatment of electromagnetism is abstract, excessively concerned with manipulating theoretical equations, and remote from real-life practicalities.

Notwithstanding the well-understood problem of accommodating large numbers of first year students, it is highly desirable that every effort should be made by the course planners to synchronize lectures and laboratory work, so that theoretical teaching in the lecture room can be succeeded quickly by laboratory experiment which incorporates and demonstrates those electromagnetic principles - preferably employing circuits which can be associated with the interests and experiences of those of university entrance age.
Those beginning Physics and Engineering courses have occasion to think more seriously about the electrical textbooks than ever before. Those who had retained their school textbooks viewed them with both an appreciation of their relatively simple expositions of fundamental principles, and with a more critical disposition towards their failings. Many of the new students expressed dissatisfaction with the textbooks recommended for their courses. This was particularly true of the "Visualizers", a considerable number of whom, both beginning Physics and Engineering, confided to me that they considered these approved books to be unnecessarily complicated for those recently accustomed to school-level works, and inadequately supplied with clear graphic illustrations. Some had the impression that those recommended books, once listed, were forgotten by the Staff - at any rate, few had been referred to any particular sections of them as a means to ease difficulties. It was the more curious and intellectually active students who located helpful texts for themselves, and communicated their discoveries to fellow students.

Reconsideration of Older Textbooks

6.36 There is undoubtedly an opportunity here for university/polytechnic teachers to materially assist their students by first familiarizing themselves with a wider range of textbooks, and thereafter directing students of a particular bias to appropriate educational works.
I consider that it would be advantageous if university/polytechnic teachers were to advise their students that the treatment of capacitance and inductance offered in some of the older textbooks might be consulted with benefit, and that they should commend some of these texts which they know to be accessible in local reference libraries.

It may be objected that it is the responsibility of the students in Higher Education to find their own texts. That is only partly true: the naivety and inexperience of the new students must be taken into consideration, and the teachers should be prepared to guide them to a variety of works of high quality and particular usefulness, from which they can later make personal choices to suit their needs and inclinations.

6.37

Recommendation of Textbooks Specifically for "Visualizers" and "Mathematics"

If during the introductory course, or very shortly thereafter, a tutor identified "Visualizers" and "Mathematics", then he is in a better position to make textbook recommendations appropriate to individual students than if he did not take that bias into account. A Physics tutor who had noted one of his new students as a "Visualizer" might direct his attention to W.J. Duffin's Electricity and Magnetism or, P. Lorraine and D.R. Corson's Electromagnetism: principles and applications; alternatively, if a person was identified as a
"Mathematic", he might recommend the much more mathematically intense text by B.I. and B. Bleaney, _Electricity and Magnetism_, or P. Lorraine and D. Corson's _Electromagnetic Field and Wave Particles_. Similarly, an Engineering tutor might recommend to a "Visualizer" R.J. Smith's _Circuits, Devices and Systems_, but consider that a "Mathematic" would be better served by the more mathematically rigorous _Electrical Technology_ by Edward Hughes.

I believe that university/polytechnic teachers should recognize another area of weakness which might be corrected by suitable reading: that a proportion of their new students urgently require to obtain some basic information on solid state devices. They should be prepared to provide them with the particulars of a number of reliable introductory texts, such as _A Practical Introduction to Electronic Circuits_ by M.H. Hartley Jones or, the _Programmed Course in Transistors_ published by the New York Institute of Technology. They should also bear in mind that more than a few of their beginning students may be handicapped in their studies because they can not adequately read, or misunderstand, the circuit diagrams which they must use. These persons could be referred to such texts as _The Beginners Guide to Reading Circuits_ by J. Traister and _Understanding Electronic Schematics_ by John D. Lenk.
I believe that a considerable proportion of the problems and difficulties suffered by the first and second term degree course students could be quickly resolved if they sought the advice of their tutors without delay (and the latter made themselves readily available). There is certainly a need to encourage the newcomers to confide more in their tutors, and to overcome their reluctance to "intrude" on the tutors' time. Without such early tutorial assistance, there is the danger that the novice may become involved in time-consuming searches in the textbooks, when that time might be better spent in advancing their studies.
This study has revealed some of the reasons for the difficulties which many learners experience at some time in their study of capacitance, inductance, and electromagnetism related to motors and generators, and also why, for a proportion of them, these difficulties may persist into the early stages of their Higher Education, or initial industrial training.

The reminiscences of the interviewees indicate that the concepts are complex, take more time to grasp, and require more personal reflection, than is often supposed among educators. There are grounds for suggesting that these principles should be examined more closely, and covered more slowly, and revised more frequently than is presently the case.

It was found that some of the problems and difficulties experienced can be related to the individual's tendencies as a "Visualizer" or a "Mathematic"; for, each responds best to instruction and educational literature which corresponds more closely to his bias. The initial interest and continuing conscientiousness of the learner can be very much affected by the manner in which the fundamental principles are offered: the "Mathematic" may easily grow bored by a series of mechanical analogies, and without numerical stimuli to exercise his particular intellectual bias, can withdraw his concentration. Similarly, the "Visualizer" whose interest is not sufficiently excited by graphic material or physically observed experiment, may absorb the new knowledge only slowly and imperfectly.
If the recommendations which have been suggested are put into practice, it seems likely that fewer beginning Physics and Engineering undergraduates will find themselves under stress, and fewer technical trainee recruits to industry will experience traumas occasioned by the inadequacies of their preparation. At all levels of electrical education there will be considerable benefit from the recognition of the contrasting characteristics of the "Visualizer" and "Mathematic", and the share of the teacher will not be less than that of the student.

This research programme has revealed a new area for educational investigation: it is to be hoped that more inquiries will follow, and in particular, that the quantitative aspects will be undertaken by a "Mathematic".
### TABLE OF INTERVIEWS

#### School Pupils

30 Extended interviews with pupils preparing for A-level examinations. These were drawn from Oxfordshire comprehensive, Oxford-college linked schools, and independent public schools.

(Tape-recorded)

#### Vocational Trainees

40 Extended interviews with 1st and 2nd year day-release and full-time students (mostly preparing for Technical Education Certificates). These were drawn from Further Education and technical colleges in Oxfordshire.

(Tape-recorded)

Also, a similar number of bench-side discussions with the trainees, not tape-recorded, but notes taken.

#### University/Polytechnic Students

90 Extended interviews with 1st and 2nd term students reading for Physics and Engineering degrees.

Also, more than 350 discussions with students engaged in practical work in the laboratories, not tape-recorded, but notes taken.

#### Industrial Employers

18 Interviews with works managers, industrial training officers, and research and development managers.

#### Educationalists

Numerous interviews with teachers preparing the three categories of students; members of staff at departments of Physics and Engineering at universities and polytechnics.
Chapter One


NOTES

Chapter Two


3. Volta invented the term "electromotive" and used it in his letter to Sir Joseph Banks in 1800.


6. James Clerk Maxwell described the theory as "perfect in form, and unassailable in its accuracy" and called Ampère "The Newton of Electricity".


9. Henry, J. (1831) On the application of the principle of the galvanic multiplier to electric and magnetic apparatus, and also to the development of great magnetic power in soft iron, with a small galvanic element. American Journal of Science Vol. XLIX

10. Henry's most precise measuring instrument was the device designed by Johann Schweigger of Halle, consisting of a looped wire close to a suspended magnetized needle. The deflection of the needle could be read off in degrees of the circle.


14. Ibid.
NOTES

Chapter Two (continued)

15. Ibid.

16. In 1837 Henry shared his knowledge of the electromagnetic relay with both Charles Wheatstone and Samuel Morse.


18. Faraday had made a similar non-inductive winding in 1832, but he did not give an account of it until his paper read before the Royal Society (January, 1835), On the influence by induction of an electric current on itself.


20. Ibid


24. He did carry out occasional research, and he assisted various experimenters — notably, Graham Bell in the design of the telephone.

25. Henry's papers were neglected in Europe, even by those who were working along similar lines of inquiry. There is evidence that Faraday either failed to read some of his important papers, or failed to recognize their significance. Among the professionals, the progressive use of higher mathematics encouraged an attitude of superiority towards the descriptive non-mathematical approach in scientific writing.


28. His experiment was reported in the Quarterly Journal of Science, July, 1825.
Chapter Two (continued)

29. Faraday bequeathed the notebooks to the Royal Institution. They have been published, edited by T. Martin (1932) as Faraday's Diaries, 1820-62, in eight volumes.

30. One American author, Thomas Coulson, in his book (1950) Joseph Henry, Princeton University Press, suggests that Faraday had learned of Henry's experiments with powerful electromagnets, and that he returned to his researches to repeat experiments with a stronger electromagnet than he had used before. He also complains that Faraday did not refer to Henry in his earlier papers. But such was his probity, that had he known of the prior achievement, Faraday would have acknowledged it.

31. Earlier experimenters, including Sir Humphrey Davy, had demonstrated that iron filings would stick to current-carrying wire; however, Faraday was the first person to use iron filings to show up the appearance of the magnetic field. Thomas Martin, in his book (1949) Faraday's Discovery of Electromagnetism, published by Edward Arnold, quotes Sir Humphery Davy's statement that Faraday had assisted him in these experiments.

32. Read before the Royal Society, 29th January 1835. There can be no doubt that Faraday had not read Henry's 1832 paper on Self-induction; and it is probable that it was also unknown to the other members present.

33. Faraday was not entirely happy with this term. He means "in close proximity" rather than "in contact".

34. Quoted by H.B. Jones (1870) Life and Letters of Faraday. London: Longmans

35. Faraday hesitated to insist upon the reality of the physical existence of the lines of force, and did not publicly state that in words until his 1852 paper before the Royal Society, On the Physical Character of the Lines of Force.


37. The issue of April, 1846


NOTES

Chapter Two (continued)

40. In 1872 William Thomson coined the terms "Susceptibility" and "Permeability".

41. Read before the Glasgow Philosophical Society, and printed in The Philosophical Magazine, June 1853.


45. Ibid. Chapter 3.


47. Ibid.

48. 25th March, 1857

49. J.C. Maxwell to R.B. Litchfield, 7th February, 1858.


53. The number of essential equations was reduced to eight.
NOTES

Chapter Three

1. Jenkin, F. (1873) Electricity and Magnetism. Edinburgh: Blackie. At the time that the author was writing, there was no common agreement concerning the use of electric symbols: he used the character "S" to represent capacitance, and "i" to represent voltage.


3. Quoted by J. Larmor, in Proceedings of the Royal Society, 1908, 81, XIX.


5. Parts of the first nine chapters were revised. This is only a portion of the Treatise, which has each part separately numbered in chapters - 56 chapters in all.


8. These developments were exhibited publicly almost simultaneously by Vally, Siemens, and Wheatstone in 1867.

9. Sir Ernest Rutherford summarized the debt of many to the book when he said at a memorial lecture to Silvanus P. Thompson, at the first "Silvanus P. Thompson Lecture" delivered to the Röntgen Society in April, 1918:
   "I would like to express the debt which I, and I am sure many of the scientific men of this audience, owe to his admirable textbooks. I gained my first knowledge of electricity from "Elementary Lessons", that remarkable and perennial book which has served to interest and instruct scientific youth in all parts of the world."

10. The Science and Art Department examiners of South Kensington set papers and examined candidates for the widespread external examinations which for many years were the recognized entry qualifications to Art and Technical institutions, and for the various stages of progress within them.

NOTES

Chapter Three (Continued)

12. Research noted in the Philosophical Magazine, August 1886

13. Ibid.

14. The idea of representing the properties of a dynamo machine by means of a characteristic curve is due to Dr. John Hopkinson, who in 1879 described such a curve to the Institution of Mechanical Engineers. The name "Characteristic Curve" was given in 1881 by M. Marcel Dupres to describe "Hopkinson's Curves".

15. The last edition is dated 1963.

16. A "Laboratory Book" was prepared by C.E. Clewell (1912), New York: John Wiley. It consisted of experiments related to the text of Timbie's book, with added commentary on the experiments, and helpful diagrams showing electrical connections, and with recommendations for the recording of observed results.

17. The phenomenon in which electrons emitted from a heated element within an evacuated tube flow to a second element connected to a positive potential.

18. The other two being, Programmed Course in Basic Electronics, and Programmed Course in Basic Transistors.

19. Three years ago I called at the New York Institute of Technology and there discussed these programmed texts with members of the Electrical Engineering staff. They told me that the texts had proved extremely valuable in practice. They are now recommended to all students as a preliminary study in advance of joining any of the first year courses.
NOTES

Chapter Four


NOTES

Chapter Five


NOTES

Chapter Six


5. The first of nine editions.

6. First published in 1911


BIBLIOGRAPHY


American Journal of Science (1818-80). New Haven, USA.


The Electrician (1861-1952) London: Thomas Piper


Faraday, M. (1837) On Induction. (Read before the Royal Society, 21st Dec. 1837.)


Jenkin, F. (1873) Electricity and Magnetism. Edinburgh: Blackie


Kant, E. (1781) Critique of Pure Reason. (Translated by Norman Kemp Smith, 1933. London: Macmillan.)


Library of Useful Knowledge (1828-42), London.


Nature (1869-) London: Macmillan

New York Institute of Technology (Staff of) (1958-64) Programmed Course in Basic Electricity; Programmed Course in Basic Electronics; Programmed Course in Basic Transistors. New York: New York Institute of Technology.


Niven, W.D. (Editor), (1890), The Scientific Papers of James Clerk Maxwell. Cambridge: Cambridge University Press.


Scientific American (1845-) New York: Scientific American Inc.


