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Unifying Electric Theory and Circuits in Engineering Curriculum

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ABSTRACT

A sample survey of syllabi of engineering colleges in India reveals a lack of coherence in the structure of the courses which deal with topics in electromagnetic field theory, circuit theory and radiation and light. For example, Interference of light is introduced followed by topics on electromagnetic theory. A scrutiny reveals the lack of an early comprehensive treatment of topics in Field theory and a unified approach to fields and circuits, which make students, struggle to understand advanced topics in electrical and electronic circuit theory. Experts in science education proposed an infusion of new concepts like the role of surface charges, and a revised hierarchical organization of topics. This paper initially discusses the difficulties in teaching and learning electricity and magnetism and is followed by a discussion on a restructured course proposed by experts. Then, results of studies comparing the performance of students of the revised electricity and magnetism (E&M) course with the performance of students who have undergone a traditional E&M course are presented. Finally, a set of guidelines to assist Universities in modifying course structures is provided.

Keywords

ENGINEERING PHYSICS, ENGINEERING CURRICULUM, ELECTRICITY AND MAGNETISM, REVISED STRUCTURE, MACRO/MICRO CONNECTIONS, CENTRAL FIELD CONCEPT, UNIFIED TREATMENT, ELECTROSTATICS AND CIRCUITS, TRANSIENTS, STEADY-STATE, QUASI STEADY STATE

INTRODUCTION

Traditional electricity and magnetism (E&M) courses in University engineering curricula have not undergone any change over the past several decades. In some universities in India, Field theory is taught in the engineering physics course and follows topics on light and optics. Such a sequence makes the ideas of light disconnected to electromagnetism and deprives students of knowing "Maxwell's equations and the classical explanation of the nature of light that are one of the crowning intellectual achievements of classical physics".

In introductory circuit theory, according to Härtel[1] (in 2008) "the term voltage is usually introduced as cause for the flow of electrons". Then, after defining the electric field and potential, finally the term "voltage between A and B" is defined as potential difference = work done to move a unit charge from A to B $=\Delta V=\Delta E_p/q$, where ΔE_p is the work done to move a charge q. This sequence of explaining voltage makes it a "highly abstract and mathematically elegant approach" but, it "sets aside any causal mechanism which could explain the flow of electrons within electric circuits".

Several students and teachers could not explain the reason for the electric field being constant in a curvilinear wire carrying a steady current, because these students were not aware of the presence of surface charges in relation to electric currents, and "knowledge, based only on the definitions of electric field, energy, potential and potential difference does not supply any hint for an explanation".

Students who have completed a traditional course of circuit theory in which they learned to analyze circuits using currents and voltages are puzzled by the appearance of the electric field when deriving the expression for the *p-n* junction diode current, when discussing the effect of stray capacitances on the high-frequency behavior of transistors, and the voltage and current waves of transmission lines. Students are unable to distinguish the distinct process which makes a curly-patterned electric field to be associated with a time-varying magnetic field[2,3].

There is an urgent need to devote teaching time towards an explicit treatment of surface charges and its distribution among the different parts of an electric circuit in engineering curriculum.

1. ELECTRIC THEORY AND CIRCUIT THEORY ARE HARD TO UNDERSTAND

In an engineering curriculum, a course in Mechanics usually precedes a course in electromagnetic theory which precedes a course in circuit theory. Such a sequence enables an introduction to concepts of velocity, force, potential energy, kinetic energy, momentum and the effects of gravitation between material bodies which students can easily relate to from examples in their daily lives. This will raise students' level of preparedness to understand complex and abstract concepts of electric theory in the E&M course in which they learn about quantities which are invisible being either microscopic such as electrons or abstractions such as field, flux and potential. A survey of syllabi of engineering colleges in India reveals that the approach is to teach Mechanics and E&M concurrently and topics on optics are introduced too early preceding topics on electromagnetic theory.

In some universities, courses on field theory and circuit theory are run concurrently without the common connecting thread that the field concept provides.

The sequence of topics covered in the traditional E&M field theory segment after a brief introduction to charges and their attractive and repulsive forces is, Coulomb's Law, Gauss's Law and Electrostatic fields of distributed charge configurations. This is followed by discussions of topics in Magnetism, Biot-Savart Law, Ampere's circuital Law, Faraday's Law and finally Maxwell's Equations and applications in wave propagation.

The authors (1 and 2) have observed several instances when teachers burdened by tight syllabus completion deadlines, manage this onslaught of abstract concepts of charge, electric force, field, flux, and Gauss's law followed by ideas of potential, potential difference, and electric current and ways of reasoning, by glossing over the concepts, and spending most of the course on rote problem solving.

Students are overwhelmed by this rapid introduction of abstract ideas and usually are not given sufficient practice to be able to apply these concepts reliably, or to discriminate them from each other.

Professor Hermann Härtel[1], laments that if qualitative models are presented, their "inconsistencies are overlooked or hidden under shallow explanations with the excuse that, students would …only be confused by any further and more detailed explanation". Härtel cautions teachers who may have a belief that students should not worry about inconsistencies and that the truth is within the equations themselves.

Härtel has criticized the statement made by Hertz, "The Physics of Electromagnetism is Maxwell's equations". Such statements express clearly the attitude of overemphasizing the quantitative side and even denying the existence of qualitative models and questions about the underlying ontology as part of physics.

2. INCOHERENCE IN COURSES OF ENGINEERING CURRICULUM WITH ELECTRICAL AND ELECTRONICS MAJORS

In a traditional Engineering curriculum, students of a first course in electrostatics learn that a charge "creates" an electric field around it and that its strength varies inversely proportional to the square of the distance (d^2). The electric field around the charge is essentially a three dimensional abstraction and usually depicted by tiny vectors. They then learn how to develop the field patterns of different charge configurations, dipoles, line charge and sheet charge. In the sequence of introductory circuit theory they are taught that there exists a potential difference across a resistor powered by a battery and the abstraction of a field (when mentioned if at all), is treated essentially as one dimensional, the field considered directional along the resistor with the tiny field in the wire not considered.

It should be noted that in both the courses, the common thread of the field configurations due to surface charges which is a proven phenomenon[4] of circuits, is ignored. Further, the student is taught that current is "charges in motion" with little or no qualification to the structure of the conductor at the microscopic level and a detailed description of the motion of the charges themselves[2,3]. A micro connection (structure of atoms, electron sea) with the macroscopic phenomenon of current is lacking.

It is not surprising to find students exiting the courses with several misconceptions such as the electric field inside a metal is always zero (even when the system is not in static equilibrium); drifting electrons push each other through a wire just as water molecules push each other through a pipe (despite charge neutrality inside the metal); there cannot be any potential difference across an open switch because V = IR, and there is no I; electrons travel at the speed of light in wires, and a circuit requires two separate wires for operation[2].

3. THE OBJECTIVES OF THE NEW APPROACH

Experienced senior and research scientists in studies conducted in engineering colleges in the United States, found a gap between electric theory and circuit theory not unlike the gap observed in colleges in India and that this could be bridged by making an approach which would enable students to explain a wide range of phenomena by applying a small number of fundamental principles[5]. Addressing the growing concern of waning interest of students in learning abstract concepts such as fields, they suggested a unified approach to electrostatics and circuits with emphasis on the effects of interaction of fields with matter.

They further observed that students should clearly understand the power of classical and semiclassical models at a microscopic scale and should know the limitations of purely classical, macroscopic models[5].

In the traditional (contemporary) approach, students develop systematic problem-solving skills and practice in applying mathematics which does not allow them to appreciate the unity of physics, except knowing which formula should be used in a particular problem with little conceptual coherence.

Chabay and Sherwood[3], developed a modern calculus-based introductory curriculum in Mechanics and Electricity and Magnetism (E&M) that "guides students through the process of starting from these (fundamental) principles in analyzing physical systems, on both the macroscopic and microscopic level".

The organization of topics in the E&M course is hierarchical, and the overarching theme of the entire E&M sequence is the field concept which will help students to develop microscopic models that facilitate reasoning about complex systems. The sequence is organized into four large segments; i) Stationary charges, ii) Moving charges, iii) Reasoning about patterns of fields in space, and iv) Time-varying fields and accelerated charges.

4 FIELD AS AN ABSTRACTION – IT'S CENTRAL ROLE IN A MODIFIED E&M COURSE STRUCTURE

In a traditional course on circuit theory, the discussion begins with the notion of voltage and current but, the presence and source of electric and magnetic fields in and around conductors is not presented.

According to Chabay and Sherwood[5], students can understand Maxwell's equations and the classical explanation of the nature of light if they have had sufficiently varied experiences with electric and magnetic fields and the effects of these fields on matter.

In a revised curriculum, the field concept, which is central to electricity and magnetism, is made "concrete and connected to the behavior of matter" by an emphasis on the crucial role of dipoles, both electric and magnetic, permanent and induced. The fields made by dipoles and the creation of dipoles by applied fields play a significant role in the revised sequence.

4.1 MAGNETIC FIELD

In the new sequence the concept of Magnetic field and magnetic force is introduced early. This affords students more time to gain adequate experience with the topic before they are taught the effects of fields on matter.

Ampere's Force law does not include a magnetic field. However, nowadays all textbooks on electromagnetism utilize this concept. A revised E&M course should make mention of the experiments performed by Ampere and his Force Law between current elements which conforms to Newton's Third Law[6].

4.2 MATTER AND ITS INTERACTION WITH FIELDS

Students who fail to understand the attraction of a neutral object, whether a conductor or an insulator, to an object with a nonzero net charge of either sign, should be encouraged to think about the effect of applied fields on the electrons in the neutral material.

Chabay and Sherwood[5] mention that even students, who are familiar with the ball and spring model of a solid introduced in the course on Mechanics, are surprised by the existence of a mobile electron sea in metals.

Microscopic models support the discussion of the transients involved in the separation of charges in neutral atoms or polarization of conductors and insulators, and makes it possible for students to reason step-by-step about the processes involved in the approach to static equilibrium (or later, in circuits, the approach to the steady state, or the quasi-steady state in RC circuits). This focus on transient processes leads to discussions of the role of retardation, setting the stage for later simple explorations of fields in moving reference frames. Retardation and other relativistic effects are important in many aspects of modern science and technology and when introduced even in an introductory field theory course, can afford an intuitive cognition of these concepts.

5 UNIFIED APPROACH TO ELECTROSTATICS AND CIRCUITS

In a traditional electromagnetic theory course sequence, electrostatic phenomena are analyzed in terms of charge and field, while circuits are analyzed in terms of current and potential, and the connection between these two sets of concepts is not made salient.

5.1 MICROSCOPIC AND MACROSCOPIC CONNECTIONS IN CIRCUIT THEORY

In the area of electrostatics and electrodynamics, the concept of current and voltage are treated n a different and inconsistent way according to the macroscopic and microscopic level. Current is usually explained to students as a microscopic phenomenon by the "Principle of Conservation of Charge" and the movement of electrons within a closed circuit. In traditional circuit theory, voltage is usually introduced at a macroscopic level. In electrostatics, the voltage also is connected to a microscopic level. The work done to separate charges explains the electric energy which is then used to define the voltage. In electrodynamics, however, the voltage is only connected to potential difference which is directly related to energy considerations. The main problem is not that the microscopic explanation for voltage is missing. Consider a circuit shown to a student as in Fig. 1.

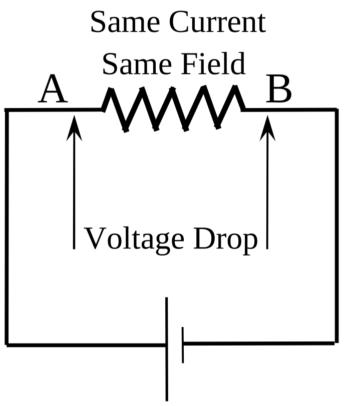

Fig. 1 What corresponds to the voltage drop ?

The real problem is that a student searching for such an explanation for the circuit shown in Fig. 1 would be confronted with a contradiction, which arises from the following facts[7]:

- In electrostatics, the concept of voltage is connected to separated charges.
- For the dynamic case of a constant current flow, the microscopic model predicts an identical situation between two cross-sections before and after a resistor. The same number of electrons is drifting through these cross-sections, and also the field is the same.
- Between these two cross-sections, there is a voltage drop but no explanation on a microscopic level.

The conclusion that there is no microscopic difference between the cross-sections A and B according to the model for the current would lead to the contradictory result that a voltage drop can exist between two points which are identical on a microscopic scale. This is contradictory because one could change the scale continuously from the macroscopic to the microscopic scale and ask when the voltage would disappear. There would be no answer. A solution out of this problem would be to assume a difference between the voltage in electrostatics and electrodynamics but this assumption is also not supported by Maxwell's theory. The key to understanding the source of the electric field at the microscopic level is the surface-charge model of circuits. This concept of surface charges relates to a rather small effect which is normally neglected in any quantitative approach[4]. For qualitative reasoning, however, the size of an effect is relatively unimportant; what is important is the fact that it exists at all and that it plays a causal role in the ensuing behaviour.

Through the surface charge models students acquire a deep sense of the mechanism for circuit behavior in which feedback [2,3], is an important natural and elegant transient process through which the steady state is established.

5.2 RESISTOR-CAPACITOR CIRCUITS

In the traditional E&M course, methods to obtain the static electric field pattern due to individual charges, dipoles and of charges on plates of capacitors are taught based on the principle of superposition. In a later part of the course, students learn to set up differential equations of Resistor-Capacitor (RC) circuits but with no connection to the ideas students learned about the field patterns of charge distributions.

In a traditional course in circuit analysis, the charging process of a capacitor subject to a step voltage, is described by stating “provided the current is finite, the voltage across a capacitor cannot change instantaneously”. Such statements deprive students from gaining an intuitive cognition of the charging process involving fields.

Shown in Fig. 2 is a circuit used to charge a capacitor comprising a battery, connecting wires and a bulb.

On closure of the circuit, the net field E is due just to battery and surface charges. The field sourced from charges on plate A which is in contact with the battery positive terminal, penetrates the gap between the plates and then penetrates the plate B.

During the first few nanoseconds, while the surface charges were arranging themselves, it is as though the capacitor weren’t there – as though there were a continuous wire with no break in it[2,3].

There is no electric field E_{cap} and fringe field because there is no initial charge on the capacitor.

Surface charges appear on the plate B and further, appear on the wire to the bulb. The capacitor is not “charged” at this instant, yet.

Thus, the voltage of plate B is equal to the voltage of the battery positive terminal. The variation in voltage of plate B versus time is plotted in the graph of Fig. 2 which shows the (step) voltage V_{Batt} of plate B at the instant of turn ON. Note without charges on its plates, the voltage across the capacitor is zero at this instant.

Then, the free-electron sea shifts in plate B due to polarization and negative charges begin to appear on the inner side of plate B as more and more electrons travel along the wire connected to the bulb, and charges will run in the wires, governed by the relation $J = \sigma E_{net}$[2,3].

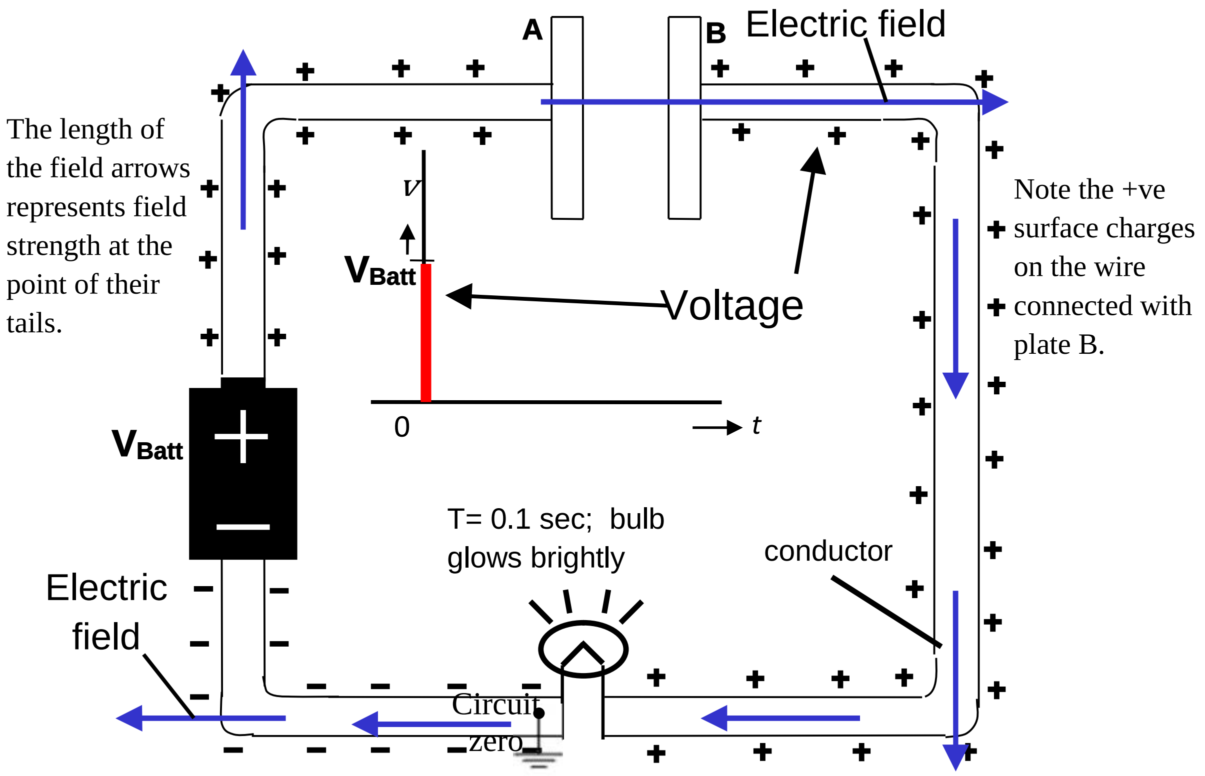

Fig. 2 Charging a capacitor using a bulb – voltage shown at the instant of turn ON.

6. GAUSS' LAW

Gauss's Law in a traditional E&M course is introduced early to prove that excess charge is found only on the surface of conductors, when students are struggling with what is for them a subtle distinction between charge and field. Yet Gauss's Law embodies a complex topological relationship between charge and patterns of field in three-dimensional space.

Chabay and Sherwood, therefore, have introduced the sequence of Gauss's Law after students have gained sufficient experience with patterns of electric and magnetic fields in different contexts, including electric circuits[5]. Gauss's Law can be used to show that the interior of a wire is neutral in a steady-state circuit[3] as shown in Fig. 3.

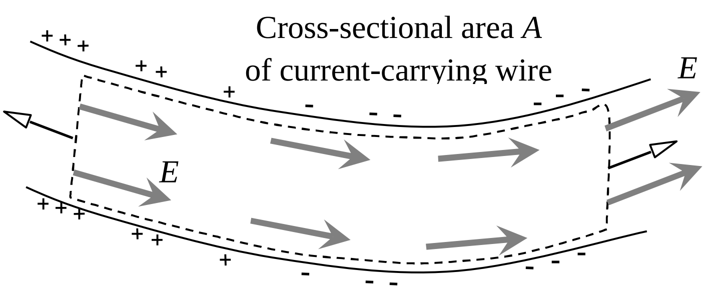

Fig. 3 In the steady-state, excess charges arrange themselves on the surface of such a wire so that the electric field *E* has the same magnitude at different locations along the wire, and is everywhere parallel to the wire. The dashed tube-shaped Gaussian surface nearly fills the wire.

Along the sides of the tube the electric field is parallel to the surface and contributes no flux. Assume that the area of cross-section of the wire is *A*. The right end of the tube contributes an amount of flux *EA*, but the left end contributes –*EA*, so the total electric flux on the Gaussian surface is zero, which means that there must *not* be any net charge inside the Gaussian surface; all excess charge is on the surface of the wire. Therefore, the interior of the wire is neutral.

7. FARADAY'S LAW

In a restructured curriculum, motional emf, which is the important phenomenon[2,3] responsible for the development of emf by electric generators, can be usefully discussed in context with the magnetic force before the introduction of Faraday's law. In a traditional course of Electrical Technology, students find it difficult to apply Faraday's law directly. Introducing motional emf before encountering Faraday's law helps[5] students make an important distinction between these two very different mechanisms for producing emf (magnetic force on moving charged particles versus a time varying magnetic field), which often are not clearly differentiated in the traditional sequence.

Faraday's Law is usually difficult[5] for students because it involves *associating* a curly-patterned non-conservative electric field (it is usually taught with the concept of emf in a traditional E&M course and these further compounds the learning difficulty) with a time-varying magnetic field in circuit theory. It is introduced in most curricula in the integral form, which involves the concept of flux. Since flux is introduced at the start of the course in the context of Gauss's Law, the effect is to use a forgotten concept (flux) to relate a line integral of electric field (emf) to the time derivative of a surface integral of a quantity with which the students had inadequate practice (magnetic field).

Therefore, Faraday's Law is best introduced[5] following motional emf and Gauss's Law. This sequence makes the recently learned flux concept (Gauss's Law) useful to easily learn and understand Faraday's law.

8. ELECTROMAGNETIC RADIATION AND THEORIES IN ELECTRODYNAMICS

In a traditional engineering curriculum on communication engineering, the phenomena of the production and propagation of electromagnetic fields are often described using formulae, depriving students the opportunity to learn electromagnetic radiation from the classical physics viewpoint. Chabay and Sherwood recommend that following the discussion of Faraday's law, animated diagrams[3,9] can be used to show how an accelerated charge produces transverse radiation fields and the equations stated without proof. A sense of the mechanism for the production of radiation is important in making accessible the classical interaction of electromagnetic fields with matter, especially re-radiation[5].

Beginning from the early theories of an aether, several theories of particle interactions with fields (Electrodynamic theories) were postulated; Action-at-a-distance (without a field), Emission (noting that the Emission Theory of Leigh Page conforms to the postulates of Special Relativity while earlier emission theories do not), Classical Field, and the more recent Quantum Field theory. These are fundamental aspects of Physics and concern the conservation laws of energy and momentum, which is usually, explained with the example of colliding billiard balls. There is an action force and a corresponding reaction force at the point of contact. The Coulomb forces between two charged carriers are equal and opposite, but they do not act at the same point in space. Each charge carrier experiences a single force due to its interaction with the field; but locally, there is *no reaction* back onto the field. (This can be expected since the field is an abstraction having zero mass).This reaction force is found when the force on the opposite charge carrier is taken into account. This reaction force, again, is the result of an interaction of field and charge with no reaction back onto the field.

On the magnetic interaction Härtel in a communication (2017) remarked, "a single force acts on a moving charge carrier within a magnetic field which results in an acceleration of the charge carrier perpendicular to its velocity. There is no local reaction back onto the magnetic field. Such a single force or a single acceleration is a contradiction to Newton's Third Principle. For the magnetic interaction, this principle is only fulfilled when the reaction of the moving particle with the *complete* system,… the interaction between the moving charges as origin of the magnetic field and the single moving charge …is taken into account". (Once again, this can be expected since the field is an abstraction having zero mass).

Similar difficulties arise when explaining the loss of momentum due to reradiation when an electromagnetic wave interacts with a charged particle in an object.

Härtel states that in present-day textbooks, authors summarize that Action-at-a-distance theories such as Wilhelm Eduard Weber's force law[16] are "false and should be ignored. This is wrong, because it is not that the theories are false, but that the *interpretation* of such theories is false". Maxwell has acknowledged the accuracy of Weber's Force law.

The authors of this paper recommend that after completing the discussion of fundamental laws; Gauss's law, Lorentz Force law, Faraday's law including the Maxwell-Lorentz law, when students would have gained sufficient experience with the field concept, the principal ideas of the theories of particle interactions including Weber's Force law should be introduced and qualitatively discussed. Then, the Lorentz Force Law from the viewpoint of the Theory of Special Relativity should be introduced leading to show how magnetism is relativistic[9].

Such an introduction to the theories of particle interactions and the relativistic nature of magnetism will be useful for students to qualitatively study the theories and find discrepancies and inconsistencies, which could be used in a constructive way for revision and further development.

9. COURSE MODIFICATIONS AT AN INTRODUCTORY LEVEL IN ENGINEERING CURRICULA

A random survey of syllabi in colleges in India offering electrical and electronics majors reveals that there are several topics in courses which are overburdening both the faculty and students. Viewed from the standpoint of the recommendations made by Chabay and Sherwood, it would be necessary to reorganize the topics of the courses in a manner that lays more emphasis on unifying aspects of electric theory and circuits and bringing out micro/macro connections.

For example, the E&M segment of the engineering physics course should initially introduce topics of the atomic structure of conductors and insulators. This can be followed by a qualitative discussion of the nature and properties of electric and magnetic fields and their effects on matter. The structure of conductors and insulators should be discussed and the formation of the electron sea in conductors. The effects of fields in matter and the formation of dipoles can then be followed by a treatment of the ways of producing an electric field by charge separation[2,3]. **Note:** Topics on light, optics, lasers, quantum physics, Theory of Relativity and other advanced topics in Physics in syllabi in traditional engineering physics courses should be sequenced appropriately, preferably after a discussion of basic electromagnetic theory or E&M and Radiation.

It would be appropriate at this juncture to introduce the magnetic field associated with a current (Biot-Savart Law) followed by a discussion on the nature and properties of the magnetic field. The patterns of electric and magnetic fields of electric and magnetic dipoles and simple charge and current distributions (line charge, sheet of charge, line current and current loop) with formulas to determine the strength of the fields at points in space should be introduced[2,3].

Simple circuits and the role of surface charges in the conduction process can then be introduced with a discussion on the neutrality of the interior of current-carrying conductors and the property of resistance and resistors. In engineering curricula in India it is necessary to ensure that the courses on electromagnetic theory and circuit analysis do not run concurrently and it is preferable that the electromagnetic theory precedes the circuit analysis course. In addition, the electromagnetic theory course should incorporate theoretical aspects of the unified aspects of electric and circuit theories; for e.g. surface charges, capacitor fringe fields, and polarization of inductors by non-Coulomb fields to produce induced Coulomb fields[2,3].

The ideas of a mechanical battery[2,3] instead of chemical battery is a simple yet, powerful construct to explain the ideas of emf and energy balance in simple electric circuits and the discussion on the neutrality of conductors can be repeated.

The above sequence will give the students sufficient practice with fields before a discussion of Gauss's Law, motional emf, and Faraday's Law and more advanced topics of complex systems involving capacitive and inductive circuits.

10. ASSESSMENT OF STUDENT LEARNING

Students in the revised E&M sequence of Chabay and Sherwood were able to solve difficult problems involving RC circuits significantly better than did students in a traditional curriculum according to a report by Thacker, Ganiel, and Boys[5]. Students in the revised curriculum were also able to give better microscopic and mechanistic explanations of their reasoning, while the other students relied on algebraic manipulation of formulas and were less frequently correct. The performance of over 2000 students in introductory calculus-based electromagnetism (E&M) courses[10] in Carnegie Mellon University (CMU), Georgia Institute of Technology (GT), North Carolina State University (NCSU), and Purdue University (Purdue) was measured using the Brief Electricity and Magnetism Assessment (BEMA) and the results clearly indicate that the restructured Matter and Interactions curriculum is more effective than the traditional curriculum at teaching E&M concepts to students. Course structures in a few of these universities and followed in Macquarie University, Australia are available in the University webpages[11,12,13].

Härtel's question[7] "Is it possible to develop a consistent qualitative concept for electromagnetism which could be used in a generic form to support an introductory course and which could be developed in a consistent way when more facts and phenomena are presented and higher levels of abstraction are addressed?" by itself shows the difficulty of the task which lies ahead, and it the authors' belief that a beginning must be made soon.

11. RECOMMENDATIONS FOR RESTRUCTURING THE ENGINEERING CURRICULUM

That the traditional approach has shortcomings is evident from the large number of students, who after completing the course, have several misconceptions about electricity, magnetism and circuit processes. There is an urgent need for academicians in Indian Universities to view the engineering curricula holistically before restructuring the existing courses. The authors recommend that the Mechanics course should precede the Electricity and Magnetism (E&M) course.

An excellent set of resources and tools for Instructors making a switch to a restructured curriculum is available online[14] including lecture-demos and video clips from lectures by Ruth Chabay (Mechanics) and Matthew Kohlmyer (E&M).

Following is a set of guidelines prepared for restructuring the traditional electricity and magnetism (E&M) or Field Theory and Circuit theory segments by the authors. These can be implemented after amalgamation with the engineering physics course.

i. Students should be encouraged to practice sketching field and flux patterns in electrostatics of different charge configurations (dipoles and of line charge, sheet of charge), their production by charge separation and should be taught the use of computerized tools to generate patterns. Students should practice sketching field and flux patterns of moving charges in magnetostatics (line current, current in a single loop and multiple loops)[2,3,7].

ii. Topics on the integration of the atomic nature of matter and macro/micro connections and the modeling of real physical systems, such as conductors and insulators should be introduced[2,3].

iii. The notion of magnetic force with topics on the microscopic view of magnetic forces on currents should be introduced early and Motional emf should be discussed before Faraday's Law which associates a curly-patterned electric field with a time-varying magnetic field should follow Gauss's Law[2,3,5,9]. The idea of generating an electromagnetic wave by an accelerated charge[7,3,9] should be introduced at this juncture without proof which can be provided later in a course on electromagnetic waves.

Note Advanced topics which should be included in the curriculum either in an advanced E&M course or incorporated in other courses: theories of electrodynamics[6,9] (Aether, Emission, Classical Field, Quantum Field) with discussions of "inconsistencies in a constructive way", Theory of Special Relativity[9].

iv. A unified treatment of electrostatics and circuits and the role of surface charges in circuits which maintain a constant field in curvilinear wires should be discussed [2,3,15].

v. RC circuits should include discussions of the role of the fringe field in modulating the current during charging and discharging[15] of the capacitor[2,3].

vi. RL circuits should include discussions of the role of the coulomb field in modulating the current in the inductor[2,3].

vii. Weber's force law[16] and Ampere's force law[6] should be introduced before a discussion of the Lorentz force law in Electrodynamics segment of Electrical Technology.

Practical laboratory experiments should preferably be conducted with experiments in Mechanics first, followed by experiments in electrostatics, magnetostatics and then electromagnetic, and ensuring that experiments on optics (diffraction, interference, lasers and optical fibers) are conducted towards the end of the revised E&M course.

It is the authors' recommendation that the above guidelines be followed when preparing modifications to E&M courses in Engineering curricula offering electrical and electronics majors.

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