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Restructuring the Basic and Advanced Level Courses in Electromagnetic Fields

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ABSTRACT

In traditional electricity and magnetism (E&M) segment of introductory physics courses many increasingly abstract concepts, embodied in complex formal relations, such as Faraday's law are introduced at a rapid pace. Consequently, many students find the electricity and magnetism (E&M) course significantly more difficult than classical mechanics and struggle to understand advanced topics in circuit theory and electronic circuits. This paper identifies the problem areas in the present structure of the E&M course, and defines goals for a revised hierarchical organization of topics. The revised structure lays emphasis on making the central field concept more comprehensible and useful to students and recommends inclusion of advanced topics on electrodynamic theories in engineering curricula offering electrical and electronics courses as majors. Finally, results of studies comparing the performance of students of the revised E&M sequence with the performance of students who have undergone a traditional E&M course are presented.

Keywords

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

INTRODUCTION

A reexamination of the content of electricity and magnetism (E&M) courses and their sequence in Engineering and Applied Sciences curricula has long been overdue. Traditional E&M courses have not undergone any change and according to Härtel[1] (in 2008) "the term voltage is usually introduced as cause for the flow of electrons". "Most classroom activities on this level are focused on Ohm's law and the rules about serial and parallel circuits (Kirchhoff's laws)". Then, "the electric field E is introduced and defined as E = F/q. This is followed by the definition of the potential of a point A as energy E (with respect to infinity) per unit charge (V=E/q) and finally the term "voltage between A and B" is defined as potential difference, equal to the amount of energy E which is needed or provided if a unit charge q is moved from A to B ($\Delta V=\Delta E_p/q$). According to Härtel this sequence of explaining voltage makes it a "highly abstract and mathematically elegant approach" that "sets aside any causal mechanism which could explain the flow of electrons within electric circuits".

Härtel has reported[1] that several students and teachers could not explain the reason for the electric field being constant in a curvilinear wire carrying a steady current. This is because no student had been told about 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.

It is possible to improve the learning results for the majority of our students (in the field of electricity) by increasing the amount of teaching time devoted towards an explicit treatment of surface charges and its distribution among the different parts of an electric circuit.

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The authors have encountered several instances of students who have completed a traditional course of circuit theory where they had learnt to analyze circuits using currents and voltages, puzzled by the appearance of the electric field when deriving the expression for the *p-n* junction diode current and when discussing the effect of stray capacitances on the high-frequency behavior of transistors.

1. THE DIFFICULTIES IN TRADITIONAL TEACHING AND LEARNING OF ELECTRICITY AND MAGNETISM

Traditionally[2] students of Applied Science and Engineering are taught topics in an E&M course after they have completed a course in Classical Mechanics. While important concepts, such as velocity and force, are easily related to everyday experience, the E&M world is one in which almost all of the quantities are invisible being either microscopic such as electrons or abstractions such as field, flux and potential.

In most curriculum, the sequence of topics covered in the 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.

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

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.

Härtel[1] 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.

Härtel[3] 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. Worse yet, there may even be a belief that students should not worry about inconsistencies; truth is within the equations themselves".

2. RESTRUCTURING THE CURRICULUM

In traditional Engineering and Applied Sciences curricula, which incorporate a course in electrostatics followed by a course in circuit theory, students in the first course 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. 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.

There being a strong incoherence in both the courses which ignore the common thread of the field configurations due to surface charges in the steady-state, students fail to make a connection between the two concepts; the charge on the terminals of the battery and on the wires (electrostatics) and the potential difference across the resistor when incorporated in a circuit (circuit theory).

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.

Research scientists and experts in physics education[2] reexamined the problem of the structure of courses in Science and Engineering, incoherent teaching methodologies and subsequent faulty assimilation of ideas by students. They stated the necessity to emphasize a small number of fundamental principles, a unified approach on the integration of the atomic nature of matter and macro/micro connections, and the modeling of real physical systems, including computational modeling.

3. THE OBJECTIVES OF THE NEW APPROACH

The aim of this approach will enable students to explain a wide range of phenomena by applying a few fundamental principles[2]. They should clearly understand the power of classical and semiclassical models even at a microscopic scale and become aware of the limitations of purely classical, macroscopic models. Students should be able to use approximations productively, including the use of numerical methods.

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[2], 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.

4.1 FIELD- AN INTERMEDIATE LEVEL OF ABSTRACTION[2]

The concept of field is central to electricity and magnetism. This has been lacking in traditional syllabi and part of the reason can be attributed to the early introduction of analyzing circuits using formulas for current and voltage and calculating equivalent resistance and mutual inductance. Traditional courses on circuit theory begin with the notion of voltage and current and no concepts are presented about the presence and sources of electric fields in, and magnetic fields around, conductors.

According to Chabay and Sherwood[2], Maxwell's equations and the classical explanation of the nature of light are one of the crowning intellectual achievements of classical physics and introductory students can understand this if they have had sufficiently varied experiences with electric and magnetic fields and the effects of these fields on matter.

One of the ways is to make the field concept[2] "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 throughout the new sequence".

4.1.2 MAGNETIC FIELD

Magnetic field and magnetic force are introduced very early in the sequence so that students have more time to gain adequate experience with the topic before they are taught the effects of fields on matter.

Curiously, "Ampere never worked with the concept of a "magnetic field"[4]. 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.

4.1.3 EFFECT OF FIELDS ON MATTER

Fields by themselves are very abstract, but experience with fields comes from observing their effect on material objects.

It is observed that students, 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. This can be understood only by thinking about the effect of applied fields on the electrons in the neutral material.

Chabay and Sherwood mention that even students who are familiar with the ball and spring model of a solid are typically surprised by the existence of a mobile electron sea in metals.

The discussion of the microscopic model supports the discussion of the transients involved in the separation of charges in neutral atoms or polarization of conductors and insulators. This 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 introductory E&M can provide a relatively easy introduction to these concepts[2].

5.1 UNIFIED TREATMENT OF ELECTROSTATICS AND CIRCUITS

In a traditional E&M 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.

5.1.1 RESISTIVE CIRCUIT

Fig. 1 shows the pattern of the electric field and a schematic charge distribution on a simple circuit consisting of a battery connected to a resistive wire of constant cross-section and composition. In the steady state there is a gradient of surface charge density on the surface of the resistive wire, which is a major contributor to the field $\vec{E}$ inside the wire.

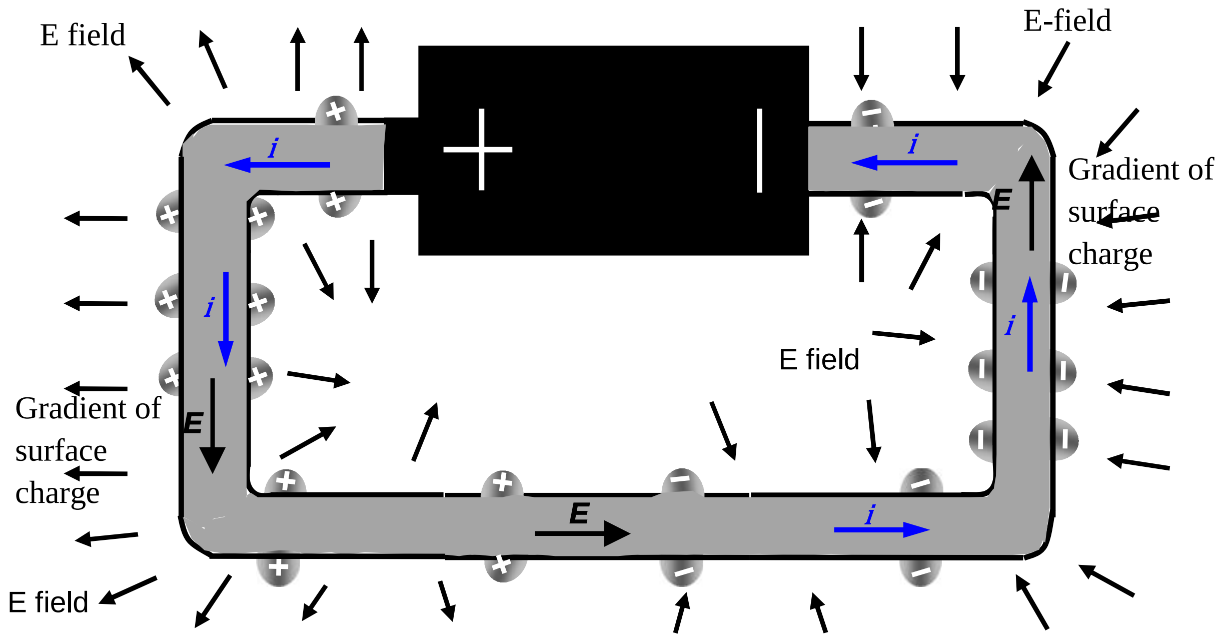

Fig. 1 The steady state pattern of electric field ***E*** inside the wires set up by surface charges of both polarities on the connecting wire and charges on the battery plates. The surface charge is shown at sample locations along the wire to depict a charge gradient which is a major contributor to the field ***E*** inside the wires. The current *i* in the steady-state is also shown.

Through the surface charge model students can acquire a deep sense of the mechanism for circuit behavior, including the transient in which the steady state is established through feedback[5,6].

5.1.2 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 learnt about the field patterns of charge distributions.

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The authors have further explored the ideas of surface charges and fields to explain how the output voltage of a Capacitor – Resistor circuit becomes negative at the trailing edge of a positive going pulse input. Beginning with the concept of a fringe field which exists at a point outside the plates of charged capacitors and the fact that the electric field penetrates through matter the process of the development of excess charge on the capacitor plates is followed by how the electric field in the wires modulates the current. One plate of the capacitor holds a bunch of excess negative charge and is responsible for the sudden transition of the potential at the trailing edge of the pulse. A snapshot view of the field components is shown in the Fig. 2 at the instant when the pulse goes to zero volts.

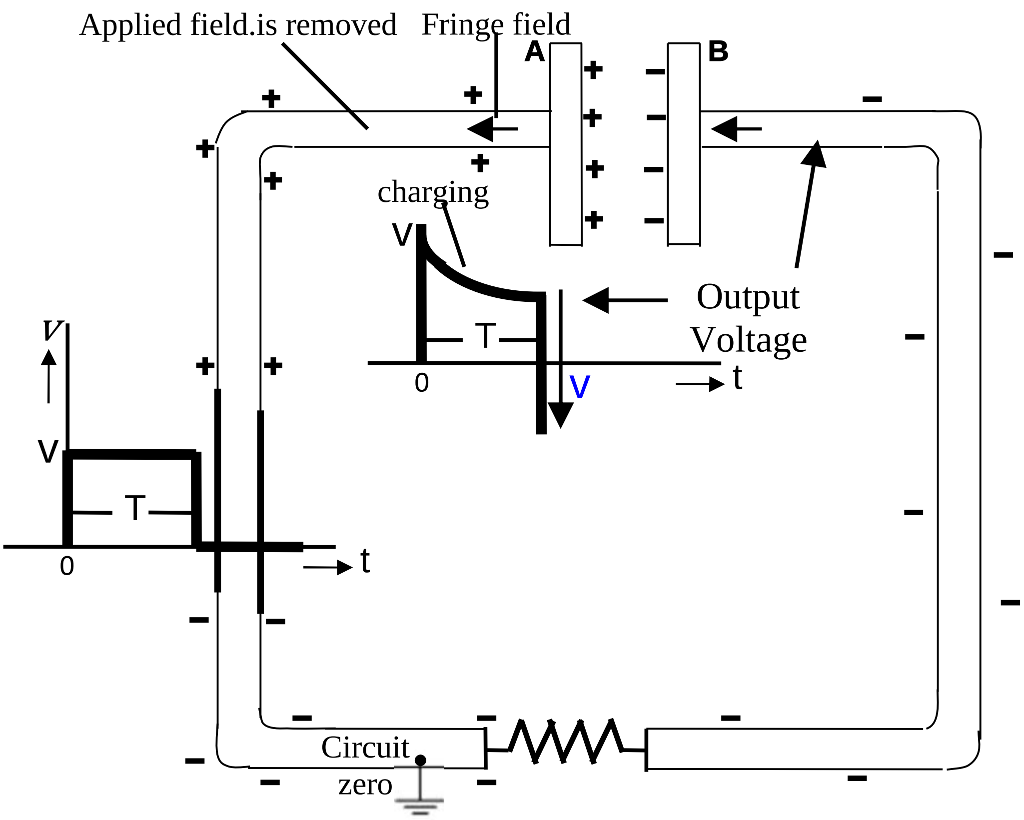

Fig 2 Pulse input to a CR circuit – input voltage is made zero.

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[2]. Gauss's Law can be used to show that the interior of a wire is neutral in a steady-state circuit[6] as shown in Fig. 3.

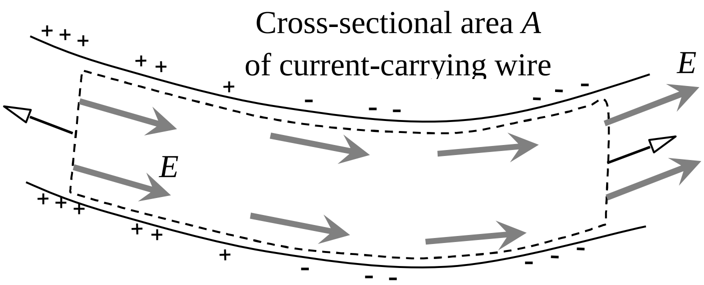

Fig 3 In the steady-state, excess charges arrange themselves on the surface of such a wire so that the electric field *E* has the same magnitude at different locations along the wire, and is everywhere parallel to the wire. The dashed tube-shaped Gaussian surface nearly fills the wire.

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

Faraday's Law is usually difficult[2] for students because it involves associating an 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. It is introduced in most curricula in the integral form because students have not yet encountered divergence and curl in calculus courses. The integral form involves the concept of flux, which is traditionally introduced at the start of the course in the context of Gauss's Law and 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).

Faraday's Law is best introduced[2] following the treatment of Gauss's Law with an emphasis on the curly electric field that is found surrounding a region of time-varying magnetic field. With this sequence students will find the treatment of the recently learned flux concept, useful to easily learn and understand Faraday's law.

In a restructured curriculum, motional emf, which is the important phenomenon[5&6] 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[2] 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.

8. ELECTROMAGNETIC RADIATION

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 one of the crowning achievements of classical physics, electromagnetic radiation. Chabay and Sherwood recommend that following the discussion of Faraday's law, animated diagrams can be used to show how an accelerated charge produces transverse radiative 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[2].

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9. ADVANCED E&M TOPICS IN ENGINEERING CURRICULA WITH ELECTRICAL AND ELECTRONICS MAJORS

Beginning from the early theories of an aether (Sir Isaac Newton made a mention of Aether when describing the force of attraction between bodies) up to the era when Maxwell, Faraday and Lorentz believed in the existence of aether which carried electromagnetic undulations, until Einstein made the aether superfluous, several theories of particle interactions with fields were postulated; Action-at-a-distance (without a field), Emission, Classical Field, and the more recent Quantum Field theory. These theories were postulated by theoretical physicists as answers to questions which are summarized in Fig. 4.

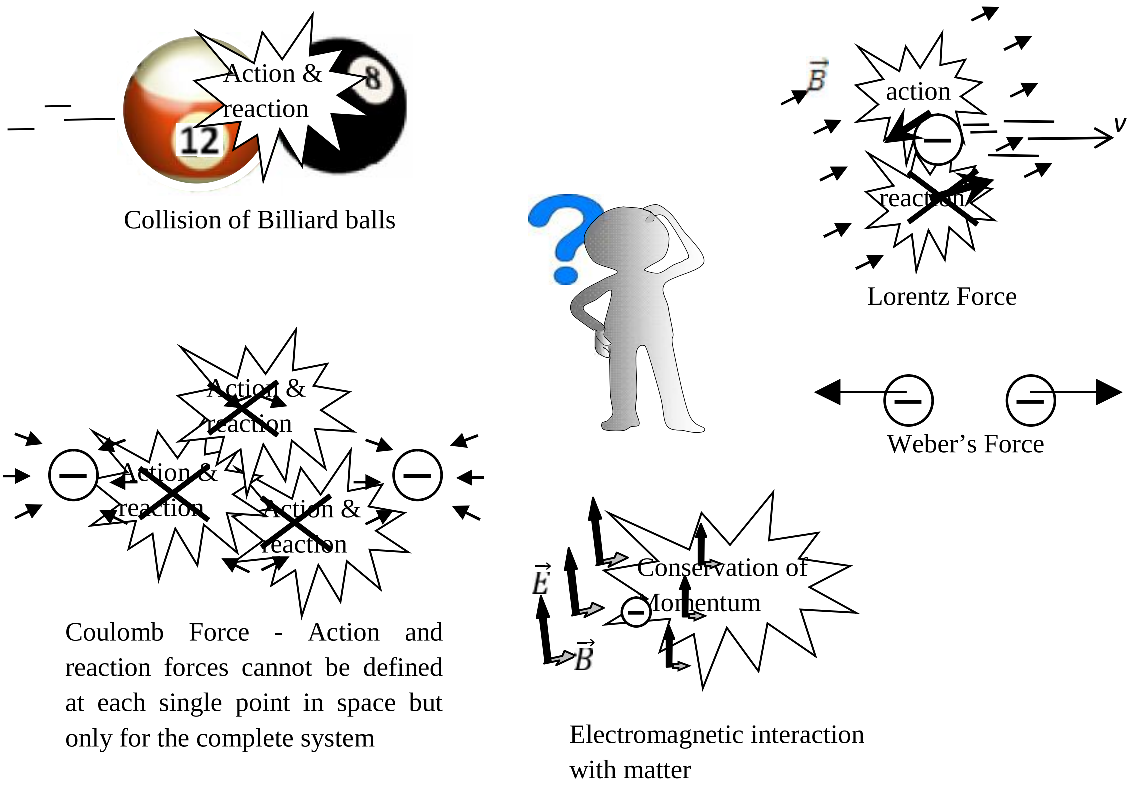

Fig. 4 The collision of a pair of billiard balls, Coulomb force, Lorentz force, Weber's Force and Electromagnetic interaction with matter.

These are fundamental aspects of Physics and concern the conservation laws of energy and momentum. The conservation of momentum is usually explained by 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 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) has 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".

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, most authors summarize that Action-at-a-distance theories such as Wilhelm Eduard Weber's force law 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, students pursuing degrees in engineering with majors in electrical and electronics can be introduced to the principal ideas of the theories of particle interactions including Weber's Force law, and Lorentz Force Law from the viewpoint of the Theory of Special Relativity. Magnetism is relativistic and it would be useful if the idea is qualitatively introduced[7].

The Lorentz Force Law, which can be derived from Ampere's Force law, can also be derived using the postulates of the Theory of Special Relativity[7].

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.

10. ASSESSMENT OF STUDENT LEARNING

The restructuring of existing E&M course as suggested by the sequence advocated by Chabay and Sherwood will certainly not be easy. That the traditional approach has shortcomings is evident from the large number of students who have several misconceptions after completion of the traditional E&M course.

Thacker, Ganiel, and Boys[2] found that students in the revised E&M sequence were able to solve difficult problems involving RC circuits significantly better than did students in a traditional curriculum. Students in the revised curriculum were also able to give better explanations of their reasoning, which were often microscopic and mechanistic, while the other students relied on algebraic manipulation of formulas and were less frequently correct. Engelhardt and Beichner[2] found that students from a course using the revised sequence outperformed students from a traditional course on a test of students understanding of dc circuits.

Härtel's question[3] "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 is the authors' belief that a beginning must be made without much waste of time.

11. RECOMMENDATIONS FOR RESTRUCTURING THE E&M CURRICULUM

In summary, the authors bring to the attention of Academicians and Universities the need to restructure the existing E&M course based on the following recommendations.

i. Electromagnetic Theory topics should provide more experience to students with practice of field patterns of different charge configurations, their production by charge separation and should include the use of computerized tools to generate patterns[6].

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.

iii. Students should practice sketching field and flux patterns in electrostatics and moving charges (magnetostatics). More practice with field patterns using computerized tools is recommended[6]. The notion of magnetic force with a presentation on the microscopic view of magnetic forces on currents should be introduced early and Motional emf[2,5,6,7] should be introduced before discussing Faraday's Law.

iv. A unified treatment of electrostatics and circuits should be included in the E&M course and the role of surface charges in circuits which maintain a constant field in curvilinear wires should be discussed[5,6].

v. Faraday's law (curly field pattern of the electric field associated with a time-varying magnetic field) should be introduced soon after the discussion of Gauss's Law. The idea of generating an electromagnetic wave by an accelerated charge[6,7] should be introduced at this juncture without proof which can be provided later in a course on Wave Theory.

vi. RC circuits should include discussions of the role of the fringe field in modulating the current during charging and discharging of the capacitor[5,6].

vii. RL circuits should include discussions of the role of the coulomb field in modulating the current in the inductor[5,6].

viii. Introduction to Weber's force law and Ampere's force law[4] before a discussion of the Lorentz force law in Electrodynamics segment of Electrical Technology.

ix. Advanced topics that may be included in the curriculum either in an advanced E&M course or incorporated in other courses: theories of particle interactions[4,7] with discussions of "inconsistencies in a constructive way", Theory of Special Relativity[7], Generation of an electromagnetic wave by an accelerated charge[6,7].

These recommendations are applicable to Engineering Curricula offering electrical and electronic majors, Applied Sciences and Physical Sciences at Post-graduate level.

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