Revitalizing Theoretical Aspects in Electrical and Electronics Engineering Curricula

Sridhar Chitta[1], Dr. V. Kamaraju[2], A. Mahesh Kumar[3]

[1]*Associate Professor (Retd.), Electronics and Communication Engineering*
Hyderabad,(India)

[2]*Principal (Retd.), JNTU Kakinada, Electrical Engineering*
Hyderabad, (India)

[3]*Assistant Professor, Deptt. of Electrical and Electronics Engineering*
Mahaveer Institute of Science and Technology, Hyderabad, (India)

ABSTRACT

In the past several decades there has been a divide between the theories of Electricity and Magnetism (E&M) and Circuit Theory taught in engineering courses which has prevented students with Electrical and Electronics majors, from acquiring cognitive skills necessary for the analysis and application of Electrical science in advanced circuit theory and design. One of the chief reasons many students struggle to understand advanced topics in circuit theory and electronic devices and circuits is the rapid pace in the introduction of abstract concepts using sophisticated field theory and neglect of key concepts in E&M which directly affect circuit processes. After describing the difficulties of teaching and learning E&M, this paper describes proposals made by experts in Science Education for a revised E&M structure which will lend coherence to the disconnected subjects of electrostatics, magnetostatics and fields of moving charges and circuits. Then, the results of performance tests of students in the new E&M sequence is presented followed by a set of guidelines the authors have prepared to assist in restructuring existing engineering curricula in Universities.

Keywords - Engineering Curriculum, Syllabus Revision, Revised Electricity and Magnetism Structure, Unified Treatment of Electrostatics and Circuits

I.INTRODUCTION

In most traditional E&M courses, during which teachers are focused on explaining Ohm's law and Kirchhoff's laws, inadequate descriptions such as voltage being the "cause for the flow of electrons" are provided [1]. 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. According to Professor Hermann Härtel [1], this sequence of explaining voltage makes it a "highly abstract and mathematically elegant approach" but which "sets aside any causal mechanism which could explain the flow of electrons within electric circuits". The role of surface charges in the conduction process and microscopic descriptions of electron motion (of the millions and millions of electrons in conductors) is missing which provides the correct causal mechanism [3][6][7].

Laboring to meet syllabus completion deadlines, teachers are unable to discuss the central role of the field in

ISBN: 978-93-86171-56-6

electric theory and circuits that could lead to more meaningful discussions on induced emfs in inductors, and the effect of stray capacitances on the high-frequency behavior of transistors.

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

In the Classical Mechanics course, students easily relate to the concepts of velocity and force, because these are observed in their daily lives. In the E&M world, however, almost all of the quantities are invisible being either microscopic such as electrons or abstractions such as field, flux and potential [2].

In traditional E&M courses, teachers gloss over the abstract concepts of charge, electric force, field, flux, and Gauss's law followed by ideas of potential, potential difference, and electric current. The onslaught of concepts and ways of reasoning is making teachers go through the fundamentals at high speed and to devote most of the time allotted on rote problem solving. Overwhelmed by this rapid introduction of abstract ideas students are not able to "apply these concepts reliably, or to discriminate them from each other" [2].

For example, in a traditional sequence students learning electrostatics are taught that a charge "creates" an electric field whose strength is inversely proportional to distance squared. This is followed immediately by introductory circuit theory, in which students learn that there exists a potential difference across a resistor powered by a battery. Because of the strong discontinuity, students fail to make a connection between the two concepts; the charge on the battery terminals and the potential difference across the resistor.

Then, with little or no qualification to the structure of the conductor at the microscopic level they are told that current is "charges in motion".

Härtel [1] has reported that several students and teachers could not explain the reason for the electric field being constant in a curvilinear wire carrying a steady current. Without ideas about surface charges in relation to electric currents, and with knowledge "based only on the definitions of electric field, energy, potential and potential difference", students have no hint for an explanation.

Hertz once made a statement, "The Physics of Electromagnetism is Maxwell's equations", which Härtel has criticized. Such statements show an "attitude of overemphasizing the quantitative side and even denying the existence of qualitative models and questions about the underlying ontology as part of physics" [3].

Härtel recommends that if qualitative models are presented, this should be done with their inconsistencies, and teachers should desist from giving shallow explanations with the excuse that, students would only be confused by any further and more detailed explanation. Teachers should stop making statements such as "truth is within the equations themselves" [3].

II. RESTRUCTURING THE E&M COURSE OF THE ENGINEERING CURRICULUM

There is a thread running in the study of circuits of field configurations of static charges, which research scientists and experts in physics education found missing when they examined the structure of present traditional courses in Engineering, in which the circuit theory course was found more focused on describing circuit phenomenon using voltage and current. They also noted that a few important concepts (for example, surface charges, coulomb fields produced by polarization of conductors by non-Coulomb fields, and atomic structure of conductors and insulators) which were discovered in the early and middle of the 20^{th} century need to be introduced to eliminate the incoherence students experience while studying advanced topics in the subjects of electrodynamics and electromagnetic theory. These deficiencies are the main cause which resulted in incoherent teaching methodologies being adopted and subsequent growth of confusion among students. The experts also stated the necessity to emphasize a small number of fundamental principles, and the modeling of real physical systems, including computational modeling.

III. OBJECTIVES OF A RESTRUCTURED CURRICULUM

Experienced senior and research scientists stated that the gap between electric theory and circuit theory can 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. They 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. The E&M course should engage students by emphasizing a unified approach based on the integration of the atomic nature of matter and macro/micro connections, and on the modeling of real physical systems, including computational modeling [2].

In a few Universities in countries like India, topics in Physical Optics such as Interference, Polarization of light and Fibre optics are introduced in the first year engineering Physics course even before students are introduced to topics in Mechanics. Such a sequence deprives students of sufficient practice in electric and magnetic fields and Maxwell’s equations, which are essential before a discussion on light.

Originally devised by Chabay and Sherwood [2] for undergraduate degree programs, Matter and Interactions (M&I, in short) is a calculus-based Physics course which begins with Modern Mechanics followed by 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”.

Chabay and Sherwood note that a distinction is made between the fundamental laws of nature and empirical rules that are useful approximations for more complex physics in their Mechanics course. However, even students who have done well in Mechanics course often find E&M to be difficult and confusing [5].

With a sustained emphasis on the field concept forming an overarching theme of the entire E&M sequence and with the organization of topics made hierarchical, Chabay and Sherwood’s curriculum[2] has helped students to develop microscopic models that facilitate reasoning about complex systems. The E&M 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 [2][5].

IV. A CENTRALISED FIELD CONCEPT OF THE REVISED E&M COURSE

In traditional electric theory and circuit theory courses, concepts about the presence and sources of electric fields in conductors are not treated effectively.

The concept of field is central to electricity and magnetism, which is lacking in traditional engineering curricula. Part of the reason can be attributed to the early introduction of circuit analysis using formulas for current and voltage and calculating equivalent resistance and mutual inductance.

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 [2].

The field concept can be made more connected to the behavior of matter by an emphasis on the crucial role of dipoles, electric and magnetic, permanent and induced. In Chabay and Sherwood's restructured curriculum [2], the fields made by dipoles and the creation of dipoles by applied fields play a significant role throughout the new sequence.

4.1 Magnetic Field and Magnetic Force

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.

Curiously, "Ampere never worked with the concept of a "magnetic field"[14]. 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.

4.2 The Effect of Fields in Matter

A field by itself is very abstract and this includes the Gravitational, Electric and Magnetic fields. It is not surprising students find it difficult to understand the nature and properties of fields in general and of electric and magnetic field in particular. Fields by themselves are very abstract, being without mass and invisible, but as an abstraction, they offer a means to provide valuable intuitive cognition in explaining several phenomena in electrostatics, magnetostatics and circuit operation. Chabay and Sherwood [2] have observed that "experience with fields comes from observing their effect on material objects". Fields affect the electrons in neutral material and by thinking about this, students can be easily made 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.

Further discussions on the separation of charges in neutral atoms or polarization of conductors and insulators, makes it possible for students to reason step-by-step about the processes involved in the approach to static equilibrium beginning from the very initial transient (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].

ISBN: 978-93-86171-56-6

V.THE UNIFICATION 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. Instead, students lose themselves in a maze of circuit formulas and field equations, with no sense for the underlying unity of the two sciences.

5.1 A Simple Circuit Comprising a Battery and Thick and Thin Wires

In a simple circuit comprising a wire and a battery, a surface charge gradient establishes a constant current in the steady-state which follows the very initial transient when the circuit is made [3][6][7]. The effect of resistance in respect to electron flow can easily be explained through geometric arrangement. Shown in the circuit of Fig. 1 comprising a battery, thick wires and a thin wire (resistor) are surface charges in zones A, B, C and D which always exist in the presence of a changed cross-section.

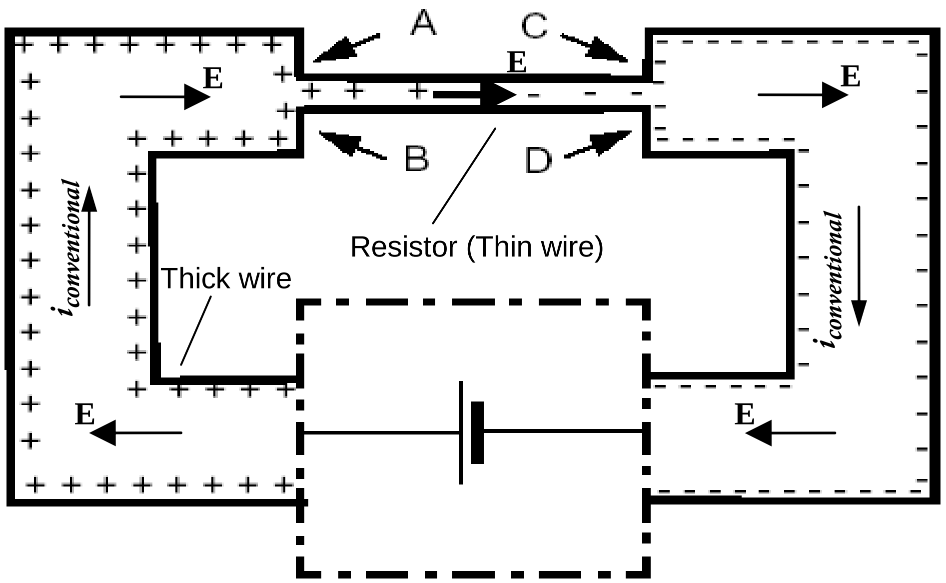

Fig. 1 Surface charges and Current (conventional opposite to electron flow) in a circuit with a Resistor (Thin wire)

The charges in these zones oppose the effect of the original charges on the battery terminals and will thus, reduce the intensity of the current flow in the thick wire [3][6].

The gradient of the surface charge distribution is larger along the thin wire than along the thick wires. Therefore, a stronger force due to a stronger field **E** is exerted on the free electrons within the resistor, leading to a higher drifting speed. When equilibrium is reached, the current is *constant* in the circuit. The drifting speed, however, will be different at different cross-sections.

The key to understanding the source of the electric field at the microscopic level is the surface-charge model of circuits [2]. Through the surface charge models students acquire a deep sense of the mechanism for circuit behavior in which feedback [6][7], is an important natural and elegant transient process through which the steady state is established.

ISBN: 978-93-86171-56-6

VI. 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 [7] 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. Gauss's Law can be used to show that the interior of a wire is neutral in a steady-state circuit [7] as shown in Fig. 2.

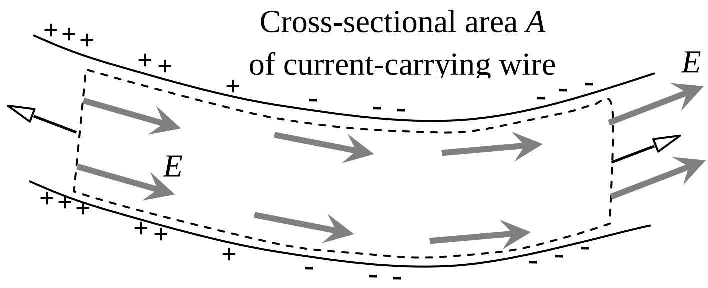

Fig. 2 In the steady-state, excess charges arrange themselves on the surface of such a wire so that the electric field *E* has the same magnitude at different locations along the wire, and is everywhere parallel to the wire. The dashed tube-shaped Gaussian surface nearly fills the wire.

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.

VII. FARADAY'S LAW

Faraday's law is introduced in most curricula in the integral form because students have not yet encountered divergence and curl in calculus courses. It is usually taught with the concept of emf in a traditional E&M course with a time-varying magnetic field and these further compounds the learning difficulty.

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, the magnetic field, with which the students had inadequate practice. Therefore, it comes as no surprise that students usually find Faraday's Law as applied in inductive circuits difficult to understand.

ISBN: 978-93-86171-56-6

7.1 A Resistor-Inductor Circuit

Fig. 3 shows a circuit comprising a power supply whose output voltage can be varied, a resistor and an inductor.

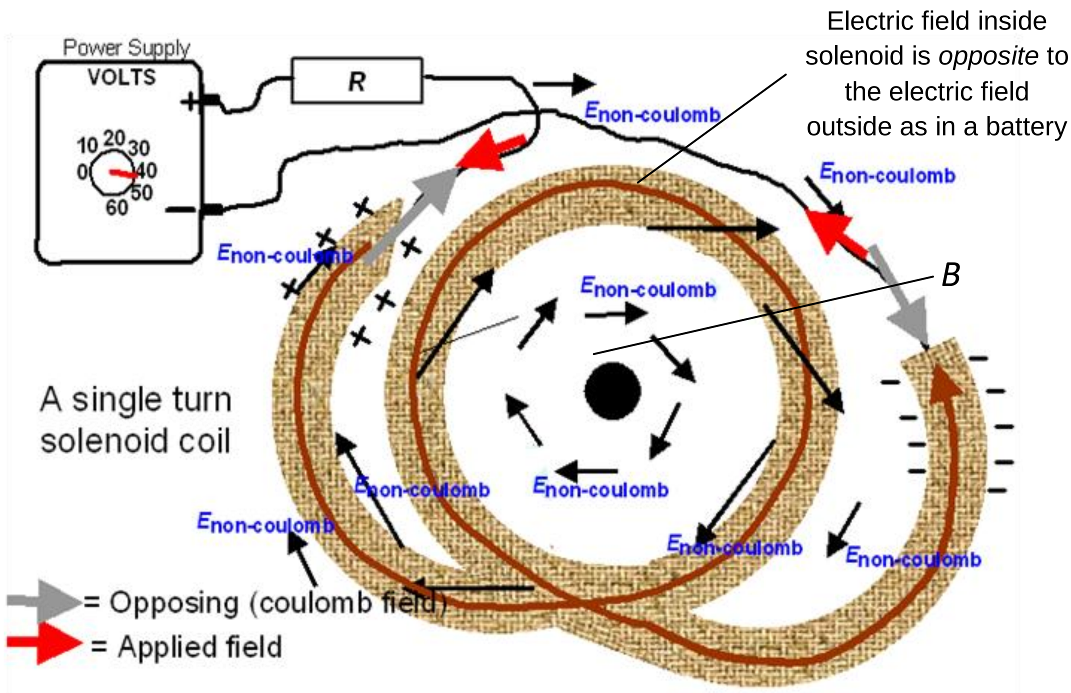

Fig. 3 Varying the voltage applied to an inductor (one turn of coil shown for clarity)

An exaggerated view of one turn of the multi turn inductor is shown for clarity. It is *hard* to change the current, because the attempt to change the current in the coil associates a non-Coulomb electric field in the same coil. If there was no coil, the current would have changed *instantly* in response to a change in input voltage.

Due to the presence of the inductor, a non-Coulomb curly patterned electric field E_{NC} appears when the voltage is changed, which is associated with the change in current with it's associated magnetic field *B*. The electric field E_{NC} polarizes the solenoid and *surface charges* appear which produce a coulomb electric field E_C. The field component E_C is the cause for the self-induced emf, which acts in a direction that opposes the original cause of magnetic field *B* change. This makes the current in the coil of wire to respond sluggishly [6][7].

In the final stage of development, a strong electric field is set up in the resistor and the field follows the wire and points opposite to the *non-Coulomb field*. If the resistance of the solenoid is very small, the *magnitude of the two electric fields is nearly equal* ($E_C \sim E_{NC}$) and the resultant is very small because the two component fields are very nearly equal. This small resultant produces the current in the coil.

 ISBN: 978-93-86171-56-6

In a traditional E&M course, usually the manner of production of the self-induced emf is mentioned by the formula $\oint E_{NC} \cdot d\vec{l} = -\frac{d}{dt}\int \vec{B} \cdot \hat{n} dA$, without making a clear distinction on whether it is a curly field or a diverging Coulomb type field. With reference to the operation of the circuit of Fig. 3, both effects are involved in the process of generation of emf. Again, in a traditional E&M course, it is mentioned that "the voltage across an inductor can change instantaneously", with no explanation of how this happens. On the other hand, a qualitative explanation using magnetic field change and the associated curly patterned electric field can develop a more meaningful intuitive cognition useful in analyzing complex inductive circuit behavior.

In a restructured curriculum, motional emf, which is the important phenomenon [2] responsible for the development of emf by electric generators, can be usefully discussed in context with the magnetic force before the introduction of Gauss's Law. Faraday's Law should be discussed after introducing Gauss's Law. This sequence enables students to easily learn and understand Faraday's law and the association of a curly electric field with a time-varying magnetic field.

In a traditional course of Electrical Technology, students find it difficult to apply Faraday's law directly. Introducing motional emf [6][7] before encountering Faraday's law helps 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.

VIII. ADVANCED E&M TOPICS IN ENGINEERING CURRICULA

In the past century and to the present, several theories of particle interactions were postulated: Aether, Action-at-a-distance (without a field), Emission (without the postulates of Special Relativity and Page's theory with the postulate of Special Relativity), Classical Field, Semi-classical and the more recent Quantum Field theory. These theories were postulated by theoretical physicists as answers to questions which are summarized in Fig. 4.

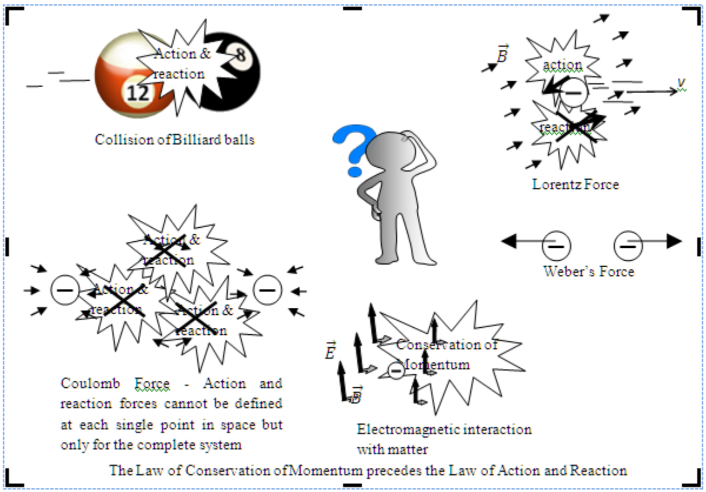

Fig. 4 The collision of a pair of billiard balls, Coulomb force, Lorentz force, Weber's Force and Electromagnetic interaction with matter.

These are fundamental aspects of Physics and concern the conservation laws of energy and momentum. The conservation of momentum is usually explained with the example of colliding billiard balls in which a reaction force is generated 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) 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".

Explaining the loss of momentum due to reradiation when an electromagnetic wave interacts with a charged particle in an object is also rather difficult.

Härtel in a communication (2017) states that in present-day textbooks, 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". In *Treatise on Electricity and Magnetism*, Maxwell has acknowledged the accuracy of Weber's Force law.

The authors of this paper recommend that after completing the discussion of fundamental laws of Gauss, Lorentz Force, Faraday including the Maxwell-Lorentz law, when students would have gained sufficient experience with the field concept, they 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][8].

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 [8].

Such an introduction to Classical and Semi-classical Electrodynamics from the relativistic viewpoint of magnetism will be useful for students to qualitatively study the theories of particle interactions with their inaccuracies and inconsistencies, and could be used in a constructive way for revision and further development.

IX. ASSESSMENT OF STUDENT LEARNING

Thacker, Ganiel, and Boys [2] found that students in the revised E&M sequence advocated by Chabay and Sherwood 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 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 [9] 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 [10], [11], and [12].

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 the authors' belief that a beginning must be made soon.

X. SUMMARY AND RECOMMENDATIONS

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 Universities to restructure the existing E&M course. An excellent set of resources and tools for Instructors making a switch to a restructured course is available online [13] including lecture-demos and video clips from lectures by Matthew Kohlmyer.

Following is a set of guidelines prepared by the authors for restructuring the traditional Engineering Physics course with topics on Mechanics introduced before the Electric and Magnetism (E&M) 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 (magnetostatics) [3][6][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 [6][7].

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][6][7][8]. The idea of generating an electromagnetic wave by an accelerated charge [3][7][8] 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 particle interactions [8][14] with discussions of "inconsistencies in a constructive way", Theory of Special Relativity[8], Generation of an electromagnetic wave by an accelerated charge[7][8].

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 [6][7][15].

v. RL circuits should include discussions of the role of the coulomb field in modulating the current in the inductor [6][7].

vi. Weber's force law and Ampere's force law [14] 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 electronic majors.

REFERENCES

[1] Hermann Härtel, 2008, *Voltage - a Basic Term in Electricity Shortcomings of the traditional approach and new ideas for improvement*, Institute for Theoretical Physics and Astrophysic, University Kiel. http://www1.astrophysik.uni-kiel.de/~hhaertel/PUB/voltage_girep.pdf
Homepage of Hermann Härtel http://www1.astrophysik.uni-kiel.de/~hhaertel/index_e.htm

[2] Ruth W. Chabay and Bruce A. Sherwood, 2005, *Restructuring the introductory electricity and magnetism course*, Department of Physics, North Carolina State University.
Homepage of Ruth W. Chabay https://www.physics.ncsu.edu/people/faculty_chabay.php
Homepage of Bruce A. Sherwood https://www.physics.ncsu.edu/people/faculty_sherwood.php

[3] Hermann Härtel, Revised 2008 (First published 1987), *A Qualitative Approach to Electricity A Guide to Visualising Eletrodynamics using symbols and images*, Institute for Theoretical Physics and Astrophysic, University Kiel. http://www1.astrophysik.uni-kiel.de/~hhaertel/PUB/Quality-Electricity.pdf

[4] Ruth W. Chabay and Bruce A. Sherwood, *Matter and Interactions*, **Section 3**, Research-Based Reform of University Physics, http://www.compadre.org/per/items/detail.cfm?ID=4989

[5] Ruth W. Chabay and Bruce A. Sherwood, *Matter and Interactions*, **Section 4**, Research-Based Reform of University Physics, http://www.compadre.org/per/items/detail.cfm?ID=4989

[6] Sridhar Chitta, *Circuit Process Mechanism*, Rev. (2013), I.K. International Publishing House Pvt. Ltd., New Delhi, India.

[7] Ruth W. Chabay and Bruce A. Sherwood, 2010, *Matter and Interactions Vol II, Electric and Magnetic Interactions*, John Wiley.
Webpage https://matterandinteractions.org/

[8] Edward M. Purcell, *Electricity and Magnetism*, Tata McGraw-Hill, India.

[9] Matthew A. Kohlmyer, Marcos D. Caballero, Richard Catrambone, Ruth W. Chabay, Lin Ding, Mark P. Haugan, M. Jackson Marr, Bruce A. Sherwood, and Michael F. Schatz, *A Tale of Two Curricula: The performance of two thousand students in introductory electromagnetism*, Physical Review Special Topics - Physics Education Research, arXiv:0906.0022 [physics.ed-ph], DOI: 10.1103/PhysRevSTPER.5.020105

[10] Physics Courses in Georgia Tech, USA, http://introphys.gatech.edu/2017/Spring/2211/Schedule/schedule.html
Mechanics:
https://pe.gatech.edu/sites/pe.gatech.edu/files/SOUP/soup.2015.PHYS2211.syllabus+courseschedule.pdf
Electricity and Magnetism: https://pe.gatech.edu/sites/pe.gatech.edu/files/agendas/PHYS-2212Q-Intro%20Physics%20II%20%28QUP%29.pdf

[11] Physics Courses in Purdue, USA
Mechanics: https://engineering.purdue.edu/ME/Academics/Undergraduate/Courses/phys172.pdf

ISBN: 978-93-86171-56-6
Electricity and Magnetism: http://www.physics.purdue.edu/phys272/

[12] Physics Courses in Macquire, Australia
Mechanics: http://unitguides.mq.edu.au/unit_offerings/6531/unit_guide
Electricity and Magnetism: http://unitguides.mq.edu.au/unit_offerings/6644/unit_guide

[13] Instructor Resources in the Matter and Interactions webpage
https://matterandinteractions.org/instructors/adopters/

[14] A. K. T. Assis and J. P. M. C. Chaib, 2015, *Ampère's Electrodynamics Analysis of the Meaning and Evolution of Ampère's Force between Current Elements, together with a Complete Translation of his Masterpiece: Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience*, Apeiron, Montreal. http://www.ifi.unicamp.br/~assis/Amperes-Electrodynamics.pdf.
Homepage of A. K. T. Assis http://www.ifi.unicamp.br/~assis/

[15] R. W. Chabay and B. A. Sherwood, *A unified treatment of electrostatics and circuits* (2006), WWW Document available online at www.compadre.org/introphys/items/detail.cfm?ID=10026

About the Authors

Sridhar Chitta graduated from Regional Engg. College, Tiruchirapalli (now NITT) with a B.E. in Electronics and Communication Engineering (Madras University) and obtained M.E. in Control Systems in Electrical Engineering from the University of Bombay (V. J. T. Institute) in 1980. He has over 22 years of experience in industry and worked as a development engineer of controls for large airconditioning systems, material handling equipment, Special Purpose Machines, CNC drilling machines and Industrial material handling robots in India, the Middle East and Canada. After returning to India he joined as faculty in a private engineering college and shared his rich industrial experience among peers and students for more than a decade. He is pursuing a Ph.D degree in the area of Large-Scale Control Systems. He has authored the book *Circuit Process Mechanism* published by IK International, New Delhi and is currently authoring an expanded edition *Fundamentals of Electric Theory and Circuits*. He retired as Associate Professor in the Dept. of Electronics and Communication Engg. in an engineering college in Hyderabad, Telangana, India.

V. Kamaraju obtained his Ph.D in High Voltage Engineering from the Indian Institute of Science, Bangalore. He was formerly a Professor and Principal at the JNTU College of Engineering, Kakinada, Andhra Pradesh and retired from service in 2001. He was a visiting Professor at the Middle East Technical University, Gaziantep, Turkey during 1981-82. Professor Kamaraju is a Chartered Engineer and a Fellow of the Institution of Engineers (India). He has published many research papers and has been consultant to various industries and to the Andhra Pradesh State Electricity Board. He has published *High Voltage Engineering* in 1991, *Electrical Distribution Systems* and *Linear Systems*: *Analysis and Applications* during 2006-08, and *High Voltage Direct Current Transmission* in 2011, all by McGraw Hill Education (India). He received the Best Teacher award from the Government of Andhra Pradesh, India in 2001. Professor Kamaraju has done extensive research in the areas of liquid and solid dielectrics, composite insulation and partial discharges. He joined in a private institution as Professor and Head of Dept., Electrical Engineering for 12 years and with a total of 50 years of teaching experience, he finally retired in 2015. **Email** v.kamaraju@yahoo.com. **Phone** +91- 9849984747.

A. Mahesh Kumar obtained a B.Tech degree in Electrical and Electronics Engineering from Sri Venkateswara Engineering College (Jawaharlal Nehru Technological University), Hyderabad, Telangana, India in 2009. In 2011 he obtained an M.E degree in Power System & Power Electronics from Chaitanya Bharathi Institute of Science & Technology, (Osmania University), Hyderabad, Telangana in 2011. He is presently pursuing a Ph.D in Osmania University, Hyderabad, India in the area of Power Systems in the discipline of Electrical and Electronics Engineering.