List of *AJP* E&M Articles

The following 40 *American Journal of Physics* articles on electricity and magnetism were useful for understanding student difficulties, and for clarifying topics in advanced electromagnetism that are often ignored, unclear, or glossed over in undergraduate textbooks. Some are written from a pedagogical perspective, others are analyses of interesting problems in electrodynamics. A few of them inspired some of the in-class tutorials developed as a part of this project. Many (particularly #'s 1-26) are at a level of difficulty where upper-division physics students should be able to comprehend the majority of the content (at least with a little effort). They are presented in no particular order, though we highly recommend #'s 3-5, 17, 23, 25, 29, & 31.

As part of our learning goals, we decided that students should be given some exposure to scientific journal articles, which address topics differently than in undergraduate textbooks. The FA11 and SP12 E&M II courses at CU asked students in a homework assignment to read and briefly summarize a physics article relevant to electromagnetism. Students were free to choose any article they wished for the assignment, though we provided an abbreviated version of this list to students as suggestions.

1. Angular momentum in static electric and magnetic fields: A simple case

H. S. T. Driver
Am. J. Phys. **55**, 755-757 (1987)

The concept of the momentum carried by combined static and electric magnetic fields has been discussed in a number of articles [...]. The purpose of this note is to present a system of fields and conductors for which the calculation of torques and angular momenta is significantly simpler than in the models discussed in previous papers. It is hoped that this simplicity will encourage instructors to discuss this challenging topic with students taking introductory courses in electricity and magnetism.

2. Field just outside a long solenoid

J. Farley and R. H. Price
Am. J. Phys. **69**, 751-754 (2001)

Simple lessons about static magnetic fields are often taught with the model of an "infinite'' solenoid, outside of which the fields vanish. Just outside a very long but finite solenoid of length L, the field must be a decreasing function of L. We show that this external field is approximately uniform and decreases as L^{-2}. Furthermore, we show that the study of this external field provides interesting and surprisingly simple illustrations of techniques for analyzing magnetic fields.

3. The charge densities in a current-carrying wire

D. C. Gabuzda

Am. J. Phys. **65**, 412-414 (1997)

In the lab frame the total linear charge density of a current-carrying wire must be zero, while in the rest frame of the electrons making up the current the total volume charge density must be zero. These two pieces of information enable the determination of the volume, surface, and linear charge densities of such a wire in both of these frames using only straightforward relativistic length contractions and simple mathematics.

4. Magnetic force due to a current-carrying wire: A paradox and its resolution

D. C. Gabuzda

Am. J. Phys. **55**, 420-422 (1987)

A straightforward investigation at an introductory level of the interconnection between electricity and magnetism initially leads to the paradoxical result that a charge at rest with respect to a current-carrying wire feels a magnetic force due to that current. Students may benefit from a presentation of this paradox and its resolution.

5. Energy transfer in electrical circuits: A qualitative account

I. Galili and E. Goihbarg

Am. J. Phys. **73**, 141-144 (2005)

We demonstrate that the use of the Poynting vector for a model of the surface charge of a current carrying conductor can help qualitatively explain the transfer of energy in a dc closed circuit. The application of the surface charge model to a simple circuit shows that electromagnetic energy flows from both terminals of the battery, mainly in the vicinity of the wires (and not inside them) to the load where it enters and is converted into heat at a rate obtained from Ohm's law.

6. Teaching Faraday's law of electromagnetic induction in an introductory physics course

I. Galili, D. Kaplan, and Y. Lehavi

Am. J. Phys. **74**, 337-343 (2006)

Teaching Faraday's law of electromagnetic induction in introductory physics courses is challenging. We discuss some inaccuracies in describing a moving conductor in the context of electromagnetic induction. Among them is the use of the ambiguous term "area change" and the unclear relation between Faraday's law and Maxwell's equation for the electric field circulation. We advocate the use of an expression for Faraday's law that shows explicitly the contribution of the time variation of the magnetic field and the action of the Lorentz force, which are usually taught separately. This expression may help students' understanding of Faraday's law and lead to improved problem solving skills.

7. Charge density on a conducting needle

D. J. Griffiths and Y. Li

Am. J. Phys. **64**, 706-714 (1996)

We attempt to determine the linear charge density on a finite straight segment of thin charged conducting wire. Several different methods are presented, but none yields entirely convincing results, and it appears that the problem itself may be ill-posed.

8. Energy flow from a battery to other circuit elements: Role of surface charges

M. K. Harbola

Am. J. Phys. **78**, 1203-1206 (2010)

A qualitative description of energy transfer from a battery to a resistor using the Poynting vector was recently published. We make this argument quantitative by considering a long current carrying wire and showing that the energy transferred across a plane perpendicular to the wire is equal to the Joule heating in the wire beyond this plane.

9. The Origins and Developments of the Concepts of Inductance, Skin Effect and Proximity Effect.

T. J. Higgins

Am. J. Phys. **9**, 337-346 (1941)

Comment: A nice exposition on some of the contributions to electromagnetism by a few of the big names in the history of physics.

10. Electromagnetic momentum density and the Poynting vector in static fields

F. S. Johnson, B. L. Cragin and R. R. Hodges

Am. J. Phys. **62**, 33-41 (1994)

Many static configurations involving electrical currents and charges possess angular momentum in electromagnetic form; two examples are discussed here, an electric charge in the field of a magnetic dipole, and an electric charge in the vicinity of a long solenoid. These provide clear evidence of the physical significance of the circulating energy flux indicated by the Poynting vector, as the angular momentum of the circulating electromagnetic energy can be converted to mechanical angular momentum by turning off the magnetic field. Electromagnetic momentum is created whenever electric fields change in the presence of a magnetic field and whenever magnetic fields change in the presence of an electric field. When simple dielectrics are involved, the momentum density can be resolved into two components, […]

11. Electromagnetics from a quasistatic perspective

J. Larsson

Am. J. Phys. **75**, 230-239 (2007)

Quasistatic models provide intermediate levels of electromagnetic theory in between statics and the full set of Maxwell's equations. Quasistatics is easier than general electrodynamics and in some ways more similar to statics, but exhibits more interesting physics and more important applications than statics. Quasistatics is frequently used in electromagnetic modeling, and the pedagogical potential of electromagnetic simulations gives additional support for the importance of quasistatics. Quasistatics is introduced in a way that fits into the standard textbook presentations of electrodynamics.

12. Is the electrostatic force between a point charge and a neutral metallic object always attractive?

M. Levin

Am. J. Phys. **79**, 843-849 (2011)

We give an example of a geometry in which the electrostatic force between a point charge and a neutral metallic object is repulsive. The example consists of a point charge centered above a thin metallic hemisphere, positioned concave up. We show that this geometry has a repulsive regime using both a simple analytical argument and an exact calculation for an analogous two-dimensional geometry. Analogues of this geometry-induced repulsion appear in many other contexts, including Casimir systems.

13. The story of c

K. S. Mendelson

Am. J. Phys. **74**, 995-997 (2006)

The letter c is the standard symbol for the speed of light, but that was not always the case. I describe how c was first introduced into the theory of electromagnetism and the stages by which it came to be used to denote the speed of light.

14. A constructive approach to the special theory of relativity

D. J. Miller

Am. J. Phys. **78**, 633-638 (2010)

Simple physical models of a measuring rod and of a clock are used to demonstrate the contraction of objects and clock retardation in special relativity. It is argued that models can help student understanding of special relativity and distinguishing between dynamical and purely perspectival effects.

15. Challenges to Faraday's flux rule

F. Munley

Am. J. Phys. **72**, 1478-1483 (2004)

Faraday's law (or flux rule) is beautiful in its simplicity, but difficulties are often encountered when applying it to specific situations, particularly those where points making contact to extended conductors move over finite time intervals. These difficulties have led some to challenge the generality of the flux rule. The challenges are usually coupled with the claim that the Lorentz force law is general, even though proofs have been given of the equivalence of the two for calculating instantaneous emfs in well-defined filamentary circuits. I review a rule for applying Faraday's law, which says that the circuit at any instant must be fixed in a conducting material and must change continuously. The rule still leaves several choices for choosing the circuit. To explicate the rule, it will be applied to several challenges, including one by Feynman.

16. In what frame is a current-carrying conductor neutral?

P. C. Peters

Am. J. Phys. **53**, 1165-1169 (1985)

A current-carrying conductor is often used as an example to illustrate the transformation laws of the electric and magnetic fields. The conductor is usually assumed to be neutral in the rest frame of the lattice of positive ions, in which frame the free-electrons have a drift velocity v. A re-examination of this question, taking into account a self-induced Hall effect, shows that the bulk of the conductor is negatively charged in this frame. The bulk of the conductor is neutral, however, in the frame in which the free-electrons are at rest, just the opposite of what is usually assumed for this system. A simple ring circuit driven by an induced emf is used to understand the role of surface charge densities on the conductor, and implications for more general circuits are discussed.

17. Surface charges and fields of simple circuits

N. W. Preyer

Am. J. Phys. **68**, 1002-1006 (2000)

Interest in the surface charges on circuits, and their utility in the conceptual understanding of circuit behavior, has recently increased. Papers and textbooks have discussed surface charges either with qualitative diagrams or analytic results for very special geometries. Here, I present the results of numerical calculations showing the surface charges on several simple resistor-capacitor circuits. Surface charges are seen to guide the motion of charges and create the appropriate electric potential and Poynting vectors for the circuit, and hence are an important factor in the teaching of circuit theory.

18. The transient magnetic field outside an infinite solenoid

R. J. Protheroe and D. Koks

Am. J. Phys. **64**, 1389-1393 (1996)

The electromotive force (emf) in a loop outside an infinite solenoid with changing current is usually calculated using the vector potential because the magnetic field outside an infinite solenoid is supposed to be zero. However, the magnetic field will only be zero for steady currents. A change in the applied voltage will give rise to a change in the current, which will propagate along the solenoid in the same way as a wave on a transmission line. This gives rise to a transient magnetic field outside the solenoid. It is quite possible to calculate this transient magnetic field and use it in Faraday's law to calculate the emf directly without using the vector potential. In practice, it is usually simpler to use the vector potential. However, care should be taken to ensure that students are not given the impression that there is no magnetic field and that it is the vector potential that acts on charges in the loop. We give examples of the magnetic field configuration outside an infinite solenoid for steplike change in driving voltage and for an ac driving voltage.

19. Physical Significance of the Poynting Vector in Static Fields

E. M. Pugh and G. E. Pugh

Am. J. Phys. **35**, 153 (1966)

Even in static fields, where there is no observable energy flow, Poynting vector momentum must be considered to avoid an apparent violation of the angular-momentum law. This often-neglected aspect of the Poynting vector is illustrated in an easily calculated example. Two other simple and rigorously solvable pedagogical examples illustrate the role of the Poynting vector in defining energy flow in static fields.

20. Forces and work on a wire in a magnetic field

J. A. Redinz

Am. J. Phys. **79**, 774-776 (2011)

We illustrate the role of magnetic forces in lifting a current-carrying wire by discussing the various forces acting on the positive ions and the electrons that compose the wire.

21. B and H, the intensity vectors of magnetism: A new approach to resolving a century-old controversy

J. J. Roche

Am. J. Phys. **68**, 438-449 (2000)

The B and H controversy, which has persisted for more than a century, is at bottom a debate over the structure of the macroscopic magnetic field, both in a vacuum and in a magnetized body. It is also a controversy over units and notation. It is paralleled by the problem of D and E in dielectrics. Its origins are traced to a dual magnetic field concept of William Thomson, to an altogether different dual field concept of Faraday, and to Maxwell's attempt to bind the concepts of Thomson and Faraday together. The author argues that severe ambiguities were inadvertently introduced to this subject during its foundational period and subsequently, and that many of these still remain embedded in the present-day interpretation of the subject. The article attempts to clear up a long history of misunderstanding by dealing with each difficulty in the same sequence in which it was introduced to electromagnetism.

22. How batteries work: A gravitational analog

D. Roberts

Am. J. Phys. **51**, 829-831 (1983)

There is a region in any battery where the charges move in a direction opposite to that of the electric force on them. A "gravitational cell" is used to show that this motion is a diffusion analogous to that against pressure gradients in osmotic pressure situations. The driving mechanism for the diffusion is the existence of lower lying states in one region compared to an adjacent region, and it is relaxation into these low lying states that is the source of energy for the circuit.

23. What do "voltmeters" measure?: Faraday's law in a multiply connected region

R. H. Romer

Am. J. Phys. **50**, 1089-1093 (1982)

A long solenoid carrying a varying current produces a time-dependent magnetic field and induces electric fields, even in the region exterior to the solenoid where $\partial\mathbf{B}/\partial t$ and therefore curl $\mathbf{E}$ vanish. By paying attention to (a) what it is that a "voltmeter" measures and (b) the simplest properties of line integrals (e.g., under what circumstances the line integral of $\mathbf{E}$ is path independent), it is easy to use Faraday's law to predict the readings of voltmeters connected to various points in a circuit external to the solenoid. These predicted meter readings at first seem puzzling and paradoxical; in particular, two identical voltmeters, both connected to the same two points in the circuit, will not show identical readings. These theoretical predictions are confirmed by simple experiments.

24. How batteries discharge: A simple model

W. M. Saslow

Am. J. Phys. **76**, 218-223 (2008)

A typical battery is a set of nominally identical voltaic cells in series and/or parallel. We consider the discharge of a single voltaic cell. As the cell discharges due to current-carrying chemical reactions, the densities of the chemical components decrease, which leads to an increase in the internal resistance of the voltaic cell and, upon discharge, a decrease in its terminal voltage and current. A simple model yields behavior similar to what is observed, although accurate battery models are more complex.

25. Thoughts on the magnetic vector potential

M. D. Semon, J. R. Taylor

Am. J. Phys. **64**, 1361-1369 (1996)

We collect together several ideas that we have found helpful in teaching the magnetic potential **A**. We argue that students can be taught to visualize **A** for simple current distributions and to see **A** as something with physical significance beyond its bare definition as the "thing whose curl is **B**."

26. Faraday's law, Lenz's law, and conservation of energy

L. T. Wood, R. M. Rottmann, and R. Barrera

Am. J. Phys. **72**, 376-380 (2004)

We describe an experiment in which the induced electromotive force in a coil caused by an accelerating magnet and the position of the moving magnet are measured as a function of the time. When the circuit is completed by adding an appropriate load resistor, a current that opposes the flux change is generated in the coil. This current causes a magnetic field in the coil which decreases the acceleration of the rising magnet, as is evident from the position versus time data. The circuit provides a direct observation of the effects that are a consequence of Lenz's law. The energy dissipated by the resistance in the circuit is shown to equal the loss in mechanical energy of the system to within experimental error, thus demonstrating conservation of energy. Students in introductory physics courses have performed this experiment successfully.

27. The Lorentz Theory of Electrons and Einstein's Theory of Relativity

S. Goldberg

Am. J. Phys. **37**, 982 (1969)

The development of Lorentz' theory of electrons is reviewed insofar as it relates to the problem of the electrodynamics of moving bodies. It is shown that the principle of relativity did not play an important role in the Lorentz theory, and that though Lorentz eventually realized the distinctions between his own work and that of Einstein, he was unwilling to completely embrace the Einstein formulation and thereby reject the ether.

28. Hidden momentum, field momentum, and electromagnetic impulse

D. Babson, S.P. Reynolds, R. Bjorkquist and D.J. Griffiths

Am. J. Phys. **77**, 826 (2009)

Electromagnetic fields carry energy, momentum, and angular momentum. The momentum density, $\varepsilon_0(\mathbf{E}\times\mathbf{B})$, accounts (among other things) for the pressure of light. But even static fields can carry momentum, and this would appear to contradict a general theorem that the total momentum of a closed system is zero if its center of energy is at rest. In such cases, there must be some other momenta that cancel the field momentum. What is the nature of this "hidden momentum" and what happens to it when the electromagnetic fields are turned off?

29. Why the speed of light is reduced in a transparent medium

M.B. James and D.J. Griffiths

Am. J. Phys. **60**, 309 (1992)

It is well known from optics that the speed of light in a transparent medium is reduced by a factor of n (the index of refraction) as compared with vacuum. Maxwell's electrodynamics provides a simple account of this phenomenon, and relates n to the electric susceptibility of the material. But the conventional analysis does little to illuminate the mechanism involved. This paper offers some elucidation of the "miracle" by which the radiation from many induced molecular dipoles conspires to produce a single wave propagating at the reduced speed.

30. Electric fields and charges in elementary circuits

M.A. Heald

Am. J. Phys. **52**, 522 (1984)

In an effort to clarify the role of surface charges on the conductors of elementary electric circuits and the electric fields in the space around them, we present a quantitative analysis of (two-dimensional) circular current loops. It is also noted that, in general, lines of Poynting flux lie in the equipotential surfaces of quasistatic systems.

31. Surface charges on circuit wires and resistors play three roles

J.D. Jackson

Am. J. Phys. **64**, 855 (1996)

The significance of the surface electric charge densities associated with current-carrying circuits is often not appreciated. In general, the conductors of a current-carrying circuit must have nonuniform surface charge densities on them (1) to maintain the potential around the circuit, (2) to provide the electric field in the space outside the conductors, and (3) to assure the confined flow of current. The surface charges and associated electric field can vary greatly, depending on the location and orientation of other parts of the circuit. We illustrate these ideas with a circuit consisting of a resistor and a battery connected by wires and other conductors, in a geometry that permits solution with a Fourier-Bessel series, while giving flexibility in choice of wire and resistor sizes and location of the battery. Plots of the Poynting vector graphically demonstrate energy flow from the battery to the resistive elements. […] The discussion is in terms of time-independent currents and voltages, but applies also to low-frequency ac circuits.

32.The Poynting vector and power in a simple circuit

S. Majcen, R.K. Haaland and S.C. Dudley

Am. J. Phys. **68**, 857 (2000)

This paper outlines a simple technique for visualizing the flow of energy from a power supply to elements in a circuit as a flow through the electric and magnetic fields—or the Poynting vector—surrounding the circuit. In addition to providing the reader experience with the Poynting vector and its relation to energy flow and power, we also present a quick method for solving Laplace's equation in two dimensions.

33. Electric fields in the presence of conducting objects

J.L. Rodriquez Marrero

Am. J. Phys. **78**, 639 (2010)

When a conducting object is placed in a region where there is an electric field, charges are induced on its surface. We seek the unique surface charge density that produces an electric field that cancels the original field inside the conductor. When the external sources are point charges or uniform fields, it is easy to determine the field that the induced charges must produce inside the conducting object. Up to a constant, this field gives the potential on the conducting surface, which suffices to determine the potential function outside the conductor. The perturbing field produced by the induced charges is obtained from this potential, and a simple boundary condition gives us the induced surface charge density.

34. Magnetic Forces Doing Work?

E.P. Mosca

Am. J. Phys. **42**, 295 1974

Consider a conducting circuit moving with velocity **v** through a constant magnetic field **B**. The induced emf is given by ∫ **v x B . dl** were the integral is taken once around the circuit. Some texts refer to **v x B** as the force the magnetic field exerts on a unit charge moving around the circuit. This is incorrect as magnetic forces can never do work. The force the conductor exerts on an electron is shown to do this work.

35. Two-capacitor problem: A more realistic view

R.A. Powell

Am. J. Phys. **47**, 460 (1979)

A popular circuit problem encountered in introductory physics and electromagnetics texts is discussed here in a more realistic manner by considering the self-inductance of the circuit. For practical values of the circuit parameters, the model usually put forth to solve this problem, a series *RC* circuit, appears inappropriate.

36. The concical resistor conundrum: A potential solution

J.D. Romano and R.H. Price

Am. J. Phys. **64**, 1150 (1996)

A truncated cone, made of material of uniform resistivity, is given in many introductory physics texts as a nontrivial problem in the computation of resistance. The intended method and answer are incorrect and the problem cannot be solved by elementary means. In this paper, we (i) discuss the physics of current flow in a nonconstant cross-section conductor, (ii) examine the flaws in the "standard" solution for the truncated cone, (iii) present a computed resistance found from a numerically generated solution for the electrical potential in the truncated cone, and (iv) consider whether any problem exists to which the standard solution applies.

37. Electromechanical implications of Faraday's law: A problem collection

W.M. Saslow

Am. J. Phys. **55**, 986 (1987)

A collection of problems illustrating the electromechanical implications of Faraday's law is presented. They are appropriate for well-prepared freshman and all undergraduate physics majors. A number of interesting examples are worked out analytically, including Thomson's jumping ring demonstration. They are of interest in part because they include the effects of inductance and capacitance more fully than in the usual textbook treatments.

38. Eddy currents: Levitation, metal detectors, and induction heating

G. Wouch and A.E. Lord, Jr.

Am. J. Phys. **46**, 464 (1978)

A metal object placed in the alternating magnetic field of a current distribution experiences a lifting force (electromagnetic levitation) and heating. These effects are caused by eddy currents induced in the metal. The eddy currents also change the inductance of the current generator. A simple and accessible calculation is given of these effects for a sphere in the field of a single circular loop of alternating current. Hopefully these simple calculations will help towards the inclusion of eddy current effects in the upper undergraduate physics E & M syllabus.

39. Elegant calculations of the Coulomb force between two hemispherical surfaces with uniform charge densities

X. Xie and X. Huang

Am. J. Phys. **62**, 952 (1994)

Many examples of the calculation of the Coulomb forces between stationary point charges have been given in university physics books. Also, people often calculate easily the force between two large uniformly charged plates separated by a certain distance. In recent years, some discussions about calculations of electric forces have been published in this journal. In this note we show that the electrostatic force between two uniformly charged hemispherical surfaces can also be calculated conveniently by two elegant and easy methods.

40. Why we use retarded potentials

J.L. Anderson

Am. J. Phys. **60**, 465 (1992)

The use of retarded potentials in solving the wave equation is usually justified on physical grounds or by an appeal to causality. It is shown here that these potentials are asymptotic solutions obtained by solving the wave equation as an initial value problem and imposing only the condition that the initial field energy be finite. The relation of this result to the so-called electromagnetic arrow of time is discussed.