Physics 218: Electricity and Magnetism II

Spring 2004

This course is all about *light*, viewed as a consequence of the same principles that bring us the Maxwell equations. We'll discuss electromagnetic wave propagation; the generation of electromagnetic radiation by time dependent charges, currents, and fields; the interaction of radiation and linear media; diffraction and the foundations of physical optics; and the relation of electrodynamics and the special theory of relativity.

Professor: Dan Watson (B&L 418, 275-8576, dmw@pas.rochester.edu, www.pas.rochester.edu/~dmw).

Grader: Kyoung Hee Kim (B&L 373, 275-4001, khkim@pas.rochester.edu)

Textbooks: David J. Griffiths, *Introduction to electrodynamics*, third edition (1999) is the only required text. Also recommended are Francis S. Crawford, *Waves: Berkeley physics course v.3* (1968); Edward M. Purcell, *Electricity and magnetism: Berkeley physics course v.2*, second edition (1985); Eugene Hecht, *Optics*, fourth edition (2002). All of these books are on two-hour reserve in the Physics-Optics-Astronomy library. Additional, useful, books will be found below on the Reading List.

World Wide Web site: www.pas.rochester.edu/~dmw/phy218/. In these pages one will find complete lecture presentations, a calendar of class meetings and office hours, homework-problem solutions, exam solutions, practice examinations, study aids, links to other useful Web sites, and even a copy of this document.

Lectures: In B&L 270, 11:00-11:50 AM, Mondays, Wednesdays and Fridays, conducted by Dan. All students are expected to attend all of the lectures. Complete electronic copies of each lecture presentation can be found on our Web site, about a week before the lecture is given, and can be downloaded and printed in a format that's handy for taking additional lecture notes.

Recitations: In B&L 270, 2:00-3:15 PM, on Fridays following new homework assignments, conducted by Dan. All students are expected to attend all of the recitations. These classes will usually operate as workshops, in which the students will work in small teams (3-4 students each) to set up and/or solve practice problems similar to those on the homework and exams. They are scheduled strategically on Friday afternoons; in Dan's experience, most students do most of the work on their problem sets over the weekend.

E-mail list server: phy218@mail.rochester.edu. Messages sent to this address will be re-sent to everybody in the class. Obviously this provides a good way to make general announcements. Dan also encourages use of the list server to ask questions about readings, lectures, homework problems and the like; the rest of the class will probably also be interested in your questions and the answers you'll receive. (He will answer e-mail questions privately, too.)

Homework: Eight problem sets, assigned at regular intervals during the term. Each problem set counts equally toward the final grade. Normally, detailed solutions to the problem sets will be posted directly following the lecture they are due, which will make it difficult to accept late homework.

About two-thirds of every homework assignment will be designated as *solo* problems, and the rest as *team* problems. For the solo problems, students are expected to work independently, but the team problems are to be worked out by groups of 3-4 students working together. Each student is meant to submit solutions of all of the problems, but of course the solutions of the team problems would be essentially identical to those of the other team members. The problems chosen for the team homework usually will be the most difficult ones in the assignment. At least at first, the teams will be those formed rather arbitrarily during the first recitation. We will take care to rotate the membership of the teams as the semester progresses. Dan will be the official arbiter of homework-team membership.

Examinations: One midterm exam, covering most of the study of plane waves, will be given on 27 February 2004 during the time and in the place normally scheduled for recitation. A final examination, covering the whole course, but with emphasis on the latter parts, will be given on 6 May 2004, 8:30-11:30 AM. Detailed solutions will be posted at the conclusion of each exam. If you miss an exam due to illness or emergency, a makeup exam may be scheduled by appointment. ***All makeups will be oral examination***s, lasting as long as the exams they replace, and will be administered and graded by Dan.

To each exam you are allowed to bring only a writing instrument, a calculator, and one letter-size sheet on which *you* have written as many notes, formulas, and physical constants as you like. No computers, or graphing calculators into which text and graphics may be downloaded, are allowed.

The best way to study for the examinations is to do the homework problems, to work out the sample exams that are available (with solutions) in our World Wide Web pages, and to make a good cheat sheet to bring to the exam.

Grades: Based 32% on the homework and 68% on the examinations. The midterm is worth 30%, and the final exam 38%, of the final grade, with each problem set counting for 4%. In terms of the percentage of the maximum possible score, the grading scale will be as follows:

Percentage score	≥ 85	≥ 80	≥ 75	≥ 70	≥ 65	≥ 60	≥ 55	≥ 50	≥ 40	< 40
Final grade	A	A-	B+	B	B-	C+	C	C-	D	E

Last time Dan taught this course, in Spring 1991 (!), 21 students took it, and they received an average percentage score of 73.4, for an average grade of B. We round up to integers before assigning the final grade.

Academic honesty disclaimer: For our purposes, *cheating* consists of submission of solo-homework or exam solutions that are not one's own work, or submission of such work under someone else's name. According to University rules, any detected act of cheating that is not the result of a simple misunderstanding must be handed over to the Board on Academic Honesty for investigation.

Help: Office hours are posted on the Calendar page of the PHY 218 Web site. Dan can also be found most afternoons in or near his office or lab. Please come and talk to him whenever you want. Or email him, privately or through the list server. He will be happy enough to deal with specific questions about the course, homework or exams, but would be even more interested in talking to those who find the course confusing enough that they're not even sure what to ask.

Course outline

The material we will cover is mostly found in the required textbook, *Introduction to Electrodynamics* (third edition, 1999), by D.J. Griffiths; in the relevant volumes of the Berkeley Physics Course: *Waves* (1968), by F.S. Crawford, and *Electricity and Magnetism* (second edition, 1985), by E.M. Purcell; and in *Optics* (fourth edition, 2002), by E. Hecht. Except for the material on rainbows, the lectures will follow these books fairly closely in content; reading assignments corresponding to each lecture are given in the following, in the hope that you will at least glance over the pertinent material in advance.

Lecture, date — ***Subject*** — ***Reading***

Electrodynamics. Putting the finishing touches on Maxwell's equations, we complete the foundations of electrodynamics, in preparation for the study of light.

Lecture	Date	Subject	Reading
42	14 January	Displacement current, Maxwell's repair of Ampere's Law, and the final version of Maxwell's equations.	Griffiths, pp. 321-330
43	16 January	Boundary conditions. The potentials V and $\boldsymbol{A}$ in electrodynamics.	Griffiths, pp. 331-333
44	21 January	Gauge transformations; the Coulomb and Lorentz gauges. Force, momentum and energy in electrodynamics.	Griffiths, pp. 345-349, 416-422
45	23 January	Conservation of momentum and energy in electrodynamics: Poynting's theorem, the Maxwell stress tensor. Review of the various systems of units in use with electrodynamics.	Griffiths, pp. 349-359, 558-561

Electromagnetic Waves. We derive a wave equation from Maxwell's equations, solve it, and from the solutions we obtain a description of the basic properties of light: refraction, reflection, absorption, dispersion, polarization and interference.

Lecture	Date	Subject	Reading
46	26 January	The wave equations in electrodynamics and in mechanics (waves on a string), and the simplest solutions. Phase velocity.	Griffiths, pp. 364-370; Crawford, pp. 50-59
47	28 January	Transverse waves and polarization. Boundary conditions for transverse waves, reflection and transmission.	Griffiths, pp. 370-374; Crawford, pp. 394-406
48	30 January	Analogy between waves on a string and those in electrical circuits: reflection and transmission of impedance discontinuities. Impedance matching.	Crawford, pp. 191-196, 226-240
49	2 February	Propagation of plane electromagnetic waves in vacuum; energy and momentum of plane waves.	Griffiths, pp. 374-382
50	4 February	Plane electromagnetic waves in linear media. Reflection and transmission for normal incidence on dielectric surfaces.	Griffiths, pp. 382-386; Crawford, pp. 243-248
51	6 February	Derivation of Fresnel's equations for the reflection and transmission coefficients of light at oblique incidence. Snell's Law.	Griffiths, pp. 386-390

Lecture, date		***Subject***	***Reading***
52	9 February	Total internal reflection, polarization on reflection and Brewster's angle.	Griffiths, pp. 390-392; Crawford, pp. 342-346, 407-419
53	11 February	Interference: transmission and reflection by finite-thickness linear media, antireflection coatings.	Crawford, pp. 245-252
54	13 February	Electromagnetic waves in conducting media. Attenuation of the waves within the conductor: skin depth.	Griffiths, pp. 392-395
55	16 February	Reflection and transmission by conducting surfaces. Radiation pressure.	Griffiths, pp. 396-398
56	18 February	Dispersion relations. Frequency-dependent conductivity, dielectric constant and permeability. Group velocity. Dispersion and absorption in *LRC* circuits.	Griffiths, pp. 398-399; Purcell, pp. 298-318
57	20 February	Nonconducting media: anomalous dispersion, absorption, Cauchy's equation.	Griffiths, pp. 399-404; Crawford, pp. 176-184
58	23 February	Dispersion in conductors. Plasma frequency. Example of the ionosphere.	Crawford, pp. 184-191
59	25 February	Waveguides. *TE* and *TM* modes in rectangular waveguides.	Griffiths, pp. 405-410; Crawford, pp. 337-342
60	27 February	*TEM* waveguide modes: their absence in hollow metallic waveguides, and their presence in coaxial metallic and hollow dielectric waveguides	Griffiths, pp. 411-412
	27 February	**Midterm examination 1** on all material covered to date	

Electromagnetic Radiation. Here we receive an introduction to some of the most interesting electromagnetic phenomena, involving radiation of electromagnetic waves by moving charges, and scattering and diffraction of light by apertures and obstructions. This includes a description of rainbows, and the reason for the blue color and polarization of the sky. In the discussion of radiation-reaction forces, we also discover some interesting apparent limitations to classical electrodynamics.

61	1 March	Retarded potentials. Cause and effect in electrodynamics.	Griffiths, pp. 422-428
62	3 March	Electric dipole radiation. Spherical waves. Near-field and far-field domains. Dipole antennas.	Griffiths, pp. 443-449; Crawford, pp. 366-378
63	5 March	Cross section of dipole radiators. Rayleigh's explanation of the blue sky. Magnetic dipole radiation.	Griffiths, pp. 451-454; Crawford, pp. 378-380
64	15 March	Radiation from arbitrary charge and current distributions. Larmor's formula for the radiated power.	Griffiths, pp. 454-458
65	17 March	Retarded potentials for a point charge in motion. The Liènard-Wiechert formulae.	Griffiths, pp. 429-434
66	19 March	Derivation of the fields from a moving point charge.	Griffiths, pp. 435-440
67	22 March	Power radiated by point charges in motion: bremsstrahlung and synchrotron radiation.	Griffiths, pp. 460-464

Lecture, date		*Subject*	*Reading*
68	24 March	The Abraham-Lorentz formula for the radiation-reaction force. Radiation damping.	Griffiths, pp. 465-468
69	26 March	The origin of radiation reaction; a fundamental inconsistency of classical electrodynamics with Newton's third law?	Griffiths, pp. 469-472
70	29 March	Application of Huygens' principle to electromagnetic waves: far-field (Frauenhofer) diffraction.	Crawford, pp. 478-491; Hecht, pp. 443-445
71	31 March	Diffraction from a square aperture or square obstacle. Babinet's principle.	Hecht, pp. 464-467, 508-509
72	2 April	Diffraction from a circular aperture: dark rings and the Airy disk. Angular resolution of the eye and of telescopes.	Hecht, pp. 467-474
73	5 April	Application of refraction, interference and diffraction:	
74	7 April	the optics of raindrops, and how rainbows and glories work	

Electrodynamics and Relativity. Maxwell's equations, as we have written them already, are invariant under Lorentz transformations; therefore the special theory of relativity is already built into our description of electrodynamics. Here we will review special relativity, introduce four-vector and tensor notation, and explore the reasons that relativity came to be incorporated without any deliberate effort on our part.

75	9 April	The special theory of relativity: Einstein's postulates, relativity of simultaneity, time dilation, Lorentz contraction	Griffiths, pp. 477-493
76	12 April	The Lorentz transformations and the velocity addition rule.	Griffiths, pp. 493-498
77	14 April	Four-vectors and their Lorentz transformations. Covariant and contravariant four-vectors. Invariant intervals. Spacetime diagrams; world lines and the light cone.	Griffiths, pp. 500-506
78	16 April	The four-velocity and energy-momentum four-vectors. Proper time.	Griffiths, pp. 507-511
79	19 April	Energy and momentum conservation in relativity: annihilation, pion decay, Compton scattering.	Griffiths, pp. 511-515
80	21 April	Force and momentum in relativity: inapplicability of Newton's third law; the Minkowski force.	Griffiths, pp. 516-521
81	23 April	The relativistic invariance of electric charge. Magnetism as a relativistic phenomenon.	Griffiths, pp. 522-525; Purcell, pp. 176-199
82	26 April	Relativistic transformation of the electric and magnetic fields.	Griffiths, pp. 525-532; Purcell, pp. 235-241
83	28 April	The electromagnetic field tensor; the equations of electrodynamics in tensor notation	Griffiths, pp. 535-540
	6 May	**Final Examination** covering the entire course	

Reading list

Here are the books that will be on reserve in the Physics, Optics and Astronomy Library. The titles of required and recommended textbooks appear in ***bold italics***. The brief descriptions of each give an idea of what they're best at, so as to encourage you to read them.

1. D.J. Griffiths, ***Introduction to Electrodynamics*** (third edition, 1999). This is the principal required textbook for the course. It is extremely well written and easy to read, with good problems and lots of examples, and reaches a high level of mathematical elegance. This makes it especially good as preparation for a graduate E&M course that uses the book by Jackson (see below), except for its use of MKS units throughout instead of CGS. It lacks discussions of some topics in radiation that Dan would not like to omit, which will be filled in by use of the other textbook and lectures.

2,3. G.L. Pollack and D.R. Stump, *Electromagnetism* (2002); R.K. Wangsness, *Electromagnetic Fields* (second edition, 1986). Very similar in approach, content and style to Griffiths' book; these books should be your next recourse. They are very well written and have good examples. They also use MKS units.

4. M.H. Nayfeh and M.K. Brussel, *Electricity and Magnetism* (1985). Their discussions of the principles are very brief and dry, compared to those in Griffiths, but they include a very large number of examples on every topic, including many not found in the other books. Also uses MKS units.

5. M.A. Heald and J.B. Marion, *Classical Electromagnetic Radiation* (third edition, 1995). A nice book which seems a little too heavy on electromagnetic radiation and too light on electrostatics and magnetostatics to use as a textbook for PHY 217, but will be a useful reference here in PHY 218. It is also the only good junior-level textbook that uses CGS units.

6. J.D. Jackson, *Classical Electrodynamics* (second edition, 1975; third edition, 1999). You will become intimately familiar with this book if you go to graduate school in physics. It's the classic, definitive text for E&M, very well written and reflecting a profound understanding of the subject. The relevant parts are sometimes helpful for you undergrads, especially since you don't have to worry about solving the diabolically clever and extremely difficult problems at the ends of the chapters. CGS units are used throughout the second edition, which is still widely preferred to the third edition; the appendix in either edition that tells you all you need to know about unit conversions is better than similar discussions in the other books.

7. E.M. Purcell, ***Electricity and Magnetism*** (second edition, 1985). Also known as Volume 2 of the Berkeley Physics Course, this book will serve as a supplementary text through the treatment of relativity in Physics 218. Although it was originally intended as a freshman-level text, it has rarely performed that function, but it is used frequently in junior E&M because it is eminently readable, and has all of the physics of the more mathematically-advanced texts, presented succinctly and beautifully. The author was a very distinguished physicist; he won the Nobel Prize (1952) for his role in the development of nuclear magnetic resonance studies of atomic and molecular structure, and also has the co-discovery of interstellar neutral atomic hydrogen to his credit. Dave Griffiths, the author of our main textbook, was Purcell's graduate student.

8. F.S. Crawford, ***Waves*** (1968). The third volume of the Berkeley Physics Course is not used as widely as the second, but it is full of insight into how electromagnetic waves work, useful mechanical analogies, and clever uses of mathematics that one might consider too advanced for the anticipated sophomore audience. Dan hopes that the latest printing still includes the "optics kit" that came with his copy.

9. E. Hecht, ***Optics*** (fourth edition, 2002). This is one of the two optics books that seem to be on every physicist's bookshelf: an excellent introduction to geometrical and physical optics, very thorough, complete, well-written, and fairly modern. We won't use it very much in PHY 218 – only for the short section on diffraction – but those of you who plan to take AST 203 should probably buy it anyway, as it is the main text for that course. (The other optics book you need for your collection is the famous *Principles of Optics,* by Max Born and Emil Wolf, but you don't need it yet.)

10. R.P. Feynman, R.B. Leighton, and M. Sands, *The Feynman Lectures On Physics*, volumes 1 and 2 (1963). You are probably already familiar with these lectures by one of the most famous and brilliant scientists in history (Nobel Prize in Physics, 1965, for the invention of much of quantum electrodynamics). They are full of terrific insights into electrodynamics, as well as all other basic branches of physics, and are worth reading at every stage of your physics education.