

Physics 516: Electromagnetic Phenomena
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Spring 2007

27 January 1884. Thought about electromagnetic rays.
11 May. Hard at work on Maxwellian electromagnetics.
13 May. Nothing but electromagnetics.
8 July. Electromagnetics, still without success.
17 July. Depressed; could not get on with anything.
24 July. Did not feel like working.
7 August. Saw from Rie's book that most of what I have found so far is already known.
– From the Diary of Heinrich Hertz

Our goal in this course is to examine some electromagnetic phenomena relevant to the research being done in this department, then obtain them as mathematical consequences of classical electrodynamics. We want to look at the phenomena through the lens of mathematics, to see common themes. Finally, we want to consolidate many bits of information you've gathered in your previous courses into a more coherent whole.

Announcements: <http://courseweb.library.upenn.edu/>

Time: Lectures WF 10:00–11:00 and Th 12:00–1:00 in DRL room 2C4. The recitation on Mondays at 10:00 will usually be a problem-solving session. Sometimes we will instead use this hour for makeup lectures or pre-exam review.

Additional office hours: We'll arrange these to suit the class.

Assignments: Biweekly problem sets, midterm, final.

General policies: see "Course Info" handout.

General prerequisites:

Familiarity with Maxwell equations in differential and integral form. Familiarity with electro- and magnetostatics. Familiarity with special relativity, some linear algebra, and some Lagrangian mechanics, at the levels of PHYS351 and 361–362 and MATH240. Facility with some computer-math package, such as *Maple* or *Mathematica*.

Books (more are listed in the References):

Recommended:

Pollack and Stump, *Electromagnetism* (Addison Wesley, 2002). If you find any errors in the book, please bring them to my attention so I can distribute to the class.

Also useful (and available in the Math/Physics Reserve):

Landau and Lifshitz, *Classical theory of fields* and *Electrodynamics of continuous media*

Feynman lectures: The definitive and extended edition volumes 1–2

JD Jackson, *Classical electrodynamics*

E Purcell, *Electricity and magnetism*

Tentative Outline

We can't cover all of this, so let me know if there's a topic you really want to see. See the weekly Assignments for reading and homework assignments.

Meet Mr. Maxwell

Gladstone: "What is the practical worth of electricity?"

Faraday: "One day, Sir, you may tax it."

1. What the equations say

Necessity of the field idea. Lorentz force law gives meaning to the quantities appearing in Maxwell. Charge density, and current, and the continuity formula.

Demo: *Polaroid sheets. Microwave phenomena.*

Demo: *Lorentz force law in Crookes tube. Electrophoresis visualized using pepper in water; then add a magnetic field.*

2. Dimensions and units.

SI sí, CGS no.

3. Static charges

The potential. Electrostatic multipole expansion. Earnshaw theorem. Conductors and capacitance. Cell membrane capacitance measurement. Electrocardiogram. Separation of variables in Laplace's equation: Nearfield scanning optical microscopy probe.

4. Stationary, nonstatic sources

Vector potential. Bohm–Aharanov effect: the vector potential is real. Current dipole field and magnetoencephalography. Magnetostatic multipole expansion. Magnetic tweezers.

5. Time dependence

Induced EMF; nonconservative electric fields. Self- and mutual inductance.

6. Simplest wave solutions

Plane waves in vacuum. Polarization. Reflection interference contrast microscopy.

Waves transport momentum and energy.

Demo: *Newton Rings; RICM video.*

Relativistic classical fields

That... one body can act on another at a distance, through a vacuum and without mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it." – Isaac Newton, as an old man

7. Why Maxwell's equations look like that

Rotational invariance and tensors in 3D. Relativistic invariance and tensors in 4D.

Doppler shift, aberration of starlight, Fizeau/Zeeman experiment. Dipole anisotropy of the cosmic microwave background radiation. Invariant form of Maxwell equations; need

for the displacement term, and its sign. The essential role of charge conservation.
Demo: *Light travels in vacuum but not sound. Doppler shift for sound.*

8. **Variational formulation**

4-vector potential. Lagrangian for EM fields, and for particles+fields. Noether theorem.

9. **Energy and momentum of fields**

Energy–momentum tensor. Faraday’s imagery and its mathematical implementation.
Demo: *The jumping ring. The cryogenic jumping ring. Levitation of a magnet by a superconducting plate.*

10. **Wave polarization, full and partial**

Spin of the photon. Linear and circular polarization. Stokes parameters.
Lorentz-invariant meaning of circular polarizations.

11. **Waveguides and transmission lines**

A ladder of lumped elements. Dispersion and cutoff. Boundary conditions at a perfect conductor. Modes in a rectangular or circular guide. Zero-mode guides and single-molecule biophysics.

Demo: *Marshmallows in microwave.*

Fiat Lux

“It is difficult to deal with an author whose mind is filled with a medium of so fickle and vibratory a nature...; We now dismiss... the feeble lucubrations of this author, in which we have searched without success for some traces of learning, acuteness, and ingenuity, that might compensate his evident deficiency in the powers of solid thinking...” – Henry Brougham, 1803 [Criticizing Thomas Young’s wave theory of light]

12. **Radiation**

An accelerated charge develops kinked field lines. Retarded potentials. Jefimenko formulas. Application to terahertz generators.

13. **Diffraction and the ray-optics limit**

Replacement of a slit by a row of fictitious sources. Stationary phase and the criterion for sharp shadows.

14. **Slowly-moving sources**

Far fields of an oscillating electric dipole; magnetic dipole; higher multipoles.
Defocused orientation and position imaging (DOPI).. Antennas. How pulsars radiate.
Near fields: near-field scanning optical microscopy.

15. **Rapidly-moving sources**

Relativistic beaming. Liénard–Weichert potentials and fields. Bremsstrahlung and synchrotron radiation. Wigglers and undulators.

16. **Free electrons and waves**

Single electrons: Thomson scattering. Its polarization. Mean free path of radiation in the Sun. Polarization of CMBR reveals quadrupole moment of the cosmic inhomogeneity.

17. Waves in plasmas

Mean field approximation. Dispersion relation. The ionosphere: Why you can hear Europe. EM waves in metals; skin depth. Why pulsars seem to chirp. Faraday rotation in magnetized plasma; measurement of cosmic magnetic fields.

Demo: *Distortion of flame by an electrostatic field. Electrical conductivity of flame.*

Light in matter

May: “Have the crystals faults like us?” Lily: “Certainly, May. Their best virtues are shown in fighting their faults. And some have a great many; and some are very naughty crystals indeed.”
– John Ruskin, 1866

18. Bound electrons

Atomic polarizability and its classical representation. Permanent and induced moments. Anisotropy: the symmetric polarizability tensor. Single-dipole scattering, its frequency dependence, and its polarization. Blue, polarized sky versus white, unpolarized clouds. Mie scattering. Vibrating scatterer: Classical Raman effect.

Demo: *Scatter white light from milk suspension.*

19. Transmission by dilute matter

Plane wave incident on a polarizable sheet. Origin of refraction. How can matter slow down light, when matter is mostly empty space? Absorption.

20. Magnetic polarizability

The full polarizability tensor. Isotropic, but parity-noninvariant contributions; scattering from a helical wire. Optical activity.

Demo: *Optical activity: syrup of various depths; sucrose vs Serge Haroche, Jean-Michel Raimondfructose; rotation angle increases with thickness.*

21. Applications to biophysical chemistry

Circular dichroism and optical rotatory dispersion.

22. Scattering by dilute matter

Many isotropic dipoles: Density fluctuations. Masses and sizes of particles in solution can be measured using Rayleigh scattering. Diffusion constant can be measured by dynamic light scattering.

23. Effective form of Maxwell equations in dense matter

Polarization density. Bound charge and current densities. Spatial, not time averaging. Clausius–Mossotti relation. Energy of fields+media. Stress–energy tensor.

Demo: *Diamagnetic levitation of graphite.*

24. Waves in linear dielectric material

Dichroism and birefringence. Phase contrast microscopy.

Demo: *Dichroism: polaroid sheets. Birefringence: Calcite. Polystyrene. Home-grown crystals. Quartz. Polyethylene baggie or food wrap: stretch it.*

25. Discontinuities in homogeneous, linear media

Reflection and refraction at interfaces. Optical tweezers. Optical torque wrench. Total internal reflection. Evanescent wave. Total internal reflection fluorescence microscopy.

Fresnel equations; Brewster angle.

Demo: *Light pipes. Brewster angle; TIR angle.*

26. **Transport along optical fibers.**

Example: the TE mode.

27. **Waves in metamaterials**

“Negative” materials. Superlenses. Mathematical equivalence between exotic inhomogeneous material and curved space. Cloaking.

Optional 1: Quantum electrodynamics

“You boil it in sawdust, you salt it with glue, you condense it with locusts and tape, Still keeping the principal object in view: To preserve its symmetrical shape.” — Lewis Carroll

28. **Quantum fields**

Scalar fields become spinless particles. Nonlinear terms in field equations become interactions among particles. Noether charges become conserved quantities carried by particles.

29. **Charged scalar field**

Global versus gauge invariances. The covariant derivative. Gauge invariance gives massless photons with no self-interaction.

Optional 2: And now for something completely nonlinear

“The objective of physics is to establish new relationships between seemingly unrelated, remote phenomena.” — L. D. Landau

30. **Gravitation**

Is the metric on spacetime really given *a priori*? Mach’s paradox. If the metric is not fixed, can we find any reasonable equation of motion for it? What sort of properties must such an equation have? Gauge-type invariance of the metric. There’s a unique relativistic, gauge-invariant, linearized gravitation theory. Vistas: Beyond linearized approximation.

31. **Nonabelian gauge invariance**

How and why to generalize gauge invariance. The Yang–Mills lagrangian and field equations.

32. **The Standard Model and beyond**

Spontaneous symmetry breakdown; Higgs phenomenon. Electroweak and grand unification. An exact classical solution: The ’t Hooft–Polyakov magnetic monopole.

Books and Articles

General:

- Charles Brau, *Modern problems in classical electrodynamics*.
Feynman lectures: The Definitive and Extended Edition volumes 1–2
 DJ Griffiths, *Introduction to electrodynamics*
 MA Heald and JB Marion, *Classical electromagnetic radiation*
 JD Jackson, *Classical electrodynamics*
 Landau and Lifshitz, *Classical theory of fields*
 Landau and Lifshitz, *Electrodynamics of continuous media*
 DK Misra, *Practical electromagnetics: From biomedical sciences to wireless communication* (Wiley 2007)
 Ohanian, *Classical electrodynamics*
 E Purcell, *Electricity and magnetism*
 K. Thorne and R. Blandford, *Applications of classical physics*
<http://www.pma.caltech.edu/Courses/ph136/yr2004/> .
 J Vanderlinde, *Classical electromagnetic theory*

Popular/historical:

- D. Bodanis, *Electric universe* (Crown, 2005).
 Conant, *Tuxedo park*.
 A. Hirshfeld, *The Electric Life of Michael Faraday* (Walker, New York, 2006).
 B. Mahon, *The man who changed everything: The life of James Clerk Maxwell* (Wiley 2003).
 D Park, *The fire within the eye*
 David Rittenhouse, *Trans American Philos Soc Vol 2: Three papers by Rittenhouse, e.g. on p202*.
 Morris Shamos, *Great experiments in physics*

Tensor analysis:

- Frank Chorlton, *Vector and Tensor Methods* (Chichester, 1976)
 NMJ Woodhouse, *Special relativity* (Springer 1992)
 J Foster, JD Nightingale, *A short course in general relativity* (3rd ed., Springer-Verlag, New York, 2005)
 B Schutz, *First course in general relativity*

Optics:

- Born and Wolf, *Principles of optics*
 EU Condon, "Theories of optical rotatory power," RMP 9:432(1937)
 Hecht, *Optics*
 JF Nieves and PB Pal, "Third electromagnetic constant of an isotropic medium," AJP 62:207 (1994).
 J.F. Nye, *Physical properties of crystals: Their representation by tensors and matrices* (Oxford University Press, 1985).
 Yariv, *Optical electronics*
 L. Novotny and S. J. Stranick, "Near-field optical microscopy and spectroscopy with pointed probes," *Ann. Rev. Phys. Chem.* vol. 57, pp. 303-331, 2006; Anger P, Bharadwaj P, Novotny L "Enhancement and quenching of single-molecule fluorescence" *PHYSICAL RE-*

VIEW LETTERS 96 (11): Art. No. 113002 MAR 24 200; “Theory of Nanometric Optical Tweezers” L. Novotny, R. X. Bian, and X. S. Xie Phys. Rev. Lett. 79, 645-648 (1997).

Calculation:

Gerd Baumann, *Mathematica for theoretical physics: Electrodynamics, QM, GR, and fractals* 2d ed. (Springer 2005).

Plasma:

Richard Fitzpatrick, <http://farside.ph.utexas.edu/teaching/plasma/lectures/lectures.html>

RM Kulsrud, *Plasma physics for astrophysics* (Princeton 2005)

Astrophysical:

Scott Dodelson, *Modern cosmology*

MS Longair, *High energy astrophysics*

Peebles and Wilkinson, “Comment on the anisotropy of the primeval fireball,” Phys Rev 174:2168(1968).

J Portsmouth and E Bertschinger, “A tensor formalism for transfer and Compton scattering of polarized light” 2006 (<http://arxiv.org/abs/astro-ph/0412094>).

EN Parker, *Conversations on electric and magnetic fields in the cosmos* (PUP 2007).

GB Rybicki and AP Lightman, *Radiative processes in astrophysics*

SL Shapiro, SA Teukolsky, *Black holes, white dwarfs, and neutron stars: the physics of compact objects*

Biological/medical:

W Allison, *Fundamental physics for probing and imaging* (Oxford 2006).

G Benedek and F Villars, *Physics with applications from medicine and biology*, vol 3.

RK Hobbie, *Intermediate physics for medicine and biology*.

P Nelson, *Biological Physics*

J-F Allemand, Thèse de doctorat, Université de Paris VI, 1997.

Micromanipulation:

Arthur La Porta and Michelle D. Wang Optical Torque Wrench: Angular Trapping, Rotation, and Torque Detection of Quartz Microparticles Phys. Rev. Lett. 92, 190801 (2004).

Review by K Neuman and SM Block. Review of Scientific Instruments (2004)

<http://www.stanford.edu/group/blocklab/Neuman%20Block%20T%20Review%202004.pdf>

C Gosse and V Croquette, “Magnetic tweezers,” Biophys J 82:3314-29 (2002).

K Svoboda and S Block, “Biological applications of optical forces,” Annu Rev Biophys Biomol Struct 23:247–285 (1994).

Single-molecule imaging etc.:

Axelrod et al., Annual review of biophysics and bioengineering 1984. 13:247–268.

Levene, MJ; Korlach, J; Turner, SW; Foquet, M; Craighead, HG; Webb, WW. 2003. Zero-mode waveguides for single-molecule analysis at high concentrations. SCIENCE 299 (5607): 682-686.

Erdal Toprak, Joerg Enderlein, Sheyum Syed, Sean A. McKinney, Rolfe G. Petschek, Taekjip Ha, Yale E. Goldman, and Paul R. Selvin. Defocused orientation and position imaging

(DOPI) of myosin V. PNAS 103 64956499 (2006). See also the videos: <http://www.pnas.org/cgi/content/ful>

New Fluorescent Tools for Watching Nanometer-Scale Conformational Changes of Single Molecules Erdal Toprak1 and Paul R. Selvin Annu. Rev. Biophys. Biomol. Struct. 2007. 36:34969

Bartko AP, Dickson RM. 1999. Imaging three-dimensional single molecule orientations. J. Phys. Chem. B. 103:1123741.

Bartko AP, Dickson RM. 1999. Three-dimensional orientations of polymer-bound single molecules. J. Phys. Chem. B. 103:305356.

M. Bohmer and J. Enderlein, "Orientation imaging of single molecules by wide-field epifluorescence microscopy," J. Opt. Soc. Am. B 20, 554-559 (2003) <http://www.opticsinfobase.org/abstract.cfm?URI=j20-3-554>.

Biophysical Chemistry:

K. E. van Holde, W. C. Johnson, and P. S. Ho, *Principles of physical biochemistry*.

Cantor and Schimmel.

Tinoco, Sauer, Wang, Puglisi.