

**Physics 3310 Week-by-week outline**  
As taught in Spring 2008 by Steven Pollock  
At CU-Boulder

**Course Outline**

- Mon, Tues – HW help session. (1 hr Mon, 1.5 hr Tues)
- Friday – tutorial/group activities
- HW due on Wednesdays in class.
  
- First Exam – February 19th
- Second Exam – March 18th
- Final Exam – Tues May 6th, 4:30 pm.

**Week 1 (Jan 14-18)**

Homework: Pre-test, due Wed (with noncredit version due ASAP)

Friday Activity: Tutorial on circle of charge ("GPS" was the gimmick, though we should add an element [at the end] to point out /let them decide regarding whether the gimmick aspect was just for fun or realistic?)

**Monday Jan 14 L1**

Lecture 1: Intro, syllabus, E&M's place in physics, Maxwell, Possibly Coulomb's law and curly R.) Reading \*for\* today: (Anything from Chapter 1.1 - 1.3 which you feel you need to review)

Activities: Passed out white boards - (brief discussion of "how and why") Concept map of physics on white board. Everyone does it on their own, then share with neighbors. What is physics? Think of the BIG ideas, and then organize them (connect the parts that need connecting - perhaps the connections themselves have names...) It can be by courses, topics, ideas, whatever you think represents the whole world of physics on one whiteboard!

**Weds Jan 16 L2**

Reading for today: Advertisement, 1.1.4 (position vector), 1.3 (Calculus III), 2.1

Activities: Maybe the kinesthetic lambda and sigma activity.

Lecture 2: field review, (both mathematics and  $E = F/q$ ), finding E for continuous charge distributions (more on curly R)

Some "deep questions" discussed (e.g., WHY is Coulomb  $1/r^2$ , WHY is it the product of charges. What IS charge anyway? Opened this up to them, let them discuss a little, some questions we can/will address - like  $1/r^2$  in coulomb. Others, perhaps not, like "what is charge")

### **Fri Jan 18 L3**

Reading for today: 1.2.4, 2.2.1

Lecture 3: Rho, sigma, and lambda - setting up integrals, doing an example problem, including limits

Kinesthetic activity: Asked about 6-10 students to stand up. "Make a linear charge density for me, a lambda". Then, lots of discussion and other variations - Make lambda bigger. Is this really a lambda, or an approximation? What if the charges were only on your heads, is that more "lambda-like". In what way(s)? Does it matter that the charges are coming in chunks, does THAT make it "not a line charge"? Make it nonuniform. Make it curl around - is it still a lambda?)

Whiteboard: Work out the integral for the example we're working in class (E from a finite line of charge, with constant lambda) (and click answers to sub-questions for this in the meantime) This is practice in constructing "script R", mostly.

## Week 2

Homework 2 due Weds (on E field and Coulomb)

Friday activity: Tutorial on SLAC (delta functions, and Gauss' law) **Mon Jan 21**

Lecture: This is a holiday (MLK)

### Weds Jan 23 L4

Lecture 4: - Start Gauss' Law, and the Divergence Thm., introduce delta function

Reading needed *for* Today: 1.5, and 2.2.2.

Activities: Discussion re "which is more fundamental, Gauss or Coulomb" (and, why) Let them discuss. (Pointed out the Coulomb came first, historically. And that from one, you can show the other, in statics. But also pointed out Coulomb is *wrong*, but Gauss is always true, in non-static cases. Also pointed out Gauss is always true but not always *helpful* to solve for E in a given problem...)

### Fri Jan 25 L5

Lecture 5: More on delta function and Divergence theorem, and applying Gauss' law.

Reading needed *for* Today: 2.2.3

Activities: Whiteboard to compute the charge distribution from  $E=c r(\text{vector})$  (which is also a clicker question) and then to compute  $Q(\text{enclosed})$  of the resulting  $\rho$ .

ALso, kinesthetic activity: given an origin in the corner, and defining obvious x/y/z axes in the room, everyone close your eyes and POINT in the direction of  $\hat{y}$ , then  $\hat{r}$ ,  $\hat{\theta}$ ,  $\hat{\phi}$ . (Discussion of which *should* be different from each other!)

## Week 3

(Homework 3 due Weds, on Gauss)

Friday activity: Tutorial on div and curl and voltage, based loosely on Griffith's by inquiry. Demo with the Jacob's ladder and guiding question went along with it.

### Mon Jan 28 L6

Lecture 6: Wrap up Gauss, start Curl of E and stokes, (introduction to Voltage.)

Reading needed \*for\* Today: 2.2.4, 2.3.1

Activities: (?)

### Weds Jan 30 L7

Lecture 7: More on stokes, Voltage (Laplace/Poisson intro) calculating V

Reading for Today: 2.3.1-3,

Activities: (?)

### Fri Feb 1 L8

Lecture 8: Calculating V, the "triangle" (connecting V, E, and rho), intro to "boundary conditions" ideas.

Reading for Today: 2.3.4, 2.3.5,

Activities: Let them whiteboard the "Griffiths' triangle", with E, rho, and V on vertices. Asked them to fill in how to go from one to the other.

## Week 4

(Homework 4 due Weds, on Voltage)

Friday activity: Tutorial on Gauss, with some demos (Faraday ice pail and electroscope, Van deGraaf with dissectible Leyden jar.

### Mon Feb 4 L9

Lecture 9: Connecting  $V$  and energy, talking about energy of systems. Discuss  $E^2$  as energy density.

Reading for Today: 2.4

Activities: Big sign on the door as they walked in "Phys 3310 students: You are all positively charged. PICTURE the  $E$  field as you enter. What EXTERNAL WORK is needed to get you to your seat?"

### Weds Feb 6 L10

Lecture 10: Conductors,  $E$  field in conductor,  $E$  field outside conductor.

Reading for Today: 2.5

Activities: Started class with a square on the board,  $E$  upper left,  $F$  lower left,  $V$  upper right (and a blank which became  $PE$  lower right later on), and talked about how " $E$  is to  $F$  as  $V$  is to  $PE$ " and " $E$  is to  $V$  as  $F$  is to  $PE$ ", and so on. (Basically, connecting back to 2210 and 1110 ideas)

Also, at end, we whiteboarded the  $E$  field in a cubical conductor with a cubical cavity, with a  $+Q$  on the outside. Not enough time to finish!

### Fri Feb 8

Lecture 11: Continuing with Gauss' law in the presence of conductors, and Capacitors.

Reading for Today: Finished Chapter 2.

Activities: I showed them <http://www.falstad.com/emstatic/>, but it was just at the end of class. See next Wed for more details!

## Week 5

Homework 5 due Weds. No homework due next week (exam#1)

Friday activity: None - there is no homework due NEXT week, which is exam week.

### Mon Feb 11

Lecture 12: Wrap up Chapter 2 (I didn't finish the energy story for capacitors on Friday), motivate the big picture of Chapter 3. Then discuss Laplace, examples of Laplace (e.g. a 1-D physical example), the key theorems (like uniqueness, no maximum...)

Reading for Today: Griffiths 3.1

Activities: (none)

### Weds Feb 13

Lecture 13: Earnshaw's theorem, but largely Method of images today.

Reading for Today: Griffiths 3.2

Activity: I reviewed last class by imagining one wall of the room a giant conductor at 0 V, the other a giant conductor at +100 V, and we "visualized" the  $E$  field and equipotential planes in the room.

Activity: This time, I made good class use of I showed them <http://www.falstad.com/emstatic/>

Prep it ahead of class: Setup was "conducting box". You must first set mouse = "make floater",

then make the box floating potential, then set mouse = "adjust voltage", and adjust the voltage to zero. (It helps to temporarily increase brightness to REALLY set voltage=0) Then finally, turn brightness back down, and set mouse = add +draggable charge. You can put the charge outside, or drag it inside the box - you can see the polarization of the box, you can see the shielding, and the "shielding of position information" when  $Q$  is inside.

Then, I switched the setup to "charge and plane", which is a great setup for the method of images problem. And after SOLVING method of images, you can instantly "flip" the sim from "charge and plane" to dipole, it works great, you can visibly see that the  $E$  field on the upper half of the screen is unchanged!

Whiteboards: I set up the "method of images" problem (with  $+Q$  above, and  $-Q$  below), and had THEM, in pairs, write the formula for  $V(x,y,z)$ . (They struggled surprisingly with this!) I then had them evaluate  $V(x,y,0)$  and  $V(\text{anything} \rightarrow \text{infinity})$ . Lastly, I had the faster groups work out  $E_x$ ,  $E_y$ , and/or  $E_z$ , and evaluate it on the plane.

## Fri Feb 15

Lecture 14: Wrap up images (energy, and "multiple images) for about 20 minutes, then Separation of variables. I motivated WHY separation of variables might work, we set up an example problem (infinite "gutter" with grounded deep walls and a "high voltage" base). Separated, got to the separation constant, exponential (or hyperbolics) in one v'ble, sin/cos in the other. Ended there.

Reading for Today: Griffiths 3.3.1

Activities: Preclass, I posted this "On paper (don't forget your name!) in your own words (by yourself): What is the idea behind the method of images? What does it accomplish? What is its relation to the uniqueness theorem?" and collected their answers.

Activity later: Had no whiteboards, but could have used them. Instead I just had them use paper. First: Given the example problem, Sketch the E field lines. (Some struggled with this, I had a lot of lines running with opposite curvature of how it should be, i.e. instead of lines "arcing towards the grounding walls", they were concentrating down the y axis, i.e. heading off to infinity) Later, I asked them to come up with an  $f(x)$  and a  $g(y)$  such that  $f(x)+g(y)=0$ . (Most are familiar with this game!!)

## Week 6

No homework due this week - exam #1 is Tuesday evening.

Friday activity: Tutorial on Sep of variables.

### Mon Feb 18

Lecture 15: Some brief exam review, then continuing with sep of variables, including Fourier's trick. Worked out one of the canonical "waveguide-style" Sep of variable problems.

Reading for Today: 3.3.1 still

Activities: None, really. Tried to get them to suggest next steps (e.g., when I separated variables, I purposely chose the signs for the separation constant backwards/wrong for  $X(x)$  and  $Y(y)$ , then had them puzzle out how to "resolve" the dilemma (of trying to get a sum of exponential solutions to vanish at two places. ) They had lots of ideas - separation of variables \*failed\*, set both coefficients to zero, let the plate distance be a variable...)

### Weds Feb 20

Lecture 16: Wrapping up Fourier's trick (Cartesian), starting separation in spherical. Introduce Legendre Polynomials and radial solutions.

Reading for Today: 3.3.2

Activities: Whiteboards - draw sinh and cosh, is it even/odd, what's the curvature, behaviour as  $x=0$ , infinity, what's  $\cosh(\pi)$ , etc...

Show my mathematica solution in powerpoint (I did \*not\* show the 2D "0-V0-0-V0" boundary value problem, called "alternative\_separation\_variables.nb")

### Fri Feb 22

Lecture 17: Separation in spherical coordinates. Practice with the Legendre polynomials, and orthogonality, and "Legendre Fourier".

Reading for Today: 3.3.2 still

Activities: Show the PhET Fourier sim. Also show the mathematic notebook I made where we can \*look\* at the Legendre Polynomials.

## Week 7

Homework 6 due Weds

Friday activity: On multipoles and spherical legendre expansions

### Mon Feb 25

Lecture 18: On Legendre expansions - including the classic example of the conductor in a uniform field

Reading for Today: 3.3.2 still

Activities: (none)

### Weds Feb 27

Lecture 19: Finish up Legendre. Discussion of boundary conditions, ( $dV/dn$  out - in =  $-\sigma/\epsilon_0$ , and  $V$  is continuous). Finished and followed up that example of conductor in uniform field. Solved the problem where  $\sigma$  (rather than  $V$ ) is given on a boundary. Intro to the idea of the multipole expansion. Derivation of the approximate potential from a \*real\* dipole, and definition of dipole moment.

Reading for Today: 3.4.1, 3.4.4

Activities: (none)

### Fri Feb 29

Lecture 20: (Gues lecture by SVC) E field from Dipole, sources of dipoles ( natural and induced), little "model" for induced dipole ( $p$  proportional to  $E$ ) torque on a dipole, meaning of dipole moment (connection to multipole expansion)

Reading for Today: Rest of 3.4, 4.1

Activities: Whiteboard: sketch the E field from an ideal dipole, given the formula (and from a real dipole)

## Week 8

Homework 7 due Weds

Friday activity: Tutorial on Polarization and D

### Mon Mar 3

Lecture 21: Review/summarize multipoles. Motivate multipoles, when is it useful? (Show that Sep of variables leads us to believe  $V$  can be written in this way) Derive multipole expansion formally, ending with the "trick" to show that dipole moment is integral of  $r(\text{vectro}) \cdot \rho$ . Talk about monopole vs dipole moment vs quadrupole. What about ambiguity of dipole moment of  $Q$  is not zero? Introduce Polarization, and why this might be useful.

Reading for Today: 4.1 (finish)

Activities: (none)

### Weds Mar 5

Lecture 22: Griffiths 4.2.1 and 4.2.2, bound charges and polarization. Derived but also physically motivated  $\sigma$  bound and  $\rho$  bound.

Reading for Today: 4.2

Activities: We had a whiteboard activity today. Imagine two fluids, red (positive) and blue (negative), each uniform, identical, in a rectangular shape (area  $A$ , height  $H$ ). This fluid is made up from  $N$  "atoms"/ $m^3$ , and each "atom" (or unit) has available a charge  $q$  (which can separate/move). Imagine the red fluid moves UP the page, uniformly, a distance " $d$ ". For them to work out

- 1) How much charge  $Q$  appears on the top surface? (How much on the bottom? the sides?)
- 2) What is  $\sigma$  on the top, in terms of the given variables ( $N$ ,  $q$ ,  $d$ ,  $A$ , and/or  $H$ )
- 3) What is the polarization  $P$  in terms of those variables?
- 4) What is  $\sigma$  on the top in terms of  $P$ ?
- 5) What if we displace the fluid that same distance " $d$ ", but at an angle  $\theta$  with respect to the vertical. What are the answers above?

Purpose was for THEM to derive  $\sigma(\text{bound}) = P \cdot \hat{n}$ . Took about 10 minutes, 10/12 whiteboards we looked at afterwards had gotten through part 4 correctly, and a few had dealt with the  $\theta$  story. Many had a hard time getting started, visualizing the story, deciding if " $q$ " was all the info they needed or if there was some OTHER "charge"

needed. Some were confused about whether or not "H" plays a role, (e.g. a couple thought the polarization P should be calculated by looking only at the top and bottom sheets, and the distance H between them)

### **Fri Mar 7**

Lecture 23: More on polarization and bound charges, the "dielectric slab in a uniform field", (simple model,  $P = N q d$ ), including the idea of the "electret" (frozen in polarization, what field does it produce?) and the idea of superposing the external field with this induced field to get the total field. Then did the "dielectric sphere with frozen in permanent P" - reminded/redid the calculation of Voltage and E field in and out from a spherical sigma that goes as  $\cos(\theta)$ , made sense of the field in and out. Ended with motivation and definition of the "D" field, and some talk about how P is created by E, but then alters E, which feeds back on P (etc).. to set up/motivate the "linear dielectric" approx we'll use next time.

Reading for Today: 4.2.3, 4.3.1,

Activities: I brought rods (+ and -), an empty coke can to attract, a small smooth plastic wine cork (which CAN be budged, although friction is high so it doesn't do much, but that's really part of the point) and I brought a small low friction pivot (from Mike Thomason, it's used to put a bar magnet on, but I just laid a 1 meter wooden stick on it, and was able to get enough torque to easily move it around by attraction through polarization) Also brought an electroscope to show sign of charges.

## Week 9

Homework 8 due Weds

Friday activity: None (Exam week coming up)

### Mon Mar 10

Lecture 24: The D field - how to find it (in cases of symmetry) and how it's helpful, but also why it's not the same as E (curl might not vanish) Several examples (including electret, slab, and sphere) and then introduced the "linear dielectric" formulas and terminology.

Reading for Today: 4.4.1

Activities: (nothing special)

### Weds Mar 12

Lecture 25: Linear dielectrics - the capacitor (including weakening of field, field in gaps, voltage and capacitance) Started discussion of continuity/discontinuity of E. The meaning of "free charge".

Reading for Today: 4.4.2-4 (I'm not really covering much of 4.4.3 or 4, just quick/qualitative)

Activities: (None)

### Fri Mar 14

Lecture 26: Boundary conditions on E and D. Spent a lot of time on this, and on the example (whiteboard) question below. Then set up the dielectric sphere problem. We re-did the old conducting sphere in an E field problem, and I started the dielectric sphere example.

Reading for Today: 4.4.2 again

Activities: Whiteboards - (a decent one!) I drew an E arrow approaching a boundary (angle  $\theta_1$  with normal) and an E arrow leaving the boundary (angle  $\theta_2$ ) epsilon is given (and different in both regions, both are linear dielectrics). There are no free charges in the region shown. Find  $\tan(\theta_1)/\tan(\theta_2)$ . Gave them ~10 minutes for this, about half finished. (Followup question - does the E vector point more "towards the normal" in the lower, or higher dielectric region? Is this like Snell's law?)

## Week 10

No homework due this week (exam)

Friday activity: None (break coming up)

### Mon Mar 17

Lecture 27: Wrapping up Chapter 4: Linear dielectrics and boundary conditions, solving in some detail the problem of the dielectric sphere in an external field (including the math, the interpretation, the connection to a conductor in that same field). Briefly discussed (but did not work out) the charge above a dielectric plane. Then, quick discussion of energy and force with dielectrics (couple of clicker questions on capacitor with dielectric inserted - happens to energy, what's the force?) Didn't work out in detail, but sketched the idea. Ended (~15 min) with a discussion of magnetism. New force, but related to/connected to E. But for now, we focus on it as something new. Lorentz Force law, current as "source", pattern. (And a little history!)

Reading for Today: Finish 4.4, and 5.1.1

Activities: I brought the "Maxwell's equations" board to show the B formulas and see the parallels and differences. I also brought some strong magnets and Magz toys - the magz are dipoles, and I used them to engage in a class discussion of "how do you know this is NOT just electrostatics". They would come up with solutions ("you can't ground it, if it was electric you could") which I tried to counter ("it's coated in a thin plastic film") ("So scrape off the plastic" -> "Maybe it's an electret") ("If you cut it in half, you get two smaller magnets" -> "As I said, maybe it's an electret" ...)

### Weds Mar 19

Lecture 28: Magnet force, helical paths + cyclotron/synchrotron, crossed E&B fields (velocity selector, cycloidal motion derivation)

Reading for Today: 5.1.2

Activities: I Googled "cycloid" and pull up Mathematica's webpage, it has a very nice animation of the cycloid.

### Fri Mar 21

Lecture 29: (Brief exam discussion) Reviewed the "no work" idea for B fields. Current: defined it, talked about/derived  $I = n q v$ , or  $\lambda v$ , and then motivated and defined surface and volume currents, talked about their connections, and then ended with current conservation in terms of J, and Maxwell's equations (in electrostatics) all together on the board.

Reading for Today: 5.1.3

Activities: I motivated J by thinking about the "flow of the Mississippi" compared to "flow of Boulder Creek", and characterizing flow as total current (Mississippi clearly vastly bigger) but what about "water flowing at me through this circle I am making with my fingers". Then perhaps Boulder Creek even wins - so there's some OTHER quantity to characterize flow, which motivates our definition of "current density" as current/area. (Then rotate the circle to show them that it's really perpendicular area needed to DEFINE this current density).

Also, nice discussion built on student question, would current in a wire be only on the edges (since we've learned excess charge goes there). Lots of things to talk about - wires needn't have excess charge, visualize the "negative electron fluid" displacing in an E field, and so on...

**Spring break**

# Week 11

Homework 9 due Weds

Friday activity: Tutorial on Ampere's law (which we started in class on Friday)

## Mon Mar 31

Lecture 30 Quick review of I, J, and K (current/current density, and current conservation). Then Biot Savart. Motivated it as "just like Coulomb's law"... Did the infinite line problem (let them set up curly R with clicker questions) Talked about symmetry (does it matter where the origin is? What about when the current is just a piece of a bigger problem?) Discussion of RHR, and Biot-Savart vs the old Phys 1120 "circles around the wire" result. Discussed units (and definition of  $\mu_0$ ). Derived the force between parallel wires.

Reading for Today: 5.2

Activities: Had them "think like an 18th century physicist" to \*come up\* with Biot-Savart. Also good class discussion about "is it meaningful to talk about a tiny chunk of current" (like we talk about a tiny chunk of charge) Issues of current conservation, but also vector nature came up (it bugged some that  $d\mathbf{l}$  has to stretch over SOME length, but  $dq$  is truly a point)

## Weds Apr 2

Lecture 31 Moving from Biot-Savart to Ampere's law. First, though, we finished B-S with example of loop - I spent a fair amount of time, making sure THEY did the geometry, thought about the vector nature and components, etc. Then, Maxwell's equations (in statics), reminder of connection of Gauss to Coulomb, and now the connection of B-Savart to Ampere. Talked about Stoke's theorem (so, integral and differential forms of Ampere's law), and how to interpret the "current through".

Reading for Today: 5.3.1-2

Activities: Brought a dip-compass needle to see the dramatic dip angle in the room (and brief discussion of geo-magnetic field). Also brought a small "loop with arrow" which turned out to be a useful prop throughout class. One thing I did near the end was hold the compass near the loop, and pointed out B is NOT zero, and  $\mathbf{B} \cdot d\mathbf{l}$  is NOT zero, at various points around the loop... so, what if we integrate? Got the class to discuss that it must be zero ("backside of loop" cancelling with front) and that this was correct, since there's no current in the room...

## Fri Apr 4

Lecture 32 - started with proof (demonstration?) that Biot Savart for infinite line leads to Ampere's law even for complicated loop. Discussion of sign conventions on current, and

whether "I through" has a cosine built in? (This proved quite confusing for many students) Also discussion of Ampere law in the "given B, what is J" direction, talking about curl of fields.

Reading for Today: 5.3.3

Activities: I had a prop (a strip of paper, white on one side, yellow on the other) which I could twist to show the concept test idea about "direction/sign of current through a loop"

Had a "Tutorial" (2 pages from Darren's Ampere's law Tutorial) which we used for the last ~10 minutes of class. Worked ok, it was about symmetry arguments for the direction of B around a wire...

## Week 12

Homework 10 due Weds

Friday activity: Tutorial on Vector Potential. (With donuts :-)

### Mon Apr 7

Lecture 33: Finishing Ampere's law today, doing a number of examples. Worked pretty long/hard on the "symmetry arguments", for why you KNOW the B field wraps around a long wire e.g. (You can use Biot-Savart, but you can also e.g. argue against a radial component from  $\text{del} \cdot \mathbf{B} = 0$ , OR by a lovely argument where you flip the direction of current). Also why "symmetry" tells you that B won't depend on z or phi (not just saying it, but constructing a convincing argument) We also did the Solenoid (with extended discussion, again, about WHY exactly symmetry tells you directions and dependences. Some discussion about whether you "know"  $\mathbf{B} = 0$  outside by some simple argument, or if you need to really go through the Amperian loop argument. (Which I think you do?) Also did the Torus (and brief talk about Tokomaks/fusion)

Reading for Today: 5.3.3 still

Activities: none

### Weds Apr 9

Lecture 34: Start with Toroid example/review of Ampere. Intro to Vector potential. Review of Maxwell's equations and "why V". Then move to A: motivate it, set up the curl of curl of A equation, discuss how nice it would be if  $\text{del} \cdot \mathbf{A}$  term vanishes -> gauge freedom, Coulomb gauge. ("Proof" that we can do this) Discussion of ease of solving for A now as an integral over J/R, but then (clicker q) about interpreting such a "vector" equation. Some discussion of role of A in quantum (and quantum field theory!) but its (relative) unimportance in classical E&M, certainly in e-statics. (but, it'll come back with waves)

Reading for Today: 5.4.1,

Activities: None

### Fri Apr 11

Lecture 35: More on the vector potential today, trying to make it more intuitive. Began by computing A for uniform B field in z direction. Lot of good discussion, what SHOULD it look like (We saw the formula for A (integral of J over R), talked about the fact that "A points like J" at least in simple cases.) and, discussed how the equation relating J to B is analogous to that relating B to A (so our intuition about a 'uniform upward current', like a thick wire, can help here!) Then did it in detail, pointing out many different A fields that all give same curl (e.g.  $(B_0 y, 0, 0)$ , or  $(0, -B_0 x, 0)$ , or the average of these, which can be

written in terms of  $\hat{\phi}$ ) I then went through a number of simple A fields (like  $\hat{\phi}$  multiplied by various functions of  $s$ , including  $s$ ,  $1/s$ , and  $1$ ) and just computing the curl, then "making sense" of the resulting B field (in some cases). Pointed out that you can get the field inside and outside of a solenoid this way, AND have the nonzero A field out there (for continuity, which I discussed) rather than just setting  $A=0$  there. Mentioned Aharonov-Bohm "demo" that A really is nonzero out there - which several thought was very cool. Discussed other cases (like A field in  $z$  direction with  $\ln(s)$  dependence  $\Rightarrow$  from infinite wire), and ended with walk-through of dipole pattern for B (azimuthal for A) from a spinning charged sphere (and why that leads into next topic, B field in matter, as a simple "model" of atoms) Ended with mention of John Taylor's article's point about " $1/2 mv^2$  is not conserved, but it is if you add  $qV$ . Similarly, vector momentum  $mv$  is not conserved, but  $mv + qA$  is"

Reading for Today: 5.4.1

Activities: (none)

## Week 13

Homework 11 due Weds

Friday activity: Tutorial - diamagnetism

### Mon Apr 14

Lecture 36 - Continuity of  $A$ , the "magnetostatics triangle", magnetic dipole moment: start with the current loop, work through the "analogy" of the multipole expansion of  $V$ , (law of cosines, involves inverse curly  $R$ , pull out  $r$ , do the expansion in  $r'/r, \dots$ ) Talked about monopole term and dipole term, showed (but did not derive!) the origin of the magnetic dipole \*moment\*, talked about integrating  $dA$  (as a vector)

Reading for Today: 5.4.2 and 5.4.3

Activities: Whiteboard - had them write out the triangle, took ~5 minutes. (There's still one "leg" they haven't gotten, some figured it out on the fly, it's a homework problem due Wed)

### Weds Apr 16

Lecture 37 - magnetic dipoles, the field (and vector potential) of the dipole. Talked about torque on, and force on, magnetic dipole moments, Talked about para and diamagnetism - including the simple model for both, and what that says about the "internal"  $B$  field.

Reading for Today: 6.1

Activities: Started with a writing exercise, basically "what is the  $A$  field, how is it used" (see my powerpoints for the wording) Gave ~3 minutes for that.

Later, I put up the FORMULA for the  $B$  field from an ideal magnetic dipole (from Griffiths), and asked them to sketch it, as well as sketching the field for a \*real\* current loop of finite radius, and think about the differences. Gave about 5 minutes for this, they did it on paper but talked to each other. It was a very useful exercise - we'd done this before for the electric dipole (same thing!) but they STILL struggled in a variety of ways. Some (most) "knew the answer" either from memory or their heuristics about fields around rings, but they were not good about seeing the connection to the formula. I poked some groups with questions like "on the  $x$  axis, at very small  $x$ , what is the direction of  $B$  for the two cases (ideal and real), and can you reconcile these"?)

### Fri Apr 17

Lecture 38 - magnetization, parallels with polarization. Talked about force and torque, and diamagnetism and paramagnetism (e.g. which gets attracted into magnet) Talked about integral for  $V$ , and what happens when you have a polarized material. (So not the

integral of  $\rho/R$ , but rather the integral of  $(\mathbf{P} \cdot d\mathbf{r})/R^2$  formula) Then made the analogy for A. Talked about how "integration by parts" pulls the voltage integral into a sigma bound and rho bound, and same thing for A. Got to the separated terms, but didn't go into the explanation (although, a student asked at the very end "is that a real current", so I ended with that discussion, drawing many little atoms side by side and talking about cancellation in the middle, but leftover at the edges.

Reading for Today: 6.2 (started)

Activities: Start of class, asked them to write down (on paper) everything they could remember about P (electric polarization). ~3 minutes for that. Then, got in groups of three (new groups, this time!) and went to \*boards\* (so we had 6 groups, each group got one "board section") and they had to write down what their group came up with. ~5 minutes for that. Then the "scribes" sat down, we picked the nicest handwriting to go first, and they read/explained what they had done. Other groups erased what they had that was duplicated, and we argued when groups had disagreements (e.g. if there is an  $\epsilon_0$  in the formula  $\mathbf{P} = \chi \mathbf{E}$ , if there is a minus sign in  $\rho_{\text{bound}} = -\nabla \cdot \mathbf{P}$ , etc. ) until all groups had presented. In the end, we had reviewed much of Chapter 4, and the analogies to Ch 5 (magnetization) were on everyone's fingertips. Took a little long (~20 minutes) but was fun, seemed pretty worthwhile. Many old formulas and ideas got "dredged up", they hit almost everything except the integral formulas for potential.

## Week 14

Homework 12 due Weds

Friday activity: Chandra has a special "GRE/review" session, different from usual.

### Mon Apr 23

Lecture 39: Begain with reminder on board of the formulas for  $V$  from bound charges, and  $A$  from bound current, as well as the formulas to find bound (whatever) from polarization/magnetization. Discussed the physical meaning/interpretation of bound currents, starting with a "microscopic picture" showing (square) current loops in a bulk material. Discussed how knowing these bound currents tells you about  $B$  in any of a variety of ways (formulas on board give  $A$ , but you might also use Biot-Savart, or Ampere's law) Talked about sensemaking the  $M \times n$  (direction and magnitude) formula. Then went through a simple example in which  $M$  is not uniform (I let it point in the  $z$  direction, out of the board, but increase in magnitude linearly with  $x$ ). Again, went through the sense-making for why the curl of  $M$  resulted in a bound current, the idea of conservation of that current, and several ways (pictorial and mathematical) to get at the same result. Clicker questions on bound currents were all very easy for them today! DTalked about the "uniformly magnetized sphere", I connected it with the old Griffiths/lecture example of a spinning surface charged sphere. Ended with discussion of  $J_{free}$  and  $J_{bound}$ , and did the separation to derive the formula for the  $H$  field.

Reading for Today: 6.2 (finished), start 6.3

Activities: (none)

### Weds Apr 25

Lecture 40: Started with review, then discussed linear magnetic materials. Talked about susceptibility and permeability, para and dia magnets again (signs). Starting concept tests were again very easy for them today. Talked about  $B$  field inside of real wire. Talked about continuity equations (discovered not everyone has this "trick" down of using divergence theorem to learn about continuity of perpendicular component, or stokes to learn about continuity of parallel, so spent time on that) Ended with example of  $B$  field inside a uniform magnetized material in which you dig a small hole. Good discussion of a number of ways to \*think\* about that (including direction and location of bound currents, and continuity arguments, but also thinking about the external  $B$  field that "causes" this situation, and the difference between the bulk and the hole). (This will lead to a wrong answer to the starting question next time, so that will be interesting!)

Reading for Today: 6.3

Activities: (None - But, did FCQ's last 10 min of class)

### Fri Apr 27

## Lecture

Lecture 41: Started class discussing homework problem of magnet "floating" above another magnet. Review of Boundary conditions on B and H. Talked about "carving flat hole" problem. Discussed mu-metal, and how it works, how it is similar and different from Faraday cage. Did the "falling ring problem" (as a prelude to Lenz' law), discussed Lenz but also " $\mathbf{qv}$  cross  $\mathbf{B}$ " ways to think about it. Showed the MIT videos, and we spent a lot of time looking at them, thinking about direction of current, behavior of field lines, superposition, thinking about field lines as "material". Ended with introduction to ferromagnetism.

Reading for Today: 6.4

Activities: Had several MIT sim/quicktimes, showing B field for falling superconducting ring onto a magnet (or vice versa, or with finite resistance) See <http://web.mit.edu/8.02t/www/802TEAL3D/visualizations/faraday/index.htm>

Also had two demos - the "magnet floating above another magnet" one (which provoked some questions and discussion - what determines the height, how does it scale, what happens if you let TWO strong magnets "stick" and then try to float them...) Also brought in a solenoidal electromagnet and nails, to introduce ferromagnets.

## Week 15

Homework 13 due Weds

Friday activity: (none)

### Mon Apr 28

Lecture 42 - Ferromagnets. Discussion of physics, reminder that  $H$  is what it is (from free currents), but  $B$  (and  $M$ ) can be huge. Talked about quantum mechanics, and symmetrization, domains, and real materials. (Lots of questions!) Wrote Maxwell's eqns (time independent) on board, and introduced the idea that they break relativity (moving conductor in  $B$  field generates current, but moving magnet does not... we need to fix them up)

Reading for Today: 6.4.2, and 7.2.1

Activities: (none)

### Weds Apr 30

Lecture 43 - Posttest only.

Reading for Today: (none)

Activities: (Post test, all period)

### Fri May 1

Lecture 44 - (Final exam brief review) Review of conservation of charge in " $d(\rho)/dt = -\text{div } J$ " form. Then Maxwell's equations - discussion of Faraday's law, and relativity of  $E$  and  $B$ . (Different frames can "see" an  $E$ , or not...) (Some discussion that the mathematics of Faraday's law parallels that of Ampere's law) Then, discussion of problem with Maxwell's equations:  $\text{del dot del cross } B$  does not necessarily vanish. Maxwell's resolution, introduction of the displacement current. Restoration of "symmetry" - and a consequence, travelling EM waves in vacuum!

Reading for Today: 7.2.2, 7.3.1-3

Activities: (Writing exercise for Chandra)