Modern Physics for Engineers
Summary of Topics, Methods, and Common Student Difficulties

1. Review of EM Waves
Sim: *Radio Waves and Electromagnetic Fields*

- ~40% of class thinks charges moving at constant speed generate light (because charges in light bulb filament move at constant speed, because a spark is a charge moving at constant speed, because they don't see why it wouldn't.
- Many students think EM waves consist of something physically moving up and down in space, rather than fields increasing and decreasing in magnitude. We have clicker questions to address this. There is always some confusion over wording, but also real issues of students not understanding the physics.
- We review how classical EM wave energy independent of frequency because students don't know classical model when we get to photoelectric effect.

2. Photoelectric Effect
Sim: *Photoelectric Effect*

- This is a much harder topic for students than professors think. For details, see: http://jilawww.colorado.edu/~mckagan/papers/photoelectric.pdf
- Common student difficulties (many can be resolved with sim):
  - think voltage rather than light takes electrons off plate
  - think current increases with speed of electrons
  - can't explain basic function of experiment
  - can't explain classical model of light
  - can't explain ***why*** PE experiment leads to photon model of light
- A general problem that first appears here is that some students have no ability to think hypothetically and can't separate what was expected classically from what really happens.

3. Probability and Randomness and Wave particle duality
Sim: *Quantum Wave Interference*

- When we ask how students visualize light, ~40% have "Bohmian" view of particle traveling alongside EM wave.
- We use sim to demonstrate how the double slit experiment shows that light must be both a wave that goes through both slits and a particle that hits the screen at a single location. This lecture led to an unexpected onslaught of deep, fundamental questions that took up nearly an entire class period. Many students ask whether the particle is actually inside wave with a definition location that we just don't know. Students get pretty frustrated with this class.

4. Rutherford Scattering
Sim: *Rutherford Scattering*

- In interviews we found that after instruction some students described the plum pudding model as cloud of negative charge filled with protons. They're probably mixing it up with the Schrodinger model.

5. Atomic Spectra and Discharge Lamps
Sim: *Discharge Lamps*

- We teach spectra before the Bohr model in order to emphasize how Bohr was able to explain the observed spectra with his model.
- Students often have trouble with the idea that the energy of light corresponds to the *difference* between the levels rather than the *values* of the levels. They need lots of explicit practice to get this distinction straightened out.

- We get lots of questions about how the electron chooses which level to jump down to, and how it decides when to jump down. These questions are useful later for emphasizing why the Schrodinger model of the atom is better than the Bohr model.
- The simulation and associated homework really help students build a clear model of how a discharge lamp work. The one place they had trouble was relating this model to what they see in a real discharge lamp, even though we did a demo with real discharge lamps and diffraction gratings. It's important to be really explicit in this demo about how the physical lamps relate to the model in the sim.
- When reminding students of Coulomb potential energy, they remember the equation kq_1q_2/r, but often don't realize that this is the same as $-ke^2/r$.
- The idea of how fluorescent lights work is harder for students than you might think because they have trouble with the idea that red+blue+green light looks like white light to the eye. We get a lot of questions here about how the eye works.

6. Lasers

Sim: *Lasers*

- We originally covered Lasers towards the end of the course, but we realized that we didn't actually use anything other than the basics of spectra in our treatment, and the engineers got grumpy if we spent too long on fundamentals without any applications, so we moved Lasers to so that there was more emphasis on applications early in the course. This worked much better.
- When we ask students why laser beams are so powerful, it's split 50/50 between more power in the beam and more concentrated light.
- The homework on lasers starts with basic questions about absorption and spontaneous and stimulated emission, works through the steps of building a laser and troubleshooting a broken laser, and ends with essays on why a population inversion is necessary to build a laser and why this requires atoms with three energy levels instead of two. Most students are able to give coherent explanations in these essays. Students get less frustrated by the homework if it follows a lecture demo of the sim.

7. Balmer Series

- We emphasize the point that Balmer came up with his formula by playing around with numbers and didn't know what it meant. This is probably lost of students who think all of physics is like that.

8. Bohr and deBroglie Models of the atom

Sim: *Models of The Hydrogen Atom*

- For details about why and how we teach this topic, see: http://jilawww.colorado.edu/~mckagan/papers/bohr.pdf
- This is really an opportunity to teach modeling and the significance of Bohr explaining where Balmer's equation came from and deBroglie explaining *why* there are fixed energy levels. This is a really difficult section for students who have trouble thinking hypothetically.
- In the Bohr model, students often mix up total and potential energy, for example, thinking that -13.6eV is the potential energy. This confusion is confounded by the way the total energy lines are drawn on top of the potential energy curves.

9. Double slit and Davisson Germer experiment

Sims: *Quantum Wave Interference*, *Davisson Germer: Electron Diffraction*

- Students have a much harder time thinking of electrons as waves than photons, because electrons have mass.
- Students often think that the size of the wave packet, rather than the wavelength, should determine the spacing of the interference pattern.
- We have noticed that students often miss the point of the Davisson Germer experiment. They remember that electrons were only detected at certain angles, but cannot explain why. They view the electrons as particles that happen to bounce off at

certain angles for some reason they can't understand, rather than recognizing how the observations can be explained by the wave nature of electrons. We have found two things that really help to address this:

- Start with a review of the double slit experiment, a context where students understand interference much better, talking about how you would like to do this to test deBroglie's hypothesis, and then explain why this is really hard to do and then talk about how the Davisson Germer experiment is analogous.
- Use the *Davisson Germer* sim to illustrate how wave interference leads to peaks in intensity at certain angles.

10. Wave functions and probability

- When we first introduce wave functions with arbitrary functions, students often don't recognize these as waves because they think "waves" are sine waves.
- "Wave number" is usually new and unfamiliar to students, and it's worth spending 5 minutes to discuss why we define this quantity and how it relates to wavelength.

11. Wave packets and uncertainty principle

Sims: *Quantum Wave Interference*, *Quantum Tunneling*, *Fourier: Making Waves*

- We introduce wave packets early because they are much more intuitive than plane waves and easier to relate to "particles."

12. Wave equations and Differential equations

- It is worth emphasizing that the way we solve differential equations in physics, by just "guessing" the solution, is completely different from the way they have been taught to solve differential equations in math classes. Many students make this section way too hard by attempting to use complicated methods they have learned in math classes.

13. Schrodinger equation for free particle

Sim: *Quantum Tunneling*

- You can use the *Quantum Tunneling* sim to demonstrate free particles by just setting the potential to "constant."
- Students often have difficulty understanding the meaning of complex wave functions. This can perhaps best be illustrated by the observation that students frequently ask, "What is the physical meaning of the imaginary part of the wave function?" but never ask about the physical meaning of the real part, even though both have the same physical significance.

14. Potential Energy

- We have found that without explicit instruction on how to relate potential energy diagrams to physical systems, most students don't know what a potential energy diagram means or how it relates to anything real. When we do give explicit instruction on this, students start asking a lot of questions, and it becomes clear what a struggle it is for them to make sense of it.
- The fact that we often use the symbol V for potential energy and use the words "potential" and "potential energy" interchangeably leads to a lot of students thinking that V is actually the electric potential. It is worth emphasizing repeatedly that this is NOT what it means.

15. Infinite and Finite Square Wells

Sim: *Quantum Bound States*

- We illustrate a finite square well with the physical example of an electron in a short wire, and illustrate an infinite square well with the same system with a really big work function. We justify why this potential energy represents this system by building it up from a microscopic model of the atoms in the wire. Before we did this, we found that students often mixed up wells and barriers. Afterwards, this happened much less.

- The practice of drawing potential energy, total energy, and wave function on the same graph leads students to confuse these quantities. We have several clicker questions to elicit and address this confusion.

16. Quantum Tunneling, Alpha decay and other applications of Tunneling

Sim: *Quantum Tunneling*

- Language such as "potential well," "step," and "barrier" often leads students to interpret potential energy diagrams as physical objects. It is worth pointing out that these words are only analogies, and using examples such as an electron tunneling through an air gap where there is clearly no physical barrier.
- There is a lot of research showing that students often believe that energy is lost in tunneling, and we have incorporated a tutorial and homework designed to address this belief. Two main reasons that students think this are that they mix up energy and wave function and interpret the exponential decay of the wave function as energy loss, or that they think of a classical object penetrating a physical barrier, in which case there is always dissipation. To address the first reason, we avoid drawing the wave function and the energy on the same graph, and ask several clicker questions designed to elicit and address this confusion. To address the second reason, we emphasize that there is no dissipation in the Schrodinger equation.
- While plane waves are mathematically simple, conceptually it is quite difficult to imagine a wave that extends forever in space and time, especially when it is tunneling. The language we use to describe tunneling is time-dependent. For example, we say that a particle approaches a barrier from the left, and then part of it is transmitted and part of it is reflected. This language is difficult to reconcile with a picture of a particle that simultaneously incident, transmitted, and reflected, for all time. We find that it works much better to start instruction with wave packets, using a qualitative description and the *Quantum Tunneling* sim, and then show how plane waves make the math easier.
- Determining the potential energy function for a physical example such as an STM or α decay actually requires understanding many steps and approximations, and is not trivial for students. If you simply present students with these potential energy functions, they usually don't know how to relate them to the physical systems they are supposed to represent. We have many clicker questions designed to help students build a model for the potential energy functions for STMs and α decay.

17. Reflection and Transmission

Sim: *Quantum Tunneling*

- There is a lot of math here and it's very easy to get lost in the math and forget why you're doing it. When asking students to work through it in homework, it's very useful to ask them to stop after each step in the math and explain in words what they just did.

18. Superposition, measurement, and expectation values

Sim: *Quantum Bound States*

- Modern Physics textbooks typically do not cover superposition and measurement. We do, because it seems to us that if you don't talk about measurement, you don't know what you're actually doing in QM or how it relates to the real world.
- We have chosen to cover expectation values in some semesters and not others. It helps to relate it to more familiar examples such as grade distributions and gambling.

19. Hydrogen atom

Sims: *Models of the Hydrogen Atom*, *Rutherford Scattering* (also falstad.com/qmatom)

- It is extremely important in this section to relate the Schrodinger model of the atom back to the discussion of models of the atom earlier in the course (section 8), and show how this is the next step in the progression of models. Otherwise, students are

likely to view this section as just one more example of a solution of the Schrodinger equation and not realize that we are actually talking about another model of the atom.
- We have a homework in which we ask students to work through the simulations and explain the reasons for and limitations of each models. It's amazing how difficult this is for students.

20. Multielectron atoms
- We cover this topic very qualitatively, talking about how quantum mechanics explains the patterns in the periodic table, but not doing any calculations.

21. Molecular bonding and solids
Sim: *Quantum Bound States*
- Most engineers don't seem very interested in learning the quantum mechanical basis of chemistry, and many complain that this is one of their less favorite topics.

22. Conductivity
Sim: *Conductivity*
- This section is fairly straightforward and the engineers are usually familiar with band theory and interested in seeing how it relates to what they've learned in this class. However, they have often learned a very specific vocabulary for talking about bands, and get frustrated when our discussion is not consistent with this vocabulary.

23. Diodes and LEDs
Sim: *Semiconductors*
- In the typical representation of diodes, excess filled energy levels above a gap are represented by –'s and empty energy levels below a gap are represented by +'s. This is extremely confusing and often leads students to believe that the –'s and +'s represent excess charges, which they do not. We have several clicker questions designed to help students see what's going on here and correctly interpret this representation.

24. CCDs
- This topic was pretty complicated, and required a lot of steps to understand. The students complained that it was too hard. It probably would have been fine if we spent more time on it, but we had only one lecture and it was rushed.

25. Spin and MRI
Sims: *Stern Gerlach Experiment*, *Simplified MRI*
- We cover only enough details about spin to discuss MRI and EPR. All we really say is that it's an additional quantum number than can be measured as up or down.
- Our treatment of MRI, and our simulation, closely follows the description given in Bloomfield's textbook *How Things Work*.

26. EPR paradox
- We have covered this topic in one day or two. One day is pretty rushed, but possible. Throughout the course, students have been asking whether the electron *really* goes through both slits or we just don't know which it went through, whether it *really* has an undefined momentum when its position is known or we just don't know what it's position is, and other similar questions. In this lecture we finally answer those questions. Some students really love this lecture, and some find it confusing and don't get it (there are a lot of steps of hypothetical reasoning in it). I don't know what percentage of students falls into each category.