Modern Physics notes – Spring 2007

Paul Fendley `fendley@virginia.edu`

Lecture 1

- What is Modern Physics?
- Topics in this class
- The books and their authors
- Quantum mechanics

- Feynman 1.1

What is Modern Physics?

The class you're taking is usually called Modern Physics. People often use the word "modern" to mean "contemporary", but that's not the usage here. Modern (in art as well as physics) often means work that was done in the first part of the twentieth century. In the case of this class, most of this work was done in the years 1890-1930. These were years of a great revolution in physics, and most of the work done today directly descends from work done in this period. A lot of time in this class will indeed be devoted to physics discovered in this period. This is still a big step forward in time from your earlier classes, where the physics you studied was done in the nineteenth century or earlier (you got up to 1905 if you did special relativity). Therefore, even though a lot of this work is fairly old, you should view this class as being an introduction to current problems in physics.

The topics

In the course of the class, we'll try to really understand the key ideas of quantum mechanics. Some of them are downright weird when compared to the everyday way of seeing things. Some of you have seen relativity before, and know that this seem pretty weird as well. But I would say that although some parts of relativity seem counter-intuitive to our everyday world, once you adjust to some new facts (e.g. nothing can go faster than the speed of light), it's not that bizarre. Quantum mechanics, however, requires much more than adjusting one's intuition. It's a fundamentally new world which exists at very small distances. The completely different behavior in this new world is what makes a great deal of modern technology possible. In other words, it's a feature, not a bug.

We'll discuss the "classic" stuff like the uncertainty principle, bosons and fermions, and black-body radiation. For the latter, we'll take some time and actually derive the formula, as opposed to just quoting it. It's a bit of work, but it doesn't require very sophisticated mathematics, just some time and some new physics. We'll apply quantum mechanics to problems of more current relevance like the key physics behind lasers and behind transistors. I say "key physics" because we're not going to worry about the (quite difficult) problem of how to actually make these things. Instead, we'll focus on the properties of quantum mechanics which make these things possible. In particular, we'll go through the laser quite carefully.

Quantum mechanics will take up roughly 2/3 of the course (probably 9 weeks out of the 14). Then we'll move on to do special relativity. I know some but not all of you have seen it, so I'll try to redo the key ideas in a slightly different way. Hopefully, those of you who have seen it before won't be bored, and those who haven't will still be able to understand. We'll then do general relativity. This is the one topic where we'll only be able to give a qualitative idea of what's going on – the most important physics comes from Einstein's equation, and to understand that requires understanding some differential geometry. (If you want to be a theoretical physicist, then I strongly recommend that you take differential geometry at some point as an undergrad.)

After general relativity, we'll then apply both quantum mechanics and relativity to a very interesting problem of great current interest: cosmology. In particular, we'll go through the big-bang scenario as quantitatively as possible. Of course people have wondered for millenia how the universe started; the reason I say "current" is that in the last decade, there has (finally) been a huge amount of precise data on cosmology. For the first time in history, we're now pretty sure about much of what happened in the early universe.

The books

Introductory books in physics these days tend to be written as problem-solving guides. They pull out the formulas with the minimum possible explanation of where they come from, and then focus on teaching you how to do problems using these formulas. Thus they insert lots of examples into the text. This is fine, but now that you've all had two or three semesters of physics, you've mastered this way of doing things. As you might have guessed, life isn't this easy, and you're ready to move on to learn things a little bit deeper. To make what I mean by "move on" clearer: in this class there will be no calculators, no notes on the tests. If you'll need some complicated formula which isn't easy to recall off the top of your head, then I'll give it to you. My point is that this is not really a plug and chug class.

In my opinion, there are three problems with conventional modern physics texts. The first is that they still follow the problem-solving approach of your first physics books, and as I said, I think you're ready to move on. The second is that they're guilty of the "mile wide, inch deep" approach to physics. This isn't that horrible: there are a lot of interesting things in physics, and to have at least heard of some of these problems is a good thing. But still I'd rather dig deeper. The third is that they're obscenely expensive. The two I considered using both cost more than $110, and of course they continually come out with new editions so you can't buy used copies.

For far less than $110, you can buy many great books written by great physicists. I think the three I've chosen belong in this category. The most important thing I can say about these books is that you actually need to *read* these books. The authors are really trying to explain what's going on, not provide a convenient problem-solving guide. So if you wish, you should view the class and in particular the section as your problem-solving guide. This means I strongly recommend that you've looked through the problems *before* your section meeting, so that you can ask the relevant questions there (and in class as well). My guess is that you won't be able to do the homework the way it's usually done in physics classes, which is to wait til the night before and then skim the book for the correct formulas. I realize that most of you will still wait til the night before to do the homework, but what I'm trying to get across to you is that it would be a good idea to at least think about it before then.

In general, as you move on through physics, the mathematics gets more and more sophisticated. This, however, is *not* going to be true of this class. All three of our texts use *less* mathematics than these standard textbooks on these topics does. This is particularly ironic because all three authors are Nobel-prize winning theoretical physicists, and all are known for their mathematical abilities as well as their physical insight. Born's book and Weinberg's book are allegedly written for a popular audience, so their avoidance of math beyond algebra is not so surprising. But Feynman's book barely has an integral, and you'll notice huge chunks of just pure text. This is why I say that to understand what's going on, you have to actually read it, not just look in it for the right formula.

One thing to note with regards to our texts is the difference between "outdated" and "not up-to-date". Outdated means that there is now a better way to think about the subject which perhaps wasn't obvious when the author wrote the book. Not up-to-date means that there have been subsequent interesting developments. None of our texts are outdated, but, actually, the most recent text book, Weinberg's, is least up-to-date. Since he wrote his book (and especially since his 1994 update) there have been some very interesting recent observations in cosmology. However, everything he says you need to know is necessary to understand the recent developments, so his book is not outdated at all, even though it is not up-to-date. After we get through the material in his book, I'll then devote a lecture or two to subsequent developments.

The authors

Even though Born's book is about relativity, he's best known for his contributions to quantum mechanics. We'll soon learn about one of his major results, the necessity of the "probabilistic" interpretation of quantum mechanics. He's also Olivia Newton-John's grandfather, a fact which seemed far more interesting when I was a student then it does now.

Even though Weinberg's book is about cosmology, he's best known for his contributions to particle physics. (He's still active, and still very smart. For example, legend has it that when he was lured from Harvard to the University of Texas about 20 years ago, he made his move contingent on his being paid more than the football coach.) We'll discuss Weinberg's contributions to particle physics on the slim chance we have a few lectures to spare at the end of the class.

Finally, Feynman is probably the best-known physicist in the world post-Einstein. He made numerous contributions to both particle physics and condensed-matter physics, and his influence is still felt all over physics. In particular, pretty much every practicing physicist has read at least some of these lectures. Feynman's "memoirs" (basically a collection of his anecdotes) were best-sellers, even though I think he ends up depicting himself basically as a clever jerk. But as a physicist, he was basically without parallel in this half of the century. I recommend Gleick's biography of him "Genius" highly.

There's an interesting characterization of a genius, made I think by the mathematician Mark Kac after observing Feynman. You can find it in Gleick's book. He divides geniuses into two categories: the "ordinary" and the "magicians". The ordinary genius is like we are, just a lot smarter and quicker. Once we understand what they've done, we think we could have done that too. On the other hand, magicians like Feynman just seem to be seeing things in a different way than we do. Even after we understand what they do, we have no idea where it came from. Certainly that seems to be true for a number of discoveries Feynman made. There's no telling how long it would have taken for someone else to have made these discoveries had Feynman not been around to make them.

His lectures on quantum mechanics are not mysterious at this level. However, he did totally rethink the way of presenting things, and realized that you don't really need a lot of mathematics to understand what's going on. You also don't need to present the material historically. Most presentations of quantum mechanics and in particular modern physics are basically historical, which first go through the early partial successes (called e.g. the "Bohr atom" and the "de Broglie hypothesis") before explaining the way people understand things now. In fact, with regards to my earlier mentioning outdated books, I would say that regarding quantum mechanics, most current modern physics texts are outdated! Although it's historically interesting, there's really no need to discuss Bohr's atom – it misses some key points. So while there are to be sure idiosyncrasies in Feynman's lectures, I think it'll be much more rewarding (for me as well as you!) to go through his book.

By the way, this does not mean at all that it is not interesting to understand how these discoveries were made. In fact, it is often quite instructive to understand what the great intellectual leap was, and to understand that requires knowing where the field was before the leap. When Michael Fowler taught this class a few years back, he didn't use the standard texts either. In fact, he turned it more or less into a very interesting class on the history as well as the modern physics itself. His extensive lecture notes are available on the web; as we go along I'll indicate where to look. He spends more time on relativity and less on quantum mechanics than we will, but I still think you'll find them useful.

Quantum Mechanics

Since the bulk of the course is devoted to studying quantum mechanics, I thought it would be useful to say a little about what it is. The "mechanics" part of it you already know – it has to do with understanding how stuff moves around. But quantum mechanics is much more than that – it's how stuff behaves at very small distances, on the length scale of atoms (the "atomic scale").

So here's a puzzle. Imagine an electron going around a nucleus. You learned in your mechanics class that this requires a (centripetal) acceleration to keep it going around. The necessary force is electromagnetism: the nucleus is positively charged, the electron negatively charged. So far, this is nothing you haven't heard before. But here's a fact you may not have learned in your E&M class: a consequence of Maxwell's equations is that an accelerating charge *emits* radiation. So as the electron accelerates on its way around the nucleus, it must emit light waves. But by conservation of energy, the electron must then lose energy. When it loses energy, it must go into an orbit closer to the nucleus. It keeps doing this, and should spirals into the nucleus. But we know this doesn't happen: atoms are stable! This means the physics you learned must be modified at small length scales.

The laws governing physics at atomic scales are called quantum mechanics. The word "quantum" means a distinct unit. In the atom it turns out that there are not orbits for the electron at any distance. There are a (countable) number of possible orbits for the electron. There are still an infinite number, but countable means I can put them all in a list. (I can't count the number of radii: between any two radii I put in a list, there are an infinite number of other radii!) We say that the orbits are "quantized". For a given electron, there is an orbit of lowest energy which is stable.

So why are there stable orbits? Understanding this takes a fair amount of work, which we're going to do. You'll see that much weirder things happen. We'll end up seeing that at small length scales, light behaves as a particle (another "quantum" – it's a bundle of light). We'll also see that at these scales, electrons behave in some ways like waves! This turns out not to be a contradiction, but the key to the whole picture.

I want to emphasize that what you learned in your earlier classes is not wrong: it's just that it applies only at length scales much longer at the atomic scale. Quantum mechanics does not contradict classical mechanics. In fact, one can show (ch. 7 in Feynman) that at long enough distances, quantum mechanics reduces to classical mechanics. And eventually, quantum mechanics gets supplanted as well. To understand the physics of the nucleus itself (what holds protons and neutrons together) you need to combine quantum mechanics and relativity together, and do quantum field theory. And people believe that at even smaller length scales, something else probably happens. You might need to combine quantum field theory with gravity, and so far the only way to do this that might work are some very elaborate theories called string/M theory.