ALLAN ADAMS: Hi everyone. Welcome to 804 for spring 2013. This is the fourth, and presumably final time that I will be teaching this class. So I'm pretty excited about it. So my name is Allan Adams. I'll be lecturing the course. I'm an assistant professor in Course 8. I study string theory and its applications to gravity, quantum gravity, and condensed matter physics. Quantum mechanics, this is a course in quantam mechanics. Quantam mechanics Is my daily language. Quantum mechanics is my old friend. I met quantum mechanics 20 years ago. I just realized that last night. It was kind of depressing. So, old friend. It's also my most powerful tool. So I'm pretty psyched about it.

Our recitation instructors are Barton Zwiebach, yea! And Matt Evans-- yea! Matt's new to the department, so welcome him. Hi. So he just started his faculty position, which is pretty awesome. And our TA is Paolo Glorioso. Paolo, are you here? Yea! There you go. OK, so he's the person to send all complaints to.

So just out of curiosity, how many of you all are Course 8? Awesome. How many of you all are, I don't know, 18? Solid. 6? Excellent. 9? No one? This is the first year we haven't had anyone Course 9. That's a shame. Last year one of the best students was a Course 9 student.

So two practical things to know. The first thing is everything that we put out will be on the Stellar website. Lecture notes, homeworks, exams, everything is going to be done through Stellar, including your grades. The second thing is that as you may notice there are rather more lights than usual. I'm wearing a mic. And there are these signs up. We're going to be videotaping this course for the lectures for OCW. And if you're happy with that, cool. If not, just sit on the sides and you won't appear anywhere on video. Sadly, I can't do that. But you're welcome to if you like. But hopefully that should not play a meaningful role in any of the lectures.

So the goal of 804 is for you to learn quantum mechanics. And by learn quantum mechanics, I don't mean to learn how to do calculations, although that's an important and critical thing. I mean learn some intuition. I want you to develop some intuition for quantum phenomena. Now, quantam mechanics is not hard. It has a reputation for being a hard topic. It is not a super hard topic. So in particular, everyone in this room, I'm totally positive, can learn quantum mechanics. It does require concerted effort. It's not a trivial topic.

And in order to really develop a good intuition, the essential thing is to solve problems. So the way you develop a new intuition is by solving problems and by dealing with new situations, new context, new regimes, which is what we're going to do in 804. It's essential that you work hard on the problem sets. So your job is to devote yourself to the problem sets. My job is to convince you at the end of every lecture that the most interesting thing you could possibly do when you leave is the problem set. So you decide who has the harder job.

So the workload is not so bad. So we have problem sets due, they're due in the physics box in the usual places, by lecture, by 11 AM sharp on Tuesdays every week. Late work, no, not so much. But we will drop one problem set to make up for unanticipated events. We'll return the graded problem sets a week later in recitation. Should be easy. I strongly, strongly encourage you to collaborate with other students on your problem sets. You will learn more, they will learn more, it will be more efficient. Work together. However, write your problem sets yourself. That's the best way for you to develop and test your understanding.

There will be two midterms, dates to be announced, and one final. I guess we could have multiple, but that would be a little exciting. We're going to use clickers, and clickers will be required. We're not going to take attendance, but they will give a small contribution to your overall grade. And we'll use them most importantly for non-graded but just participation concept questions and the occasional in class quiz to probe your knowledge. This is mostly so that you have a real time measure of your own conceptual understanding of the material. This has been enormously valuable.

And something I want to say just right off is that the way I've organized this class is not so much based on the classes I was taught. It's based to the degree possible on empirical lessons about what works in teaching, what actually makes you learn better. And clickers are an excellent example of that. So this is mostly a standard lecture course, but there will be clickers used. So by next week I need you all to have clickers, and I need you to register them on the TSG website.

I haven't chosen a specific textbook. And this is discussed on the Stellar web page. There are a set of textbooks, four textbooks that I strongly recommend, and a set of others that are nice references. The reason for this is twofold. First off, there are two languages that are canonically used for quantum mechanics. One is called wave mechanics, and the language, the mathematical language is partial differential equations. The other is a matrix mechanics. They have big names. And the language there is linear algebra. And different books emphasize different aspects and use different languages.

And they also try to aim at different problems. Some books are aimed towards people who are interested in materials science, some books that are aimed towards people interested in philosophy. And depending on what you want, get the book that's suited to you. And every week I'll be providing with your problem sets readings from each of the recommended texts. So what I really encourage you to do is find a group of people to work with every week, and make sure that you've got all the books covered between you. This'll give you as much access to the texts as possible without forcing you to buy four books, which I would discourage you from doing.

So finally I guess the last thing to say is if this stuff were totally trivial, you wouldn't need to be here. So ask questions. If you're confused about something, lots of other people in the class are also going to be confused. And if I'm not answering your question without you asking, then no one's getting the point, right? So ask questions. Don't hesitate to interrupt. Just raise your hand, and I will do my best to call on you. And this is true for both in lecture, also go to office hours and recitations. Ask questions. I promise, there's no such thing as a terrible question. Someone else will also be confused. So it's a very valuable to me and everyone else.

So before I get going on the actual physics content of the class, are there any other practical questions? Yeah.

AUDIENCE: You said there was a lateness policy.

ALLAN ADAMS: Lateness policy. No late work is accepted whatsoever. So the deal is given that every once in a while, you know, you'll be walking to school and your leg is going to fall off, or a dog's going to jump out and eat your person standing next to you, whatever. Things happen. So we will drop your lowest problem set score without any questions. At the end of the semester, we'll just dropped your lowest score. And if you turn them all in, great, whatever your lowest score was, fine. If you missed one, then gone. On the other hand, if you know next week, I'm going to be attacked by a rabid squirrel, it's going to be horrible, I don't want to have to worry about my problem set. Could we work this out? So if you know ahead of time, come to us. But you need to do that well ahead of time. The night before doesn't count. OK? Yeah.

AUDIENCE: Will we be able to watch the videos?

ALLAN ADAMS: You know, that's an excellent question. I don't know. I don't think so. I think it's going to happen at the end of the semester. Yeah. OK. So no, you'll be able to watch them later on the OCW website. Other questions. Yeah.

AUDIENCE: Are there any other videos that you'd recommend, just like other courses on YouTube?

ALLAN ADAMS: Oh. That's an interesting question. I don't off the top of my head, but if you send me an email, I'll pursue it. Because I do know several other lecture series that I like very much, but I don't know if they're available on YouTube or publicly. So send me an email and I'll check. Yeah.

AUDIENCE: So how about the reading assignments?

ALLAN ADAMS: Reading assignments on the problem set every week will be listed. There will be equivalent reading from every textbook. And if there is something missing, like if no textbook covers something, I'll post a separate reading. Every once in a while, I'll post auxiliary readings, and they'll be available on the Stellar website. So for example, in your problem set, first one was posted, will be available immediately after lecture on the Stellar website. There are three papers that it refers to, or two, and they are posted on the Stellar website and linked from the problem set. Others? OK.

So the first lecture. The content of the physics of the first lecture is relatively standalone. It's going to be an introduction to a basic idea then is going to haunt, plague, and charm us through the rest of the semester. The logic of this lecture is based on a very beautiful discussion in the first few chapters of a book by David Albert called *Quantum Mechanics and Experience.* It's a book for philosophers. But the first few chapters, a really lovely introduction at a non-technical level. And I encourage you to take a look at them, because they're very lovely. But it's to be sure straight up physics. Ready? I love this stuff.

today I want to describe to you a particular set of experiments. Now, to my mind, these are the most unsettling experiments ever done. These experiments involve electrons. They have been performed, and the results as I will describe them are true.

I'm going to focus on two properties of electrons. I will call them color and hardness. And these are not the technical names. We'll learn the technical names for these properties later on in the semester. But to avoid distracting you by preconceived notions of what these things mean, I'm going to use ambiguous labels, color and hardness.

And the empirical fact is that every electron, every electron that's ever been observed is either black or white and no other color. We've never seen a blue electron. There are no green electrons. No one has ever found a fluorescent electron. They're either black, or they are white. It is a binary property.

Secondly, their hardness is either hard or soft. They're never squishy. No one's ever found one that dribbles. They are either hard, or they are soft. Binary properties. OK? Now, what I mean by this is that it is possible to build a device which measures the color and the hardness. In particular, it is possible to build a box, which I will call a color box, that measures the color.

And the way it works is this. It has three apertures, an in port and two out ports, one which sends out black electrons and one which sends out white electrons. And the utility of this box is that the color can be inferred from the position. If you find the particle, the electron over here, it is a white electron. If you find the electron here, it is a black electron. Cool?

Similarly, we can build a hardness box, which again has three apertures, an in port. And hard electrons come out this port, and soft electrons come out this port. Now, if you want, you're free to imagine that these boxes are built by putting a monkey inside. And you send in an electron, and the monkey, you know, with the ears, looks at the electron, and says it's a hard electron, it sends it out one way, or it's a soft electron, it sends it out the other.

The workings inside do not matter. And in particular, later in the semester I will describe in considerable detail the workings inside this apparatus. And here's something I want to emphasize to you. It can be built in principle using monkeys, hyper intelligent monkeys that can see electrons. It could also be built using magnets and silver atoms. It could be done with neutrons.

It could be done with all sorts of different technologies. And they all give precisely the same results as I'm about to describe. They all give precisely the same results. So it does not matter what's inside. But if you want a little idea, you could imagine putting a monkey inside, a hyper intelligent monkey. I know, it sounds good.

So a key property of these hardness boxes and color boxes is that they are repeatable. And here's what I mean by that. If I send in an electron, and I find that it comes out of a color box black, and then I send it in again, then if I send it into another color box, it comes out black again. So in diagrams, if I send in some random electron to a color box, and I discover that it comes out, let's say, the white aperture. And so here's dot dot dot, and I take the ones that come out the white aperture, and I send them into a color box again.

Then with 100% confidence, 100% of the time, the electron coming out of the white port incident on the color box will come out the white aperture again. And 0% of the time will it come out the black aperture. So this is a persistent property. You notice that it's white. You measure it again, it's still white. Do a little bit later, it's still white. OK? It's a persistent property.

Ditto the hardness. If I send in a bunch of electrons in to a hardness box, here is an important thing. Well, send them into a hardness box, and I take out the ones that come out soft. And I send them again into a hardness box, and they come out soft. They will come out soft with 100% confidence, 100% of the time. Never do they come out the hard aperture. Any questions at this point?

So here's a natural question. Might the color and the hardness of an electron be related? And more precisely, might they be correlated? Might knowing the color infer something about the hardness? So for example, so being male and being a bachelor are correlated properties, because if you're male, you don't know if you're a bachelor or not, but if you're a bachelor, you're male. That's the definition of the word.

So is it possible that color and hardness are similarly correlated? So, I don't know, there are lots of good examples, like wearing a red shirt and beaming down to the surface and making it back to the Enterprise later after the away team returns. Correlated, right? Negatively, but correlated.

So the question is, suppose, e.g., suppose we know that an electron is white. Does that determine the hardness? So we can answer this question by using our boxes. So here's what I'm going to do. I'm going to take some random set of electrons.

That's not random. Random. And I'm going to send them in to a color box. And I'm going to take the electrons that come out the white aperture.

And here's a useful fact. When I say random, here's operationally what I mean. I take some piece of material, I scrape it, I pull off some electrons, and they're totally randomly chosen from the material. And I send them in. If I send a random pile of electrons into a color box, useful thing to know, they come out about half and half. It's just some random assortment. Some of them are white, some of them come out black.

Suppose I send some random collection of electrons into a color box. And I take those which come out the white aperture. And I want to know, does white determine hardness. So I can do that, check, by then sending these white electrons into a hardness box and seeing what comes out. Hard, soft.

And what we find is that 50% of those electrons incident on the hardness box come out hard, and 50% come out soft. OK? And ditto if we reverse this. If we take hardness, and take, for example, a soft electron and send it into a color box, we again get 50-50.

So if you take a white electron, you send it into a hardness box, you're at even odds, you're at chance as to whether it's going to come out hard or soft. And similarly, if you send a soft electron into a color box, even odds it's going to come out black or white. So knowing the hardness does not give you any information about the color, and knowing the color does not give you any information about the hardness. cool? These are independent facts, independent properties. They're not correlated in this sense, in precisely this operational sense. Cool? Questions? OK.

So measuring the color give zero predictive power for the hardness, and measuring the hardness gives zero predictive power for the color. And from that, I will say that these properties are correlated. So H, hardness, and color are in this sense uncorrelated. So using these properties of the color and hardness boxes, I want to run a few more experiment's. I want to probe these properties of color and hardness a little more.

And in particular, knowing these results allows us to make predictions, to predict the results for set a very simple experiments. Now, what we're going to do for the next bit is we're going to run some simple experiments. And we're going to make predictions. And then those simple experiments are going to lead us to more complicated experiments. But let's make sure we understand the simple ones first.

So for example, let's take this last experiment, color and hardness, and let's add a color box. One more monkey. So color in, and we take those that come out the white aperture. And we send them into a hardness box. Hard, soft. And we take those electrons which come out the soft aperture. And now let's send these again into a color box.

So it's easy to see what to predict. Black, white. So you can imagine a monkey inside this, going, aha. You look at it, you inspect, it comes out white. Here you look at it and inspect, it comes out soft. And you send it into the color box, and what do you expect to happen?

Well, let's think about the logic here. Anything reaching the hardness box must have been measured to be white. And we just did the experiment that if you send a white electron into a hardness box, 50% of the time it comes out a hard aperture and 50% of the time it comes out the soft aperture. So now we take that 50% of electrons that comes out the soft aperture, which had previously been observed to be white and soft. And then we send them into a color box, and what happens?

Well, since colors are repeatable, the natural expectation is that, of course, it comes out white. So our prediction, our natural prediction here is that of those electrons that are incident on this color box, 100% should come out white, and 0% should come out black. That seem like a reasonable-- let's just make sure that we're all agreeing. So let's vote. How many people think this is probably correct? OK, good. How many people think this probably wrong? OK, good. That's reassuring.

Except you're all wrong. Right? In fact, what happens is half of these electrons exit white, 50%. And 50% percent exit black. So let's think about what's going on here.

This is really kind of troubling. We've said already that knowing the color doesn't predict the hardness. And yet, this electron, which was previously measured to be white, now when subsequently measured sometimes it comes out white, sometimes it comes out black, 50-50% of the time.

So that's surprising. What that tells you is you can't think of the electron as a little ball that has black and soft written on it, right? You can't, because apparently that black and soft isn't a persistent thing, although it's persistent in the sense that once it's black, it stays black. So what's going on here?

Now, I should emphasize that the same thing happens if I had changed this to taking the black electrons and throwing in a hardness and picking soft and then measuring the color, or if I had used the hard electrons. Any of those combinations, any of these ports would have given the same results, 50-50. Is not persistent in this sense. Apparently the presence of the hardness box tampers with the color somehow.

So it's not quite as trivial is that hyper intelligent monkey. Something else is going on here. So this is suspicious. So here's the first natural move. The first natural move is, oh, look, surely there's some additional property of the electron that we just haven't measured yet that determines whether it comes out the second color box black or white. There's got be some property that determines this.

And so people have spent a tremendous amount of time and energy looking at these initial electrons and looking with great care to see whether there's any sort of feature of these incident electrons which determines which port they come out of. And the shocker is no one's ever found such a property. No one has ever found a property which determines which port it comes out of. As far as we can tell, it is completely random.

Those that flip and those that don't are indistinguishable at beginning. And let me just emphasize, if anyone found such a-- it's not like we're not looking, right? If anyone found such a property, fame, notoriety, subverting quantum mechanics, Nobel Prize. People have looked. And there is none that anyone's been able to find.

And as we'll see later on, using Bell's inequality, we can more or less nail that such things don't exist, such a fact doesn't exist. But this tells us something really disturbing. This tells us, and this is the first real shocker, that there is something intrinsically unpredictable, non-deterministic, and random about physical processes that we observe in a laboratory. There's no way to determine a priori whether it will come out black or white from the second box. Probability in this experiment, it's forced upon us by observations.

OK, well, there's another way to come at this. You could say, look, you ran this experiment, that's fine. But look, I've met the guy who built these boxes, and look, he's just some guy, right? And he just didn't do a very good job. The boxes are just badly built.

So here's the way to defeat that argument. No, we've built these things out of different materials, using different technologies, using electrons, using neutrons, using bucky-balls, C60, seriously, it's been done. We've done this experiment, and this property does not change. It is persistent. And the thing that's most upsetting to me is that not only do we get the same results independent of what objects we use to run the experiment, we cannot change the probability away from 50-50 at all.

Within experimental tolerances, we cannot change, no matter how we build the boxes, we cannot change the probability by part in 100. 50-50. And to anyone who grew up with determinism from Newton, this should hurt. This should feel wrong. But it's a property of the real world. And our job is going to be to deal with it. Rather, your job is going to be to deal with it, because I went through this already.

So here's a curious consequence-- oh, any questions before I cruise? OK. So here's a curious consequence of this series of experiments. Here's something you can't do. Are you guys old enough for you can't do this on television? This is so sad. OK, so here's something you can't do. We cannot build, it is impossible to build, a reliable color and hardness box. We've built a box that tells you what color it is. We've built a box that tells you what hardness it is. But you cannot build a meaningful box that tells you what color and hardness an electron is.

So in particular, what would this magical box be? It would have four ports. And its ports would say, well, one is white and hard, and one is white and soft, one is black and hard, and one is black and soft. So you can imagine how you might try to build a color and hardness box. So for example, here's something you might imagine. Take your incident electrons, and first send them into a color box. And take those white electrons, and send them into a hardness box.

And take those electrons, and this is going to be white and hard, and this is going to be white and soft. And similarly, send these black electrons into the hardness box, and here's hard and black, and here's soft and back. Everybody cool with that? So this seems to do the thing I wanted. It measures both the hardness and the color. What's the problem with it?

AUDIENCE: [INAUDIBLE]

ALLAN ADAMS: Yeah, exactly. So the color is not persistent. So you tell me this is a soft and black electron, right? That's what you told me. Here's the box. But if I put a color box here, that's the experiment we just ran. And what happens? Does this come out black? No, this is a crappy source of black electrons. It's 50/50 black and white. So this box can't be built. And the reason, and I want to emphasize this, the reason we cannot build this box is not because our experiments are crude. And it's not because I can't build things, although that's true. I was banned from a lab one day after joining it, actually. So I really can't build, but other people can. And that's not why.

We can't because of something much more fundamental, something deeper, something in principle, which is encoded in this awesome experiment. This can be done. It does not mean anything, as a consequence. It does not mean anything to say this electron is white and hard, because if you tell me it's white and hard, and I measure the white, well, I know if it's hard, it's going to come out 50-50. It does not mean anything. So this is an important idea. This is an idea which is enshrined in physics with a term which comes with capital letters, the Uncertainty Principle.

And the Uncertainty Principle says basically that, look, there's some observable, measurable properties of a system which are incompatible with each other in precisely this way, incompatible with each other in the sense not that you can't know, because *you* can't know whether it's hard and soft simultaneously, deeper. It is not hard and white simultaneously. It cannot be. It does not mean anything to say it is hard and white simultaneously. That is uncertainty. And again, uncertainty is an idea we're going to come back to over and over in the class. But every time you think about it, this should be the first place you start for the next few weeks. Yeah. Questions. No questions? OK.

So at this point, it's really tempting to think yeah, OK, this is just about the hardness and the color of electrons. It's just a weird thing about electrons. It's not a weird thing about the rest of the world. The rest of the world's completely reasonable. And no, that's absolutely wrong. Every object in the world has the same properties. If you take bucky-balls, and you send them through the analogous experiment-- and I will show you the data, I think tomorrow, but soon, I will show you the data. When you take bucky-balls and run it through a similar experiment, you get the same effect. Now, bucky-balls are huge, right, 60 carbon atoms.

But, OK, OK, at that point, you're saying, dude, come on, huge, 60 carbon atoms. So there is a pendulum, depending on how you define building, in this building, a pendulum which is used, in principle which is used to improve detectors to detect gravitational waves. There's a pendulum with a, I think it's 20 kilo mirror. And that pendulum exhibits the same sort of effects here. We can see these quantum mechanical effects in those mirrors.

And this is in breathtakingly awesome experiments done by Nergis Malvalvala, whose name I can never pronounce, but who is totally awesome. She's an amazing physicist. And she can get these kind of quantum effects out of a 20 kilo mirror. So before you say something silly, like, oh, it's just electrons, it's 20 kilo mirrors. And if I could put you on a pendulum that accurate, it would be you. OK? These are properties of everything around you. The miracle is not that electrons behave oddly. The miracle is that when you take 10 to the 27 electrons, they behave like cheese.

That's the miracle. This is the underlying correct thing.

OK, so this is so far so good. But let's go deeper. Let's push it. And to push it, I want to design for you a slightly more elaborate apparatus, a slightly more elaborate experimental apparatus. And for this, I want you to consider the following device. I'm going to need to introduce a couple of new features for you. Here's a hardness box. And it has an in port. And the hardness box has a hard aperture, and it has a soft aperture.

And now, in addition to this hardness box, I'm going to introduce two elements. First, mirrors. And what these mirrors do is they take the incident electrons and, nothing else, they change the direction of motion, change the direction of motion. And here's what I mean by doing nothing else. If I take one of these mirrors, and I take, for example, a color box. And I take the white electrons that come out, and I bounce it off the mirror, and then I send these into a color box, then they come out white 100% of the time. It does not change the observable color. Cool? All it does is change the direction.

Similarly, with the hardness box, it doesn't change the hardness. It just changes the direction of motion. And every experiment we've ever done on these, guys, changes in no way whatsoever the color or the hardness by subsequent measurement. Cool? Just changes the direction of motion. And then I'm going to add another mirror. It's actually a slightly fancy set of mirrors. All they do is they join these beams together into a single beam. And again, this doesn't change the color. You send in a white electron, you get out, and you measure the color on the other side, you get a white electron. You send in a black electron from here, and you measure the color, you get a black electron again out. Cool?

So here's my apparatus. And I'm going to put this inside a big box. And I want to run some experiments with this apparatus. Everyone cool with the basic design? Any questions before I cruise on? This part's fun.

So what I want to do now is I want to run some simple experiments before we get to fancy stuff. And the simple experiments are just going to warm you up. They're going to prepare you to make some predictions and some calculations. And eventually we'd like to lead back to this guy. So the first experiment, I'm going to send in white electrons. Whoops. Im. I'm going to send in white electrons. And I'm going to measure at the end, and in particular at the output, the hardness.

So I'm going to send in white electrons. And I'm going to measure the hardness. So this is my apparatus. I'm going to measure the hardness at the output. And what I mean by measure the hardness is I throw these electrons into a hardness box and see what comes out. So this is experiment 1. And let me draw this, let me biggen the diagram. So you send white into-- so the mechanism is a hardness box. Mirror, mirror, mirrors, and now we're measuring the hardness out.

And the question I want to ask is how many electrons come out the hard aperture, and how many electrons come out the soft aperture of this final hardness box. So I'd like to know what fraction come out hard, and what fraction come out soft. I send an initial white electron, for example I took a color box and took the white output, send them into the hardness box, mirror, mirror, hard, hard, soft. And what fraction come out hard, and what fraction come out soft.

So just think about it for a minute. And when you have a prediction in your head, raise your hand. All right, good. Walk me through your prediction.

AUDIENCE: I think it should be 50-50.

ALLAN ADAMS: 50-50. How come?

AUDIENCE: [INAUDIBLE] color doesn't have any bearing on hardness. [INAUDIBLE]

ALLAN ADAMS: Awesome. So let me say that again. So we've done the experiment, you send a white electron into the hardness box, and we know that it's non-predictive, 50-50. So if you take a white electron and you send it into the hardness box, 50% of the time it will come out the hard aperture, and 50% of the time it will come out the soft aperture. Now if you take the one that comes out the hard aperture, then you send it up here or send it up here, we know that these mirrors do nothing to the hardness of the electron except change the direction of motion. We've already done that experiment.

So you measure the hardness at the output, what do you get? Hard, because it came out hard, mirror, mirror, hardness, hard. But it only came out hard 50% of the time because we sent in initially white electron. Yeah? What about the other 50%? Well, the other 50% of the time, it comes out the soft aperture and follows what I'll call the soft path to the mirror, mirror, hardness. And with soft, mirror, mirror, hardness, you know it comes out soft. 50% of the time it comes out this way, and then it will come out hard. 50% it follows the soft path, and then it will come out soft. Was this the logic? Good. How many people agree with this? Solid. How many people disagree? No abstention. OK. So here's a prediction. Oh, yep.

AUDIENCE: Just a question. Could you justify that prediction without talking about oh, well, half the electrons were initially measured to be hard, and half were initially measured to be soft, by just saying, well, we have a hardness box, and then we joined these electrons together again, so we don't know anything about it. So it's just like sending white electrons into one hardness box instead of two.

ALLAN ADAMS: Yeah, that's a really tempting argument, isn't it? So let's see. We're going to see in a few minutes whether that kind of an argument is reliable or not. But so far we've been given two different arguments that lead to the same prediction, 50-50. Yeah? Question.

AUDIENCE: Are the electrons interacting between themselves? Like when you get them to where--

ALLAN ADAMS: Yeah. This is a very good question. So here's a question look you're sending a bunch of electrons into this apparatus. But if I take-- look, I took 802. You take two electrons and you put them close to each other, what do they do? Pyewww. Right? They interact with each other through a potential, right? So yeah, we're being a little bold here, throwing a bunch of electrons in and saying, oh, they're independent. So I'm going to do one better. I will send them in one at a time. One electron through the apparatus. And then I will wait for six weeks. [LAUGHTER]

See, you guys laugh, you think that's funny. But there's a famous story about a guy who did a similar experiment with photons, French guy. And, I mean, the French, they know what they're doing. So he wanted to do the same experiment with photons. But the problem is if you take a laser and you shined it into your apparatus, there there are like, 10 to the 18 photons in there at any given moment. And the photons, who knows what they're doing with each other, right? So I want to send in one photon, but the problem is, it's very hard to get a single photon, very hard.

So what he did, I kid you not, he took an opaque barrier, I don't remember what it was, it was some sort of film on top of glass, I think it was some sort of oil-tar film. Barton, do you remember what he used? So he takes a film, and it has this opaque property, such that the photons that are incident upon it get absorbed. Once in a blue moon a photon manages to make its way through. Literally, like once every couple of days, or a couple of hours, I think.

So it's going to take a long time to get any sort of statistics. But he this advantage, that once every couple of hours or whatever a photon makes its way through. That means inside the apparatus, if it takes a pico-second to cross, triumph, right? That's the week I was talking about. So he does this experiment. But as you can tell, you start the experiment, you press go, and then you wait for six months.

Side note on this guy, liked boats, really liked yachts. So he had six months to wait before doing a beautiful experiment and having the results. So what did he do? Went on a world tour in his yacht. Comes back, collects the data, and declares victory, because indeed, he saw the effect he wanted. So I was not kidding. We really do wait. So I will take your challenge. And single electron, throw it in, let it go through the apparatus, takes mere moments. Wait for a week, send in another electron. No electrons are interacting with each other. Just a single electron at a time going through this apparatus. Other complaints?

AUDIENCE: More stories?

ALLAN ADAMS: Sorry?

AUDIENCE: More stories?

ALLAN ADAMS: Oh, you'll get them. I have a hard time resisting. So here's a prediction, 50-50. We now have two arguments for this. So again, let's vote after the second argument. 50-50, how many people? You sure? Positive? How many people don't think so? Very small dust. OK. It's correct. Yea. So, good. I like messing with you guys. So remember, we're going to go through a few experiments first where it's going to be very easy to predict the results. We've got four experiments like this to do. And then we'll go on to the interesting examples. But we need to go through them so we know what happens, so we can make an empirical argument rather than an in principle argument.

So there's the first experiment. Now, I want to run the second experiment. And the second experiment, same as the first, a little bit louder, a little bit worse. Sorry. The second experiment, we're going to send in hard electrons, and we're going to measure color at out. So again, let's look at the apparatus. We send in hard electrons. And our apparatus is hardness box with a hard and a soft aperture. And now we're going to measure the color at the output. Color, what have I been doing?

And now I want to know what fraction come out black, and what fraction come out white. We're using lots of monkeys in this process. OK, so this is not rocket science. Rocket science isn't that complicated. Neuroscience is much harder. This is not neuroscience. So let's figure out what this is. Predictions. So again, think about your prediction your head, come to a conclusion, raise your hand when you have an idea. And just because you don't raise your hand doesn't mean I won't call on you.

AUDIENCE: 50-50 black and white.

ALLAN ADAMS: 50-50 black and white. I like it. Tell me why.

AUDIENCE: It's gone through a hardness box, which scrambled the color, and therefore has to be [INAUDIBLE]

ALLAN ADAMS: Great. So the statement, I'm going to say that slightly more slowly. That was an excellent argument. We have a hard electron. We know that hardness boxes are persistent. If you send a hard electron in, it comes out hard. So every electron incident upon our apparatus will transit across the hard trajectory. It will bounce, it will bounce, but it is still hard, because we've already done that experiment. The mirrors do nothing to the hardness.

So we send a hard electron into the color box, and what comes out? Well, we've done that experiment, too. Hard into color, 50-50. So the prediction is 50-50. This is your prediction. Is that correct? Awesome. OK, let us vote. How many people think this is correct? Gusto, I like it. How many people think it's not? All right. Yay, this is correct.

Third experiment, slightly more complicated. But we have to go through these to get to the good stuff, so humor me for a moment. Third, let's send in white electrons, and then measure the color at the output port. So now we send in white electrons, same beast. And our apparatus is a hardness box with a hard path and a soft path. Do-do-do, mirror, do-do-do, mirror, box, join together into our out.

And now we send those out electrons into a color box. And our color box, black and white. And now the question is how many come out black, and how many come out white. Again, think through the logic, follow the electrons, come up with a prediction. Raise your hand when you have a prediction.

AUDIENCE: Well, earlier we showed that [INAUDIBLE] so it'll take those paths equally--

ALLAN ADAMS: With equal probability. Good.

AUDIENCE: Yeah. And then it'll go back into the color box. But earlier when we did the same thing without the weird path-changing, it came out 50-50 still. So I would say still 50-50.

ALLAN ADAMS: Great. So let me say that again, out loud. And tell me if this is an accurate extension of what you said. I'm just going to use more words. But it's, I think, the same logic. We have a white electron, initially white electron. We send it into a hardness box. When we send a white electron into a hardness box, we know what happens. 50%

of the time it comes out hard, the hard aperture, 50% of the time it comes out the soft aperture.

Consider those electrons that came out the hard aperture. Those electrons that came out the hard aperture will then transit across the system, preserving their hardness by virtue of the fact that these mirrors preserve hardness, and end up at a color box. When they end at the color box, when that electron, the single electron in the system ends at this color box, then we know that a hard electron entering a color box comes out black or white 50% of the time. We've done that experiment, too.

So for those 50% that came out hard, we get 50/50. Now consider the other 50%. The other half of the time, the single electron in the system will come out the soft aperture. It will then proceed along the soft trajectory, bounce, bounce, not changing its hardness, and is then a soft electron incident on the color box. But we've also done that experiment, and we get 50-50 out, black and white. So those electrons that came out hard come out 50-50, and those electrons that come out soft come out 50/50.

And the logic then leads to 50-50, twice, 50-50. Was that an accurate statement? Good. It's a pretty reasonable extension. OK, let's vote. How many people agree with this one? OK, and how many people disagree? Yeah, OK. So vast majority agree. And the answer is no, this is wrong. In fact, all of these, 100% come out white and 0 come out black. Never ever does an electron come out the black aperture.

I would like to quote what a student just said, because it's actually the next line in my notes, which is what the hell is going on? So let's the series of follow up experiments to tease out what's going on here.

So something very strange, let's just all agree, something very strange just happened. We sent a single electron in. And that single electron comes out the hardness box, well, it either came out the hard aperture or the soft aperture. And if it came out the hard, we know what happens, if it came out the soft, we know what happens. And it's not 50-50. So we need to improve the situation. Hold on a sec. Hold on one sec. Well, OK, go ahead.

AUDIENCE: Yeah, it's just a question about the setup. So with the second hardness box, are we collecting both the soft and hard outputs?

ALLAN ADAMS: The second, you mean the first hardness box?

AUDIENCE: The one-- are we getting-- no, the--

ALLAN ADAMS: Which one, sorry? This guy? Oh, that's a mirror, not a hardness box. Oh, thanks for asking. Yeah, sorry. I wish I had a better notation for this, but I don't. There's a classic-- well, I'm not going to go into it. Remember that thing where I can't stop myself from telling stories?

So all this does, it's just a set of mirrors. It's a set of fancy mirrors. And all it does is it takes an electron coming this way or an electron coming this way, and both of them get sent out in the same direction. It's like a beam joiner, right? It's like a y junction. That's all it is. So if you will, imagine the box is a box, and you take, I don't know, Professor Zwiebach, and you put him inside. And every time an electron comes up this way, he throws it out that way, and every time it comes in this way, he throws it out that way. And he'd be really ticked at you for putting him in a box, but he'd do the job well. Yeah.

AUDIENCE: And this also works if you go one electron at a time?

ALLAN ADAMS: This works if you go one electron at a time, this works if you go 14 electrons at a time, it works. It works reliably. Yeah.

AUDIENCE: Just, maybe [INAUDIBLE] but what's the difference between this experiment and that one?

ALLAN ADAMS: Yeah, I know. Right? Right? So the question was, what's the difference between this experiment and the last one. Yeah, good question. So we're going to have to answer that. Yeah.

AUDIENCE: Well, you're mixing again the hardness. So it's like as you weren't measuring it at all, right?

ALLAN ADAMS: Apparently it's a lot we weren't measuring it, right? Because we send in the white electron, and at the end we get out that it's still white. So somehow this is like not doing anything. But how does that work? So that's an excellent observation. And I'm going to build you now a couple of experiments that tease out what's going on. And you're not going to like the answer. Yeah.

AUDIENCE: How were the white electrons generated in this experiment?

ALLAN ADAMS: The white electrons were generated in the following way. I take a random source of electrons, I rub a cat against a balloon and I charge up the balloon. And so I take those random electrons, and I send them into a color box. And we have previously observed that if you take random electrons and throw them into a color box and pull out the electrons that come out the white aperture, if you then send them into a color box again, they're still white.

So that's how I've generated them. I could have done it by rubbing the cat against glass, or rubbing it against me, right, just stroke the cat. Any randomly selected set of electrons sent into a color box, and then from which you take the white electrons.

AUDIENCE: So how is it different from the experiment up there?

ALLAN ADAMS: Yeah. Uh-huh. Exactly. Yeah.

AUDIENCE: Is the difference that you never actually know whether the electron's hard or soft?

ALLAN ADAMS: That's a really good question. So here's something I'm going to be very careful not to say in this class to the degree possible. I'm not going to use the word to know.

AUDIENCE: Well, to measure. [INAUDIBLE]

ALLAN ADAMS: Good. Measure is a very slippery word, too. I've used it here because I couldn't really get away with not using it. But we'll talk about that in some detail later on in the course. For the moment, I want to emphasize that it's tempting but dangerous at this point to talk about whether you know or don't know, or whether someone knows or doesn't know, for example, the monkey inside knows or doesn't know. So let's try to avoid that, and focus on just operational questions of what are the things that go in, what are the things that come out, and with what probabilities.

And the reason that's so useful is that it's something that you can just do. There's no ambiguity about whether you've caught a white electron in a particular spot. Now in particular, the reason these boxes are such a powerful tool is that you don't measure the electron, you measure the position of the electron. You get hit by the electron or you don't.

And by using these boxes we can infer from their position the color or the hardness. And that's the reason these boxes are so useful. So we're inferring from the position, which is easy to measure, you get beaned or you don't, we're inferring the property that we're interested in. It's a really good question, though. Keep it in the back of your mind. And we'll talk about it on and off for the rest of the semester. Yeah.

AUDIENCE: So what happens if you have this setup, and you just take away the bottom right mirror?

ALLAN ADAMS: Perfect question. This leads me into the next experiment. So here's the modification. But thank you, that's a great question. Here's the modification of this experiment. So let's rig up a small-- hold on, I want to go through the next series of experiments, and then I'll come back to questions. And these are great questions.

So I want to rig up a small movable wall, a small movable barrier. And here's what this movable barrier will do. If I put the barrier in, so this would be in the soft path, when I put the barrier in the soft path, it absorbs all electrons incident upon it and impedes them from proceeding. So you put a barrier in here, put a barrier in the soft path, no electrons continue through. An electron incident cannot continue through.

When I say that the barrier is out, what I mean is it's not in the way. I've moved it out of the way. Cool? So I want to run the same experiment. And I want to run this experiment using the barriers to tease out how the electrons transit through our apparatus.

So experiment four. Let's send in a white electron again. I want to do the same experiment we just did. And color at out, but now with the wall in the soft path. Wall in soft. So that's this experiment.

So we send in white electrons, and at the output we measure the color as before. And the question is what fraction come out black, and what fraction come out white. So again, everyone think through it for a second. Just take a second. And this one's a little sneaky. So feel free to discuss it with the person sitting next to you.

[CHATTER]

ALLAN ADAMS: All right. All right, now that everyone has had a quick second to think through this one, let me just talk through what I'd expect from the point of these experiments. And then we'll talk about whether this is reasonable. So the first thing I expect is that, look, if I send in a white electron and I put it into a hardness pass, I know that 50% of the time it goes out hard, and 50% of the time it goes out soft. If it goes out the soft aperture, it's going to get eaten by the barrier, right? It's going to get eaten by the barrier.

So first thing I predict is that the output should be down by 50%. However, here's an important bit of physics. And this comes to the idea of locality. I didn't tell you this, but these armlinks in the experiment I did, 3,000 kilometers long. 3,000 kilometers long. That's too minor. 10 million kilometers long. Really long. Very long. Now, imagine an electron that enters this, an initially white electron.

If we had the barriers out, if the barrier was out, what do we get? 100% white, right? We just did this experiment, to our surprise. So if we did this, we get 100%. And that means an electron, any electron, going along the soft path comes out white. Any electron going along the hard path goes out white. They all come out white. So now, imagine I do this. Imagine we put a barrier in here 2 million miles away from this path. How does a hard electron along this path know that I put the barrier there?

And I'm going to make it even more sneaky for you. I'm going to insert the barrier along the path after I launched the electron into the apparatus.

And when I send in the electron, I will not know at that moment, nor will the electron know, because, you know, they're not very smart, whether the barrier is in place. And this is going to be millions of miles away from this guy. So an electron out here can't know. It hasn't been there. It just hasn't been there. It can't know. But we know that when we ran this apparatus without the barrier in there, they came out 100% white. But it can't possibly know whether the barrier's in there or not, right? It's over here.

So what this tells us is that we should expect the output to be down by 50%. But all the electrons that do make it through must come out white, because they didn't know that there was a barrier there. They didn't go along that path. Yeah.

AUDIENCE: Not trying to be wise, but why are you using the word know?

ALLAN ADAMS: Oh, sorry, thank you. Thank you, thank you, thank you, that was a slip of the tongue. I was making fun of the electron. So in that particular case, I was not referring to my or your knowledge. I was referring to the electron's tragically impoverished knowledge. Yeah.

AUDIENCE: But if they come out one at a time white, then wouldn't we know then with certainty that that electron is both hard and white, which is like a violation?

ALLAN ADAMS: Well, here's the more troubling thing. Imagine it didn't come out 100% white. Then the electron would have demonstrably not go along the soft path. It would have demonstrably gone through the hard path, because that's the only path available to it. And yet, it would still have known that millions of miles away, there's a barrier on a path it didn't take. So which one's more upsetting to you? And personally, I find this one the less upsetting of the two.

So the prediction is our output should down by 50%, because a half of them get eaten. But they should all come out white, because those that didn't get eaten can't possibly know that there was a barrier here, millions of miles away. So we run this experiment. And here's the experimental result. In fact, the experimental result is yes, the output is down by 50%. But no, not 100% white, 50% white. 50% white. The barrier, if we put the barrier in the hardness path. If we put the barrier in the hardness path, still down by 50%, and it's at odds, 50-50. How could the electron know? I'm making fun of it. Yeah.

AUDIENCE: So I guess my question is before we ask how it knows that there's a block in one of the paths, how does it know, before, over there, that there were two paths, and combine again?

ALLAN ADAMS: Excellent. Exactly. So actually, this problem was there already in the experiment we did. All we've done here is tease out something that was existing in the experiment, something that was disturbing. The presence of those mirrors, and the option of taking two paths, somehow changed the way the electron behaved. How is that possible? And here, we're seeing that very sharply. Thank you for that excellent observation. Yeah.

AUDIENCE: What if you replaced the two mirrors with color boxes, so that both color boxes [INAUDIBLE]

ALLAN ADAMS: Yeah. So the question is basically, let's take this experiment, and let's make it even more intricate by, for example, replacing these mirrors by color boxes. So here's the thing I want to emphasize. I strongly encourage you to think through that example. And in particular, think through that example, come to my office hours, and ask me about it.

So that's going to be setting a different experiment. And different experiments are going to have different results. So we're going to have to deal with that on a case by case basis. It's an interesting example, but it's going to take us a bit afar from where we are right now. But after we get to the punchline from this, come to my office hours and ask me exactly that question. Yeah.

AUDIENCE: So we had a color box, we put in white electrons and we got 50-50, like random. How do you know the boxes work?

ALLAN ADAMS: How do I know the boxes work? These are the same boxes we used from the beginning. We tested them over and over.

AUDIENCE: How did you first check that it was working? [INAUDIBLE]

ALLAN ADAMS: How to say-- there's no other way to build a box that does the properties that we want, which is that you send in color and it comes out color again, and the mirrors behave this way. Any box that does those first set of things, which is what I will call a color box, does this, too. There's no other way to do it. I don't mean just because like, no one's tested--

AUDIENCE: Because you can't actually check it, you can't actually [INAUDIBLE] you know which one is white.

ALLAN ADAMS: Oh, sure, you can. You take the electron that came out of the color box. That's what we mean by saying it's white.

AUDIENCE: [INAUDIBLE]

ALLAN ADAMS: But that's what it means to say the electron is white. It's like, how do you know that my name is Allan? You say, Allan, and I go, what? Right? But you're like, look that's not a test of whether I'm Allan. It's like, well, what is the test? That's how you test. What's your name? I'm Allan. Oh, great, that's your name. So that's what I mean by white. Now you might quibble that that's a stupid thing to call an electron. And I grant you that. But it is nonetheless a property that I can empirically engage. OK, so I've been told that I never ask questions from the people on the right. Yeah.

AUDIENCE: Is it important whether the experimenter knows if the wall is there or not?

ALLAN ADAMS: No. This experiment has been done again by some French guys. The French, look, dude. So there's this guy, Alain Aspect, ahh, great experimentalist, great physicist. And he's done lots of beautiful experiments on exactly this topic. And send me an email, and I'll post some example papers and reviews by him-- and he's a great writer-- on the web page. So just send me an email to remind me of that.

OK, so we're lowish on time, so let me move on. So what I want to do now is I want to take the lesson of this experiment and the observation that was made a minute ago, that in fact the same problem was present when we ran this experiment and go 100%. We should have been freaked out already. And I want to think through what that's telling us about the electron, the single electron, as it transits the apparatus.

The thing is, at this point we're in real trouble. And here's the reason. Consider a single electron inside the apparatus. And I want to think about the electron inside the apparatus while all walls are out. So it's this experiment. Consider the single electron. We know, with total confidence, with complete reliability, that every electron will exit this color box out the white aperture. We've done this experiment. We know it will come out white. Yes? Here's my question. Which route did it take?

AUDIENCE: Spoiler.

ALLAN ADAMS: Not a spoiler. Which route did it take?

AUDIENCE: Why do we care what route?

ALLAN ADAMS: I'm asking you the question. That's why you care. I'm the professor here. What is this? Come on. Which route did it take? OK, let's think through the possibilities. Grapple with this question in your belly. Let's think through the possibilities. First off, did it take the hardness path? So as it transits through, the single electron transiting through this apparatus, did it take the hard path or did it take the soft? These are millions of miles long, millions of miles apart. This is not a ridiculous question. Did it go millions of miles in that direction, or millions of miles in that direction? Did it take the hardness path? Ladies and gentlemen, did it take the hard path?

AUDIENCE: Yes.

ALLAN ADAMS: Well, we ran this experiment by putting a wall in the soft path. And if we put a wall in the soft path, then we know it took the hard path, because no other electrons come out except those that went through the hard path. Correct? On the other hand, if it went through the hard path, it would come out 50% of the time white and 50% of the time black. But in fact, in this apparatus it comes out always 100% white. It cannot have taken the hard path. No. Did it take the soft path? Same argument, different side, right? No.

Well, this is not looking good. Well, look, this was suggested. Maybe it took both. Maybe electrons are sneaky little devils that split in two, and part of it goes one way and part of it goes the other. Maybe it took both paths. So this is easy. We can test this one. And here is how I'm going to test this one. Oh, sorry. Actually, I'm not going to do that yet. So we can test this one.

So if it took both paths, here's what you should be able to do. You should be able to put a detector along each path, and you'd be able to follow, if you've got half an electron on one side and half an electron on the other, or maybe two electrons, one on each side and one on the other. So this is the thing that you'd predict if you said it went both. So here's what we'll do. We will take detectors. We will put one along the hard path and one along the soft path. We will run the experiment and then observe whether, and ask whether, we see two electrons, we see half and half, what do we see.

The answer is you always, always see one electron on one of the paths. You never see half an electron. You never see a squishy electron. You see one electron on one path, period. It did not take both. You never see an electron split in two, divided, confused. No. Well, it didn't take the hard path, didn't take the soft path, it didn't take both. There's one option left. Neither. Well, I say neither. But what about neither? And that's easy. Let's put a barrier in both paths. And then what happens? Nothing comes out. So no.

So now, to repeat an earlier prescient remark from one of the students, what the hell? So here's the world we're facing. I want you to think about this. Take this seriously. Here's the world we're facing. And when I say, here's the world we're facing, I don't mean just these experiments. I mean the world around you, 20 kilo mirrors, bucky-balls, here is what they do. When you send them through an apparatus like this, every single object that goes through this apparatus does not take the hard path, it does not take the soft path, it doesn't take both, and it does not take neither. And that pretty much exhausts the set of logical possibilities. So what are electrons doing when they're inside the apparatus?

How do you describe that electron inside the apparatus? You can't say it's on one path, you can't say it's on the other, it's not on both, and it's not on neither. What is it doing halfway through this experiment? So if our experiments are accurate, and to the best of our ability to determine, they are, and if our arguments are correct, and that's on me, then they're doing something, these electrons are doing something we've just never thought of before, something we've never dreamt of before, something for which we don't really have good words in the English language. Apparently, empirically, electrons have a way of moving, electrons have a way of being which is unlike anything that we're used to thinking about. And so do molecules. And so do bacteria. So does chalk. It's just harder to detect in those objects.

So physicists have a name for this new mode of being. And we call it superposition. Now, at the moment, superposition is code for I have no idea what's going on. Usage of the word superposition would go something like this. An initially white electron inside this apparatus with the walls out is neither hard, nor soft, nor both, nor neither. It is, in fact, in a superposition of being hard and of being soft.

This is why we can't meaningfully say this electron is some color and some hardness. Not because our boxes are crude, and not because we're ignorant, though our boxes are crude and we are ignorant. It's deeper. Having a definite color means not having a definite hardness, but rather being in a superposition of being hard and being soft.

Every electron exits a hardness box either hard or soft. But not every electron is hard or soft. It can also be a superposition of being hard or being soft. The probability that we subsequently measure it to be hard or soft depends on precisely what superposition it is. For example, we know that if an electron is in the superposition corresponding to being white then there are even odds of it being subsequently measured be hard or to be soft.

So to build a better definition of superposition than I have no idea what's going on is going to require a new language. And that language is quantum mechanics. And the underpinnings of this language are the topic of the course. And developing a better understanding of this idea of superposition is what you have to do over the next three months.

Now, if all of this troubles your intuition, well, that shouldn't be too surprising. Your intuition was developed by throwing spears, and running from tigers, and catching toast as it jumps out of the toaster, all of which involves things so big and with so much energy that quantum effects are negligible.

As a friend of mine likes to say, you don't need to know quantum mechanics to make chicken soup. However, when we work in very different regimes, when we work with atoms, when we work with molecules, when we work in the regime of very low energies and very small objects, your intuition is just not a reasonable guide.

It's not that the electrons-- and I cannot emphasize this strongly enough-- it is not that the electrons are weird. The electrons do what electrons do. This is what they do. And it violates your intuition, but it's true. The thing that's surprising is that lots of electrons behave like this. Lots of electrons behave like cheese and chalk. And that's the goal of 804, to step beyond your daily experience and your familiar intuition and to develop an intuition for this idea of superposition. And we'll start in the next lecture. I'll see you on Thursday.