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Atom interferometry

Splitting and recombining atom waves

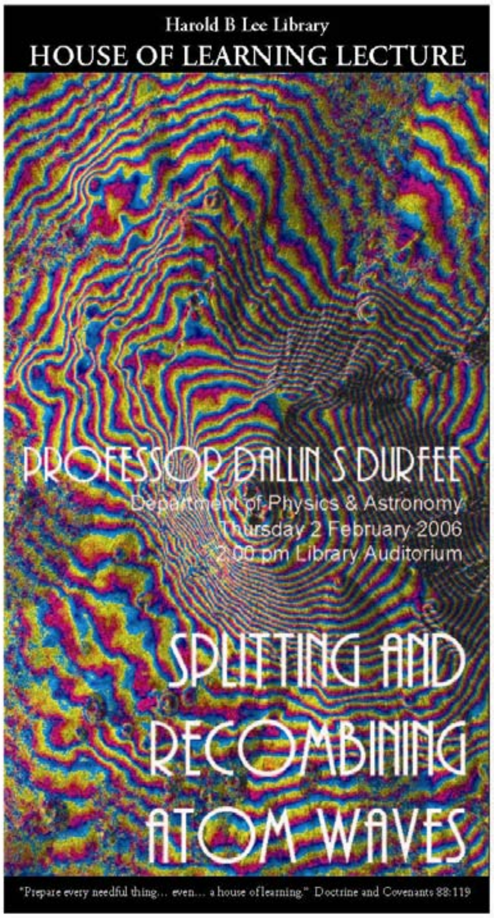
House of Learning

408

(Season 4, Episode 8)

OFFICIAL TRANSCRIPT

Produced by the Harold B. Lee Library
At Brigham Young University
Thursday January 26, 2006



Thank you very much. It’s a privilege to be here today. I love any opportunity I have to talk about well, the things that I think are really interesting and drive my life outside of my family of course. Today we are going to be talking about splitting and recombining atom waves. And this is kind of a big topic to try and swallow in one presentation, so here we go. We are going to try.

But first, before I dive into this I’d like to just acknowledge a whole bunch of people that have helped me out and have worked with me. In particular I’d like to point out that there have been a lot of undergraduates that have worked on this. And its really undergraduate students who’ve done most of the work uh in my lab that I’m going to leading up to in this talk.

Also, before we get started, I have to give you a quick disclaimer. I am not presenting quack science. This happens to me all the time when I give a lecture based on quantum mechanics. What I will discuss is the result of something called quantum mechanics, and if you aren’t familiar with quantum mechanics it’ll sound really counter intuitive. But, quantum mechanics has been tested in many experiments and the strange things I tell you are based on ideas found in any good modern physics text book. Some day we will find a theory that goes beyond quantum mechanics. It’s inevitable that quantum mechanics is wrong, but until then, quantum mechanics is the name of the game. And when we finally do find another theory, the chances are it is going to be even weirder. So, live with it.

Alright, now before I can talk about interfering atom waves, I need to make clear what a wave is and what waves do. Right, so what exactly is a wave? Well, a wave in a sense is a wave that energy can transfer itself from one place to another. For example, if you study waves with me in physics 123 you will be issued a slinky and what you thought was a lot of fun will turn into hard homework problems. Alright, but the basic idea is here if I whack the end of this slinky, you’ll see a little compression wave bounce back and forth. What is happening is as I push on one piece of the slinky, it compresses that piece. It doesn’t want to be compressed, it wants to stretch out, and so it pushes on the piece next to it and compresses it. Well, it doesn’t want to be compressed so it pushes on the piece next to it. And that wave, the energy travels down the slinky. Another example of a wave is my voice. As I talk to you, my mouth is emitting energy, and that energy is reaching your ears. Alright, it is not the actual air that is getting to you it is the energy. That way you can hear me without actually having to smell my breath. That is one of the wonderful things about waves.

Now let’s talk about some of the properties of waves. Imagine that I have a stereo and I play a pure tone. A pure frequency threw both speakers. Right next to the speaker I have got this speaker cone that is moving back and forth and it’s pushing the air, it’s compressing the air. So right next to the speaker cone you’ll see the pressure of the air go up and down in time and that is what I am representing here. And that pressure, that little pulse of pressure then travels outward. Now imagine you are sitting right between two stereo speakers and they are both doing exactly the same thing at the same time. What you hear then is the combination of both of those sound waves coming from both speakers, so you hear the sum of those two. You add them together and you get an even bigger wave, alright. But what would happen if I'd accidentally wired up one of my speakers backwards, I flipped the wires. Well now, when this speaker is moving that way, the other speaker is moving this way. And you can see the pressure waves are out of phase we say. This one is going up when that one is going down. So when these two waves reach your ear, you add them together and they just cancel each other out. And you hear no sound.

Now if you have ever wired up your stereo systems backwards, you probably didn't hear no sound because there is all kinds of idealizations going on here. In a real stereo, in a real room you'll also get sounds that don't come straight from the speaker but ones that maybe reflect off of a wall or a ceiling and come to you. But you will notice if you sit right between the speakers there is a lot less vivacity, there is a lot less volume to the sound, alright.

Now let's imagine another scenario. Imagine that my speakers are wired up correctly, they are both doing the same thing at the same time but imagine you are sitting at a place that is closer to one speaker than the other. Well, the speaker that's further away, its sound wave has to travel further and it takes a longer time before it reaches your ear. And as a result, the wave is shifted a little in its phase, it's delayed a little. So now, if I have, if I'm sitting at just the right position, it turns out I can actually have those two waves cancel out at my ear, even though both speakers are exactly in phase, alright.

So let's do a little demonstration of that shall we. I've got two speakers here, I'll turn up the volume, and what I want you to do is close one ear and then lean side to side and listen to how the volume changes. Who can hear that? Alright, so this phenomenon where waves can add together or they can cancel out is known as interference. And interference is something that waves do, alright. Here's just a little animation of what just occurred. I have one speaker and its emitting these waves. I have another speaker that's emitting waves; if I add these two waves together I get this. There are places where the waves cancel each other out and not much happens. There are places where they add together and I get a lot of sound. Now if I come over here and detect what places, there is lots of sound and what places there is not, that is known as an interference pattern. Waves interfere, they form interference patterns.

Ocean waves can do the same thing, alright. Imagine that I have some waves that are traveling. There we go. Imagine that I have some source of waves that are making ocean waves travel kind of up and to the right here, alright. Now let's turn off that sources and turn on another source which is traveling up and to the left. What happens if I have both sources on at the same time? Well, before I show you that, I'm just going to show you another little video where I have the left going wave and then we are going to fade over to the video of the right going wave, alright. And it will just fade back and forth. Now if I stop, we are seeing kind of both videos overlaid on top of each other. And you notice along this line right here, wherever the left going wave has a trough; the right going wave has a trough. Wherever the left going wave has a peak, the right going wave has a peak, alright. So along this line you expect really big waves, because they both contributions are doing the same things at the same time. If you move over a bit, you look right here, look, the left going waves is a trough but the right going wave is a peak at that point. So when I add those two waves together they are going to cancel out. Up here, the right going wave is a trough and the left going wave is a peak. So all along this line here, the waves are going to cancel each other out. So let's see what happens when I add these two waves together, and there it is. If you are on a beach somewhere and these waves are coming in. If you are sitting right here you'll say "oh boy, surf's up, a lot of big waves." If you are planning on going surfing because you heard that there are some big waves being generated on the ocean, but you happen to show up on this piece of beach here, you'd be disappointed because the waves will cancel out; there is nothing there, alright.

Now, another type of wave is light; light from the laser pointer, the light that's coming and projecting this image on this screen. Light is also a wave. Now, how do we know that light is a wave. Well, if I look at ocean waves I can actually see these wavy things moving along, right. But with light, the spacing between these waves is really really small. And the rate at which they oscillate is really really fast, so you can't go and directly measure the waves in a light waves. So how do we know that light is a wave? Well, what do waves do? They interfere. So, I can do an interference experiment. For example, I can take a laser, split it into two pieces and send those two pieces together. Just like our ocean waves colliding together, we should see stripes, we should see places where the two waves add together brightly and two places where they cancel out, alright. So that is what we should see, what do we actually see. Let's go over to a little laser I have here and I'll show you alright. So, turn this laser on. So what you see are a couple of spots, alright. I have a beam of light, I'm blocking; I have two beams of light, but I'm blocking one of them. Let's see what the other beam of light looks like, aright. It looks like that; it looks a lot the same. But what if I put the two of them together…welah! I see interference. And it turns out the spacing between those interference frequencies depends on the angle of the two beams, so if I make small changes to the relative angle of these beams I can make the interference fringes get bigger and smaller. So, there you have it.

So the verdict is in. Light is a wave. Alright, and it turns out when I take a beam of light it, and split it or recombine it to see an interference pattern, the device that I have made is an interferometer. And I told you that I was going to talk about interferometers, but I didn't say I was going to talk about light interferometers I said I was going to talk about atom interferometers. So, we've better move on. Um, well before we move on we have to put a little history behind this. Back at the end of the 19th century there were a lot of people that said that physics was done, and there are people that think that today too. But then and now, there are some things that you can't just really explain very well with the models of physics. So they had, Maxwell's equations, they had Newton's laws and they thought that that was all there was. But, there are some puzzling inconsistencies and one of which had to do with black body radiation. Black body radiation is the light that something gives off when it gets hot. You turn the burner on your stove and it starts to glow, that is black body radiation. You turn on a light bulb, current flows through a filament, it heats up and glows, that is black body radiation. Um, the sun, its big, its hot, and it glows, that's also black body radiation.

Alright, so back at the end of the 19th century experimentalist were measuring the different colors that came out at different temperatures. Well, you take the so called understood physics at the time and you predict the entirely wrong thing. And nobody understood why. Well a guy by the name of Max Plank started thinking about this and he took a kind of interesting approach. What he did is he first found an empirical formula that's fit all the experimental data without wondering about what the physics was behind it and then he asked himself, what do you have to do to derive this formula, alright. And what he found is that in order to derive his equation, he had to assume that the energy in the radiation had to come in packets. The light coming out in blackbody radiation came in little energy packets. Now if you think of an ocean wave. An ocean waves doesn't look like little packets of anything does it. It is a big continuous thing. So, what kinds of things some in packets, well particles. You know, a marble. It is as if the light are little bee bee's shooting through the air. So the conclusion then is that light is a particle. Light is like little bee bee's moving through the air, little packets of energy. But wait a minute, we already proved that light is a wave, so we've got a dilemma. But before we solve this dilemma uh I need to introduce you to a man by the name of Albert Einstein if you have never heard of him before.

Now what did Einstein win his noble prize for? A year if I'd asked you, most of you probably would have said relativity. But sense as you all know, last year was the world year of physics, celebrating the 100th anniversary of the year that Einstein published his 3 most famous papers, you probably saw something on PBS that told you otherwise right? Um, the thing that Einstein actually won his noble prize was a phenomenon known as the photoelectric effect. And the photoelectric effect is basically a phenomenon where I shine light at a piece of metal and electrons come shooting out. And once again, experimentalists did different things. They changed the color of light on the metal, they measured the energy of the electrons coming out, and guess what the classical theory did not describe what they were seeing. So Einstein looked at this problem and he thought long and hard about it and he came up with an amazing conclusion. An incredible conclusion. So incredible, that they gave him a noble prize for it. And this is Einstein's amazing statement that won him a noble prize. Plank was right, alright. Light really is like little particles, alright. And it turns out then that the way we reconcile wave experiments where we prove that light is a wave and other experiments that prove that light is a particle is that in fact that lights acts as both. There are times when it behaves as a wave and times that it behaves as a particle, which is kind of weird. We call this the wave particle duality, alright.

Now, soon after this, a man by the name of de Broglie was sitting and thinking. And in his journal, he says that this idea came to him like a bolt out of the blue. And this was his idea. If light, which we thought of as waves, behaves like a particle then maybe things we think of particles behave as waves. And very soon after he made this conjecture, a couple of experimentalist by the name of Davis and Engerimer where shooting electrons at a little piece of nickel and they saw a diffraction pattern. They had never heard of de Broglie's conjecture unfortunately so they had no idea what it was, but eventually they found out about de Broglie's work and said, ah ah this is true we have seen it, electrons behave as waves alright. And it turns out that atoms behave as waves too. And in fact people have done interference experiments with things as big as molecules of 60 atoms. It turns out its harder and harder to do this as things get bigger and bigger. But the supposition is that everything behaves as a wave, this table, you and I, the planet earth, are all described by a wave function, alright. Here's just a little, how do we tell if atoms are really waves? I guess I blew the punch line there. We look for interference.

Here's a picture of interference that I took as a graduate student. What we did is we took too little clouds of really cold sodium atoms, inside of a magnetic trap. Then we turned off the magnetic trap and let these little puffs of gas expand into one another. And after some time we measured the density of atoms in a plane, and this a plot of that density. And what do you see? Interference fringes. So indeed, atoms are waves. And if atoms are waves, I can make an interferometer out of atoms. Ok, so atoms, matter is made out of waves, what good does that do us. Well, it turns out you can do all kinds of really cool experiments and make all kinds of cool devices because atoms are waves.

And here is just one example. Uh, one example is a sanyack interferometer. Now a sanyack interferometer is a way to use interference to measure rotation. And people have been making sanyack interfermeters for some time using light and in fact laser sanyack interfermeters are used today to help navigate airplanes and missiles and submarines, alright. And the way that it works is, imagine that I have a beam of light and I know this light is really a wave, it is something oscillating back and forth. I send this light to a thing called a beam splitter. And a beam splitter is just a mirror that lets a little bit of light through. So this beam splitter lets some light through and reflects some light, so now I've split my laser beam in half. Half of the light will go up here, hit a mirror and be redirected down to a second beam splitter. Half of the light will come and hit this mirror and be then better redirected to the second beam splitter. Now if I look, the light traveling this path, when it hits this beam splitter, some of it will go through the beam splitter and some of it will reflect. The light that takes this path, some of it will go through the beam splitter and some of it will reflect. So what I get coming out here is a sum of light that went that way and light that went that way. So I get a little bit of wave that went this way, and a little bit of wave that went that way and they add together to make a bigger wave. But if I look at the light coming down here, it turns out that the light going that way and the light going that way, it phase shifted when they reflected off these different devices such that they're out of phase with one another and when they add together you get zero, they cancel each other out.

But now, what happens if my whole apparatus starts to rotate. Well, the light doesn't care that the experiment is rotating it still travels a straight path. So what happens if I start to rotate the whole experiment by the time these two bits of light get together on this beam splitter, the beam splitter will have moved. So now this light has to travel less distance than that light, and that causes a delay in the arrival time of the two bits of light which causes a phase shift. So now, this beam, the contribution from the upper path, is not exactly in phase with the bit from the lower path. They don't oscillate up at exactly the same time any more, so when I add them together I don't get quite as big a wave anymore. And then down here if I look at the light coming in this direction, they don't totally cancel each other out anymore and I get a little bit of white coming out this port. So what would a photo detector here and measure how much light comes out in that direction I can infer then how fast my experiment is rotating. And it turns out that you can make a very sensitive gyroscope that way. Well you can do that with a laser beam, so can also do that with atoms.

So how do you make an atom interferometer? Well you need certain things in order to make an interferometer. For the light interferometer we had a source of light, a laser. We had a beam splitter to split the laser beam in half, we had a mirrors to take the two halves of the wave and bring them back together again and we had a detector to see how much light came out in one direction verses the other. So how do we do that with atoms? Well, in all the experiments I've worked on our source of atoms has been an oven. We heat up some chunk of metal and we heat it up enough that some of the atoms start to vaporize and then some of that vapor escapes through a hole in the oven and makes an atomic beam.

How do I make a beam splitter for atom waves? Well, it turns out we use a laser beam. How do we make mirrors? We also use a laser beam. And to detect what port the atoms come out in we use a laser beam, plus a photo dial to detect the light that the atoms scatter, alright. So how do I make a mirror or a beam splitter with a laser beam? I'm about to explain that. Here we have got an atom, that's not really what an atom looks like but that will represent an atom, and here we have something known has an energy level diagram. It turns out, quantum mechanics tells us that I can put energy into an atom and it can store that energy, but that atom can only be in a certain allowed energy states. I can't put an arbitrary amount of energy into the atom. So I've depicted two of those allowed energy states with lines here. The lower line means a lower energy state, and the higher line means a higher energy state and this little dot here says that the atom right now is in the lower energy state, alright.

Along come a photon and the atom absorbs it. A photon by the way is what we call a particle of light. So the atom absorbs this little particle of light. What happens? Well that little packet of light carries energy. So, the atom absorbs that energy and goes into a higher energy state, but the little particle of light also carries momentum. So it absorbs the light it gets a little recoil kick. And now my atom is flying along, alright. I had to stop on my overhead here because I didn't want it to flash the screen, but imagine this atom is just flying away now, alright. So I can deflect an atom simply by shooting light at it. What happens now if my atom is in its excited state and its flying away, what happens if another light particle comes along. Well, here comes my light particle. Well, the atom can't absorb its energy anymore because it's already in the higher energy state, but Einstein figured out that what the atom can do is it can feel the presence of that photon, and that photon can tickle the atom and make it give off its energy. So that photon will tickle the atom, forcing the atom to go back into the lower energy state and it does that by emitting a second photon which is identical to the one that tickled it. And incidentally this is the process that makes lasers work.

Alright, so now that photon carries off the energy that the atom had but it also carries off the momentum we've given the atom and so the atom will come to a stop again, alright. So that is how I can make a mirror. I can make an atom deflect and then I can stop it again. If I want the atom to go that way, I send a laser beam and I deflect it that way, if I want it to stop I send another laser beam in that direction and I can get it to stop.

Now, how do I make a beam splitter? Well, it turns out that I have only describes one of the things the atom can do. When this light particle comes along, it can absorb the light particle and recoil away. But the other thing it can do is totally ignore the light and let it divide. And it turns out that if we adjust the intensities of our lasers just right we can set up a situation where the atom actually does both, where half of its wave thinks that its absorbs a photon and recoils away and the other half of its wave thinks it hasn't absorbed a photon and continues on its way. So here's a diagram of an experiment that I worked on just before I came to BYU that measured rotations using this sanyack effect I described earlier and the way it worked is we'd send a beam of cesium atoms in and that's represented by the black. The black line represents the cesium atom in the lower energy state, then we have the laser beam that the atom interacts with and half of its wave thinks it hasn't absorbed light and the other half thinks it has goes into the excited state and recoils away. At this point, we have another laser beam which is twice as intense which assures that with near 100% probability this atom and part of the wave in the ground state, in the lower energy state, absorbs a photon. And this piece up here in the higher energy state is induced to emit a photon with 100% certainty, so this one now gets a momentum kick and this one loses its momentum kick, so now they fly towards each other, and right where they are overlapping we have a third laser beam which allows these two states to interfere and mix, alright.

So now, all you have to do is to detect which way the atoms are coming out and it turns out detecting which way they come out is the same thing as detecting what state they are in, whether they are in the lower or the higher energy state. So here, there is a lot of data on this plot, but if you just look at the black line here, this black line is a plot of the number of atoms per second, coming out in the uh excited state as a function of the rate at which the apparatus was rotating at. And so you can see, by measuring the number of atoms coming out in the excited state you can figure out how fast the apparatus is rotating at. Here is a picture of the apparatus I worked on; it's basically a big vacuum chamber because the atoms need…we can't let them collide with air. So we suck all the air out, this little piece of tin foil covers an oven where we heat the cesium up, the cesium then flies through this vacuum chamber and you can see kind of three places where laser beams come in and interact with the atoms.

Now how good was this atom interferometer gyroscope? Well imagine that I draw a line all the way across the country. Now I'm going to let that line rotate very slowly at the smallest rotation rate that our gyroscope could detect, alright. So here is a real time uh enactment of the type of rotation rate our interferometer could detect, here we go. How fast is that moving? Not very fast, in fact the type of rotation we could detect would have this line; have the end of this line sweeping about half the distance of half the thickness of my pinky per second. And my pinky is very small compared to the state of California so that why it appears that this line is not moving. So it's a very sensitive device, it is the most sensitive gyroscope ever built.

Now, if you have a really sensitive gyroscope it turns out there are some cool fun things you can do. Um, it turns out that there is weird thing that Einstein's general relativity predicts called the gravitomagnetic force which causes something called the lens therin effect. Now, if you have seen on PBS a show on Einstein's general relativity, you probably know that the way that Einstein describes gravity is that he says that massive objects actually bend space time; they warp it and that makes stuff and that makes stuff come towards it, alright. So this grid here represents space time. If I throw a big planet or a big star in the middle here, it'll distort space time. Gravity distorts space time, alright. But now imagine this planet, say earth for example, is rotating. It turns out there is a higher order effect and what happens is, this rotating mass of body can actually swirl space time. So if you were to look at the stars and watch how the stars appear to rotate, you know it is not really the stars that are rotating, it is the earth that's rotating, right? So you can calculate how fast the earth is rotating by looking at the stars. But now imagine you make a really, really good gyroscope and measure how fast the earth is rotating with your gyroscope. Well it turns out, if you do this very, very precisely, you'll find that the two measurements disagree with each other by a tiny amount because the stars are far away from the earth, but the gyroscope is here where space time is being curled up and spun up by the rotating earth. So there's an experiment with the gyroscope up in space that is trying to measure this, but you know if you had an atom interferometer that was 10 times longer than the one I described you could beat those guys in a heartbeat. So, that's something fun you can do with a gyroscope.

Now, the atom interferometer we're building in my lab right now uses a slightly different configuration, uh for reasons which I don't have time to explain. Instead of using 3 laser beams we use 4 to split and recombine our atom beam. Here is part of the experiment; we're actually building pieces of it in different places. Here is the vacuum chamber where all our optics is going to sit and our atoms are going to fly through there. Here is one of my undergraduate students working on it. He's also been building an ultra stabilized laser that's on another table that is going to be part of this. And we have someone, a couple other students building a cooling laser and a couple of students trying to temperature stabilize this oven better and make our atom interferometer more precise. So there are a lot of parts being built and it will eventually all end up all these pieces once they work to collect around this big chamber here.

What is our atom interferometer going to be good for? Well, one of the things it'll be good for is it will represent a better atomic clock. By better, I mean more precise, alright. This is the very first atomic clock that was used as a national time standard. And uh, atomic clocks have made a lot of interesting things possible, like the global positioning system for example. Um, there is a lot of interesting things you can do with the atomic clock. Um, to explain how an atomic clock works, the best way to do that is to teach you a dance. It's the, it's the Ramsy's method of separated oscillatory fields dance. But unfortunately, to interpret this dance you have to know a lot more math and physics than I have time to describe today, so we'll forgo the dance. But if you ever take an advanced atomic physics class from me, I will teach you the dance of the atomic clock.

Now, if you have a really good atomic clock, there are some fun things you can do. For example, you can do tests of special relativity. Einstein's special theory of relativity says that if I have two twins, I leave one on earth, I put one on the starship enterprise and fly him far out into space, traveling nearly the speed of light and then back again. When the space bound twin comes back, he'll find that the twin that stayed on earth is a lot older than him. Time passed more slowly for the one who was moving quickly. Now, we've tested this theory by doing such things as taking unstable particles and we know how long it takes for them to decay on average and we accelerate them going really fast. Now, in the particles reference frame they still decay at the same rate they normally would, but we observe a longer time before they decay. And we can calculate how long it should take from Einstein's equations, and it turns out that they are correct.

But Einstein's relativity should not just apply to things moving quickly, it should also apply to things moving at reasonable velocities. For example, if I take one of the track team at BYU, when he is running at me he should be aging just a little bit slower than he does when he stands still, alright. But it is such a small effect that you don't notice it. But it should still be there and it would be need to go and see if you could test that and see if Einstein's equations really do meet up with Newton's equations in the way we expect them to. Well, if you were carrying an atomic clock, maybe we could figure this out, alright. And it turns out that the apparatus for building, if it works the way we predict it will, we should be able to see these little changes in the rate of time, even if our apparatus is only moving at about a meter per second, alright. And that is something that's totally achievable.

Einstein also predicted with this theory of general relativity that if I were to put a clock on top of, well a clock on the ground and a clock on top the Eyring science center, because they are sitting in different places, the influence of gravity will change the rate at which they run. And the clock on the ground will actually run a little slower than the clock on the top. Now, experiments have been done using much greater distances and they've found tiny, tiny effects. Our clock if it works the way we expect it to, should be able to actually measure this precise scenario right here, alright.

Now, as I have showed you, you could make a gyroscope with an atom interferometer, you can also make an accelerometer. And our device ought to; in addition to acting like a clock we should be able to configure it to operate also as an accelerometer and a gyroscope, which is really useful for navigation. If you are flying an F-15 over Iraq, or I guess Iraq is old news now right? The next country we choose to invade. Um, maybe their dictator is going to jam the GPS signal, we rely a lot on GPS but it turns out that it is a really weak signal and for about $6000, there is actually a webpage I shopped once where you can pay $6000 and buy the technology you needed to basically jam GPS around the entire boarder of Iraq. This came up during the Iraq war. So it's very fragile technology. So if you are flying an F-15 you will be comforted to know that there is an inertial navigation with accelerometers and gyroscopes that takes over when you lose the GPS signal.

If you were on a submarine, when you are a under water you don’t pick up GPS. Furthermore, there are no land marks underwater, you can’t see underwater. So submarines rely almost exclusively on accelerometers and gyroscopes to basically feel how they are moving and figure out where they are based on the forces they have felt as they were moving around. If you don’t have a good accelerometer or a gyroscope, things like this can happen. So there are some practical applications of our work as well as fundamental ones.

And the one last application that I want to point out is a search for changing constants. Now, according to the standard model and Einstein’s general theory of relativity, the constants are constants. You write them down and you live with them forever. But there are some new theories of physics that people are wondering if maybe this is the next step beyond our current model of physics and some of them allow the constants to change. Now there was a big stir a few years ago when some people looked at the light coming from very distant objects out in space. Light that had been traveling for over a billion years. And they found that the wavelength of that light is a little bit different than the light that would be emitted by the same types of atoms here on earth, and their conclusion was the constants must have changed a little bit over the past million years, past billion years.

Well it turns out these measurements are pretty noisy, and uh most of the people who look at the raw data are not as confident as the people that publish the paper that they have really seen what they think they are seeing. But this is of paramount importance if we want to discern between different perspective new theories of physics that will take us beyond what we know today, so we’d like to maybe do an earth bound experiment, where we measure these things in the laboratory. And the way you do that is that you make an atomic clock, and then you make another atomic clock and you use two different elements in your two clocks and you compare how the relative frequencies of those two clocks drift in time.

In our experiment we actually have it set up so that we can put two different elements in the same clock and have two different laser beams traveling over the same path, so that a lot of the noise and things that might wash out your signal will cancel out when we measure the relative frequencies of the two. So we think our device will be really fabulous for these types of measurements. Anyway, that is I think all the time I have, so I guess at this point we take questions. Thanks again for having me. (clapping)