The Mother of All Pendulums

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You can derive how long it takes for the pendulum to make one complete oscillation. And we call that the period of the pendulum. And I'd arrive in class that that period equals 2 pi times the square root of L over g. You already know what L is. If you don't know what pi is, you might as well leave right now. And g is what we call the gravitational acceleration, which is approximately the same everywhere on Earth. But it is very close in Boston to 9.80 meters per second per second. And you will say, well, that's meters per second per second. What that means is that if you have an object and you drop it from a very large altitude, very high a few hundred meters high and I dropped it 0 speed. After one second, it will have a speed of 9.8 meters per second. But after another second, it will add to that 9.8 meters per second. So it's twice that. And after three seconds, it's 3 seconds. So now you understand why it is meters per second per second. And so that's the meaning of g. There is something weird about this equation, something that must go against your intuition. And you shouldn't feel bad because it also goes against my intuition. So we have the pendulum, and suppose I bring the pendulum all the way out here. We call that the amplitude of the pendulum. And we let is swing back and forth. There's a certain period. But now, we bring it out only this far. It doesn't have to travel very much at all. Doesn't that make a difference in the periods? The equation says no, it doesn't.

Because if it did make a difference, there would be in that equation the amplitude, which is not. And I'm going to demonstrate that to you, that it is quite remarkable that indeed that period is independent of amplitude if you don't go to extreme values of the amplitude. There is something else in here, which is even more non-intuitive. And that is doesn't it matter whether the bob we call this the bob whether it is 1 kilogram or 500 kilograms? You would think, well, that must make a difference in the period. But the equation says sorry, it doesn't. And I'm going to demonstrate that to you, too. We have here by the way, if you ever want to test this pendulum, this equation for yourself, put in L equals 1 meter and use this number. You will get a period of 2.0 seconds. It's very easy to do at home. You make one meter. You put an apple at the bottom and you swing it. The one meter has to be accurate. You see that it's going to be 2.0 seconds. Our pendulum that we have here is really the mother of all pendulums. Look at it. 15 and 1/2 kilograms and the length of this pendulum is 5.21 meters. However, you must understand that it is very difficult to measure that to very high accuracy. And so there is an uncertainty in the measurement of the lengths that we have to be honest about because we are physicists, after all. And the uncertainty we estimate is about 5 centimeters. So we could be off by 5 centimeters. That means that is 1%, 5 centimeters is 1% out of 521. But since L only shows up as the square root, it means the uncertainty in the time that we predict is only half a percent. And if you don't see the reason why the 1% becomes half a percent, that's OK, then just forget about it. You take my word for it. So now, I can make a prediction. So I predict using this equation that's all I do. I put in 5.21. I put in 9.80. I multiply by 2 pi, and I make the prediction that the period of that pendulum is 4.58 plus or minus 0.02 seconds. Why the plus or minus 0.

02? Well, that is the half a percent uncertainty due to the square root of L. You can immediately see that 2 is about half percent of 458. So my prediction can be no better than that. Now comes the problem. I have to measure the period to convince you that it is independent of amplitude and to convince you that it is independent of mass. So the biggest problem now is Walter Lewin himself, which is my reaction time. How accurately am I able to make that measurement? That has nothing to do with our lack of knowledge of the exact length. Now, the last time that I gave this lecture with the pendulum is 12 years ago. I was 63. And at that time, I told the class my reaction time is a tenth of a second. And it was. But now, I'm 75. And so my reaction time is no longer 0.1 seconds. What is it? Well, I do not know. But I have a feeling that if you want to be kind to me for a change, let us assume that my reaction time at age 75 is now 2/10 of a second. So if you can live with that, then every measurement that I make, no matter how long it is, it is uncertain to 2/10 of a second. Do not confuse that with that 0.02. That has to do with the length. All right. So I'm going to first make a period measurement at 5 degrees, and then at 10 degrees amplitude. And I'm going to measure 10 periods, not 1. Some of you may think, well, isn't that a waste of time to do 10 periods if you can get away with 1? You will very quickly see why it is 10. You will see that . So the 10T is then going to be some number plus or minus my own inability, which is my 0.2 seconds reaction time. I can't change that. And so then I do the 10 degrees. And then we get again, 10T. We get a number. And then we get again, plus or minus 0.2 seconds. And I'm going to demonstrate to you that within the uncertainty of the measurements, that I get the same numbers in all three cases, within the uncertainty. So if you're ready for that, you see here the timer. All of your can see. And here you see the pendulum.

And I have two marks on the floor here. If I hold the bob here, then it is 5 degrees. This is 5 degrees. And when I hold the bob here, it is 10 degrees. Timing is not easy. The best way to do it is to start the timing when the pendulum comes to a stop. That is rather well defined. And then you let it swing 10 times. And then when it comes to a stop, you stop it. And it would help me if you would count how many oscillations we have made, because then I don't have to look at it. All I have to do is when I come close to 10, I have to watch for the moment of stopping, and then I will end it. So we'll do this first at 5 degrees. I'm going to start it when it comes here. OK. Now you count. One, two, three, four. You're doing very well. Five. You're going to pass this course. 6, 7, 8, 9, 10. 45.7. So that becomes that T. That means this whole equation now has to be divided by 10. And now you will see why I measured 10 oscillations. So T is going to be 4.57 plus or minus 0.2 divided by 10. That is, plus or minus 0.02 seconds. And you see comfortably within the prediction. So maybe my reaction time is a little better than 2/10 of a second. Don't count on it because you haven't seen the rest yet. So now 10 degrees. That moment is crucial. That moment is crucial. That's where you can lose 4/10 of a second, and then you look like an idiot in front of your students. 3, 4, 5, 6, 7, 8, 9, 10. Now comes the hardest part. The hardest part is that we have to change the mass of this object. And the way that I'm going to do that is prominently demonstrated on the cover of my book. Yes, I'm going to hang on that pendulum. It is a difficult demonstration. First of all, it is painful. It really is. Second, the timing is tricky. Because when you look at the pendulum and when you see it standstill, that is really well defined plus or minus 0.1 seconds. When you're swinging yourself however, then you can only do it by sensing the moment that you think you standstill.

And that's what I will do. And then you will do the counting. And this is very unpleasant. It is. Oh, there's something else I haven't told you. If you're a good physicist, you will say, if you're going to sit on that bob, then effectively you bring the mass of the bob up. And so the lengths of the pendulum will shorten. And so you get a shorter period. And I know that, too. Therefore, I will have to stretch my body so that when it is here, that it is almost completely parallel to the floor. If I don't do that, I will not be able to convince you that the period is independent of the mass. And that makes it very difficult for me. So I will start it at some moment. You will see when, and then you do the counting. Are you ready? Yes. OK. You count. One. This happens sometimes. And in fact, nobody knows why. Have to start all over. I did not stop it. I really didn't. Oh, it's still counting? OK, I have enough energy to give it one more attempt, but not to give it two more attempts. OK. You're ready? Yeah. OK. 1, 2, 3 Ah, this really hurts. 4, 5 Can't you count a little faster? 6, 7, 8, 9, 10. 10T with Walter Lewin. What is it? 45.9 plus or minus 0.2. Period is 4.59 plus or minus the 0.02. I told you, physics works. If I have a tennis ball in my hand and I dropped the tennis ball from a certain height, give it no speed, and it will bounce back, then it can never bounce higher than where it started from. If it did, then we physicists would say that is a gross violation of the conservation of energy. And that is the holiest or all laws in physics. It cannot go higher. Suppose the object has a mass m and is a distance h from the floor. Here's the floor. Here's the objects, h. We associate with the position of that object an energy that has a name.

We call that potential energy. And that potential energy is m g h. You already know what g is. Well, h is this distance in meters. So when the object is here on the floor, h is 0. So there is no potential energy. As the object goes down, it picks up speed and we associate with speed energy, which we call kinetic energy. And the kinetic energy of an object with mass m is 1/2 mv squared. m is the mass and v is the speed of that object. If the object goes down and it hits the floor, then the potential energy is 0. And all that energy is now converted to kinetic energy. Because energy, we believe, is conserved. Now, when it hits the floor, some of that kinetic energy may be converted into heat because of the compression. If it were a tennis ball, that would certainly happen. So in other words, when it bounces back, the total energy is no longer the full energy h, but is a little less, and so it won't bounce as high. But there's no way that it could come up higher than h. Suppose it could come after one bounce up here. Well, that would solve the world's energy problem. Because you simply sit down and you watch the ball game. And there goes the ball higher, and the second one it goes again higher. But if it goes the first time higher, it will do that the second time. And so after an hour, that thing is about a few thousands meters in the sky. And when it comes down on the floor, it has an enormous speed, great amount of kinetic energy. And so you got energy out of nothing. But there is no such thing in physics as a free lunch, so that's not going to happen. So the object can never go any higher than h. And with a tennis ball, there is also what we call the dissipation of heat when it hits the floor. Now, the situation is difficult with a pendulum because a pendulum doesn't hit the floor. And so there is no heat loss because it doesn't hit the floor. So if you bring a pendulum at a certain distance above the ground like this, and you let it swing, when it comes back here, it is almost exactly at that same height.

It cannot be higher. That would be a violation of the conservation of energy. But since the air drag is so small, there's almost no damping. And in fact, when you saw the demonstration I just did, you may have noticed that you really didn't see this. It really kept going and it kept going. As long as you realize that if I release it from a certain location with 0 speed, it can never, when it comes back, be higher than that location. This whole idea is behind demolishing buildings. With a building demolishing, you take a huge mass. You lift it up over a distance h. And then, you put your target, which is your house, or whatever it is, right at the bottom when all these potential energy is being converted to kinetic energy. And so this object is hit with an enormous amount of energy, at high speed, and you demolish, thereby, the wall. Here, we have a glass plate. You better go out of the way because this is a dangerous experiment. This is a glass wall. So if I bring this object exactly at that glass wall and if I'm clever enough to let it go with 0 speed, it could not break that glass. But if my hands shake a little, and if I gave it a little push, then of course, it can come back. And it may want to go higher than this. And that would mean I know you, guys. Students love it when the glass breaks. That's why they pay such a high tuition at MIT. That's OK. Just take that off. Now comes an experiment, which is emotionally the most difficult for me of this whole evening. I'm going to put my life on the line to show you that I am really a believer of the conservation of energy. And you will see how I'm going to do that. I'm going to take the place of the glass. And I'm going to hold this object at my chin. And I cannot move any further back, so there's no cheat here. I'm going to release it right from my chin here. You realize, as you have just seen, that the slightest push and this will be my last lecture.

And no book signing afterwards. So I need your collaboration. When I count down from 3 to 0, no noise, no coughing. And I would even appreciate it, if for those 3 seconds, you would not even breathe. And I have to tell you something. I couldn't sleep all night. I'm going to close my eyes. I don't want to see it. And I'm going to count down from 3 to 0. 3, 2, 1, 0. And normally, after this demonstration, tell the class physics works, and I'm still alive. And when an article was written about me in The New York Times a few years ago, on the second page of The New York Times is the wisdom of the day. And the wisdom of the day was physics works, and I'm still alive. White light, like sunlight, is composed of all the colors that you see in the rainbow. If I scatter white light off very small particles, then the blue light is scattered more than the red light. And we give that a name in physics, we call that Rayleigh scattering. Rayleigh scattering only happens when the particles of which the white light scatters is smaller than a tenth of a micron. That means a thousand times smaller than the thickness of your hair. So it has to be a very, very small. If the particles are as large as half a micron, then there is no longer Rayleigh scattering. There is no scattering for the blue light. All colors scatter equally, and so white light scattered off particles at a half a micron or larger remains white. The dependence of the power of scattering so I'll give that P, the power is proportional when we have Rayleigh scattering. This is the only equation that may bother you, to 1 over lambda to the fourth, and lambda is the wavelength of light. And I will not bother you to tell you what the wavelengths of light is. That may confuse you. But I will tell you that blue light has a wavelength which is about 1.5 times lower than red light. And so if you take 1.5 to the power 4 trust me. Yeah, 1.5 to the power 4, you get 5. And that means, in Rayleigh scattering, blue light has a five times higher probability to scatter than red light.

And I'm going to demonstrate that to you in two complete different ways. The first way that I'm going to do that is to make it completely dark in the lecture hall and have light going straight up here. Then, I will light a cigarette, and the smoke of a cigarette has particles that are smaller than a 10th of a micron. And so the light that you will see that is scattered off the smoke will be blue. So you have seen, in front of you own eyes, Rayleigh scattering. Because the red lights, more or less, goes through. It is really the blue that dominates it, that has the highest probability. So we're first going to do that demonstration to show you Rayleigh scattering of cigarette smoke. And then I have a surprise for you to also show you Mie scattering. But let's first do the Rayleigh scattering with cigarette smoke. This is also not a pleasant demonstration. For those of you who think that lecturing is easy, no. OK. I'm going to make it completely dark, and then I'm going to hold it in there. All lights off. All off. All off. So we all agree that this is white light, which is coming up. And you don't see the light here because there is nothing that scatters it in your direction. So you don't see light here. But now look. Those of you who see blue say yeah. Yeah. Those of you who do not see blue, say no. No. You better see an eye doctor. Now comes the hardest part. If I inhale the smoke and I leave it in my lungs for a minute, there is water vapor in my lungs. And this water vapor will precipitate onto these very small smoke particles. And so the smoke particles will grow. They will become small water drops, larger than all 0.5 microns. And that means if I hold it one minute in my lungs and puff it out, you will not see blue light, but you will see white light. Because you're now in the Mie scattering domain, all colors scatters equally.

I will tell you that just before I puff it out and you will see the white smoke, I will just before I do that, I will remind you of the color that you see now. I will only do that for a few seconds. Then I will remove it and I will empty my lungs. Terrible demo. Who saw the white light? Just say yes. Yes. If any one of you has the courage to say so no, who did not see white light? No. Thank you. And now I'm going to explain to you in fact, you could probably guess that why the sky is blue and why clouds are white. Clouds consist of very small water drops, surely larger than half a micron, which is Mie scattering. So the white light of the sun scattered off the cloud white remains white. So you now, for the first time in your life, may have an explanation why clouds are white. And you should, or may, also understand now why the sky is blue. Here is the ground and you are here. And here is, say, roughly the top of the atmosphere. And the sunlight comes in like this. Sun is infinitely far away, so the sun comes in like this. The atmosphere is full of very small dust particles, smaller than a 10th of a micron. And even the density fluctuations of the air molecules themselves are clearly smaller than the 10th of a micron. And so you get ideal Rayleigh scattering. So white light comes in, you're standing here. But what is the light that comes to you? Predominantly blue. So the sky is blue. The light that is scattered here, comes to you is predominantly blue. So that's why the sky is blue. And so the reason is simply that it is Rayleigh scattering of the dust particles in the atmosphere. If the sun is high in the sky, the total amount of sunlight that is scattered in your direction is only 1%. So it's very little. If the sun is 5 degrees above the horizon, then the sunlight has to travel through a lot more atmosphere. And so I think here a situation which is extreme, when we have sunrise or sunset.

So the sun is there and the light comes from this side and you are standing here. This is not to scale. This layer of atmosphere is now so enormously large that more than 99% of all the sunlight on the way to you is scattered away. So what is scattered away? The blue is gone. But if you look at 1 over lambda to the fourth, the green is gone. All colors are gone. There's only one color which has the largest wavelengths, which by the way, is 650 nanometers. I wasn't supposed to tell you, but I decided. So the only light that makes it through you is red. And so that is the reason why the sun looks red. And there is a cloud here in the sky, and that cloud sees light where all the small wavelengths have been scattered out. And so this side of the cloud is also red. You can now understand that the more pollution there is in the air, the more beautiful sunsets are. And it is well known that after volcanic eruptions, the sunsets and the sunrises are truly fantastic. It's also the moon that is red when it comes up. And even the stars and the planets. You may never have noticed it because it's not an overwhelming thing. It is the sun that is the overwhelming thing that makes the entire sky red. And so I have decided that I'm going to create in 26-100, a blue sky for you and a red sunset, killing two birds with one stone. And for the physicists in my audience, I'm going to kill three birds with one stone. But the third bird comes a little later. I have here a bucket which is filled with sodium thiosulfate in this bucket. And when I turn the light on, you will not even see any light from that bucket. Nothing is scattered in your direction. I think of that as being the sun, by the way. Now I'm going to add a little bit of sulfuric acid. And when I do that, very small sulfur particles, smaller than the 10th of micron, will precipitate in that solution. Rayleigh scattering. And so the light that will come to you is blue. And you will see blue light, just like with the smoke.

But now, as time goes on, we will get more and more and more and more of those 0.1 micron particles. And so the light that comes out here has no blue in it anymore. It doesn't have any green in it anymore. It's all scattered in your direction, just like here with the sunset. So what color do you think the sun is going to get? Red. It's going to be red. That's why I said I'm going to kill two birds with one stone. So I will add the sulfuric acid. The difficulty with this experiment is always if you put too much sulfuric acid in it, the whole process goes too fast. And if you put too little in it, then you will become impatient. At least, MIT students would. So I'm going to put this in and stir. And then, make it immediately dark. And I want you to look at the sky, which is here is the sky. If you sit all the way there, you don't see it so well. But look, how much did you pay for this? These people have a better view. So just keep looking. For me, it's already beginning to turn a little bluish. We'll just give it a little bit more time. The sun looks just white light as it was before. I always have a backup you see. If this takes too long, then what I do, I add another teeny, weeny little bit of sulfuric acid to speed up the process a little. I see blue light. And when I look at the sun, it looks a little reddish already. For the physicists among you, light that scatters over an angle of 90 degrees, this light that scatters in this direction the people who paid the most tonight, who are sitting right here, the light is also linearly polarized. That was also the case with the smoke experiment, but I didn't mention that. But for those of you who are sitting here, I can show you with my polarimeter, when I rotate my polarimeter, that I can the blue sky completely dark. And the blue sky completely bright again. The people who are sitting there, the angle of scattering is not 90 degrees. So they won't see it so well. But you people see it very well, don't you? Yes.

100% polarized. Look at that sun. Let's face it, isn't this incredibly romantic? In 26-100, at the center of MIT, you are seeing, in the lecture hall, a red sunset. And in fact, the sun is so red now, that I think the sunset is very close. I have given, in this lecture hall, about 800 lectures. And it is wonderful to be back here, but it really hurts to know that this is my last lecture in 26-100. I have, therefore, decided that I want to leave you in style. And the way I will do that is to leave 26-100 in my own private rocket. Thank you. Thank you. So now we have about 15 minutes left for questions. And if you have a question, raise your hand. Then Claire will come to you with the microphone. And then, I hope we can communicate that way. You phrase the question and I will try to give the answer. So who wants to go first? There's a person there. Yes, we see your hand here. You'll come next. Thank you for a beautiful lecture. I am tempted to ask you what pi is. It's not so easy for me to understand you. Thank you for a beautiful lecture. I'm tempted to ask you what pi is. But I think I'd better ask instead Have you ever gone to a Thanksgivings dinner? OK. That is what pie is. Are you familiar with the alleged phenomenon of a green flash at sunset. And the answer is yes. Can you explain that, please? I've seen it many times. The explanation is not as simple as you may think. I would suggest and I mean that seriously. Since a short answer is not possible, that you look it up on the web. It's well described. I have seen it many times in Austria in the mountains. That, indeed, the last fraction of setting of the sun, that you may, but not always, see a green flash. And if you ever want to see it, you have to be with two people.

One person has to be standing next to you and you should not look at the sun. Because if you look at the sun, even though there's almost no sunlight left, your retina is still too overexposed. And so the person next to you, when you look like this, should say, look now. And then you look, and that's the way it is. There's a question right here. Why don't we take that first? And then, there's a woman over there. And this gentleman also. Well, I just wanted to thank you for the lecture. As a youngster, I read a book which told me to stare at the sun, then I can change things by staring at things. Now what I did was I used to stare at sun at sunset. You stare at the sun? At sunset. At sunset. Not a very good idea. You have to be very careful. I found out the hard way. And so you damaged your eyes and you asked for it. But the key thing was that after that, I was supposed to stare at a white wall, which I did. But what I saw a red I know exactly what you saw. A red spot moving around wherever Probably the spot was not red, but green. It's a well-known phenomenon. So you have, indeed, done something to your retina and the message that is sent to you brains then tell you the green aftereffect. It's very well-known effect. You don't even have to look to the sun. You can even do it with a light like that and stare in that light for some time. And then, all of a sudden look at the white wall and you see a different color. It's a very interesting thing. And physics cannot explain that. But you see, this is neurology. And so it's not our responsibility to explain it.

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