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Transcript – Lecture 26

When we take a spring, something that we are so familiar with now, and the spring has length l in a relaxed state, spring constant k, I can extend the spring with some force that I apply.

The spring, then, will counter it with the spring force and it will be in equilibrium there.

I call this the zero position, and let's call this now delta l instead of x, which we have done before.

If I double the force, delta l will double.

Hooke's Law says that the force is linear with delta l; in other words, delta l is proportional with F.

Nothing new, as long as Hooke's Law holds.

If I make the spring twice as long, I would get double the extension, because when I have two springs in series, each one, under the influence of this force, will get longer by this amount.

Since I have two springs in series, I will get twice delta l.

So delta l is also proportional to the length of my spring.

If I take two springs parallel, one like so and one like so, relaxed length l, both the same spring constant k, and if now I apply a force on it, then each one of these spring forces is only half this one.

Together they counter this force.

In other words, the extension delta l that I obtain from this external force is now only half as much as it would be with one spring, and if I had three springs parallel, all identical, I would only get one-third of the extension for a given force.

In other words, delta l is also inversely proportional to the number of springs that I have, assuming that they are identical springs.

Now I'm going to use a rod or wire which has cross-sectional area A and length l, and I'm going to apply a force here.

As a result of that force it will get longer by a certain amount delta l, exactly like the spring.

And clearly, when I make this force stronger, delta l will increase, and as long as Hooke's Law holds that the spring force provided by the rod balances this out--

provided that the spring force is linearly proportional with delta l--

I have again that delta l will be proportional with the force.

Double the force, I get twice delta l.

If I put two of these rods together--

so I double the length of the rod--

then clearly I will get twice delta l, because each rod will experience the force, each rod will get longer by delta l, and so two rods will get longer by two delta l.

So again, delta l is proportional with l.

Suppose, now, I have two of these rods next to each other--

notice the parallel with the two parallel springs here--

and I apply a force F.

Then the spring force on each one of them--

if I call that the spring force--

will only have to be half to counter this force.

So they both have a cross-sectional area A, and so now with double the cross-sectional area, I get only half of delta l.

And so now we have a situation that if I made a rod whereby this was 2A, just one rod, which is completely equivalent to this situation, I'm only getting half delta l for a given force.

And so now we have that delta l is proportional...

inversely proportional to the cross-sectional area of the rod.

So now we can make up the balance, and we can say, "Aha! Delta l is proportional to the force, proportional to l, "and inversely proportional to the area, the cross-sectional area." So F divided by A is then proportional to delta l over l, and that proportionality constant we give a name, and that is capital Y, and that is called Young's modulus.

So this is Young's modulus.

F over A, which has the dimension of pressure--

force per unit area--

is what we call stress.

And delta l over l, which is dimensionless, we call that strain.

If we compare two rods with different values of Young's modulus, then the one with the smaller value of Y for the same stress will give you a larger strain.

In other words, it's easier to make it longer.

If Young's modulus is very high, then the rod is extremely stiff.

Then it is very difficult to make the rod longer.

I have here for you some numbers which, of course, are on the Web so you don't have to copy them.

And you have Young's modulus there for various metals, and I also have it down there for nylon, and today we will work with that quite extensively.

We could first do a simple example just to get a feeling for what is at stake here.

I can take a rod with a radius r, which is 0.5 centimeters.

That would give me a cross-sectional area of eight times ten to the minus five square meters.

So, yay thick, the rod.

I make it very simple--

I make the length one meter, and I hang on the rod, at the bottom, a mass M, which, let's say, is 500 kilograms.

Do I want 500 kilograms? Yes, I want 500 kilograms.

In other words, the force which I pull on the rod is about 5,000 newtons.

So I can now ask myself how much longer is this rod going to be? So we're going to have that delta l is going to be F divided by A times l divided by Young's modulus.

And we do know what F is, we know what l is and we know what A is.

So in our case, this number is 6.3 times ten to the seventh for the numbers that we have.

And so now we can look at steel as an example.

So we take steel.

Y is 20 times ten to the tenth newtons per square meter.

And we substitute that in here, and we find that we get an extension delta l which, I believe, is only a third of a millimeter--

indeed, 0.3 millimeters.

Think about this: steel rod, a centimeter thick, and it has a length of one meter, and I hang 500 kilograms on it and it only gets longer by three-tenths of a millimeter.

You couldn't even see that.

However, if you go and make the rod, which would be really a rope...

If you make it out of nylon, which has a Young's modulus...

Oh, well, it's 55 times lower.

I don't have to use that number.

It's about 55 times lower, so the delta l will then be 55 times larger.

And so, instead of a third of a millimeter, I will get something like 17 millimeters.

And that you can see with your naked eye.

I take a rope yay thick of nylon.

I hang 500 kilograms on it and I will see it gets longer by 1.7 centimeters.

You can see that right in front of your eyes.

If I start adding more weight on these bars, then very interesting things are going to happen as we will discuss today.

One thing which is obvious that will ultimately happen if you keep loading down, keep adding mass, it will break.

And the breaking point is given there in the third column, and we call that the ultimate tensile strength.

So when F over A--

when this value--

becomes too large, that's what it comes down to, then it will simply break.

If we take the case that we have here, the steel rod, for which F over A is 6.3 times ten to the seventh--

because l is one, remember--

then you can look there under steel that it wouldn't break.

We would be very safe, because it wouldn't break until F over A becomes five times ten to the eighth.

So we're a factor of ten away from that--

there's no problem.

Even nylon would be very safe, because that wouldn't break until the stress is three times ten to the eighth.

However, if we chose aluminum, if we made the bar out of aluminum, then you're very close to this number 6.3 times ten to the seventh.

And so if you add a little bit more mass than 500 kilograms, your aluminum bar would break.

So you see, the properties of these metals are very, very different indeed.

Now, before it breaks, we reach a situation that the strain is no longer proportional to the stress.

In other words, we abandon Hooke's Law, as I will show you also today with a demonstration.

The material begins to deform.

It begins to flow, in a way.

And even when you take the weights off, it will no longer have its original length.

It will not return to the original length but it will be much longer.

And I will try to sketch you here what a curve of stress versus strain typically looks like.

So here I'm going to plot delta l over l, and here F over A.

So this is the stress and this is the strain.

In the beginning, you will see a portion that is linear.

That's Hooke's Law.

And then, when you keep adding force--

which we will do by gravity, we will just hang weights on it--

then it starts to bend over, up to a point here which we call the elastic limit.

And even though this portion is no longer linear--

so even though Hooke's Law no longer holds--

still, if you take the weight off the wire, off the rod, it will still come back to zero.

Once you are past this point, that is no longer the case.

You will now see also that a small increase of stress will give a huge strain, so the rope will... the rod will get very long all of a sudden with a little bit of extra stress.

And if now you were to take the weight off the rod, it would not come back to zero but it would come back somewhere to here so it's permanently deformed.

And in general the rod gets hot, and the work that you have done goes into heat and goes into the deformation of the rod.

And so it goes like this and then it goes like this and here it breaks.

At this value for F over A, which is that third column there, it will break.

I'd like to discuss with you this horizontal portion.

With a little bit of luck we may actually be able to see that with my demonstration, but it's hard to get exactly at that point.

If this part of the curve is horizontal, it means that without any increase of F over A, the wire will continue to get longer and longer, and we call that plastic flow.

So this whole portion here is plastic flow.

It almost becomes like a liquid.

And then right here there is something very strange that is happening.

Then when it breaks, the stress here is actually lower than there, and this is something I can never show you in class, but I can explain to you why that happens.

When you are past this point here, the rod begins to pinch, and you get this.

It's unpredictable where it will pinch, but somewhere it will start to pinch so that the area here is A prime whereas the cross-sectional area here is A.

And so F divided by A prime will be larger than F divided by A.

If you could do this experiment in a controlled fashion--

and there are machines designed to do that--

then you could actually lower F over A so that the stress actually goes down but that F over A prime would still go up, and therefore delta l will increase.

And there are machines who are specially designed to test these metals, and what they do is they go up in very small steps of F--

and so they trace this whole curve--

but by the time that they get into the plastic flow area, they... before they increase the force, they decrease it first.

And if delta l gets larger when they decrease it, they continue to decrease it, and so that's the way that they can map out also this portion.

But we will not be able to do that.

There are metals which are extremely brittle, and even though the curve would look very similar--

it has all these characteristics--

this point, then, would lie all the way here.

So this whole curve, then, is squeezed into very small parameter space of the strain.

And so I want you to see most of this, at least some of this, and we do that with a demonstration which we have there, and I will make a drawing of the basic idea.

We have a copper wire--

you will get the dimension from me very shortly--

and we attach to the copper wire a rod, a solid rod.

And at the end of the solid rod is a mirror.

This is a mirror.

And we're going to hang weights on here.

But this mirror is on a little platform and can pivot at this point but cannot lower itself.

The platform is fixed.

For those of you who are very close, this is where that platform is.

That is a fixed platform.

And so the mirror can only tilt but cannot go down.

And so now I will show you what happens when this wire gets longer.

So here is the wire, and this is where the...

This is this line here.

But now the wire has become longer.

So the wire is now longer by an amount delta l.

So this is now the point where this bar, this rod is attached.

And so the mirror will now be like this.

We have tilted the mirror.

And we have tilted the mirror over an angle delta theta, and this length is l.

And we're going to load it down with a mass M, which we're going to increase.

And then we have a laser beam which we shine onto the mirror.

The laser beam comes in like so.

And this is the normal to the mirror, so this angle here is delta theta.

The laser beam bounces off and returns... like so, and this angle, of course, is also delta theta.

That's the property of a mirror.

And this beam...

This is the laser beam here that we shine into the mirror.

Here's the laser, it goes into the mirror, and the spot there of that return is all the way there on the wall.

So we are going to show you where this spot is on the wall, and the wall is very far away.

It's a distance capital L from the wire.

And you'll see very shortly why we do it that way.

Let me first give you the dimensions of this instrument.

L is 36 centimeters.

It is copper.

This bar, which has length d, is 7Ω centimeters.

The distance to the wall is about 16 meters.

The radius of the wire...

or actually, the diameter of the wire, of the copper wire is 20/1,000 of an inch.

I give it in terms of the diameter because that's the way that the manufacturer gives it to us.

And that translates into a cross-sectional area of that wire of 2.0 times ten to the minus seven meters squared.

All right, notice that delta theta, that angle...

the angle here, delta theta, is delta l divided by d.

So delta theta equals delta l divided by d.

The light that returns hits the wall there at a distance l, so y at the wall, or I can call it delta y--

that is at the wall, I call that displacement there delta y--

divided by l will be two delta theta.

This is a small-angle approximation; it's a very good approximation, and theta is in radians.

It is two delta theta, because you see here that the change is over an angle two delta.

And so delta y equals 2L delta theta...

2L delta theta times delta l divided by d.

And look what we have done now: We have convert something that is immeasurable, delta l--

which is fraction of millimeters--

we have convert that to something on the wall that we can measure, because this ratio, 2L over d, in our case, for the dimensions that I have chosen, is about 425; it's like
a magnification factor.

So if we see a displacement of that laser beam on the wall of 40 centimeters, which is easy to see, it means that the wire got longer by only one millimeter.

So 40 centimeters there translates to one millimeter there, and if we would see that laser beam go up four meters, it would mean that the wire would only have become one centimeter longer.

So it is a wonderful way to magnify the effect and to measure it.

So I will now make an attempt to load down the copper wire.

Oh, we can actually leave this here, so you can see that curve.

So we start here with...
we load up with half kilograms.

We will write down, then, how much that laser spot goes up on the wall.

And then, in between increasing the weight, increasing the force we will take the masses off to see whether they return...

whether the length of the rod returns to the original length.

And you will see after a while that you get permanent deformation, then it no longer comes back to its original length.

In other words the laser spot will not return to zero on the wall but it will stay higher.

So Ron, if you are there...

Oh, boy, you're hiding behind...

Um, maybe we want to move the view graph out of the way so that students can also see.

So, here is that copper wire which will be hard to see for some of you--

it's only 20/1,000 of an inch thick--

and here is that mirror which can pivot and can tilt.

And Ron is going to put weights on here, and then we will take the weights off in between and we will try to construct a curve of the stress versus strain, except that it is practical for me to put here just the mass--

how many kilograms we have on there--

because we know what A is, so we can calculate F over A.

That's not so important now.

And here I simply have delta y.

But keep in mind that delta y is always 425 times larger than delta l.

So we're going to plot it, and we're going to see whether we can come up with a curve that is somewhat similar to that one.

So, Ron, if you put on the first half kilogram...

The mirror always starts to oscillate a little bit and so we have to be a little patient, and in the beginning, you may be bored because--

tja!-- we're going through that linear part of the curve.

So it goes up very slowly, very gradually.

We have five centimeters for the first half kilogram.

Could you remove the half kilogram? It returns practically to zero.

Maybe it's a little higher, but that's not very significant.

Could you make it one kilogram? Ah, ah, it's clearly higher.

Ja, ja... oh, it's about nine centimeters, nine, ten, so you see it's in the linear part--

nine to ten centimeters.

Can you remove the half kilogram, Ron? The one kilogram, there was one kilogram on it.

We have to just wait, let it damp out a little.

It's oscillating.

It's possible that you already begin to see a small deformation which may be one or 1Ω centimeters.

I put a question mark there--

it's possible.

Can you put 1Ω kilograms on? Yeah, I think it is...

You can almost remove the question mark.

So now we are at 1Ω.

So if it is strictly linear, you would expect something like 15.

Yeah, that's what it is, 15, so it's still doing quite well.

Can you take them off? One and a half.

Ah, but you see it no longer wants to return to its original length.

It's clearly longer now.

Permanent deformation has already occurred, and so we're now something like six centimeters.

Can you make it two kilograms? Two kilograms.

If it's linear, you would expect near 20.

It's still amazingly linear.

It's as close as I can see it to 20, but all these readings are no more accurate than half a centimeter or so.

So can you remove the two kilograms? Oh, boy, look at that--

there's clear deformation now.

It no longer returns to zero, and it is...

Oh, it's comfortably ten centimeters long now.

So can you make it 2Ω? You're now slowly approaching the part that I hope you are going to see, and that is that it is going to take off like a rocket, that with a little bit of extra weight, it will start to move substantially.

We haven't reached that point yet, but we are close to it.

We're now 26--

25, 26...
it still looks quite linear.

Can you take it off, Ron? Actually, there's no need to take it off anymore because it's clear that we...

that we have permanent deformation, and there's no sense in following that, so why don't you make it three kilograms? So what was it? What did I say it was? What was the number I said? 20 what? 25 or so? So we have three now? Boy, this wire is hanging in there, I must tell you.

32, yeah.

Can you make it four? Watch very closely now on the wall, because the drama is about to start now.

What did I say, 30...? I said 32.

Four.

Ooh, still moving, still moving.

52... settles at 53.

Now, don't look at the board--

now, look at this spot now.

Can you add... remember the number, right? 53.

Can you add one kilogram now? And look at that.

It became almost twice as long and it is still moving.

Still going... still going.

I hope it will settle.

I'm going to write down my 53.

Five kilograms.

We're at five, right? 97--

now put on six.

97--

remind me, 97.

Now, watch this point.

Yay! Now you're clearly in that plastic flow portion.

By adding one kilogram, look where that point is--

it's still moving.

What was five? 97? So we're now at six kilograms.

Oh, actually, that is still easy for me to estimate.

I would say it's about double the length of that stick that we have on the wall, and the stick is two meters long.

Is it moving? That's still moving a little bit.

It's a little more than four meters.

Close enough, four meters, just for the idea.

Four meters, so that's 400.

Put on seven.

It will go through the ceiling now.

So we'll lose it.

But what I want to do now, I want to get to the breaking point.

We can no longer measure the displacement, but we're very close to the breaking point now.

So we're going to load it up to the point that it will break, and that allows us to measure the ultimate tensile strength.

We're at seven now--

can you put eight on? Oh, we're running out of...

[chuckles]

Oh, God! You could just see it sag when the eight was put on.

Did you actually look at the wire? Okay, so at eight kilograms, it breaks.

Okay, let's put these numbers in here.

So, we have 1Ω...

or half a kilogram, we have five centimeters.

Let me do this in color.

So that gives me a point here.

And then at one, we have about ten.

And at 1Ω, we have about 15.

And at two, we have about 20.

And at 2Ω, we have 25.

Oh, I was a little bit too high here, perhaps.

I want to go a little bit more carefully because this is really terrific data.

So this was at...

And then we have...
at 2Ω, we have 25.

Amazing how well...
how linear that is! And then at three, we have 32.

Ah! It looks like it's beginning to bend over.

At four, we have 53, no question.

Oh, yeah.

And then at five, we have 97.

Here is five--

97, that's here.

And then our last point that was...

Oh, we even have a 400 here.

Ooh, that's great.

Here is 400.

And what do we have there? A six.

One, two, three, four, five, six.

That's our last point.

And then we don't have the rest.

But look how wonderful this is, isn't it? Isn't that a great curve? Very linear in the beginning.

Then it starts to bend over, over.

And you draw that line anywhere you want to...

and then it breaks.

And so we can now actually make an attempt to calculate Young's modulus from the data.

Of course, you'll have to select a portion where you think that the data are reasonably linear.

So Young's modulus itself...
equals F divided by A.

Here you have here the equation.

Young's modulus equals F divided by A times l divided by delta l.

We know what A is, we know what l is.

It's still on the blackboard there.

And so now it's a matter of where do we think that Hooke's Law still holds? I think this whole portion would be fine, so we could take this point as well as this point, because anywhere on this straight line, you will get the same value for Young's modulus.

So I will use two kilograms and 20 centimeters--

I will use this point.

So F equals 200 newtons, and then we have delta y equals 20 centimeters.

And so that means delta l equals 20 divided by 425 centimeters.

So this is F divided by A, l, and then we have here delta y times 425.

And let's see what that is.

So F is 200--

that's right.

No, no, F is 20--

ooh, ooh, ooh, ooh, ooh.

I'm glad that we caught that simultaneously.

So F is 20--

20 newtons, that's right.

The area is two times ten to the minus seven, and I divide by the area.

I multiply by the length, which is .36.

I multiply by 425 and I divide by delta y.

But I need delta y in centimeters, so...

in meters, so that's .2.

And I get 7.7 times ten to the tenth.

And that is not bad at all because I think, from what I remember, is that it is 11 times ten to the tenth.

That's what it is.

So that is quite amazing for such a crude measurement that we do here.

We can also measure the ultimate tensile strength.

That is, we can measure the value for F over A when it broke.

So that happened, I think...
wasn't that eight kilograms? So that will be 80 divided by the area that we know, and so that gives me 80 divided by two times...

divided by ten to the minus seventh, and that is four times ten to the eighth newtons per square meter.

And this is also newtons per square meter.

And that's not bad.

It's a little higher than we have there, but it's a very crude measurement.

And don't forget, we were unable to follow the portion when it was going down.

We only went up in mass, in weight, and so that value there takes into account that the curve comes down, something we could not do.

We didn't have the means of doing that.

The percentage strain is actually extremely low in the portion that the curve is linear.

You can ask yourself the question "What is delta l divided by l in terms of percentages during this portion here?" Well, we know the length, 0.36, and when we take the case where we sort of reach the end of the Hooke's Law parameter space, we have a delta l which is 425 times lower than this, so we have 20 divided by 425, and that is, um...

four point seven times ten to the minus two, but that is in terms of centimeters and we want it in terms of meters, so we have to multiply by another factor ten to the minus two.

So the exponent's changed--

minus two... divided by 0.36, and that gives me 1.3 times ten to the minus three.

In terms of percentages, that would be 0.13%.

So the wire, when it reaches the end of its Hooke's Law parameter space, has only become longer by 0.13%.

And when the wire breaks...

In general, for metals it's maybe five or ten percent longer than its original length.

That's a typical value for metals.

Now, as long as I am in the linear portion of the curve, I can generate a simple harmonic motion.

I want to show you that.

I need my wiper.

Because in the linear portion of the curve where Hooke's Law holds, I could hang a weight on the rope... or on the rod and I could let it oscillate vertically.

So the force that you have equals y times A times delta l divided by l.

That's the force that I apply.

So the spring force is opposing that, so the spring force has a minus sign here to indicate the direction.

And so this is similar to F equals minus kX that you have seen with the spring.

This now is our k, and delta l is our x.

And so you can predict that it will start to oscillate with an angular frequency of omega square root of k divided by m and with a period which is two pi...

two pi times the square root of m over k, and m is now the mass that I'm hanging here.

If we take our copper wire, we know what y is.

If I take the value 11 instead of the one that we found, but it's very close, anyhow...

So if I take our copper wire, then I will find, depending upon the mass that I hang on it...

then I'll find in any case for k, for this value k I find five times ten to the fourth newtons per meter.

So if now I hang on it a mass of one kilogram, I can calculate the period of one oscillation, and one over the period is the frequency F, and I believe that is something like 38 hertz.

So it would start to oscillate like this, 38 times per second, and if I hang two kilograms on it, then this frequency would become something like 25 hertz, because a higher mass gives me a longer period, gives me a lower frequency.

The speed of sound also depends on Young's modulus.

Without proof--

you will see this if you ever take 803--

I will tell you that the speed of sound is the square root of Young's modulus divided by the density of the material.

And I have listed those there on the view graph.

Oh, this is by, yeah, the square root--

I have that, yeah.

And so the higher Young's modulus is, the higher the speed of sound is, and that is intuitively sort of pleasing.

I can sort of understand that although the square root is hard to see.

If I have here a rod, a bar and I give this bar here a bang, I hit it, if this bar were infinitely stiff--

that means Young's modulus were infinitely high--

then the bar would instantaneously move here when I hit it there.

But if the bar is not infinitely stiff, if it has a certain amount of elasticity, then what happens... then I hit it here and I produce here some kind of local increased pressure which is going to propagate to this end--

it's like a pressure wave, like sound is a pressure wave--

and that takes time.

And the larger Young's modulus is, the stiffer the material is, the faster that will go.

If Young's modulus is very low, the material is more elastic.

It will take a longer time for this pulse to reach this end.

So it is sort of intuitively pleasing for me that the stiffness of the material is related to the speed of sound.

I have here a magnesium bar, and the magnesium bar has a length l.

And I can calculate the speed of sound for magnesium by taking its Young's modulus, which is there, divided by rho, which is there, and I come up with the speed of sound, which is about five kilometers per second.

If you look at those numbers, they are all substantially higher than the speed of sound in air, which is only some 340 meters per second.

So the speed of sound for magnesium is some 15 times larger than the speed of sound in air.

If this bar has a length l, this pressure disturbance will start to move to the left, and then it'll come back here, so it will have made a complete journey, which I call the period...

It has made a complete journey in so many seconds--

2L divided by the speed of sound.

And so the frequency of this bar--

the frequency at which it would like to oscillate when I give it a bang--

is one over T, and that is the speed of sound divided by 2L.

Now, for those of you who will take 803 in the future, you will see a much better derivation of this frequency, so this is a poor man's version.

The speed of sound is about five kilometers per second.

The length of the bar is about 122 centimeters, and so that translates into a frequency of roughly 2,200, 2,100 hertz.

So the frequency for this magnesium bar is about 2,100 hertz, and you can hear that.

It's a beautiful tone.

I hold it here and I will bang it here.

[bar chimes, tone oscillates]

Can you hear it? No?

[bar chimes, tone oscillates again]

You hear it? 2,100 hertz--

beautiful tone.
Remember earlier in the course that we were wrestling with this problem.

We had a block and we had two strings attached to it.

Here is one string, here is the block, and here is another string.

And we're going to pull on this here with force F.

Nothing was happening, so the tension here, T, is F.

Here, there is both the force F plus the weight of the object, so here you have... call it T prime equals F plus Mg.

And so we argued if you increase F and if the strings are identical that it should break first here and then here, because the breaking point where the force is too large for the string will occur first here, then it occurs here, because you have the extra amount Mg.

But yet when we jerked on it very fast, it would break here, and when we pulled very slowly--

I will do it again--

it would break here.

And now we can fully understand that.

Because what does it mean, that this string is going to break? It means that string has to get longer by a certain amount delta l before it says, "Sorry, I got to go," and it breaks.

For this string to get longer by a certain amount delta l, this block has to come down.

Now, if I pull here with a certain force F--

F equals Ma--

the block will come down with an acceleration a, and in the time delta t, it will move over a distance a delta t squared, which is the delta l that this string will feel.

But that takes time to reach the delta l at which it wants to break, and so if I pull very fast, I don't give it that time.

And that's why, then, the one at the bottom will break, and if I pull very slowly, the one at the top will break.

So here is a very thin wire--

you can't see it very well--

and here is one, too.

It's a string, and they're identical, and this is my emergency safety rope.

And if I pull very fast, you see the bottom one breaks.

I have this in my hand, and the top one is still safe.

However, if I repeat this, and I do it very gently...

It's always hard to get this in.

There we go.

Uh-oh...

Okay, so now I'm going to slowly increase the force.

I give the block plenty of time to come down, plenty of time, and now the upper one goes.

Have a good weekend.

See you Monday.