SCOPE,
SEQUENCE,
and
COORDINATION

A National Curriculum Project for High School Science Education

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Student Materials

Learning Sequence Item:

1018

Hooke's Law, Vibrations, Mechanical Waves, and Sound

February 1997
Adapted by: Bill G. Aldridge

Contents

This micro-unit was adapted by **Bill G. Aldridge** (SciEdSol, Henderson, Nev.)

Student Sheet

Science as Inquiry

How Do Springy Things Vibrate?

Why do some things vibrate faster than others?

Overview:

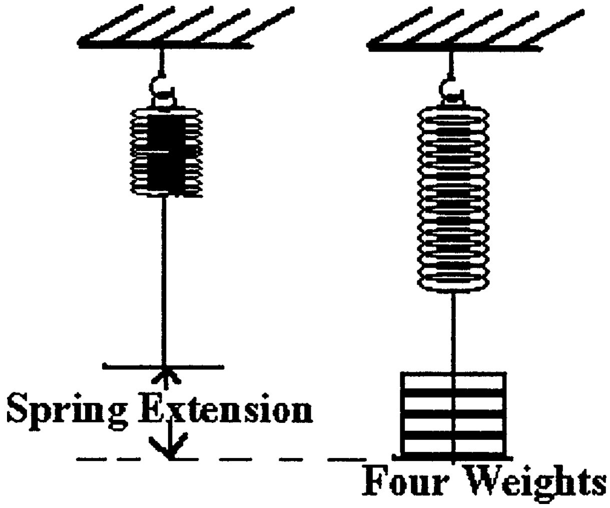
When you carried out activities in Micro-unit 921, you saw that when you push or pull on something that is springy, like a rubber band or a spring, it pulls back on you. You also saw that when you graph the force in newtons needed to extend a spring by a certain amount, with the extension of the spring in meters, the slope of the graph is a measure of the stiffness of the spring. Since a graph with this force on the vertical axis and spring extension on the horizontal axis gives a straight line that goes through the origin (zero for both force and extension), you can describe the relationship with a very simple equation, $F = -KX$, where F is the force on the spring, X is its extension, and the value of the slope of the graph, that we called K, is the spring constant. The minus sign indicates that the spring pulls in a direction opposite to its extension. You saw that the spring constant K was larger when springs were stiffer.

Let us now see how a mass attached to a spring vibrates.

Procedure:

Attach one end of a spring to a tabletop or ring stand and place some weights onto the other end as shown in the figure. Then pull down on the weights, extending the spring about 3 to 4 centimeters. Let go and watch the weights vibrate up and down. Use a stop watch to measure the period of oscillation of the weights. You will recall that the period is how long something takes to go from its present position to some new position and return (from Micro-unit 1015).

Using your stop watch and counting 10 oscillations should give you a good measure of the period for one oscillation. Do this for several different initial amplitudes (defined in 1015) and for at least four different mass values used as weights. Repeat these observations with springs of different stiffnesses.



Questions:

1. Does the period of oscillation depend upon the amplitude?

2. For each spring, make a graph with period of oscillation on the vertical axis and total mass attached to the spring on the horizontal axis.

3. If the graph is not a straight line, try graphing the period versus the square or the period versus the square root of the mass. Does either of these approaches give a straight line? If so, what does this mean?

4. You have been given the spring constants (stiffness measures for springs). Graph the period of oscillation versus the spring constant and find this relationship as you did for mass in question 3. What is the result?

5. Describe in words the relationship between the period of oscillation of a mass on a spring and the value of the mass. Do the same for the relationship between the period and the spring stiffness. Write these relationships as proportions.

6. Write the relationships between the frequency of oscillation and the mass and stiffness constants ($f = 1/T$).

Science as Inquiry

How Do Strings on Musical Instruments Vibrate?

Why does some music sound different than others?

Overview:

You have just learned in Activity 1 that the frequency of oscillation of a mass on a spring is inversely proportional to the square root of the mass and directly proportional to the square root of the spring constant (measure of stiffness) of the spring. Although on the surface that result does not appear to be very important, it has an enormous number of applications in science, from the way musical instruments work to the vibrations associated with sound and heat.

Let us now examine a particular example, the vibrations of guitar strings, and the sound that is produced.

Procedure:

You have been provided a guitar with six strings as well as additional 10-cm lengths of the same six strings. You have also been given a pitch pipe so that you can tune the guitar. You have a spring balance calibrated in newtons and a metric scale for measuring distances.

Adjust the tension in the thickest guitar string so that it is loose but still under some tension. Then pull it aside at its midpoint and release it. You can see that it vibrates, much as the mass on the spring vibrated. If the tension is not too great you may hear only a very low pitch or nothing at all. Now tighten the string and do the same thing. Even though you cannot easily see the string vibrating, you can feel it by touching the string lightly with your finger. Thus you know that guitar strings vibrate to produce sound.

Now tune the guitar carefully using the pitch pipe. Have one of your lab partners who knows music show how this can be done properly.

Next, attach the spring scale to the midpoint of each string and pull outward until the string has been displaced 1.0 centimeters. Record the force in newtons required for each of the six strings to be displaced at the midpoint by 1.0 centimeters. These forces are measures of the tension in each string. (For each force F, $F = 4xT/L$, where x is the distance you pull the string sideways at its midpoint, T is the tension in the string, and L is its length from bridge to nut. The tension T would then be given by $T = FL/4x$.)

Using a microbalance or precise triple-beam balance, measure the mass of each length of guitar string provided. Then divide the mass of each string segment expressed in kilograms by its length expressed in meters (0.10 meters).

Questions:

1. For a properly tuned guitar, record the values of force required to displace each string at its midpoint by 1.0 cm. Calculate the tension in the guitar string for each of these cases ($T = FL/4x$). How do these tensions compare? What do you think would be the design implications for a guitar in terms of stresses on parts of the guitar if the guitar were not made this way?

2. The frequencies of a properly tuned guitar (in *just intonation*, not even tempered) are from thickest to thinnest string as follows:

Note	Frequency
EE	165 Hz
AA	220
D	297
G	396
B	495
E'	660

Make a graph of frequency f on the vertical axis and mass/length M/L on the horizontal axis. If this is not a straight line, use the methods of Activity 1 to find the relationship between f and M/L. How does this result compare with that for a mass on a spring?

Student Sheet

Science as Inquiry

Using a Weak Sound to Make a Loud Sound

How does a singer break a glass with her voice?

Overview:

Why does a guitar have a body, bridge, and sound hole? Why do other stringed instruments have similar bodies and holes? How can you produce a sound by blowing across the opening of an empty bottle? Why does a pipe organ have so many long pipes?

To answer these questions, you need to make several observations.

Part 1

Procedure:

Hang a guitar string from a ring stand with a weight attached to its free end. The string should be the same length as the distance between the nut and bridge on the guitar with an attached weight that will give the same force on the string as the tension in the guitar string (use tension found in Activity 2). Now you have a guitar string that is the same as the string on the guitar, except there is no bridge, sound board, or sound hole. Strum the guitar string and describe what you hear. Then strum the freely hanging string and describe what you hear. In your own words, how are the sounds different?

Select any two adjacent strings on the guitar and strum the one with highest pitch at the midpoint between the nut and the bridge. Then hold the adjacent string down against various frets and strum it at the midpoint between the bridge and the fret against which you are holding it until you find where it sounds like it has the same pitch as the open string. When these two strings sound like they have the same pitch, lightly touch them to stop the vibrations.

Now fold and place a small bit of paper so that it hangs at the midpoint of the open string. Holding the adjacent string against the fret, strum it at its midpoint to produce the same pitch as the open string had previously when strummed at its midpoint. What happens to the bit of paper? Repeat the process without the attached bit of paper. After strumming the string, almost immediately touch the center of this string to stop its vibration. What do you hear then? And where is this sound coming from?

What you have observed is a phenomenon given the name *resonance*. There are many other such examples. If you push a child in a swing and give a little push each time the swing comes back to where you are standing, the swing is resonant with your push. If you rub a crystal glass edge with a damp finger round and round, the glass can be made to "ring." This is resonance. Supposedly it is resonance that causes the glass to break when the opera singer sings. When you stand on a hanging footbridge and jump up and down with just the right frequency, it begins to oscillate up and down and will ultimately collapse. A famous case of this kind of resonance was the Tacoma Narrows Bridge collapse, where wind set up the resonant frequency of the torsional motion of the bridge, leading it to collapse completely. A tragic example of resonance was the collapse of balconies at a Hyatt Regency Hotel in Kansas City, where patrons keeping rhythm to the music at a tea dance set the balconies into their resonant frequencies, causing the balconies to collapse and kill and injure many people.

To better understand this phenomenon, you can examine something very simple, the vibrations of a Slinky®.

Part 2

Procedure:

Attach one end of a Slinky® firmly to a tabletop. Holding the free end of the Slinky®, move away from the table until the coil is well-extended. Then move the free end of the Slinky® up and down quickly. What do you see moving along the coil? Describe what you observe. Notice that this wave or pulse moves down the Slinky®, hits the fixed end, and comes back to you. Notice also that the pulse is inverted after reflection.

Now start moving the free end of the Slinky® up and down at a very low rate, adjusting the rate of oscillation until the wave you send to the fixed end reflects back at just the right time to "add" to the vibration of the entire coil. Soon you will have the Slinky® moving so that its midpoint is moving up and down with steadily increasing amplitude. In fact, if you kept moving the free end up and down too strongly, the Slinky® might get such a large amplitude that it would break. When you are making the Slinky® move up and down at its midpoint with this kind of vibration, you have produced what is called a "standing wave."

Now swing the end of the Slinky® up and down at a faster rate until you get a standing wave pattern that has two segments moving up and down on opposite sides of the Slinky® with the midpoint almost stationary. The stationary point is called a *node*, and the places where the amplitude is greatest are called *antinodes*. How does the frequency of the up-and-down motion of your hand holding the Slinky® compare for the two cases you have observed? See if you can move your hand even faster and get three or even four antinodes. These standing waves are produced when your hand is moving with a frequency that is equal to the resonant frequency of the Slinky®, twice that frequency, three times that frequency, etc. These higher frequencies are called *harmonics.*

Go back to the guitar and strum a string at its midpoint. Then move that midpoint down against a fret. What do you hear? Next strum the same string at a point near the sound hole and then hold the string against a fret at its midpoint. What do you hear now? Describe what you think is happening in terms of resonance and harmonics.

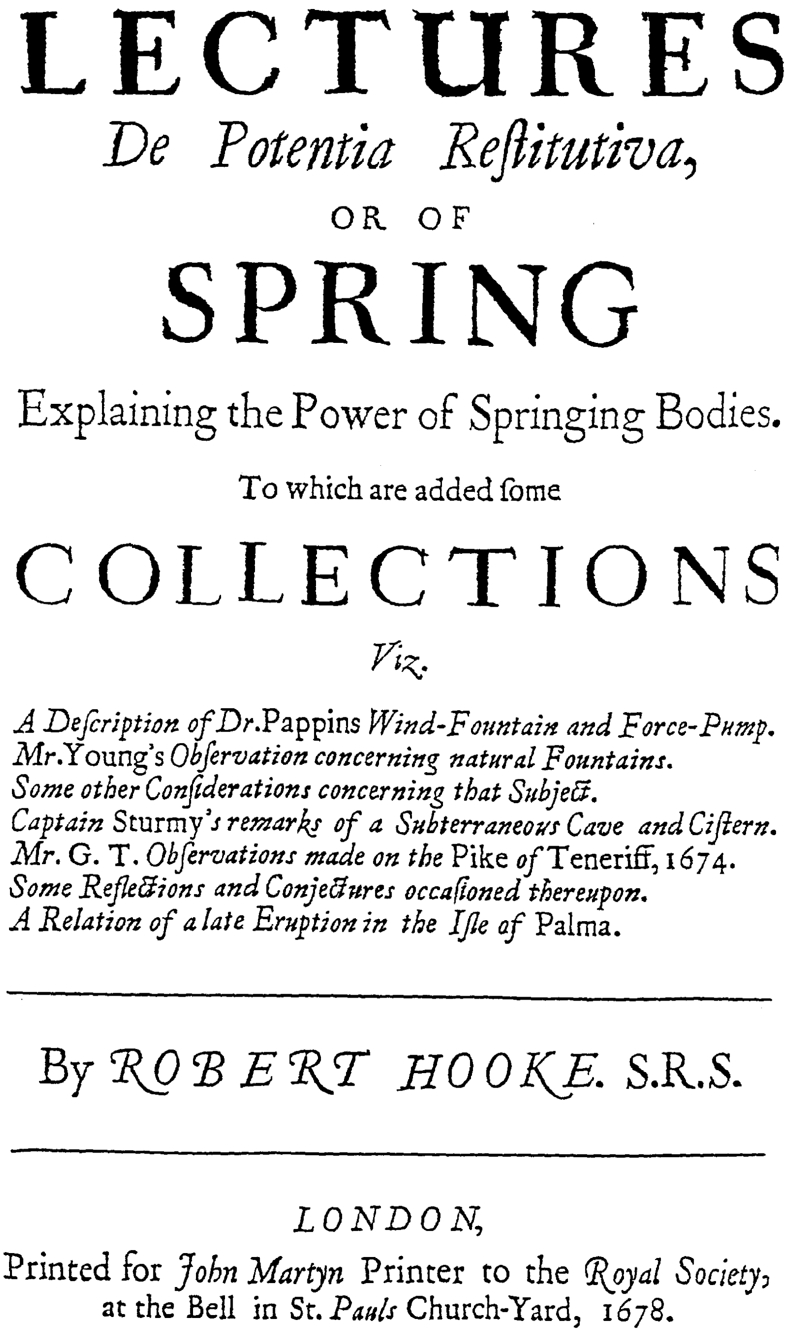
You might try various things with a guitar to produce resonances and harmonics. For example, if you sprinkle some fine powder, like lycopodium, on the sound board and then strum one of the guitar strings, what happens to the powder? How can you explain this observation? You might also hold strings down against certain frets after strumming the string and listen to faint sounds of various frequencies. You should offer explanations of these observations in terms of harmonics.

Questions:

1. When a string identical to a guitar string and under the same tension is plucked at its midpoint, how does its sound compare with the sound produced by the same string on a guitar? What could account for these differences?

2. If you pluck a guitar string, what happens to an adjacent open guitar string tuned to the same frequency? How would you explain this observation in terms of energy and the relationship between the strings?

History and Nature of Science



LECTURES
De Potentia Reſtitutiva,
OR OF
SPRING
Explaining the Power of Springing Bodies.

To which are added ſome

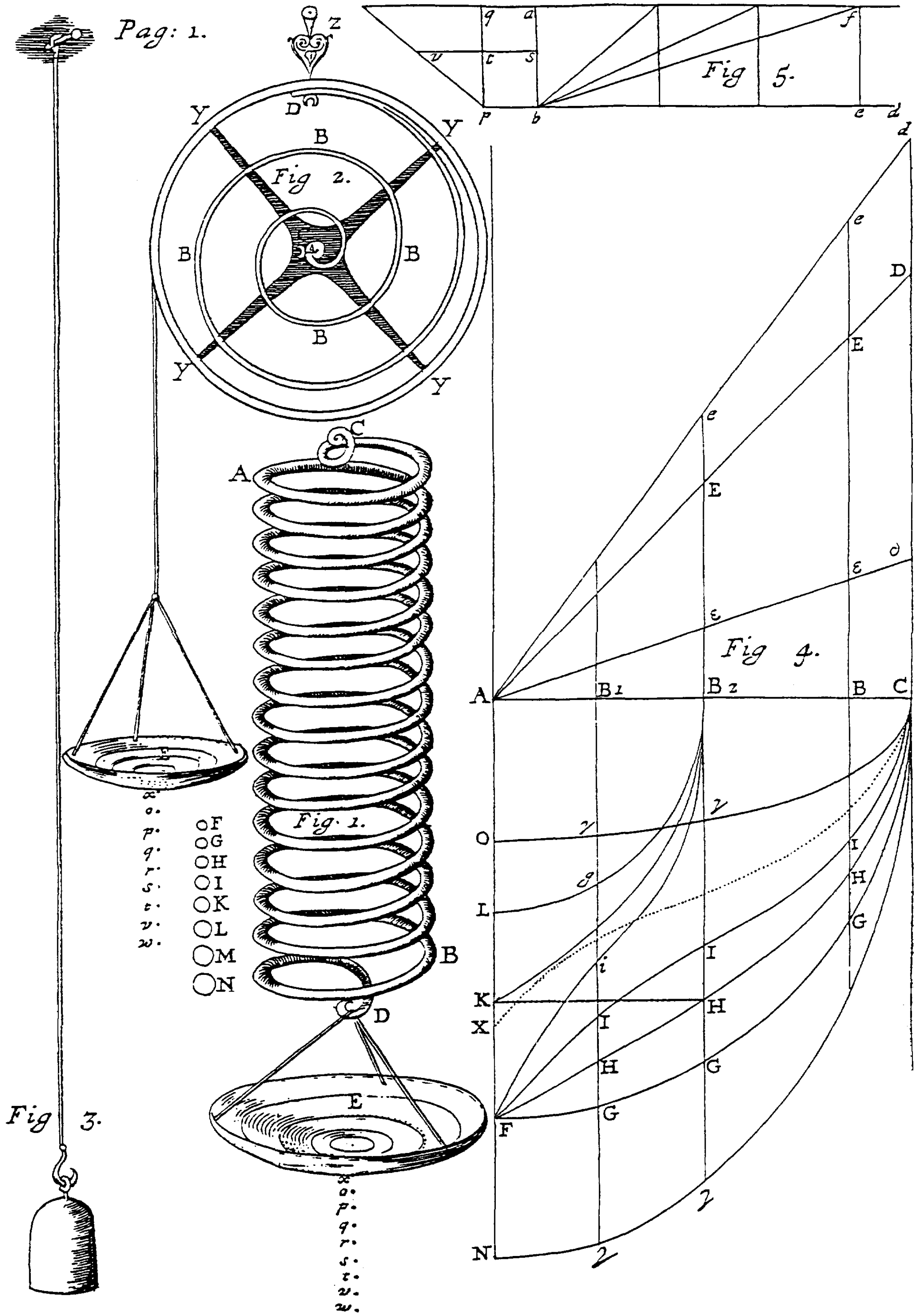
COLLECTIONS

Viz.

*A Deſcription of Dr.*Pappins *Wind-Fountain and Force-Pump.*
*Mr.*Young's *Obſervation concerning natural Fountains.*
Some other Conſiderations concerning that Subject.
Captain Sturmy's *remarks of a Subterraneous Cave and Ciſtern.*
Mr. G. T. *Obſervations made on the* Pike *of* Teneriff, 1674.
Some Reflections and Conjectures occaſioned thereupon.
A Relation of a late Eruption in the Iſle of Palma.

By *ROBERT HOOKE.* S.R.S.

LONDON,
Printed for *John Martyn* Printer to the *Royal Society,*
at the Bell in St. *Pauls* Church-Yard, 1678.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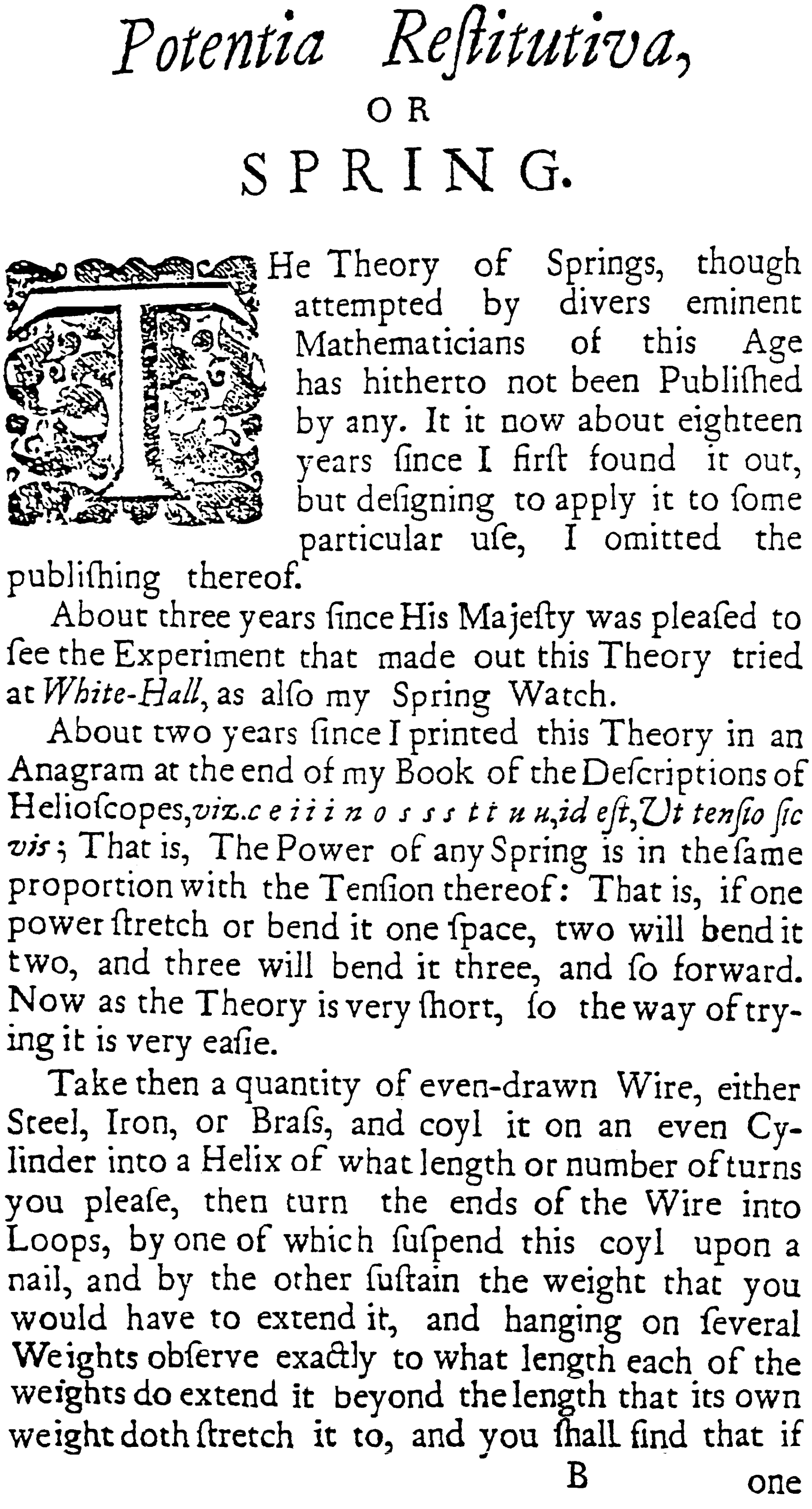


Potentia Reſtitutiva,
O R
SPRING.

THe Theory of Springs, though attempted by divers eminent Mathematicians of this Age has hitherto not been Publiſhed by any. It it now about eighteen years ſince I firſt found it out, but deſigning to apply it to ſome particular uſe, I omitted the publiſhing thereof.

About three years ſince His Majeſty was pleaſed to ſee the Experiment that made out this Theory tried at *White-Hall*, as alſo my Spring Watch.

About two years ſince I printed this Theory in an Anagram at the end of my Book of the Deſcriptions of Helioſcopes, *viz. c e i i i n o s s s t t u u, id eſt, Ut tenſio ſic vis*; That is, The Power of any Spring is in the ſame proportion with the Tenſion thereof: That is, if one power ſtretch or bend it one ſpace, two will bend it two, and three will bend it three, and ſo forward. Now as the Theory is very ſhort, ſo the way of trying it is very eaſie.

Take then a quantity of even-drawn Wire, either Steel, Iron, or Braſs, and coyl it on an even Cylinder into a Helix of what length or number of turns you pleaſe, then turn the ends of the Wire into Loops, by one of which ſuſpend this coyl upon a nail, and by the other ſuſtain the weight that you would have to extend it, and hanging on ſeveral Weights obſerve exactly to what length each of the weights do extend it beyond the length that its own weight doth ſtretch it to, and you ſhall find that if

B one

one ounce, or one pound, or one certain weight doth lengthen it one line, or one inch, or one certain length, then two ounces, two pounds, or two weights will extend it two lines, two inches, or two lengths; and three ounces, pounds, or weights, three lines, inches, or lengths; and ſo forwards. And this is the Rule or Law of Nature, upon which all manner of Reſtituent or Springing motion doth proceed, whether it be of Rarefaction, or Extenſion, or Condenſation and Compreſſion.

Or take a Watch Spring, and coyl it into a Spiral, ſo as no part thereof may touch another, then provide a very light wheel of Braſs, or the like, and fix it on an arbor that hath two ſmall Pivots of Steel, upon which Pivot turn the edge of the ſaid Wheel very even and ſmooth, ſo that a ſmall ſilk may be coyled upon it; then put this Wheel into a Frame, ſo that the Wheel may move very freely on its Pivots; faſten the central end of the aforeſaid Spring cloſe to the Pivot hole or center of the frame in which the Arbor of the Wheel doth move, and the other end thereof to the Rim of the Wheel, then coyling a fine limber thread of ſilk upon the edge of the Wheel hang a ſmall light ſcale at the end thereof fit to receive the weight that ſhall be put thereinto; then ſuffering the Wheel to ſtand in its own poſition by a little index faſtned to the frame, and pointing to the Rim of the Wheel, make a mark with Ink, or the like, on that part of the Rim that the Index pointeth at; then put in a drachm weight into the ſcale, and ſuffer the Wheel to ſettle, and make another mark on the Rim where the Index doth point; then add a drachm more, and let the Wheel ſettle again, and note with Ink, as before, the place of the Rim pointed at by the Index; then add a third drachm, and do as before, and ſo a fourth, fifth, ſixth, ſeventh, eighth, *&c.* ſuffering the Wheel to ſettle, and marking the ſeveral places pointed at by the Index, then examine the Diſtances

Diſtances of all thoſe marks, and comparing them together you ſhall find that they will all be equal the one to the other, ſo that if a drachm doth move the Wheel ten degrees, two drachms will move it twenty, and three thirty, and four forty, and five fifty, and ſo forwards.

Or take a Wire ſtring of twenty, or thirty, or forty foot long, and faſten the upper part thereof to a nail, and to the other end faſten a Scale to receive the weights: Then with a pair of Compaſſes take the diſtance of the bottom of the ſcale from the ground or floor underneath, and ſet down the ſaid diſtance, then put in weights into the ſaid ſcale in the ſame manner as in the former trials, and meaſure the ſeveral ſtretchings of the ſaid ſtring, and ſet them down. Then compare the ſeveral ſtretchings of the ſaid ſtring, and you will find that they will always bear the ſame proportions one to the other that the weights do that made them.

The ſame will be found, if trial be made, with a piece of dry wood that will bend and return, if one end thereof be fixt in a horizontal poſture, and to the other end be hanged weights to make it bend downwards.

The manner of trying the ſame thing upon a body of Air, whether it be for the rarefaction or for the compreſſion thereof I did about fourteen years ſince publiſh in my *Micrographia*, and therefore I ſhall not need to add any further deſcription thereof.

Each of theſe ways will be more plainly underſtood by the explanations of the annexed figures.

The firſt whereof doth repreſent by A B the coyl or helix of Wire, C the end of it, by which it is ſuſpended, D the other end thereof, by which a ſmall Scale E is hanged, into which putting Weights as F G H I K L M N, ſingly and ſeparately they being in proportion to one another as 1 2 3 4 5 6 7 8, the Spring will be thereby equally ſtretcht to *o,p,q,r,s,t,u,w*,

B 2 that

that is, if F ſtretch it ſo as the bottom of the Scale deſcend to *o*, then G will make it deſcend to *p*, H to *q*, I to *r*, K to *s*, L to *t*, M to *u*, and N to *w*, &c. So that x*o* ſhall be one ſpace, x*p*, 2, x*q*, 3, x*r*, 4, x*s*, 5, x*t*, 6, x*u*, 7, x*w*, 8.

The ſecond figure repreſents a Watch Spring coyled in a Spiral by C A B B B D, whoſe end C is fixed to a pin or Axis immovable, into the end of which the Axis of a ſmall light Wheel is inſerted, upon which it moves; the end D is fixed to a pin in the Rim of the Wheel y y y y, upon which is coyled a ſmall ſilk, to the end of which is fixed a Scale to receive the weights. To the frame in which theſe are contained is fixed the hand or Index z; then trying with the former weights put into the Scale E, you will find that if F put into the Scale E ſinks the bottom of it x to *o*, then G will ſink it to *p*, and H to *q*, I to *r*, K to *s*, L to *t*, and z will point at 1,2,3,4,5,6,7,8 on the Wheel.

The trials with a ſtraight wire, or a ſtraight piece of wood laid Horizontal are ſo plain they need not an explication by figure, and the way of trying upon Air I have long ſince explained in my *Micographia* by figures.

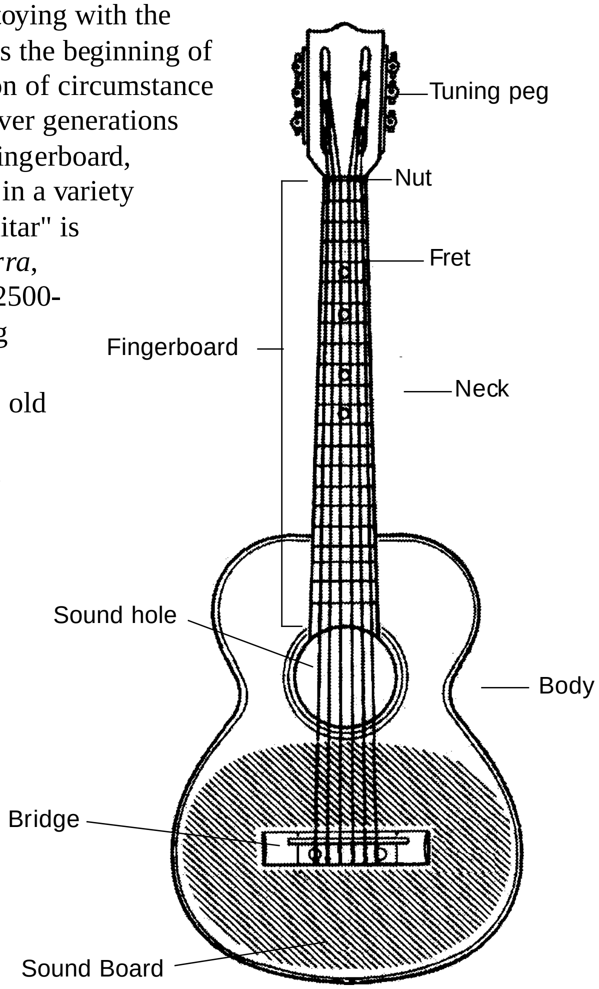
From all which it is very evident that the Rule or Law of Nature in every ſpringing body is, that the force or power thereof to reſtore it ſelf to its natural poſition is always proportionate to the Diſtance or ſpace it is removed therefrom, whether it be by rarefaction, or ſeparation of its parts the one from the other, or by a Condenſation, or crowding of thoſe parts nearer together. Nor is it obſervable in theſe bodys only, but in all other ſpringy bodies whatſoever, whether Metal, Wood, Stones, baked Earths, Hair, Horns, Silk, Bones, Sinews, Glaſs, and the like. Reſpect being had to the particular figures of the bodies bended, and the advantagious or diſadvantagious ways of bending them.

Science in Personal and Social Perspectives

What Guitars Do

Guitars are used to change vibrations of a taut string into sound. Ancient Egyptian and Hittite carvings show guitar-type instruments being made and played as far back as 3000 years ago. One might imagine a man toying with the variations of his bow-string "twang" as the beginning of stringed instruments. By a combination of circumstance and intuition, craftsmen and players over generations have developed the sound board, the fingerboard, more strings, a body, and sound holes in a variety of stringed instruments. Our word "guitar" is much like the old Spanish word *guitarra*, which possibly was derived from the 2500-year-old Sanskrit *chhatur-tar,* meaning "four strings.

The guitar of today is similar to the old Spanish guitar with six strings and an "hour-glass" body. This type of guitar, shown in Figure 1, is one of the most popular of instruments. It is estimated that in the U.S. alone, there are 15 to 20 million guitar owners.



Aldridge, B., A. Strassenburg, and G. Waldman, "What Guitars Do." From *The Guitar: A Module on Wave Motion and Sound*, 1972.