

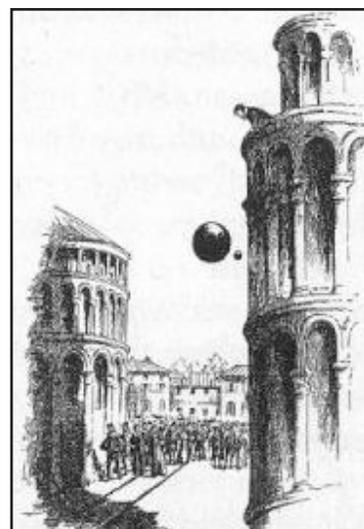
# GRAVITY



Most people think that the study of gravity began with Newton. They know the story of the apple falling off the tree, giving Newton the notion that there was a force pulling it to earth. If you could ask Newton who was the first scientist to study gravity, he'd probably tell you that it was the man who died the year Newton was born-- Galileo Galilei.

Galileo spent a great deal of time thinking about how and why things move. He had been taught in his college classes that heavy objects fell faster than light ones. Aristotle had proclaimed this principle over a thousand year ago, and since that time no one had believed otherwise. (Well, almost no one. One Italian historian of the 1500s (about a decade before Galileo was born) mentions very briefly that a few scientists were beginning to challenge this idea, but he doesn't give names.) Galileo believed in performing experiments to learn things-- a shocking concept in his day! His experiments had shown him very clearly that Aristotle was wrong.

Probably the most well-known story about Galileo is the famous Leaning Tower of Pisa demonstration. Galileo, it is said, took balls of different sizes and weights (including a canon ball) up to the top of the Leaning Tower of Pisa. He made sure that the professors of the university of Pisa were watching (from a safe distance, of course, not right underneath the tower). Then he pushed the balls off the railing, making sure they all got launched at exactly the same moment. The balls all hit the ground at the same time. The professors, however, were not impressed. They still chose to continue believing Aristotle's theory even after seeing Galileo's demonstration. (Eventually, of course, they had to give in and admit Galileo was right. If you study at the University of Pisa today, you will not be taught Aristotle's theory!)



Some historians doubt that this event actually took place. The only written record we have of it was written by one of Galileo's students a decade after Galileo's death. The student claimed that Galileo told him he had done this experiment several times. However, Galileo himself never recorded it in his journals. But even if it never happened, it certainly *could* have happened because all the main elements of the story are true. Galileo really was being taught Aristotle's ideas. He really did live in Pisa. You really could climb to the top of the tower. The tower really was leaning enough so that objects dropped from the low side would be in no danger of hitting the walls on their way down. Galileo really did do and say outrageous things when he was a young man. And the professors really didn't change their minds even after seeing demonstrations. In fact, the professors could prove Galileo wrong by dropping a ball and a feather. The feather fell more slowly. Galileo suspected that the behavior of the feather was being affected by the air, but since the nature of air was still a mystery at that time, Galileo couldn't formulate a precise theory about what was going on.

After Galileo's time, the theory of falling bodies was refined to take into account the effect of air. Now we say that objects ***in a vacuum*** fall at the same rate. (You know that we're not talking about a

vacuum cleaner, of course. A vacuum is a place without air molecules.) If you really want to do an accurate test of the theory of falling objects, you need to do it in a place with no air. This is not easy. You either have to pump all the air out of a very tall jar, or... go to the moon! During the Apollo 15 mission on the moon, astronaut David Scott was filmed dropping a hammer and a feather onto the surface of the moon. Since the moon does not have an atmosphere, it's pretty close to being in a complete vacuum-- a perfect opportunity to test Galileo's theory in ideal conditions. Did it work? You can watch and see for yourself.

Oops...



## ACTIVITY #1 Watch Galileo's experiment being performed on the moon

Go to YouTube and type in key words such as "astronaut, feather, hammer, moon, Apollo 15." Many uploads of this famous video will appear. It doesn't matter which you click on-- they'll all be the same video.

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## ACTIVITY #2 Another way to test gravity without air "getting in the way"

You will need a heavy book (or a piece of wood about the size and shape and weight of a book) and a small piece of paper (just a few centimeters square).

1) Hold the book and the paper up, one in each hand. Drop them at precisely the same moment. (NOTE: Don't drop the book so that it lands on a corner! This might damage the spine of the book. Drop it so that it lands on a flat side.) Notice what happens. Which hit the ground first?

2) Now put the paper on top of the book. Drop the book again. Watch what happens to the paper. Does it stay on top of the book?



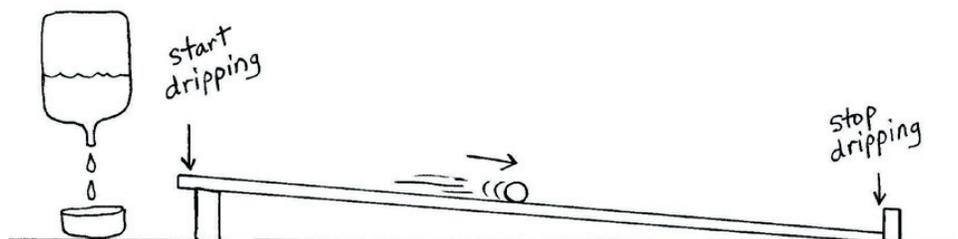
The paper stayed on top of the book because the book acted as a plow, pushing through the air molecules ahead of the paper. The paper "hid" behind the book and didn't come into contact with all the air molecules rushing by. If Aristotle had been right, the book would have fallen faster, getting to the ground well ahead of the paper. As you saw for yourself, the book and the paper fell at exactly the same rate.

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Galileo didn't stop thinking about falling objects after he figured out that they fall at the same rate. He wanted to know more about the way they fell. But it was hard to study the motion of falling objects because they fell so fast-- he wished he could slow them down a bit. One day he figured out a way to do this. He thought about a ball rolling down a ramp. What if he made the ramp steeper and steeper? The ball would go faster and faster. What if he finally made the ramp so steep that it was pointing straight down? Then we would say that the ball was "falling." So was falling just a very fast type of rolling? Galileo thought so. He began constructing very long ramps that could allow him to study rolling motion. To find out exactly how far and how fast the balls were rolling, he used a "water timer." This is how Galileo described his water timer and how he used it:

*"We employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent [of the rolling ball]. The water thus collected was weighed, after each descent, on a very accurate balance; the difference and ratios of these weights gave us the differences and ratios of the times."*

Galileo started the water timer as soon as he let go of the ball. It kept dripping the whole time the ball was rolling, with the water running into a little collection dish. When Galileo stopped

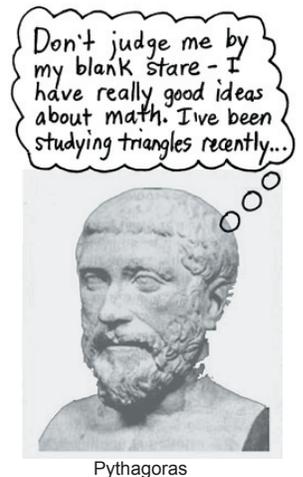


the ball, the water timer was shut off. He weighed the water to find out how much had been collected, recorded this number, then did the experiment again. He stopped the ball at various points down the track and collected all these numbers. When he looked at his results, a definite pattern appeared. The ball started out slowly and picked up speed as it went down. By the time it reached the bottom it was going very fast. When he compared the weights of the water collections, he found that the numbers formed a pattern. He always got the same number pattern regardless of how steep the incline was

or how heavy the ball was. This pattern was very similar to the one he found for pendulums. Galileo said, "We always found that the distances the ball traveled were in proportion to each other as the squares of the times." Square roots again!

Aristotle may have been wrong, but another ancient Greek, Pythagoras, had been right when he said that mathematics was the foundation on which the natural world was built. He believed that eventually, mathematical patterns would be discovered for almost everything we see and hear. Galileo was beginning to prove him right.

You can do what Galileo did, using a simple water timer to find the mathematical pattern formed by falling objects. You'll need to make some special equipment, however, so the instructions for this lab are provided on a separate sheet at the back of this packet.



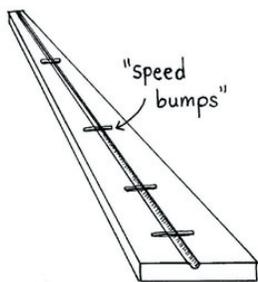
Pythagoras

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### ACTIVITY #3 Do Galileo's famous ramp experiment

*The instructions for this lab are in the back of the packet. It takes a bit of time to do this lab, so if you are short on time, you can skip this lab and keep reading the text.*

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Galileo thought of another way to experiment with the math behind gravity. (Though he did not use the term "gravity." This term would be invented decades later by Newton.) Galileo had inherited his father's musical talent. His father was not only a very talented musician and composer but also an amateur scientist who made discoveries about the mathematical ratios between musical notes. Galileo decided to use his excellent sense of rhythm to do even more investigation about falling objects. He made small "speed bumps" for his track. As the ball rolled over the bump it made a clicking sound. He could move these bumps up and down the track until the sound of the clicks made a steady beat.

After the clicks were even, he measured the distances between the bumps. He used the distance between the first and second bumps as his basic unit of measure. (He didn't have to worry about inches or centimeters for this experiment, just the original distance between the first two bumps.) He found that the distance between the second and third bump was 3 of those first units. So the total distance covered in two clicks was 4. The distance between the third and fourth bumps was 5 original units. So the total distance covered in 3 clicks was 9. The distance between the fourth and fifth bumps was 7 times the original distance, so the total distance covered in 4 clicks was 16 units. See a pattern? Galileo did, too. 4 is the square of 2, 9 is the square of 3, 16 is the square of 4. He had discovered one of the basic mathematical principles of the universe. It was very similar to what he had discovered about pendulums. As pendulums get longer, the rate at which they swing gets slower by the square root of the amount by which the length was increased.

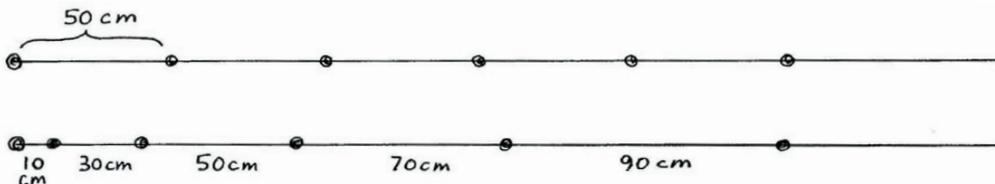


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### ACTIVITY #4 Listen to gravity, like Galileo did

*You will need two pieces of string that are at least 2.5 meters each, and some small heavy objects that can easily be tied on the string, such as nuts or washers. (If you can get fishing sinkers easily and inexpensively, you can use the type of sinker that clips on to the line.)*

1) Tie (or clip) the nuts (or sinkers) at these intervals:



2) Hold the first string (with the washers spaced evenly) by the tag end and stand on a chair. If your chair and ceiling are high enough, let the string dangle so that the end washer is 50 cm off the floor. If not, let the end washer just barely touch the floor.

3) Predict what the washers will sound like as they hit the floor. Perhaps you could even clap your hands in the rhythm that you expect to hear.

4) Drop the string and listen carefully as the washers hit the floor. You may want to do this several times since the sounds happen so fast. (Was your prediction right?)

5) Now do the same thing with the other string. Hold the string so that the end washer is just a few centimeters off the floor. Predict what you will hear.

6) Drop the second string and listen. Does what you hear surprise you?

This experiment produces “counter-intuitive” results. Looking at the strings, your intuition tells you that the string with the washers evenly spaced will produce sounds that are evenly spaced. However, as you found out, this is not true. Gravity is not linear. The washers higher up on the string fall long enough that they experience more acceleration. So now we need to learn a bit about acceleration...



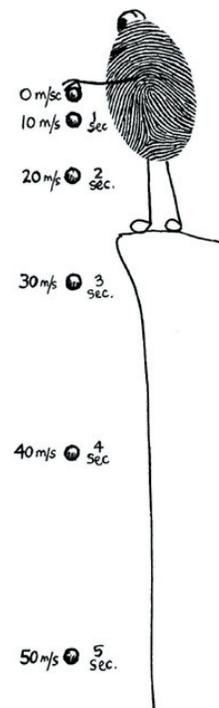
What Galileo discovered is that gravity causes **acceleration**. You know that cars have foot pedals called accelerators. What does the accelerator do? It makes the car go faster, of course. Once you reach the speed at which you want to travel, you no longer have to apply the accelerator. (At least not much. You do still have to apply just a little gas, to overcome the drag that friction is causing. But if there was no friction, you would not have to apply the gas at all.)

To accelerate means to increase your speed, going faster and faster with each passing second. The word **speed** can be defined with a number and measuring unit, such as “35 kilometers per hour,” or “6 meters per second.” It’s a steady rate. But you can’t measure acceleration this way. One second you are going 35 km/hr, a split second later you are going 37 km/hr, another split second later you are going 41 km/hr. The numbers are constantly changing. If someone asked you what your speed was during this time, what would say? By the time you gave your answer, another second would have gone by, and your speed would have changed again!

Acceleration measures the rate at which change is happening. Galileo found that no matter what his actual numbers were, the rate at which the numbers got bigger (the mathematical ratios) stayed the same. He concluded that gravity applied the same rate of acceleration to all objects. Scientists have calculated this rate of acceleration using the metric system, (based on meters), and found the rate of acceleration to be about 10 meters per second for each second (or “per second, per second”). You write it like this:  $10 \text{ m/s}^2$ . The  $\text{s}^2$  can be read as “per second, per second” or “per second squared.” (A more exact figure is  $9.81 \text{ m/s}^2$ .)

So what does this mean? It means that one second after an object is dropped, it is going 10 meters per second. After two seconds of falling, it is traveling at 20 meters per second. At the end of 3 seconds, it is falling at the rate of about 30 meters per second. Every second it falls, it gets 10 meters per second faster.

What would happen in an object kept falling for forever? Would its speed keep increasing infinitely? This might seem like a logical conclusion, but actually there is a



limit to how fast something can fall. This limit is called the **terminal velocity**. Eventually, the force of air resistance becomes so great that the object can't fall any faster. You can feel how strong air resistance is if you put your hand out the window (just a bit!) when you are in a car that is going very fast on a highway. Imagine that your hand is actually an object falling through the air. You can see how strong the pressure of air can be.

Skydivers reach terminal velocity as they fall toward earth. Even before they put up their parachute, they can feel the air pressure slowing their fall. Then, when their parachute opens, the air pressure gets stronger and their velocity decreases (they fall less quickly). The parachute slows their velocity enough that they can land without injuring themselves.



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### **ACTIVITY #5** A video showing skydivers reaching terminal velocity.

Watch a short video about the physics of skydiving and terminal velocity. Go to [www.YouTube.com/eejm63](http://www.YouTube.com/eejm63), click on the "Physical science stuff" playlist, then find the video called "Physics of Skydiving."

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The scientist who continued Galileo's study of gravity was Isaac Newton. Yes, here comes that famous apple story again. However, the famous version of the story probably isn't entirely true. Newton did indeed sit under an apple tree one day watching apples fall. He did realize at that time that a force was pulling the apple to the ground. But it was not until years later that he realized that the same force that pulled the apple down was the force that kept the moon in orbit around the earth. A group of astronomers at the Royal Observatory were discussing the possibility that Newton's mysterious "gravitational force" could be applied to the solar system and could help explain irregularities they observed in the motion of the moon and the planets. They contacted Newton and asked him if he would like to join their discussion. As soon as Newton received the invitation, everything fell into place in his mind. He realized that gravity applied not just to the Earth, but to the rest of the universe as well. Several years after this, he published his famous book: *Mathematical Principles of Natural Philosophy*. (The word "science" was not used back then. What we call "science" they called "natural philosophy.") Not long after, astronomers began using Newton's "Universal Theory of Gravity" to calculate the complex interactions between the sun, the planets, and even the stars.

One of the key elements of Newton's theory was that all objects, no matter how small or how large, have some gravitational attraction. The earth is extremely large, so it has a huge amount of gravitational pull. An apple is small, so it has very little pull. Technically, the apple and the earth are both pulling, so they are falling toward each other, but the pull of the apple is so incredibly small that we can't detect it. The earth appears to stand still while the apple falls toward it.



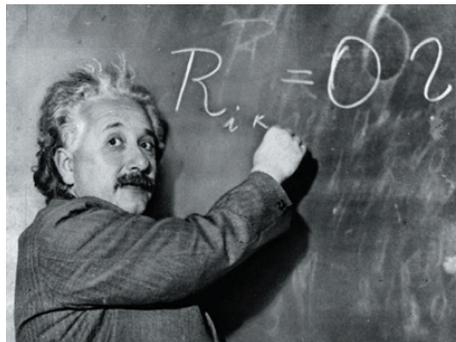
The moon, on the other hand, is large enough to have an effect on the earth. Newton proposed that the moon's gravitational force was responsible for the ocean tides. Until Newton, the cause of the tides had been a perplexing mystery that no one could solve. Newton also proposed that the moon didn't orbit the earth, but that they orbited each other. In a similar manner, the earth does not orbit the sun--they orbit each other. Then what about the other planets? The mechanics of the solar system are very complicated, and the math gets very messy. Astronomers must be expert mathematicians.



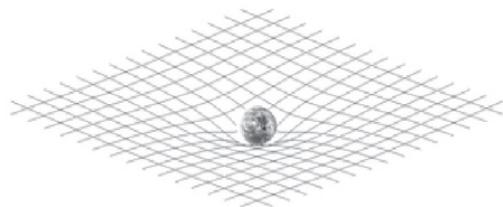
This illustration shows the earth and moon with correct proportions for both size and distance. The distance between them is approximately 350,000 km (240,000 miles).

Some of Newton's math paralleled what Galileo had discovered. Newton calculated that the gravitational attraction between planets and stars follows the old "inverse square" pattern. When the distance between planets doubled, the gravity went down to 1/4. When the distance tripled, the gravitational force dropped to 1/9.

Newton's theory of gravity simply described it as an invisible force. He didn't know what it was. No one really had any new ideas about gravity until Albert Einstein came along. Einstein began thinking about some of the things that still puzzled astronomers about the motions of the planets. He also thought a lot about light and about the electro-magnetic spectrum. He eventually came to some conclusions, and in 1916 he proposed a theory that rocked the scientific world. This was, of course, his famous "General Theory of Relativity." His study of math had led him to the conclusion that there was a one general theory that could explain quite a few things, including gravity. He proposed that space was not empty. The universe, he said, is made of a "space-time continuum" where time functions as a fourth dimension (the first three being length, width and height). When an object occupies a space, it "warps" this continuum. Little objects only warp it a small amount, and large objects (such as planets) warp it a lot. To help non-mathematically-inclined audiences understand how the continuum works, it is often shown as sort of a giant trampoline. The plane of the trampoline is only two-dimensional, but this analogy is still successful in aiding our understanding of the three-dimensional continuum.



Einstein's most famous equation is  $E=mc^2$ .



The sun would be like a giant bowling ball sitting in the middle of the trampoline, stretching it downward in the center, creating a huge funnel shape all around it. The Earth would be like a marble rolling in a circle around the bowling ball. As the marble rolls, it follows the curve of the funnel shape. Thus, the marble stays in an orbit around the bowling ball.

Applying this to the solar system, according to Einstein the reason the Earth stays in orbit around the sun is not because of an invisible force pulling it, but because it is following the warped shape that the sun makes in the space time continuum.

The strangest thing about Einstein's theory is that it predicts that time can be warped by gravity, not just space. In recent decades, time keeping devices have become so precise that scientists have been able to test this prediction. They've found that gravity seems to slow down time. Clocks at sea level run more slowly than clocks at the tops of mountains because the sea level clocks are closer to the center of the Earth and are therefore more affected by gravity. Gravity can also slow down light. Gravity, light, space and time are all interconnected.

Amazingly enough, after 100 years of unquestioned acceptance, the Theory of Relativity is now being questioned. Our scientific equipment is getting so good that we can make more precise observations about the physics of the universe and there are still some things that the Theory of Relativity can't explain. Gravity continues to be a mystery that fascinates physicists.

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### **ACTIVITY # Watch a short video about the theories of gravity**

Go to the *Basement Workshop* YouTube channel, click on the *Physical Science stuff* playlist, and then click on "Gravity-- From Newton to Einstein-- The Elegant Universe." This video has some really nice graphics that demonstrate the warping of the space time continuum.

## OPTIONAL GRAVITY LAB: Repeat Galileo's famous ramp experiment

Here is a video of college students (maybe high school seniors) doing this lab. Their ramp was a bit too short and too steep, but once you see their set up all these written directions will make more sense.

<http://www.youtube.com/watch?v=ZUgYc6Bi46w>

You will need a long ramp of some kind. I used an 8 ft. piece of molding that had a concave shape on one side. It was a bit flexible so I attached it to a more sturdy piece of lumber. The track needs to be straight, and not sagging down at all. You don't have to use the materials I did, however. You can rig a track of whatever size and length you want to. Longer tracks will give more accurate results, but shorter tracks will still give you the idea of what Galileo did. The ball that you use should fit into the track so that it neither touches the sides (adding unwanted friction) nor wobbles back and forth as it goes down ("wasting" some of its energy). The track should be inclined just enough so that the ball rolls slowly but steadily down the track. The exact degree of incline is not important, just don't get the track too steep. You'll also need to put something sturdy at the end of the track, to stop the ball. (Tip: Try to find something that makes a thud or click when the ball hits it. You'll use this sound to tell when to stop the water clocks. The louder the sound, the easier this will be.)

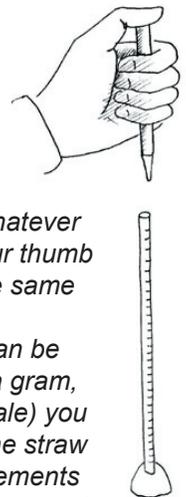
Your track will need to have lines drawn across it, to be used as starting lines for various "runs" of the ball. The first run will be from the first line, so choose a distance you can actually time. One centimeter would be a bit too short. If you have a very long track, you could use 10 centimeters perhaps; for a shorter track maybe 5. You'll then use this measurement to make marks up the track, marking where twice that distance is, three times the distance, etc., all the way up to the top.

You'll also need "water clocks." These can be made very easily from a mechanical pencil. Just take out the "guts" of the pencil, leaving the long plastic tube with a large opening at the top and a very tiny opening at the bottom. Fill the tube with water (an eye dropper is great, but you can use whatever you have on hand that works). If you put your thumb over the top, the water will stay in. By taking your thumb on and off the top, you can start and stop the flow of water out. (Galileo's device operated in much the same fashion, only he had a very large tank and a metal spout.)

You will need to collect and measure small amounts of water during your experiments. This can be done in two ways. If you have a balance (scale) that can measure very accurately, down to tenths of a gram, you can weigh your collected water for each run of the ball. If you don't have an accurate balance (scale) you can use a homemade graduated cylinder made from a plastic straw. Make evenly spaced marks up the straw using a permanent marker or pen (a very sharp one that makes thin and precise lines). Make the increments about half a centimeter apart. You can keep the straw standing up by placing it in a lump of waterproof clay. If you don't have clay, use whatever you have one hand that can plug up the end of the straw so that water does not leak out. (Folding the straw at the bottom and taping it might help make it leak-proof.)

Finally, you will need a copy of the chart provided. The charts have been left blank so that you can fill in whatever units you are using-- ounces, grams, or simply numbers. If you are using a straw as a graduated cylinder, your units would be just numbers-- 1 through how many lines you made on the straw. As long as you are consistent with whatever system you use, the units of measure don't matter. What matters is how each run of the ball compares to the first run.

- 1) Place the ball on the first line. At the word "Go," let the ball go and start the water clock. When the ball hits the stopper at the end of the ramp, stop the water clock.
- 2) Measure the amount of water collected on the this first run. Record this figure as accurately as you can.
- 3) Do this again. A third time would be great, if you have the patience. Average these figures to come up with a final figure you will record as a dot on your graph.
- 4) Refill your water clock so it's ready to go again. If you are using a graduated cylinder, empty it so it is ready.
- 5) Place the ball on the second line. At the word "Go," let the ball go (be careful not to push it) and start the water clock. When the ball hits the end of the track, stop the water clock and measure how much water you collected on this run. If you have any doubts as to accuracy, do the run again.
- 6) Continue doing this for lines up the track. (If you start to run out of time, make sure you get at least one run of the ball from the highest line, and maybe a few others from high up on the track.)
- 7) Record all these results on the chart as dots corresponding to the distance the ball traveled and amount of water collected. Make a smooth "best fit" curve through the points. What shape do you get? Can you see any points that are obviously the result of an error in your method (thumb slipped off water clock, started ball at wrong place, etc.)? Can you find a mathematical pattern to your data?



## Galileo's famous ramp experiment

Galileo wanted to study gravity, but found that objects fell too fast for him to be able to study them. Then he figured out that he could slow down the action of gravity by using a ramp. His ramp was about 7 meters long (23 feet) and had a narrow groove cut along the center. Galileo sanded and polished this groove until it was as friction-free as possible. He used a very smooth bronze ball. For a stopwatch, Galileo used a water time that dripped droplets at a constant rate. He could start and stop the water drops each time he rolled the ball a certain distance. Then he could measure how much water he had collected on each trial and try to figure out if the ratios followed any kind of mathematical pattern. The pattern he found was very similar to the pattern he found for pendulums.

Record the data from your ramp experiments below. Make sure to label each axis and and write what the units represent. Two graphs are provided in case you would like to do the experiment twice, changing a variable such as the steepness of the ramp or the mass of the ball.

