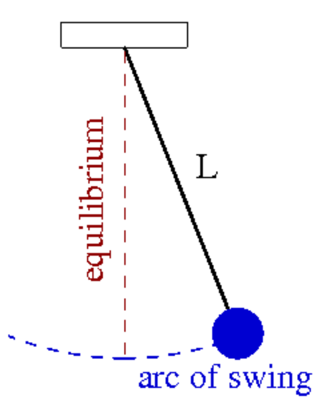
Physics Quanta: The Pendulum's Swing

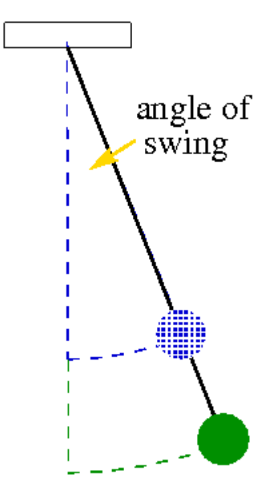
(Note: this is the beginning of a new series of posts, in which I explain a basic physics concept and put it in a wider context. Since the title of the blog is Galileo's Pendulum, I thought starting with the pendulum would be appropriate. A *quantum* is a small quantity of something; the plural is *quanta*, so the series "Physics Quanta" consists of bite-size chunks of physics.)



A simple pendulum

Everybody has seen pendulums of one type or another. Pendulums lurk everywhere, often in disguised form, but the basic pendulum (as shown on the right) is simple to describe. You can make one by taking a piece of string and tying something heavy to it — the main thing is that the object be heavier than the string, and preferably it should be compact so that it doesn't spin around too much. The mass on the end is called a *bob* (which you can feel free to call Bobby or Bobbi or even Roberta if you're feeling formal).

Let's look at the pendulum through Galileo's eyes: according to his own account, he was in the church in Pisa and noticed a lamp swinging back and forth overhead. He observed that the lamp repeated the same pattern of swing — it always followed the same arc, which is the dashed blue line on the figure. Using his pulse to time the swing, he determined that the amount of time for the pendulum to trace the arc was the same on each swing. This is called the *period of oscillation*. If left alone, the pendulum will sit so that its string is perfectly vertical; that position is called *equilibrium*, which is the position at which the forces acting on the bob are perfectly balanced.



A longer string will have a larger period of oscillation

Galileo made another intuitive leap that turns out to be approximately true, but not exactly so: he surmised that the length of the string is only thing that determines the period. The size of the arc? Not important. The mass of the pendulum bob? Also not important. (He was right on that one: it turns out the exact mass of the bob isn't important, as long as it's sufficiently heavier than the string. The reason for this, believe it or not, is connected to Einstein's general theory of relativity and something known as the *equivalence principle* — I'll return to that idea later on.) A longer string will take a greater amount of time to complete one swing than a shorter string, which you can see from the second figure: it has to travel a larger distance for the same angle of swing. For those unafraid of the math, the relationship is a square root: if you want to double the period of oscillation, you need a string *four times* the length; to triple it, you need a string *nine times* longer, etc.

Galileo recognized that over time the pendulum would come to a stop due to air resistance, but under ideal circumstances the pendulum would continue to swing on forever. That's one area where Galileo excelled: extrapolating from highly non-ideal circumstances to ideal thought experiments which highlight important physical principles. We put all sorts of fancy terms on top of Galileo's basic ideas today: conservation of energy, which (by Noether's theorem) is another way of saying that if we look at the ideal pendulum at some much later time, it's going to be swinging back and forth in exactly the same way. Galileo turned out to be wrong about the string length being the only factor in the period: the size of the swing does make a difference, but for small arcs, the contribution is negligible. I'll return to this idea in a future post, in the interests of keeping things bite-sized.

Now we're in a good position to understand the awesome pendulum video I posted a few weeks ago: each pendulum has a slightly different length of string, and the relative lengths consistently (but not linearly!) increase along the apparatus. This means the period of oscillation isn't going to be the same for each pendulum, even though they all swing through the same angle. The exact relationship between string lengths is designed to create the illusion of a wave; in addition, as the pendulums slow down due to air resistance, the pattern changes. (Again, I'll discuss the way air resistance works in the follow-up post.)

Finally, let's see why the mass of the bob isn't important. Isaac Newton defined mass as the resistance to motion: the more mass an object has, the harder it will be to get it moving if it's at rest, or to change its direction or bring it to a stop if it's already in motion. He also recognized that the larger the mass, the greater the gravitational attraction that object will possess. But here's the interesting part: there's no inherent reason these two qualities of an object should be the same! The amount of gravitational attraction an object exerts doesn't *have* to be directly correlated to amount of resistance it gives when pushed. Contrast this with electricity: a proton and an electron have exactly the same magnitude of electric charge (one is positive and the other is negative, but the *size* of their charge is the same), but a proton is roughly 10,000 times more massive. If you put a proton and an electron into the same electric field, the size of the force acting on them — determined by the size of the charge — will be the same, but the proton will respond far more slowly because of its greater mass.

For gravitation, the "charge" is precisely its mass. Einstein called this the *equivalence principle*, and when you carry the idea to its logical extreme, it leads to his general theory of relativity. For our humble pendulum, the equivalence principle just implies that the resistance to motion as the bob swings back and forth is proportional to its mass, but so is the force acting on the bob due to gravity. With the same proportionality for both cause — the force — and effect, the mass drops out of the picture! When we put other forces into the system such as air resistance, we'll see that relationship change, but the special nature of gravity that leads to phenomena like black holes sneaks into systems even as simple as a pendulum.

I will follow this post up with two more specifically relating to pendulums. The first will explore how the simple pendulum of Galileo changes when we add in air resistance or let the arc of swing be large. The second will bring pendulums into the context of quantum mechanics, and how a system as basic as this can help us understand some phenomena that don't look at all like a mass on the end of a string. I hope you will find these topics to be worthwhile reading!

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15 responses to "Physics Quanta: The Pendulum's Swing"

Whose Job is Public Science Education? « Galileo's Pendulum
May 25, 2011 at 10:58 am

[…] Galileo's Pendulum The Pendulum is Mightier Than the Sword « Physics Quanta: The Pendulum's Swing […]

Physics Quanta: Pendulums Revisited « Galileo's Pendulum
May 31, 2011 at 5:16 pm

[…] week, I began with the simple pendulum, so go back and reread that post before starting this one. (I'll wait here; no rush.) Two things we assumed last week: that the pendulum swings through […]

Physics Quanta: From Identical Twins to Voltron, Physics Style « Galileo's Pendulum
June 24, 2011 at 12:00 pm

[…] of a series of posts, in which I explain a basic physics concept and put it in a wider context. The first two dealt with pendulums; I do have one more post about pendulums to come as […]

Finding Mass Without a Scale « Galileo's Pendulum
July 21, 2011 at 5:09 pm

[…] influence on other objects. (That this is the same mass as in definition 1 is called the equivalence principle, and is the starting point for Einstein's general theory of relativity. The equivalence […]

From Pendulums to Quantum Oscillators « Galileo's Pendulum
August 18, 2011 at 5:02 pm

[…] explain a basic physics concept and put it in a wider context. The first Physics Quantum introduced the basic physics of ideal pendulums undergoing small oscillations; the second extended the idea to large oscillations and added in air […]

Learning To Be a Better Teacher By Writing « Galileo's Pendulum
August 19, 2011 at 11:46 am

[…] know I've been running an occasional series explaining basic physics concepts, starting with simple oscillators (pendulums) and going from there. (I'm not done with oscillators yet, either — I intend to do at […]

Sync or Swim « Galileo's Pendulum
September 14, 2011 at 5:24 pm

[…] giving rise to phenomena such as lasers and the spectra of stars. We've come a long way from masses on strings: we can understand oscillators as any system that repeats in some manner. This post will look at a […]

Foucault's Pendulum: It's Not Just a Conspiracy Theory! « Galileo's Pendulum
September 19, 2011 at 8:37 pm

[…] Virginia. I will write a post about Foucault pendulums soon(ish), as a continuation of the general oscillator […]

What Are Neutrinos, Anyway? « Galileo's Pendulum
September 30, 2011 at 2:41 pm

[…] with the time of oscillation dictated by the difference in masses between the flavors. (Have I pointed out yet how many things in nature are oscillators?) Interestingly, we have a better handle on the […]

2011: A Year of Oscillation « Galileo's Pendulum
December 30, 2011 at 10:10 am

[…] May: "Revisiting Schrödinger's Cat" and "Physics Quanta: The Pendulum's Swing" […]

The Temperature of History « Galileo's Pendulum
March 9, 2012 at 5:50 pm

[…] you can run time forward or backward just as easily, and the laws of physics don't change. A pendulum will swing back and forth forever, planets orbit the Sun, following the same approximate paths for […]

Inverse Square Law: A Tale of Luminosity, Gravity, and Topology « Galileo's Pendulum
June 28, 2012 at 10:31 am

[…] cover the outside with some kind of gravitational detector as well, say a huge number of pendulums of a precise […]

1e Proposal for Scientific Research | Thomasb2012
September 17, 2012 at 1:15 am

[…] d. Francis, Matthew. "Galileo's Pendulum." Galileo's Pendulum. N.p., 24 May 2011. Web. 17 Sept. 2012. https://galileospendulum.org/2011/05/24/physics-quanta-the-pendulums-swing/. […]

Chaos! (Science Advent 3) « Galileo's Pendulum
December 4, 2012 at 9:57 am

[…] is a plot of the velocity of a pendulum as a function of its position, taken over many cycles. A normal pendulum would describe a circle (or more accurately a slow spiral inward as air resistance slows the […]

Portrait of a black hole, part 1 | Galileo's Pendulum
October 3, 2013 at 11:45 am

[…] more about phase portraits, see my earlier posts on pendulum motion. For a lot more information, I recommend reading up on nonlinear dynamics! See […]