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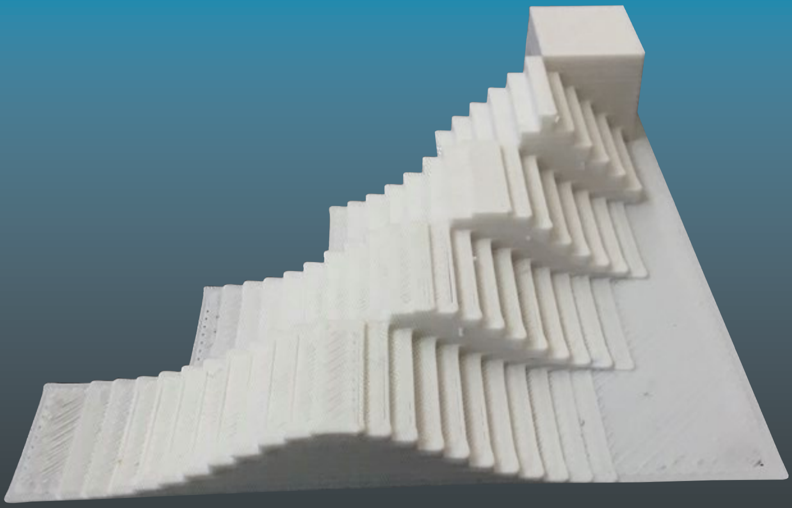

3D Printed Science Projects Volume 2

Physics, Math, Engineering and Geology Models

Joan Horvath
Rich Cameron

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3D Printed Science Projects Volume 2: Physics, Math, Engineering and Geology Models

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To Steve Unwin, for encouragement, patience, and physics

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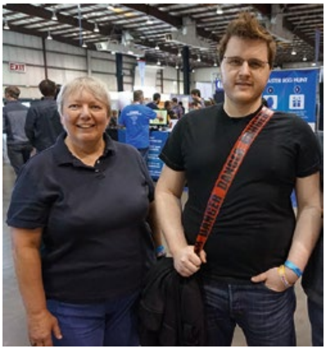
About the Authors



Joan Horvath and **Rich Cameron** are the cofounders of Nonscriptum LLC, based in Pasadena, California. Nonscriptum consults for educational and scientific users in the areas of 3D printing and maker technologies. Joan and Rich find ways to use maker tech to teach science and math in a hands-on way, and want to make scientific research cheaper and more accessible to the public.

This book is their sixth collaboration for Apress, and it particularly builds on their earlier *3D Printed Science Projects* (Apress, 2016). They also teach online classes in 3D printing and maker tech for LERN Network's U Got Class continuing education program. Links for all of the above are on their website, `www.nonscriptum.com`.

In addition to her work with Rich, Joan also has an appointment as core adjunct faculty for National University's College of Letters and Sciences. She has taught at the university level in a variety of institutions, both in Southern California and online. Before she and Rich started Nonscriptum, she held a variety of entrepreneurial positions, including VP of business development at a Kickstarter-funded 3D-printer company. Joan started her career with 16 years at the NASA/Caltech Jet Propulsion Laboratory, where she worked in programs including the technology transfer office, the Magellan spacecraft to Venus, and the TOPEX/Poseidon oceanography spacecraft. She holds an undergraduate degree from MIT in aeronautics and astronautics and a master's degree in engineering from UCLA.

Rich (known online as "Whosawhatsis") is an experienced open source developer who has been a key member of the RepRap 3D-printer development community for many years. His designs include the original spring/lever extruder mechanism used on many 3D printers, the RepRap Wallace, and the Deezmaker Bukito portable 3D printer. By building and modifying several of the early open source 3D printers to wrestle unprecedented performance out of them, he has become an expert at maximizing the print quality of filament-based printers. When he's not busy making every aspect of his own 3D printers better, from slicing software to firmware and hardware, he likes to share that knowledge and experience online so that he can help make everyone else's printers better too.

Acknowledgments

The consumer 3D-printing ecosystem would not exist in its current form without the open source 3D printing hardware and software community. This is particularly true of Marius Kintel, the main developer and maintainer of OpenSCAD software, and his collaborators, for their software which was used to develop the objects in this book. We are also grateful for the support of the MatterHackers team and their MatterControl software, particular Lars Brubaker, Kevin Pope, and Mara Hitner. The maker community as a whole has also been very supportive. The picture of Joan and Rich in the "About the Authors" section was taken at the 2015 San Mateo Makerfaire by Ethan Etnyre; we appreciate how much we have been inspired by looking at projects made by everyone at maker events large and small.

The Apress production team was there for us to solve problems as they arose and let us have great creative freedom otherwise. We dealt most directly with Natalie Pao, Jessica Vakili, Corbin Collins, and Welmoed Spahr, but we also appreciate the many we did not see.

We picked a lot of scientists' brains as we thought about how to model some of the concepts in this book. Joan's astronomer husband, Stephen Unwin (to whom this book is dedicated as a long-overdue thanks), was a huge help as we reminded ourselves about all the basic physics we had forgotten. Frank Carsey, Sue Digby, members of the LIGO team (particularly Alan Weinstein at Caltech), and many others helped us out by reading a chapter draft or giving us some of their time to discuss their science.

We were inspired to create 3D-printable educational models originally by discussions with people in the community of teachers of the visually impaired, notably Mike Cheverie, Lore Schindler, and Yue-Ting Siu.

Finally, we are grateful to our families for putting up with our endless brainstorming, kitchen table commandeering, and test runs of explanations. As always, we learned a lot writing this book, and we hope you will get as much out of reading it and playing with the models as we did creating it.

Introduction

When we wrote our first book of 3D-printable science projects, we knew that students, parents, and teachers would get excited about using a 3D printer, might download a 3D model, print it, and then wonder what to do next. Or they might get into creating models from scratch and become discouraged by the limitations of easier 3D modeling programs or the learning curves of the more capable ones.

In our first book, we created a middle path: models that you could just print but that would be reasonably easy to alter if you wanted to do more. Further, we designed the models so that they would be useful to learn science or math principles by changing their features. In particular, we wanted to create some seeds of science fair or extra-credit projects—that is, open-ended, meaty explorations that could be explored at a variety of levels. In that first book, we were surprised at how hard this turned out to be. Most textbooks and online sites endlessly recycle versions of the same 2D projection of models of science concepts.

You would think we would have learned better by now and that we would be able to just sit back, crack our knuckles, and pound out a model in an afternoon or so. Not even close. As with the first book, in each chapter we have a "Learning Like a Maker" section where we talk about our adventures in defining and implementing the models.

Some of the deceptively simple models (like the pendulums in Chapter 1 and weighted wheel in Chapter 5) actually involve some subtle physics to make them work well at a tabletop scale. For the interactive models that can be used for some simple demonstrations, we tried to use measuring equipment that pretty much anyone would have in their home, supplemented by free smartphone apps. This sometimes made accurate-enough measurement challenging, and we talk about how to deal with that in each case.

Speaking of accurate measurement, we were excited to create a simplified model of one of the biggest scientific observations in recent memory: gravitational waves (Chapter 8). We enjoyed the challenge of wringing out approximations that would preserve some behavior while not taking users into complicated exercises in downloading output of scientific user models (although we encourage you to use our model as inspiration and move on to endeavors along those lines!)

This book presumes you know a little bit about 3D printing already. If you don't, Appendix A and the resources linked there should get you up to speed. The models are all written using the OpenSCAD free and open source 3D modeling program. If you know how to program in a language like C, Java, or Python, that will help but is not strictly necessary to alter the models. Appendix A and the OpenSCAD materials linked there will help you out with that too.

We have found that teachers use 3D printers in one of two fundamental ways: either they want to create a model to pass around in class to help students visualize a concept, or they want students to use a printer either to learn engineering and design per se or to do classroom explorations of physical concepts such as moment of inertia. Since most of these models lend themselves to being used in many different ways, we have not included a grade level or explicit lesson plans.

To show our readers who are teachers (in the United States) what we had in mind, though, at the end of most chapters we suggest Next Generation Science Standards that we thought might benefit from these models. These science standards, from the group NGSS Lead States, are documented in *Next Generation Science Standards: For States, By States* (The National Academies Press, 2013). Links are given at the end of relevant chapters.

We do not pretend to be experts in K-12 education, but we looked through the standards as engineers to find the best fit in our opinion from the technical practitioner point of view. If you are a teacher, you may want to check with your state or school standards as well to see the best fit.

The models span a variety of topics, and we tried to cover as many disciplines as possible. We have aimed these at students who know some basic algebra (enough to read an equation with an exponent in it). If you know some calculus, you will understand some of the models more quickly, but you might teach yourself more if you do not! Briefly, here is what you can look forward to:

Chapter 1 discusses pendulums and allows you to create simple and compound ones.

Chapter 2 lets you create models of geological formations that can be hard to describe: synclines, anticlines, and a particular type of dune called a barchan dune.

Chapter 3 moves you to cooler climates and allows you to create an iceberg (and explore how it floats) and snowflakes.

Chapter 4 lets you explore the world of high-speed motion, with models of Doppler shift and shock waves.

Chapter 5 creates a deceptively simple wheel that you can weight with pennies to understand moment of inertia.

Chapter 6 is an exploration of topics in probability, from rolling dice in role-playing games to how to visualize the probability of two things varying at the same time.

Chapter 7 explores logic gates as puzzles to put together.

Chapter 8 allows you to print the gravitational waves coming from two black holes merging and throwing off inconceivable amounts of energy.

Finally, as we noted earlier, Appendix A reviews how to 3D print, and Appendix B aggregates all the links in the book.

You may also want to check out the models in our earlier *3D Printed Science Projects* book. Many of the models here build on those earlier ones. We note it where that is the case.

Finally, we are making the 3D-printable models used in this book (although not the book itself!) open source, licensed under a Creative Commons Attribution- ShareAlike 4.0 International License (`https://creativecommons.org/licenses/by-sa/4.0/`). That means you can use them for any purpose and alter and remix them as long as you credit us, and any derivativatives you distribute must carry the same license. In Appendix A we have some notes about where to find the repositories if you would like to add to these models. We hope these models are just the first iteration of a set of learning tools that students everywhere can play with and learn from for a long time to come.

CHAPTER 1

Pendulums

This chapter looks at the deceptively simple world of pendulums. First we cover why pendulums swing back and forth as they do, and tie this into the general idea of simple harmonic motion—a type of oscillatory motion in which a system stores energy (in a spring or by working against gravity) and then uses that stored energy to move back to its original position.

Some of the experiments in this chapter are classic high school or undergraduate physics demonstrations, and in some cases would benefit from non-3D-printed parts. However, if you do not have access to typical school lab items, you can still do some respectable explorations with the parts we give you in this chapter, plus a pair of chairs and some string. We point out possible upgrades as we go.

This chapter (like all the others in this book) first lays out a bit of science background and then develops 3D-printable models that explore these concepts. We talk about what we learned just by the process of creating the model, and finally give some tips about how you might use these models to teach the topics they demonstrate. The models are available for download from the link on the copyright page of this book.

Simple Harmonic Motion

What makes a pendulum swing back and forth, or a ball on a spring boing back and forth? ***Simple harmonic motion*** is a phenomenon that occurs when something moves in a way that converts energy from ***potential energy*** to ***kinetic energy*** and back again. In an ideal world, the sum of something's kinetic energy plus its potential energy is always a constant. If you raise something up high, it has potential energy. It is not moving, but you had to expend energy to get it where it is. When you let go, it falls—converting this potential energy into kinetic energy, the energy of motion. When it hits the ground, it dissipates that energy into making a big hole or cloud of dust.

But simple harmonic motion is about conversion of potential into kinetic energy in a ***back and forth*** way. Suppose you have a table built into the wall. Imagine that you have a big spring attached to the wall, with a heavy ball attached in turn to the spring and resting on the table. If you stretch the spring by pulling the ball away from the wall, and then let go, it will bounce back and forth for a while across the table. It is oscillating because you stretched the spring to start things off (storing potential energy in the spring).

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When you let go, the spring converted that potential energy into kinetic energy (motion). It will likely then compress the spring and stop when the spring is compressed by the same amount that you stretched it initially, and then shoot back out. This process will continue until friction and air resistance bring it to a stop.

■ **Note** The principle that the force needed to compress or extend a spring is proportional to the distance the spring is extended or compressed is called ***Hooke's Law***. British physicist Robert Hooke proposed it over three and a half centuries ago, in 1660.

It is pretty easy to think about a mass on a spring oscillating back and forth on a table as an example of trading off potential and kinetic energy. But what about a pendulum swinging back and forth without any external forces on it (other than being pulled to one side to start the motion)? The more you pull the pendulum bob to one side, the more potential energy you are giving it because you are also raising it. When you let go, the mass will fall (converting some of its potential energy into kinetic energy), constrained by its string. It will have enough kinetic energy to carry the mass up to the other side, and stop, having converted all the kinetic energy back into potential energy. Air resistance and friction at the pivot point will eat away at the total energy over time, but if these can be minimized a pendulum can oscillate for a long time.

■ **Note** The basic work on pendulums has its heritage in the work of Galileo Galilei (1564–1642), Christiaan Huygens (1629–1695), and Isaac Newton (1643–1726). Early practical applications focused on pendulum clocks. Huygens is credited with developing the first working pendulum clock.

As it turns out, the period of a simple pendulum (a weight swinging on a light string or wire) is given by the equation

$$\textit{Period} = 2 * \pi * \textit{sqrt}(l / g)$$

where l is the length of the string and g is the acceleration due to gravity (9.8 meters per second squared on earth). This formula only applies for swings under about 15 degrees either side of the centerline. It is an approximation that starts to become inaccurate for bigger swings. There are other terms proportional to the square (and higher powers) of the sine of this angle to the vertical. These terms are small when the sine of this angle is small, but become significant as the angle gets larger.

■ **Note** We use the programming convention of using * to mean ***multiply***, and sqrt(…) for ***square root of***, plus the standard abbreviations for meters (m), centimeters (cm), and other metric quantities. Thus meters per second squared becomes m/s^2.

The important property, though, is that the period depends only on the length of the string supporting the mass and not on the mass (unlike the spring example) or any other property of the pendulum. This is why pendulums were of interest first in clocks, and later on in other investigations that we talk about a little later in this chapter.

Friction (including air resistance) will eventually stop these oscillatory motions in the real world. The existence of friction acts as a ***damping*** force which takes energy out of the system, eventually bringing it to rest. As you will read in the "Learning Like a Maker" section in this chapter, we spent a lot of time battling friction in our designs.

The Models

In this chapter we start out with a simple pendulum (a mass on a string) and then move on to ***physical*** (sometimes called ***compound***) pendulums, which are stiff parts that swings back and forth as a whole. Finally, we combine some of these to show the counterintuitive behavior of two or more simple pendulums connected together, or of a ***double pendulum***, which connects two physical pendulums. The double pendulum displays ***chaotic behavior***—seemingly-random oscilations.

■ **Tip** If you are new to 3D printing, you might want to look at Appendix A first, which talks about both 3D printing in general and using OpenSCAD in particular. All the models in this book are written in OpenSCAD. Electronic copies of all the models in this can be downloaded from the publisher's page for this book. Go to `www.apress.com` and search on this book's title to get to the correct page.

Simple Pendulum

The first model is a simple pendulum bob designed to be hung from a string. It has room for a few coins to be packed inside to weigh it down a little. It is set up to take up to four United States pennies, but there is a parameter, `coins_diameter`, which is the diameter of the desired coin, in mm. For U.S. pennies, it should be 19.5 mm; for quarters, 25 mm. If you live in other countries, you can find out the relevant coin dimension by doing an online search for the word "diameter" followed by the name of your coin. Add about half a millimeter to the actual diameter to allow for imprecision and some tolerance to allow the coins to be inserted and removed easily. The simple pendulum model (sized for pennies) is shown in Figure 1-1.

Figure 1-1. *The simple pendulum*

■ **Caution** Many of the models in this chapter and elsewhere in this book have small parts and should not be used around young children. Treat them as science experiments, not as toys.

To test it out, put four pennies into the hollow area. Tie a piece of string to the top of the pendulum bob, and either tie the other end to someplace where it can swing freely (for example, a curtain rod with the curtains pulled back, or held in place with a heavy book at the edge of a table, as in Figure 1-2). Next, you will need to know the distance from the center of mass of the pendulum, which we will assume is roughly at the center of the pennies. Measure from the center of the coins to where the string is free to move at the top.

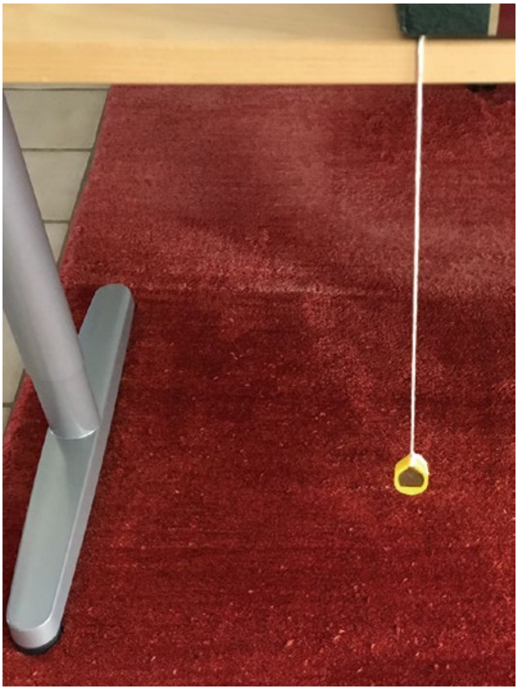

Figure 1-2. *Experimental setup, simple pendulum with a short string*

Next, pull the pendulum to one side, say 15 degrees or so from the vertical. Start a stopwatch (you probably have one in your phone's clock application) and see how long it takes for the pendulum to return 50 times to one extreme position, for example all the way to the right, and then divide by the number of oscillations. (We have the little triangle on the bottom to make it easier to see positioning.) That time it takes for the pendulum to make a full swing and back again is the ***period***. Note that the longer the string, the easier it is to measure the (slower) period.

It is a little tricky to do this measurement. Start the pendulum swinging first. Then start the stopwatch when the pendulum reaches an apex of its swing; then count the number of times it returns to that apex. We discovered that it is best to measure the actual distance of the pivot point of the string to the center of mass when the pendulum is actually hanging up—strings stretch a bit, and tying it introduces a lot of errors.

The period should be $2 * \pi * sqrt(l / g)$. If we have a one-meter-long string, the period is: $2 * 3.14159 * sqrt(1\ m / 9.8\ m/s^2)$, or 2.0 seconds. We did two trials and got 59.9 and 59.6 seconds for 30 swings, for a period of 1.99 seconds—accurate within our ability to stop the stopwatch, measure the distance, and other parameters.

Listing 1-1 is the OpenSCAD model for this pendulum bob. If you wanted to use different coins, you would change the `coins_diameter` and `coins_depth` parameters. These should both be a little bit (a few mm) bigger than the dimensions of the stack of coins you want to have inside the bob. Note that `coins_depth` is the thickness of the coin multiplied by how many of them you want to have in there.