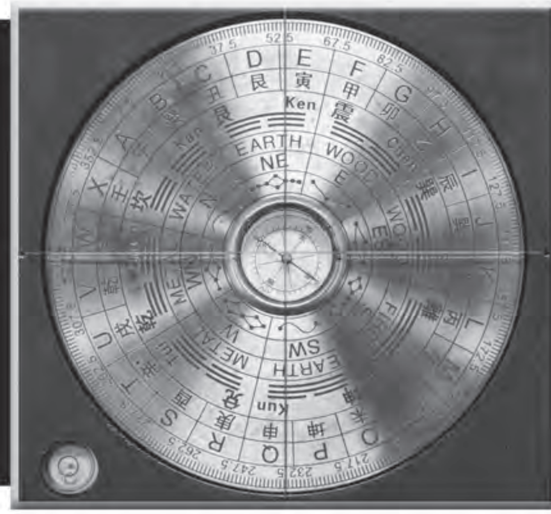
Ancient Chinese Science and the Teaching of Physics

By Matthew Marone



Qi meter, navigational aid, or magnetometer?
Note: Images in this article are courtesy of the author except where other sources are indicated.

Editor's Note: A syllabus for the course described in this article is available in the online supplements for this issue.

The scientific accomplishments of ancient China provide an exciting foundation for the teaching of introductory physics. Traditional physics classes are almost always taught from a Eurocentric point of view that rarely exposes students to the scientific accomplishments of other cultures. At Mercer University, I am experimenting with a new method of teaching physics that infuses Chinese culture, while at the same time, exposes our students to the principles and practice of modern experimental science. Ancient Chinese Science and Technology was originally developed as a laboratory science class for students in Mercer's Asian Studies program. Our intention was to develop a class that allowed Asian Studies minors to complete their general education science requirement in an Asian theme. Interest in the class has spread well beyond the Asian Studies program, and students come from a wide range of nonscience majors. A key aspect of this class is the laboratory component, in which we examine several Chinese technologies using modern experimental methods. Our class is a unique blend of physics, chemistry, materials science, optics, and acoustics, with a touch of foreign language, history, and philosophy.

As we encounter the inventions and discoveries of ancient China, we are guided by two overarching ideas. First, we seek to understand how the particular technology or discovery was interpreted in its authentic historical and cultural context. Then, we analyze the topic from the modern scientific point of view. Students in traditional physics classes often struggle with understanding why they are studying abstract mathematical models and how these models are connected to seemingly unrelated topics. By starting with the technology first, students understand the purpose of the analysis and can relate the topics to their daily lives.

Subject	Canon
Force	A221
Time	A44
Movement	A50
Stopping	A51
Local Noon	A57
Space and Length	B13, B14
Shadows and Light Sources	B17, B19, B20, B21
Mirrors and Images	B22, B23, B24
Steelyard Balance and Lever	B25
Lifting and Atwood's Machine	B26

Table 1. Some examples of physics discussed in the *Mozi*.

The structure of the class combines a survey of selected topics found in a traditional two-semester physics sequence. Since this class is not intended for science or engineering majors, there are no external constraints as one would have in a class intended to prepare students for medical school admission or engineering accreditation. The first unit we cover is a short introduction to Chinese pronunciation and the pinyin method of phonetic transcription. Some students have a familiarity with Chinese, but most do not have any prior experience with the language. Chinese proper names and terminology are used throughout the class, much in the same way that one would encounter Italian terms in a class on music theory. These terms do appear on tests in the form of matching questions with simplified characters and pinyin.

The eclectic nature of this class and the substantial laboratory component make it difficult to describe in a single article. There are certain canonical topics that show up in most physics classes. In this article, I will discuss several of these topics and how I introduce them in a way that seems comfortable and appealing to the typical humanities student. Our class begins with a short discussion of the groundbreaking work of Joseph Needham and his voluminous work *Science and Civilization in China*. This, of course, leads to the inevitable discussion of the Needham question: why did ancient science stimulate advanced technology in the West, but not in China and India?[1] The Needham question is always lurking in the background and provides lively debate right from the outset. After a brief discussion of Chinese history, we move on to a unit covering basic mechanics.

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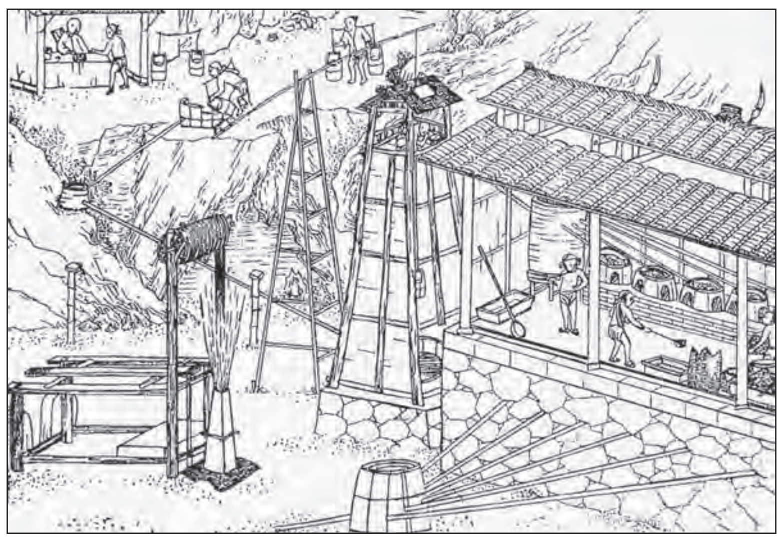
Our unit on mechanics begins with readings from the *Mozi* and a discussion of motion. Readers familiar with Chinese philosophy may wonder how a Warring States-period philosopher has any relation to physics. Little is known about Mozi's early life, but we do know that he was a carpenter and skilled in making mechanical devices. There is a surprising amount of physics mixed in with his condemnations of elaborate funerals and teachings on universal love. Much of the physics is found in the section known as *Canons and Explanations A and B*. Table 1 shows a list of physical principles and the corresponding canons. This is not intended to be an exhaustive list, but it does cover topics we discuss in class.

In the *Mozi*, we find several statements concerning force and motion. In *Canons and Explanations A21*, we find the statement, "Force is what moves a body."[2] This may sound simple at first but is fertile ground for a physics discussion. If you slide an object on a smooth surface, why does it continue to move after it has left your hand? Your hand is no longer in contact with the object and no longer exerts any force, yet the object continues to move. Here is an even more interesting example. Suppose you pull a box across the floor with a string. There are several different forces acting on the box in various directions. Just as an accountant speaks of a net gain, a physicist examines the net force acting on an object. We simply sum all the forces in a particular direction to arrive at the net force in that direction. Now in the case of our box, the string pulls in a direction opposite of that of the friction produced by the floor. When two forces act in opposite directions and have equal magnitudes, the result is a net force of zero. If the horizontal component of the tension in the string is equal in magnitude to the frictional force exerted by the floor, then the net force acting on the object in the horizontal direction is zero. How can the object move if the net force is zero and we believe the statement that force is what moves the body? Anyone who has studied some physics understands that the object continues to move after it is released because of inertia, and this is in keeping with Newton's laws of motion. In the case of the object pulled by a string, we again encounter Newton's laws and the idea of acceleration. Since the net force acting on the object is zero, it has no acceleration and continues to move with a constant velocity. All this discussion of motion, acceleration, and velocity requires us to mathematically define what these quantities mean. We observe a moving object in class and then create mathematical terms that can be used to describe its motion. In this way, we move into the subject of kinematics. Now the initial motion question does not require an ancient Chinese philosopher to get the conversation going. In fact, Aristotle struggled with the same questions and came up with answers that were inconsistent with Newton's laws of motion. Perhaps what this shows is a more universal idea of how the observation of natural phenomena spurs thinking people to seek more detailed explanations that ultimately give rise to scientific thought.



A sketch originally from *The Annals of Salt Law of Sichuan Province*. A "Kang Pen" drum is seen in the center foreground, with gas pipes feeding the salt stoves in the open building. At the top, brine from a remote well is being carried in buckets by men, who feed it into a bamboo pipeline that runs down to the stoves (from Zhong & Huang). Source: "Ancient Chinese Drilling" by Oliver Kuhn on the *Recorder* website at http://tinyurl.com/hbdcxea.

Our studies in kinematics naturally lead to a discussion of the energy associated with moving objects and the principle of the conservation of energy. This topic is typically introduced by analyzing the motion of a ball thrown straight up into the air. The analysis becomes far more interesting when the object is a 200 kilogram fishtail percussion drill bit used to drill for salt brine in ancient Zigong. Few students in the Western world know of

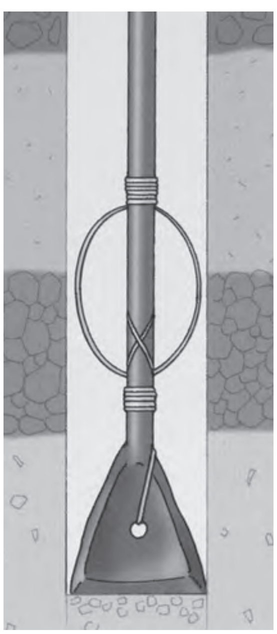
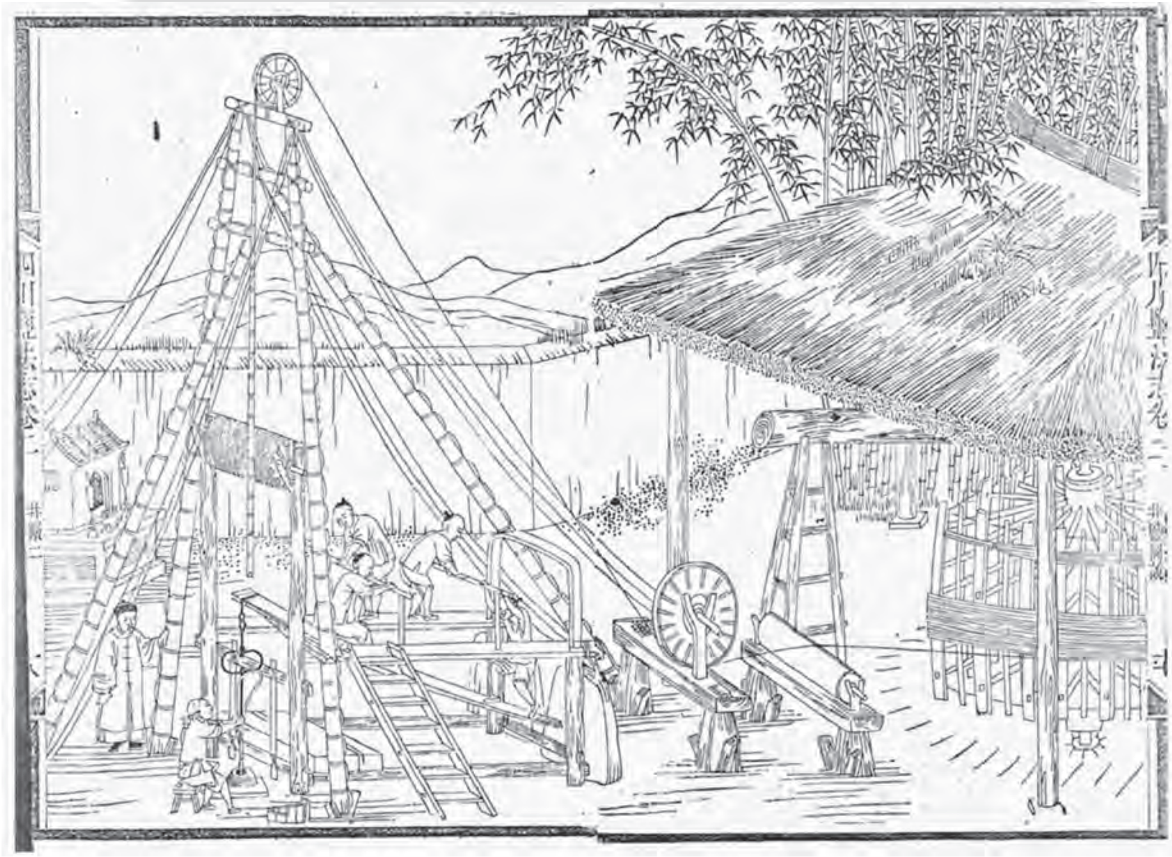


Diagram showing the "fishtail" drill bit. Source: "Ancient Chinese Drilling'" by Oliver Kuhn on the *Recorder* website at http://tinyurl.com/hbdcxea.

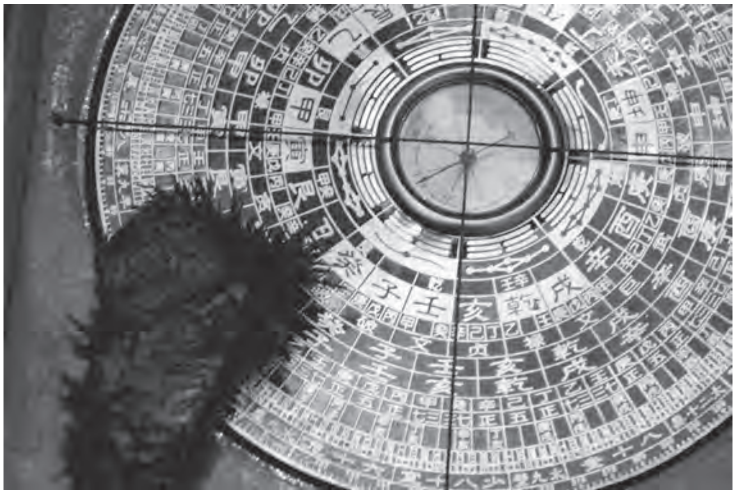


Late nineteenth-century drawing of well drilling in Ziliujing District, Sichuan Province, China. Source: Page 133, *Chinese Mechanical Knowledge and the Jesuit Intervention*, ed. Zhang Baichun and Jürgen Renn, http://tinyurl.com/gp9pglt.

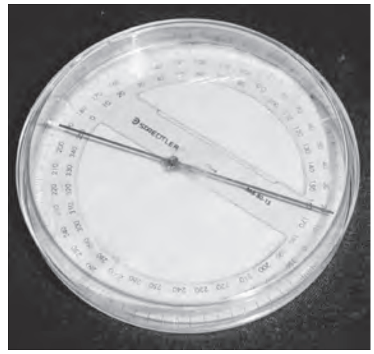
the ingenious system used to drill salt and natural gas wells some 2,000 years ago. The ancient Chinese drilled wells that produced both salt brine and natural gas. Natural gas was used to fuel burners placed under pans of salt brine. Once the water was evaporated away, large salt cakes were formed. Salt provided a very lucrative commodity and became a vital part of the Chinese economy. This simple backstory provides a starting point for a number of discussions relevant to the study of physics and chemistry. One can turn the discussion in a number of directions, including the chemistry of natural gas, boiling points of liquids, and geology. The physics behind the drilling method is used to illustrate the principle of energy conservation. As shown in the image above, a large drill bit is suspended by a cable. Adjacent to the drill bit are several horizontal boards, just above the ladder, which can rotate like a seesaw. Workers stand on the board to lift the drill bit above the ground. When they jump off the board, the bit falls, cutting into the rock and earth below. As the drill bit progresses down the bore hole, it is repeatedly lifted and dropped several meters above the bottom of the hole. The process is slow, but continuous drilling can produce wells hundreds of meters deep. In terms of mechanical energy, we can consider the gravitational potential energy that the drill bit acquires as a result of being lifted and the kinetic energy associated with the motion of the drill bit.

Gravitational potential energy is the energy an object acquires by virtue of lifting it above a reference position. The amount of gravitational potential energy an object gains is proportional to the mass of the object and its height above a specified reference. The higher the object is lifted, the more energy is gained. As the drill bit is raised above the bottom of the well, it increases its gravitational potential energy, with respect to the bottom of the bore hole.

Kinetic energy is the energy an object has by virtue of the fact that it is moving. This type of energy is proportional to the mass of the object and the square of the object's speed. If two objects have the same mass but move at different speeds, the faster object has more kinetic energy. The law of conservation of energy tells us that we can convert one form of energy into another in such a way as the total energy remains constant. When the drill bit falls, its gravitational potential energy is converted to kinetic energy. As it falls, the gravitational potential energy of the drill bit decreases and the kinetic energy increases. This kinetic energy is then released into crushing the material at the bottom of the well. If the bit falls without scraping the sides of the well, all the potential energy gained from the



Luopan needle attracted to a piece of magnetite.



Compass made in laboratory class, white mark on needle indicates south.

In our Western way of thinking, we automatically think of a compass needle pointing north, but in China, the principal direction is considered to be south.

lift is transferred into kinetic energy. Energy comes in many forms, including the chemical energy released by explosions.

A fun exercise we do in class is a calculation of the energy equivalent of the drill bit in terms of weight of explosive material such as TNT. It may take several years to drill a well. Power is the rate at which work is done, and we can calculate how much power is expended in drilling the well. All the calculations performed in this analysis are just like what I would do in a more traditional physics class, but they have the added feature of the amazing story of this ancient technology.

Magnetism is another area in which the Chinese excelled. Well before the publication of William Gilbert's comprehensive work *De Magnete* (1600), Song Dynasty scientist Shen Kuo tells us about south-pointing needles and how to build a compass. Shen's famous work *Dream Pool Essays*, published in 1088, not only gives a clear description of the magnetic compass but also contains the first known reference to magnetic declination. Shen tells us, "Diviners can make a needle point to the south by rubbing it with a magnetic stone. However, the needle often inclines to the southeast direction, not pointing to due south."[3] In our Western way of thinking, we automatically think of a compass needle pointing north, but in China, the principal direction is considered to be south. Of course, if one end of the needle is pointing to the south, then the other end must be pointing to the north. Facing south allows one to face the sun, a source of *yang* in the *yin-yang* principle. It is instructive to point out that the Chinese word for compass, *zhinanzhen,* literally means a south-pointing needle.

Magnetic declination is shown in the slight deflection to the east. This is an indication of the fact that true north and magnetic north differ. I use this observation as a steppingstone to introduce my students to a wide range of physical and astronomical concepts. I discuss the magnetic field of the Earth in terms of its interaction with the compass and also with the solar wind. It is well-known that the magnetic field of the Earth changes over time and that the position of the magnetic north pole has moved considerably over the past century. The generation of the Earth's field leads us to a discussion of the sources of magnetic fields and the magnetic fields produced by currents in wires. Most of our students think of the compass only as a navigational instrument. They are surprised to find that the earliest magnetic compass was the *luopan*, utilized for making measurements associated with *feng shui*. One of the objectives of this class is to explain technologies in their original historical context. That is, we try to understand different ways of knowing that are often far removed from the modern scientific method. It is not that we abandon scientific principles but rather that we try to understand how the ancients fit these phenomena into their understanding of the world. In the laboratory component of the class, we make a simple compass and use it as an instrument to measure the strength of the magnetic field produced by a long, straight wire. From the compass readings, we can graph the magnetic field strength as a function of the distance from the wire and as a function of the current through the wire. These graphs are compared to what we would expect from the theoretical expression for the field produced by a wire.

Wax model and finished ring made in bronze casting experiment.

I also cover units on astronomy, waves, optics, engineering, and materials science. Space constraints prohibit an in-depth discussion of these topics in this article. The unit on astronomy covers sunspots, solar wind, and other solar phenomena. The ancient Chinese studied the motion of comets and discovered that comet tails pointed away from the sun, which they attributed to the sun's *qi*. The introductory astronomy class at Mercer is well-equipped with portable telescopes and has access to several dark locations. Few people realize that the "modern" equatorial telescope mount owes its origin to ancient Chinese equatorial astronomical instruments. As part of the astronomy unit, I conduct several night labs in which students learn about telescopes and both Chinese and Western constellations.

Waves are studied with special emphasis on the physics of Chinese musical instruments. The *Guzheng* serves as a model for our study of wave phenomena. We study the effects of string tension, string length, wave velocity, and plucking position. Students are introduced to a wide range of Chinese stringed, wind, and percussion instruments that produce unfamiliar sounds. Although the instruments and their sounds are exotic, the underlying physical principles are the same.

Optics is explored by comparing statements in the *Mozi* to actual observations made with concave and convex mirrors. For example, in *Canon B23*, we are told that a concave mirror produces two images. One image is small and changed (inverted), and the other is large and upright. These observations are easily modeled using the mirror equation, which relates the image distance to the object distance and the focal length. We also explore the metaphysical aspects of mirrors that are found in Chinese culture.

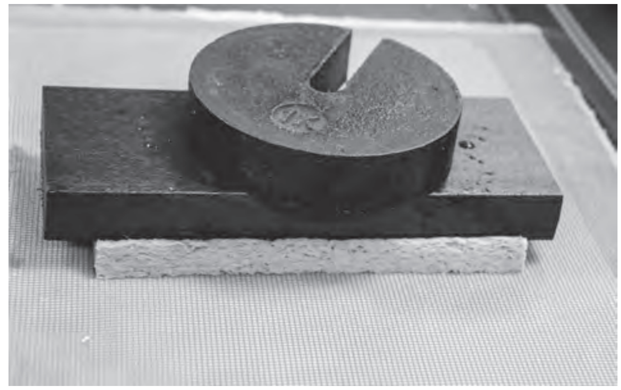
Our last unit covers engineering and materials science. In this unit, we explore lacquerware as an example of the first plastic. Porcelain, printing, and metallurgy are studied, with special emphasis on bronze casting. China has a long history of bronze casting, which makes a convenient starting point for discussions of materials properties. We discuss the basic properties of metals, the periodic table, and crystal structures. Bronze casting is also our final laboratory exercise. Each student in the class makes a small bronze object using the lost wax technique.

Laboratory Exercises

Ancient Chinese Science and Technology fulfills the laboratory science requirement for nonscience majors. We perform laboratory exercises related to papermaking, the steelyard balance, silk, magnetism, astronomy, standing waves, and bronze casting. Each laboratory experiment is designed to introduce students to analytical techniques, mathematical models, and experimental methods while studying an important ancient technology. In many cases, the students make something that they can take home and show their friends. The laboratory portion of the class is very extensive and full of details that are beyond the scope of a single article. It is my hope to publish a manual of laboratory exercises to aid in the development of similar classes.

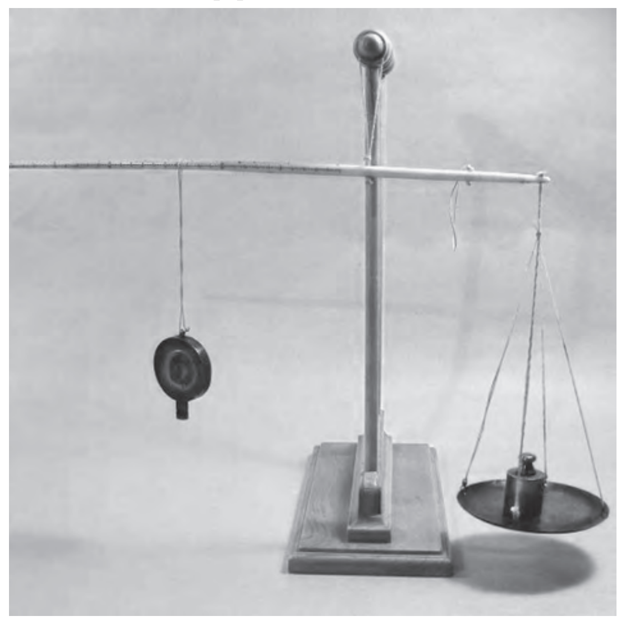
Measuring the thickness of handmade paper for statistical analysis.

Our first laboratory exercise is making paper. Paper is, of course, a major Chinese invention that has many uses in the modern world. In ancient times, paper was used for wrapping, padding, insulation, personal hygiene, money, windows, and even armor. I use papermaking to introduce measurement techniques, statistics, and graphical analysis. Handmade paper is not nearly as uniform as the machine-made paper we are accustomed to. In this experiment, students measure the thickness of their paper in several different places. From this data, they calculate the average thickness and standard deviation. During the papermaking process, a sponge is pressed against the paper to remove water. By altering the force applied to the sponge, one can change the thickness and smoothness of the paper. A weighted board placed on the sponge during drying provides a means for exploring the effect of drying pressure on the average thickness and the variation of the thickness. As each sheet of paper is formed, fiber is withdrawn from the pulp and the pulp becomes more watery. For each sheet of paper formed, the density of the pulp is measured. If each sheet is formed from the same volume of pulp, the resulting thickness decreases. Graphs are an important technique for determining if there is a relationship between two experimental variables. Students learn how to search for such relationships by graphing the thickness of the paper sheets as a function of the density, drying force, or the number of sheets produced. Students walk away from this lab with a nice collection of handmade paper and a greater understanding of experimental methods. The graphical analysis techniques they learn in this exercise are used in several other laboratory experiments.



Drying handmade paper with a weighted sponge to determine how drying force affects paper thickness.

The *cheng*, or steelyard balance, has been a marketplace fixture in China for over 1,000 years. Even with modern digital scales widely available, you still find vendors using the traditional balance. The principle behind the device is torque balance and static equilibrium. Students build a simple cheng out of PVC pipe. This laboratory exercise is designed to supplement our study of torque and force. Beyond learning about torque and force, the cheng experiment is also designed to illustrate random and systematic error. Students weigh a series of calibrated laboratory masses and compare their measurements to the known values. From this data, they plot a graph of the percent difference, or error, between their measurement and the known mass as a function of the calibrated mass. Since there is some friction in the fulcrum of the balance, the percent difference is not constant, but varies over the useful range of the device. At the low end of the range, the error values cluster, showing a systematic error. In other cases, the error values spread out and change signs, indicating a random error. Each lab group makes one cheng, which they are allowed to keep.



Antique Chinese steelyard balance. Source: *CollectingME.com* at http://tinyurl.com/h3ty95d.

These are just two examples of the way we explore an ancient technology using the modern scientific method. Nearly all our laboratory experiments involve making some object or device that the students get to keep. They often show their creations to their friends and find themselves teaching their friends some basic physics. Most of our students have very little hands-on experience, and they learn quite a bit about themselves as they try to build a simple device.

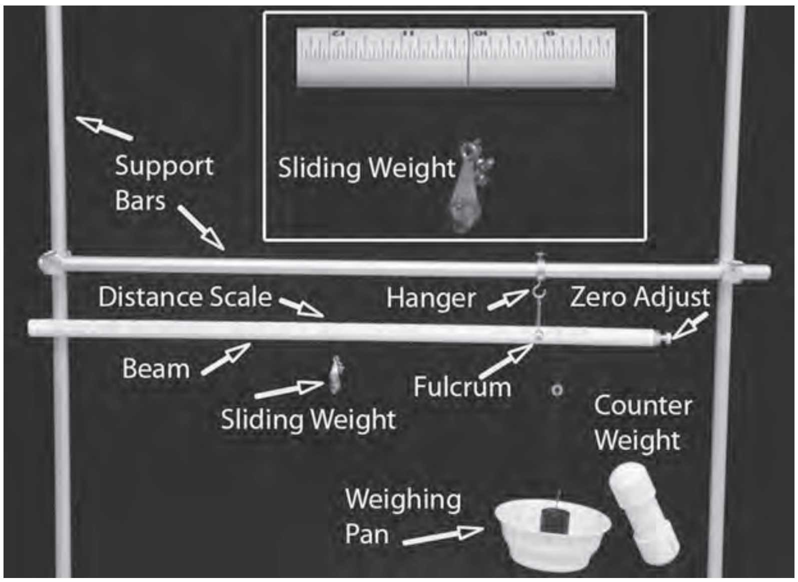
Students anonymously record their thoughts about the class at the beginning, midterm, and end of the semester. We are particularly interested to see how their ideas about the class develop over time. The evolution of their thought process is not explored in this article. A common thread is that they have learned a tremendous amount of material and enjoy the class even though it is challenging for them. These thoughts are reflected in the following comments:

Students building a cheng in the laboratory class.

This has easily been my favorite course that I've taken probably ever. It has been very rewarding and I have learned so much. Thank you for being so accepting of us business majors and I will miss this class.

We're only a few days in and this class is already mind-blowing. I think this will be a fun semester, though I'm a little afraid of the physics stuff. After all, I failed the first physics class I ever took and to this day it remains my only F.

This class has been one of the most challenging and unique classes that I have ever taken, even though my grade isn't what I would ideally want. I do not regret taking it and am thankful for all of the knowledge I will walk away with.



Cheng, or steelyard balance, made in laboratory class to illustrate torque balance.

That was fun! Really really fun. Sometimes it was trying and difficult, but never impossible. I really learned a lot about ancient China and old technology. Even if I don't make an A, at least I have that knowledge.

This class balanced the culture and math portions of the course. A great combination.

The course was very fun overall. I enjoyed the wide variety of content in the course, and having the ancient historical aspect accompany the physics made learning the material much easier. The labs were interesting, engaging, and quite fun. The material was interesting. The labs were fun, the tests were hard, and I am worried about the final.

Conclusions

As a colleague of mine once said, "Students vote with their feet." The class is becoming a popular alternative to more traditional laboratory classes. Since these students are not preparing for a career in science, I am satisfied with the amount of physics and related sciences they learn. Perhaps more importantly, they learn how to think, bring together facts from a wide range of disciplines, and overcome their fear of science. ■

NOTES

1. The question that Needham wrestled with is "Why did modern science, the mathematization of hypotheses about nature, with all its implications for advanced technology, take its meteoric rise only in the West at the time of Galileo [but] had not developed in Chinese civilization or Indian civilization?" See Joseph Needham, *Science and Civilization in China Vol. 7,* part 2*: The Social Background, General Conclusions and Reflections* (Cambridge: Cambridge University Press, 2004).
2. We follow the translation given by Ian Johnston, *The Mozi: A Complete Translation* (New York: Columbia University Press, 2010), 391.
3. We follow the translation given by Wang Hong and Zhao Zheng, *Brush Talks from Dream Brook* (UK: Paths International Ltd., 2011), 351.

MATTHEW MARONE (PhD, Clemson University) teaches Physics and Astronomy at Mercer University. In the early 1990s, he worked as a postdoctoral researcher at the Chinese Academy of Science in Beijing studying superconductivity. In addition to researching ancient technology, he works in the area of space mining. He has served as a consultant for NASA in projects related to Lunar and Martian resources.