David A. Thomas
Blue Ridge Torch Club, November 13, 2007
(Minor revisions from prior presentation to Frederick
Torch Club, February 23, 2004)

Galileo, Scientific Trailblazer

Introduction

Science has no beginning and no end, but it changed course drastically in the 16th and 17th centuries, led by Galileo Galilei (1564-1642) in Italy. To explain, I view science as one manifestation of human curiosity about the world in which we live. In the beginning, that curiosity took the form of religion and philosophy, however primitive. To find the necessary background for science in Galileo's time, we must go back to Aristotle and the Greeks

Aristotle's great writings charted the course of Western knowledge for almost 2000 years. His "natural philosophy" -- a rough equivalent for the science of the Greeks – strove to reveal the underlying causes of all things in nature. For example, ***local*** motion was caused by application of a force. Once the force no longer acted, motion ceased. Thus, if a body was set into motion, say by throwing a stone, the force was thought to travel with the stone. When the force ceased to act, the stone would fall vertically to the ground. The force acting on a falling body resulted from its weight, so that the heavier the body, the faster it would fall. Careful observations of earthly events were considered irrelevant to their causes, so tests of motion were simply not part of Aristotelian thinking.

Aristotelian cosmology held that ***celestial*** motions – the motions of the sun, planets, and stars -- were different, being caused by rotation of invisible spheres around the earth, with each body attached to one of the spheres. Improbable as these concepts of earthly and celestial motions seem to us today, they were integral parts of a comprehensive, enduring scheme of natural philosophy. Following Aristotle, Ptolemy refined astronomy but retained

Aristotle's earth-centered cosmology. Euclid, Archimedes, and others also made important and lasting contributions to mathematics and science.

A glimpse of the fertile times in which Galileo lived is seen from the coincidences that he was born the year that Michaelangelo died, the same year that Shakespeare was born, and Isaac Newton was born the year that Galileo died. Copernicus, Martin Luther, and Queen Elizabeth I of England were near-contemporaries, and universities were becoming well established. European exploration and settlement of the New World were in full swing.

In such times, it is not surprising that individuals were also questioning Aristotelian authority on the science of motion, which we know from historical records of the 16^{th} century. The scientific revolution soon began, with Galileo as perhaps its most important trailblazer.

Galileo's Studies of Motion

Galileo is rightly known for his telescopic observations of the solar system and for his studies of falling bodies, but his interests ranged widely. He studied magnetism, floating bodies, pumping of water, proposed a novel although incorrect theory of ocean tides, and produced an extensive body of results on the strength of structures. This latter was the first of his Two New Sciences, a book that is impressive even to today's scientists and engineers. It included a correct understanding of the comparative bone sizes of large versus small animals, and the reason that tubular beams are stronger than solid ones of the same weight. This concept applies equally to the bones of birds, which are both light and strong, and to bicycle frames, which are always made from tubes for the same reason.

However, Galileo's foremost interest, from at least as early as 1589 at Pisa, was simply ***motion***, the second of his Two New Sciences. In fact, Galileo's interest in the newly discovered telescope in 1609 was because it enhanced the ability to observe celestial motions. But Galileo's dramatic observations with the telescope were possible because of his skill in grinding superior glass lenses, and because his mind went beyond traditional thinking in grasping the significance of his observations. For example, he recognized that the craters seen on the surface of the moon were real, and not just visual artifacts as claimed by Aristotelians. These same traits of experimental skill and an inquiring mind were the hallmarks of Galileo's remarkable career.

Now let us pursue some of Galileo's studies of motion. His teachers at the University of Pisa were Aristotelians, as they were in virtually all universities. Several years later, then as a teacher at Pisa, he began to study falling bodies. He wrote about his work in de Motu (on Motion), but never published it. As was customary at the time, it was largely a commentary on Aristotelian thought.

But clearly his thinking changed. He carried out experiments with the free fall of bodies of different weights and materials, although it is doubtful that he actually performed the tests attributed to him at the Leaning Tower of Pisa. He found that studying free fall was difficult, since events took place so quickly that it was difficult to observe them. Already, though, he was thinking mathematically about falling bodies. His early idea was that the velocity of a falling body increased in direct ratio to the distance of fall, that is, doubling the distance of fall would double the velocity of the body. But we must note additional problems of the time in trying to describe motion. One was that 16th century thinking did not even conceive of velocity changing continuously; instead it was pictured as changing only by steps. Although Galileo eventually discarded this notion, it was not until the mathematics of calculus was invented by Newton and Leibniz a half-century later that continuous change could be treated mathematically. Second, any effort at all to describe motion was not worthy of study to Aristotelians, because it did not deal with causes.

Are these not examples of barriers to new ideas in any human endeavor? "Thinking the unthinkable" is difficult, until someone first thinks it!

Galileo was intrigued by the motions of pendulums. As we know from watching the pendulum swing of a grandfather clock, the motions are much slower than in free fall. He found that the time for a complete swing, the ***period***, did not measurably change as the pendulum weight was raised to different heights -- the faster swing from greater heights exactly compensated for the longer distance of the swing. He confirmed this by measuring the times for as many as 100 swings of a pendulum. He also found that the period increased as the pendulum was lengthened, and eventually found a simple mathematical relationship between length and period, in complete agreement with modern theory. He also realized over time that the slow fall of a pendulum weight should be related to free fall. Based on this, but by a circuitous route, he finally arrived at his trailblazing "time-squared law" of free fall. The occasion when Galileo realized this was uncovered by the noted Canadian historian of science, Stillman Drake (1910-1993), on page f.189v1 of Galileo's papers. Fortunately, most of his original working papers still reside in Florence at the Biblioteca Nazionale Centrale di Firenze.

Here is the time-squared law, as stated in <u>Two New Sciences</u>: "If a moveable descends from rest in uniformly accelerated motion, the spaces run through in any times whatever are to each other as the duplicate ratio of their times; that is, are as the squares of those times."

In modern language we say that the distance a body falls from rest is proportional to the square of the time. So if a body falls a unit of distance in one second, in 2 seconds it falls 4 units (the square of 2), in 3 seconds it falls 9 units (the square of 3), and so forth.

If you are a science cynic, you might ask, "So what? Why is that so special?" The answer is simply that this is the first recorded mathematical description of a natural phenomenon. Furthermore, the time-squared law is the ***correct*** description, and any other description is ***wrong***. Notice that the law just ***describes*** what happens in free fall, but says nothing about the ***cause***. Aristotelians objected vigorously to Galileo's findings because they saw that it presaged the overthrow of their unified natural philosophy of motion. Historians of science find that their resistance lasted into the 18^{th} century, but its demise was inevitable.

Galileo was bold in seeing the significance of his work, as he also wrote, "We bring forward a brand new science concerning a very old subject. There is perhaps nothing in nature older than MOTION, about which volumes neither few nor small have been written by philosophers; yet I find many essentials of it that are worth knowing which have not even been remarked, let alone demonstrated. ... there will be opened a gateway and a road to a large and excellent science of which these labors of ours shall be the elements, [a science] into which minds more piercing than mine shall penetrate to recesses still deeper."

Hardly a modest statement, but he was remarkably on target. Science has penetrated to recesses deeper than anyone could have imagined, with such notables as Newton, Darwin, Einstein, and countless others. Science continues to accelerate today, often with profound and unforeseeable consequences for our world.

After his breakthrough with the time-squared law, Galileo followed with a flood of theorems on motion, often leading to surprising and useful results. First, Galileo correctly deduced that the velocity in free fall was directly proportional to the elapsed time, rather than to the distance fallen, as he and others had previously thought. He then turned to motion along an inclined plane, where a ball would roll more slowly than it would fall vertically.

Suppose we hold a ball at waist height, say 3 feet, and drop it to the floor. The time of fall is easily calculated, but not easily measured, to be 0.43 second. Then suppose that we make a grooved inclined plane 24 feet long that starts at waist height and descends gently to the floor. For a ball rolling down the groove, Galileo proved mathematically in his usual ingenious way, using Euclidean geometric proportionalities rather than modern algebra or calculus, that the velocity reached at the floor level was exactly the same as the ball dropped from the waist reached at floor level. He also proved that the time of descent was in the ratio of 24 feet/3 feet, or 3.46 seconds, which he could measure by his heart pulse. By making repeated tests, he claimed an accuracy of one tenth of a pulse beat -- a claim that was verified by replicating his tests in 1961. Similarly, the time of descent could be determined for inclined planes of different slopes. They were consistent with his theory, thus giving confidence that the velocity predictions were correct. Although today we can measure velocities with radar, as we do for speeding cars or baseball pitches, Galileo had no way at all to measure velocities directly.

The inclined plane law enabled Galileo to observe trajectories in flight, by rolling a ball down the inclined plane, then onto a table for a short distance until it projected horizontally into space. After that, the ball moved forward at constant velocity, while simultaneously accelerating downward. By starting the ball from a greater height on the inclined plane, the ball reached a higher velocity and thus traveled farther in air before it struck the floor. The observed locations of the striking points confirmed that the trajectories were parabolic, in accord with Galileo's theory. He then proceeded to calculate with confidence the parabolic trajectories for projectiles launched at angles above horizontal. He proved, as is now well known, that the longest trajectory results from a launch angle of 45 degrees.

This is another instance that directly contradicts Aristotle, who said that only one type of motion was possible at a time, as we saw earlier. If an observer thought that a projectile went in a curved path, the error lay in the observation, since the underlying cause was to be believed rather than imperfect human experience. Thus we have another case in which Aristotelians disputed Galileo's science.

At this point, I need to add that Galileo did not explicitly describe his inclined plane experiments in Two New Sciences, as would be done in a scientific publication today. Instead he inferred that he made such experiments, and many historians of science believed that he should not be credited with experimental confirmation of his theories. However, Stillman Drake's meticulous examination of Galileo's working papers in Florence found unequivocal records of time measurements of inclined plane falls and pendulum swings.

Galileo's Two New Sciences was not formally published until 1638, although the time-squared law of free fall was used without proof six years earlier in Dialogue Concerning the Two Chief World Systems: Ptolemaic and Copernican. However, his work on motion was already known in learned circles in the early 1600s, when it was opposed, as we have seen, but also highly acclaimed.

In this paper we have taken a brief look at a new kind of science, which describes particular aspects of nature by what we now call "***laws***," but does not deal with cause in the Aristotelian sense. Through Galileo's extraordinary insight, mathematical talent, and experimental ability, he opened the door for science as we know it today.

Modern science continues as a growing body of knowledge, subject only to being extended, generalized, and at times replaced by later insights. Nevertheless, Galileo's science stands firm, and is it presented without correction in the above discussion. Yet within 50 years of the publication of Two New Sciences, his laws of motion were encompassed and generalized by Isaac Newton's great Principia.

Galileo and The Church

Galileo is most widely known for his conflict with the Roman Catholic Church over his belief in the sun-centered world system of Copernicus, proposed in 1543. Rather than make a futile attempt to settle a complex controversy here, I will just comment on some aspects of it.

By all accounts, Galileo was a devout Roman Catholic, and he did not publicly support the Copernican system (which, incidentally, had never been forbidden by the Church). In 1615, when Galileo's contributions to astronomy had brought him fame, he cited Cardinal Baronius (1538-1607) who said, "The Bible tells us how to go to Heaven, but not how the heavens go." Nevertheless, considerable evidence suggests that he believed the Copernican system was correct, despite the fact that it was not proved conclusively for another century. Galileo's opponents urged the Church to reprimand him, and in 1616, he was ordered not to "hold, defend, or teach that the sun is stationary and the earth moves." Accordingly, in 1632 he submitted his Dialogue to church authorities for approval before publication, and made revisions as requested. Nevertheless, the Dialogue ridiculed a character, cunningly named 'Simplicio,' for rejecting the hypothesis of the sun as the center of our planetary system.

Stillman Drake makes a good case that the Church finally brought Galileo to trial in 1633 at the urging of his Jesuit philosopher opponents, who continued to be committed Aristotelians. They had some justification because Galileo, while an eloquent writer and speaker, was also brash in dealing with critics. All parties — Galileo, the philosophers, and the Church -- were probably guilty of excess concerning his views. However, he professed throughout his career that science could never supplant faith, but that Biblical applications to science were inappropriate. Science was studying the natural world that God had created; science might illuminate God's world, but never in conflict with faith.

Galileo's famous trial took place when he was 69 years old. He was condemned for teaching the Copernican system, but he was not convicted of heresy. Notably, three members of the panel of ten Cardinals abstained from the verdict. The strictures were that he not publish any further writings, and that he remain under house arrest for life. Initially he was held in the Tuscan embassy in Rome, but at the urging of the ambassador he was moved briefly to Siena and finally to Florence, where he had lived and worked for many years. He was not closely watched and was allowed to have visitors. Undoubtedly with Galileo's approval, one visitor clandestinely took the manuscript for <u>Two New Sciences</u> and arranged for its publication in Holland.

Later, Galileo wrote this warning in his own copy of the <u>Dialogue</u>, "Take note, theologians, that in your desire to make matters of faith out of propositions relating to the fixity of sun and earth, you run the risk of eventually having to condemn as heretics those who would declare the earth to stand still and the sun to change position ... "

When Galileo became blind in his final years, a talented young student, Vicenzio Viviani, came to live and work with him. Over the objections of Viviani and others, Galileo was buried in 1642 in an obscure room in the church of Santa Croce in Florence. Viviani was determined to have Galileo's body moved to a place of honor, but it remained to Viviani's heirs to accomplish this in 1737. His final resting place is now marked by a large marble tomb to the right of the main entrance to Santa Croce, facing Michaelangelo on the opposite side of the church.

In 1835, the <u>Dialogue</u> was removed from the Index of Prohibited Books. In 1992, following ten years of study by a Papal Commission, Pope John Paul II endorsed Galileo's scientific philosophy and how the marvelous discoveries of science and technology have led "to that transcendent and primordial thought imprinted on all things." Today, both Galileo's science and his standing with the Church are secure. And with that, this brief tale of Galileo ends.

Selected Bibliography

James MacLachlan, Galileo Galilei, First Physicist. Oxford University Press (1997), 126 pages.

Dava Sobel, Galileo's Daughter, A Historical Memoir of Science, Faith, and Love. Walker Publishing Company (1999), Penguin Books (2000), 420 pages.

George Sim Johnston, The Galileo Affair, Scepter Press, Princeton, NJ, 10 pages.

Galileo, Two New Sciences, translated, with a new introduction and notes, by Stillman Drake, also including History of Free Fall: From Aristotle to Galileo. Wall & Emerson, (2000), 426 pages.

Galileo, Dialogue Concerning the Two Chief World Systems: Ptolemaic and Copernican, translated and with revised notes by Stillman Drake. The Modern Library (2001), 526 pages.

Stillman Drake, Galileo: A Very Short Introduction. Oxford University Press (1980), 127 pages.

George Sim Johnston, The Galileo Affair, Scepter Press, Princeton, NJ, 10 pages.

Optional, but recommended, for publication of this paper:

Life and Times of Galileo Galilei (1564-1642)

Some other notables: Aristotle (384-322 BC)
Leonardo Da Vinci (1452-1519)
Nicolaus Copernicus (1473-1543)
Michaelangelo Buonarroti (1475-1564)
Martin Luther (1483-1546)
Elizabeth I of England (1533-1603)
Isaac Newton (1642-1727)

1589	Starts teaching at the University of Pisa, begins to study falling bodies.
1592	Moves to the University of Padua.
1604-08	Discovery of "time-squared law" of free fall, and parabolic trajectories.
1609	Improves telescope invented in 1608 in Holland, lunar observations.
1610	Discovers phases of Venus and moons of Jupiter, appointed chief mathematician and philosopher to grand duke of Tuscany, Cosimo II.
1611	Elected to membership in the Lyncean Academy (founded in 1603).
1612	Publishes Bodies That Stay Atop Water or Move Within It, in Florence.
1616	Ordered not to "hold, defend, or teach that the sun is stationary and the earth moves."
1632	Publishes Dialogue Concerning the Two Chief World Systems: Ptolemaic and Copernican.
1633	Stands trial for heresy, instead is condemned. Dialogue is prohibited.
1638	Two New Sciences, published in Holland.
1835	Dialogue dropped from the Index of Prohibited Books.
1992	Following ten years of re-examination, Pope John Paul II endorses Galileo's scientific philosophy.