Physics Today

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Citation: Physics Today **65**(9), 36 (2012); doi: 10.1063/PT.3.1716
View online: http://dx.doi.org/10.1063/PT.3.1716
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/65/9?ver=pdfcov
Published by the AIP Publishing

Anatomy of a fall: Giovanni Battista Riccioli and the story of *g*

Christopher M. Graney

A centuries-old Latin text suggests that Earth's gravitational pull was first measured not by Galileo but by a little-known Italian astronomer and priest.

Every physics student learns about falling bodies and *g*, the acceleration due to Earth's gravitational field. But few physicists learn the story of the first experiments—now more than three centuries old—to measure *g*. That story begins in earnest with the famed Italian astronomer Galileo Galilei. In his 1632 tome, *Dialogue Concerning the Two Chief World Systems*, Galileo writes that

> the acceleration of straight motion in heavy [falling] bodies proceeds according to the odd numbers beginning from one. That is, marking off whatever equal times you wish . . . if the moving body leaving a state of rest shall have passed during the first time such a space as, say, an ell, then in the second time it will go three ells; in the third, five; in the fourth, seven, and it will continue thus according to the successive odd numbers. In sum, this is the same as to say that the spaces passed over by the body starting from rest have to each other the ratios of the squares of the times in which such spaces were traversed.[1]

To Giovanni Battista Riccioli—an astronomer, Jesuit priest, and fellow Italian—Galileo's claims were dubious, especially the assertion that an iron ball dropped from a height of 100 cubits took five seconds to reach the ground.[2] The ball seemed too heavy, and the time of fall too long, to be plausible. Plus, Galileo had provided few details about his experimental procedure.

So Riccioli conducted his own free-fall study. His experiments, which for the most part vindicated Galileo's theory, have come to be regarded by historians as the first precise measurements of *g*.[3–6] Although historians of science have discussed the experiments in some detail, Riccioli's own report has yet to be fully translated into a modern language. That remains the physics world's loss, for Riccioli's report on falling bodies tells the story of a remarkable experiment performed by a remarkable scientist.

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Almagestum novum

Riccioli's report is found in his encyclopedic 1651 treatise *Almagestum novum* (see figure 1).[7] It is a massive, influential work of more than 1500 oversized pages, densely filled with text and with occasional diagrams. It includes a finely detailed lunar map, shown in figure 2, that established our modern system of lunar nomenclature; information on the telescopic appearance of stars and planets; perhaps the earliest description of the Coriolis effect (reference 8; see also PHYSICS TODAY, August 2011, page 8); and an extensive discussion of the debate over heliocentrism versus geocentrism.

Riccioli was himself a geocentrist; he correctly figured that a rotating Earth should produce a Coriolis effect, but since the effect had not yet been detected, he took it as evidence that Earth was at rest.

Historian Edward Grant notes that unlike other geocentrists who

> were not scientists properly speaking but natural philosophers in the medieval sense using problems in Aristotle's *De caelo* and *Physics* as the vehicle for their discussions, Riccioli was a technical astronomer and scientist.[9]

Riccioli's scientific sensibility is apparent in *Almagestum novum*. The treatise is filled with extensive tables of experimental data, assessments of the data's agreement with particular models, and descriptions of how the data were obtained, so that anyone wishing to reproduce the work could do so. It reflects close, careful work, including a methodical study that led Riccioli to conclude that only small-amplitude oscillations of a pendulum are isochronous, whereas large-amplitude oscillations gradually increase their frequency as they decay.[10]

In describing Riccioli's efforts to construct a pendulum whose strokes would measure precise seconds—a standard pendulum against which quicker ones might be calibrated—historian Alexandre Koyré finely illustrates the Italian's near-obsessive concern for detail and accuracy:

> For six consecutive hours, from nine o'clock in the morning to three o'clock in the afternoon, he counts (he is aided by the R. P. Francesco Maria Grimaldi) the oscillations. The result is disastrous: 21,706 oscillations instead of 21,660. Moreover, Riccioli recognizes that for his aim the sundial itself lacks the wanted precision. Another pendulum is prepared and "with the aid of nine Jesuit fathers," he starts counting anew; this time—the second of April 1642—for twenty-four consecutive hours, from noon to noon: the result is 87,998 oscillations whereas the solar day contains only 86,640 [sidereal] seconds.[3]

Koyré goes on to describe a third attempt, this time with a pendulum just over 3 feet 4 inches long, slightly shorter than its predecessors. Riccioli discards the sundial, opting instead to use sidereal time, a more reliable standard based on the positions of the stars. The third trial, again a day long, ends with the pendulum having overcounted by 599 strokes, an error of less than 1%. At that point the yeoman's work begins to take its toll on Riccioli's colleagues, but as Koyré writes, Riccioli is neither satisfied nor dissuaded:

> Disappointed yet still unbeaten, Riccioli decides to make a fourth trial, with a fourth pendulum, somewhat shorter this time, of 3 feet, and 2.67 inches only. But he cannot impose upon his nine companions the dreary and wearisome task of counting the swings. Father Zeno and Father F. M. Grimaldi alone remain faithful to him to the end. Three times, three nights, the nineteenth and the twenty-eighth of May and the second of June 1645, they count the vibrations from the passage through the meridian line of the Spica (of Virgo) to that of Arcturus. The numbers are twice 3,212 and the third time 3,214 for 3,192 seconds.

History, however, has been ungenerous to Riccioli. Although Grant considers Riccioli's discussion on the mobility of Earth "probably the lengthiest, most penetrating, and authoritative analysis made by any author of the sixteenth and seventeenth centuries,"[11] many historians dismiss it as an assessment of the quantity of arguments rather than their quality. They charge Riccioli with invoking religious authority instead of science—even though *Almagestum novum* reveals the contrary to be true[12]—or they portray the Jesuit priest as an undercover scientist who hid his true thinking for religious reasons.[13]

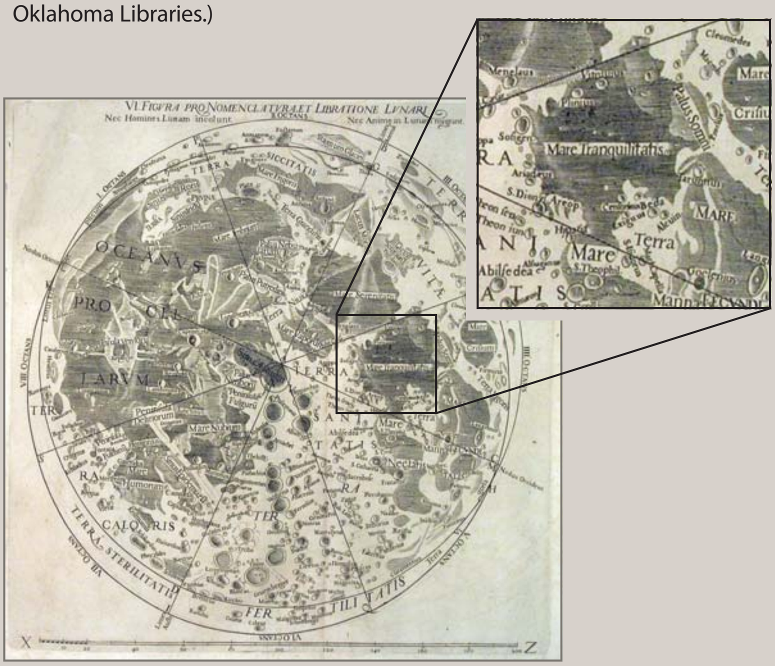
Free falling

Almagestum novum was written during a time when the mere idea that a body gains velocity as it falls

ALMAGESTVM NOVVM
ASTRONOMIAM VETEREM NOVAMQVE COMPLECTENS
OBSERVATIONIBVS ALIORVM, ET PROPRIIS
Nouisque Theorematibus, Problematibus, ac Tabulis promotam,
IN TRES TOMOS DISTRIBVTAM
QVORVM ARGVMENTVM
Sequens pagina explicabit.
AVCTORE
P. IOANNE BAPTISTA RICCIOLO
SOCIETATIS IESV
FERRARIENSI
Philosophiæ, Theologiæ, & Astronomiæ professore.
BONONIÆ
Ex Typographia Hæredis Victorij Benatij M DC LI.
SVPERIORVM PERMISSV.

Figure 1. *Almagestum novum*, a 1500-page treatise by the Italian astronomer and theologian Giovanni Riccioli, covers topics as diverse as lunar cartography, planetary motion, and the acceleration of free-falling bodies. At left is the book's title page, and at right is its frontispiece. The topmost images in the frontispiece allude to telescopic discoveries of the phases of Mercury and Venus and of Jupiter's cloud bands and moons. The center depicts the debate over heliocentrism versus geocentrism. Weighing down the right side of the scale is Tycho Brahe's geocentric theory, in which the Sun orbits Earth and the planets orbit the Sun. (At the time, the theory was compatible with previous telescopic discoveries.) Ptolemy's already-discredited geocentric theory, in which planets orbit Earth, lies discarded below. (Images courtesy of the History of Science Collections, University of Oklahoma Libraries.)

Figure 2. The detailed lunar map found in *Almagestum novum* established the modern system of lunar nomenclature. Giovanni Riccioli named broad features of the lunar surface after weather phenomena and specific craters after accomplished astronomers. Among the features named by Riccioli is *Mare Tranquillitatis* (Sea of Tranquility), famed landing site of *Apollo 11*. (Images courtesy of the History of Science Collections, University of Oklahoma Libraries.)



was still a matter of dispute. And so Riccioli opens his report with a review of common experiences and literary anecdotes that support the notion of an acceleration due to gravity: A ball dropped on a metal bowl from a height of 20 feet yields more noise than a ball dropped from 10 feet; a ball dropped from a great height stings the hand when caught, but one dropped from a small height does not; in mythology, the eagle that killed Aeschylus by dropping a turtle on his head instinctively knew that height increases the force of impact; a ball dropped from a greater height rebounds to a greater height.[14]

Next, Riccioli gets down to the business at hand, "the measuring of the space which any heavy body traverses in natural descent during equal time intervals." He describes the experiment in exquisite detail, should anyone care to repeat it:

> [Previously] I calibrated pendulums of various lengths using the transit of fixed stars through the middle of the heavens. For this experiment I have selected the smallest one, whose length measured to the center of the little bob is one and fifteen hundredths of the twelfth part of an old Roman foot, and a single stroke of which [that is, a half period] equals one sixth of a second, as I have shown and set forth in book 2 chapter 21. As a single second exactly equals six such strokes, then one single stroke is nearly equal to that time with respect to which the notes of semichromatic music are usually marked, if the choirmaster directs the voices by the usual measure.
>
> The oscillations or strokes of so short a pendulum are very fast and frequent, and yet I would accept neither a single counting error nor any confusion or fallacious numbering on account of the eye. Thus our customary method was to count from one to ten using the concise words of the common Italian of Bologna (*vn, du, tri, quatr, cinq, sei, sett, ott, nov, dies*), repeating the count from one, and noting each decade of pendulum strokes by raising fingers from a clenched hand. If you set this to semichromatic music as I discussed above, and follow the regular musical beat, you will mark time as nearly as possible to the time marked by a single stroke of our pendulum. We had trained others in this method, especially Frs. Francesco Maria Grimaldi and Giorgio Cassiani, whom I have greatly employed in the experiment I shall now explain.
>
> Grimaldi, Cassiani, and I used two pendulums; Grimaldi and Cassiani stood together in the summit of the Asinelli Tower, I on the pavement of the underlying base or parapet of the tower; each noted separately on a leaf of paper the number of pendulum strokes that passed while a heavy body was descending from the summit to the pavement. In repeated experiments, the difference between us never reached one whole little stroke. I know that few will find that credible, yet truly I testify it to have been thus, and the aforementioned Jesuit fathers will attest to this.

Riccioli then describes the various locations used for the experiment, giving special attention to the Asinelli Tower (see figure 3):

> [It] is 312 feet high altogether, and 280 feet from the summit to the base or parapet. The Asinelli is as commodious as possible to this sort of experiment, just as if it might have been constructed for this purpose. It is a delight to the eye.

A measure of gravity

In the end, the experiment largely vindicated Galileo's ideas about falling bodies. Riccioli's data, presented in figure 4, show that a ball falls 15 Roman feet (Rmft) in one second, 60 Rmft in two seconds, 135 Rmft in three seconds, and so on—the distance increases as time squared. Riccioli himself did not calculate g per se, but a fit of his data to the appropriate free-fall equation, $d = gt^2/2$, yields $g = 29.8 \pm 0.7$ Rmft/s^2 (see figure 5). Here, d is distance and t is time. Modern-day measurements[15] show that the Asinelli Tower—described by Riccioli as having a height of 312 Rmft—stands at 98.37 m, so Riccioli's Roman foot was probably close to 0.301 m. His g, then, would translate to 9.36 ± 0.22 m/s^2, about 5% off from today's accepted value, $g = 9.8$ m/s^2.

Riccioli also calculated the incremental distances traveled by a falling body for successive, regular time intervals. That distance, the average velocity in a given interval, grew linearly with time, following the same sequence of odd numbers that had been prescribed by Galileo—the ball falls one unit distance in the first unit of time, three in the second, five in the third, and so forth.

The pattern was remarkably consistent—and, to Riccioli, remarkably surprising. His own expectation had been that velocity should grow not linearly but exponentially, a misconception that he addresses frankly in *Almagestum novum*[14]:

> I did not understand or recognize the proportion of the growth of the velocity of heavy bodies related by Galileo in the second day of his dialogue of the system of the world, and asserted by him to be following odd numbers begun from unity. . . . I suspected it to be continually triple, as in these numbers: 1, 3, 9, 27.
>
> Yet still later the opportunity was granted to me of reading Galileo's dialogues, which the Holy Congregation of the Index had prohibited. I found in the dialogues on page 217 of the Italian or 163 of the Latin the aforementioned growth, discovered by experiment, to be following simple odd numbers from unity, as in 1, 3, 5, 7, 9, 11, etc. Still, I was suspecting something fallacious to lurk in the experiments of Galileo, because in the same dialogue, following page 219 of the Italian, 164 of the Latin, he asserts an iron ball of 100 Roman pounds released from an altitude of 100 cubits reaches the ground in 5 second's time. Yet the fact was that my clay ball of 8 ounces was descending from a much greater altitude . . . (280 feet, which is 187 cubits) in precisely 26 strokes of my pendulum: 4 and 1/3 seconds time. I was certain that no perceptible error existed in my counting of time, and certain that the error of Galileo resulted from times not well calibrated against transits of the fixed stars—error which was then transferred to the intervals traversed in the descent of that ball. Furthermore, I was scarcely believing that Galileo had been able to use an iron ball of such great weight, especially when he did not even name the tower from which he might have arranged for such a ball to be released.

Figure 3. The Asinelli Tower, which Giovanni Riccioli considered to be "as commodious as possible" to falling-body experiments, stands nearly 100 m above the heart of Bologna, Italy. **(a)** Riccioli's sketch illustrates his experimental findings: A ball dropped from the tower's summit, point O, reaches points C, Q, R, S, and T in times corresponding to 5, 10, 15, 20, and 25 pendulum strokes, respectively. (Image from ref. 14.) **(b)** A photo shows the tower as seen today.

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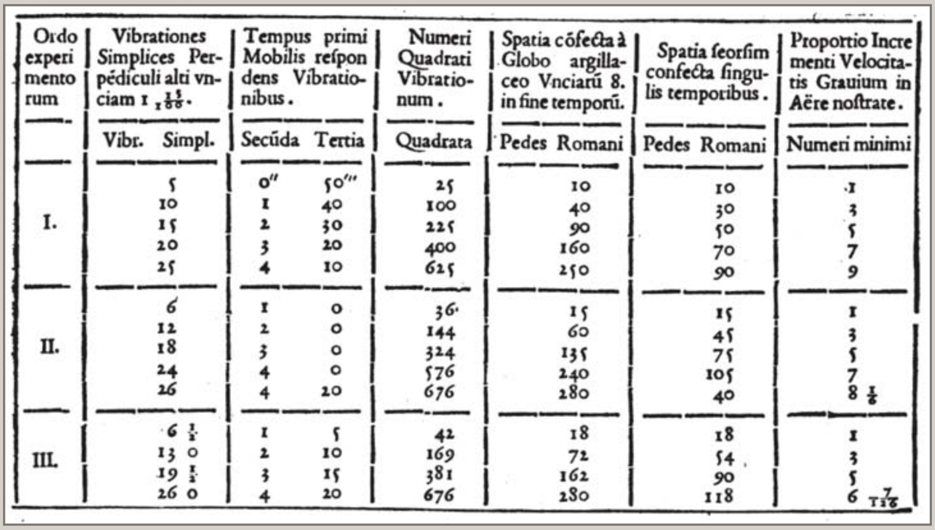
> And so, full of this suspicion, I began exacting measure of this growth. . . . I hoped to contrive my own idea about this that was nearer to the truth; but rather I have in fact discovered to be true that which Galileo asserted. And indeed as I set forth in the preceding experiment, I have acknowledged the growth to follow the proportion of 10, 30, 50, 70, 90 feet, which expressed in smallest numbers is just 1, 3, 5, 7, 9.

And, having found Galileo to be right,

> Fr. Grimaldi and I went to talk to the distinguished Professor of Mathematics at the Bologna University, Fr. Bonaventure Cavalieri, who was at one time a protégé of Galileo. I told him about the agreement of my experiments with the experiments of Galileo, at least as far as this proportion. Fr. Cavalieri was confined by arthritis and gout to a bed, or to a little chair; he was not able to take part in the experiments. However it was incredible how greatly he was exhilarated because of our testimony.

Elsewhere in *Almagestum novum*, Riccioli goes on to describe free-fall experiments with balls of



Ordo experimentorum	Vibrationes Simplices Perpédiculi alti vnciam 1 15/60.	Tempus primi Mobilis respondens Vibrationibus.		Numeri Quadrati Vibrationum.	Spatia cõfecta à Globo argillaceo Vnciarũ 8. in fine temporũ.	Spatia seorsim confecta singulis temporibus.	Proportio Incrementi Velocitatis Grauium in Aëre nostrate.
	Vibr. Simpl.	Secũda	Tertia	Quadrata	Pedes Romani	Pedes Romani	Numeri minimi
I.	5	0″	50‴	25	10	10	1
	10	1	40	100	40	30	3
	15	2	30	225	90	50	5
	20	3	20	400	160	70	7
	25	4	10	625	250	90	9
II.	6	1	0	36	15	15	1
	12	2	0	144	60	45	3
	18	3	0	324	135	75	5
	24	4	0	576	240	105	7
	26	4	20	676	280	40	8 $\frac{1}{6}$
III.	6 $\frac{1}{2}$	1	5	42	18	18	1
	13 0	2	10	169	72	54	3
	19 $\frac{1}{2}$	3	15	381	162	90	5
	26 0	4	20	676	280	118	6 $\frac{7}{18}$

Figure 4. Free falling. Judging by this table from *Almagestum novum*, Giovanni Riccioli measured the free-fall time, from release to impact, for objects dropped from three different heights. He then dropped a ball from various heights that, per Galileo Galilei's prediction, would yield multiples of those free-fall times. A final drop was from the top of the Asinelli Tower. In the end, Riccioli's experiment confirmed Galileo's idea that free-fall distance increases as time squared. The columns show, from left to right, the experiment number; the free-fall time in pendulum strokes; the free-fall time in seconds (″) and sixtieths of seconds (‴); the square of the free-fall time, in pendulum strokes; the total free-fall distance; the incremental free-fall distance; and the normalized incremental free-fall distance. (Image from ref. 14.)

various weights and sizes—experiments that were designed to tease out the effects of air resistance and that led him to the conclusion that smaller and less dense balls are most affected by air.[16] Then it is on to bodies falling through water, and more.

A model scientist

Riccioli set a fine example for all the free-fall experiments that would follow. He was thorough. He provided an extensive description of his experimental procedure. He gathered data of sufficient quality to assess accurately the model in question.

But Riccioli's work is also a standard of scientific integrity: He had set out expecting to disprove Galileo, but even when his experiments vindicated Galileo, he made a point of promptly sharing the news with an interested colleague. His attitude, like his experiment, was that of a fine scientist.

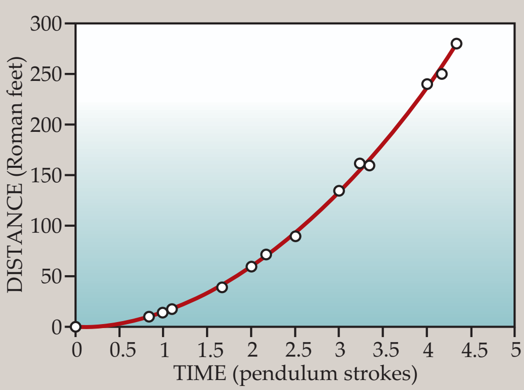


Figure 5. Giovanni Riccioli's data, plotted here, provide sufficient information to calculate *g*, the acceleration due to Earth's gravitational field. (A pendulum stroke corresponds to 1/6 s.) A fit to the function $d = gt^2/2$, where d is the fall distance and t is time, yields $g = 29.8 \pm 0.7$ Roman ft/s^2, or 9.36 ± 0.22 m/s^2, which is about 5% off from today's accepted value of 9.8 m/s^2.

I thank Christina Graney for her most valuable assistance in translating Riccioli's writings from Latin.

References

1. G. Galilei, *Dialogue Concerning the Two Chief World Systems: Ptolemaic and Copernican*, S. Drake, trans., Modern Library, New York (2001), p. 257.
2. Ref. 1, p. 259.
3. A. Koyré, *Proc. Am. Philos. Soc.* **97**, 222 (1953), p. 230.
4. A. Koyré, *Trans. Am. Philos. Soc.* **45**, 329 (1955).
5. D. C. Lindberg, R. L. Numbers, eds., *God and Nature: Historical Essays on the Encounter Between Christianity and Science*, U. California Press, Berkeley (1986), p. 155.
6. J. L. Heilbron, *The Sun in the Church: Cathedrals as Solar Observatories*, Harvard U. Press, Cambridge, MA (1999), p. 180.
7. G. B. Riccioli, *Almagestum novum astronomiam veterem novam que complectens . . .*, Bologna, Italy (1651).
8. C. M. Graney, *Phys. Perspect.* **13**, 387 (2011).
9. E. Grant, *Trans. Am. Philos. Soc.* **74**, 1 (1984), p. 12.
10. D. B. Meli, *Thinking with Objects: The Transformation of Mechanics in the Seventeenth Century*, Johns Hopkins U. Press, Baltimore, MD (2006), p. 131.
11. E. Grant, *Planets, Stars, and Orbs: The Medieval Cosmos, 1200-1687*, Cambridge U. Press, Cambridge, UK (1996), p. 652.
12. C. M. Graney, *J. Hist. Astron.* **43**, 215 (2012).
13. A. Dinis, in *Giambattista Riccioli e il merito scientifico dei gesuiti nell'età barocca*, M. T. Borgato, ed., L. S. Olschki, Florence, Italy (2002), p. 49.
14. See ref. 7, vol. 2, p. 384. For an English translation, see C. M. Graney, http://arxiv.org/abs/1204.3267.
15. E. Bertacchini, E. Boni, A. Capra, C. Castagnetti, M. Dubbini, "Terrestrial Laser Scanner for Surveying and Monitoring Middle Age Towers," presented at 24th FIG International Congress, 11–16 April 2010. Available at http://www.fig.net/pub/fig2010/ppt/ts04d/ts04d_capra_bertacchini_et_al_ppt_4445.pdf.
16. See ref. 7, vol. 2, p. 387. For an English translation, see C. M. Graney, http://arxiv.org/abs/1205.4663v1. ■