Learning about Scientific Methodology and the "Big Picture" of Science: The Contribution of Pendulum Motion Studies

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A common feature of contemporary science education reforms around the world is the prominence they give to "Learning About the Nature of Science." In numerous national documents, "science literacy" is deemed to mean knowing some appropriate amount of science, and additionally knowing something about science — its history, philosophy and interrelations with society, commerce, technology and culture. In other words, students should learn something of the "Big Picture" of science.[1] The United States National Science Education Standards, for instance, say that "Scientific literacy also includes understanding the nature of science, the scientific enterprise, and the role of science in society."[2]

Undoubtedly an important part of the "big picture" is the methodology of science. Although often confused with the method of science, or worse, with "process" skills, methodological matters are at heart epistemological and should be separated from method or process skills. The latter can usefully be thought of as skills in obtaining data, or taking measurements. Methodology pertains to how to interpret data and how to appraise its bearing upon claims to knowledge.

Appreciation of methodology can be realized in classrooms if the common and routine topic of pendulum motion is taught in a manner that is cognizant of its history and its philosophy. In particular, the seventeenth century debates about pendulum motion, specifically between Galileo and his patron Guidobaldo del Monte, provide exemplary material for deepening students' epistemological awareness.

The Contribution of the Pendulum to the Scientific Revolution

The pendulum played a pivotal role in the scientific revolution. Among other things, the pendulum provided the first effective measure of time, without which modern quantitative mechanics (as distinct from statics that depended just on length and weight measures) would be impossible. Stillman Drake identifies Galileo's discovery of the pendulum laws as "marking the commencement of the early modern era in physics."[3]

Galileo used pendulum motion to establish his law of free fall, his law of conservation of energy, and to undermine the crucial Aristotelian conceptual distinction between violent and natural motions. In a letter of 1632, Galileo surveyed his achievements in physics and recorded his debt to the pendulum for enabling him to measure the time of free-fall, which, he said, "we shall obtain from the marvellous property of the pendulum, which is that it makes all its vibrations, large or small, in equal times."[4]

The pendulum played a comparable role in Newton's work. He used the pendulum to determine the gravitational constant g, to improve timekeeping, to disprove the existence of the mechanical philosophers' aether presumption, to show the proportionality of mass to weight, to determine the coefficient of elasticity of bodies, to investigate the laws of impact, and to determine the speed of sound.

Surprisingly the importance of the pendulum for the scientific revolution has not been widely recognized. One exception is the historian Richard Westfall who did acknowledge that: "the pendulum became the most important instrument of seventeenth-century science...Without it, the seventeenth century could not have begot the world of precision."[5] Concerning the pendulum's role in Newton's science, Westfall has said, "It is not too much to assert that without the pendulum there would have been no *Principia*."[6] No small commendation.

Epistemology and the Analysis of Pendulum Motion

Understanding the methodological innovation of the scientific revolution is especially important for theories of knowledge, or for epistemology. An epistemology that pays no attention to the scientific revolution, or is at odds with its achievements and its methodological innovations, is at best ill-nourished and at worst irrelevant — this, unfortunately has been the case with a good deal of epistemology in the analytic tradition of philosophy.

The view that epistemological theories should be developed with cognizance of the methodology of science has a long and distinguished heritage, going back at least to Bacon, Spinoza and Locke in the seventeenth century, and including Kant in the eighteenth century, Whewell in the nineteenth century, and Karl Popper and many others in the twentieth century. All these philosophers thought it incumbent upon them to articulate their theories of knowledge in the light of their understanding of the new science of Galileo and Newton. Popper is perhaps the best known twentieth-century advocate of the position, saying that: "The central problem of epistemology has always been and still is the problem of the growth of knowledge. *And the growth of knowledge can be studied best by studying the growth of scientific knowledge*."[7]

Having this nexus between epistemology and science and, subordinately between epistemology and the history of science, is not, of course, without its problems. It is easy to misunderstand the science from which one is to draw epistemological lessons; the history itself is affected by prior methodological commitments of the historian; the scientific episode examined may not be representative of science; and, finally, science itself moves on, its methods and methodologies change, and philosophers can be left drawing epistemological lessons from an obsolete science.[8]

These difficulties are pronounced when delineating the methodological achievements of the scientific revolution and trying to have epistemological theories fit those achievements. There are many "readings" or interpretations of the scientific revolution.[9] And grasping the mix of experiment, mathematics, *apriorism*, philosophy and empiricism that characterized the achievements of Galileo and Newton is notoriously difficult — Bacon, for example, did not think that Galileo had much to offer the new science, and Spinoza valued Descartes' mechanics far more than Galileo's. There has been, predictably enough, a large element of Pygmalian projection onto Galileo. Many have noted that a good clue to a commentator's own epistemology is the epistemology they attribute to Galileo.[10]

Mindful of this natural tendency to, as Francis Bacon put it, "believe most what we want to believe," nevertheless it is possible to both delineate Galileo's epistemological position and, four hundred years later, draw lessons from it for a better understanding of the methodology and epistemology of science.[11] This can well be done by comparing Galileo's and del Monte's differing account of pendulum motion. Further, this great methodological debate that took part at the birth of the modern intellectual world is accessible to students if their pendulum motion lessons are conducted in a manner that is informed by the history and philosophy of the topic.

Galileo's Idealizations and the Beginning of Modern Science

Galileo's marvellous mathematical proofs of the pendulum's properties — that period was independent of weight, that period was independent of amplitude, that period varied directly as the square root of length, and that oscillations were isochronic[12] — did not receive universal acclaim. On the contrary, learned scholars were quick to point out substantial empirical and philosophical problems with them. Guidobaldo del Monte and others repeatedly pointed out that actual pendula do not behave as Galileo maintained.[13] Galileo never tired of saying that *ideal* pendula would obey the mathematically derived rules. Del Monte retorted that physics was to be about this world, not an imaginary mathematical world. The claim of isochronic motion, for instance, was plainly inconsistent with the observational fact that pendula ceased swinging after a certain number of oscillations.

The empirical problems were examples where the world did not "correspond punctually" to the events demonstrated mathematically by Galileo. In his more candid moments, Galileo acknowledged that events do not always correspond to his theory; that the material world and his so-called "world on paper," the theoretical world, did not correspond. For instance, immediately after mathematically establishing his famous law of parabolic motion of projectiles, he remarked that:

> I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola.[14]

The law of parabolic motion was supposedly true, but not of the world we experience: this was indeed as difficult to understand for del Monte as it is for present-day students. Furthermore it confounded the Aristotelian methodological principle that the evidence of the senses is, with some qualifications, paramount in ascertaining facts about the world. That is, with a healthy observer, in a normal situation, what the eyes see is what is the case.

Idealization and Counter-Evidence

There is a vexing *methodological* problem presented here. Galileo needed to introduce idealizations in order to move beyond Aristotle's science, and in order to have a physics that could be represented mathematically: inclined planes represented as straight lines, weights on balances represented as parallel lines, projectile flight represented as a parabola. Galileo was right to discount perturbations and accidental factors, and to keep his eye on what he regarded as the salient features, or essential properties, of the situation. This is so clearly evident in his historic claim that projectiles follow a parabolic path.

Galileo is not deterred by the "perturbations," "accidents," and "impediments" that interfere with the behavior of the free falling, rolling, and projected bodies with which his New Science is dealing.[15] His procedure is explicitly stated immediately after the above disclaimer about the behavior of real projectiles in contrast to his ideal ones. Galileo says:

> Of these properties [*accidenti*]…infinite in number, it is not possible to give any exact description; hence, in order to handle this matter in a scientific way, it is necessary to cut loose from these difficulties; and having discovered and demonstrated the theorems, in the case of no resistance, to use them and apply them with such limitations as experience will teach.[16]

There is, however, a problem of idealization hiding fundamental mechanisms in the world. Keeping one's eye on the essential property is scientifically commendable, provided that it is the essential property, and that concentration on it does not blind one to other significant influences or properties. Galileo was scientifically blind when he held his conviction about the isochrony of circular motion. He dismissed experimental deviations as "accidents," saying they were due to air resistance, friction, compounding effect of the weight of the string. Some of the deviation was accidental, but not all of it. The core deviation of experiment from theory was because the theory was wrong: it was the cycloid, not the circle that was isochronous.[17]

Undoubtedly there was an element of metaphysics in Galileo's adherence to the circle as the tautochrone, or non-vertical curve of quickest descent. The same conviction perhaps that led him to discuss and defend Copernicus's theory of *circular* planetary orbits, despite Kepler's *elliptical* refinement of Copernicus's views being published in 1619, fourteen years before Galileo's great *Dialogue*, and Galileo having a copy of the work in his library. The same conviction perhaps led Galileo to the doctrine of *circular* inertia.[18]

The empirical discrepancies between circular and isochronic motion were not great. For small amplitudes (less than 2°) a circular path was almost identical to a cycloid, and thus small amplitude circular pendulums were nearly isochronic (other distorting factors being excluded). A circular pendulum with an amplitude of 5° gained 41 seconds per day, one of 6° gained 59 seconds, and one of 12° gained 236 seconds.[19]

Whatever its source, it would have been easy, and acceptable, to attribute the non-isochrony of Galileo's pendulums to "accidental" factors, thus maintaining the circular path of the free moving pendulum as the basis of the pendulum clock. This was *nearly* correct, but no matter how much it was refined it would not yield an accurate timekeeper.[20] The theory was wrong. But of course this is not always the case. Sometimes data are corrupted, mistaken or in other ways flawed and thus to be discarded or ignored.

Observation, Theory, and Experiment

The crucial methodological point at issue in the Galileo-del Monte debates over pendulum motion, a point which is characteristic of the whole Galilean-Newtonian methodology, is captured in Richard Westfall's observation that:

> Beyond the ranks of historians of science, in my opinion, the scientific revolution is frequently misunderstood. A vulgarized conception of the scientific method, which one finds in elementary textbooks, a conception which places overwhelming emphasis on the collection of empirical information from which theories presumably emerge spontaneously, has contributed to the misunderstanding, and so has a mistaken notion of the Middle Ages as a period so absorbed in the pursuit of salvation as to have been unable to observe nature. In fact medieval philosophy asserted that observation is the foundation of all knowledge, and medieval science (which certainly did exist) was a sophisticated systematization of common sense and of the basic observations of the senses. Modern science was born in the sixteenth and seventeenth centuries in the denial of both.[21]

Children have the same difficulty seeing the properties of pendulum motion that the sixteenth century Aristotelians had. Even with highly refined school laboratory pendulums, they do not see isochrony of large and small amplitude swings, and their cork pendulums soon cease swinging, whilst the brass ones continue much longer. All of this experiential evidence is hard to reconcile with the "laws" of pendulum motion. Children can either think they are stupid and need to take everything on authority, or they can conclude, as one German student did in a recent survey that "physics is not about the world."[22] This is a case of children being in the position of the early pioneers of a science. No amount of looking will reveal isochronic motion. Looking is important, but something else is required, namely a better appreciation of what science is and what it is aiming to do, an epistemology of science.

Laura Fermi and Gilberto Bernardini draw attention to the same methodological point regarding the centrality, for Galileo's science, of abstracting from everyday experience. They put the matter this way:

> In formulating the 'Law of Inertia' the abstraction consisted of imagining the motion of a body on which no force was acting and which, in particular, would be free of any sort of friction. This abstraction was not easy, because it was friction itself that for thousands of years had kept hidden the simplicity and validity of the laws of motion. In other words friction is an essential element in all human experience: our intuition is dominated by friction.[23]

Koyré draws out this Kantian moral concerning experiment, and its role in the development of science,[24] when he writes:

> [O]bservation and experience — in the meaning of brute, common-sense observation and experience — had a very small part in the edification of modern science; one could even say that they constituted the chief obstacles that it encountered on its way.… [T]he empiricism of modern science is not *experiential*; it is *experimental*.[25]

These epistemological considerations are not irrelevant to education. Some accounts of teaching for students' conceptual change in science, especially accounts proferred by constructivists, innocently maintain that it is discrepant *events* or *phenomena* that students need to be confronted with in order to change their understandings. The foregoing account of experimentation, and its role in the development of science, suggests that this pedagogical strategy is almost precisely the wrong one. School experiments rarely work, and when they do, the phenomena exhibited are most likely to *confirm* wrong ideas, and *falsify* the correct scientific formulation.

DATA, PHENOMENA, AND THEORY

Nearly all of the foregoing considerations point towards the importance of distinguishing data from phenomena, and both of these from theory. The data are observed, phenomena characteristically are not. Scientific laws and theories are about the phenomena, not about the data.[26] If this is understood, a number of things about science, and especially studies of pendulum motion, become clearer.

Real objects (processes, events, occurrences, states) are observed either in natural (Aristotle's preference) or experimental settings (Galileo's preference). The observation can be immediate (with eyes, microscopes) or inferred (meter readings, instrument displays). All of this occurs in the realm of the real, not the realm of discourse. The observations are then verbalized, described, written, or tabulated. This has to be done in a language (including mathematics), and according to some theoretical standpoint. This is all done in the realm of discourse. These descriptions are characteristically sifted, sorted and selected — lots of readings and descriptions are simply thrown away, or ignored. The result is scientific data. These then are the raw representations of real objects (processes, events, occurrences, states). This step is clearly theory dependent. A range of falling red apples, or swinging weights on a string are, in physics, represented as points on a graph, as printouts on a tickertape, as lines on a screen. These representations are not meant to mirror, or copy, the real. They are precisely meant to represent the real. Adequacy of representation simply does not mean correspondence of representation, in the sense of the representation mirroring the object.

Scientific representations can change. Leonardo represented the pendulum diagrammatically, Galileo and Huygens represented it in geometric form, Newton represented it algebraically. The variously theorized pendulums are not meant to correspond to real objects: What does it mean for a sentence to correspond to a real object? For a point to correspond to an apple? Likewise the idea of a group's average age may not correspond to anything, in the sense that no one may be the average age. Yet the notion of a group's average age, weight, intelligence, longevity etc. is perfectly respectable and usable, and is the "thing" that social scientific theories have to explain, and are judged against. Representations are in the domain of discourse, and are separate from the domain of the real. Thus they cannot, in any serious sense, mirror or correspond to real states of affairs. Their adequacy and theoretical utility does not depend upon correspondence.

For pendulums, even highly refined experimental apparatus will give a scatter of data points. The laws of pendulum motion are not meant to, and cannot, explain these data points. They are too erratic. However in science, from data come phenomena; and it is the phenomena which are the subject of scientific laws and theories. Often a line of best fit is put through the data points, and the line is then taken to represent the phenomena being investigated. Thereafter it is the phenomena which are discussed and debated, not the data. Any number of individual telescopic observations, when corrected and selected, constitute astronomical data. From this we infer, construct, invent planetary phenomena: circular orbits, elliptical orbits, heliocentric or geocentric orbits. The latter are not seen. They are not observational.

But this is no scientific impediment. Once we settle on the phenomenon, it becomes the subject matter of our scientific theories.

Newton, in Book II of his *Principia,* after laying out his Rules of Reasoning in Philosophy (our science), has a section on Phenomena. Among six phenomena that he believes his System of the World has to account for, are:

> That the fixed stars being at rest, the periodic times of the five primary planets, and (whether of the sun about the earth, or) of the earth about the sun, are as the 3/2th power of their mean distances from the sun….That the moon, by a radius drawn to the earth's centre, describes an area proportional to the time of description.[27]

These are not observational statements, and they are not data in the terms we are using. They are statements of the phenomena to be explained. As Newton acknowledged, these phenomena come from the work of the giants on whose shoulders he stood: Galileo, Kepler and Brahe.[28]

Kepler's "elliptical planetary paths" were, in turn, phenomena separate from, and not necessarily implied by his astronomical data and measurements. As William Whewell noted in the nineteenth century in his critique of Mill's inductivist account of science, the concept of an elliptical path was supplied by Kepler's mind, not by his data. There is usually no univocal inference from data to phenomena. Phenomena are underdetermined by data, just as theory is underdetermined by evidence. In the above case, the data are probably consistent with periodic times of 5/4th power of mean distance.

In educational research it is notoriously hard to establish the phenomena, even when data are uncontroversial. Data from IQ testing are consistent with phenomena of low intelligence, low motivation, low reading ability, and so on. In this case, just what are the phenomena that theory has to explain, is up for grabs, or up for ideological contest. Are we to explain a group's low intelligence, their low motivation or their low reading ability? It all depends on what phenomenon we take the data as revealing. Is the phenomenon to be explained in the Gulf War defense of democracy or defense of petroleum interests? Does a child's behavior reveal Attention Deficit Disorder or Spoilt Brat Syndrome? Is a person acting morally or serving their self-interest? Are the police maintaining law and order or furthering the interests of the ruling class? Is a woman exercising her right to choose or is she killing an infant? And so on. The theoretical explanations will differ depending on how the phenomenon is described and conceptualized. The road from data to phenomena is rocky, and strewn with methodological, theoretical, ideological and cultural obstacles.

Data are idiosyncratic. Different scientists, using different equipment, test procedures, statistical analyses, will generate different data. But this does not necessarily imply different phenomena. Pooling idiosyncratic data, triangulating, and other such research procedures are meant to establish more firmly the relevant, but by no means unique or uncontroversial, phenomena. Behaviorists might massage an array of data from rat observations to isolate the phenomenon of a conditioned response; more cognitively inclined ratologists might regard the very same data as establishing the phenomenon of avoidance behavior. Medievals looked at pendulum data and saw the phenomenon of impetus decaying; Newtonians looked at the same data and saw the phenomenon of inertia being counteracted by friction.

CONCLUSION

Classroom lessons on the pendulum, a universal topic in science programs, clearly provide occasion to introduce a number of core methodological issues to students: the role of idealization in science; the distinction between worldly events, data, phenomena and theory; the place of mathematics in physics; how evidence relates to theory apprisal, and much more. I advisedly say "introduce methodological issues" as there is lively controversy among scholars on just how the particular issues are to be resolved. Teachers should not become, knowingly or otherwise, propagandists for one or other side of the debate.[29] They can champion or defend one side, but they ought not exclude counter arguments, or demand allegiance to their side.

The pendulum can also shed light on the broader topics of science and technology (specifically the development of the pendulum clock), science and commerce (specifically solving the longitude problem and opening the world to European navigation), science and culture (specifically the role of the clock metaphor in theology and philosophy), and science and society (specifically Huygens's proposal of the seconds pendulum, a meter, as a universal standard of length).[30]

In the recently adopted U.S. National Science Education Standards, two pages are devoted to the pendulum. Unfortunately there is no mention of the history, philosophy, or cultural impact of pendulum motion, no mention of the pendulum's connection with timekeeping, no mention of the longitude problem, and in the suggested assessment exercise (making a pendulum that beats six times per second) the obvious opportunity to connect standards of length with standards of time (by making a pendulum that beats in seconds), is not taken.[31]

The *Standards* document was reviewed by tens of thousands of teachers and educators, and putatively represents current best practice in science education. That nothing of the rich context and history of pendulum studies appears is a testament, if another is needed, to the gulf between the science education communities and the history and philosophy of science communities.

The *Standards* document says that all science students should come "to understand the nature of science."[32] I hope this essay has indicated that a historically and philosophically informed approach to teaching pendulum motion can help realize this laudable goal.

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1. For the intellectual and educational background to these international developments, see Michael R. Matthews, *Science Teaching: The Role of History and Philosophy of Science* (New York: Routledge, 1994). For an account of the various curriculum documents, see William McComas and Joanne Olsen, "The Nature of Science in International Science Education Standards Documents," in *The Nature of Science in Science Education: Rationales and Strategies,* ed. W.F. McComas (Dordrecht: Kluwer Academic Publishers, 1998), 41-52.

2. National Research Council, *National Science Education Standards* (Washington: National Academy Press, 1996), 21.

3. Stillman Drake, *Galileo: Pioneer Scientist* (Toronto: University of Toronto Press, 1990), 6.

4. Stillman Drake, *Galileo at Work* (Chicago: University of Chicago Press, 1978), 399.

5. Richard Westfall, "Making a World of Precision: Newton and the Construction of a Quantitative Physics," in *Some Truer Method. Reflections on the Heritage of Newton,* ed. F. Durham and R.D Purrington (New York: Columbia University Press, 1990), 67.

6. Ibid, 82.

7. Karl Popper, *The Logic of Scientific Discovery* (1934; reprint, London: Hutchinson, 1959), 15.

8. Good discussion of the difficulties, but also the benefits, in the marriage of philosophy of science with the history of science can be found in D. Garber, "Learning from the Past: Reflections on the Role of History in the Philosophy of Science," *Synthese* 67, no. 1 (1986): 91-114; Marx W. Wartofsky, "The Relation Between Philosophy of Science and History of Science," in *Essays in Memory of Imre Lakatos,* ed. R.S. Cohen, P.K. Feyerabend, and M.W. Wartofsky (Dordrecht: Reidel, 1976), 717-38; Ernan McMullin, "The History and Philosophy of Science: A Taxonomy," *Minnesota Studies in the Philosophy of Science* 5 (1970): 12-67; Ernan McMullin, "History and Philosophy of Science: a Marriage of Convenience?," *Boston Studies in the Philosophy of Science* 32 (1975): 515-31; and Dudley Shapere, "What Can the Theory of Knowledge Learn from the History of Knowledge?" *The Monist* 60, no. 4 (1977): 488-508.

9. The most comprehensive study of the different interpretations of the scientific revolution is Floris Cohen's *The Scientific Revolution: A Historiographical Inquiry* (Chicago: University of Chicago Press, 1994).

10. On this tendency to project one's own philosophical position onto Galileo, see also Alasdair Crombie's essay on "Philosophical Presuppositions and the Shifting Interpretations of Galileo," in *Theory Change, Ancient Axiomatics, and Galileo's Methodology,* ed. J. Hintikka et al. (Boston: Reidel, 1981), 271-86.

11. The following are especially comprehensive accounts of Galileo's methodological innovation and its relation to other medieval and renaissance traditions: Ernan McMullin, "The Conception of Science in Galileo's Work," in *New Perspectives on Galileo,* ed. R.E. Butts and J.C. Pitt (Dordrecht: Reidel Publishing Company, 1978), 209-58; Ernan McMullin, "Galilean Idealization," *Studies in the History and Philosophy of Science* 16 (1985): 347-73; Ernan McMullin, "Conceptions of Science in the Scientific Revolution," in *Reappraisals of the Scientific Revolution,* ed. D.C. Lindberg and R.S. Westman (Cambridge: Cambridge University Press, 1990); W.L. Wisan, "Galileo's Scientific Method: A Reexamination," in Butts and Pitt, *New Perspectives on Galileo,* 1-58; W.L. Wisan, "Galileo and the Emergence of a New Scientific Style," in *Theory Change, Ancient Axiomatics, and Galileo's Methodology,* vol. 1, ed. J. Hintikka, D. Gruender, and E. Agazzi (Dordrecht: Reidel, 1981), 311-39; William A. Wallace, "Galileo and Reasoning *ex suppositione*," in *Prelude to Galileo,* ed. William A. Wallace (Dordrecht: Reidel, 1981), 129-59. In terms of the epistemological lessons to be learned from Galileo's scientific innovations, few articles are better than Jürgen Mittelstrass, "The Galilean Revolution: The Historical Fate of a Methodological Insight," *Studies in the History and Philosophy of Science* 2 (1972): 297-328. See also a fine discussion in Wallis A. Suchting, "The Nature of Scientific Thought," *Science & Education* 4, no. 1 (1995): 1-22.

12. For Galileo's mathematical proofs see Michael R. Matthews, "Galileo's Pendulum and the Objects of Science," in *Philosophy of Education 1987,* ed. Barbara and Don Arnstine (Normal Ill.: Philosophy of Education Society, 1988), 309-19 and Michael R. Matthews, *Time for Science Education: How Teaching the History and Philosophy of Pendulum Motion can Contribute to Science Literacy* (New York: Kluwer Academic/Plenum Publishers, 2000), 96-100.

13. Del Monte was Galileo's patron and one of the giants of late sixteenth century Italian mathematics and mechanics. For something of del Monte's life and achievements see Michael R. Matthews, *Time for Science Education,* 100-7; and M. Henninger-Voss, "Working Machines and Noble Mechanics: Guidobaldo del Monte and the Translation of Knowledge," *Isis* 91, no. 2 (2000): 233-59.

14. Galileo Galilei, *Dialogues Concerning Two New Sciences,* trans. H. Crew and A. de Salvio (New York: Dover Publications, 1954), 251.

15. On Galileo's recourse to "accidental" factors, and their crucial role in his scientific methodology, see Ernan McMullin, "Galilean Idealization," *Studies in the History and Philosophy of Science* 16 (1985): 347-73 and Noretta Koertge, "Galileo and the Problem of Accidents," *Journal of the History of Ideas* 38, (1977): 389-409.

16. Galileo, *Dialogues,* 252.

17. A cycloid is the path created by a point on the circumference of a circle moving along a plane surface. It is a somewhat "flattened" circle. It was first identified by Charles Bouvelles in 1501, and first studied extensively by a group of seventeenth-century mathematicians.

18. Alexandre Koyré, "Galileo and Plato," *Journal of History of Ideas* 4 (1943): 400-28 and Edwin Burtt, *The Metaphysical Foundations of Modern Physical Science* (London: Routledge and Kegan Paul, 1932), 61-95, regarded this metaphysical conviction as evidence of Galileo's Platonism. Thomas McTighe in his, "Galileo's Platonism: A Reconsideration," in *Galileo Man of Science,* ed. E. McMullin (New York: Basic Books, 1967), 365-88, discusses some of the issues surrounding Galileo's putative Platonism.

19. For formula for circular error, K, is: $K = 1.65x^2$ where x is the amplitude in degrees. The formula is independent of the length of the pendulum. On this see David S. Landes, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge: Harvard University Press, 1983), 420.

20. Except if the circular arc is greatly reduced, so that the difference between it an a cycloidal arc in negligible. This small amplitude option was tried, but it has its own mechanical drawbacks, namely increased susceptibility to interference.

21. Richard Westfall, "Newton and the Scientific Revolution," in *Newton's Dream,* ed. M.S. Stayer (Kingston: McGill-Queen's University Press, 1988), 4-18.

22. Horst Schecker, "The Paradigmatic Change in Mechanics: Implications of Historical Processes on Physics Education," *Science & Education* 1, no. 1 (1992): 75.

23. Laura Fermi and Gilberto Bernardini, *Galileo and the Scientific Revolution* (New York: Basic Books, 1961), 116.

24. On the topic of experiment, and its role in science, see Alan Franklin, *The Neglect of Experiment* (Cambridge: Cambridge University Press, 1986); Peter Galison, *How Experiments End* (Chicago: University of Chicago Press, 1987); and Ian Hacking, *Representing and Intervening* (Cambridge: Cambridge University Press, 1983).

25. Alexandre Koyré, "Galileo and Plato," in Alexandre Koyré, *Metaphysics and Measurement* (London: Chapman and Hall, 1968), 90.

26. The distinction between scientific data and scientific phenomena has been developed by Ronald Laymon "The Path from Data to Theory," in *Scientific Realism,* ed. J. Leplin (Berkeley: University of California Press, 1984), 108-23 and James Bogen and James Woodward, "Saving the Phenomena," *The Philosophical Review* 97, no. 3 (1988): 303-50. For an interpretation of Galileo's work in terms of the data/phenomena distinction, see D. Hemmendinger, "Galileo and the Phenomena: On Making the Evidence Visible," in *Physical Sciences and the History of Physics,* ed. R.S. Cohen and M.W. Wartofsky (Dordrecht: Reidel, 1984), 115-43.

27. Issac Newton, *Mathematical Principles of Mathematical Philosophy,* trans. A. Motte, rev. F. Cajori (Berkeley: University of California Press, 1934), 404-5.

28. For an analysis of the meaning of "phenomena" in Newton's work, see Peter Achinstein, "Newton's Corpuscular Query and Experimental Philosophy," in *Philosophical Perspectives on Newtonian Science,* ed. P. Bricker and R.I.G. Hughes (Cambridge: MIT Press, 1990), 135-73.

29. On the dangers of indoctrination in methodological matters, see Michael R. Matthews, "In Defense of Modest Goals for Teaching About the Nature of Science," *Journal of Research in Science Teaching* 35, no. 2 (1998): 161-74.

30. This larger canvas of pendulum applications is developed in Matthews, *Time for Science Education*.

31. On these missed opportunities in the U.S. Standards see Matthews, *Time for Science Education,* 314-17.

32. *National Science Education Standards*, 21