b. Obviously, we have to conclude that the results were adjusted to meet expectations; but even so, Galileo's theory at least survived the test: not incompatible with the results

5. So, with Riccioli have evidence for 1,3,5,... progression in free-fall comparable to Galileo's evidence for inclined plane, and evidential lacuna somewhat filled
   a. How good was Riccioli's value for fall in the first sec, 15 (Roman) ft?
   b. If the Roman foot is taken to be 29.57 cm (Koyré, Klein), then Riccioli's implied value for the acceleration of gravity amounts 887 cm/sec/sec, wrong by around 9.5 percent
   c. If instead (as Steven Weinberg proposed to me) his Roman foot is taken to correspond to his claim that the Tower of Asinelli is 312 Roman feet high -- now said to be 97.20 meters high -- it is 935 cm/sec/sec, wrong by a less than 5 percent; this seems far more plausible, given that a uniform error across all the distances must be an error in the distance measure
   d. Either way, it is close enough to reveal a clear difference between rolling and falling if any-one had done the experiment, for the value for rolling would have been less than 12 (Roman) ft whichever the measure, a clear discrepancy from the value expected from Riccioli's value
   e. Interesting question, given their concerns about the accuracy of their experiments, whether they would have taken the result seriously if they had done the experiment, or whether they would have instead attributed it to some sort of experimental vagary along the lines Mersenne did when confronted by a paradoxical result
6. At any rate by 1651 have not only some empirical evidence for Galileo's law of free-fall, but were also at least in a position to run an experiment showing the need to distinguish rolling from falling
   a. Through substantially improved means of measuring time
   b. Through measurement of a then comparatively easy and stable value to obtain, the distance traversed in the first second
   c. And through quite elaborate experimental programs in Riccioli's case, over a 10 year period

I. The Evidential Difficulties as of 1651: A Recap

1. Because the experimental evidence for Galileo's "law" of free fall will be important later, let me summarize the difficulties in adducing evidence for it as of the early 1650s
2. The "law" makes a claim about what happens in the absence of resistance, yet no resistance-free experiments could be carried out at the time
   a. The most that could be done was to take measures that seem to minimize the effects of resistance
   b. But then no experiment could be expected to yield precise agreement, and discrepancies were open to differing interpretations
3. The best hope for carrying out precise, repeatable tests, the inclined plane, had the lacuna of assuming that inclined plane motion amounts to the same thing as vertical fall

    a. Galileo's postulate tantamount to claim that inclined plane acceleration is g*sin(angle)
    b. Statics evidence to support this in second edition
    c. But this evidence misleading, for unbeknownst to them the postulate conflates rolling and falling
4. Inclined planes at low angles could provide good evidence of a 1,3,5,... progression, but only at low angles
    a. At higher angles, a mixture of rolling and falling, leading to conflicting results that were likely not to have been repeatable
    b. In absence of rolling-falling distinction, no principled basis for discounting higher inclination results
    c. Raises an interesting question: does an experiment that yields confirming results only under certain special circumstances and yields disconfirming results in other circumstances, with no explanation of why, nevertheless provide evidence for a claim?
        (1) A more widespread phenomenon in experimental science than you might think
        (2) Issue at the heart of the "epistemology of experimentation"
        (3) {See the works of Allan Franklin for more on the epistemology of experimentation}
5. Direct measurements of rate of vertical fall -- i.e. distance in first sec -- had promise of allowing a host of follow-on tests once the value was established (as by Riccioli; but efforts fail to stablilize on a single value)
    a. Because of the care in the experiments, Riccioli's result should have taken precedence over Mersenne's
    b. But the difference between them raised questions, including about whether Riccioli's value the final word
    c. No attempt to bound uncertainty at the time, but we can see in retrospect (and Huygens saw in the 1650s) still off by almost 4 percent, if not almost 10 percent
6. The experimental community appears not to have been at all aggressive in looking for converging support of results and in investigating sources of discrepancies in experimental results
    a. As indicated most of all by failure to take vertical-fall values and conduct inclined plane tests using them
    b. Probably reflects lack of confidence in the potential of experiments
    c. Nevertheless, a failure to realize that the way to improve experiments is to carry out complementary ones, looking to improve technology and identify sources confounding the results
7. If you wonder why historians of science have become inclined to discount the importance of evidence in the acceptance of theoretical claims, this episode instructive
    a. Much harder to carry out telling tests of a claim than is generally recognized

b. Even when have fairly good confirming results, usually also have a host of conflicting results and lacunae

IV. Galileo's Contribution to Science: Some Issues

A. Galileo's Place in the History of Mechanics

1. Even this brief glance at the problems Galileo and his contemporaries faced in getting a science of motion off the ground shows how precarious the familiar claim is that Galileo invented a new science of motion, which Newton then combined with Kepler's laws to form modern mechanics
   a. Not at all clear that Galileo has left us with much more than conjectures that others are going to have to straighten out and confirm
   b. And given how differently he conceptualizes motion from us, not clear that his conjectured "laws" are even ours, even though they have somewhat the same mathematical form and the evidence can be interpreted as bearing on our modern form as well
2. The legend of Galileo diminishes in somewhat similar ways from a careful examination of his historical context, for his work in mechanics did not proceed out of whole cloth; he was the culmination of a 100 year tradition in Italian mechanics
   a. Starting from Leonardo da Vinci, who had strong interests in various practical questions within mechanics
   b. Tartaglia, Benedetti, and Guido Ubaldo developed accounts of such mechanisms as the balance, lever, pulley, and wedge, and challenged Aristotelian accounts of motion
   c. Galileo's unpublished early work -- *De Motu* (1591) and *Le Mechaniche* (1594) -- transparently within this tradition
3. Galileo also probably used some of the fruits of a late Medieval tradition on uniformly accelerating motion
   a. Mertonians (at Oxford from 1320-1350), and Buridan and his student Oresme at Paris (also during the 14th century)
   b. Buridan, in particular, developed his account in terms of "impetus", and Oresme offered a "graphical" determination of distance traversed that was still being taught at Padua when Galileo was teaching there (see Clagett's *The Scinece of Mechanics in the Middle Ages* for originals, Dijksterhuis's *The Mechanization of the World Picture* for commentary)
4. Moreover, others like Stevin (1548/9-1620) and Beeckman (1588-1637) in Holland were developing mechanics in parallel with Galileo
   a. Stevin: monumental work on theory of inclined planes, and various problems in statics -- that is, on equilibrium and its loss in "machines" like the lever, the pulley, the balance, etc. (what the word "mechanics" meant in the first half of the 17th century)
   b. Beeckman, with Descartes assisting, developed "law" of free-fall independently of Galileo around 1618

5. Galileo unquestionably a leading, central figure in the development of the modern science of dynamics, but his precise contribution to that science is more complicated, and requires more qualification, than legend would have it
    a. Legend, of course, makes it all sound so easy: once Galileo had rid himself of Aristotelian confusions, he proposed the law of free-fall, which, once proposed, was readily seen to be true
    b. In fact, in addition to Galileo's efforts over a 50 year period, we find Mersenne devoting effort over 15 years and Riccioli over 10 years to the experimental verification of Galileo's proposed law

B. Galileo's Contribution to Scientific Method

1. The legend that Galileo was the "father of" modern experimental science also begins to evaporate a little once one looks carefully into what Galileo did
    a. The old common view can be found in Mach's *The Science of Mechanics* (1893), which emphasizes the experiments Galileo describes in support of his claims
    b. But Mach fails to mention, or maybe to realize, that these experiments could not always be carried out with sufficient precision at the time to yield especially meaningful results
2. Galilean scholarship during middle of 20th century, led by Koyré, produced a radically different picture, under which Galileo was scarcely committed to experiment at all
    a. A Platonist who used crude measurements heuristically and as supporting demonstrations -- in contrast to designing experiments where the world would yield an answer to a question
    b. Thought-experiments instead of actual ones, making him seem more like Descartes: rational science
    c. Claims about experimental results so much polemical excess
3. Galilean scholarship during the last 45 years, led by Drake, has produced a more complex, and in some ways more balanced picture of Galileo's methodology
    a. Empirical observations and experiments played a critical role in Galileo's discoveries, especially from 1590 to 1610
    b. This fact somewhat suppressed in *Dialogue* and *Two New Sciences*, where experiments described as yielding rather more impressive results than we have reason to think he usually achieved
    c. Still, this revisionist view contrasts him sharply with the standard picture of Descartes
4. Whether Galileo performed most of the experiments he said he did or not, his verbal commitment to their importance in the development of any scientific theory is beyond dispute
    a. In other words, his insistence on experimentation had its impact independently of what he actually did, as we have already seen with Mersenne and Riccioli, and as we will continue to see with Huygens and Newton

b. But he may well have misled many into thinking that the experimental confirmation of a theory is much easier and much more straightforward than it is, especially than it is in the early stages of theory construction

5. Galileo had a clear idea of how an experiment could be used to put the lie to theories – Aristotelian theories in particular – and he understood the role of experimentation as a corrective to misleading observations of nature

   a. The latter especially important insofar as it leads to a change of focus from saving the phenomena as they occur in nature to saving the phenomena as they occur in specially contrived circumstances that may never happen in nature

   b. But, granting that Galileo ever did perform any first rate experimentation in mechanics himself, neither it nor the logic behind it is altogether accurately reported in his principal works (sometimes for reasons of which he was not aware)

6. And though it was founded by his followers 15 years after he died, the Florentine Accademia del Cimento (1657-1667) -- as its name says, dedicated to experiment -- was inspired by him and his many statements about experiments (see Boschiero)

C. Philosophical Disputes Over *Two New Sciences*

1. In sum, not just Galileo the person and scientist, but also his chief scientific work, *Two New Sciences*, turns out on closer inspection to be complex and many sided

   a. An unqualified hero to some, a tainted hero to others, with experts on Galileo in each camp

   b. Though notice that still a hero either way, whether because of his substantive contribution or because of his sociological impact

2. Given this complexity and many-sidedness, it is not surprising that Galileo has become a central figure in some of the current philosophical disputes about the "rationality of science"

   a. Kuhn and those who agree with him that evidence plays a much more circumscribed role in the history of science than is customarily suggested offer Galileo as a prime example

   b. And people like Dudley Shapere, who want to defend the rationality of science, offer re-interpretations of Galileo in reply (*Galileo: A Philosophical Study*, 1974)

3. Paul Feyerabend, someone very much in the same camp as Kuhn, has used Galileo to argue in his *Against Method* that the very idea of a scientific method is almost always going to impede the development of science in one way or another

   a. Feyerabend argues that, on the one hand, Galileo violated almost every dictate of scientific method that anyone has ever proposed, yet, on the other hand, is unquestionably one of the greatest scientists of all time

   b. Since his violations of the dictates seem almost indispensable to many of his principal scientific successes, the only reasonable conclusion is that we would all be better off to abandon all such dictates and follow a policy of anarchism in science

4. By looking at Galileo's work on uniformly accelerated motion in a slightly broader context, hope to have shown that the issues being raised here cannot be addressed by looking at Galileo alone, but require attention to his historical context
    a. As Mersenne's and Riccioli's efforts make clear, however brilliant and original *Two New Sciences* was, its theory of uniformly accelerated motion quickly became a community wide project
    b. A project in which it was not blindly accepted and developed, but was subjected to serious critical scrutiny, within the limits that experimental technology at the time would permit
5. But this alone will not answer those who offer Galileo as a paragon of "irrationality" in science, for we have yet to begin showing that the community managed to bring substantial empirical evidence to bear on Galileo's proposed "laws"
    a. Galileo was central to the transition from an immature to a mature science of motion
    b. Kuhn would argue that that transition will invariably have a large irrational element to it -- a conjectural element reaching beyond all the available evidence
    c. Nothing we have said so far would contradict this -- it was extremely hard at the time to bring all that much telling evidence to bear

D. Issues We Must Face and Our Approach to Them

1. Before we finish with Galileo, then, we need to become more clear about exactly what contribution he made first to the substance of science
    a. To what extent did he put forward the cornerstones of the modern physics of motion -- e.g. laws like those discussed this time and next
    b. And to what extent were these laws the product of efforts subsequent to him
2. We also need to become clear about exactly what contribution he made to the methodology of science
    a. What is his conception of an idealized science and how is it open to empirical verification, falsification, and refinement
    b. What is his conception of the logic of experimentation, in contrast to mere observation, and how is experimentation to interact with theory
    c. And, more narrowly, how did Galileo's approach to establishing generalizations about "local" motions – specifically, the four fundamental "Galilean" principles listed in the Appendix – differ from Kepler's approach to establishing generalizations about celestial motions
3. Want to become clear not just about his conception of what science is and how it is limited, but also the conception of the prominent figures around him, like Mersenne and Gassendi, on whom he had so much influence and who then influenced others
    a. Is he – and are they – committed to the idea that the science of motion is inherently imperfectible – that is, can never become and hence ought not to try to be an exact science

b. Is he – and are they – committed to the idea that science should focus on "how" rather than "why" – that is, should postpone concerns about causes and concentrate on what actually happens

4. In worrying about such questions, we need to distinguish between four quite different things:
   a. What Galileo originally did to "discover" – i.e. to convince himself of – the various results he announced
   b. What Galileo offers in print in the way of support for these results
   c. What others at the time took Galileo to be offering in the way of support for the results
   d. What others at the time did, following Galileo, to develop support for the results
5. Galilean scholars are primarily interested in the first two, while we are primarily interested in the last two
   a. Our ultimate question: from the point of view of Newton, what was and was not known in 1684
   b. This dictated by the evidential arguments in the community
   c. But we should not entirely lose sight of Feyerabend's challenge as we proceed

<u>Select Sources</u>

Galilei, Galileo, *Discourses and Mathematical Demonstrations Concerning Two New Sciences Pertaining to Mechanics and Local Motions*, tr. Stillman Drake, including "History of Free Fall: Aristotle to Galileo," Wall & Emerson, 1989.

--------, *Mathematical Discourses and Demonstrations Touching Two New Sciences, pertaining to the Mechanicks and Local Motion*, tr. Thomas Salusbury, London, 1665.

--------, *Galileo's Early Notebooks: The Physical Questions, A Translation from the Latin with Historical and Palelological Commentary*, William A. Wallace, University of Notre Dame Press, 1977.

--------, *Galileo's Notes on Motion, Arranged in Probable Order of Composition and Presented in Reduced Facsilime*, Stillman Drake, Istituto e Museo do Storia della Scienza, Monografia n. 3, 1979.

--------, *Discourse on Bodies in Water*, tr. Thomas Salusbury, Dover Publications, 2005.

--------, *Dialogue Concerning the Two Chief World Systems*, tr. Stillman Drake, Modern Library, 2001; reprint, with different pagination of 2nd revised ed., University of California Press, 1967.

Drake, Stillman, *Galileo at Work: His Scientific Biography*, University of Chicago Press, 1978; reissued by Dover.

--------, *Essays on Galileo and the History and Philosophy of Science*, 3 vol., University of Toronto Press, 1999.

Galluzzi, Paolo, *Momento: Studi Galileiana*, Ateneo e Bizzarri, 1979.

Renn, Jürgen (ed.), *Galileo in Context*, Cambridge University Press, 2001.