Huygens and the Beginnings of Rational Mechanics

I. Science in the Thirty Years after Galileo's Death

A. The Development of Astronomy: 1642-1672 (a brief summary, in anticipation of next class)

1. During the thirty or so years following Galileo's death, orbital astronomy began to take on a distinctly modern form, taking advantage of increasingly precise measurements in order to use discrepancies between observation and theory as a source of further evidence
   a. The kind of approach exemplified by Kepler and followed by Horrocks: proceeding by successive approximations
   b. But now with a concerted effort by much of the community
2. The standard of accuracy of the Rudolphine Tables -- e.g. allowing for occasional exceptions, within 4 min of arc for Mars -- had become accepted as the minimal standard by all, but it had been more or less met in different ways:
   a. Kepler: ellipse and area rule, with 3/2 power law inferred
   b. Boulliau: ellipse and special correction to equant at focus (1645, 1657)
   c. Wing: ellipse and equant oscillating about focus, and later a geometric construction (1651, 1656, 1669)
   d. Streete: ellipse and Boulliau's rule, but using 3/2 power law instead of measurements to determine mean distances (following Horrocks) (1661)
   e. Mercator had shown that, with an ellipse for Mars, the rule for location versus time has to approximate the area rule in order to reach Kepler's level of accuracy, and he had then added his own geometric alternative to the area rule (1669, 1676)
   f. Horrocks's *Opera Posthuma* published in early 1670s
3. The Royal Observatory of Paris, with state-of-the-art equipment, was beginning to function, and the one at Greenwich was soon to follow, both directed by superior observational astronomers
   a. Both committed to replacing Tycho's data with a new body of more precise data, taking advantage of the new technology
      (1) Paris focusing on planet positions and related matters
      (2) Greenwich on a new star catalog
   b. Not just careful observations, but through comparison with one another to cross-check
4. The Royal Academy had taken on the project of pushing Kepler's approach to its limits, pursuing the very best orbital elements in order to determine true residual discrepancies
   a. Choice of Kepler (by Picard and Huygens) instead of Boulliau never explained publicly, but none better than Kepler, and also because Horrocks had shown Kepler offered more promise if solar paralax reduced and orbital elements improved (*Venus in sole visa*, published 1662)
   b. Approach was first to determine such fundamental quantities as solar parallax and refraction affecting all observations, then turn to elements

5. During the 1670's this approach had begun to yield some notable results, though nothing yet on planetary orbits themselves
   a. Solar parallax definitely less than 12 sec, and probably less than 9.5
   b. Single table of refraction corrections, consistent with Snel's law
   c. Corrected obliquity of the ecliptic
   d. A method of determining longitude differences between points on earth, based on synchronized observations of eclipses of Io, that permits more accurate mapping
   e. From discrepancies in the eclipses of Io, a rough measure of the speed of light, and associated correction rules
   f. The discovery of an apparent movement of the North Star, revealing a further anomaly that would have to be understood before full advantage could be taken of the telescope
6. Meanwhile, primarily in England, attention was focusing on possible physical mechanisms that could account for the curvilinear trajectories of planets and comets
   a. Focus initially on why not a straight line, not on why other than a circle -- i.e. proceed from first approximation
   b. Gravity hypothesis, advocated by Wren and Hooke, led to proposal that gravity varies inversely with distance squared after Huygens' work on centrifugal force became known in 1673
7. In sum, the two great advances of the first half of the 17th century -- Kepler's discoveries and the telescope -- became assimilated during the 30 years following Galileo's death, and a (broadly) Keplerian approach was increasingly being taken to the problem of extracting answers to empirical questions from observations -- via successive theoretical approximations, trying to use discrepancies as an evidential basis for further refinements

B. Post-Galilean Developments in Mechanics

1. Thus, the modern science of astronomy had largely come into being by the mid-1670's; I will be arguing tonight that much the same can be said of the modern science of mechanics
   a. I.e. the modern form and approach of this science had largely come into being by the mid-1670's, primarily through the efforts of Huygens
   b. With the publication of the *Horologium Oscillatorium* in 1673, taking a giant step toward completing Galileo's fragment of a theory on "local" motion
2. The development of mechanics following Galileo's and Torricelli’s deaths proceeded slowly until the late 1650's when Huygens made major breakthroughs by extending Galileo's theory of local motion to constrained curvilinear trajectories
   a. Many of the results became known in the 1660's, but publication with some (though not all) of the proofs was delayed until 1673 -- *Horologium Oscillatorium*
   b. Huygens himself was working as much under the inspiration of Mersenne (and indirectly Gassendi) as Galileo, but his efforts filled the most glaring holes in the latter's theory

3. Galileo's principal protegés in Italy, Torricelli (1608-1647) and Viviani, were continuing work on problems he had posed at the new Accademia del Cimento (Academy of Experiment) in Florence
   a. E.g. the effort to detect a finite speed of light mentioned in the reading for next class
   b. The Accademia, perhaps even more so than Galileo himself, was committed to the idea that the empirical world ought to be the ultimate arbiter
4. Torricelli's theoretical efforts on mechanisms had led him to formulate a principle of some importance: "two interconnected heavy bodies cannot put themselves into motion unless their common centre of gravity descends" [Dijksterhuis, p. 362]
   a. An axiom for Torricelli, supported by the argument that two such bodies in effect form a single body with parts and by fact that center of gravity descends with a pulley
   b. Used to derive the law of inclined planes -- an alternative to the argument in *Two New Sciences*
5. Related to the work for which Torricelli is most famous, the creation of the mercury barometer, which he used (following a suggestion of Galileo) to explain why pumps can raise water only so high
   a. Barometer understood as a device in which air pressure was balancing the weight of a column of mercury, especially following the brilliant experiments by Pascal (1623-1662) in 1649
   b. The idea of vertical limits to natural and related processes a common theme to both efforts and to Galileo's other work
6. Torricelli's principle important because it offered an alternative to impetus theory as a means for deriving inclined plane law via pathwise-independence
   a. Though independent of Descartes' concern for foundations, dovetails with this concern, offering a possible basic principle that has the potential for by-passing talk of forces
   b. Independently developed in France by Pascal
   c. (Of course, the principle is just a special, limited form of the conservation of energy)

C. Christiaan Huygens (1629-1695): a chronology until 1673

1. Youth in the great days intellectually and politically of Holland
   a. Born in 1629, son of Constantine Huygens, the “Thomas Jefferson of Holland” (in U.S. eyes): among first major poets in Dutch, composer of music, a more than major figure in politics and in intellectual life of Holland (with such close friends as Rembrandt, Descartes)
   b. Christiaan educated at Leiden (1645-47) and College of Orange (1647-49)
   c. In 1646 derives theory of uniformly accelerated motion independently of Galileo, which father sends to his friend Mersenne, who from afar takes him under his wing
   e. First published paper on quadratures of hyperbolas, ellipses, and circles (1651)
2. 1650s: becomes a major figure in the scientific world
   a. Sometime in 1652-1656: solution for spheres in impact, but not published
   b. Together with his brother Constantine, becomes the leading grinder of telescopic lenses and develops the “Huygens eyepiece” in mid-1650s

c. 1655: first extended visit to Paris, where Gassendi introduces him to others

d. 1656: using his superior telescopes, discovers Titan (satellite of Saturn) and solves the riddle of Saturn's rings

e. 1656: designs first successful pendulum clocks, culminating in publication of his *Horologium* describing the design -- most notably, the escapement -- in 1658

f. 1657: first textbook on probability theory, inspired by his time in Paris and published as an appendix to a Van Schooten book -- Bayesian in spirit, emphasizing "expectation"

g. 1659: publication of *Systema Saturna*

3. 1660-1673: becomes the leading figure in the world of science

a. Late 1659: centifugal force, conical pendulum, cycloidal pendulum, measurements of g, cycloidal pendulum clocks

b. 1660 (and 1663-64) visits to London where he announces his results on impact, cycloidal pendulum, cycloidal pendulum clocks, and measurements of g

c. 1663: first foreign Fellow of the Royal Society

d. 1664: approached (by Colbert) to be a founding member of the French Royal Academy of Sciences, which he joins at its inception in 1666

e. 1669: cause of gravity, analytical and experimental efforts on motion under resistance, and trials of his clocks at sea (for finding longitudes); publication of his results on impact, announcing conservation of linear momentum, *vis viva*, and center of gravity principle

e. 1673: publication of his *Horologium Oscillatorium*

D. Huygens and the Measurement of g (1659)

1. During the last three months of 1659 Huygens became preoccupied with the problem of measuring the strength of gravity (as described in Joella Yoder's *Unrolling Time*)

a. He knew Riccioli's measurement, and he repeated Mersenne's, concluding that it could not be perfected to the extent needed

b. Initially addressed the problem Mersenne had posed -- compare the time for a pendulum to fall through 90 deg to the time of vertical fall through the same height

c. Knew, both from Mersenne and from his development of the basic pendulum clock, that the circular pendulum is not isochronous

2. First effort in an earlier version of De Vi Centrifuga, exploiting the discovery that uniform circular motion involves uniform acceleration just as vertical fall does

a. Leads to theory of conical pendulum, including result that the period of revolution = $2*\pi*\sqrt{(h/g)}$, as presented in our version of De Vi Centrifuga (published posthumously in 1703)

b. Infer g from measurement of period: 15 and 6/10 Rhenish ft "proxime" in the 1st sec (979 cm/sec/sec), by far the best value to date (Riccioli: 935 cm/sec/sec)