5. Huge amount of research over 45 year period, especially from 1655 to 1665, with profound influence on others through personal contact
   a. Work in astronomy primarily in 1650's -- including lense grinding and the better telescopes in the first of these years -- culminating in *Systema Saturnium* (1659), which established him worldwide as a major figure
   b. In mechanics, from 1640's on, culminating in *Horologium Oscillatorium* (1673), which in a sense completes and replaces last two days of Galileo's *Two New Sciences*
   c. In other areas of physics -- most notably optics and light and gravity -- from the late 1660's on, culminating in *Traité de la Lumière* (1678 (draft), 1690) which presents a wave theory of light and *Discourse on the Cause of Gravity* (1669, 1678, 1684 (drafts), 1690)
   d. In mathematics, the first textbook in probability theory (1657), the theory of evolutes, and extensions of post-Cartesian geometry to numerous further curves, including logarithmic and exponential, tied to quadratures of hyperbola
   e. In technology, the leading designer of clocks, as well as several other contributions, and for a period in the 1650s the source for the world's best telescopes, with his correcting eyepieces
6. The person on the list who may have known Descartes best from his teen years and, because of his research in the third of the above categories, often thought to be a Cartesian; nevertheless, more accurately thought of as the chief follower of Galileo and Mersenne
   a. Extends the best in Galileo -- mathematical theories, telescopes, experiment, uniformly accelerated motion, etc. -- but with Mersenne's emphasis on clear empirical confirmation
   b. As such, the style-setter in science in the years between the two *Principia*'s

II. Astronomy from 1642 to 1660: Revisitations

A. Boulliau's Geometrical Orbital Theory

1. Need to start with another French priest from Descartes' generation, Ismaël Boulliau (1605-1694), who developed the first serious rival to Kepler's orbital theory
   a. Opposed not just to Kepler's physics, but to all physics in mathematical astronomy -- restore discipline to branch of geometry by insisting throughout on geometrical arguments
   b. Restore Copernican foundations by insisting on uniform circular motion, while allowing ellipse

   "To bring the motions of Mercury under numerical laws was difficult if not in fact impossible for pre-Keplerian astronomers who used only the circular hypothesis." (Boulliau, 1645)

   d. Thus with an underlying cosmology of sorts, though no physical explanation for the ellipse or for timing along it, and nothing about what resists tendency to recede from center
   c. Because area rule not geometrical, insofar as no geometrical solution to Kepler's equation, Boulliau rejected it as part of his goal of returning astronomy to branch of geometry
2. Basic idea: planet slides from circle to circle defined on a conical surface, resulting in an ellipse with one focus on axis of cone and the other at the Sun (see Appendix); in *Astronomia Philolaica*, 1645

a. Uniform motion on each circle results in faster motion (smaller circle) near perihelion, slower (larger circle) near aphelion

b. Considered geometrical grounds for concluding that oval definitely an ellipse

3. Claimed his method provided a direct solution to problem of finding true anomaly from mean anomaly, but at last moment realized solution resulted in excessive geocentric longitude errors (> 7 min)

a. Hence inserted Kepler's equation of center (i.e. area rule) at last moment in 1645 book

b. In 1653, however, Seth Ward showed (1) that uniform circular motion about conical axis equivalent to an equant on that axis and (2) Boulliau's method not consistent with his own claim of uniform circular motion

4. Boulliau, who knew that the simple elliptical hypothesis (equant at other focus) won't work, offered a modified method in (1657) in response to Ward's critique: *Astronomiae Philolaicae fundamenta clarius explicata et asserta*

a. Straightforward new geometrical construction to determine true anomaly ("Boulliau's method")

b. Claimed this is consistent with uniform circular motion, for reflects a small additional inequality due to "translation of the motion of the planet from a circle into an ellipse"

5. Resultant orbital theory of the same level of accuracy as Kepler's even though it replaces the area rule by a computationally more tractable alternative (using the same 28 comparisons with Tycho's data for Mars near opposition that Kepler had used, as shown in the Appendix)

a. Raises questions about the indispensability of the area rule, even though the alternative could be viewed as nothing more than a computational contrivance, akin to devices others (including Horrocks) had suggested for approximate solutions to Kepler's equation

b. At same time, however, success of both original and corrected versions lent further weight to conclusion that the orbit elliptical

B. Other Alternatives to Kepler's Orbits

1. Boulliau's orbital theory the principal rival to Kepler's in the 1640's and 1650's, for no other was both comparable in accuracy and had at least the pretense of an underlying cosmology

a. But there were several other rivals to Kepler's orbital theory put forward as well, along with some approximate solutions replacing the area rule (e.g. Cavalieri)

b. More often than not in an effort to avoid having to face Kepler's equation in determining true anomaly from mean anomaly

c. (In *Rudolphine Tables*, "eccentric anomaly" used, with direct solutions then for both mean and true, but requiring interpolation in former, and hence not strictly geometric)

2. Riccioli's *Almagestum Novum* was published in 1651, containing not only his work in mechanics, but also a complete orbital system, with Jupiter, Saturn, and the sun orbiting the earth

a. Rejected elliptical orbits on grounds that the evidence for bisected eccentricity inadequate at the time; in process was putting greater demands on the evidence

b. In 1665 switched to elliptical after Cassini’s efforts in Bologna provided high quality empirical evidence for bisected eccentricity, in the process removing one of the shaky steps in Kepler
c. System not a serious contender for various reasons, among them a large number of calculation errors; but book of interest because of its extensive review and critical analysis of others

3. The simple elliptical hypothesis, with equant point at the other focus, continued to be put forward in spite of Kepler's explanation in the *Epitome* of why it does not work
   a. Ward, ironically, was criticizing Boulliau in order to justify resorting to equant, as he did in 1656
   b. Boulliau's 1657 reply showed that the equant is not empirically satisfactory
   c. Pagan nevertheless published Keplerian elements with equant at focus that same year
4. Wing (*Harmonicon coeleste*, 1651; *Astronomia instaurata*; 1656, Ephemerides for 1659-1671, 1658; *Astronomia Britannica*, 1669) adapts Boulliau's original method of calculating the equation of center, while abandoning completely Boulliau's geometrical cosmology and cone ("a mere supposition")
   a. "No such thing in nature as mean motion" -- an openly calculational approach, with no concern for underlying physics in 1651
   b. Actual construction akin to an oscillating equant point in 1651 (just as Kepler said was necessary), yielding reasonable agreement with observation (Wing's first method)
   c. Shifts to different method in 1656 and 1669, in which an empirically based geometrical correction term used to relocate planet, different from Boulliau’s, but in same spirit
   d. (Tries to conflate Kepler and Cartesian vortex in 1669)
5. Two other important approaches eschewing the area rule published in England between 1660 and 1676, by Streete and Mercator, will be discussed below
6. One thing to notice in all these attempts is that nothing emerges to show Kepler wrong
   a. Ellipse becomes conceded, constituting a form of assimilation of Kepler, as does accuracy comparable to area rule, which requires some special contrivance or other in each case
   b. Notice also that Tycho's data the empirical base for these efforts, with no attempt to use either new data or discrepancies between Kepler and observation to generate better accounts, in the way Horrocks did, making these efforts less an assimilation of Kepler than his was

C. The Development of the Pendulum Clock

1. The limited accuracy of clocks -- e.g. Tycho's observations involve as much as 1/4 hour error in time -- was holding back astronomy in two respects:
   a. Some observations were simply being misstated -- direct measurements of latitude and longitude at a specified time (as opposed to measurements relative to certain nearby stars)
   b. Lack of standardization impeded simultaneous measurements at different sites, as well as comparison of measurements at slightly different times
2. Although Galileo had proposed ways of turning the pendulum into a clock, Huygens was the first to produce a completely functioning pendulum clock in 1656 (announced in his *Horologium* of 1658)