THE NEWTONIAN REVOLUTION – Part One

Philosophy 167: Science Before Newton's *Principia*

Class 9

Descartes' *Principia*: The Vortex Theory of the Heavens

October 28, 2014

Philosophy 167: Science Before Newton's Principia

Assignment for November 2

Descartes' *Principia*: The Vortex Theory of the Heavens

Reading:

Descartes, Principia Philosophiae, Part III, Articles 31-157, after reviewing Articles 1-30.

---- Part IV, Articles 199-207.

---- Letter to Mersenne of 11 October 1638.

Questions to Focus On:

1. **What evidence does Descartes offer to support the claim that the planets and their satellites are carried around their principals by (unseen) fluid vortices?**

2. **Descartes offers an argument in favor of the Copernican system over the Tychonic. How does his argument deal with the fact that the two systems can be formulated to assign the same relative positions to all celestial objects? To what extent does his argument settle the issue?**

3. **Although Descartes never expressly discusses Kepler's "laws" of motion, he does remark in Article 34 that the trajectories of the planets "are continuously changed by the passing of the ages," and he adds other remarks of this sort elsewhere in discussing details of planetary movement. What implications do such remarks have for Kepler's "laws" -- in particular, for whether the "laws" are nomological at all?**

4. **Descartes is among the first to insist that an explanation is owed for how the planets remain in orbits at all, given centrifugal effects (i.e. given what we now call the principle of inertia). How adequate on its face is his explanation of their maintaining orbital motion? Is it more adequate than Kepler's?**

5. **Descartes claims that his vortex theory is comprehensive: all planetary and celestial phenomena are explained by it. What is the most serious criticism anyone could have lodged against it in 1650?**

6. **At the end of Part IV Descartes claims that there is almost no possibility of his account being wrong. What reasoning does he offer in support of such an extraordinary claim?**

Descartes' *Principia*: the Vortex Theory of the Heavens

I. The Cartesian "Shift" of Emphasis in Science

A. Understanding as One of the Goals of Science

1. Part II of Descartes' *Principia* contrasts sharply with such works as Kepler's *Epitome* and Galileo's *Two New Sciences*, suggesting a very different view about what is important in science
   a. In particular, Descartes seems on the surface to be emphasizing a goal of explanation and understanding to a greater extent than they did
   b. I.e. explanation in terms of the fundamental or ultimate workings of the material world
2. Descartes was scarcely responsible for the idea that one of the goals of empirical inquiry is to provide an understanding of the world around us
   a. Ptolemaic astronomy was surely trying to explain -- i.e. provide an understanding of -- such phenomena as retrograde motion and patterns of variation in it
   b. And many of the Medieval and Copernican critiques of such aspects of Ptolemaic astronomy as the equant were tantamount to denying that he was providing such an understanding
3. As Ptolemaic astronomy and Aristotelian physics attest, however, one can achieve what at the time seemed a satisfactory level of understanding, yet subsequently conclude it was all illusory
   a. The issue is not just whether a particular line of explanation yields satisfactory understanding, but further whether it is true, so that the understanding is not an illusion
   b. For example, the line of explanation and the understanding it provides should stand up over time, as we learn more in the way that the telescope led us to
4. If Descartes and the other advocates of the mechanical philosophy added anything here, it was through their insistence on no compromises in explanation
   a. They were as willing as anyone to allow the positing of unseen theoretical entities in order to explain phenomena
   b. But, in insisting that we must be able to understand exactly how such entities work, they were placing a new burden on theorizing
5. By contrast, Kepler and Galileo were prepared to leave such detailed workings open so long as they had other grounds for pursuing their theories
   a. For example, Kepler allowed questions about how magnetism works to remain open, thinking that the promissory note can ultimately be redeemed since magnetism a natural phenomenon
   b. And Galileo allowed questions about why things accelerate vertically to be put off entirely

B. The Focus on the Foundations of Science

1. The most glaring shift in emphasis we see in Part II of the *Principia* is the concern with the ultimate foundations of all material processes
   a. From the title of Part II on, Descartes is engaged in a project of a completely different sort from Kepler and Galileo

b. Endeavoring to lay the foundations for all empirical knowledge!

2. One way of motivating his preoccupation with foundations is as a response to the pseudo-explanations of Aristotelian science and Renaissance naturalism
   a. Need to maintain sharp contrast between theorizing that yields a real understanding of why phenomena are the way they are and schemes that allow us to talk of phenomena coherently and without obtrusive anomalies
   b. To the extent that can identify all -- or at least some -- of the basic mechanisms of the material world, in a position to draw this contrast and then at least to recognize when all we have is a comfortable way of describing phenomena
3. Another way of putting this is that we want to be clear about what questions we are asking about the material world, and what we are demanding in the way of answers to those questions
   a. In particular, which why-questions call for answers other than, "that's just the way things are", and what sorts of answers to these questions we want -- e.g. answers that do not give rise to a multiplicity of further why-questions
   b. Descartes here following the lead of Aristotle, but in setting forth the fundamental principles of the material world, trying to minimize the number of why-questions to which the answer, "that's just the way things are", is appropriate
4. This focus on questions -- especially on why-questions -- is tantamount to trying to make explicit and clear what has subsequently become known as the conceptual (or metaphysical) foundations of science
   a. Not an irrelevant or premature undertaking, for the way we conceptualize phenomena is surely going to have an impact on any empirical theories we advance about them
   b. E.g. Kepler conceptualized motion as requiring a continuing push, Galileo conceptualized rolling as fully akin to falling, and Copernicus conceptualized uniform circular motion as calling for no further explanation
5. As we shall see, regardless of whether Descartes thought he was setting out the ultimate mechanisms of the material world or just making his way of conceptualizing motion and its change clear, his new focus on foundations had quite an effect
   a. Not just Newton, but virtually all others working in mechanics for the next 150 years extremely careful to lay out foundations -- often in prima facie conflict with one another
   b. Contrast this with work on mechanics before Galileo -- e.g. by the Italian and Dutch -- and even to Galileo, who focused on axioms -- mathematical foundations -- not on conceptual or explanatory foundations

C. Comprehensive Versus Piecemeal Science

1. The other dramatic shift in emphasis we find with Descartes is the demand for a comprehensive explanation of all phenomena

a. Or, judging from the qualification Descartes offers at the end of the *Principia* (IV, 206), at least the broad outlines of such a comprehensive explanation
b. In a way this is what is primarily responsible for his *Principia* seeming so different from the other things we have read from the first half of the 17th century

2. Both Kepler and Galileo were entirely comfortable with engaging in piecemeal science -- i.e. cutting off some comparatively distinct domain of phenomena and constructing theories about it
   a. Kepler: planetary motion, ignoring such things as cometary motion, novas etc., with no explicit defense that this domain is thus isolable
   b. Galileo: even more restrictive theoretical domains, idealizing away from nature, but with an explicit defense that empirical theory will not be forthcoming otherwise
3. Descartes, by contrast, shows a deep distrust of such piecemeal approaches to science not just in *Le Monde* and the *Principia*, but also in his critical comments about others -- e.g. Galileo
   a. "Top down science" insofar as at least the broad outlines of an overall comprehensive theory need to be in place before turning to such limited phenomena as magnetism
   b. Descartes' reason clear: thinks theorizing about limited phenomena inadequately constrained otherwise, and hence cannot be successful
4. The common response to this aspect of Descartes -- e.g. by Drake in his response to Descartes' critique of Galileo -- is simply to say that he was a philosopher and not an empirical scientist
   a. That is, Descartes' insistence on comprehensive instead of piecemeal science was nothing but an unfortunate vestige of his scholastic education and of his view that the goal is to replace the Aristotelian scheme with a new such scheme
   b. The trouble with this response is that it brushes aside all questions about whether there is any sort of valid scientific reason to adopt such a top down approach
5. This raises the question, did Descartes have any strictly "scientific" reasons for objecting to piece-meal science and insisting on a more comprehensive approach
   a. For example, could he have argued that only in this way will high quality empirical evidence be possible
   b. Given the struggles with evidence at the time, not a wild idea
   c. We have added reasons for raising this question and keeping it in mind as we proceed, for questions about top-down versus bottom-up science persist today in many fields

D. The Legacy of Descartes' Mechanics
1. The mechanics Descartes laid out in Part II of his *Principia* left a notable legacy
   a. I.e. ideas, principles, and approaches that became central to 18th century mechanics -- what we now call "Newtonian mechanics"
   b. Whether in the hands of those who took his insistence that mechanics be rooted in metaphysics seriously, or in the hands of those who preferred to divorce mechanics from metaphysics

2. Part of legacy: the notion of a conservation principle -- some quantity the total amount of which must remain constant throughout the universe
    a. For Descartes, conservation of total motion, owing to fluid-filled universe and constancy of God
    b. A sidelight of the mechanical philosophy: some quantity being exchanged while keeping the total constant a requisite for a mechanical universe!
    c. (Give some thought to the evidence problem in establishing any such conservation principle)
3. Part of legacy: idea that all curvilinear motion requires some sort of intervening action to prevent it from being rectilinear (III- 56-59), authorizing an inference from the contrapose of inertia
    a. Descartes' chief contribution to our principle of inertia
    b. Curvilinear motion involves a "centrifugal" (the word is Huygens's) tendency or endeavor -- *conatus* -- that must be counteracted to maintain curvilinearity
    c. A source of confusion, originating in Descartes, for, as we shall see below, he speaks both of a tendency of motion to continue in a straight line and a radially outward tendency
4. Part of the legacy: proposal that the endeavor to recede from the center can be measured by the tension in e.g. the sling or rope restraining the object!

    "We see, too, that the stone which is in a sling makes the rope more taut as the speed at which it is rotated increases; and since what makes the rope taut is nothing other than the force by which the stone strives [*conatur*] to recede from the center of its movement, we can judge the quantity of this force by this tension" (III, 59) [Millers' translation]

    a. Descartes says nothing about how to measure the tension in the rope
    b. But the science of statics did provide ways of measuring the tension in ropes in e.g. pulleys, so that the suggestion was not off-the-wall at all, as we shall see below and later in the course
    c. For both Huygens (1659) and young Newton (ca. 1666) independently picked up on this idea, leading them into the modern mathematical solution for uniform circular motion
5. Part of legacy: the importance of the mechanics of impact
    a. In mechanical philosophy the only forces are ones of contact
    b. Hence the laws of impact become laws of motion
    c. A great deal of attention given to these laws over the 20 years or so following Descartes' death, by such notables as Huygens (mid-1650s), young Newton (mid-1660s), Wallis, and Wren
    d. Usually restricted to the laws of head-on impact of spheres -- just the simplest case
    e. {Given the diversity of shapes of particles in Descartes' scheme of things, clearly need a generalization to other forms of impact as well}
6. Descartes also had a notable effect on the already widespread discussions of the mechanism of gravity among the adherents to the mechanical philosophy
    a. Heaviness -- the tendency to fall -- the prototypical natural quality which mechanical philosophers had to replace by a contact mechanism

b. Descartes' idea of some sort of vortex motion caught on widely

c. Question: how far does the effect extend above the surface of the earth, and is it uniform or does it diminish with distance

(1) Descartes thought this should be settled by experiments

(2) As we shall see, others tried to do so

d. Question: is gravity truly directed radially toward the center of the earth, and if so why

(1) Descartes had to fashion a special explanation for why a vortex that moves in parallel with the rotation of the earth on its axis does not produce a gravitational effect directed toward the axis

(2) Others found his explanation inadequate, leading to alternative versions of the vortex theory of gravity

7. Descartes' views about gravity challenged Galileo's (and the earlier Beeckman-Descartes) account of vertical fall

a. Descartes: once body reaches high enough velocity, effects of vortex on its top and bottom become equal, giving a terminal velocity after short distance of fall

b. Independence of weight from freedom of globules to pass through lower density bodies

c. Account directly challenges idea of separating fall in absence of air resistance from resistance effects -- a false dichotomy on Descartes' view

8. Finally, as is already clear, Descartes' mechanics engendered interest in the motions of fluids, especially the vortex motion of fluids

a. Contrast between isolated bodies contacting one another and bodies surrounded by fluid contacting one another

b. On Descartes' view former a conceptual idealization with no counterpart ever in reality

E. The Problem Addressed by the Vortex Theory

1. To begin assessing the adequacy of Descartes' foundations of science and the value of his top-down approach, we need to turn to his substantive science

a. In particular, to the vortex theory of planetary motion, which is really part of a broader, comprehensive vortex theory of the entire celestial realm

b. For this is the specific scientific theory put forward in the *Principia* that had by far the most influence

2. This theory is also something that is different from and complements the various efforts of Kepler and Galileo

a. Kepler and Galileo offered accounts of our planetary system, but not remotely as extensive in scope as Descartes'

b. Both of them, like Descartes, were preoccupied with settling the issue raised by the Copernican system, but Descartes' goal clearly did not stop with this or with orbital motion

3. As the title of Part III makes clear, the vortex theory is an account of the entire visible universe
    a. I.e. of the universe to the extent that it is visible to us, excepting those parts from which no light reaches us
    b. Logically prior to dealing with phenomena on the earth, for many of the latter are just manifestations of things covered in the vortex theory -- i.e. phenomena that result from the earth within the cosmos
4. As the earlier ***Le Monde*** makes clear, Descartes saw the vortex theory as offering both a resolution to the issue of Copernicanism and an account of the nature of light
    a. The interplay of planetary motion and light in the earlier work -- in particular, the support each lends the other part of the theory -- is a critical element
    b. Indeed, perhaps the element of the theory that Descartes thinks represents its greatest virtue -- the main advance it offers
5. In the process, however, he is equally giving us a cosmology to replace that of the celestial spheres
    a. And, like that cosmology, it must first and foremost explain the motion of the planets, including their various irregularities
    b. In this regard his project is closer to Kepler's, and is attempting to fill a gap that is clearly not filled in Galileo's *Dialogue*

II. The Vortex Theory of the Heavens

A. The Basic Picture of the Vortex Theory

1. An argument from analogy lies behind the vortex theory, specifically an analogy with water vortices or whirlpools, which carry objects along with them in orbits [30]
    a. Objects carried along often induced to rotate in vortices about their own center -- Descartes' straw
    b. Such vortices not perfectly circular, but instead continually undergoing small fluctuations
2. The argument gains much of its force from two constraints, which Descartes is imposing on all explanations of planetary motion
    a. By virtue of the laws of motion, *something* must be resisting the centrifugal tendency (conatus) of the planets, forcing them into curvilinear orbits: inference to something even if unseen
    b. That something must be material bodies impacting the planet and maintaining it in an orbit
    c. Given these two constraints, the one naturally occurring phenomenon on earth that meets them is the obvious starting point for further theorizing
3. The universe consists of a large number of such three dimensional vortices pressing on one another, each with a distinct polar orientation [Figures VI and X]
    a. Poles generally not aligned, for if they were they would join to form a single vortex
    b. Different vortices are of different sizes and strengths, resulting in a complex, three-dimensional dynamic structure

4. This structure arose from a process in which matter formed into three distinct types as a consequence of the initial circuits of motion that God introduced into the universe
   a. First type: extremely small, high speed slivers that formed in the process of filling interstices -- the sole matter of the sun and stars
   b. Second type: small spherical globules, larger than that of the first type, though small by comparison to matter on earth -- the material of the heavens, varying in size and speed
   c. Third type: larger particles of matter, forming planets and the sensible objects around us, including air
5. At the center of each vortex is a star -- a body made up of matter of the first type in intense agitation, rotating at high speed, and hence pressing against the globular matter surrounding it
   a. Spherical in shape because of the tendency to recede, on the one hand, and the ability of these elements to occupy comparatively ideal spaces because of their small size, on the other
   b. Matter of second type surrounding the spherical star rotates too, but because of larger size, some slippage in speed from resistance effects
6. The various vortices interact with one another, with matter of the first type passing between them, and matter of the second type of adjacent vortices pressing on one another
   a. Matter of the first type circulates, entering a vortex radially at its poles and centrifuging outward at the equator
   b. Basic centrifugal stability of any vortex arises from effects of contiguous vortices pressing on it -- no where for this matter to go in spite of its centrifugal tendency
   c. But this is a dynamic process, with continual variations in the overall shape of a vortex and in patterns within it as a consequence of impact effects from matter of adjacent vortices

B. The Sun, the Planets, and their Satellites
1. Our planetary system one such vortex, with sun at its center and the various planets orbiting in a comparatively small circle near its center [circle HQ in Figure X]
   a. Provides an immediate explanation for why all the (known) planets orbited in more or less the same ecliptic plane: a preferred direction of motion
   b. Total size of vortex huge compared to radius of outermost planet; vortex unable to support planets in equilibrium at more remote reaches
2. The planets themselves are former stars, formed when sunspots enveloped them, interfering with the centrifugal pressure exerted by the star on its surrounding globules and thus allowing neighboring vortices to intrude and destroy the original vortex
   a. Once planet (or comet) formed and vortex around it collapses, engulfed by and moves within adjacent vortex
   b. Planet when it migrates to a point where it reaches an equilibrium of motion with the surrounding globules of the planet

3. Speed of globular particles varies with distance from Sun in a way that accounts for the variation in planetary periods
   a. Primary effect is centrifugal tendency, so that higher speed globules migrate to outside of vortex
   b. Rotation of sun augments motion of globules near it, causing them to move fast; these globules are small, for otherwise they would migrate to a higher radius because of centrifugal effects
   c. Speed thus diminishes until reach a point where globules all of the same size, beyond which speed increases [HQ in Figure X]
4. Moon and other satellites are just planets orbiting the Earth and Jupiter, instead of orbiting the Sun
   a. Satellites have same density as principal, and hence should circulate at same distance from the sun, but owing to their smaller size tend to move faster
   b. Only way to satisfy both conditions: moon orbits the earth, inducing a vortex of globules along with it, resulting in a vortex within the main vortex [Fig XV]
   c. Irregularities of motion of moon from eccentricity of vortex with respect to earth (153)
   d. Two accounts of the earth's rotation: induced by vortex associated with the moon's motion around it, and a residual consequence of its prior rotation as a star
   e. Tides related to Moon: IV, 49-56 [Figure XIX]
5. This is all a dynamic process in which local variations would constantly occur because of interactions with adjacent vortices
   a. Short term changes from vortex variations, and long term changes from gross alterations in the structure of the cosmos
   b. Account thus gives a natural way in which solar system could have formed, exhibit both regularities and continual small fluctuations, and be subject to gross long term changes!

C. The Physics of Curvilinear Motion

1. Descartes struggles in III 56-59 to explain the tendency to recede from the center of motion in curvilinear motion, culminating in the seminal passage quoted above

   "And we experience the same thing with the sling: by means of the greater speed, to be sure, at which the stone in it rotates, the rope is stretched all the more; and indeed this tension, given rise to by the force alone by which the stone endeavors to recede from the center of its motion, displays to us the quantity of force of this kind." (III, 59) [my translation]

   "Idemque etiam experimur in funda: quo celerius enim lapis in as rotatur, eo magis funis intenditur; atque ista tensio, a fola vi qua lapis recedere conatur a centro sui motus exorta, exhibit nobis istius vis quantitatem."

2. Descartes here speaks of "the force by which the stone endeavours to recede from the center of its motion," identifying it as that which issues forth in the tension in the rope of the sling
   a. The word *conatur* and the corresponding *conatus* the Millers translate as "striving," but it can equally be translated as "endeavor," "effort, "or even "tendency" insofar as Descartes himself offers the alternative "*tendere*" in Article 57

b. I tend to prefer to retain the Latin *conatus* to simplify matters

c. But do notice that Descartes speaks of the *force* of this *conatus* as giving rise to the tension

3. Descartes speaks of the need to recognize several tendencies or endeavors in Article 57 (Plate VIII), most notably the tendency to continue motion uniformly in a straight line along a tangent (i.e. from A toward C in the figure) and a tendency to recede radially from the center (from A toward D)

   a. As the Millers and many others have noted, he is here probably initiating some confusion, for the only tendency that the sling is hindering is that toward C; there is no tendency toward D

   b. But that tendency toward C does involve receding from the center (along BC and FG), and hence the phrase "tendency or endeavor to recede from the center" is not improper

   c. That is the tendency or endeavor I am calling the "centrifugal" tendency, using Huygens's term

   d. We shall see later how first Huygens and then Newton (and Hooke) clarify what is going on here

4. The phrase the Millers translate as "we can judge the quantity of this force by this tension" is literally "that tension displays to us the quantity of this kind of force"

   a. The first key notion here is that of this kind of force being or having a quantity, a measure so to speak, as earlier we saw quantity of force given by Descartes as Δ(B$*$speed)

   b. The second is that this quantity is displayed to us by its effect, namely the tension in the rope

   c. The idea, then, is that the quantity or magnitude of the *conatus* to recede from the center in curvilinear motion can be determined by the magnitude of the tension required to counteract it

5. The idea of measuring the quantity of a tendency toward a particular motion by the tension in a rope required to counteract that tendency, maintaining static equilibrium, was not novel

   a. Consider for example how Galileo invoked a weight hanging from a pulley at the top of an inclined plane to measure the reduced tendency of a given sphere on the plane toward motion

   b. The tension in the string or rope is specified by the weight required to maintain static equilibrium

   c. One can extrapolate from this (Stevin's triangle) to conclude that the tension in the rope can specify the quantity of the *conatus* of a given sphere to descend versus angle of inclination or, in Descartes' case, the *conatus* of a given stone to recede from the center versus its speed

D. The Underlying Physics of Orbital Motion

1. The physics underlying the orbital motion of the planets is just the physics of a sustained fluid vortex

   a. Key question for Descartes is what mechanism offsets the centrifugal *conatus* of the fluid in the vortex, the *conatus* that is characteristic of all curvilinear motion [56-60]

   b. Answer: any one globule is restrained centrifugally "by the other globules beyond it in the same way as the stone is restrained by the sling." [60]

   c. At outer edge globules restrained by action from globules of adjacent vortices

2. End up with complex equilibrium, in which forces [*vires*] from inner globules add to the centrifugal tendencies of outer ones, to be counterbalanced from outside

a. What we would call a varying force (or pressure) field in which globules at every distance and speed in equilibrium -- just enough resistance from globules outside to offset combination of centrifugal tendency and forces from inner

b. Size and speed of the globules then dictate where they will end up radially within the vortex

3. Planets are carried along by the globules surrounding them in just the way that objects are carried around in a fluid vortex [140]

a. Equilibrium: where solidity and motion of planet matches that of globules surrounding it

b. If closer to the sun, surrounded by smaller, faster moving globules unable to resist its tendency to recede from center

c. If further away, surrounded by slower moving globules which would decrease its tendency to move off in a straight line, and hence would force it back toward the sun

4. In effect, then, a fluid buoyancy account in which the complicated "pressure" field of the vortex accounts for where planet is in equilibrium with the ethereal fluid surrounding it, in accord with the rules of impact

a. If planet never initially arrives within circle of decreasing speed nearer the center, then a comet with no equilibrium

b. Comets accordingly are not in orbits about the sun (a conclusion in concert with Kepler, who had said that their trajectory approximates a great circle, and hence perhaps a straight line)

c. Once it arrives within this circle, in effect finds a point of equilibrium consistent with its own density [121-125, 147]

5. Secondary effects then account for vagaries in the planetary orbits

a. Space around the sun is not perfectly circular, owing to interaction with other adjacent vortices

b. Flow of matter of first type from vortex to vortex, disturbing globules and hence altering "pressure" field

c. Interaction between planets and matter of first type, as e.g. in magnetic effects from grooved particles

d. Prior movements of the planet, which it retains, such as rotation disturbing fluid surrounding it

e. Because of size, planetary motion tends to dominate globules contiguous to it (according to the rules of impact)

6. Obviously Descartes had to devise an account of the varying capacity of the globules forming the vortex to resist the centrifugal *conatus* of planets near enough to the center, but not comets further away from it

a. The details of this story are less than obvious from the text, suggesting that few really understood, much less critically assessed, his account of vortex motion

c. A careful, sympathetic reconstruction has been given by John Schuster, along with an explanation for why historically at the time it would have seemed reasonable to Descartes

E. The Physics of Light and Its Transmission

1. Vortex theory supplies an answer to a further question of interest at the time: what does light itself consist of
   a. Light is seemingly immaterial, and hence a potential problem for mechanical philosophy
   b. Light is known to have a growing number of properties, many of them detailed with geometric precision in Descartes' *Optics*
   c. Light is generated from the sun and stars, and reflected off other planets and their satellites
2. Sun rotating, with all its particles of the first type striving to recede from its center, but impeded by globules of the second type
   a. Pressure thus exerted on globules of second type
   b. This pressure transmitted in straight lines without movement in normal situations
   c. This pressure is what we call light
3. Pressure on the retina, with sources from reflection and with various refractory effects, account for optical phenomena
   a. Descartes derives laws of optics from this account of the underlying phenomenon in his *Optics*
   b. A purely mechanical account, challenging the corpusculareans to duplicate it (as both Huygens and Newton tried to do)
4. Descartes' theory of light transmission a good deal more complicated than this account suggests
   a. Interaction between particles of first two types to account for light propagating from the sun in all directions (though Descartes says weaker toward poles, and offers possible observations of comets that would confirm)
   b. Descartes does not expressly say so in the *Principia*, but everyone took him to be saying that propagation instantaneous, for like pressure exerted on rigid bodies (save for "breakage" into smaller particles)
   c. The implied claim that light transmits instantaneously will be important later
   d. Account raises questions about true positions of other fixed stars -- questions arising because of refraction effects at interface between vortices [131]
5. Descartes' ability to give an integrated account of light, including generation and transmission, a compelling feature of the vortex theory
   a. Not a late add on: *Le Monde, ou Traité de la lumière*
   b. Obvious implications for observational data, as in questions about true locations of other stars

F. Explanations of Other Cosmological Phenomena

1. Another special virtue of the vortex theory was the extent to which it provided answers to a wide range of other cosmological phenomena besides the physics of planetary motion
   a. A single integrated account of several cosmological phenomena that were largely ignored in classical and Keplerian accounts of planetary motion

b. Providing a good deal of further evidence for the basic theory -- via its ability to account for a variety of phenomena, and not just those of primary concern

2. For example, it offers a straightforward account of the formation, movement, and disintegration of sunspots [88-103]

   a. Particles of first element, of irregular shape, in effect hook together, acquiring the character of matter of the third type by agglutination

   b. They form near the poles, where there is less motion, but then migrate to the surface, forming sunspots until they are dissipated by agitation from the matter of the star

   c. An atmosphere surrounding the sun retards them, accounting for their slow rotation

3. Similarly, offers a straightforward account of novas and "deaths" -- i.e. disappearances -- of stars [104-114]

   a. Nova: star covered by spots expands from interaction with adjacent vortices, allowing matter of first type to escape through interstices

   b. If then star recompressed from action of adjacent vortices, agglutinated matter can close up, allowing no more matter of the first type to exert pressure as it endeavors to escape

4. Offers not only an account of what comets are and why they pass through the solar system, but also of some of their peculiar properties [126-139]

   a. Same as planets, but with a combination of speed and density that prevents them from reaching an equilibrium orbit

   b. Hence pass from one vortex to another within the cosmological structure

   c. Note the nearly straight line path through each vortex shown in the figure

   d. Complex optical (refraction) account of the tail [133- 139]

5. Finally, Descartes' account of terrestrial gravity is in fact a further aspect of his celestial vortex theory, tying terrestrial to celestial, for basic mechanism arises from the motion of the ethereal globular elements [IV, 20-27]

6. The overall account, like that of Kepler's, allows various special features to be added to explain special phenomena, and hence in a sense is not strictly unified

   a. On the other hand, it covers phenomena of so many different sorts, all built around the motion of three types of matter and consequent fluid mechanical effects, that the introduction of special features to explain anything in one area threatens explanations in other areas

   b. The extent to which it can cover diverse phenomena thus lends it evidential support to a greater degree than we saw with other such accounts -- e.g. Ptolemy and Kepler

G. Subsequent Variations of the Theory

1. Descartes initiated the vortex theory, but it then gained a life of its own, with variations put forward not only by Cartesians, but also by those like Huygens who would have rejected the title "Cartesian"

   a. As remarked earlier, still seen 120 years later, in no lesser hands than Euler's

   b. Almost certainly because it was the one total cosmological account, and hence was an obvious starting point for various conjectures
2. Even before his death, one of Descartes' followers, Regius, published a version adhering to Descartes' accounts of the phenomena, but now treated as mechanical hypotheses, with no reliance on general a priori principles
   a. Descartes repudiated this work, rejecting Regius as a disciple
   b. "This separation of physics and metaphysics effected by Regius set a fashion, however, that was followed by other disciples of Descartes" such as Rohault (Aiton, p. 217)
   c. One should notice that, even as put forward by Descartes, the vortex theory, though constrained by the fundamental universal laws of nature, is overwhelmingly an empirical theory -- the arguments in Part III are almost exclusively empirical
3. As with Descartes, no attention to detailed orbital theory in these subsequent efforts
   a. E.g. Malebranche: denies that the periodic times are "entirely in the proportion of their distances" in the first five editions of *Recherche de la verite*
   b. No interest in ellipse, until after Newton's *Principia*, presumably because vortex theory suggests that no single trajectory permanent
   c. But Leibniz offers a vortex account of elliptical orbits in the late 1680's, claiming (falsely) to have developed it before he saw Newton's *Principia*
4. Much more attention to a vortex theory type account of terrestrial gravity, especially on the part of Huygens in 1669 (as part of a series of special sessions on gravity at the Academy), and continuing straight through to his 1690 publication of his *Discourse on the Cause of Gravity*, which expanded on his 1669 account
   a. A more sophisticated, detailed theory, departing from Descartes', but able to account for a variety of secondary effects
   b. E.g. constant acceleration of falling bodies, as in Galileo, and variations of pendulum periods observed by Richer in the expedition to Cayenne
5. Such comparative success of the vortex theory, even at the hands of an atomist like Huygens in a work published together with his *Treatise on Light* announcing his (longitudinal) wave theory of light, helped keep it in the forefront way past the time when Descartes' mechanics had ceased being taken seriously
   a. Of course, the vortex theory not that dependent on Descartes' mechanics
   b. For he uses arguments by analogy with fluid vortices in order to bypass the derivations that would have tied his theory more to his mechanics
   c. I.e. Descartes never offers a mechanical account of fluid vortices themselves, nor do any of his immediate followers, instead proceeding just by analogy with observed phenomena and devising details as needed to explain phenomena

H. Descartes' Vortex Account of the Tides

1. A still further phenomenon for which Descartes invoked his vortex theory is the ebb and flow of the seas, but in Part IV rather than Part III
   a. Giving us a third astronomy-related account of the tides, in addition to those of Kepler and Galileo, though independent of the latter's insofar as it was already present in *Le Monde*
   b. The reason why this terrestrial phenomenon is being given astronomy-related accounts by all three is that the patterns of high tides correlate with the positions of the moon and sun
   c. Descartes' account is like those of Kepler and Galileo in making the moon's location crucial, but it differs not only from theirs otherwise, but also from Newton's subsequent account
2. The problem posed by the tides: high tide occurs twice a day (in most places), a little more than 12 hours apart, with a monthly cycle that correlates with the rotation of the moon around the earth
   a. High tide at any place is delayed typically an hour or so after the moon crosses the meridian
   b. Highest tides typically occur during full moon and new moon, though both the heights of the tides and patterns of variation differ from one place to another
   c. In addition to the latter variation, the height of the highest tides displays an annual variation
3. Descartes' account [IV, 49-56] invokes the effect of the presence of the moon on the motion of the vortex around the earth that carries it; in particular, the reduced space for the vortex to flow causes the fluid in it to move more swiftly at the line between the moon and the earth
   a. One effect of this is a displacement of the earth away from the moon along this line (resembling to some extent Galileo's thought that the moon and earth are moving in orbit around their common center of gravity)
   b. As a consequence, the space for the vortex to flow across the line from the moon to the earth extended to the other side of the earth is also reduced, with the result that the fluid moves more swiftly on the reverse side of the moon as well
   c. The swifter the fluid matter in the vortex, the more pressure it exerts on the surfaces of both the air and water, causing the water to recede on both sides of this line
   d. (Two problems: Daniel Bernoulli's law says that the pressure in a fluid varies inversely with its velocity; high tide occurs closer to the ends of the diameter of the earth that extends to the moon than the diameter 90 deg away from it)
4. Other features of the tides Descartes then presents as derivative from this basic mechanism:
   a. The time between high and low tide is a little greater than 6 hours because the moon moves forward in its orbit as the earth turns [IV, 50]
   b. Tides highest for full and new moon because vortex not perfectly round [IV, 51]
   c. Tides are higher at equinox because it is then that the plane of the earth's equator intersects the plane of the moon's orbit [IV, 52]
   d. Local variations from local variations in depths near shores [IV, 56]

5. Notice the feature common to three accounts: a celestial cause of a terrestrial phenomenon
    a. Not a wild sounding idea, if only because of the long-standing tradition of astrology
    b. Regardless, explaining the tides became a demand for astronomical theories

III. Ramifications of the Vortex Theory

A. A Candidate for the Underlying Physics

1. One thing that makes Descartes' vortex theory so important is that it offers a coherent, plausible alternative to the defunct crystalline sphere cosmology
    a. Descartes offers not just a new world picture, but a unified explanation of why that picture makes sense physically
    b. In this respect, the first real alternative to the old cosmology and late 16th century variants on it
2. Kepler's magnetic account of the physics underlying planetary motion could perhaps be considered an alternative too, but in the 1640's it had comparatively few adherents, for a combination of reasons:
    a. It was always regarded as ad hoc, with little independent evidence or rationale behind it
    b. People were unable to duplicate some of its required magnetic effects in experiments, such as a magnetically induced rotation appealed to in explaining the rotation of the earth, not to mention a magnetic flux around rotating bodies that puts other bodies into motion
    c. It was inconsistent with mechanical philosophy, hence saddled with an added burden of proof
    d. It was not in strict keeping with the principle of inertia that was coming into vogue -- in particular, it offered no account of what deflects bodies into curvilinear motion
3. Descartes' vortex theory, by contrast, was completely consistent with the mechanical philosophy, and it was responsive to the problem of centrifugal tendency
    a. Of course, it was ad hoc in many ways too, for it scarcely derived from Descartes' third law of motion or rules of impact, and it failed to address specifics of the orbits in the way Kepler had
    b. But much of it seemed dictated by the mechanical philosophy, lessening the ad hoc character, and other details were then inferred fairly directly from phenomena
    c. And it was built off a terrestrial phenomenon less mysterious than magnetism, namely fluid vortices, supported by the inference that something, even if unseen, acts on orbiting bodies
4. The picture of the universe it offers contrasts with both Kepler's and the older picture in ways that made it appear less simple-minded and more interesting
    a. E.g. no sphere of the stars, but separate star-centered systems all over the place, at indefinite distances
    b. A systematic, natural account of comets and of the origin of the planets
    c. With an account of light as an integral part of the story
5. One final contrast: a dynamic, doubtlessly evolving system, but subject to basic constraints from the fundamental principles of motion
    a. New comets, novas, deaths of stars, capture of satellites, etc.

b. Much more consistent with what was being learned than the old perfect static system was

c. But still compatible with the perfection and immutability of God

B. An Attempt to End the Issue of Copernicanism

1. In the same spirit as Kepler in the *Apologia* and *Astronomia Nova*, Descartes recognized the obligation of any account of the physics underlying the planetary system to resolve the issue of the chief world systems

   a. Descartes himself was a Copernican, as *Le Monde* makes clear

   b. But he was also a devout Catholic, and hence for political reasons, if no other, he was in need of a solution that the Church would not object to

2. He joins others in rejecting the Ptolemaic system simply because it does not accord with (telescopically) observed phase phenomena, especially Venus

   a. Note that he takes the trouble to distinguish, with empirical arguments, between bodies that give off their own light and those that give off only reflected light

   b. Thus a new basis for distinguishing planets from stars and grouping the sun with the stars

3. Descartes' argument against Tychonic system grants that it yields same relative position predictions, but claims that it must in fact attribute "more motion" to the earth [38, 39]

   a. Motion here means displacement relative to contiguous elements [II, 25]

   b. Diurnal motion of heavens entails relative motion at interface with earth, and because latter so much smaller, more proper to conclude that it moves

   c. Since other planets are carried around the sun by fluid motion, Tychonic would have to postulate some remarkable action by which the earth is separated from fluid motion, implying it is moving even more with respect to the fluid surrounding it

4. Descartes' argument for the Copernican initially holds that it is simpler and clearer, but he subsequently supports this claim with the simplicity of the vortex (and vortex within vortex) picture [Figures IV and V]

   a. This picture is simple compared to how vortices must work in the Tychonic system, where have primary vortex around earth and secondary around sun, extending past Earth

   b. Not to mention the fact that the inner planets move in the opposite direction from the outer!

   c. An anti-Tychonic line more forceful than the one Descartes chooses to present

5. Descartes' solution for the Church: earth does not really move at all, in the strict sense, for no relative displacement between it and the fluid contiguous to it either in rotation or revolution, and hence no violation of Scripture [95]

   a. Motion e.g. from the point of view of observers outside the solar system

   b. But this is compatible with the Scriptures, for only the strict sense of motion is relevant to them

   c. {Scholars disagree about whether Descartes himself took this solution seriously or thought of it as a mere subterfuge}

C. A New Fundamental Question About Planetary Motion

1. When Kepler originally argued that astronomy is a part of physics, he was insisting not only that physics resolve the dispute among the systems, but that it also settle questions about the precise trajectories of the planets and the moon
   a. From the point of view of the second of these demands, the planetary mechanics of Descartes' vortex theory shifts to a new basic question
   b. Not why the planets go round in a regular manner or why motion itself is maintained, but why they do not go off in a straight line
2. After Descartes, the centrifugal tendency was viewed as a basic feature of all curvilinear motion, posing specific as well as general questions
   a. Why curvilinear at all takes priority over other questions
   b. An end to Platonic perfect circles requiring no explanation
   c. Why specific curvilinear trajectory becomes secondary, to be answered via some specific variation on the answer to the first
3. Descartes contrasts with Kepler here, who in no way addressed the question of why curvilinear rather than straight
   a. Main "anti-centrifugal" element in Kepler involves a varying force of attraction needed for an ellipse rather than a circle
   b. Obvious post-Cartesian move: let this force be responsible for curvilinearity generally (for Keplerian flux driving planets will not do the job since it is not perpendicular to the motion)
4. Impact: those concerned with physics of planetary motion became more preoccupied with the mechanism responsible for curvilinear trajectory than with the mechanism dictating the specific oval
   a. Indeed, they were even comfortable posing this basic question for circular orbits
   b. In the process letting second-order effects or variations in basic mechanism account for deviations from circularity
5. Another question that becomes more important because of Descartes' vortex theory is whether our solar system is stable at all
   a. Kepler worried about the perfectibility of planetary astronomy, and not about basic question of stability
   b. But, given Descartes' account of how the centrifugal tendency is balanced, appropriate to ask about radical changes in motion of the planets
   c. And the account of the death of stars and vortices adds all the more reason to ask this question

D. The Implicit Challenge to Kepler's "Laws"

1. Even without the stability issue, Descartes' vortex theory raises serious questions about Kepler's "laws" -- specifically, about their nomologicality, their character as approximations, and their range of application

"We must not think that ... the circles [the planets] describe are absolutely perfect; let us instead judge that, as we see occurring in all other natural things, they are only approximately so, and also that they are continuously changed with the passing of the ages." [34]

"... But, a few centuries from now, all these things will be observed to have changed from the way in which they are now" [36] -- pertaining primarily with precession of aphelia

"For, inasmuch as all the bodies in the universe are contiguous and act on one another, the movement of each is affected by the movements of all the others and therefore varies in innumerable ways." [157]

2. One question here is whether Keplerian motion is ever compatible with Descartes' vortices
   a. Descartes never addresses this as such, though he does specify several Keplerian features, like non-circularity and the way Kepler handles latitudes, in Articles 34-37
   b. But he does leave more than enough room by granting non-circularity and satisfying the basic phenomena with regard to periods and distances
   c. Still, no specific account of the area rule or of elliptical trajectories (nor of the 3/2 power rule), so that the question whether the vortex theory is compatible with Kepler is left somewhat open
3. A different question: could Keplerian motion be a mere epochal curiosity or parochialism, so that different ovals and velocity rules will hold in the future
   a. Even if Kepler's account highly correct for the motion at the time, Descartes' vortex theory offers no mechanism underlying it, and hence offers no reason to think Kepler's generalizations should be taken to be nomological
   b. Worse, deviations from these generalizations are to be expected, given the analogy with fluid vortices, which assume all sorts of varying shapes [30]
4. One implication of the vortex theory, then, is that no special significance should be attached to Kepler's first two "laws"
   a. They are not a basis for inferences about the underlying physics
   b. They are not even a basis for distinguishing primary from second-order effects
   c. In short, the vortex theory undercuts their evidential value entirely
5. An added worry: even independently of the above considerations, there is no reason to regard the 3/2 power rule as a general feature of orbital systems
   a. The period-distance relation is peculiar to the "pressure" field and to densities of the planets
   b. So, even if it holds for our system, there is no reason in the physics for why it should hold for other orbital systems
   c. That is, Descartes' theory entails that Kepler's 3/2 power rule is an accidental feature of our system -- just as Kepler's account of this rule does
6. The impact of all of this, in some circles, was much less interest in the exactitude of Kepler's laws and in what can be learned from them than Kepler had thought appropriate

a. Of course, others had fed this tendency -- Galileo's remarks on the accuracy of the orbits in the "Fourth Day" of the *Dialogue*, and Kepler's remarks in the Preface to the *Rudolphine Tables*

b. But Descartes is pushing this line of thought much farther than either of those two did

c. As we shall see, his doing so had some consequences -- most notably for Huygens

E. A New Set of Basic Questions for Cosmology

1. The old cosmology had a limited range of questions to which it supplied answers

   a. E.g. why do all the stars remain in their relative positions, and why do the basic regular patterns of motion recur -- from Ptolemy's *Planetary Hypotheses*

   b. Descartes' vortex theory has cosmology addressing a new, radically expanded set of questions, in the process transforming the discipline

2. New questions about the origins of the cosmos and solar system, and long-range trends within both

   a. For Descartes it is fair game to speculate about origins, for once the world is set in motion, it takes its own course

   b. Speculation here consists of inference back to possible origins -- conceptually possible and compatible with the current state

   c. Equally, inferences forward to possible long-term futures

3. Questions about physics of sun and stars, the objects that are central to the modular vortex structure

   a. How they give off light, and their role in the vortex structure

   b. The "birth" and "death" of stars -- novas and other sidereal changes

   c. The formation, propagation, and evolution of sunspots and other observed vagaries

4. Questions about the structure of the universe beyond our solar system

   a. The old question was whether all the stars were on a single sphere or in some broader region

   b. Descartes opens the way to questions about complex structures elsewhere, interacting with ours and giving light to ours

   c. What is the general structure of the (nearby) universe

5. These questions are to be addressed speculatively, via hypotheses and available empirical evidence; but still an empirical program, especially for those who regard Descartes' proposed answers as one among other possible ones

   a. As Descartes himself suggests, the combination of constraints from what is possible and what exists now, related through fundamental laws of nature, provides an adequate evidential base to make this program something other than empty speculation

   b. The set of questions and the general approach to them that he proposed has remained in the forefront ever since, framing cosmology

   c. High quality answers have been forthcoming mostly within the last 120 years, as more became known about the fundamental laws of physics and more empirical information became available through technological advances in science -- e.g. spectrometers

F. A New Evidential Standard in Physical Astronomy

1. Over a roughly 50 year period Tycho and Kepler had created a new evidential standard in astronomy, replacing the 1400 year old standard set by Ptolemy's *Almagest* and *Planetary Hypotheses*
    a. General quantitative agreement with salient phenomena, constrained by requirements of physical plausibility, no longer enough (Galileo's *Dialogue* notwithstanding)
    b. The new standard required comprehensive and detailed quantitative agreement within, or at least broaching on, observational accuracy
    c. This standard gained ascendency in the 1630's following the observed transit of Mercury and subsequent growing appreciation of just how good the *Rudolphine Tables* were
    d. Kepler added the further requirement of a plausible physics of the mechanisms underlying the detailed patterns -- this to select among competing hypotheses and to avoid being misled by observational inaccuracies
2. Descartes' vortex theory undercuts this new standard in significant ways because no value can be placed on precise agreement with observation when what is being observed is not really regular
    a. Precise agreement is not a basis for having confidence either in generalizations like Kepler's "laws" or in hypotheses about the physical processes underlying them
    b. Not only is success in the pursuit of precision not a big deal, but lack of success in this pursuit is no major cause for concern
    c. Pursuit of precision is generally not worth the effort, though there may be notable exceptions where complete explanatory theories emerge
3. Yet Descartes did not really revert to the old standard of just saving the appearances with a plausible underlying physics -- the standard that reigned throughout the Ptolemaic era
    a. He insisted on a complete unified physical cosmology, with the phenomena saved by it, and not by intermediate mathematical hypotheses standing between the physics and the phenomena in the manner of Galileo and the mathematical astronomers
    b. Strength of evidence through the range of phenomena covered by the limited physical mechanisms allowed as possible by the laws of nature
    c. In other words, through completeness constrained by simplicity -- ultimately through the completeness demand of a total unified science
4. Thus, after Descartes there were two competing evidential standards within astronomy
    a. Precision within observational accuracy for geocentric longitudes and latitudes -- adopted by most mathematical astronomers
    b. Comprehensiveness of a unified explanatory system -- adopted by various others, perhaps out of a demand for an overall cosmological picture to replace the Aristotelean one
    c. These two are not straightforwardly reconcilable -- i.e. there is no obvious way of effecting trade-offs between them!

5. These two standards have contrasting implications for how one ought to go about doing physical astronomy and other sciences: piecemeal versus global approaches
   a. Descartes challenges the feasibility of doing piecemeal science on the grounds that not enough proper evidence is going to be available to prevent being led down garden paths
   b. Piecemeal science promising only when one can proceed strictly and rigorously from basic laws, thereby safeguarding against being misled
   c. Otherwise, the only adequate constraints against being misled must come from pursuing a global account
6. This tension between two approaches to marshaling evidence for scientific theories continues to the present day

IV. Cartesian Conceptions of Empirical Science

A. Descartes' Conception of the Problem

1. Reason alone can yield certainty in geometry and other matters, but it can take us only so far toward knowledge of the material world
   a. Geometry provides certainty within the realm of possibility, and it offers a standard of rigor in reasoning
   b. But the actual world -- the one God chose -- cannot be singled out from geometrical and mathematical considerations alone

      "For, seeing that these parts could have been regulated by God in an infinity of diverse ways; experience alone should teach us which of these ways He chose." [46]

   c. The problem is how to bring empirical considerations to bear in a decisive way
2. The problem Descartes saw in turning to the empirical world is reflected in his criticisms of Galileo's *Two New Sciences*

   "He seems to me very faulty in ... never stopping to explain [*explicandae*] completely any matter, which shows that he has not examined things in order, and that without having considered the first causes of nature he has only sought the reasons of some particular effects, and thus he has built without foundation [*fundamento*]. (p. 387f of Drake)

   a. Also, the account of fall is "built without foundation, for first he should have determined what weight is" (p. 390), and the theory is incomplete since it fails to treat pendular motion (p. 391)
   b. One can easily imagine similar criticisms of Kepler's orbital theory, with complaints about the *ad hoc* physics, but even more so questions about the true regularity of the trajectories, versus their being epochal parochialisms, in the absence of proper mechanical foundations
3. The standard reading of these critical remarks (*vide* Drake) is that Descartes was unwilling to pursue a strict program of empirical science; but there is another reading: he was afraid of garden paths in empirical science
   a. He could not help but see Ptolemy as a paradigm of brilliant, yet unsuccessful empirical

reasoning, and he could legitimately ask how Galileo and Kepler had insured against making similar mistakes

  b. He drew the same basic conclusion that Kepler had: the only way to safeguard against such errors is to make sure that the conclusions being drawn were consistent with true physical causes

4. A strong case can be made that, not just for Descartes, but for others in the first half of the 17th century as well, a key issue was how to avoid another garden-path
5. The suggestion, then, is that Descartes' pursuit of a comprehensive causal picture may have been not so much a commitment to a program different from empirical science, as it was a view about how to do successful empirical science
  a. No empirical conclusion is secure unless it is based on a secure causal account of the relevant phenomena
  b. The problem is how to obtain a secure causal account; clearly we cannot just put forward hypotheses based on characterizations of the phenomena, for the insecurity of these characterizations is the source of the problem in the first place
6. One obvious step toward securing foundations for such a causal account is to try to establish universal principles governing all causation in the material world -- i.e. laws of nature
  a. This amounts to identifying which questions truly call for causal answers and what sort of answers to these questions are appropriate
  b. Given his views about the role of reason in "first philosophy," it was natural for him to think that these conceptual foundations could be established *a priori*, via a clear and distinct grasp of the relevant ideas
  c. Grounding empirical science on metaphysics, including metaphysics of God, seemed necessary to him, for metaphysics on the firmer footing
7. Notice, however, that some might have viewed the foundation not as lying in metaphysics and God, but instead in fundamental principles governing motion
  a. E.g., *All departures of any body from rest or from uniform motion in a straight line require an external action or force arising from some other body (in contact with it) that effects a change in motion by transferring some of its motion to the other one, with the aggregate of their total motion remaining the same before and after*
  b. Starting from a principle of this sort, viewed as an empirical claim to be supported by empirical evidence, instead of being derived from metaphysics, is the stance Regius, and various later Cartesians, adopted

B. How To Do Science: the Cartesian Solution

1. The first goal of empirical science ought to be at least a broad outline of the causal mechanisms and processes that govern phenomena, for only then will we be in a position to judge the likelihood that empirical factors are not misleading us

a. But this is just what Aristotle tried to do, and failed

b. The question is how to safeguard against his mistakes

2. One safeguard is to restrict the list of universal, fundamental causal mechanisms as much as possible

   a. The pursuit of clarity and distinctness of understanding is our basic resource for protecting against error; hence should insist that causal explanations yield genuine understanding -- i.e. they leave no open questions

   b. For Descartes, the mechanical philosophy can thus be viewed as a means to an end, and not something he adopted beforehand

3. Through careful analysis of and attention to when we arere gaining true understanding, one ought to be able to establish, at least tentatively, general principles all causal explanations must be based on

   a. These laws and general rules of nature will then constrain causal explanations of particular phenomena

   b. Thus vastly restricting the range of hypotheses that need to be considered in pursuing the more specialized causal processes governing particular phenomena

4. The range of hypotheses can be further constrained by insisting on single, comprehensive account of all phenomena

   a. Requiring the various causal explanations not just to be consistent with one another, but to complement one another in accounting for some phenomena

   "You say that there is nothing so easy as adapting some cause to an effect. But although there certainly are several effects to which it is easy to adapt diverse causes, one to each, yet it is not so easy to adapt one identical cause to several different effects, unless it is the true cause from which they originate. There are even often some which are such that to give a cause from which they can be clearly deduced is sufficient proof of their true cause." [letter to Morin, fn to 42]

   b. In effect, classic detective work in which attempting to infer the best total explanation of the full range of phenomena, including aspects which mislead

   "And we shall know that we have correctly determined these causes when we observe that we can explain [*explicare*], by their means, not only those phenomena which we have considered up to now, but also everything else about which we have not previously thought." [42]

5. Not a hypothetico-deductive logic of evidential reasoning, but one that is highly constrained and regulated versus the standard story of hypothesis formation, deduction, and comparison

   a. Hypotheses are put forward about unseen underlying structures and processes, under the requirement that the overall system of hypotheses be comprehensive and consistent

   b. Principles of geometry and fundamental laws of nature, through which these structure and processes effect their empirical consequences, then allow "explications" of phenomena as part of a larger picture – yielding explanations and understanding of the phenomena

   c. Comprehensive accord with the phenomena then reduces the probability of error, for comparatively few sets of hypotheses can yield a unified comprehensive account of all phenoomena

d. In Descartes' own case, grounding fundamental laws of nature in metaphysics further reduces risk of garden-path

6. Although the *Principia* pursues only qualitative agreement with phenomena, the Cartesian conception is more than just compatible with pursuing exact quantitative agreement, where this is known to be appropriate and not just building on air

   a. The overall theory serves to tell us what is nomological, and hence it safeguards against our jumping to conclusions on the basis of merely apparent regularities

   b. But where appropriate -- as in optics -- exact agreement will provide a high standard of evidence

C. Empirical Dimensions of Cartesian Science

1. That Descartes was indispensably turning to empirical evidence throughout Parts III and IV of the *Principia* is obvious

   a. It is often said that the goal of Cartesian science is to reduce all material processes to geometry

   b. But the vortex theory is not geometry; the evidence put forward for it is strictly empirical, whether in the form of an analogy with everyday fluid vortices or in the form of broadly “hypothetico-explanatory” reasoning to empirical theory

   c. If there is some sense in which it is not empirical, or it is less empirical than say Galileo's theory of natural motion, then that sense is more subtle than is often recognized

2. On the view I am proposing, the main features of the approach taken in the *Principia* represent not a way of trying to avoid or minimize the appeal to empirical considerations, but a way of assuring that those considerations are marshaled most effectively

   a. Descartes is taking on a classic problem in empirical science: to devise a theory of unseen causes from their effects

   b. Admittedly, a lot of the worst science has arisen in the pursuit of such theories; Salviati's response to Sagredo's remarks about impetus in the "Third Day" is well taken

   c. But to deny such theorizing a role in empirical science -- indeed, a central role in much of the most successful science -- is to turn one's back on such things as atomic theory

   d. The question is, how to theorize about unseen causes safely

3. The principal empirical dimension of Cartesian science is the insistence on a single comprehensive causal account of all phenomena

   a. This imposes exactly the same sort of empirical constraint on theorizing as is imposed in standard detective work: inference to the best total explanation

   b. From this point of view, the correct line of response to e.g. the vortex theory is not to dismiss it as so much conjecture, but to show either that it is failing to explain various phenomena or that there is an alternative better total explanation

   c. Either of these responses is clearly empirical, which shows that the vortex theory itself is inviting an empirical response

4. Descartes himself rejected the idea that the foundations of the theory -- the laws of nature etc. -- were empirical, but, as suggested above, the Cartesian concept of science was not viewed at the time as vitiated by allowing a further empirical dimension
   a. Empirical evidence for the foundations -- i.e. for the way of conceptualizing -- via the success in achieving a total explanation of the phenomena
   b. Empirical foundations open to empirical revision in response to recalcitrant phenomena or alternative total theories
   c. Allow the discussion of the adequacy of the total theory to extend to the foundations as well
5. The progressively stronger claims that Descartes makes for his account at the end of Part IV display such empirical dimensions
   a. Minimal defense: even if theory false, it will be as good as a true theory insofar as all its empirical consequences are true -- the best "as-if" theory [204]
   b. Stronger defense: morally certain -- i.e. certain to a degree that suffices for everyday life -- for "it could scarcely have occurred that so many things should be consistent with one another, if they were false." [205]
   c. Strongest defense: at least bordering on mathematical demonstrations, for virtually forecloses any alternative explanation

      "If they sufficiently understand that we can feel no external objects unless some local movement is excited by them in our nerves; and that such movement cannot be excited by the fixed stars, very distant from here, unless some movement also occurs in these and in the whole intermediate heaven: for once these things have been accepted, it will scarcely seem possible for all the rest, at least the more general things which I have written about the World and the Earth, to be understood otherwise than as I have explained them." [206]

D. The Two Senses of 'Theory' in Science

1. Descartes' insistence on having at least the broad outlines of a comprehensive explanatory scheme can also be viewed as a response to the pursuit of empirical evidence, and not just a commitment to philosophical goals (as Drake would have it)
   a. Interlocks diverse areas of research, so that evidence in one area can become evidence in others
   b. Potential for an enormous increase in the range of data that can be brought to bear
   c. Can help safeguard against being misled by phenomena taken in isolation, just as Descartes says in his critique of Galileo
2. Can thus view the basic explanatory scheme Descartes relies on, including the analogy with fluid vortices, as another type of working hypothesis adopted to facilitate empirical evidence
   a. Facilitates taking phenomena and surface data and turning them into evidence about details of underlying mechanisms
   b. Helps in deciding which such data can be trusted, and which should be treated cautiously as perhaps not nomological

3. Bromberger (in, for example, “Science and the Forms of Ignorance”) points out that there are two senses of 'theory' in physics, as contrasted by 'atomic theory' or 'the vortex theory', on the one hand, and 'the special theory of relativity', on the other
    a. Theory_2: question-answering devices, like Kepler’s orbital theory (and Ptolemy’s!)
    b. Theory_1: general account of underlying processes and mechanisms, like Descartes'
4. There are controversies about the importance of theory_1 in empirical science, and assuming it important, what the relation is between theory_1 and theory_2 in the process of developing evidence
    a. Perhaps theory_1 plays only a heuristic role, helping us to motivate and conceptualize research
    b. But then look at modern atomic theory, where such a limited view hard to maintain
5. Main point here is that one can at least argue that the broad outlines of an explanatory scheme can help in the development of evidence, especially in the early stages of theory construction
    a. Constant danger is being led into mistaken conclusions by limited data
    b. By tying different areas to one another, explanatory scheme can reduce this risk
6. Of course, in process must be careful not to let explanatory scheme become a dogma that is impeding rather than facilitating the development of evidence

E. Grounds for Objecting to Cartesian Science

1. What then is so wrong with the conception of science exhibited in Descartes' *Principia*
    a. Reluctant to say that the only thing wrong is that content is false, as we can now so clearly see
    b. Our sense is that something is wrong methodologically -- something that those living at the time ought to have been able to see -- that separates this book from science
2. The one gain we have made is that we have not been so dismissive of the Cartesian conception that we have to be similarly dismissive of all those who at the time found it compelling -- and of others who have found similar conceptions compelling since then
    a. Attention to conceptual foundations -- i.e. to basic why-questions -- legitimate, though undoubtedly want it to be more open to empirical shaping than Descartes did
    b. Goal of unified comprehensive explanatory theory legitimate if only because it will allow more diverse data to be brought to bear
    c. Adopting at least the outlines of an explanatory scheme at the outset reasonable, for need some sort of theory in order to begin marshaling data at all -- e.g. to assess the risk of drawing conclusions from various sorts of data
3. My suggestion for what is wrong with the "science" in the *Principia* is that these elements are not really exploited to the end of marshaling empirical evidence, but instead to the polemical end of excluding alternative approaches and theories
    a. The defense of these elements offered above is that they can enhance the process of turning empirical data into evidence -- e.g. in developing the detailed physics of our vortex system
    b. For example, suppose the rules governing change in motion, together with observations of fluid

vortices, had allowed empirically based inferences about the characteristics of the unseen ethereal fluid forming the vortices or the specific velocity variation versus the radius of a vortex

c. But this is not what the rules are used for; they are used to legitimate a further elaboration of hypotheses by providing a device for warding off potential objections -- this in contrast to allowing empirical factors to warrant further hypotheses

4. Much the same objection is to be lodged against Descartes' laws of motion
   a. The problem does not come just from their introducing a different notion of force -- '*vis*', '*vires*' -- from Newton (and Huygens)
   b. Their whole point should be to provide empirical access to the unseen forces they posit
   c. Whether the way of conceptualizing that they offer is worth adopting can then be evaluated by the quality of the empirical access they provide -- e.g. by converging evidence in support of particular measures of force, etc.
   d. But Descartes goes on to block using them to infer forces from phenomena of motion, because of the complexity of fluid-like motion in a universal plenum
5. I am the first to grant Descartes that elements of theory_1 are indispensable in the early stages of theory construction, and that high quality empirical evidence is hard to come by in the early stages
   a. But the consequent danger of forming a theory "entirely built in the air" -- as he accuses Galileo of -- demands that empirical considerations be brought to bear as early and often as possible as theory is being developed
   b. And this can be done in the early stages by demanding of the theory that it be successful in allowing empirical data to be turned into empirical evidence -- in demanding that any initial theoretical commitments pay off by permitting questions to be more amenable to empirical answer than without them
   c. If, for example, a way of conceptualizing is not leading to better empirical evidence, what grounds are there for retaining it at the time, instead of trying something else
6. By my stock, then, Descartes' mistake in concluding that he had overwhelming evidence for "the more general things which I have written about the World and the Earth" (IV, 206) lay in placing way too much weight on being able to explain various phenomena, and too little on whether he was in a better position to conduct ongoing empirical inquiry
   a. The ability to explain a finite range of phenomena is not very good evidence that no future phenomena will be encountered in conflict with the explanations
   b. But the ability to bring empirical considerations to bear more effectively, allowing the theory to be reshaped and refined empirically, is good evidence that you have gotten somewhere toward being able to answer questions about the world
   c. And it is also evidence that all will ultimately come out in the wash; even if the starting point is false, empirical evidence will ultimately allow the starting point to be corrected

F. Why Cartesian Science was so Well-Received

1. That still leaves the question why Cartesian science caught on so strongly in the second half of the 17th and first half of the 18th century, at least on the Continent
    a. In the face of the advances Kepler had made in astronomy and Galileo in the mathematics of motion, both of which were followed up by continuing advances during the period when Cartesian was so widely accepted
    b. Indeed, caught on so strongly that many found Newtonian science fundamentally inadequate when considered side-by-side with it
    c. Tentative answer here derives from recognizing that empirical research can have different aims which may rarely be readily reconcilable with one another
2. One aim: to provide an account of the world around us that gives us a better understanding of it, at least to a reasonable degree of detail -- that is, at least in broad outline
    a. General answers to why- and how-questions that are not *ad hoc*, but instead invoke a relatively small number of fundamental principles
    b. A unified way of conceptualizing and explaining the world around us, at least qualitatively
3. An alternative aim: to marshal empirical considerations toward establishing secure -- i.e. once and for all -- answers to those questions that (at the time) lend themselves to such answers
    a. Focus on those questions for which seemingly conclusive empirical answers can be obtained, *whatever those questions at any time happen to be*
    b. Getting beyond conjecture as an end in itself, as much as possibly imitating mathematics
4. Still another aim: to provide means for improving our daily practical lives, especially through enabling us to achieve ends we otherwise could not achieve
    a. For example, to be able to effect an end consistently that in the past we have been able to effect only occasionally
    b. Focus on those areas where human wants and needs are greatest, regardless of the quality of understanding or the strength of the evidence for underlying principles
5. Proposal: at the time Cartesian science emerged there were comparatively few examples of success in achieving either the second or third aims,
    a. Aristotle had provided an example of the first aim for centuries, and its collapse had created a demand for a comprehensive replacement
    b. Ptolemy, the classic example of the second aim, had been exposed as a failure, leaving questions about the extent to which any precise empirical claims could be established with finality
    c. Too many loose ends in e.g. Kepler and Galileo for them to serve as exemplars at the time for most people, who wanted first and foremost a big picture
6. Regardless, this course has a built-in bias toward the second aim, but not because I am insisting that it should have primacy over the other two

a. Merely because the question of the course -- how did we first come to have high quality evidence in any of the sciences? -- imposes that bias from the outset
b. And also because of the focus on Newton's *Principia*, which itself is presented not just as pursuing that aim , but as an exemplar for how to do it

7. An important consequence of this bias is my not even attempting to present an account of Descartes' vortex theory in the detailed form that made it so plausible to him
   a. In other words, I have not even attempted to give the sort of account Kuhn calls for, in which the claims made by the science come to be viewed in the context of the contextual scheme and external circumstances that gave them the force they had at the time
   b. The goal of this semester is to put us in a position to read Newton's *Principia* in this manner, but considerations of time have then forced me not to do so for Descartes in particular, and Kepler and Galileo to a lesser extent
   c. A model of a Kuhnian account of Descartes' vortex theory can be found in Schuster (2005), worked out by focusing not on his *Principia*, but on the genesis of the theory leading up to the version of it in *Le Monde*

G. 1651: A Transition into "Modern" Science

1. The remainder of this course will take a seemingly abrupt turn toward science as we know it now, with many "textbook" elements of science emerging, one right after another
   a. Not just in contrast to Descartes, but to Kepler and Galileo as well
   b. The obvious question, granting its premise, is why, seemingly so suddenly, at this juncture of the seventeenth century
2. The basic answer is that a new post-Scholasticism generation emerges, with little felt need to build anew from the ground up, choosing instead to proceed from where their predecessors left off
   a. Galileo dies in 1642, Torricelli in 1647, Mersenne in 1648, Descartes in 1650, Gassendi in 1655
   b. The new generation, which came of age after Galileo's trial, was more post-Galilean than post-Copernican
   c. In particular, the new generation had no need to fight the old battles all over again
   d. Horrocks as an example of picking up from where Kepler left off and pushing forward
3. That alone, however, does not explain why a different sort of science seems to emerge so abruptly; to explain that we need to identify what it was in the heritage received from their predecessors that at least enabled, if not automatically engendered a different sort of science
   a. The recognition of how different science became is surely retrospective, for other than Newton those at the time seem to have seen themselves as continuing along existing lines
   b. In other words, they did not see that matters had changed as much as we can now see it
4. Let me propose, from very much a retrospective standpoint, that the following five elements having become part of the scientific culture, so to speak, were why science changed in mid-century

a. The full recognition that apparent celestial motions grossly underdetermine the true motions: spearheaded by Copernicus, Tycho, and Kepler
b. The demand that theories of those motions match observed longitudes and latitudes at all times -- a new standard: spearheaded by Tycho and Kepler (and young Horrocks)
c. A shift away from the two-millennium-old tradition of compounding curvilinear motions out of uniform circular motions to compounding them out of rectilinear motions: spearheaded by Galileo, Gassendi, and most of all Descartes
d. A shift toward employing artifice, like the telescope and pendulum timers, and intricate design of experiments in "putting the question" to nature (Bacon's phrase): spearheaded by Galileo and Mersenne, but Riccioli as well
e. The stress on what Aristotelians would have called "efficient causes" -- that is, "external" causation, as the sole proper form of answer to why- and how-questions: spearheaded by Bacon, Mersenne, and Descartes

5. Several factors within the scope of social history also fed into the change
   a. The English Civil War and the subsequent Protectorate of Cromwell had undercut the authority of the Anglican Catholic Church within the English universities
   b. This opened the way to new thought in the class room and to ties, especially between those at Oxford and London, that led to what became called the new "invisible university"
   c. In Paris, the discussion group Mersenne had formed in the 1640s continued to flourish after his death, initially under the leadership of Gassendi
   d. The new sciences were the principal subject, and the participants extended to a wide group of intellectuals, including many women
   c. And In Italy, perhaps in part because Urban VIII had died in 1644, new interest in empirical approaches to questions, especially among the Jesuits at the University of Bologna
6. 1651 seems to me an appropriate year to mark this transition, not merely because it is the year after Descartes died, but also because it is the beginning of Huygens's scientific career, and even more so because it was the year of publication of Riccioli's *New Almagest*
   a. Usually ridiculed, wrongly I think, as the last gasp of the old, pre-modern science
   b. The book, as we have already seen, reviews the claims Galileo made in the *Dialogue*, asking which among them had by 1650 become established beyond dispute, but always putting the burden of proof on the new science
   c. Its Tychonism notwithstanding, the answer it gives is -- quite a lot -- tantamount to an imprimatur for the new science, coming from a Jesuit

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<u>Credits for Appendix</u>

Slides 1-5: Drake (1978)

Slides 6, 9-11, 13-15, 21-22, 25, 28-33: Descartes (1983/84)

Slides 7, 8: Aiton (1989)

Slides 16-20: Descartes (1974-86)

Slide 23: Descartes (1983/84, 1974-86)

Slide 24: Galileo (1989), Huygens (1888-1950), Descartes (1983/84)

Slide 33: Smith and Lockwood (1976)