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 $\Delta(B*\text{speed})$
    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