the condition of the world at any given moment is the direct result of its condition in the preceding moment, and the direct cause of its condition in the subsequent moment. Law and chance are only different names for mechanical necessity.

About fifty years after the death of Copernicus, John Kepler, a native of Würtemberg, who had adopted the heliocentric theory, and who was deeply impressed with the belief that relationships exist in the revolutions of the planetary bodies round the sun, and that these if correctly examined would reveal the laws under which those movements take place, devoted himself to the study of the distances, times, and velocities of the planets, and the form of their orbits. His method was, to submit the observations to which he had access, such as those of Tycho Brahe, to computations based first on one and then on another hypothesis, rejecting the hypothesis if he found that the calculations did not accord with the observations. The incredible labor he had undergone (he says, "I considered, and I computed, until I almost went mad") was at length rewarded, and in 1609 he published his book, "On the Motions of the Planet Mars." In this he had attempted to reconcile the movements of that planet to the hypothesis of eccentrics and epicycles, but eventually discovered that the orbit of a planet is not a circle but an ellipse, the sun being in one of the foci, and that the areas swept over by a line drawn from the planet to the sun are proportional to the times. These constitute what are now known as the first and second laws of Kepler. Eight years subsequently, he was rewarded by the discovery of a third law, defining the relation between the mean distances of the planets from the sun and the times of their revolutions; "the squares of the periodic times are

proportional to the cubes of the distances." In "An Epitome of the Copernican System," published in 1618, he announced this law, and showed that it holds good for the satellites of Jupiter as regards their primary. Hence it was inferred that the laws which preside over the grand movements of the solar system preside also over the less movements of its constituent parts.

The conception of law which is unmistakably conveyed by Kepler's discoveries, and the evidence they gave in support of the heliocentric as against the geocentric theory, could not fail to incur the reprehension of the Roman authorities. The congregation of the Index, therefore, when they denounced the Copernican system as utterly contrary to the Holy Scriptures, prohibited Kepler's "Epitome" of that system. It was on this occasion that Kepler submitted his celebrated remonstrance: "Eighty years have elapsed during which the doctrines of Copernicus regarding the movement of the earth and the immobility of the sun have been promulgated without hinderance, because it was deemed allowable to dispute concerning natural things, and to elucidate the works of God, and now that new testimony is discovered in proof of the truth of those doctrines—testimony which was not known to the spiritual judges—ye would prohibit the promulgation of the true system of the structure of the universe."

None of Kepler's contemporaries believed the law of the areas, nor was it accepted until the publication of the "Principia" of Newton. In fact, no one in those times understood the philosophical meaning of Kepler's laws. He himself did not foresee what they must inevitably lead to. His mistakes showed how far he was from perceiving their result. Thus he thought that each planet is the seat of an intelligent principle, and that there is a relation between the magnitudes of the orbits of the five principal planets and the five regular solids of geometry. At first he inclined to believe that the orbit of Mars is oval, nor was it until after a wearisome study that he detected the grand truth, its elliptical form. An idea of the incorruptibility of the celestial objects had led to the adoption of the Aristotelian doctrine of the perfection of circular motions, and to the belief that there were none but circular motions in the heavens. He bitterly complains of this as having been a fatal "thief of his time." His philosophical daring is illustrated in his breaking through this time-honored tradition.

In some most important particulars Kepler anticipated Newton. He was the first to give clear ideas respecting gravity. He says every particle of matter will rest until it is disturbed by some other particle—that the earth attracts a stone more than the stone attracts the earth, and that bodies move to each other in proportion to their masses; that the earth would ascend to the moon one-fifty-fourth of the distance, and the moon would move toward the earth the other fifty-three. He affirms that the moon's attraction causes the tides, and that the planets must impress irregularities on the moon's motions.

The progress of astronomy is obviously divisible into three periods:

1. The period of observation of the apparent motions of the heavenly bodies.

2. The period of discovery of their real motions, and particularly of the laws of the planetary revolutions: this was signally illustrated by Copernicus and Kepler.

3. The period of the ascertainment of the causes of those laws. It was the epoch of Newton.

The passage of the second into the third period depended on the development of the Dynamical branch of mechanics, which had been in a stagnant condition from the time of Archimedes or the Alexandrian School.

In Christian Europe there had not been a cultivator of mechanical philosophy until Leonardo da Vinci, who was born A. D. 1452. To him, and not to Lord Bacon, must be attributed the renaissance of science. Bacon was not only ignorant of mathematics, but depreciated its application to physical inquiries. He contemptuously rejected the Copernican system, alleging absurd objections to it. While Galileo was on the brink of his great telescopic discoveries, Bacon was publishing doubts as to the utility of instruments in scientific investigations. To ascribe the inductive method to him is to ignore history. His fanciful philosophical suggestions have never been of the slightest practical use. No one has ever thought of employing them. Except among English readers, his name is almost unknown.

To Da Vinci I shall have occasion to allude more particularly on a subsequent page. Of his works still remaining in manuscript, two volumes are at Milan, and one in Paris, carried there by Napoleon. After an interval of about seventy years, Da Vinci was followed by the Dutch engineer, Stevinus, whose work on the principles of equilibrium was published in 1586. Six years afterward appeared Galileo's treatise on mechanics.

To this great Italian is due the establishment of the three fundamental laws of dynamics, known as the Laws of Motion.

The consequences of the establishment of these laws were very important.

It had been supposed that continuous movements, such, for instance, as those of the celestial bodies, could only be maintained by a perpetual consumption and perpetual application of force, but the first of Galileo's laws declared that every body will persevere in its state of rest, or of uniform motion in a right line, until it is compelled to change that state by disturbing forces. A clear perception of this fundamental principle is essential to a comprehension of the elementary facts of physical astronomy. Since all the motions that we witness taking place on the surface of the earth soon come to an end, we are led to infer that rest is the natural condition of things. We have made, then, a very great advance when we have become satisfied that a body is equally indifferent to rest as to motion, and that it equally perseveres in either state until disturbing forces are applied. Such disturbing forces in the case of common movements are friction and the resistance of the air. When no such resistances exist, movement must be perpetual, as is the case with the heavenly bodies, which are moving in a void.

Forces, no matter what their difference of magnitude may be, will exert their full influence conjointly, each as though the other did not exist. Thus, when a ball is suffered to drop from the mouth of a cannon, it falls to the ground in a certain interval of time through the influence of gravity upon it. If, then, it be fired from the cannon, though now it may be projected some thousands of feet in a second, the effect of gravity upon it will be precisely the same as before. In the intermingling of forces there is no deterioration; each produces its own specific effect.

In the latter half of the seventeenth century, through the works of Borelli, Hooke, and Huyghens, it had be-

come plain that circular motions could be accounted for by the laws of Galileo. Borelli, treating of the motions of Jupiter's satellites, shows how a circular movement may arise under the influence of a central force. Hooke exhibited the inflection of a direct motion into a circular by a supervening central attraction.

The year 1687 presents, not only an epoch in European science, but also in the intellectual development of man. It is marked by the publication of the "Principia" of Newton, an incomparable, an immortal work.

On the principle that all bodies attract each other with forces directly as their masses, and inversely as the squares of their distances, Newton showed that all the movements of the celestial bodies may be accounted for, and that Kepler's laws might all have been predicted—the elliptic motions—the described areas—the relation of the times and distances. As we have seen, Newton's contemporaries had perceived how circular motions could be explained; that was a special case, but Newton furnished the solution of the general problem, containing all special cases of motion in circles, ellipses, parabolas, hyperbolas—that is, in all the conic sections.

The Alexandrian mathematicians had shown that the direction of movement of falling bodies is toward the centre of the earth. Newton proved that this must necessarily be the case, the general effect of the attraction of all the particles of a sphere being the same as if they were all concentrated in its centre.

To this central force, thus determining the fall of bodies, the designation of gravity was given. Up to this time, no one, except Kepler, had considered how far its influence reached. It seemed to Newton possible that it might extend as far as the moon, and be the force that deflects her from a rectilinear path, and makes her revolve in her orbit round the earth. It was easy to compute, on the principle of the law of inverse squares, whether the earth's attraction was sufficient to produce the observed effect. Employing the measures of the size of the earth accessible at the time, Newton found that the moon's deflection was only thirteen feet in a minute; whereas, if his hypothesis of gravitation were true, it should be fifteen feet. But in 1669 Picard, as we have seen, executed the measurement of a degree more carefully than had previously been done; this changed the estimate of the magnitude of the earth, and, therefore, of the distance of the moon; and, Newton's attention having been directed to it by some discussions that took place at the Royal Society in 1679, he obtained Picard's results, went home, took out his old papers, and resumed his calculations. As they drew to a close, he became so much agitated that he was obliged to desire a friend to finish them. The expected coincidence was established. It was proved that the moon is retained in her orbit and made to revolve round the earth by the force of terrestrial gravity. The genii of Kepler had given place to the vortices of Descartes, and these in their turn to the central force of Newton.

In like manner the earth, and each of the planets, are made to move in an elliptic orbit round the sun by his attractive force, and perturbations arise by reason of the disturbing action of the planetary masses on one another. Knowing the masses and the distances, these disturbances may be computed. Later astronomers have even succeeded with the inverse problem, that is, knowing the perturbations or disturbances, to find the place and the mass of the disturbing body. Thus, from the deviations of Uranus from his theoretical position, the discovery of Neptune was accomplished.

Newton's merit consisted in this, that he applied the laws of dynamics to the movements of the celestial bodies, and insisted that scientific theories must be substantiated by the agreement of observations with calculations.

When Kepler announced his three laws, they were received with condemnation by the spiritual authorities, not because of any error they were supposed to present or to contain, but partly because they gave support to the Copernican system, and partly because it was judged inexpedient to admit the prevalence of law of any kind as opposed to providential intervention. The world was regarded as the theatre in which the divine will was daily displayed; it was considered derogatory to the majesty of God that that will should be fettered in any way. The power of the clergy was chiefly manifested in the influence they were alleged to possess in changing his arbitrary determinations. It was thus that they could abate the baleful action of comets, secure fine weather or rain, prevent eclipses, and, arresting the course of Nature, work all manner of miracles; it was thus that the shadow had been made to go back on the dial, and the sun and the moon stopped in mid-career.

In the century preceding the epoch of Newton, a great religious and political revolution had taken place—the Reformation. Though its effect had not been the securing of complete liberty for thought, it had weakened many of the old ecclesiastical bonds. In the reformed countries there was no power to express a condemnation of Newton's works, and among the clergy there was no disposition to give themselves any concern about the matter. At first the attention of the Protestant was engrossed by the movements of his great enemy the Catholic, and when that source of disquietude ceased, and the inevitable partitions of the Reformation arose, that attention was fastened upon the rival and antagonistic Churches. The Lutheran, the Calvinist, the Episcopalian, the Presbyterian, had something more urgent on hand than Newton's mathematical demonstrations.

So, uncondemned, and indeed unobserved, in this clamor of fighting sects, Newton's grand theory solidly established itself. Its philosophical significance was infinitely more momentous than the dogmas that these persons were quarreling about. It not only accepted the heliocentric theory and the laws discovered by Kepler, but it proved that, no matter what might be the weight of opposing ecclesiastical authority, the sun *must* be the centre of our system, and that Kepler's laws are the result of a mathematical necessity. It is impossible that they should be other than they are.

But what is the meaning of all this? Plainly that the solar system is not interrupted by providential interventions, but is under the government of irreversible law—law that is itself the issue of mathematical necessity.

The telescopic observations of Herschel I. satisfied him that there are very many double stars—double not merely because they are accidentally in the same line of view, but because they are connected physically, revolving round each other. These observations were continued and greatly extended by Herschel II. The elements of the elliptic orbit of the double star ξ of the Great Bear were determined by Savary, its period being fifty-eight and one-quarter years; those of another, σ Coronæ, were determined by Hind, its period being more

than seven hundred and thirty-six years. The orbital movement of these double suns in ellipses compels us to admit that the law of gravitation holds good far beyond the boundaries of the solar system; indeed, as far as the telescope can reach, it demonstrates the reign of law. D'Alembert, in the Introduction to the Encyclopædia, says: "The universe is but a single fact; it is only one great truth."

Shall we, then, conclude that the solar and the starry systems have been called into existence by God, and that he has then imposed upon them by his arbitrary will laws under the control of which it was his pleasure that their movements should be made?

Or are there reasons for believing that these several systems came into existence not by such an arbitrary fiat, but through the operation of law?

The following are some peculiarities displayed by the solar system as enumerated by Laplace. All the planets and their satellites move in ellipses of such small eccentricity that they are nearly circles. All the planets move in the same direction and nearly in the same plane. The movements of the satellites are in the same direction as those of the planets. The movements of rotation of the sun, of the planets, and the satellites, are in the same direction as their orbital motions, and in planes little different.

It is impossible that so many coincidences could be the result of chance! Is it not plain that there must have been a common tie among all these bodies, that they are only parts of what must once have been a single mass?

But if we admit that the substance of which the solar system consists once existed in a nebulous condition, and was in rotation, all the above peculiarities follow as necessary mechanical consequences. Nay, more, the formation of planets, the formation of satellites and of asteroids, is accounted for. We see why the outer planets and satellites are larger than the interior ones; why the larger planets rotate rapidly, and the small ones slowly; why of the satellites the outer planets have more, the inner fewer. We are furnished with indications of the time of revolution of the planets in their orbits, and of the satellites in theirs; we perceive the mode of formation of Saturn's rings. We find an explanation of the physical condition of the sun, and the transitions of condition through which the earth and moon have passed, as indicated by their geology.

But two exceptions to the above peculiarities have been noted; they are in the cases of Uranus and Neptune.

The existence of such a nebulous mass once admitted, all the rest follows as a matter of necessity. Is there not, however, a most serious objection in the way? Is not this to exclude Almighty God from the worlds he has made?

First, we must be satisfied whether there is any solid evidence for admitting the existence of such a nebulous mass.

The nebular hypothesis rests primarily on the telescopic discovery made by Herschel I., that there are scattered here and there in the heavens pale, gleaming patches of light, a few of which are large enough to be visible to the naked eye. Of these, many may be resolved by a sufficient telescopic power into a congeries of stars, but some, such as the great nebula in Orion, have resisted the best instruments hitherto made.

It was asserted by those who were indisposed to accept the nebular hypothesis, that the non-resolution was

due to imperfection in the telescopes used. In these instruments two distinct functions may be observed: their light-gathering power depends on the diameter of their object mirror or lens, their defining power depends on the exquisite correctness of their optical surfaces. Grand instruments may possess the former quality in perfection by reason of their size, but the latter very imperfectly, either through want of original configuration, or distortion arising from flexure through their own weight. But, unless an instrument be perfect in this respect, as well as adequate in the other, it may fail to decompose a nebula into discrete points.

Fortunately, however, other means for the settlement of this question are available. In 1846, it was discovered by the author of this book that the spectrum of an ignited solid is continuous—that is, has neither dark nor bright lines. Fraunhofer had previously made known that the spectrum of ignited gases is discontinuous. Here, then, is the means of determining whether the light emitted by a given nebula comes from an incandescent gas, or from a congeries of ignited solids, stars, or suns. If its spectrum be discontinuous, it is a true nebula or gas; if continuous, a congeries of stars.

In 1864, Mr. Huggins made this examination in the case of a nebula in the constellation Draco. It proved to be gaseous.

Subsequent observations have shown that, of sixty nebulæ examined, nineteen give discontinuous or gaseous spectra—the remainder continuous ones.

It may, therefore, be admitted that physical evidence has at length been obtained, demonstrating the existence of vast masses of matter in a gaseous condition, and at a temperature of incandescence. The hypothesis of Laplace has thus a firm basis. In such a nebular mass, cooling by radiation is a necessary incident, and condensation and rotation the inevitable results. There must be a separation of rings all lying in one plane, a generation of planets and satellites all rotating alike, a central sun and engirdling globes. From a chaotic mass, through the operation of natural laws, an organized system has been produced. An integration of matter into worlds has taken place through a decline of heat.

If such be the cosmogony of the solar system, such the genesis of the planetary worlds, we are constrained to extend our views of the dominion of law, and to recognize its agency in the creation as well as in the conservation of the innumerable orbs that throng the universe.

But, again, it may be asked: "Is there not something profoundly impious in this? Are we not excluding Almighty God from the world he has made?"

We have often witnessed the formation of a cloud in a serene sky. A hazy point, barely perceptible—a little wreath of mist—increases in volume, and becomes darker and denser, until it obscures a large portion of the heavens. It throws itself into fantastic shapes, it gathers a glory from the sun, is borne onward by the wind, and, perhaps, as it gradually came, so it gradually disappears, melting away in the untroubled air.

Now, we say that the little vesicles of which this cloud was composed arose from the condensation of water-vapor preëxisting in the atmosphere, through reduction of temperature; we show how they assumed the form they present. We assign optical reasons for the brightness or blackness of the cloud; we explain, on mechanical principles, its drifting before the wind; for its disappearance we account on the principles of chemistry. It never occurs to us to invoke the interposition of the Almighty in the production and fashioning of this fugitive form. We explain all the facts connected with it by physical laws, and perhaps should reverentially hesitate to call into operation the finger of God.

But the universe is nothing more than such a cloud—a cloud of suns and worlds. Supremely grand though it may seem to us, to the Infinite and Eternal Intellect it is no more than a fleeting mist. If there be a multiplicity of worlds in infinite space, there is also a succession of worlds in infinite time. As one after another cloud replaces cloud in the skies, so this starry system, the universe, is the successor of countless others that have preceded it—the predecessor of countless others that will follow. There is an unceasing metamorphosis, a sequence of events, without beginning or end.

If, on physical principles, we account for minor meteorological incidents, mists and clouds, is it not permissible for us to appeal to the same principle in the origin of world-systems and universes, which are only clouds on a space-scale somewhat larger, mists on a time-scale somewhat less transient? Can any man place the line which bounds the physical on one side, the supernatural on the other? Do not our estimates of the extent and the duration of things depend altogether on our point of view? Were we set in the midst of the great nebula of Orion, how transcendently magnificent the scene! The vast transformations, the condensations of a fiery mist into worlds, might seem worthy of the immediate presence, the supervision of God; here, at our distant station, where millions of miles are inappreciable to our eyes, and suns seem no bigger than motes in the air, that nebula is more insignificant than the faintest cloud.

Galileo, in his description of the constellation of Orion, did not think it worth while so much as to mention it. The most rigorous theologian of those days would have seen nothing to blame in imputing its origin to secondary causes, nothing irreligious in failing to invoke the arbitrary interference of God in its metamorphoses. If such be the conclusion to which we come respecting it, what would be the conclusion to which an Intelligence seated in it might come respecting us? It occupies an extent of space millions of times greater than that of our solar system; we are invisible from it, and therefore absolutely insignificant. Would such an Intelligence think it necessary to require for our origin and maintenance the immediate intervention of God?

From the solar system let us descend to what is still more insignificant—a little portion of it; let us descend to our own earth. In the lapse of time it has experienced great changes. Have these been due to incessant divine interventions, or to the continuous operation of unfailing law? The aspect of Nature perpetually varies under our eyes, still more grandly and strikingly has it altered in geological times. But the laws guiding those changes never exhibit the slightest variation. In the midst of immense vicissitudes they are immutable. The present order of things is only a link in a vast connected chain reaching back to an incalculable past, and forward to an infinite future.

There is evidence, geological and astronomical, that the temperature of the earth and her satellite was in the remote past very much higher than it is now. A decline so slow as tc be imperceptible at short intervals, but manifest enough in the course of many ages, has occurred. The heat has been lost by radiation into space.

The cooling of a mass of any kind, no matter whether large or small, is not discontinuous; it does not go on by fits and starts; it takes place under the operation of a mathematical law, though for such mighty changes as are here contemplated neither the formula of Newton, nor that of Dulong and Petit, may apply. It signifies nothing that periods of partial decline, glacial periods, or others of temporary elevation, have been intercalated; it signifies nothing whether these variations may have arisen from topographical variations, as those of level, or from periodicities in the radiation of the sun. A periodical sun would act as a mere perturbation in the gradual decline of heat. The perturbations of the planetary motions are a confirmation, not a disproof, of gravity.

Now, such a decline of temperature must have been attended by innumerable changes of a physical character in our globe. Her dimensions must have diminished through contraction, the length of her day must have lessened, her surface must have collapsed, and fractures taken place along the lines of least resistance; the density of the sea must have increased, its volume must have become less; the constitution of the atmosphere must have varied, especially in the amount of water-vapor and carbonic acid that it contained; the barometric pressure must have declined.

These changes, and very many more that might be mentioned, must have taken place not in a discontinuous but in an orderly manner, since the master-fact, the decline of heat, that was causing them, was itself following a mathematical law.

But not alone did lifeless Nature submit to these inevitable mutations; living Nature was also simultaneously affected.