Article

Kepler and the Laws of Nature

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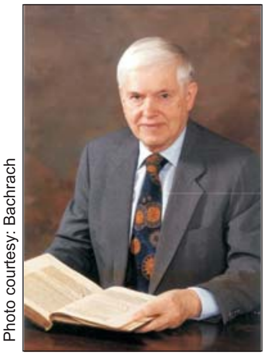

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Kepler is famous for his three laws of planetary motion, but he never assigned a special status to them or called them laws. More than a century and a half passed before they were singled out and ordered in a group of three. Nevertheless, he believed in an underlying, God-given rationale to the universe, something akin to laws of nature, and as he matured he began to use the word archetype for this concept. Most physicists today have, quite independently of religious values, a feeling that deep down the universe is ultimately comprehensible and lawful. Such ultimate laws are here called ontological laws of nature. In contrast, what we have (including Kepler's third law, for example) are human constructs, epistemological laws of nature. Belief in the existence of deep ontological laws is an implicit leap of faith. Science, insofar as it assumes the reality of mathematical laws, operates with a tacitly theistic assumption about the nature of the universe. Such insights provide a strong hint for answering Einstein's most serious inquiry: Why is the universe comprehensible?

In 1609, the same year in which Galileo and others began to use the telescope for astronomical purposes, Johannes Kepler published his *Commentary on the Motions of Mars*, a book today generally cited by its short title, *Astronomia nova*. But that abbreviated title conceals its real challenge to the Aristotelian order of things. Kepler's work was truly the "new astronomy," but the title goes on, "based on causes, or celestial physics," and it was the introduction of physics into astronomy that was Kepler's most fundamental contribution.

Aristotle's *De coelo,* "On the heavens," which dealt with the geometrical motions in the heavens, was the province of astronomy professors. However, it was his *Metaphysics* that concerned the fundamental reasons for the motions—Aristotle implied that it was the love of God that made the spheres go round[1]—and *Metaphysics* was the property of the philosophy professors. Kepler unified this dichotomy, demanding physically coherent explanations as to why planets sometimes went faster than at other times. He realized that when Mars was closest to the sun, it went fastest in its orbit. It seemed to him unreasonable that the earth, on the contrary, would always travel at the same speed regardless of its distance from the sun. And when he got that straightened out, he single-handedly improved the accuracy of predicted positions by an order of magnitude. You may have thought that finding the elliptical shape of Mars' orbit made the major leap forward in accuracy. Wrong! It was getting the earth's orbit positioned correctly. His teacher Michael Maestlin criticized him for

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mixing up physics and astronomy,[2] but it was this insight that drove Kepler to his major breakthroughs. And that approach laid the essential framework for René Descartes and Isaac Newton.

Kepler's celestial physics pointed the way to a lawful universe that could be understood in terms of underlying physical principles. Kepler is rightly famous for his three laws of planetary motion, but he never called them laws; they were not specially singled out and ordered as a group of three until 1774 in J.-J. Lalande's *Abrégé d'astronomie*, something probably conceived by the French astronomer himself. Nor did Kepler use the expression "laws of nature," and neither, for that matter, did Galileo. In fact, "laws of nature" in the modern sense did not come about until the philosophical inquiry starting from first principles as elaborated by Descartes. Let me first situate the origins of Kepler's laws within the larger framework of his discoveries and his cosmology, and then reflect on the construction of the modern concept of laws of nature.

Kepler's Discoveries and His Cosmology

In October of 1600 the young Kepler, who had lost his job as a high school teacher due to the Counter-Reformation, arrived in Prague from the Austrian provinces to work as an apprentice to Tycho Brahe, the greatest observational astronomer the world had yet known. Kepler's working notebook, which still survives, seems to show that he had not got off to a good start. The opening page of triangles and numbers is crossed off.[3] No doubt Christian Longomontanus, the senior staff assistant, looked over Kepler's shoulder and remarked, "Young man, we have a much easier way to do that here!" Sure enough, on the second page the problem is attacked using precepts from Tycho's manuscript handbook of trigonometric rules.

Nevertheless, Kepler had not come to his new post totally unprepared. Kepler owned a second-hand copy of Copernicus' major work, the *De revolutionibus,* and at the university in Tübingen he had sat with his mentor, Michael Maestlin, and together they examined a previously highlighted section of the book.[4] It was the chapter in which Copernicus inquired as to what was the center of the universe, the sun itself or the center of the earth's orbit (which were two different points because of the earth's eccentrically positioned circle). The marginal annotation from the previous owner pointed out that Copernicus did not answer the question (although for practical reasons, Copernicus used the center of the earth's orbit as a convenient reference point). Maestlin added a further brief note to Kepler's copy, which is how we know that they discussed this point in particular. Clearly, Kepler favored using the sun, a physical body, rather than an empty geometrical point as the center of the universe. Thus in Prague, armed with this prior discussion, Kepler gained Tycho's permission to use the sun itself as the reference point for the study of Mars.

Asking what is the precise center of the universe may seem like a trivial question, particularly because this pair of choices seems so irrelevant today. But for Kepler's era, and for understanding his remarkably different approach to fundamental problems facing him, this was an extraordinarily pivotal question, and one that gives significant insight into his own special genius. As stated in my opening paragraph, Kepler was focused on physical causes, quite contrary to Maestlin and his other professors. He knew that, according to Aristotle and his geocentric cosmology, the earth was solidly fixed, and heavenly motions derived their action from the outside in, the starry firmament spinning once a day and inputting its basic motion into the planets including the sun and moon. But in the Copernican system it was the distant stars that were solidly fixed, so that the motions had to be generated from the inside out, in particular from a spinning sun. Hence, it was essential for Kepler's physical understanding of the cosmos that the sun itself had to be the reference point, and not some empty spot in space. This might, at first glance, seem like some strange fantasy on Kepler's part—Maestlin probably thought so—but in the event, it was absolutely essential, for this proved to be the major step toward making the prediction of planetary positions an order of magnitude more accurate.

In tandem with Kepler's physical treatment of the sun was his physical treatment of the earth. If the earth was propelled in its orbit by some magnetical force from the rotating sun, then the earth should travel more swiftly when it was closer to the sun (at its perihelion) in January and more slowly at its aphelion in July. It was well known that summer (in the northern hemisphere) is a few days longer than winter because the sun seems to be moving more slowly then, but for Copernicus this was simply a perspective effect caused by the earth's eccentrically placed orbit. For Kepler, half of this unequal length of the seasons was a perspective effect, while the other half was caused by the earth's differing speed in its orbit. This meant changing the eccentricity and therefore the position of the earth's orbit, a radical step that had the unexpected consequence of eliminating the most egregious errors in predicting the places of Mars! (Because the apparent places of Mars depend on the positions of our observing platform, that is, the earth, then fixing the positions of the earth has an immediate effect on the predicted positions of Mars as seen from the earth.)

Kepler was to call it "the key to the deeper astronomy," and it was the climax to the first two-thirds of the *Astronomia nova*, the part he had completed even before he stumbled onto the ellipse. This paved the way for what we call his "law of areas" and what we identify as one of the most fundamental physical laws, the conservation of angular momentum. For Kepler, at this point it was essentially a working hypothesis, and not at all clearly stated: *"Now the elapsed time, even if it is really something different, is certainly measured most easily by the plane area circumscribed by the planet's path."*[5] The smooth motions of a clock's hands convert time into geometry, but Kepler's swept-out areas are something different, and very difficult to model with a mechanical device. Kepler had arrived at this point by assuming that the speed of a planet in its orbit was inversely proportional to its distance from the sun, a statement that indeed works at the perihelion and aphelion. But a handful of one-dimensional distances (from his assumed inverse distance rule) does not yield a two-dimensional area. Kepler was a good enough geometer to realize that there was a problem here, but as a physicist he seemed to have thought, "Behold! It is a miracle!" and marched bravely on.

Eventually, from his degree-by-degree calculations of the motion of Mars around the sun, Kepler saw that the orbit of Mars had to bend in from its circular shape for the area rule to hold, and from these tedious calculations, he suddenly awoke as if from a deep sleep (as he himself expressed it).[6] He realized that everything would work if the orbit was, in fact, an ellipse with the sun at one focus. It was a brilliant surmise on his part, motivated by his search for physical causes. He might have called his intuitive idea "the law of distances," that is, the speed of a planet in its orbit should be inversely proportional to its distance from the sun, but he thought in terms of archetypes, mostly geometrical, and not in terms of laws. His "law of distances" and the notion that a planet had to be pushed in its orbit was a chimera, of course, but nevertheless, the result was a stroke of genius. And ultimately, in his *Epitome of Copernican Astronomy* (1620), he got the speed relationship just right, in the modern form of conservation of angular momentum. Decades later, Newton would remark that Kepler had merely guessed that the orbit was an ellipse, implying that he, Newton, had gone farther by proving it.[7] Kepler's was a guess, but an inspired guess!

For those who think of Kepler primarily in terms of his three laws, it might seem he spent the years between the *Astronomia nova* (1609) and the *Harmonice mundi* (1619) simply treading water. In many ways, they were difficult years for Kepler: his wife and his most cherished child died, his patron Rudolph II also died, Kepler relocated from Prague to the more provincial Linz, and shortly thereafter the immensely destructive Thirty Years' War began. But during this period, he responded to Galileo's astonishing telescopic observations, prepared the theoretical treatise on the optics of telescopes, wrote a little discourse that is considered a foundational work in mineralogy, composed a pioneering precursor to the integral calculus, wrote on chronology and on comets, and prepared the first volume of his *Epitome.*

Then, in 1619, Kepler's great but idiosyncratic work on cosmology, his mind's favorite intellectual child, appeared. Within its dense texture of geometry, astronomy, astrology, and cosmic music, *The Harmony of the World* contains near the end a mathematical gem, what today we call Kepler's third law. For Copernicus, the qualitative relationship between the size of a planet's orbit and its period of revolution was an aesthetic prize, one of the most important reasons for his rejection of the traditional geocentric cosmology. Copernicus exclaimed, "Only in this way [the heliocentric arrangement] do we find a sure bond of harmony between the movement and magnitude of the orbital circles."[8] For Kepler, it was a life-long quest to convert this qualitative agreement into a quantitative expression: *the ratio that exists between the periodic times of any two planets is precisely the ratio of the sesquialter power of the mean distances*, i.e., $P_1/P_2 = (a_1/a_2)^{3/2}$. "The die is cast," Kepler wrote, "and I am writing the book. Whether it is read by my contemporaries or by posterity matters not: let it await a reader for a hundred years, as God Himself has been ready for a contemplator for six thousand years!"[9]

Kepler did not call this relationship a law. The first to call it a law was Voltaire, in his *Elements of the Philosophy of Newton* (1738). He also stated concerning the area rule that

> This Law inviolably observed by all the Planets … was discovered about 150 Years ago by Kepler … The extreme Sagacity of Kepler discovered the Effect, of which the Genius of *Newton* has found out the Cause.[10]

As indicated at the beginning of this article, it was not until 1774 that all three of Kepler's mathematical rules for planetary orbits were sorted out and designated as laws.[11] Kepler himself never assigned a special status to these three rules. Nevertheless, he believed in an underlying, God-given rationale to the universe, something akin to laws of nature, and as he matured, he began to use the word archetype for this concept. He did not use "archetype" in his *Mysterium cosmographicum* of 1596, and apparently only once in his *Astronomia nova* (1609), but when he reprinted the *Mysterium* in 1621, he added a footnote stating that the five regular polyhedra (on which he based his spacing of the planetary orbits around the sun) are the archetype for that arrangement.[12] Subsequently he elaborates,

> The reason why the Mathematicals are the cause of natural things is that God the Creator had the Mathematicals with him as archetypes from eternity in their simplest divine state of abstraction, even from quantities themselves …[13]

In his *Harmony of the World* (1619), Kepler had expressed it similarly:

> For shapes are in the archetype prior to their being in the product, in the divine mind prior to being in the creature, differently indeed in respect of their subject, but the same in the form of their essence.[14]

In other words, Kepler believed that, at the deepest level, the mathematical structures of the universe were God-given. This is, I believe, equivalent to saying that, as part of ontological reality, there are laws of nature that hold our universe together.

Today physicists seem almost unanimous that the universe operates on the basis of fundamental laws of nature. There are some deep-down, essentially inviolable, rules that govern the working of nature, whether or not we can actually find or recognize them. In other words, the universe is, at bottom, fundamentally lawful. These are what I shall refer to as "ontological laws." As far as the history of humankind is concerned, this is a relatively modern concept. From primitive times, the universe was seen as capricious. The idea that the universe is lawful undoubtedly stems from the theological origins of the concept of "laws of nature," and ultimately from the idea that Kepler surely espoused, that the universe has the ultimate coherence of an intelligent Creator.

I would wager that most physicists have, quite independently of religious values, a gut feeling that deep down the universe is rational and lawful, ultimately comprehensible, and that with careful observation and experimentation our results more and more closely approach this ontological reality. In other words, the holy grail of scientific research is finding the deep ontological laws of nature. However (as I will argue), what we have actually got are human constructs, epistemological laws of nature. In defense of this view, I cite Einstein's comment regarding scientific constructs:

> The sense experiences are the given subject-matter. But the theory that shall interpret them is man-made. It is the result of an extremely laborious process of adaptation: hypothetical, never completely final, always subject to question and doubt.[15]

The Construction of the Modern Concept of Laws of Nature

It was during the decades-long interval between Kepler's archetypes and the selecting out and designation of his three laws of planetary motion that our contemporary usage of "law of nature" developed. Let me review briefly the findings of scholars such as John Henry and Peter Harrison concerning the modern origins of this expression.[16]

According to these scholars, our modern notion of "laws of nature" derives from the writings of

Descartes. In 1619, after a day of intense concentration followed by a triad of vivid dreams, the French philosopher took the path of being his own empirical architect for a complete theory of nature. This he built from fundamental principles of matter and motion, beginning with *cogito, ergo sum*. Nevertheless, as he considered the notion of fundamental laws governing the universe, he eventually realized that he could not find an ultimate a priori origin of motion. Hence, he could only propose that motion was part of God's initial creation. Thus the conception of "laws of nature" was at its root theological in origin, just as Kepler's archetypes had sprung from an intensely theological context.

In the English language, the concept of "laws of nature" arose through the work of Robert Boyle and Newton. Boyle wrote in 1674 (in echo of Descartes) that

> The subsequent course of nature, teaches, that God, indeed, gave motion to matter; but that, in the beginning, he so guided the various motion of the parts of it, as to contrive them into the world he design'd they should compose; and establish'd those rules of motion, and that order amongst things corporeal, which we call the laws of nature. Thus, the universe being once fram'd by God, and the laws of motion settled, and all upheld by his perpetual concourse, and general providence; the same philosophy teaches, that the phenomena of the world, are physically produced by the mechanical properties of the parts of matter; and, that they operate upon one another according to mechanical laws.[17]

More famously, the idea of laws of nature stemmed from Newton and his *Philosophiae naturalis principia mathematica* (1687). Virtually at the outset of the *Principia*, Newton proposed three laws of motion, and later in the volume (in Book 3), he set forth a mathematical description of gravitation that has been universally referred to as the law of gravitation—for example, in the closing sentence of Charles Darwin's *On the Origin of Species*—even though Newton never referred to it as such. Newton introduced gravitation in a series of propositions, and he mentioned it as a principle, but he never called it a law nor set it down as a formula such as we find in modern textbooks, i.e.,

$$F = GmM/r^2,$$

where F is force, G is the constant of universal gravitation, M and m are the masses of two gravitating bodies and r is the distance between them. It is in this section of his book that Newton made his sole nod to Kepler's celestial mechanics, attributing to him the relationship we now call Kepler's third law.

These two laws, Kepler's third law and Newton's law of gravitation, afford the opportunity of probing a little more deeply into the epistemological nature of such "laws of nature." Kepler's third law essentially gives us a first approximation for sampling the strength of the sun's gravitational effect at different distances. If gravity could be abruptly turned off, each planet would assume a straight path and fly off tangent to its present orbit. But with gravity in action, at a specified distance from the sun, there is a certain amount of bending of a planet's trajectory. With just the right speed, the trajectory will be bent into a circle around the sun; thus, at that distance, the period of the planet is automatically established if the orbit is to be a circle. Likewise, an elliptical orbit samples the strength of the sun's gravitational effect at different distances because the planet's trajectory carries it closer and then farther from the sun. This calculation requires the limit concepts of the differential calculus, and is worked out in Book 1 of Newton's *Principia*. Kepler's third law is easier mathematically but more restrictive (requiring circular orbits as an approximation). Nevertheless, it did provide a path for Newton to show that the strength of gravity varied inversely with the square of the distance, that is, by $1/r^2$. Newton probably never read Kepler's *Astronomia nova* nor *The Harmony of the World*, but he could have found Kepler's P^2/a^3 relationship in his well-thumbed copy of Nicholas Mercator's *Institutionum astronomicarum* (1676).

One consequence of Newtonian physics is to show that Kepler's third law is actually only an approximation. P^2/a^3 is *not* a constant, for this ratio depends on $(M + m)$ where M is the mass of the sun and m the mass of the planet. Because M is overwhelmingly larger than m, the differing masses of the planets makes rather little difference, and in the solar system, P^2/a^3 is approximately constant. However, in other applications, the $(M + m)$ dependency is critical. What we learn here is that Kepler's third law is not really a law after all, but just a convenient (and valuable) approximation. It is a man-made representation of the universe, but decidedly limited when the $(M + m)$ dependency is omitted.

In the same way, we could inquire whether the law of gravitation is a fundamental law of nature, or something of a man-made invention. We could, for example, examine how Newton invented the basic ideas of the integral calculus to establish what distance to use in coping with a sphere, or how he used experimental pendula to establish the equality between gravitational and inertial mass. We could also turn to Einstein to show how the general relativistic solution of gravitation solved the problem of the advance of perihelion of Mercury, a conundrum that defeated Newtonian gravitation. Today, with the further puzzle of dark energy, we realize that the law of gravity is still an unresolved mystery, and the laws of nature we have so far found are man-made constructions based on a far-from-complete understanding of nature herself. In that sense, we could call these laws of nature "epistemological laws."

God's Agenda

Laws such as Kepler's, or Newton's famous laws of motion, can be classed as epistemological statements based on what we have gleaned observationally. Most scientists will, after a little contemplation, agree that these laws are man-made, but they will likely add that such formulations are approaching some deeper, inviolate laws of nature that exist whether or not we fully comprehend them. These can be called "ontological statements," referring to the fundamental nature of the universe itself, how it really is. And this is where an implicit leap of faith occurs.

For Boyle and Newton, as well as for Descartes, laws of nature as a concept grew from theological roots and the notion of Divine Law. In delineating the history of the concept, Oxford's Peter Harrison has concluded that today, science, insofar as it *assumes* the reality of mathematical laws, operates with a tacitly theistic assumption about the nature of the universe. The mere existence of this underlying rationality of the universe, its deep ontology, points toward a divine creative reality that we can label as "God's agenda."

The British physicist/theologian John Polkinghorne reasons along the same lines when he writes that we must

> face the fact that science is privileged to explore a universe that is both rationally transparent and rationally beautiful in its deep and accessible order … Something profound is going on in science's exploration of our deeply intelligible universe that calls for metascientific illumination."[18]

These insights provide a strong hint for answering Einstein's most serious inquiry: Why is the universe comprehensible?

What else does this view purchase for the religious understanding of the world in which we find ourselves? Some events that seem totally incredible to those of us who take seriously the world's stability and dependability, such as the resurrection of Jesus after his crucifixion and entombment, can be seen, not as rare suspensions of the laws of nature, but as the intersection of a more fundamental spiritual universe with the physical universe embedded in it—a physical universe in which the ontological laws of nature always hold, but which is only a subset of the total reality. It is a matter of faith that such a spiritual universe exists, and by the same token, also a matter of faith to deny its existence.

Notes

1 Aristotle, *Metaphysics,* Book XII, chap. 7.

2 Maestlin to Kepler, 21 September 1616 (O.S.), *Johannes Kepler Gesammelte Werke* 17 (Munich: Verlag, 1955), 187 (lines 25–30).

3 See James Voelkel, *The Composition of Kepler's* Astronomia nova (Princeton, NJ: Princeton University Press, 2001), 100–1. The page in Kepler's workbook is partially transcribed in *Johannes Kepler Gesammelte Werke* 20,2 (Munich: Verlag, 1998), 18, but the drama of the crossed-out part is entirely missing. The page is reproduced in Owen Gingerich, *The Eye of Heaven: Ptolemy, Copernicus, Kepler* (New York: Springer, 1993), 335.

4 See Owen Gingerich, *The Book Nobody Read: Chasing the Revolutions of Nicolaus Copernicus* (New York: Walker, 2004), 163–5.

5 William Donahue, trans., *Kepler's* Astronomia nova (Cambridge: Cambridge University Press, 1992), 468 (from the beginning of chap. 47).

6 Ibid., 543 (from the beginning of chap. 56).

7 Newton to Halley, 20 June 1686, *The Correspondence of Isaac Newton,* II, p. 436.

> For as Kepler knew the Orb to be not circular but oval and guest [sic] it to be Elliptical, so Mr. Hook without knowing what I have found out since his letters to me, can know no more than that the proportion was duplicate *quam proximè* at great distances from the center, & only guest it to be so accurately and guest amiss in extending that proportion down to the very center, whereas Kepler guest right at the Ellipsis. And so Mr. Hook found less of the Proportion then [sic] Kepler of the Ellipsis.

[8]Nicolaus Copernicus, *De revolutionibus* (Nuremberg: 1543), Book 1, chap. 10.

[9]*Johannes Kepler Gesammelte Werke* 6 (Munich: Verlag, 1940), 290 (the Introduction to Book 5 of *Harmonice mundi*). The third law is found in Book 5, chap. 3, p. 302.

[10]Curtis Wilson, "Kepler's Laws, So-Called," *Newsletter of the Historical Astronomy Division of the American Astronomical Society* (May 1994).

[11]J.-J. LaLande, *Abrégé d'Astronomie* (Paris: 1774), p. 201, paragraph 467.

[12]Kepler, *Mysterium cosmographicum* (1621), chap. 2, note no. 4 to the second edition, A. M. Duncan, trans., *Johannes Kepler: Mysterium Cosmographicum: The Secret of the Universe* (New York: Abaris Books, 1981), 103.

[13]Ibid., chap. 11, note no. 2 to the second edition, p. 125.

[14]From the beginning of Kepler's introduction to Book I of the *Harmonice mundi;* Kepler, *The Harmony of the World,* trans. E. J. Aiton, A. M. Duncan, and J. V. Field (Philadelphia, PA: American Philosophical Society, 1997), 9–10.

[15]A. Einstein, *Ideas and Opinions* (New York: Bonanza Books, 1954), 323–4.

[16]John Henry, "Metaphysics and the Origins of Modern Science: Descartes and the Importance of Laws of Nature," *Early Science and Medicine* 9, no. 2 (2004): 73–114; Peter Harrison, "The Development of the Concept of Laws of Nature," chap. 2 in Fraser Watts, ed., *Creation: Law and Probability* (Aldershot, England: Fortress Press with Ashgate Publishing, 2008), 13–36.

[17]Robert Boyle, *About the excellency and grounds of the mechanical hypothesis, some considerations* (London: 1674).

[18]John Polkinghorne, *Science and the Trinity: The Christian Encounter with Reality* (New Haven, CT: Yale University Press, 2004), 64–5.