

# Analogy in Scientific Discovery: The Case of Johannes Kepler

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**Abstract:** Analogy is often linked with scientific discovery. In this paper I lay out a theory of analogical processing and apply it to the work of Johannes Kepler. Kepler is striking not only for the magnitude of his discoveries but because of the articulateness with which he laid out his reasoning processes, including his frequent and extended use of analogies. I discuss four analogical subprocesses - highlighting common structure, projecting inferences, re-representing relations, and noticing alignable differences - by which analogy brings about new ideas and show how they apply in Kepler's work. I focus particularly on a central extended analogy in which he used the phenomenon of the *light* from the sun, which travels to the planets and illuminates them, as a base domain for a new ontological entity (a precursor of gravity) - the *vis motrix*, that causes the planets to move.

Analogical reasoning can lead to change of knowledge - not only to enrichment of existing representations but also to true conceptual change. The work of Johannes Kepler (1571-1630) offers a clear example of the use of analogical processes in discovery. Kepler seems to have been a natural analogist. He used analogies constantly, both to make local points and to frame global theories. I focus here on one central analogy that played a formative note in this thinking: an analogy between light from the sun that illuminates the planets to something else - initially a spirit and later a force or power - emanating from the sun that causes the planets to move. He conceived this idea in its initial form early in his career, and over the next 20 years, used the analogy with light to develop the idea further of a *vis motrix* (a motive power between the sun and planets). As Toulmin and Goodfield (1961, p. 198) put it, "The lifelong, self-appointed mission of Johann Kepler

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[...] was to reveal the new, inner coherence of the Sun-centered planetary system. His central aim was to produce a ‘celestial physics,’ a system of astronomy of a new kind, in which the forces responsible for the phenomena were brought to light”.

In this paper I will try to show how the cognitive processes inherent in analogy can promote conceptual change. I lay out a set of analogical mechanisms by which analogy can act to create changes in knowledge and consider how these analogical mechanisms could have brought about the kinds of theory change that Kepler experienced. I begin with a tour of Kepler’s discoveries. Then I give a brief review of the slate of knowledge existing when Kepler began his work. Then I describe the evolution of Kepler’s great analogy. Next comes a description of analogical processing followed by its application to Kepler. Finally, I consider the psychological status of Kepler’s analogies.

Kepler’s best-known discoveries are the three laws of planetary motion:

1. (1609) First Law: The planetary orbits are ellipses with the sun at our forces.
2. (1596, 1609) Second Law: A line between the sun and any planet sweeps out equal times.
3. (1634) Third Law: The square of the period of a planet’s orbit is proportional to the cube of its radius:  $T^2 = kR^3$

He made a number of other discoveries, including an incremental calculus for computing the volume of a wine barrel; the modern theory that comet’s tails consist of ejected matter; the proposal that the moon causes tides; a detailed theory of optics; writings on the comic sections and, in 1627, the Rudolphine Tables for predicting planetary motions, which were roughly 30 times more accurate than prior tables (Gingerich, 1993, p. 50).

But by far Kepler’s most important discovery was his causal theory of planetary motion. As Gingerich (1993) puts it, Kepler’s most consequential achievement was the mechanizing and perfecting of the world system. By the *mechanization* of the solar system, I mean his insistence on a “new astronomy based on the causes, or the celestial physics”, as he tells us in the title of his great book [the *Astronomia Nova*]. By the *perfection* of the planetary system, I mean the fantastic improvement of nearly two orders of magnitude in the prediction of planetary positions (p. 333).

To see the magnitude of Kepler’s discovery, we begin by reviewing the system of cosmology that Kepler inherited when he began his work in 1590. The ontology and explanatory system of medieval astronomy followed a line laid down by Plato and Aristotle and culminating in Ptolemy’s system of the II century AD:

1. The earth is at the center of the universe and is itself unmoving.
2. The earth is surrounded by physically real crystalline spheres, containing the heavenly bodies, which revolve around the Earth.
3. The heavenly bodies move in perfect circles at uniform velocity. (However, epicycles and eccentrically positioned circles were used to account for the observed motions).
4. Heavenly bodies and their spheres are composed not of the four terrestrial elements - earth, air, fire and water, but of a fifth element, the *quintessence* - a crystalline aether that is pure, unalterable, transparent, and weightless. The farther from Earth, the purer is the sphere. By the same token, celestial phenomena must be explained in different terms from earthly phenomena.
5. All motion requires a mover. In the Aristotelian universe, the outermost sphere, containing the fixed stars, is moved by an "unmoved mover," the *primum mobile*. Each sphere imparts motion to the next one in.
6. Celestial bodies have souls. In particular, each planet is controlled by its own spirit, which mediates its motion. (This last principle, descended from the Stoics, enjoyed a resurgence in the XVI century for reasons explained below).

When this Aristotelian-Ptolemaic system was integrated with Catholic theology in the early XIII century by Albertus Magnus and Thomas Aquinas, angelic spirits were assigned to the celestial spheres in order of rank, from Seraphim in the outermost and purest sphere, that of the *primum mobile*, inward to Cherubim (controlling the sphere of fixed stars) Thrones, Dominations, Virtues, Powers, Principalities, Archangels, and finally Angels, (controlling the sphere of the moon). The resulting conceptual scheme, dominant until the XVI century, was one of extreme intricacy and cohesion.

The Stoic view overlapped with the Aristotelian-Ptolemaic view in being geocentric, with a sphere of fixed stars. However, it differed in that it postulated that the heavens were filled not with pure aether but with a kind of intelligent pneuma (a combination of fire and air), which became more pure with distance from the earth. The heavenly bodies, also made of pneuma, were intelligent and capable of self-direction (Barker, 1991). There were thus two explanations for celestial motion: (1) the transmission of motion through interlocking crystalline spheres, and (2) the action of planetary intelligences or souls. Kepler dismissed the first because of two recent astronomical events. The first was a new star - a nova (or supernova) in 1572 - evidence against the Aristotelian doctrine of the unchanging and incorruptible firmament. The second was a comet in 1577 (and others not long after), whose path ran through the planetary spheres - which should therefore have been cracked. This was evidence against the view that the planets moved by

attachment to crystalline spheres. This left the idea of guiding spirits moving the planets. Throughout his career Kepler wrestled with the idea that the planets move themselves intelligently, gradually paring away aspects of intelligent thought in search of a more purely physical description.

The other major event that set the stage was Nicolaus Copernicus's publication of *De revolutionibus orbium celestium* in 1543, the year of his death - thirteen centuries after Ptolemy's model and thirty years before Kepler's birth - proposing the idea that the earth and other planets moved around the sun. Copernicus argued for his system on grounds of mathematical elegance and sufficiency, not on the basis of physical causation. Indeed, for mathematical reasons, he placed the center of the solar system at the center of the Earth's orbit, rather than the center of the sun itself.

Kepler embraced Copernicus's heliocentric characterization of planetary orbits. But from the start, he changed this conception radically, infusing it with causal significance. This causal interpretation of Copernicus's theory led to a reaxiomitization of astronomy. As Gingerich (p. 333) notes, "Copernicus gave the world a revolutionary *heliostatic* system, but Kepler made it into a *heliocentric system*. In Kepler's universe, the Sun has a fundamental physically motivated centrality that is essentially lacking in *De revolutionibus*. We have grown so accustomed to calling this the Copernican system that we usually forget that many of its attributes could better be called the Keplerian system." In part this is Kepler's own doing: he saw himself as simply making clear the real significance of Copernicus's work and titled one of his great works *The Epitome of Copernican Astronomy*.

With this as background, in 1596 the 25-year-old Kepler posed a simple but profound question: Why do the outer planets move slower than the inner planets? He noticed that the periods of the outer planets were longer, relative to those of the inner planets, than could be predicted simply from the greater distances they had to travel - that is, they traveled slower. From within the Stoic cosmology of planetary spirits, he asked whether the "moving souls" were simply weaker the further the planet. Instead, he conjectured the planets might be moved not by their own individual spirits but one spirit residing in the sun - the *anima motrix*. In this conjecture, he drew on an analogy with the sun's light (Kepler, *Mysterium cosmographicum*, 1596, p. 199):

[...] one of two conclusions must be reached: either the moving souls [*motricis animae*] are weaker the further they are from the Sun; or, there is a single moving soul [*motricem animam*] in the center of all the spheres, that is, in the Sun, and it impels each body more strongly in proportion to how near it is.

He reasons that just as light grows fainter with distance, so might this motivating spirit or power (Kepler, *Mysterium cosmographicum*, 1596, p. 201).

Let us suppose, then, as is highly probable, that motion is dispensed by the Sun in the same proportion as light. Now the ratio in which light spreading out from a center is weakened is stated by the opticians. For the amount of light in a small circle is the same as the amount of light or of the solar rays in the great one. Hence, as it is more concentrated in the small circle, and more thinly spread in the great one, the measure of this thinning out must be sought in the actual ratio of the circles, both for light and for the moving power [*motrice virtute*] [...]

Kepler was well aware of the implausibilities in his proposal. In the *Astronomia Nova* (1609), Kepler challenged his theory with the thorny question of action at a distance:

For it was said above that this motive power is extended throughout the space of the world, in some places more concentrated and in others more spread out...This implies that it is poured out throughout the whole world, and yet does not exist anywhere but where there is something movable (Kepler 1609/1992, p. 382).

He answers this challenge by invoking the light analogy:

But lest I appear to philosophize with excessive insolence, I shall propose to the reader the clearly authentic example of light, since it also makes its nest in the sun, thence to break forth into the whole world as a companion to this motive power. Who, I ask, will say that light is something material? Nevertheless, it carries out its operations with respect to place, suffers alteration, is reflected and refracted, and assumes quantities so as to be dense or rare, and to be capable of being taken as a surface wherever it falls upon something illuminable. Now just as it is said in optics, that light does not exist in the intermediate space between the source and the illuminable, this is equally true of the motive power (Kepler, 1609/1992, p.383).

It can be seen here that already by 1609 the idea of a motive *spirit* in the sun was giving way to a motive *power* or *force*. By the time of his 1621 revision of the *Mysterium cosmographicum*, Kepler had fully re-represented the “soul” of the sun to be a physical force or power (Kepler, *Mysterium cosmographicum*, 1621, p. 201):

If for the word “soul” [*Anima*] you substitute the word “force” [*Vim*], you have the very same principle on which the Celestial Physics is established [...]. For once I believed that the cause which moves the planets



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