The Laws? of Physics

Kevin H Knuth
University at Albany (SUNY), Albany NY USA

Physics is traditionally conceived of as a set of laws that universally governs the behavior of physical systems. These laws, however they are decreed, are believed to govern the behavior of not only everything in the universe, but the form of the universe itself, that is, the very nature of space and time in which everything is conceived to be embedded. The laws of physics distinguish the probable from the improbable, and separate the possible from the impossible.

But is this law-based description of the universe too anthropomorphic? Are we really to believe that when we release a rock from our hand that it is somehow compelled by this decree and thus obliged to fall to the ground? Or are there deeper reasons why the rock does what it does every time it is released? One might feel inclined to discard the legal metaphor and refer to the behavior of the rock as something more like a tendency or a habit[1]—something that all rocks in the given situation happen to do. However, without a deeper understanding, this conception of the laws of nature as tendencies or habits suggests that things could not only have been otherwise, but also that the situation could change. The unalterable character of the laws of nature and their permanence, are hypotheses that are virtually untestable if the rates or frequencies with which they change are too low. For this reason, these concepts are part of the dogma of science as a belief system, and will remain so until we either demonstrate them to be false or understand why nature is described by the laws we observe and not others. In this sense reductionism, as an act of seeking simple underlying explanations, is ultimately critical to our understanding of the nature and character of natural law.

* * *

The idea that the universe was made by a Creator is ancient, and understanding the laws of nature has been likened to knowing the mind of the Creator. But, perhaps surprisingly, a Creator assumed to have infinite powers is often conceived to have had little choice in the design of the universe. This is succinctly expressed in a discussion by Hugo Grotius[2] on some statements made by Aristotle about natural law:

> ``the Law of Nature is so unalterable, that God himself cannot change it. For tho' the Power of God be infinite, yet we may say, that there are some Things to which this infinite Power does not extend, because they cannot be expressed by Propositions that contain any Sense, but manifestly imply a Contradiction. For instance then, as God himself cannot effect, that twice two should not be four''

Grotius' statement expresses the belief that God cannot do something that would lead to contradiction. This is a dramatic way of expressing the belief that the laws of nature must be, in some sense, consistent.

Imposition of consistency is a strong constraint that has deep implications (Knuth, 2014, 2015; Skilling & Knuth, 2017). For example, if there is one physical law which must be obeyed, then this one law puts constraints on other physical laws, such that they must be consistent with and not contradictory to the one. Consistency implies that some laws of physics will be contingent upon other laws of physics. Since Newton, we have recognized this. Newton found that some laws of physics are contingent upon or derivative of other laws, and it is this fact that compels one to declare some laws to be more basic or fundamental than others. This has led to the general belief that there exists a small set of fundamental laws from which others can be derived. Whether a unique set of fundamental laws exists, and if it does, precisely how small is this set is unknown. Regardless, such ideas raise several important questions: ``What is the fundamental nature of reality,'' or more precisely, ``What are the fundamental laws and can we know them?''

Such ponderings lead one rather quickly to ask ``Why these laws and not others?'' That is, why is the universe the way it is and not something completely different? In other words, would a Creator have the freedom to choose the set of laws in the design of a universe? Or would potential choices be sufficiently constrained so that there was a single uniquely-consistent set of laws?

* * *

Some laws leave us with the impression that the situation could have been otherwise, whereas there are other laws for which it is more or less inconceivable that they could have been different (Hogan, 2000). For example, one might be able to imagine that the gravitational force could be weaker or stronger (with Newton's gravitational constant having a different value), or that the speed of light could be much slower, but it is far more difficult to imagine that two times two could be something other than four, or that an object could have a left side without there being a right side. The latter examples are difficult to imagine precisely because the suggested variation would lead to obvious contradiction---a dramatic lack of consistency.

Today many people make a distinction between situations which are determined or derivable versus those which are accidental or contingent. Unfortunately, the distinction is not as obvious as one might expect or hope. One example that comes to mind is the fact that the laws describing planetary motion are determined and derivable from Newton's three laws of motion and his law of gravity. Of course, one also needs to know what are called the `*initial conditions*,' which describe the masses, positions and velocities of the other objects in the solar system at some point in time. Knowing these `initial conditions,' one can use Newton's laws to work backwards or forwards to describe the state of the solar system at a time in the past or future, respectively. Now one might think of Newton's laws as determined (since we do not currently know with certainty if they are derivable), and the `initial conditions' as accidental or contingent. But the distinction between the two situations is far subtler.

One of the most famous stories in the history of physics and astronomy is centered on the longstanding question as to whether the number of planets in our solar system, and their orbits, are determined by some law, or are accidental or contingent on the complicated history that led to the conditions in which our solar system formed. The story involves the struggle faced by Johannes Kepler to understand the orbits of the then six known planets around the Sun. Kepler, as a deeply religious man, rejected the idea that both the number of the planets and their orbits were accidental. Instead he viewed them as divinely determined by geometry, and in his book *Mysterium Cosmographicum* (1596) he describes each orbit as a circle on a sphere circumscribed about one of the five regular polyhedra, also known as the Platonic solids[3], which are then nested within one another (Figure 1). Inspired by a comment attributed to Socrates in Plato's *Politeia VII* where he notes that musical harmony is the sister science to astronomy (van der Schoot, 2001), Kepler worked to relate each of the spheres to a musical harmony. While his model of the dimensions of the spheres based on the Platonic solids fitted the available data quite well (with approximately 10% error), Kepler could not figure out how to assign musical intervals to the spheres. Later it was Kepler himself, when confronted with Tycho Brahe's careful measurements, particularly of Mars, who came to realize that the orbits of the planets were not circular, but were instead elliptical. This forced a reconsideration of which aspects of the solar system were contingent and which were determined.

However, despite such considerations, even today we are not certain to what degree, if at all, the numbers and the orbits of the planets are accidental. For example, the Titius-Bode Law is an empirical description of the semi-major axes (approximately the Sun-planet distances) of the planets in our solar system (Nieto, 1972). The basic unit of distance is typically chosen to be the ***Astronomical Unit*** (AU), where 1 AU represents the distance from the Sun to the Earth, which is approximately 93 million miles.

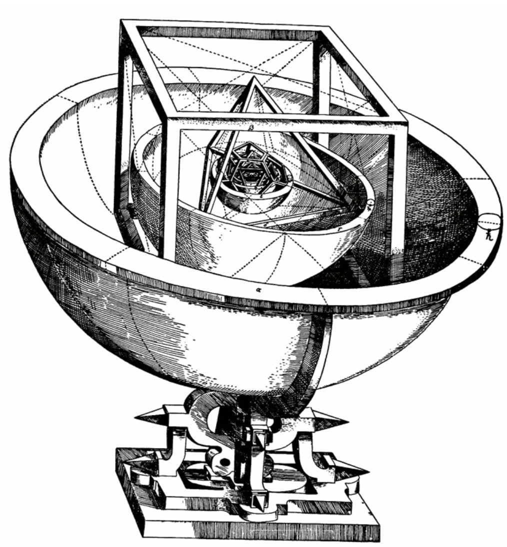


Figure 1. An illustration of Kepler's model of the solar system based on the Platonic solids nested within spheres. (Public Domain) https://commons.wikimedia.org/w/index.php?curid=3

Basically, the law predicts that each planet will be very roughly twice as far from the Sun as the previous one. This law is often described as taking the series of numbers 0, 1, 2, 4, 8, 16, ⋯ and multiplying them by 3 to get 0, 3, 6, 12, 24, 48, ⋯. This is followed by adding 4 to each number in the series and dividing each of them by 10 to obtain the predicted distances in Astronomical Units (AU) (Table 1).

The Titius-Bode Law originally held for the six known planets, and confidence in the law naturally grew with the discovery of the dwarf planet Ceres in the asteroid belt and the distant gas giant Uranus, both of which fit the law well. However, the discovery of Neptune and Pluto cast serious doubt on the validity of the law as neither planet fit the predicted pattern. It is curious that the currently hypothesized Planet Nine, thought to have a semi-major axis of about 700 AU (Batygin & Brown, 2016), would be predicted by the law to have a semi-major axis of 614.8 AU. Moreover, a generalization of the law not only fits several of the planets of the solar system, but also fits the larger moons of the planet Uranus (Neuhauser & Feitzinger, 1986).

Index	X 3	+ 4	÷ 10	Planet	Semi-Major Axis
0	0	0	0	Mercury	0.39 AU
1	3	7	0.7	Venus	0.73 AU
2	6	10	1.0	Earth	1.00 AU
4	12	16	1.6	Mars	1.52 AU
8	24	28	2.8	Ceres	2.77 AU
16	48	52	5.2	Jupiter	5.20 AU
32	96	100	10.0	Saturn	9.55 AU
64	192	196	19.6	Uranus	19.2 AU
128	384	388	38.8	Neptune	30.11 AU
				Pluto	39.54 AU

Table 1. A comparison of the Titius-Bode Law predictions for planetary distances from the Sun and the semi-major axis length of each planetary orbit.

However, despite efforts involving theory (Graner & Dubrulle, 1994), simulations (Isaacman & Sagan, 1977), as well as the recent flood of information about exoplanetary systems (Poveda & Lara, 2008; Chang, 2010), it is still not clear whether the Titius-Bode Law represents, or results from, a fundamental principle of solar system evolution, represents a highly probable configuration (Lynch, 2003), is a coincidence, or is an effect related to accidental patterns being observed in sets with small sample size (Newman, Haynes, Terzian, 1994). Only recently, has it been proposed that the spacing between the planets is defined by energetics where the spacings are defined by the regions of gravitational influence of forming protoplanets (Christodoulou & Kazanas, 2017). It is surprising that despite the fact that the motions of planets orbiting the Sun are determined by Newton's Laws, we find ourselves in a situation where it is not clear whether the number of the resulting planets, and their respective orbits, are determined or contingent.

Another relevant example of an unestablished ``law'' involves a formula that appears to relate the masses of some elementary particles. The current Standard Model says that there are two types of particles that make up matter: the quarks, which combine to form mesons and baryons, and the leptons, which include the electron, e, and its heavier cousins the muon, μ, and tauon, τ (Figure 2). These particles are grouped into three generations with the particles in each successive generation being more massive than those in the previous. At present, there exists no established theory that explains why there appear to be three generations of particles. Nor is there an established theory explaining why the particles have the masses that they do. However, in 1982 theoretical physicist Yoshio Koide found a surprisingly simple empirical formula relating the three charged lepton masses (Koide, 1982, 1983), the mass of the electron m_e (0.511 MeV), the mass of the muon m_μ (105.7 MeV), and the mass of the tauon m_τ (1.78 GeV):

$$\frac{m_e + m_\mu + m_\tau}{\left(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau}\right)^2} = \frac{2}{3}$$

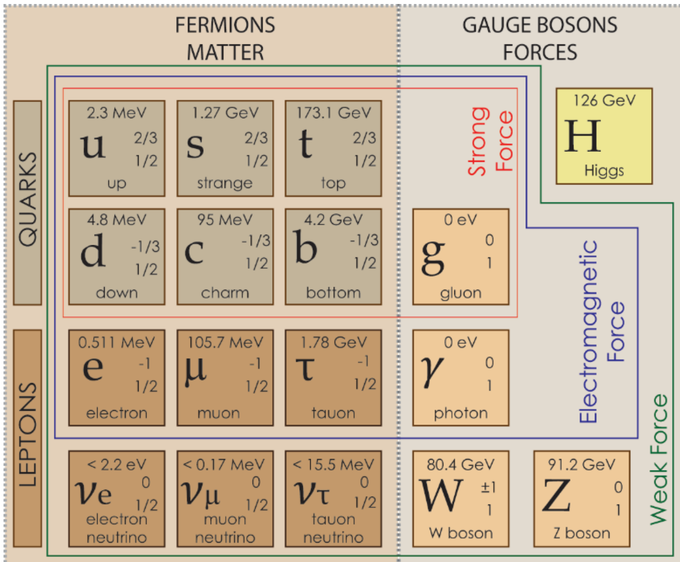


Figure 2. The Standard Model of the fundamental particles. Fermions, which are the quarks and leptons, make up matter. Gauge bosons comprise the forces. Particle masses in units of electron volts (eV) are at the top of each box. Below that is the electric charge followed by the spin. The Koide formula holds for the three massive leptons, the electron, muon, and tauon, as well as for the three heaviest quarks, strange, bottom, and top.

It is interesting to note that the formula also holds for the three heaviest quarks: the strange, bottom, and top quarks. The masses of the three lightest quarks are not known well enough to test the formula. Since there is no fundamental theory that explains the origin of the particle masses or this proposed relationship, the Koide formula remains a curiosity, much like the Titius-Bode Law.

The difficulties we face in sorting out determined and derived relationships from accidental or contingent ones is not limited to the physical laws themselves, but extends into the realm of the fundamental physical constants. While we do not always think of the number pi, π, as a physical constant, we know today that the number pi relates the radius of a circle, r, to its circumference, C, by

$$C = 2\,\pi\,r$$

and the radius of a circle to its area, A, by

$$A = \pi\,r^2\,.$$

However, thousands of years ago, the value of pi was not well known, nor was it clear that the number relating the radius of a circle to its circumference was the same number that related the radius of a circle to its area. The Babylonians and Egyptians did not have a theoretical means of calculating the number pi. Instead, they relied on estimates of pi obtained by measurement so that pi was essentially an experimentally-determined constant. For example, the Babylonians often estimated the value of pi to be 3. However, one Babylonian tablet[4], dated from between 1900 and 1680 BCE, gives the value of pi to be 3.125. In ancient Egypt, the formula

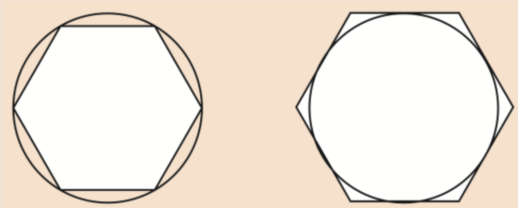
$$A = \left(\frac{8}{9}\,(2r)\right)^2$$

was used to compute the area of a circle from its radius resulting in a value of 3.1605 for pi.[4] The famous classical mathematician Archimedes of Syracuse (c. 287–212 BCE) showed that the value of pi could be determined through geometric reasoning by using a succession of polygons of increasing numbers of sides. By working with polygons having up to 96 sides, Archimedes not only was able to put bounds on the value of pi (Dun, 1996)[5]

$$3\,\frac{10}{71} < \pi < 3\,\frac{1}{7}\,,$$

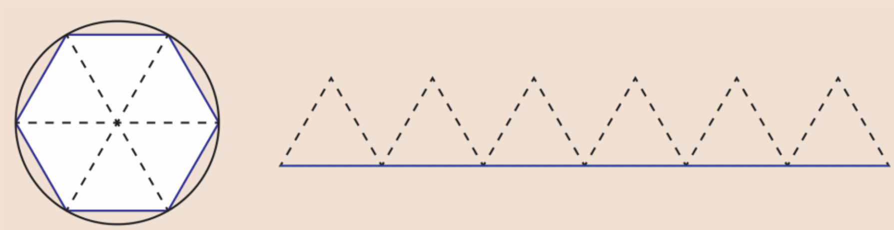
which is

Archimedes and Pi



By noting that the circumference of a circle is greater than the perimeter of an inscribed polygon and less than the perimeter of a circumscribed polygon, Archimedes found a lower and upper bound to the value of pi:

$$3\frac{10}{71} < \pi < 3\frac{1}{7}$$



The area of the circle is almost equal to the area of the circumscribed polygon. By summing the areas of the triangles, the area of the polygon is found by using the formula for the area of a triangle

$$A_{triangle} = \frac{1}{2}\, b \times h \qquad A_{polygon} = \frac{1}{2}\, p \times r$$

where the base b is the perimeter p of the polygon and the height is the radius r of the circle. Since the perimeter of the regular polygon is almost equal to the circumference of the circle $C = 2\pi r$, the area of the circle is:

$$A = \tfrac{1}{2}\, C \times r = \tfrac{1}{2}\, (2\,\pi\, r) \times r = \pi\, r^2.$$

In this way, Archimedes could show that the number pi relating the radius to the circumference was the same number that relates the radius of the circle to its area.

$$3.140845 < \pi < 3.142857,$$

but also, was able to prove that the number pi relating the radius and circumference of a circle, $C = 2\,\pi\,r$, was the same as the number pi relating the radius and area of a circle $A = \pi\,r^2$ (Borwein, 2004).

Without the insight of Archimedes or a knowledge of calculus, this is not immediately obvious.

A similar approach involving taking limits of polygons was later employed by the Chinese mathematician Liu Hui in the third century AD to find the value of pi to be 157/50 = 3.14 (Dun, 1996).

A mathematical formula leading to the derivation of the value of pi

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots$$

had to wait for almost 2000 years until the work by the Indian mathematician Madhava of Sangamagrama, who had a specific interest in infinite series.

Today we continue to question whether certain fundamental constants, such as the fine structure constant, which dictates the strength of the electric force, are derivable or contingent. The fine structure constant, α, depends on a variety of other physical constants, such as the elementary electric charge e, the electric constant ϵ_0, which is also known as the permittivity of free space, the speed of light, c, and Planck's constant h, which relates units of energy to units of frequency:

$$\alpha = \frac{1}{2\,\epsilon_0}\frac{e}{h\,c} \sim \frac{1}{137}.$$

The fine structure constant is extremely important in that it determines the size and stability of atoms, and as a result determines what chemistry is possible. If the fine structure constant had a different value, the universe might have been such that many molecules that we depend on for life would not be stable and we would not exist. In a universe without a Creator, where the fine structure constant was either derivable or contingent, one could not be assured that its value would be conducive to life. That is, the probability that life could have arisen in such a universe would be vanishingly small.

Now some might point to this fact that the physics of the universe appears to be fine-tuned to enable our existence as evidence of a Creator.[6] The nature of the envisioned Creator has varied dramatically over the ages from one or more gods all the way to more recent conceptions, which side-step the notion of a Creator, and suggest that the universe could be a sort of simulation or computer (Lloyd, 2002; Wolfram, 2002; Bostrom, 2003). Despite whatever the ultimate origin of the universe may be, the fact that the laws of physics are likely to be constrained by consistency makes this question, as to why the universe appears to be fine-tuned for life as we see on Earth, a potentially critical one.

This question is often posed in more general terms of whether the universe could have been such that the values of certain physical constants would result in atoms or molecules to be unstable. Some physicists think so, and this has led some to consider the possibility of multiverses (Davies, 2004; Adams, 2008). The speculation is that there exists a multitude of universes in which the laws of physics may vary dramatically from universe to universe. Since life can arise only in universes that can accommodate it, it may be the case that we happen to inhabit one of the many existing universes, most of which are uninhabitable (without atoms, molecules, planets, etc.). An alternate explanation could involve the idea that universes naturally evolve and that there is some kind of natural selection at play (Harrison, 1995). However, this requires that a universe spawns other universes with some kind of selection pressure.

Despite whatever situation we are in, much of the proposed potential variation in universes depends on which laws and constants are derivable and which are not. It is possible that the degree of variation is tightly constrained and that any other universes would necessarily be very much like our own. At this point, none of this is known with any certainty.

* * *

Other, more recent, schools of thought consider the laws of physics to represent rules for the optimal processing of information about Nature (Caticha, 2012), or the similar idea that the mathematical form of physical laws represent constraint equations requiring that the quantification of a physical system is consistent with inherent symmetries (Knuth, 2004; Knuth 2014, 2016; Skilling & Knuth 2017). These approaches are generally referred to as Information Physics (Knuth, 2011; Goyal, 2012). While serious efforts to derive the laws of physics by relying on these information-based perspectives (Caticha & Cafaro, 2007; Caticha, 2008; Goyal, Knuth, Skilling 2010; Goyal & Knuth, 2011; Knuth & Bahreyni, 2012; Knuth 2014, 2015; Skilling & Knuth, 2017) are relatively new, the central role of information in physics has been well-known for some time (Jaynes, 1957; Tribus, 1961; Tribus & McIrvine, 1971; Bekenstein, 1973; Wheeler, 1992). While the relevance of these perspectives will be judged based on future success in deriving the laws of physics from entropic or Bayesian inference or as a result of consistent quantification, it is already clear that these approaches have the potential to explain why some of the laws of physics appear to be observer-dependent or observer-centric, especially within the domain of quantum mechanics (Knuth, 2014). Despite this fact, from the perspective of questions raised in this essay, it is not clear how such information-based foundations could begin to explain why the laws of physics appear to be tailored to accommodate life in this universe.

Notes

1. Rupert Sheldrake refers to the law metaphor as `embarrassingly anthropomorphic' and opts to refer to natural laws as habits, which are less human-centered. However, habits and tendencies are terms that carry the connotations of both arbitrariness and non-permanence, which may not be appropriate.
2. Hugo Grotius, also known as Hugo de Groot, (1583–1645) was a Dutch legal scholar and theologian who was the founder of modern international law.
3. The Platonic solids are the five regular polyhedra, which are solids with identical faces defined by regular polygons. These are the tetrahedron (four sides), the cube (six sides), the octahedron (eight sides), the dodecahedron (twelve sides), and the icosahedron (twenty sides), which are perhaps most familiar as the shapes of dice used by role-playing gamers. One might ask, why only five? Well, the fact that there can be only five regular polyhedra is determined by symmetries.
4. L. A. Smoller (http://archive.is/UGFdX)
5. There is a typo in Dun (1996) where $3\frac{10}{11}$ is written instead of the correct value of $3\frac{10}{71}$.
6. However, it could be the case that life is instead fine-tuned to the universe, and that it is our lack of imagination that prevents us from imagining that there could be life of a very different sort in a universe with different values of the fundamental constants.

References

Batygin, K. and Brown, M.E. 2016. The Astronomical Journal 151, no. 2, 22.

Bekenstein, J.D., 1973. Physical Review D, 7(8), p.2333.

Borwein, J. M., Bailey, D. M., and Bailey, D. 2004. *Mathematics by experiment: Plausible reasoning in the 21st century*, AK Peters Natick, MA, 2004.

Bostrom, N. 2003. The Phil. Quarterly 53, no. 211, 243–255.

Caticha, A., 2008, November. From inference to physics. AIP Conf. Proc. (Vol. 1073, No. 1, pp. 23-34).

Caticha, A., 2012. Entropic Inference and the Foundations of Physics (monograph commissioned by the 11th Brazilian Meeting on Bayesian Statistics–EBEB-2012).

Caticha, A. and Cafaro, C., 2007, November. From information geometry to Newtonian dynamics. AIP Conf. Proc. (Vol. 954, No. 1, pp. 165-174).

Christodoulou, D. M. and Kazanas, D. 2017. arXiv:1705.09356 [astroph.EP].

Davies, P.C.W. 2004. Mod. Phys. Lett. A 19, no. 10, 727–743.

Goyal, P., 2012. Information, 3(4), pp.567-594.

Goyal, P., Knuth, K.H. and Skilling, J., 2010. *Physical Review A*, *81*(2), p.022109.

Goyal, P. and Knuth, K.H., 2011. *Symmetry*, *3*(2), pp.171-206.

Graner, F. and Dubrulle, B. 1994. Astronomy and Astrophysics 282, 262–268.

Harrison, E.R. 1995. Quarterly Journal of the Royal Astronomical Society 36, 193.

Hogan, C.J. 2000. Rev. Mod. Phys. 72, 1149–1161.

Isaacman, R. and Sagan, C. 1977. Icarus 31, no. 4, 510–533.

Jaynes, E.T., 1957. *Physical review*, *106*(4), p.620.

Knuth, K.H., 2004. Deriving laws from ordering relations. AIP Conf. Proc. (Vol. 707, No. 1, pp. 204-235).

Knuth, K.H., 2011. Information physics: The new frontier. In AIP Conf. Proc. (Vol. 1305, No. 1, pp. 3-19).

Knuth, K.H. 2014. Contemporary Physics, 55(1), 12-32, (Invited Submission). doi:10.1080/00107514.2013.853426. arXiv:1310.1667 [quant-ph]

Knuth K.H. 2015. The deeper roles of mathematics in physical laws, FQXi 2015 Essay Contest Entry (Third Place Prize): "Trick or Truth: the Mysterious Connection between Physics and Mathematics".

Knuth, K.H. and Bahreyni, N., 2014. *Journal of Mathematical Physics*, *55*(11), p.112501.

Koide, Y. 1982. Lett. Nuovo Cim. 34, no. 8, 201–205.

Koide, Y. 1983. Phys. Rev. D 28, no. 1, 252.

Lloyd, S. 2002. Phys. Rev. Lett. 88, 237901.

Lynch, P. 2003. MNRAS 341, no. 4, 1174–1178.

Neuhäuser, R. and Feitzinger, J. V. 1986. Astronomy and Astrophysics 170, 174–178.

Newman, W. I., Haynes, M. P., and Terzian, Y. 1994. ApJ, 431, no. 1, 147–155.

Nieto, M.M. 1972. *The Titius-Bode Law*, Oxford Univ. Press, Oxford.

Poveda, A. and Lara, P. 2008. Revista Mexicana de Astronomía y Astrofísica 44, no. 1, 243–246.

Skilling J. and Knuth K.H. 2017. The symmetrical foundation of Measure, Probability and Quantum theories. arXiv:1712.09725 [quant-ph]

Tribus, M., 1961. *Journal of Applied Mechanics*, *28*(1), pp.1-8.

Tribus, M. and McIrvine, E.C., 1971. Scientific American, 225(3), pp.179-190.

van der Schoot, A. 2001. Renaissance Studies 15, no. 1, 59–78.

Wheeler, J.A., 1992. Annals of the New York Academy of Sciences, 655(1), pp.349-364.

Wolfram, S. 2002. *A new kind of science*, vol. 5, Wolfram Media, Inc.