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Mathematical beauty should not eclipse truth

Science needs empiricism

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*The idea that the universe is fundamentally mathematical is one of the leading frameworks in modern thought. From physics to philosophy, equations are often taken to disclose reality itself. But what if this is a projection rather than a discovery? Physicist **Martín López Corredoira** invites us to reconsider, questioning whether mathematics describes the world as it is, or as we are able to conceive it.*

There are two different methodologies for studying Nature, both inherited from different ways of thinking in ancient Greece: the rationalist–deductive method and the empirical–inductive method. The rationalist–deductive method was devised by Pythagoras (ca. 570–490 BCE) and Plato (ca. 427–347 BCE), according to whom the pure relations of numbers in arithmetic and geometry are the immutable reality behind changing appearances in the world of the senses. We cannot reach the truth through observation with the senses, they argued, but only through pure reason, which may investigate the abstract mathematical forms that govern the world. In this mode of thinking, there is a predominance of abstract theories, and mathematical modelling predominates over experimental and observational results. For Pythagoras and his followers in the 6th century BCE, the cosmos was not merely describable by mathematics, but it was fundamentally mathematical. Harmony in music, proportion in geometry, and order in the heavens were all expressions of numerical relationships.

Some historians think that the idea of a world ruled by numbers is related to the introduction of coins in the marketplace in the society in which Pythagoras lived. Anything could be reduced to abstract numbers: the value of a pot, a jar of oil, a plot of land, or a slave could be expressed by an exact number of coins, as could the wealth and worth of any citizen.

Plato also emphasised that true knowledge comes through reason alone, thus diminishing the role of the senses and the earthly realm as a whole. In his dialogue *Timaeus*, Plato formulates a cosmology with a creator moulding matter into approximations of these ideal shapes to create a Universe ruled by eternal mathematical laws, laws that humans can deduce only through reason. These eternal mathematical laws are the true reality, while the changeable Universe we see is a mere appearance; the observation of nature is thus unreliable.

Mathematical elegance cannot be physics due to the lack of observational support.

There are good cases of success using a rationalist–deductive approach. An example within modern science is Albert Einstein's (1879–1955) General Relativity, which was posited from aesthetic and/or rational principles in a time when observational data did not require a new gravity theory. In fact, observational tests proved this theory successful.

Present-day physics and cosmology are partially Pythagorean when a theory is created before the observations. It is common among modern Pythagoreans to approve of statements such as the search for beauty in a mathematical construction describing physical reality, or the Divine plan by which the creator designed the Universe. The physicist–mathematician tries to achieve something close to a mystical

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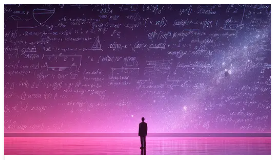

Reality cannot be turned into mathematics

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approach, tries to read into the Mind of God. Also, analogously with religion, this extremely theoretical physics and cosmology can only be understood by a priestly elite able to think in four or more dimensions, or in terms of similar abstractions.

Quantum mechanics is built on linear algebra in abstract Hilbert spaces. Particles are described by wave functions, which are mathematical objects encoding probabilities. The fundamental level of nature appears less like solid matter and more like a set of mathematical relationships.

Modern physics also reveals Pythagoreanism in the application of mathematical *symmetries*. A theorem by the mathematician Emmy Noether (1882–1935), known as Noether's theorem, shows that conservation laws arise from symmetrical properties of physical systems. The Standard Model of particle physics is based on symmetry groups, such as SU(3), SU(2), and U(1), defining strong, weak, and electromagnetic forces. These are abstract mathematical entities, yet they successfully predict the behavior of fundamental particles. The existence of particles often follows from mathematical consistency requirements before experimental confirmation—an outcome highly Pythagorean in spirit.

Another echo of Pythagoreanism is the idea that the universe might literally *be* mathematics. The physicist Max Tegmark (1967—) proposed the "Mathematical Universe Hypothesis", which claims that physical reality is a mathematical structure. In this view, mathematics is not a human invention but the substance of existence itself. Similarly, in digital physics and certain interpretations of quantum information theory, reality is understood in terms of information—discrete bits or quantum bits—suggesting a fundamentally numerical substrate.

Matter is not numbers

As opposed to the preceding method and worldview, the empirical–inductive method points out that nature should be known through observations and extrapolations of them. This is Anaxagoras' (500–428 BCE) method of knowing nature, a view of an infinite world in which there is no difference between the heavens and the Earth, with each operating on the same principles, and knowledge of nature based on observations and extrapolations of those observations to parts of the Universe distant in space and time.

Aristotle (385–322 BCE) used both inductive and deductive methods, and said that "the mathematical method is not the method of the physicists, because nature, perhaps all, involves matter" (*Metaphysics*, book II). Mathematics is useful for physicists, despite what was said by Aristotle, and this has been clear since Galileo Galilei (1564–1642) established the basis of the scientific method, but matter is not the same thing as mathematical entities. Matter is not numbers, or geometry, or arithmetic, or the analysis of functions. Matter (or, better, matter–energy) is a component of the physical Universe, and this is what constitutes the reality of nature as studied by the physical sciences.

The empiricism of Galileo Galilei might be an example in modern science, in the sense that observation and experimentation are a requisite prior to theoretization, although all scientists, even Galileo, are also partly Pythagorean. When Galileo Galilei wrote that the "book of nature is written in the language of mathematics," or he rejected Johannes Kepler's (1571–1630) hypothesis of elliptical planetary orbits by thinking that

relations, not objects

Biology, not physics, holds the key to reality

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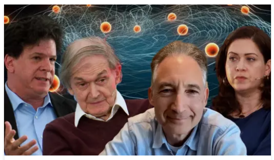

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only perfect circular motion could prevail in the heavens, he articulated Pythagorean concepts. Also, all Pythagoreans are, in part, empiricists. For example, Johannes Kepler, Pythagorean in his origins, embraced the empiricist deductive line of reasoning in his *Astronomia nova* (1609) with his analysis of Tycho Brahe's (1546–1601) measurements of the motions of Mars, which led to the first two of his three laws.

The limits of mathematical elegance

In physics itself, critics caution that mathematical elegance can mislead. The history of science includes many mathematically beautiful theories that failed experimentally.

The Vortex Theory of Atoms proposed in 1867 by William Thomson (Lord Kelvin; 1824–1907) modeled atoms as knotted vortex rings in a continuous ether. It was mathematically rich and inspired sophisticated work in topology. However, it produced no successful experimental predictions and collapsed as atomic theory and electromagnetism developed.

Arthur S. Eddington's (1882–1944) Fundamental Theory attempted to deduce the constants of nature purely from mathematical and epistemic principles. The theory was admired for its ambition and mathematical elegance, but its numerical predictions did not withstand empirical scrutiny and it failed to gain acceptance.

In his later years, Albert Einstein pursued unified field theories that sought to combine gravity and electromagnetism in a single geometric framework. These theories were mathematically sophisticated, but did not produce empirically verified predictions and ultimately failed to account for quantum phenomena.

Modern String Theory attempted to reconcile quantum mechanics and Albert Einstein's general theory of relativity, a "theory of everything," where the fundamental constituents of the universe are tiny one-dimensional vibrating filaments or loops of energy. It is often praised for its mathematical depth and internal consistency. However, despite decades of development, it has yet to produce experimentally confirmed predictions at accessible energy scales. While not falsified, it remains empirically unverified, and critics cite it as a death theory. Mathematical elegance cannot be physics due to the lack of observational support.

Max Tegmark's Mathematical Universe Hypothesis was also criticized for lacking empirical testability, placing it closer to metaphysics than physics. Furthermore, the applicability of mathematics reflects features of human cognition—our tendency to impose patterns and quantification—rather than the intrinsic nature of reality. Thus, empiricists argue that modern physics supports the effectiveness of mathematics, but not the strong Pythagorean claim that "all is number."

It is a capital mistake to theorize before you have all the evidence

In the early stages of modern cosmology, both positions, inductive and deductive, were adopted. Richard C. Tolman (1881–1948), for instance, admitted both positions to be of great merit in cosmology. Edward A. Milne (1896–1950) was in favour of a rationalist–deductive science, although some of his points of view may remind one of an empirical approach when he emphasises that space itself has no existence, and that using static space is probably more physically correct, as in ordinary physics. Considering the expansion of matter as motion in this space, he said in one of his papers:

If the curvature of space cannot be determined, if it is essentially unobservable, then it should be rejected. The time has come when we should remember William of Occam's maxim: '*Entia non sunt multiplicanda proeter necessitatem*'.

The physicist and philosopher Herbert Dingle (1890–1978) made an aggressive attack against the rationalist–deductive method in favour of the empiricist–inductive method, with terms such as "paralysis of reason," "intoxication of the fancy," "Universe mania," "delusions," "traitors," and "treachery." Arthur S. Eddington, Howard P. Robertson (1903–1961) and Willem de Sitter (1872–1934) were also in favour of an empiricist–inductive science, although Eddington was also accused by Dingle of inventing scientific hypotheses out of thin air rather than by strict immersion in observations and observational data. One may hesitate to consider him an empiricist–inductivist. Eddington used to state (ironically): "not to put overmuch confidence in the observational results… until they are confirmed by theory."

Cosmology is better derived empirically by first taking the data without preconceived ideas and then interpreting them from all possible theoretical viewpoints. There are certainly always prejudices and intuitions in our minds that push us towards certain avenues of research, but at least we should openly consider all the theoretical possibilities that might explain the data, rather than taking only one (standard) theory and always trying to squeeze the data into it in one way or another. In the words of the fictional character Sherlock Holmes: "It is a capital mistake to theorize before you have all the evidence." Holmes further opines: "Before one has data, one begins to twist facts to suit theories instead of theories to suit data."

Many historical cases illustrate a recurring lesson in physics: mathematical beauty can guide theory construction, but empirical accuracy remains the last word.

When a feature of a model is ascertained through imposition rather than by experimental or observational confirmation, it is unscientific by virtue of being merely based on personal preference. In other words, a certainty achieved that way becomes a dogma—a common occurrence in science. A rather dogmatic attitude has come to prevail in modern cosmology, so we must be wary of the danger of believing too strongly in ideas that are not confirmed by observations. Without such confirmation we render ourselves unable to distinguish between science and metaphysics.

The success of Einstein's General Relativity encouraged scientists to use purely deductive reasoning. This deductive approach formed a precedent for the way in which the science of cosmology is pursued today. As written by Einstein in 1934, the physical experience of the experimenter could not lift him into the regions of higher abstraction and science to be guided by purely mathematical, formal considerations in his search for a theory. Pure thought can grasp reality, said Einstein. He also introduced the notion of a homogeneous Universe, an idea that is still, against all empirical evidence, present in cosmology today purely on the basis of simplicity and aesthetics rather than observation. We may therefore reasonably argue that modern cosmology was born with Einstein around 1917.

Fred Hoyle (1915–2001), and independently Hermann Bondi (1919–2005) and Thomas Gold (1920–2004), proposed in 1940s a steady-state cosmological model based on the "perfect cosmological principle" by which the universe was always the same thing observed from any position at any time, eternally expanding, and maintaining constant density through continuous matter creation. The theory was mathematically coherent and philosophically appealing. However, observations, such as that distant galaxies are younger than local ones, contradicted these principles.

At present, cosmologists and particle theorists defending the standard model use the deductive method, mathematically deducing how the Universe must be. Big Bang defenders seek to derive the present, historically formed Universe from a mathematical theory with aesthetic motivations. Some astrophysicists inclined closer to observation than to theory complain about the lack of an empirical approach in cosmology. Gérard de Vaucouleurs (1918–1995), for example, known for his extragalactic surveys and Hubble–Lemaître constant measurements, wrote in 1970:

> *[There are] parallelisms between modern cosmology and medieval scholasticism … Above all I am concerned by an apparent loss of contact with empirical evidence and observational facts, and, worse, by a deliberate refusal on the part of some theorists to accept such results when they appear to be in conflict with some of the present oversimplified and therefore intellectually appealing theories of the Universe.*

The quantity of data for observational cosmology today is certainly much greater than in 1970 (although there were then ample data: the CMBR, redshifts of galaxies, abundances of light elements, etc), but de Vaucouleur's criticisms are still valid nowadays: cosmology has not changed its methodology a great deal.

Mathematics needs empiricism

In summary, the empirical–inductive and rationalist–deductive positions are extremes rarely found in their pure form, but, in any given researcher, one of the two trends tends to dominate. Apart from a few exceptions, the empirical–inductive method is more frequent in all branches of science, except pure mathematics. Many historical cases illustrate a recurring lesson in physics: mathematical beauty can guide theory construction, but empirical adequacy remains the last word. However, although the inductive method usually still stands as the ideal approach, in practice theoretical physics and cosmology are more dominated by the deductive method, which establishes what the truth about the Universe is before observing it. It then tries to adapt prejudged fact through consecutive chains of ad hoc theoretical corrections.

This text contains some edited excerpts from Chapter 8 of Fundamental Ideas in Cosmology.

Martín López Corredoira
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