MY EXPERIMENT AGREES WITH THE THEORY!

"In searching for the truth, it may be our best plan to criticise our most cherished results"[1]

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Many wise men, from Aristotle and Socrates to Descartes and Spinoza, struggled with epistemology, sometimes called the theory of knowledge. It is one of the most controversial topics of philosophy. What are our sources of knowledge and, more importantly, how do we acquire and improve knowledge? And where do we, physicists, stand?

Popper Philosophy

Several philosophies of knowledge exist and have been defended during the course of time. The two best well-known are empiricism and classical rationalism and have both clear roots in today's society. They have both in common the recognition of a "naked truth" but have different views on how to unveil it to increase knowledge. Empiricism adopts observation and experience as the ultimate source of knowledge. Its first roots were laid thousands of years ago by *e.g.* Aristotle. Classical rationalism is more recent, typically developed by Descartes, Spinoza and Leibniz during the 17th century. It asserts that our knowledge resides in reason, intuition, and ideas.

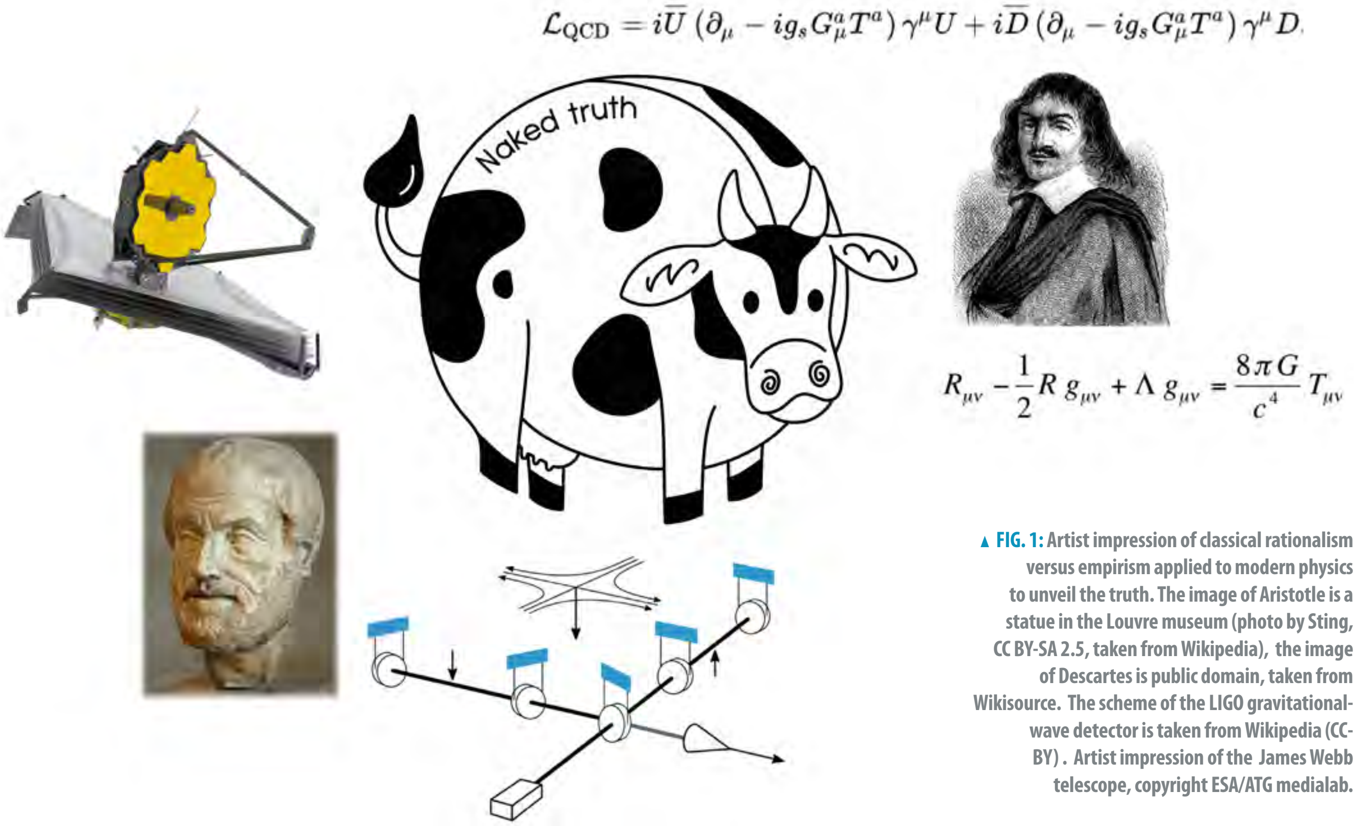
The philosophical view-point by Popper [1] – sometimes called critical rationalism - is inspired by both but also rejects both. In particular, the existence of an ultimate source of knowledge – the "naked truth" - is argued to be an illusion. According to Popper, our knowledge is human, with all imperfections that come with it. No authority exists to tell us the truth, no perfect experiment and no theory of everything will ever exist to reveal a naked truth. Observational errors constitute an unavoidable nuisance according to empiricists and ignorance is a perturbing deficiency in knowledge for classical rationalists, for the same reason that both veil the naked truth. Popper's philosophy advocates scientific progress to reside in the "imperfections" of our knowledge. Reducing imperfections increases knowledge, disagreement between observations and existing knowledge creates sources of knowledge. Justifying existing knowledge by avalanches of positive agreements is a decline towards an authoritarian model of epistemology, according to which existing knowledge, tradition or belief is confused with the ultimate truth. This model is not desired in physics, and every physicist sadly remembers the difficulties that Copernicus, Kepler and Galilei encountered from conservative authorities when they contested the sacred geocentric model of the Solar System.

In contemporary physics, experiment and theory go hand in hand, with equal roles. An experiment observes Nature the best we can, a theory formulates fundamental laws, and works them out the best we can. Upon comparing, we reject, accept or adapt, increase our knowledge and move forward. Even our most cherished theories – the Standard Model in particle physics, General Relativity and quantum theory, reveal "imperfections" that we know are not innocent and that we sometimes even call "new physics". The Popper philosophy is highly adapted to the way many of us want physics to be. With this attitude we have come far, at the expense of a regular return to square one when previous and precious knowledge is put at stake, such as Newton gravity or classical realism, to be replaced by a bigger and surprising picture. Agreement between theory and experiment is a tool to increase knowledge, but should not become the objective in itself. Despite mutual agreement both can be "wrong" and might be in due time. Recently I attended a wonderful quantum-chaos meeting in Warsaw organized by prof. Leszek Sirko where some presentations – even from my own collaborators - proudly announced experiments to be in perfect agreement with theoretical predictions, here based on Dyson ensembles. This prompted me to write this article. Of course, we are probably all to some extent "guilty" doing this. After the explanation by a beamline scientist at CERN that the huge accelerator behind him was built to verify his QED theory, Richard Feynman kindly responded: "Why, don't you believe me?".

Useful approaches in physics

Scientific approaches can be said "useful" when they produce new knowledge. They are reduced to a subjective level somewhere between "relevant" and "irrelevant" when they do not. The most common "useful" approach starts with some basic assumption or suspicion about Nature that has observable and quantitative •••

[1] K. Popper [1]



▲ **FIG. 1:** Artist impression of classical rationalism versus empirism applied to modern physics to unveil the truth. The image of Aristotle is a statue in the Louvre museum (photo by Sting, CC BY-SA 2.5, taken from Wikipedia), the image of Descartes is public domain, taken from Wikisource. The scheme of the LIGO gravitational-wave detector is taken from Wikipedia (CC-BY). Artist impression of the James Webb telescope, copyright ESA/ATG medialab.

••• consequences. In Popper philosophy, this assumption should be falsifiable, *i.e.* refutable with current or imminent technology. Well-known falsifiable hypotheses are the Cosmological Principle that our Universe is globally homogeneous and isotropic, the Second Law that heat never flows without help from a colder body to a warmer body, recently tested on the nanoscale [2], or the assertion that mass and energy are equivalent. The approach converts the assumption into a quantitative theory, observes and compares. The more revolutionary and controversial is the initial assumption, the more useful is the observation, and the more knowledge can be gathered. Formulating a hypothesis can be a struggle in itself, such as the prediction of gravitational waves by Einstein. He considered them first to be "unfalsifiable" because far too small to be observable, twenty years later he actually contested temporarily their very existence. The LIGO/VIRGO experiments one century later were a huge step forward in increasing our knowledge about the Universe.

If disagreement is a potential source for new precious knowledge, "useful" experiments should be open and designed to accept a null result, or even explicitly look out for real disagreements, for instance that the Universe is not isotropic. Well-known examples are the recent MICROSCOPE [3] project testing the equivalence principle between inertial and gravitational mass in General Relativity, the observation of the violation of Bell inequalities [4] expressing hidden variables in quantum mechanics and nobelized 40 years after the first experiment was done, or the spontaneous symmetry breaking in high-energy physics that explains mass but that required the existence of a massive and at that time unobserved scalar Higgs boson [5]. Even in Popper philosophy, being a critical observer is essential and high stakes tend to dazzle: In the competitive search for Majorana fermions some bold claims in condensed matter were soon obliged to retract [6].

Other "useful" observations go "where no man has ever gone before", triggering the need for a new idea, often conflicting existing knowledge. A great example is the Michelson-Morley experiment done in 1887, a null experiment that disagreed with the aether scenario for light propagation that was popular at that time. The experiment triggered Einstein to develop special relativity, just a few years after Lord Kelvin had declared during the British Association for the Advancement of Science that "*… there is nothing new to be discovered in physics now. All that remains is more and more precise measurement.*" This statement is highly non-Popperian! The fortuitous discovery of the cosmic microwave background radiation by Penzias and Wilson [7] is another famous example that disagreement – however annoying it may be - produces new knowledge. The mysterious noise in their Horn antenna was not due to pigeons after all but contained an essential clue about the creation of our Universe. The discovery of the Quantum Hall Effect at the High Magnetic Field Laboratory in Grenoble arguably belongs to this category of "accidental discoveries" as well. Grenoble rumour says that in their first draft – whose final published version announces the "high-accuracy determination of the fine-structure constant" [8] - the future Nobel laureates were unaware that the distance between the observed Hall plateaux of the magneto-resistance was determined by Planck's constant. In 2019 the value of ħ was defined in terms of new SI units, but before that time the Quantum Hall Effect was one of the most precise ways to measure it.

Unfortunately, "useful" approaches have become rare due to today's business model for research funding that tends to favour incremental, programmed and short-term research rather than random scientific rupture. It is much more comfortable to observe agreement and much harder – also psychologically - to claim disagreement. As the Editor-in-Chief of EPL I once accepted a work claiming the disagreement of BCS theory with the Second Law [9], two theoretical pillars in modern physics. The reviewers disagreed with the conclusion but could not say what was wrong. My decision to publish the work against recommendations was not hampered by my fear that this work would be wrong, after all wrong publications are part of science, and was justified by the lively scientific controversy that followed, undoubtedly increasing our common knowledge. The n^{th} agreement between theory and experiment confirms existing knowledge for the n^{th} time but increases our knowledge perhaps only by a factor of $1+1/\sqrt{n}$, yet one single disagreement changes everything. If an experiment is compared to a theory, disagreement must be an acceptable outcome. And this takes time, courage and effort. The assessment of projects and researchers as well as the training of our students should insist more on rupture and disruption and be an incentive to foster the growth of knowledge. Efforts that produce null results should get the appreciation they deserve.

Spherical Cows

The assumption that all cows are spherical is popular in theoretical physics to cope with complex phenomena. It can be easily criticised arguing that it is not to us physicists to oversimplify Nature. After all, cows are not spherical for a good reason, and the devil is often hiding in the details. Oversimplification is indeed a risk but simplified assumptions can be "useful" because the idealized symmetry facilitates quantitative predictions necessary to proceed. The Cosmological Principle mentioned above is the perfect spherical cow. Fields like statistical, condensed matter and particle physics have benefitted a lot from spherical cows. The famous Ising model in quantum-mechanics is a popular tool model and pops up successfully in many different fields of physics, yet neglects infinitely many phenomena. The Anderson tight-binding model for electron localization is a Kinder-Garten picture that is still believed to capture most of the quantum physics of a disorder-driven metal-insulator phase transition. The many imperfections of such models when comparing to observations should be recognised and constitute new sources of knowledge.

In recent years, a new kind of experimental physics has appeared. New technology has facilitated to perform experiments designed such that they match spherical cows. Examples are the Mott-Hubbard model describing hopping fermions on a 2D lattice with on-site repulsion [10], enabled with laser traps, almost perfect photonic bandgap materials, the kicked-rotor known in quantum chaos realized with cold atoms, or networks of Josephson junctions and capacitors to create qubits that perform operations governed by most quantum Hamiltonians that we have learned and taught at university. Many argue optimistically that, once mounted with "sufficient accuracy" in the laboratory and with "enough error control", the experiment becomes a perfect device with rules dictated by existing knowledge, whose performance cannot be refuted because we do no longer refute quantum mechanics. Of course, this would be huge step forward in technology. History has taught us that imperfections always linger, and reveal new "emerging" knowledge.

Next time when your experiment agrees with theory, I hope you think about Karl Popper and ask yourself if you really did not miss something subtle that you were not looking for. ■

About the Author

Bart van Tiggelen got his Master degree in astronomy at the Leiden Observatory and his PhD in physics at the University of Amsterdam. He is currently a CNRS research professor at LPMMC, a joint unit of the University of Grenoble Alpes and the CNRS. He works on various topics in wave propagation and QED. Between 2018 and 2022 he was Editor-in-Chief of EPL.

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