# Theoretical innovation. A new look at creativity in the natural sciences

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> The making anything known which was unknown before is an innovation in knowledge: and if all such innovations had been forbidden, men would [not] have made a notable progress in the arts and sciences.
> (George Berkeley, "Third Dialogue between Hylas and Philonous")

## Introduction

The task of accounting for observations in science is understood in two different ways: either in form of an explanation—and, if possible, a true explanation—or simply trying to save the phenomena. Much of the epistemological debate in the history of Western philosophy has focused on elucidating whether, from a position known as *realist*, science must seek true explanations of the observations, or rather, from an *instrumentalist* position, it must conform to *save the appearances.*

Well, if we were convinced that *true* explanations, *causal* explanations, were not possible, this would not imply that science should be limited to saving phenomena. Even if saving the appearances allowed us to successfully predict and intervene in Nature, it would leave us quite dissatisfied, because science is not only limited to account for what is observed; it also anticipates theoretical novelties susceptible of being tested empirically.

There is indeed a way that recommends that science focus on the search for *theoretical* explanations. These are explanations relative to a theoretical frame but disconnected from any pretension of reference to true causes. Theoretical explanations are contextual.

The case is, however, that, if the philosophy of science considered that scientific activity should only focus on the theoretical explanation of observations, it would be neglecting a no less important part of scientific practice as well: *theoretical innovation*, a new way of thinking and naming *scientific creativity.*

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Theoretical innovation is a form of scientific discovery. Therefore each innovation has to comply with the demands of novelty and theoretical value. Although concepts of *scientific discovery* can be as many as thinkers have dealt with the subject, I favour Saso Dzeroski's (2007: 3–4) definition as "the process by which a scientist creates or finds some hitherto unknown knowledge, such as a class of objects, an empirical law, or an explanatory theory (...) A defining aspect of discovery is that the knowledge should be new and previously unknown."

Theoretical innovations take place primarily at the intra-theoretical level, that is to say, in the context of a theory. The most common way to describe these innovations is as 'predictions', although there is a qualitative difference with the predictions that occur in the use of a particular theory. For the *intra-theoretical innovations* suppose the incorporation into the theoretical stock—and without resorting to other theories—of novelties hitherto unknown.

But innovations also occur at the inter-theoretical level making use of *preductive reasoning* (I made a presentation of this concept in my contribution to the *Proceedings of the VII Conference of the SLMFCE*, University of Santiago de Compostela 2012). Revolutionary discoveries in the field of relativistic quantum mechanics, some of which I will present briefly here, are an excellent example of theoretical innovations via *preductive reasoning* in contemporary theoretical physics.

There is a common element to both types of theoretical innovation: intra-theoretical *predictions* and inter-theoretical *preductions*. Both are the result of the application of deductive reasoning to the context of creativity or scientific discovery!

Of course there are other ways for the incorporation of theoretical novelties: induction, abduction and analogy as I have shown in Rivadulla (2008) and elsewhere, but scientific innovation via *preduction* is a complete novelty in the methodology of science.

The three main elements of my paper are the following:

1. The first task historically entrusted to science is to account for the facts of experience. After two and a half millennia, it remains a matter of philosophical debate if this task should consist of *explaining* the observations, that is, making the reasons for things explicit, or *saving* the appearances, that is, adjusting the observations to a theory. In the first case, it is still under discussion whether the *scientific explanation* must be *causal* or not.

2. But to question the existence of causal explanations does not mean giving up explanations at all: The alternative is *theoretical explanation*, that is, explanation by reference to theoretical frameworks, which helps to alleviate the tension between the supporters of causal explanation and those of saving the phenomena.

3. There is finally a main component of science to which contemporary philosophy has not paid the attention it deserves. I call it *theoretical innovation* and it consists of devising unexpected, sometimes surprising and in any case useful proposals for the advancement of science and culture.

# Does the Newtonian derivation of Kepler's Laws provide a causal explanation of planetary motions?

According to Herschel (1830: 302) "In this great work [*Principia*, A.R.], Newton shows all the celestial motions known in his time to be consequences of the simple law, that every particle of matter attracts every other particle in the universe with a force proportional to the product of their masses directly, and the square of their mutual distance inversely, and is itself attracted with an equal force."

For Comte (1998: 393) "we say that the general phenomena of the universe are explained, as far as they can be, by the law of Newtonian gravitation."

Stuart Mill (1970: 303–304) claimed that "it was very reasonable deemed an essential requisite of any true theory of the causes of the celestial motions that it should lead by deduction to Kepler's laws; which, accordingly, the Newtonian theory did."

And Einstein (1973: 254) maintained that "Kepler's empirical laws of planetary movement,...,confronted him [Newton, A.R.], and demanded explanation. These laws gave, it is true, a complete answer to the question of how the planets move round the sun ... But these rules do not satisfy the demand for causal explanation."

Finally Hempel (1965: 173–174) certified that "the principles of Newtonian mechanics...explain certain 'general facts', i.e., empirical uniformities such as Kepler's laws of planetary motion; for the latter can be deduced from the former."

As it seems Newtonian mechanics explains Kepler's empirical laws deductively. For its deduction, it is simply a matter of imagining a binary system consisting of two bodies of masses $M$ and $m$ respectively and separated by a distance $d$, between which there is a balance $G_N \frac{M}{d^2} = \frac{4\pi^2}{P^2} d$ between gravitational attraction and centrifugal force, from which Kepler's 3rd law $P^2 = \left(\frac{4\pi^2}{G_N M}\right) d^3$ results[2].

The big question is now: Does this *theoretical explanation* of Kepler's Third Law in the context of Newtonian Celestial Mechanics offer a *causal explanation* of planetary movements? Is Stuart Mill right when he says that this explanation is causal? The answer is: definitely not! Two reasons. First: Kepler's third law is also derivable in the context of general relativity theory (*GRT*) and, paraphrasing Mill, it should be recognized as very reasonable to consider an *essential requirement* of *GRT*, as a true theory of the causes of celestial movements, that it leads *by deduction* to Kepler's laws. Consequently, we would have two different causal explanations, the Newtonian and the Einsteinian, of the same phenomenon.

Second: *NM* and *GRT* are *incompatible* with each other, *both* at the level of their respective fundamental postulates: "the [relativistic] picture of the four-dimensional pseudo-Euclidean Universe contradicts that of the Newtonian three-dimensional Euclidean Universe" (Rivadulla 2016: 529) *and* at the level of the theoretical entities that deny each other: according to GRT, gravity is not the

[2]This law also results by combining the value of angular momentum with the area of the ellipse and Kepler's second law.

result of real forces, but of the curvature of space-time; there are no gravitational forces and the objects 'float' freely, following the geometry of space-time.

*Two causal explanations incompatible with each other is unbearable for scientific rationality!* Conclusion: It seems reasonable to relinquish to causal explanations in theoretical physics.

## *Apparentias salvare* and theoretical innovation in science

Citing Simplitius's *Commentary*, Duhem (1969: 5) states that Plato posed the following question: "What circular movements, uniform and perfectly regular, must be accepted as a hypothesis so that it is possible to save the appearances presented by the planets?"

Rheticus (1959: 136) attributed to Copernicus "that the motion of the earth could produce most of the appearances in the heavens, or at any rate save them satisfactorily."

And Cardinal Bellarmino advised Foscarini and Galileo "to content himself with speaking *ex suppositione* and not absolutely, as I have always believed that Copernicus has spoken. Because to say that, supposing that the Earth moves and the Sun is still, all appearances are saved better than with putting the eccentric and epicycles it is very well said and there is no danger, and this is enough for the mathematician" (Cortés Pla 1952: 109).

Finally Duhem (1969: 117) maintained that "the hypotheses of physics are mere mathematical contrivances devised for the purpose of saving the phenomena." And Bas van Fraassen (1980: 4) affirmed categorically that "the belief involved in accepting a scientific theory is only that it 'saves the phenomena', that is, correctly describes what is observable".

Nonetheless scientific methodology can not be content exclusively with saving phenomena. If it did, it would stop giving full account of scientific practice. Indeed, if science were merely concerned with the observable, we would have to suppose that it lacks the creative capacity, anticipatory of novel theoretical developments, sometimes surprising, generally unsuspected, and always useful for scientific progress. So, my thesis is: *Theoretical innovation is, together with the ability to account for observations, the most important task of science. Any theoretical anticipation must meet the requirements of novelty and theoretical usefulness.*

## Theoretical preduction

*Preduction* (Rivadulla, 2008) is the form of reasoning by virtue of which, by mathematical deduction compatible with dimensional analysis, the combination of previously accepted results—but not necessarily as true—of different theories and/or disciplines of physics, allows the *anticipation* of new theoretical products, which should be submitted to the trial of experience. Preductive reasoning serves both for *innovation* and *explanation* in the methodology of physics. To illustrate this point of view, I present two examples, one of each case:

- the innovative discovery of anti-matter by Dirac in relativistic quantum mechanics,
- the theoretical explanation of the existence of neutron stars in astrophysics.

## An example of preductive discovery: antimatter

Relativistic quantum mechanics, which, as its name suggests, is a theory resulting from the combination of quantum mechanics with relativity theory, anticipates the existence of antimatter. Its main equations are Klein-Gordon and Dirac. The first one describes free particles without spin, that is $s = 0$. The second one describes free particles with spin $s = {}^1/_2$, and its non-relativistic limit is the Shrödinger equation, making the physical *fiction* $c = \infty$.

To derive these equations, we start from the relativistic equation of the total energy of a particle:

$$E^2 = p^2c^2 + m^2c^4$$

If we interpret both members as operators, then we have:

$$E^2\Phi = (p^2c^2 + m^2c^4)\Phi$$

that is:

$$-\hbar^2\partial_t^2\Phi(x_i, t) = (-\hbar^2c^2\nabla^2 + m^2c^4)\Phi(x_i, t)$$

which is the equation that Schrödinger and Klein-Gordon propose as an equation of relativistic evolution.

Now, this equation admits exact solutions with negative energy. That is why Paul Dirac looked for a similar equation that excluded the possibility $E < 0$. The equation he found[3] authorizes to interpret the absence of electrons as the presence of positrons, and, therefore, anticipates the existence of positive electrons, that is, antimatter. Which is a theoretical innovation of the highest order.

## Preductive theoretical explanation. The neutron stars theoretical model

The derivation of Kepler's law in the context of Newtonian celestial mechanics offers clearly a theoretical explanation of planetary motions.

[3] $(i\partial - \mu)\psi(x) = 0$.

In physics we offer a *theoretical explanation* of an event when the mathematical expression of the event in question is recovered deductively in a given theoretical framework. Susceptible to theoretical explanation are also the theoretical laws and even theories themselves.

Examples of theoretical explanation are the deduction of Balmer's empirical formula in the framework of Bohr's atomic model, or the explanation of Planck's radiation law in Bose-Einstein's quantum statistical mechanics (Rivadulla 2005: 170–172, 175–177), among many others. These explanations are intra-theoretical, that is, they occur within the framework of a single theory. The scientific explanation thus coincides with the derivation of the explanandum in a given theoretical context, following Popper-Hempel's deductive-nomological model.

Contemporary astrophysics seriously questions the idea that science only deals with observables. Indeed, celestial objects and phenomena such as stellar atmospheres and interiors, novae and supernovae, white dwarfs, neutron stars, black holes, etc., whose internal processes, naturally, are not observable, would be left unexplained. To deal with them, astrophysicists build theoretical models. These models result from the combination of accepted results of different theories and disciplines of physics by application of *preductive reasoning.* The explanations that these models provide are, therefore, inter-theoretical explanations. Let us take the example of neutron stars to illustrate this concept.

Neutron stars are, together with black holes and white dwarfs, the most compact objects in the universe; although their origin is very different. For while the first two are remnants of supernova explosions, the white dwarfs are the rest, bright by its internal residual heat, of a small or medium star in the final stage of its life, when it no longer generates nuclear reactions in its interior. White dwarfs usually have a mass comparable to that of the Sun but a size like that of Earth. Its density is much lower than that of a neutron star. Thus, for example, the white dwarf par excellence, Sirius *B*, compared to a typical neutron star, about 10 km in radius, is 550 times larger.

The explanation of the internal structure of a neutron star can only come from a theoretical model that, by means of a *preductive* way of reasoning, by combining results from Newtonian mechanics, relativity theory, quantum mechanics, nuclear physics, particle physics, etc. gives us a picture of this kind of objects.

A neutron star model should incorporate both the history of the physical process of producing a supernova and the theoretical explanation, comparable to that of the white dwarfs, with which it shares being supercompact objects. In the case of white dwarfs, gravity itself is supported by electron degenerate pressure. In the case of neutron stars, its gravity is supported by the pressure of the degenerate neutron gas that is produced inside it.

Indeed, for densities higher than $10^{12}$ gr.cm$^{-3}$ neutron degeneracy pressure dominates electron degeneracy pressure due to the electronic capture process by which protons are transformed into neutrons. The number of electrons is reduced and the number of neutrons increases, and practically the interior of the stars is a superfluid of neutrons plus other elementary particles.

According to Ostlie & Carroll (p. 604) "a very general argument involving the general theory of relativity shows that the maximum mass possible for a neutron star cannot exceed about 3 $M_\odot$... If a neutron star's mass exceeds 3 $M_\odot$, it cannot generate pressure quickly enough to avoid collapsing. The result...is a black hole."

As a result of the collapse of the supergiant star that produces the supernova and leaves as a remnant the neutron star, it can rotate very quickly, dragging in each rotation its enormous magnetic field. It becomes a pulsar.

## Conclusion

I have started by asking if scientific explanation must be causal explanation. To answer this question I have presented the argument of inter-theoretical incompatibility between *NM* and *GRT* to conclude that *NM* can not give a causal explanation of the planetary motions, nor does *GRT*.

Next I have wondered if 'saving the phenomena' is a reasonable alternative to the commitment to causal explanation. After concluding that this 'alternative' does not take into account the work of theoretical innovation that the scientific practice involves, I conclude that the theoretical explanation *more preductivo* (which does not pretend to be causal) does seem to do justice to the double task of science: explanation and innovation.

By means of two examples from *RQM* and Astrophysics I have tried to show that explanation and innovation go hand in hand, that both constitute the joint goal of scientific theorization: The *revolutionary innovation* of Dirac offers a *theoretical explanation* of the existence of antiparticles, the *theoretical explanation* of neutron stars 'reveals' the internal structure of this kind of compact bodies, i.e. it is *innovative* as well.

## References

Comte, A. (1998). *Cours de Philosophie Positive.* Presentation et notes par Michel Serres *et al.* Paris: Hermann.

Duhem, P. (1969). *To Save the Phenomena. An Essay on the Idea of Physical Theory from Plato to Galileo.* Chicago: University Press.

Dzeroski, S., et al. (2007). "Computational Discovery of Scientific Knowledge". In S. Dzeroski and L. Todorovski (eds.), *Computational Discovery of Scientific Knowledge.* LNAI 4660, Berlin: Springer.

Einstein, A. (1973). "The Mechanics of Newton and their Influence on the Development of Theoretical Physics". In A. Einstein, *Ideas and Opinions.* London: Souvenir Press Ltd., pp. 253–261.

Hempel, C. G. (1965). *Aspects of Scientific Explanation.* New York: Free Press, 2. print.

Herschel, J. (1830). *A Preliminary Discourse on the Study of Natural Philosophy.* Chicago: Univ. Press, 1987. (Facsimile edition)

Mill, J. S. (1970). *A System of Logic Ratiocinative and Inductive.* London: Longman.

Ostlie, D. & Carroll, B. (1996). *Modern Stellar Astrophysics.* Reading, MA: Addison-Wesley Publ. Co., Inc.

Pla, C. (1952). *Galileo Galilei.* Buenos Aires: Espasa-Calpe Argentina, S.A.

Rheticus (1959). "Narratio Prima". In E. Rosen (ed.), *Three Copernican Treatises.* New York: Dover Publications.

Rivadulla, A. (2005). "Theoretical Explanations in Mathematical Physics". In G. Boniolo et al. (eds.), *The Role of Mathematics in Physical Sciences*, 161–178. Dordrecht: Springer.

Rivadulla, A. (2008). "Discovery Practices in Natural Sciences: From Analogy to Preduction". *Revista de Filosofía*, 33(1):117–137.

Rivadulla, A. (2016). "Models, Representation and Incompatibility. A Contribution to the Epistemological Debate on the Philosophy of Physics". In J. Redmond et al. (eds.), *Epistemology, Logic and the Impact of Interaction.* Switzerland: Springer, 521–532.

Van Fraassen, B. (1980). *The Scientific Image.* Oxford: Clarendon Press.