Ceteris Paribus Laws and the Concept of *Capacity* in the Philosophy of Science of Nancy Cartwright

Leyes *Ceteris Paribus* y el concepto de *capacidad* en la filosofía de la ciencia de Nancy Cartwright

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Abstract

A brief introduction to Nancy Cartwright's philosophy of science is presented along with an analysis of several of her thoughtful and controversial views. Nancy Cartwright came to revolutionize the philosophy of science by presenting original and provocative philosophical positions using specific concepts such as: *capacity, ceteris paribus laws, nomological machines*, among others. In this article it is shown that some of nature fundamental conservation laws, such as energy, momentum and angular momentum, cannot be *ceteris paribus*. Also, it is discussed among other quantum mechanical examples, the application of the concept of *capacity* to Coulomb interactions and Bohr quantum mechanics postulates for the hydrogen atom.

Keywords: Capacities, ceteris paribus laws, Nancy Cartwright, philosophy of science, quantum mechanics.

Resumen

Se presenta una breve introducción a la filosofía de la ciencia de Nancy Cartwright junto a un análisis físico y filosófico de varios de sus originales y controversiales puntos de vista. Nancy Cartwright vino a revolucionar la filosofía de la ciencia al presentar sus interesantes y polémicas posturas filosóficas haciendo uso de conceptos como *capacidades, leyes ceteris paribus, máquinas nomológicas*, entre otros. En este artículo se muestra que algunas leyes fundamentales de conservación de la naturaleza, tales como la de energía, momento y momento angular, no pueden ser *ceteris paribus*. También se discute la aplicación del concepto de capacidad para las interacciones de Coulomb y los postulados cuánticos de Bohr para el átomo de hidrógeno, entre otros ejemplos cuánticos.

Palabras claves: Capacidades, filosofía de la ciencia, mecánica cuántica, leyes ceteris paribus, Nancy Cartwright.

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Introduction

Quantum mechanics together with Relativity theory, are fundamental pillars of modern science. In particular quantum theory has been tremendously successful since none of its predictions has been wrong. In many practical and philosophical senses this theory has changed the world. For example, we may point out that one third of world economy depends on products which are developed thanks to this theory. Also, numerous technological products, from cellular phones to supercomputers and magnetic resonance machines, are the result of our understanding of the quantum description of the behavior of charged electrons and holes in semiconductors. Likewise, the laser, nonlinear optical fibers and all their many applications are the result of the quantum description of light (Yariv, 2015). Just recently it was reported the construction of transistors with a single atom, this achievement will cause a revolution in the total computer processing capacity and memory of future supercomputers in addition to the development of optical quantum computers (Wyrick *et al.*, 2019). This certainly will impact current work in artificial intelligence and probably in the experimental study of first order philosophical problems such as the mind-body problem and the origin of consciousness (Aboites, 2008).

The extraordinary precision of quantum theory is pointed out in the book *QED The strange theory of light and matter* (Feynman, 1985), where the quantum interaction theory between light and electrons is described. An initial theory developed by Paul Dirac predicted that the magnetic moment of electron has an exact value of 1.0, however experimental measurements carried out in 1948 gave the result of 1.00118. Julian Schwinger, Sin-Itiro Tomonaga and Richard Feynman for the development of this theory, won the Nobel prize in 1965, and got a value of 1.00116. The actual experimental value for this constant is 1.00115965221 whereas the theoretical one is

1.001159652. This accuracy is equivalent to measuring the distance between New York and Los Angeles with a precision better than the thickness of a human hair. However, despite the fact of its extraordinary exactness, quantum theory is also a challenge in its understanding. According to legend, Richard Feynman once said: "Anyone who claims to understand quantum theory is either lying or crazy". In the same sense, Niels Bohr (a Nobel Prize winner too), stated that: "Anyone who is not shocked by quantum theory has not understood it" (Heisenberg, 1971). The philosopher Tim Maudlin stated that:

> All physical theory must be clear and discuss two fundamental questions: What is there and what is doing. The answer to the first question is given by the ontology of the theory, whereas the answer to the second by its dynamic. Ontology must have a clear mathematical description whereas the dynamics must be stated through precise equations describing how the ontology should o could evolve (Maudlin, 2019: 37).

It is important to underline that in quantum mechanics the dynamics is given by using either the matrix formalism of Heisenberg or the Schrödinger wave equation, once the Hamiltonian and the bridge principles of the system are known. The discussion about the need of precise mathematical descriptions in science (Lange, 2013) has been widely deal with and quantum mechanics is, without a doubt, an example of this. However, quantum mechanics is among all physical theories, it is one that has immense problems, not in its application, but in its interpretation.

Nancy Cartwright, an academic at the London School of Economics and at the Universities of Durham and California, has contributed significantly on the discussion of this theory, however this discussion has been done from the perspective of her own philosophy of science. The understanding of the fundamental elements of Cartwright's philosophy of science implies to be introduced in a particular language with terms of specific meaning such as: capacities, *ceteris paribus* theories, nomological machines, representative and interpretative models, among others, have been explained and discussed in numerous publications.

In particular, her books *How the Laws of Physics Lie* (1983) and *The Dappled World* (1999), have created a notorious interest in her work and also a great deal of controversy in the scientific and philosophical communities in the world. Essentially, as it will be explained latter and in more detail, Cartwright propose a scientific world which is run by *ceteris paribus* «patchwork laws» valid in a restricted domain obtained from the observed *capacities* of the world. The *capacities* are a central part of her thesis, since they are needed to build models.

In the second section, because of the pedagogical aim of this article, we will present a brief synthesis of the main points of the philosophy of science of Nancy Cartwright. These points have been discussed by different authors and at different places (Rodríguez-Yáñez *et al.*, 2020), as they are essential to further discussions. In the third section, we will discuss the concept of *capacity* and its application to quantum mechanics —in particular, the paradoxical situation of an electron acting under the *capacities* of Faraday's Law or under the non-relativist quantum mechanics postulates that keep it in stable orbits in an atom—. Finally, the conclusions are presented.

Some concepts of Nancy Cartwright philosophy of science

The starting point of Nancy Cartwright philosophy of science is its negation of the existence of fundamental and universal theories. Fundamentalist scientists and philosophers sustain the opposite. Their believe in the existence of a fundamental law, or a set of fundamental laws, with universal validity that is able to explain and predict all observed *phenomena*, in which *phenomenon* is understood as any physical manifestation of the world or action in nature.

The most important arguments of Cartwright to support this statement are related to a realism based on a set of *ceteris paribus* laws, valid in different areas of nature. For example, the description of the free fall of a body may be provided from Newton's second law F=ma, where «a» represents the acceleration of gravity and «m» its mass. This has been carefully studied at the laboratory, however in practice and everyday life the conditions of this *ceteris paribus* law may be very different from the ones of a scientific laboratory. Otto Neurath proposes to study the fall of a bill note from the top of a building (Cartwright, 1999). According to Cartwright there is not a model able to explain this starting from Newton second law, however for a fundamentalist, this is not a reason to argue that Newton law is not applicable, since one must consider all forces acting on the bill note i.e. $\sum F=ma$, but by doing this, according to Cartwright, the problem becomes so complex that it is more sensible to accept that Newton second law does not describe the free fall of a bill note since, for example, there are factors of fluid mechanics described by Navier-Stokes equation that exceed by far the basic explanation of Newton's second law

To apply scientific laws, it is necessary to create models and also that scientists create carefully the necessary conditions, so their models will be based on the theories. However sometimes models are unable to explain reality and this does not mean that the theory is incorrect, but that the model cannot be applied; in these cases, it is necessary to adjust the model to another theory.

According to fundamentalism there are two metaphysical ways to explain the way in which theories work on the world and also in their origin: holism and nomological pluralism. Holism support fundamentalism and states that theories come from observation. When a *phenomenon* is studied, scientists develop laboratory experiments in which they are able to artificially isolate the *phenomenon* and control all variables, therefore it is possible to obtain precise results. However, outside the laboratory, scientists cannot control all variables therefore the obtained results are affected and may not be described by theories. For Cartwright, it is important to distinguish between *phenomena* taking place inside or outside the laboratory. Outside the laboratory innumerable non-planed facts may take place therefore it is not possible to create general theories from what happen inside the laboratory, however, to be able to control some variables make possible the creation of *ceteris paribus* theories.

In Cartwright's philosophy of science, the world represented by physics laws is mostly a fiction because the world in which we live (outside scientific laboratories) is chaotic and unpredictable, and so, physics regularities are not evident. In fact, to force the world to behave according to the known physics laws require a great deal of effort and skills, and this behavior is only found in a scientific laboratory when an experiment is carried out under highly controlled conditions, but this doesn't work in everyday life. The result of a fire, a flood or an avalanche is, to a great extent, unpredictable, even though these facts are ruled by science laws. On the other hand, Cartwright's nomological pluralism is against fundamentalism and holds that nature is ruled by several theories which are probably truth, and each one works in a specific domain and they may or may not be correlated among them. To hold a scientific theory as valid, it is necessary to have a limited environment with conditions able to work as *ceteris paribus*. Therefore, for Cartwright, the fact that a theory is valid does not mean that it is universal but that is valid in a specific domain. All scientific theories fulfill this characteristic and so they must be considered *ceteris paribus* theories. Cartwright states that theories are general statements and that the concepts used to define them are abstract and symbolic. Also, theories are valid in models, even though no model fits perfectly to a theory.

An important remark about *ceteris paribus* laws is that, for many scientists to doubt about the universality of some laws of physics or the fact of their validity is *ceteris paribus* may seem a nonsense. For example, we know that the law of conservation of energy in mechanical systems is the result of time homogeneity, whereas space homogeneity implies momentum conservation and finally, angular momentum conservation is the result of the isotropy of space (Landau, 1976). These three conservation laws are fundamental for all scientific theories, so to assume them as invalid, arguing a *ceteris paribus* validity, implies to assume that the universe in where we live is not always homogeneous in time and space and doesn't have spatial isotropy. This is a philosophical possibility, but it may be hardly taken seriously by most scientists. On the other hand, we may ask how could the conservation of energy, linear momentum and angular momentum laws be *ceteris* *paribus*? For example, we may say that Newton's second law is *ceteris paribus* because in order to study the free fall of a body, one assumes its mass and acceleration of gravity are constant, i.e. there is only one free term to be considered among the three available; i.e. force. However, in all three previous mentioned conservation laws, there is only one term e.g. from the temporal homogeneity of the universe follow the conservation of energy. The validity of this law depends exclusively of a single factor, i.e. temporal homogeneity, therefore this law could not be *ceteris paribus* since there is not any other factor we may keep constant, except temporal homogeneity itself. The exclusion of temporal homogeneity would mean no energy conservation whereas on the other hand, in Newton's second law, *ceteris paribus* condition is applicable since there are three terms (acceleration, mass and force) to observe and study one term can be done leaving the other two terms constant. This, however, cannot be done with the three conservation laws of energy, momentum and angular momentum, because the validity of each one of these laws depends only on one single condition, and if this condition is not present, there is not conservation law at all. We could conclude that these three conservation laws are universal and not *ceteris paribus*.

The central argument against fundamentalism of the book *The DappledWorld* states that in all laws of physics one must have the *ceteris paribus* condition and these laws represent the existent regularities of the world (Rodríguez-Yáñez, *et al.*, 2020). It also states that laws are valid only in a specific domines of reality and they satisfy what is given in nomological machines which are defined as:

> It is a fixed (enough) arrangement of components, or factors, with stable (enough) capacities that in the right sort of stable (enough) environment will, with repeated operation, give rise to the kind of regular behavior that we represent in our scientific laws (Cartwright, 1999: 50).

For Cartwright the *capacities* are the fundamental blocks of natural sciences and are the base for the construction of nomological machines. This is a key concept in her philosophy of science. From her view all things in science have properties and these are given by the *capacities* which are determined by what things do. According to Cartwright (1989): "The fact that C causes E means that C has the capacity Q to produce E".

The concept of *capacity* is introduced in order to explain the operation of causal laws, provide them with a universal character, where causal laws are *ceteris paribus*. Cartwright explains the term *capacity* taking it as a synonym of the concept of *tendency* of Mill:

> Mill believed that the laws of political economy and the laws of mechanics alike are laws, not about what things do, but about what tendencies they have [...] Substituting the Word «capacity» for Mill's Word «tendency», his claim is exactly what I aim to establish in this book [...] I suggest that the reader take my «capacity» and Mill's «tendency» to be synonymous (1989: 170).

To illustrate her idea, one may state: The increase of taxes «tend to increase» prices. This shows some similarity with the following physical law: Due to gravitational attraction, masses «have the capacity» to attract each other. Other representative examples of Cartwright are the tendency or capacity of electric charges to attract or repel each other according to Coulomb's law: $F = kq_1q_2/r^2$, as well as the already mentioned tendency or capacity of masses to attract each other according to Newton's gravitational law $F = Gm_1m_2/r^2$.

The simplest way to obtain a nomological machine is carrying out a laboratory experiment, for example, Coulomb's model or a simple pendulum, keeping everything else fixed (i.e. *ceteris paribus*). However, nomological machines may also be found in nature, for example in our planetary system, where Newton's laws apply. In both cases, the *capacities* of the components of the nomological machine generate a regular behavior. To understand nomological machines Cartwright states that one needs *capacities* instead of laws (Cartwright, 1999: 64). The concept of *capacity* is central in the philosophy of science of Cartwright and is used in order to describe what an object can do depending of its setting or physical environment. A given *capacity* is what it is because of the laws it participates in (2008: 195).

On the other hand, the application of scientific knowledge requires the design of models which, in order to explain phenomena, must be based on a theory. In general, there are two points of view about scientific theories: Realism, which states that scientific theories are truth and able to explain the world, and Instrumentalism, which consider theories as instruments that help us to understand how to handle the world. Initially Cartwright considered models as simulations useful to explain a *phenomenon*, but this does not mean that a truth about the *phenomena* is given. Cartwright gives a fiction status to models. For her, to explain a *phenomenon* is to find a model within the basic frame of a theory to obtain the complex phenomenological laws that are valid. Cartwright considers theories as tools useful in the construction of models, therefore, they do not represent reality. At this point it would be important to remember that our best scientific theories describe mainly our everyday world, but also that the most important scientific challenges are the description of small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence and the concept of time. All of these are inevitable within a demarcated domain and under *ceteris paribus* conditions.

Cartwright in *The Dappled World* states that there are different theories valid in a domain that may be applied through models, but not everything occurring in the world can be explained by laws, only of those things we have models, these models are *blue prints* to design *nomological machines*. Finally, Cartwright considers two types of models: representative and interpretative. The first ones are used to describe specific phenomena and one must go beyond the theory. The second ones elaborated within a theory using bridge principles which do not provide a way of going from abstract to concrete terms, but there is a way to interpret the terms of a theory, where the meanings are restricted but not fixed. An example of a bridge principle is the requirement of having mass planets much smaller that the sun planet, in order to apply Newton's gravitational law to describe the movement of a planet around the sun. Only in this way theory can predict an elliptic orbit of the planet around the sun. In the next section, it is discussed the usefulness of the concept of *capacities* to deal with some classic and quantum mechanics problems.

Capacities and Quantum Mechanics

As was already said, quantum mechanics is one of the most successful theories available. Cartwright has written numerous works about this theory. In *How the Laws of Physics Lie* (1983) assumes a realist interpretation for the wave functions, which later on is changed in another of her works, *The Dappled World* (1999). For Cartwright, to build models supported in theories represents real situations that are present in the world, something that she calls representative models. Though in *How the Laws of Physics Lie*, these models were called phenomenological models. In *The Dappled World* she holds that theories in physics do not represent generally what happens in the world, but only in models. She believes that theories only provides abstract relations between abstract concepts. They provide information about *capacities*. Once models are able to reproduce regular and repeatable situations, we have the blueprints of nomological machines. Science predicts using models that represent what actually happened. Finally, she holds that knowledge of the world must be obtained anywhere, it is possible even in addition to any theory, without paying attention to how fundamental or universal elements are considered (1999: 180-181). Whereas in *How the Laws of Physics Lie*, Cartwright has a negative attitude, showing from concrete examples how is that laws of physics lie; in *The Dappled World* she has a positive attitude arguing how much can be achieved applying the laws of physics without forgetting the applicability limits they have. To apply a theory, it is necessary to see the available models in order to find the correct one given the conditions of an agreed situation, because a theory is a set of models, however Cartwright denies that even the most successful theories represent what actually happened. An example of this is superconductivity, which is a quantum phenomenon.

In quantum theory there are basically four interpretative models to deal with real quantum problems, they are: central potential, scattering, Coulomb interaction, and harmonic oscillator. With these models and the use of bridge principles, it is possible to obtain the Hamiltonians for concrete situations. An example widely used by Cartwright widely is the superconductivity model developed by Bardeen, Cooper and Schrieffer: Model BCS (1957). From this Hamiltonian it is possible to obtain the predictions of the phenomenological superconductivity model of Ginzburg-Landau, Model G-L. The model G-L it is not obtained from a Hamiltonian but from *ad hoc* assumptions from thermodynamics, electromagnetism and quantum mechanics. In fact, Gorkov (1959) showed that the Ginzburg-Landau equation may be obtained from the quantic model used by the BCS model. Superconductivity is a quantum phenomenon because superconductive material can be represented by models provided by quantum mechanics. The Hamiltonian used in the BSC has four terms, the first two ones represent the energy of non-interacting charged particles and the periodic potential of the positive ions of a Bravaris lattice; the third term of the Hamiltonian represents the Coulomb interaction between these particles; the fourth term represents the interaction between these particles through the exchange of a virtual phonon which is represented by a scattering interaction. This Hamiltonian is obtained through *ad hoc* theoretical and phenomenological considerations. For Hamiltonians theoretical physicists to solve a problem and compare their results with experimental data, by trial and error, it is important to adjust each term they use. However, how are related quantum and classical properties? Cartwright holds that in practice there is not a general formula to do this. For example, a very important application of superconductivity takes place in magnetometers based in superconductive devices of quantum interference called «SQUID» (superconducting quantum interference device) based on superconductive rings of Josephson junction. In these devices the current flux in the circuit is given by:

$$J_s = (e^* \hbar/2m^* i)(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) - (e^{*2}/\mathrm{m}^*)|\Psi|^2 A^2$$

It should be noticed that the left side of this expression contain a measurable classical current, whereas in the right side, are quantum terms linked with the wave function ψ as well as with the electromagnetic vector potential A. Another similar example is the tunneling effect of quantum quasi particles in Josephson junction, where there are expressions using classical terms such as current, voltage and resistance, as well as quantum terms such as wave functions and the probabilities that they describe. These examples show, as Cartwright underlines, that: "quantum mechanics and classical mechanics are both needed but none is enough" (1999: 225), finally she also holds that from an epistemological point of view quantum mechanics is not in a worst situation than classical mechanics. As a realist scientific, she points out that quantum states must be taken as a genuine fact of reality and not in an instrumentalist way as a convenient form to obtain states, this is a subject widely discussed in contemporary literature (e.g. Chen, 2019; Gao, 2016; Rodríguez-Yáñez, 2020).

The capacities of entities in the quantum world are finally responsible of the calculated quantum states. For example, Bohr hydrogen atom may be calculated using the Hamiltonian function for a central potential in Schrödinger equation. The four postulates of a Bohr quantized atom (Griffiths, 1995) state that: There is a Coulomb potential between an electron in stable planetary motion and a proton at the nucleus. The allowed orbits are those for which the electron angular momentum is an integer multiple of «n» of Planck constant, i.e. $n\hbar$; where $\hbar=h/2\pi$. An electron is a stable orbit that does not radiate, and, absorption or emission of radiation takes place when an electron has a transition from a lower to a higher orbit in the first case, or the other way around in the second.

Atomic stability is explained by the last postulates, that is by the fact that despite Coulomb's attraction law, electrons do not collapse in the nucleus. However, analyzing this situation from a *capacities* point of view, there are two possibilities: to take the capacities as electrically charged particles described by Coulomb's law, or to take those given by the Bohr's quantization postulates about quantum mechanics. The interaction of electric charges is given by the *capacities* displayed in Coulomb's law, in this way they show the capacity to attract or repel each other. However an electron in an atomic orbit will behave according to the *capacities* given by Bohr's postulates, therefore they are able to change their orbit through the exchange of photons. However, when studding the behavior of an electron, how does one know what *capacities* should be applied? The ones of a free electron that find a nucleus and interact with it according to Coulomb's law, or the ones of an electron in an atomic orbit ruled by quantum laws? This apparent inconsistency is not real, because as Cartwright points out: «The fact that C causes E means that C has the capacity Q of producing E», therefore, this previous apparent inconsistency is not a problem from Cartwright's perspective, because whatever it may occur: E, is a consequence of the present capacity: Q, and it may be a classical or quantum result. This is an elegant form to solve this apparent inconsistency within Cartwright framework. However, it is possible to ask if this explanation would be applicable to other quantic situations such as the transit of electrons through a double slit. In this case, we know that only if one slit is open, electron will show in the detection screen an image with a bell distribution, whereas, if both slits are open, then electrons will show in the detection screen a classic interference pattern. The naive question would be: how the electron *capacities* change depending on, whether one or two slits are open? Clearly it is not because an electron «knows» if there is one or two slits opened. Once again, from Cartwright's framework the simplest answer for any of the two possible cases is given by: «The fact that C causes E, means that C has the capacity Q to produce E». The philosophical and scientific richness of Cartwright's view is undeniable and is an open door for intellectual exploration.

Conclusions

Nancy Cartwright is one of the most important contemporary philosophers of science. Her central idea about a scientific world ruled by patchwork *ceteris paribus* laws had an important impact in science and philosophy of science. She has introduced new concepts such a *ceteris paribus laws, nomological machines and capacities*, which have been studies and analyzed by many philosophers and scientists. In particular, the concept of capacity can be taken as a property shown by objects, therefore, we may define them from their capacities. For example, an electron may have the capacity of Coulomb's law of attraction or repulsion. However, how is than an electron may have certain capacities depending on the experiment on which we are studding it? This question, may represent one of the most important problems for the use of the concept of *capacities*, however, the answer of Cartwright to this pseudo problem is elegant and simple and is given by the fact that «The fact that C causes E, means that C has the capacity Q of producing E». On the other hand, considering that the capacity of an object depends on the studied nomological machine given some *ceteris paribus* characteristics, explains why an object has different capacities. This is important when studding systems that may have quantum and classical states. In this article, in particular, it is shown that the behavior of a free electron or one in a stable atom, —both of them with different classic and quantum capacities— is explained simply by taking into account that «The fact that C causes E means that C has the capacity Q of producing E». This approach is helpful to pose and analyze classic and quantum controversies.

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