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Rigor and objectivity as foundations of the rationality of physics in Evandro Agazzi

Rigor y objetividad como fundamentos de la racionalidad de la física en Evandro Agazzi

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Abstract

There are two opposing attitudes in current epistemology towards the empirical sciences. On the one hand, they appear as an essential tool for the advancement of knowledge. On the other hand, there is doubt about the metaphysical and epistemological bases of this confidence in scientific knowledge, which has led science down paths of skepticism and pragmatism. This paper aims to contribute philosophically to the rationality and ontological status of physics, taking as a starting point some works of the philosopher of science Evandro Agazzi. The article introduces Agazzi's thought and the core issues of his epistemology. It then defines the concepts of rigor and objectivity as understood by Agazzi, and finally establishes criteria of rigor and objectivity for physics, showing how they are verified in two classical experiments. Based on these ideas, it is shown that physics, as the science, has criteria of rigor and objectivity that allow it to effectively reach the real, thus responding to the formalist and pragmatist challenge. Thus, the article does not exhaust itself in a description of Agazzi's thought, but will apply his ideas to the concrete field of physics, making explicit ideas that have not been sufficiently made explicit by the Italian philosopher.

Keywords

Philosophy of science, science of science, basic sciences, epistemology, metaphysics, physics.

Resumen

En la epistemología actual, hay dos actitudes opuestas en relación con las ciencias empíricas. Por una parte, aparecen como herramienta esencial para el avance del conocimiento. Por otro lado, existe duda sobre las bases metafísicas y epistemológicas de esa confianza en el saber científico, lo cual ha llevado a la ciencia por caminos de escepticismo y pragmatismo. Este trabajo se propone aportar filosóficamente a la racionalidad y al estatuto ontológico de la física, teniendo como punto de partida algunas obras del filósofo de la ciencia Evandro Agazzi. El artículo que aquí se presenta introduce al pensamiento de Agazzi y a asuntos nucleares de su epistemología. Posteriormente, define los conceptos de "rigor" y "objetividad" según los entiende Agazzi, finalmente, establece criterios de rigor y objetividad para la física, mostrando de qué manera se verifican en dos experimentos clásicos. Con base en estas ideas, se demuestra que la física, como ciencia que es, cuenta con criterios de rigor y objetividad que le permiten un alcance efectivo de lo real, respondiendo así al desafío formalista y pragmatista. Así pues, el artículo no se agota en una descripción del pensamiento de Agazzi, sino que aplica sus ideas al ámbito concreto de la física, explicitando ideas que no han sido lo suficientemente explicitadas por el filósofo italiano.

Palabras clave

Filosofía de la ciencia, ciencia de la ciencia, ciencias básicas, epistemología, metafísica, física.

Introduction[1]

In the vast and diverse landscape of the philosophy of contemporary science, Evandro Agazzi stands out as one of the most influential and academically qualified thinkers. His contributions have addressed a wide range of topics, from logic and epistemology to the ethics of science. In particular, its emphasis on rigor and objectivity as fundamental pillars of scientific rationality has generated a solid theoretical framework for understanding scientific practice, especially in the field of physics. This article focuses on analyzing and developing Agazzi's ideas on these key

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concepts and their specific application to physics, highlighting their relevance and contributions to the philosophy of science.

The aim is to examine the notion of rigor and objectivity in the work of Evandro Agazzi, with special attention to its application in physics. It demonstrates how these concepts not only constitute the basis of scientific rationality according to Agazzi, but also how they provide a normative criterion for evaluating scientific practice. Through a critical analysis, it is intended to establish the coherence and validity of its arguments, as well as its impact on the development of a robust philosophy of science applicable to contemporary challenges in physics.

The main problem is the understanding and articulation of rigor and objectivity in science as posed by Evandro Agazzi, and its relevance in the context of modern physics. In an environment where science faces growing epistemological and methodological challenges, how can Agazzi's ideas provide an adequate framework to ensure the rationality and credibility of physics? This question is addressed by exploring both the theoretical foundations and practical implications of his thinking.

The main idea to defend is that rigor and objectivity, according to Agazzi's conceptualization, are not only essential but also sufficient to sustain the rationality of physics. Through a detailed analysis of his writings and a comparison with other philosophical perspectives, it will be argued that these notions provide a solid basis for the understanding and evaluation of scientific practice in physics, offering clarity and structure to a field that, by its nature, can be deeply abstract and complex.

The importance of this topic lies in its ability to offer a deep and nuanced understanding of the principles underlying scientific practice. At a historical moment where trust in science and its methodology faces significant challenges, a critical and detailed review of concepts such as rigor and objectivity is crucial. Agazzi's ideas not only enrich the philosophical debate, but also have practical implications for science education, science communication, and science policy making.

The topicality of the issue is evident. Physics, as one of the most fundamental sciences, remains being a dynamic field where accuracy and reliability are essential. Moreover, in a global context where science and technology play essential roles in everyday life and political decision-making, understanding the philosophical underpinnings that ensure the integrity of scientific research is more relevant than ever. Agazzi's contributions offer insights that can inform and guide current debates about science in society.

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The methodology of this work is based on a critical and hermeneutic analysis of the texts of Evandro Agazzi, complemented by a comparative review of the relevant literature in philosophy of science. Exegetical approaches will be used to interpret Agazzi's key concepts, and his ideas will be contrasted with other contemporary theories in the philosophy of science. In addition, an analytical framework will be applied to assess the internal coherence and applicability of their notions of rigor and objectivity.

The document is structured in the following sections: a first section about physics as rigorous and objective knowledge according to Agazzi; a second section about rigor criteria as an expression of the rationality of physics; a third moment about the criteria of objectivity as an expression of the rationality of physics. Finally, some considerations about rigor and objectivity are presented based on two experiments, and the conclusions.

Physics as rigorous and objective knowledge according to Evandro Agazzi

Throughout his academic career, the Italian philosopher of science and physicist Evandro Agazzi has argued that there are two essential requirements when it comes to understanding scientific rationality. These requirements are *rigor* and *objectivity*. In the future, both concepts will be explained, so that, in the future, they will be presented as an expression of the rationality of physics.

> Agazzi distinguishes empirical sciences and formal sciences to elucidate the concept of rigor. In the former, justification can be given by appealing to the formal deduction that would justify the statements from other propositions drawn directly from experience; it can also be given by combining the deductive and the empirical through a hypothesis […]. In the formal sciences, on the contrary, the essential role is played by the axiomatic method according to which starting from some initial statements or axioms is possible to achieve their logical effects through a formal demonstration (Castellanos, 2021, p. 70).

However, according to Agazzi, the deductive method and the hypothetical method demonstrate the wonder and vulnerability of the experimental sciences. The vulnerable becomes evident when examining its conditions of validity with logical criteria, since elementary logic indicates that the fact that true logical consequences can be deduced from a statement is not sufficient reason to declare the truth of that statement.

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Agazzi's studies of scientific rigor and objectivity provide the foundation for the reliability of experimental sciences, i.e. the real capacity to achieve their two main objectives: to grant the necessary tools to sustain the rigorous nature of scientific explanations and to control nature as an effect of the knowledge that man acquires on it.

According to the Italian philosopher, scientific rigor "corresponds to the requirement to 'give reasons' for something that is declared in science (it consists of explaining *how* and *why* a particular declaration was reached)" (Agazzi, 2019, p. 21). This definition is complemented by Agazzi with a historical context on the traditional notion of the concept of *science* that runs through a period from the Athens School to the Renaissance. In this conception of science, *truth* and *rigor* were the essential traits. The idea that science offers knowledge of the highest level:

> It was gradually emerging in Greek philosophy by requiring such knowledge to explain the reasons for what happens and not just what happens. Providing a reason (*logon didonai*) carried the classical notion of science as a discourse of demonstrative character, i.e. it grants convincing logical evidence of what it declares (Castellanos, 2021, p. 72).

Regardless of what the compelling logical evidence is in each case, in providing it lies a fundamental feature of the scientific rigor that the notion of *scientific truth* requires and presupposes. Precisely for this reason, it could not be considered as science to an exclusively empirical knowledge, even if it were true. At most, it would be considered *history* in a broad sense of the term.

Thus, it is easy to understand that, in the history of the West, *rigor* as an indispensable requirement has been one of the essential characteristics of the concept of *science*. This requirement is the result of the claim to verify the truth of certain propositions through the use of logic and starting from more elementary truths that would provide sufficient reasons for the content of such propositions, i.e. that would confirm this truth making it credible (Agazzi, 2019).

To summarize what has been said so far, it must be clarified that the notion of rigor is analogical, not unequivocal or equivocal. The same can be said about the concept of objectivity and the concept of science. *This* can be explained by saying that, according to what Aristotle affirms, concepts that possess a single meaning and apply in a single way to a particular type of objects are known as univocal. On the other hand, concepts that apply in the same way to different objects are called equivocal

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(Agazzi, 2019). Finally, a concept is analogous or analog if it refers to different things, partially in the same way and partially in a different way.

Regarding the concept of objectivity, it is worth starting with a few words from Agazzi:

> The meaning of the word "objectivity" seems, first of all, characterized through a (indirect) reference to the *subject*, not the object. When one says, for example, that a certain judgment is objective, that an investigation was conducted objectively, or that something or someone objectively possesses a quality, it is usually meant to mean that judgment, investigation, or quality do not depend on the subject or subjects expressing the judgment (Agazzi, 2019, p. 69).

In other words, subjectivity, despite being the first step of all knowledge, is considered, simultaneously, its worst defect. Humanity has fought against this defect for centuries, since the goal is a type of knowledge that has a validity superior to the group of subjects that have acquired it and is independent of them.

Apparently, the human being has been concerned with achieving a *corpus* of knowledge independent of the subjects, because in the mind of Western civilization is embodied the idea that there is only one way to verify whether the efforts of human understanding to know reality have achieved its end, namely, to verify that the representation of what is real is "independent of the subject", that other subjects agree in relation to the truth of that representation.

> Claims as simple as "People live in Ecuador" or "cats are animals" express true facts, which simply mean that the veracity of the claims is nothing more than a connection between the claims and their content. To this extent, there is nothing innovative, as Aristotle has already stated it. And Gabriel rightly states that nothing is easier than the truth [while remembering] […] sometimes it is difficult to discover what the truth is. And it is here that is the error of constructivism that confuses truth with recognition by the institutions created by the human being. We could not even communicate without the existence of truth, because a set of common beliefs is necessary since any disagreement on an important issue presupposes that we share a common system of opinion (López, 2021, p. 143).

The natural end of human knowledge is none other than to apprehend reality and it could be affirmed, more technically, that such an end is reached when one reaches *objective knowledge*, i.e. knowledge that corresponds to the portion of reality with which one seeks to correspond. This

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is nothing more than an echo of the classical Aristotelian definition of the concept of truth, which González (2021) explains in the following terms

> That righteous truth, that minimal definition of truth is that of Aristotle, who expressed: "It is false, in fact, to say that what is, is not, and that what is not, is true, that what is, is, and what is not, is not." This is already relevant information in a double sense. First because it offers clues about the age of the problem. Second, because there is a surface on which to start thinking about post-truth. It is, in an abstract way, a departure from the original sense of what we mean "is" (p. 95).

However, the human being always harbors a fear of not being able to achieve this end; his concerns in this regard are rooted in the evident fact that, continuously, very diverse people, located before the same portion of reality, describe it in very different ways. The conclusion is simple: if different images of the same reality are presented:

> Then none of them (or perhaps only one) can be objective, i.e. only one can "correspond to the object", while all the others (with some possible exception) must be considered merely "subjective", as if they expressed a particular way of conceiving objective reality, which is typical of an individual subject (Agazzi, 2019, p. 70).

Everything said to this point is so simple that it seems obvious, however, it clarifies several of the essential features of objectivity. As seen, the existence of various subjective images should be sufficient for none of them to be considered within objective knowledge. Therefore, the fact that knowledge is independent of the subject is a *sine qua non* of its objectivity, but it is not sufficient to guarantee it. Herein lies a deep and complex philosophical problem: determining what additional condition should add to this necessary independence of the subject.

It is not so simple to establish what that condition is that would ensure the complete objectivity of knowledge. This is one of the thorniest issues in the history of philosophy, as it involves a profound reflection on the very nature of knowledge and reality. The crucial point is obvious: the nuclear problem lies in having a tool that provides the assurance that, in a specific case, knowledge is independent of the subject. This allows us to understand why objectivity has maintained a type of indirect characterization, i.e. through the subject, who, initially, should not be related to the notion of object.

With this indirect characterization in mind, *universality* and *necessity* are better understood as two indispensable characteristics of any

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authentic knowledge throughout the history of philosophy. Agazzi (2019) explains it in the following words:

> Although these conceptions of universality and necessity were, and remain, distinct, a practical confluence of the two took place in the history of philosophy, and helped each other achieve the status of distinctive marks of objectivity. To express this fact in a synthetic way, it could be said that both the ontological structure of the object and the guarantees of having a solid knowledge of it have emphasized the two characteristics of universality and necessity until they become the most outstanding fundamental marks of objectivity (p. 72).

All human knowledge activity is intrinsically characterized by the purpose of being objective, understanding objective as the ability to capture the real characteristics of objects. In this regard, the Italian philosopher notes:

> As a result of the above discussion, it must be said that, *if* this undertaking is successful, *then it* must result in something universal and necessary, which is equivalent to saying that universality and necessity, taken together, arise as a *necessary condition* for a form of knowledge to be objective (p. 72).

This section aims to understand the ontological and epistemological bases that enable rigor and objectivity in physics from the scientific realism of Evandro Agazzi. Thus, it focuses on analyzing the essential features of the ontological status of physics. As Islas (2021) states, "in the scientific field some defenders of certain realistic positions of science have considered that truth is the most important goal of scientific activity" (p. 65). Scientific realism broadly holds that scientific entities and theories refer to real-world objects and processes independently of the human mind (Agazzi, 2012a). According to Agazzi's realistic approach, it is possible to understand the essential features of the ontological status of physics from three characteristics that will be presented.

Structural nature of the real

A highly relevant element in Agazzi's approach is the emphasis on the structural nature of everything real. The Italian philosopher argues that scientific theories capture models and links of a structural nature found in the physical world (Agazzi, 1997). Therefore, according to Agazzi's scientific realism, the ontological status of physics implies understanding reality as structured and organized by its own nature (Alonso, 1995). This

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conception involves recognizing that science not only gives superficial presentations of facts and objects, but also seeks to demonstrate the deep relationships and laws that underlie nature, and, fundamentally, how things are:

> The thesis mentioned in this book is that science is first of all an authentic way of knowing: even the only way of knowing objectively, even if it is not an absolute knowledge, i.e. absolute and incontrovertible. As such, science makes us genuinely aware of reality, although it never exhausts this knowledge (Agazzi, 1978, p. 15).

In this character or structural nature of reality, some points stand out for their relevance and meaning. The first is *systematicity*. Agazzi asserts that reality is not simply a chaotic set of objects and facts, but, on the contrary, is characterized by models, links and regularities. These underlying models or patterns are what make it possible for science to establish theories and laws that denote and explain phenomena observed by the scientific community (Agazzi 2008).

The second point is the *definition*. The scientific community can abstract and define through scientific theories, through concepts, specific aspects of the totality of the real. These theories make possible the identification and analysis of the essential structures and relationships that make up the studied phenomena. The precise definition of concepts is fundamental for constructing scientific knowledge, since it allows clear communication and a shared understanding between researchers, facilitating the advance and accumulation of knowledge.

The third point concerns *understanding* and *predictability*. Once it has understood the structures and relationships that underlie the real, science is able to detail and explain present facts, and to predict future facts. In this sense, scientific theories allow predictions to be made based on the regularities that can be identified. The predictive ability of theories is one of the most robust tests, as it validates the robustness of models and provides tools to anticipate and prepare responses to future events.

The fourth point is *interdisciplinarity*. The notion of "structural nature of the real" also indicates that scientific disciplines are linked, because, on many occasions, the same structures and relationships can be applied to phenomena in different areas of knowledge (Agazzi, 2012a). This interconnection between disciplines favors the development of integrative and multifaceted approaches to solving complex problems, promoting a more holistic knowledge and enriched by the perspective and methods of different areas of knowledge.

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In addition to these four points, it is important to note that the structural nature of reality suggests a continuous process of discovery and revision. Science, when approaching reality in a systematic and structured way, must be open to modifying its theories and models in the light of new data and better interpretations. This openness is essential for scientific progress and for maintaining the relevance and accuracy of scientific explanations in a world in constant change and evolution.

Existence of physical entities

Agazzi's scientific realism asserts that physical entities, for example black holes, electromagnetic fields, and subatomic particles exist objectively in the real world and are not mere constructs of human perception. They are not conventions arising from the human mind or mathematical abstractions but are genuine and concrete components of reality (Agazzi, 1988).

Agazzi points out that physical entities, even unobservable ones, are real and exist independently of human perception. This essentially realistic conception inspires the idea that science aims at the discovery and understanding of the world as it is in itself, transcending the perceptions and subjective experience of individuals.

On the other hand, even if there are physical entities that are directly unobservable, such as subatomic particles, science can infer the existence of such entities and describe their properties from the empirical evidence given by experiments and observations. As part of this process, scientific theories provide a conceptual and mathematical framework for understanding and explaining the phenomena being observed.

In the epistemology proposed by Agazzi (1978), physical entities are involved in causal links and cooperate with the movement and development of natural systems, which means that physical entities are not reduced to being mere abstract concepts, but have consequences and an essential role in natural processes.

The consistency and correspondence of scientific theories in elucidating the facts of the natural world supports the existence of physical entities. Theories offer the scientific community conceptual patterns that detail the traits of these entities and allow prediction of their behavior in different situations.

Thought does not produce reality, as the classical idealist philosophers claimed, but, at the same time, it must be admitted that whenever it is believed possible to affirm that a certain discourse is true, the very notion of truth forces us to admit that, for the same reasons, it must also be

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admitted that there are the referents of this discourse. Otherwise, nothing would be true. At this moment, a fruitful perspective opens up: if one accepts that there are very different types of discourses that are normally considered true, one must also admit that there are different types of referents about whom these discourses are true (Agazzi, 2022).

In summary, in Agazzi's scientific realism, the existence of physical entities is supported by a basic metaphysical realism that affirms the reality and objectivity of such entities as genuine *things* in the world, regardless of human perception and knowledge. This perspective highlights the importance of understanding science as a knowledge that aspires to the unveiling of truth about nature and about the underlying reality.

Independence of theories

According to Agazzi's scientific realism, theories, although they are constructions of human understanding, can denote and signify objective and real elements, i.e. belonging to the totality of the real, which are transcendent to human perception and to the mental constructions of which human understanding is capable. In other words, theories correspond to real-world aspects and relationships and are not merely subjective inventions.

Some key points related to the independence of scientific theories in Agazzi's scientific realism are the following: first, the *correspondence* with reality. The philosopher of Bergamo has always maintained that scientists describe and explain natural phenomena through theories, which are their instruments. These theories are not limited to arbitrary inventions but are intended to manifest real elements that exist independently of human perception.

Second, *scientific progress*. The independence of theories implies that, as science progresses and develops, theories are adapted and perfected to achieve a more accurate representation of the real. Scientific progress has as its essential feature an increasingly precise approach to the primordial attributes of the natural world (Mark, 2015).

The third point is the reference to *real entities and processes*. Agazzi argues that scientific theories refer to entities and processes with metaphysical consistency and real-world existence, even if they cannot be observed directly. Theories provide a way to understand and explain how these entities and processes relate in different circumstances and scenarios (Minazzi, 2015).

The fourth point is *empirical procedure*. Despite the independence of the theories, Agazzi acknowledges the importance of empirical evi-

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dence in verifying scientific theories. Observations and experiments provide the foundation for examining the correspondence between theories and natural facts.

To summarize, in the philosophy of science proposed by Agazzi, the independence of the aforementioned theories highlights that scientific theories, although they are creations of human understanding, have an objectivity status and represent authentic elements of reality. This conception places the emphasis on scientific theories being consistent with empirical results and progressing as science advances its understanding of nature.

Criteria of rigor as an expression of the rationality of physics

The rigor criteria of physics are set out and explained below:

- *Logical coherence*: refers to the internal consistency and the solid logical structure that should have theories and statements within physical science. This requires that the different components of a theory connect with each other in a coherent way and lack logical contradictions. For Agazzi (1978), logical coherence is fundamental because a theory that lacks internal coherence or that presents contradictions lacks scientific validity and reliability. If a theory lacks coherence, it is very likely that its predictions and explanations are not accurate or correspond to the observed reality.
- *Mathematical precision*: refers to the requirement that theories and scientific propositions be formulated clearly and accurately, using rigorous mathematical language. In other words, mathematical precision implies that scientific characterizations and patterns must be formulated precisely and numerically, using determined mathematical terms (Rossi, 1986). Agazzi argues that mathematical precision is fundamental in physics because it provides a firm and stable basis for the transmission, testing, and examination of theories. Accurate mathematical representation facilitates that scientific propositions are communicated in a clear and intelligible way, which allows and favors the cooperation and interaction of knowledge between scientists. In addition, mathematical precision is essential when preparing calculations and forecasts (Agazzi, 2011).

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- *Empirical dimension*: it has to do with the transcendental relevance of the scientific theories based on empirical verification, i.e. on observation and on experience. Agazzi emphasizes that scientific theories must be verifiable or falsifiable through information gathered in direct contact with the facts and phenomena of the natural world. In the specific context of physics as a science, the empirical dimension implies that theoretical propositions must be supported by explorations and measures that are repeatable and evaluable by researchers other than the one that, for the first time, explores and measures. Theories that cannot be empirically tested do not meet the criterion of rigor, because they lack a consistent foundation in observed reality. The empirical dimension also refers to theories being in line with experimental data (Agazzi, 2019).
- *Relationship with previous theories*: there is rigor when new theories and scientific propositions are in line with theories proposed previously and supported by empirical evidence. In other words, new theories must be attuned to, and compatible with, the existing *corpus* of scientific knowledge, and must not contradict it. Agazzi (2014) insists that scientific progress is gradual and cumulative. Thus, novel theories are built on previous ones and expand or perfect human knowledge of reality.
- *Critical examination and control*: science, as rigorous knowledge, is inherent in the permanent process of examination and questioning of scientific theories in a strict and systematic way. This criterion highlights the imperative need for theories to be thoroughly scrutinized and continually tested to reach an ever better and more perfect understanding of the real. Critical examination and control involve aspects such as constant review, contrast with empirical evidence, analysis of inconsistencies, debate and scientific discussion, and independent or intersubjective validation (Agazzi, 1996).
- *Cultural independence and subjectivity*: for Agazzi, rigor in physics demands independence from cultural and subjective factors. Scientific theories and propositions must be universally applicable and cannot depend on hermeneutics of a cultural or personal nature, being free of social influences, prejudices and biases of a personal nature. Agazzi (2007) emphasizes that genuine science is characterized by an impartial and universal effort to understand natural reality, regardless of the culture,

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subjective points of view or worldviews that scientists personally have. This implies diminishing cultural and subjective influences on the formulation, evaluation and application of scientific theories.

Objectivity criteria in physics

- *Scientific agreement*: Agazzi considers it vital that the scientific community participate in the evaluation and revision of physical theories (Bolaños and Carvajal, 2019). Peer review and scientific agreement are essential to ensure the objectivity and quality of scientific knowledge. In relation to the subject, a scholar of his thought states the following:

> Weak *objectivity*, i.e. understood as *intersubjective* agreement, is based on the plurality of the *subjects'* observations. This is important for Agazzian thought, since it is not enough with the verification of a subject with respect to the object for it to be considered objective, in addition, it is essential that this constancy exists for more than one subject or for the same subject in different situations, because, with it, the object is confirmed by a group of determinations concerted by the totality of subjects that intervene in it, thus achieving validity for a plurality of subjects (Castellanos, 2021, p. 77).

- *Experimental character*: implies that theories should be able to be tested with data obtained from experience and from observations. A given theory must be revised or discarded if it proves to be incompatible with the results of meticulously designed and repeatable experiments. Agazzi argues, on the other hand, that experimental character is linked to the possibility of reproducing experiments and objectivity in the collection and analysis of information. It is an essential requirement of objectivity that results can be verified by other researchers in various places, circumstances and times, which contributes decisively to the validity and reliability of empirical evidence (Agazzi, 1977).
- *Absence of external influences to scientific methodology*: Agazzi emphasizes the need for no cultural, political, ideological or personal factors in scientific inquiry, as they are alien to a properly scientific methodology. Scientists must strive to be far from preconceptions and orientations that may influence a distortion of the results of their research, thereby affecting the

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objectivity that makes knowledge properly science. This approach involves aspects such as universality, reduction of bias, unbiased critical assessment and diversity of perspectives. While Agazzi acknowledges that various factors such as intentions, proposals and interests interact in science, it is necessary to "ensure that the effect of such a complex interaction, even if it leads to some 'shaping' of scientific knowledge, does not destroy its 'defining characteristics', since this would amount to eliminating science as such" (Agazzi, 2019, p. 450).

- *Replicability of methods and procedures*: Objectivity is promoted through the accurate and thorough description of the methods and processes used in scientific research. This allows other scientists to replicate the experiments and obtain similar results, which strengthens the validity of the findings. The fact that other scientists or other scientific communities cannot replicate the results obtained could be indicating methodological or information interpretation problems. The inability to replicate entails the need to critically review procedures and contributes to the identification of possible errors or sources of variability (Agazzi *et al*., 1989).
- *Assessment*: Objectivity is achieved through a permanent assessment procedure by the scientific community. Scientists should submit their theories and findings to peer review and be willing to modify their conclusions based on feedback and new data. This assessment implies constant review, since scientific knowledge is never definitive and is not immutable; contrast with empirical evidence, because, in the absence of correspondence, it is necessary to seek explanations or adjustments that can improve concordance; the analysis of inconsistencies, since the assessment involves identifying and treating any inconsistency or contradiction that may originate in the elaboration of a theory; and the debate and scientific discussion, to question theories and approaches in a joint effort to improve collective understanding (Agazzi, 2015).
- *Interpretative neutrality*: Scientists should strive to present data in a neutral and objective way. Accurate presentation of information allows other scientists to assess it impartially. In his book *Science and the Soul of the West*, the Italian philosopher speaks out:

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> It is recognized that science does indeed have the structure and means to provide objective and rigorous knowledge that is independent of social motivations and conditionings, so it is and must be "neutral" in this regard. On the other hand, it cannot and should not be, if it is considered as a *human activity*, which legitimately depends on demands of a social nature and must also respond to demands from society. The real problem, then, is to make these two aspects compatible (Agazzi, 2011, p. 299).

Some considerations about rigor and objectivity in physics

After referring to the scientific rationality of physics under the criteria of rigor and objectivity described by Agazzi, it is possible to test some canonical phenomena and experiments that have been key to the development of this science. Experiments such as Galileo's free-fall experiment gave rise to the scientific method and overthrew the Aristotelian tradition that had prevailed until now, establishing the foundations of mechanical physics or classical mechanics that Newton would later perfect. Similarly, experiments such as the double slit experiment by the English scientist Thomas Young in the early 19th century demonstrated the wave-like nature of light and how it behaves when passing through two narrow slits. The experiment has also been repeated with subatomic particles such as electrons to illustrate interference and diffraction phenomena, which are fundamental in quantum theory.

Free fall experiment

Galileo Galilei's experiment of falling bodies is one of the fundamental historical events that contributed to the development of the scientific method and laid the foundation for classical physics. Here are some of the key features of the experiment and its importance:

- *Observation and curiosity*: Galileo began his research by observing how objects fell to the ground from different heights. This curiosity and attention to initial details are essential to the scientific method, since they start from the observation of natural phenomena (Bilbeny, 2015).
- *Manipulation of variables*: Galileo changed one variable in his experiment: the height from which objects *fell.* By varying this

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height, he could observe how the time it took for objects to fall to the ground changed. This controlled manipulation of variables is a fundamental principle of the scientific method (Ruvalcaba *et al*., 2021).

- *Hypotheses and predictions*: Galileo formulated a hypothesis: objects, as long as there is no air resistance, precipitate with equal speed. In addition, he predicted that the fall time would increase with the square of the height. This formulation of a hypothesis and the derivation of measurable predictions are essential to the scientific method (Perilla, 2005).
- *Experimentation and measurement*: Galileo dropped objects from different heights and measured the time it took for them to fall to the ground. These precise measurements are a crucial component of the scientific method, since they allow comparing the results with theoretical predictions (Quiroz, 2015).
- *Comparison with reality*: the results of Galileo's experiments contradicted the ideas accepted at the time, according to which the speed of the fall depended on the weight of the objects. However, Galileo's measurements showed that all objects fell at the same speed, as long as the resistance of the air was ruled out. This confrontation between experimental results and previous theories is a fundamental part of the scientific process (Agazzi, 1994).
- *Analysis and conclusions*: Based on his observations and measurements, Galileo concluded that objects fall to the ground with constant acceleration. This conclusion laid the foundation for the modern understanding of gravity (Guevara, 2020).
- *Iteration and refinement*: as Galileo conducted more experiments and refined his methodology, he was able to further confirm his conclusions. This shows how the scientific method is an iterative process in which scientists continue to refine their ideas as they gain more data and evidence (Romo, 2005).

The Galileo body drop experiment was an important milestone in the development of the scientific method and classical physics. Its features, such as observation, hypothesis formulation, controlled experimentation, and comparison with reality, laid the foundation for the systematic, evidence-based approach that characterizes modern science.

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Rigor and objectivity in the free fall experiment

The principles of rigor and objectivity in this context refer to the application of precise scientific methods and impartial observations to reach reliable conclusions. In the free fall experiment, objects were dropped under controlled conditions and observations were recorded in detail.

Rigor, in this context, refers to the precision and accuracy in the conduct of the experiment and in the measurement of the data. To meet rigor, the experiment must be conducted in a consistent and controlled way (Agazzi, 1996). Factors such as the drop environment (atmospheric pressure, temperature, etc.), the height from which the object is precipitated, and the time measurement method must be carefully controlled to obtain reliable and reproducible results. The following is what Agazzi says in each of its parts:

- *Logical coherence*: lies in the way Galileo collected data, analyzed it, derived mathematical relationships, and finally formulated general laws that explained observed behavior. For example, when studying the fall of bodies, Galileo observed that all objects, regardless of their mass, fall at the same rate in the absence of air resistance. He analyzed these data and formulated the law of free fall, which states that the distance traveled by a falling object is proportional to the square of the elapsed time. This evidence-based approach and logic laid the foundation for the scientific method and notoriously impacted the evolution of physics and the understanding of object motion (Agazzi, 1994).
- *Mathematical precision*: it is shown that the relationship proposed by Galileo perfectly correlates with experimental data, which shows that its mathematical model is an accurate representation of the behavior of objects in free fall. This evidence of mathematical precision supports the validity of the relation, and by extension, the law of the fall of bodies that it formulated (Agazzi, 2019). By using inclined planes to slow the fall of objects and measure time more accurately, Galileo was able to demonstrate that the acceleration of an object in free fall is constant. These precise observations and calculations proved the validity of his mathematical models and supported the law of falling bodies, which is fundamental in classical mechanics.
- *Empirical dimension*: Galileo was noted for its empirical approach to collecting direct data through repeatable observations and experiments. He used innovative methods to measure

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time and distance, such as inclined planes, which allowed him to perform controlled and repeated experiments. Comparing these data with his theoretical predictions allowed him to support and verify his conclusions about the movement of objects in free fall, thus laying the foundations for a scientific approach based on empirical evidence (Agazzi, 2012b).

- *Relationship to previous theories*: Evidence shows how Galileo's observations and experiments directly contradicted Aristotelian beliefs about the movement and fall of bodies. Aristotle argued that objects fell at speeds proportional to their mass, an idea that Galileo refuted with his empirical approach. By demonstrating that all bodies fall at the same speed in the absence of air resistance, Galileo not only contradicted previous theories, but also marked the beginning of a new era in science, based on observation and experimentation rather than authority and speculation. His empirical approach and results led to a fundamental revision of previous ideas and marked the beginning of a new era in scientific understanding (Agazzi, 1978).
- *Critical review and control*: allowed to eliminate confusing factors, refine the understanding, and reach more accurate, evidence-based conclusions. For example, by carefully controlling experimental conditions and removing air drag, Galileo was able to conclusively demonstrate the constancy of acceleration in free fall. This rigor in variable control and accurate measurement laid the foundation for the modern scientific method, emphasizing the importance of critical analysis and repeatability in scientific research (Agazzi, 1994).
- *Cultural independence and subjectivity*: By focusing on objective observation, data collection and empirical evidence, its rigorous approach paved the way for the development of the modern scientific method, which values objectivity and universality of results over cultural or subjective beliefs (Agazzi, 2000). This rigorous approach allowed his discoveries to be accepted and verified by other scientists, regardless of their cultural or personal contexts, paving the way for the development of the modern scientific method that is universal and based on observable and reproducible facts.

Objectivity refers to impartiality and neutrality in the experimentation and interpretation of facts. In the free-fall experiment, objectivity

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implies that data is collected and analyzed in an unbiased way, without bias or subjective interpretations. For example, the fall time would be measured using accurate and calibrated methods and devices, and any systematic errors would be considered and corrected; it will be presented as follows:

- *Agreement of the scientific community*: despite initial resistance over time, as his ideas were supported by solid evidence, logical arguments, and the gradual recognition of the validity of his conclusions, his work eventually gained acceptance and became a milestone in the development of modern physics. As other scientists replicated their experiments and confirmed their findings, Galileo's conclusions about free fall were consolidated as fundamental truths in physics. This gradual process of recognition and acceptance in the scientific community is a testament to the objectivity of his work, as it is based on evidence and logical reasoning rather than authority or tradition (Agazzi *et al*., 1989).
- *Experimental character*: it is reflected in its rigorous and systematic methodology, which was based on direct observation, controlled variation of parameters, collection of accurate data and quantitative analysis. This experimental approach laid the foundation for the development of the modern scientific method, had a significant impact on the understanding of physics, and enabled the collection of accurate data and its quantitative analysis. For example, by measuring the distance traveled and the fall time of different objects, Galileo was able to formulate mathematical laws describing uniformly accelerated motion. This experimental approach laid the foundations of the modern scientific method and transformed the understanding of physics (Drake, 1970).
- *Absence of external influences to scientific methodology*: Overall, the absence of external influences to scientific methodology in Galileo's free fall experiment is reflected in its objective, systematic and evidence-based approach. For example, it controlled variables such as air resistance and used precise mechanisms to measure time. This attention to detail and removal of external factors ensured that its conclusions truly reflected the observed physical phenomena, setting a precedent for independence and objectivity in scientific research. His work laid the foundation for independence and objectivity in scientific research, which

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is essential to obtain reliable and robust results in any scientific field (Akhutin, 1982).

- *Replicability of methods and procedures*: evidenced through their ability to describe their methods in detail, record data carefully, and communicate their results to the scientific community. By providing complete and accurate information, it allowed other scientists to conduct similar experiments and obtain consistent results, which is critical to the validity and reliability of scientific research. His use of inclined planes to slow the fall of objects and measure time allowed others to reproduce their experiments and confirm their results. This replicability is fundamental to the validity and reliability of scientific research, ensuring that discoveries do not depend on a single researcher or experimental context (Agazzi, 2011).
- *Assessment*: manifests itself in its focus on observation, empirical evidence, objectivity, logic, and scientific debate. His work laid the foundation for the modern scientific method, which values the pursuit of evidence-based truth and objectivity over pre-existing assumptions and beliefs (Agazzi, 1994).
- *Interpretative neutrality*: manifests itself in how it presented data, observations and conclusions in an objective and non-judgmental manner. Its evidence-based and objective approach laid the foundation for an impartial and rigorous scientific method, where results are evaluated in a neutral manner, without subjective interpretative influences (Agazzi, 2019).

Thus, the free fall experiment in classical mechanics exemplifies the principles of rigor and objectivity advocated by Evandro Agazzi. These principles are essential to ensure that scientific results are reliable, accurate and valid (Ruvalcaba *et al.*, 2021).

Double slit experiment

The double-slit experiment is one of the most iconic and surprising in the field of quantum physics. This experiment illustrates the unique and often disconcerting properties of subatomic particles, such as electrons and photons. In the double-slit experiment, a particle, such as an electron or photon, is fired into a barrier that has two open slits. Behind the barrier, there is a sensitive screen that records the location of the particles when they arrive. The main question to be answered is what pattern of interference forms on the screen behind the cracks (Giacosa *et al.*, 2019).

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In classical physics, one would expect to see two separate patterns behind the slits, each corresponding to a slit, since the particles should pass through one slit or the other. However, something surprising happens when the experiment is performed with quantum particles, such as electrons, photons or even atoms. An interference pattern is observed on the screen. This pattern is similar to that observed whenever light is transported through two slits and a light and shadow pattern occurs on the rear screen. This implies that the particles are showing undulatory phenomena, such as interference.

What is disturbing is that, when one tries to observe which specific slit goes through each quantum particle (for example, by placing detectors to measure the path), the interference pattern disappears and a two-band pattern is obtained behind the slits, as in classical physics. This is due to quantum interference and the principle of superposition, which says that a particle can be in multiple states at the same time until measured (Idarraga, 1994).

The double-slit experiment highlights the wave-particle duality of the quantum nature of particles and raises profound questions about how particles interact with their environment and how they behave under different circumstances. Furthermore, this experiment is an example of how quantum physics often challenges human intuition and entails questioning the very nature of reality at the subatomic level.

Against this background, it can be argued that an interpretation of quantum mechanics should be consistent with experimental data and supported by a sound theoretical framework. In addition, the importance of interpretation to accurately predict experimental results and to be able to maintain consistency with other scientific theories could be emphasized. This experiment is fundamental in understanding the key concepts of quantum mechanics, but it also raises philosophical and epistemological questions. From Agazzi's perspective, a rigorous and objective analysis of the double-slit experiment could involve the following.

As for rigor there are:

- *Logical coherence*: interpretation must be logically coherent and avoid internal contradictions. For example, when considering the dual properties of particles, a coherent interpretation must be able to explain how a particle can behave as a wave in certain circumstances and as a particle in others, without incurring paradoxes. This requires a precise logical formulation that integrates both behaviors within a single conceptual framework,

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such as Copenhagen's interpretation of quantum mechanics, which posits that the quantum state is a superposition of all possible positions and states of a particle until a measurement is made (Agazzi, 1996, 2019).

- *Mathematical precision*: lies in how quantum theory accurately describes the seemingly contradictory behaviors of particles at the subatomic level and how wave functions, probability calculations and mathematical operators allow predicting and explaining the results observed in experiments. Mathematical precision is crucial in describing the seemingly contradictory behaviors of particles at the subatomic level. Quantum theory employs wave functions, probability calculations, and mathematical operators to predict observed results. For example, the Schrödinger equation allows one to calculate the probability of finding a particle at a given position, while the wave function describes the quantum state of the system. These mathematical calculations have been experimentally corroborated with high precision, demonstrating the effectiveness of quantum theory in predicting phenomena such as the interference pattern observed in the double-slit experiment (Agazzi, 2019).
- *Empirical dimension*: It is based on the observations and concrete experimental results that confirm quantum theory and associated concepts. The presence of interference patterns and the response of particles to direct observations support the idea that quantum particles exhibit dual wave-particle behavior, as predicted by the theory. Quantum theory must be corroborated by concrete observations and experimental results. In the double-slit experiment, the observation of interference patterns when particles pass through the slits without being directly observed, and the absence of such patterns when direct observation is performed, confirm the wave-particle duality. These experimental results support quantum theory and its predictions, showing how particles can exhibit different behaviors depending on whether they are observed (Agazzi, 2012b).
- *Relationship between theories*: Interpretation must be compatible with, and not conflict with, other physical theories, such as quantum field theory and relativity. For example, quantum field theory extends quantum mechanics to include the creation and annihilation of particles, while special relativity introduces the need for physical laws to be invariant under Lorentz transfor-

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mations. A rigorous interpretation of the double-slit experiment must respect these compatibilities, integrating the results of the experiment into a framework consistent with both theories (Alonso, 1995).

- *Critical examination and control*: refers to how the way the experiment is observed and controlled and how it can change the behavior and results of quantum particles. This highlights the influence of the observer and the environment on the interpretation of quantum phenomena and highlights the complex and subtle nature of physics at the subatomic level. For example, in the double slit experiment, the introduction of a measuring device to detect which slit a particle passes alters the interference pattern. This underscores the importance of observation in quantum mechanics and the need for a critical examination of how experimental conditions and the environment affect observed outcomes. This phenomenon is known as the observer influence, highlighting the non-deterministic and contextual nature of quantum physics (Agazzi, 1994).
- *Cultural independence and subjectivity*: they manifest themselves in how different people and cultures interpret and make sense of the results and concepts of the double-slit experiment. Quantum physics has given rise to many philosophical discussions and debates about the very essence of the real and about the link between observation and observed phenomenon. These issues often relate to how people interpret the results of the experiment and its broader meaning. Quantum physics has generated numerous philosophical debates about the nature of reality and the relationship between observation and observed phenomenon. For example, some philosophical interpretations, such as structural realism or instrumentalism, offer different approaches to how to interpret experimental results and what implications they have for our understanding of the world. These debates reflect how subjectivity and cultural context influence the interpretation of quantum phenomena, highlighting the need for a broad and critical perspective when analyzing such experiments (Agazzi, 2000).

On the other hand, in terms of objectivity there are:

- *Agreement of the scientific community*: although there are agreements around certain aspects, quantum physics has also gi-

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ven rise to diverse interpretations and philosophical debates. Interpretations range from Copenhagen theory to the theory of the many worlds, among others. These interpretations can influence how quantum phenomena are understood and explained, leading to ongoing discussions and explorations in the scientific community (Agazzi *et al.*, 1989). For example, the Copenhagen interpretation, advocated by Niels Bohr and Werner Heisenberg, suggests that quantum phenomena have no definite properties until they are observed. In contrast, Hugh Everett's theory of the many worlds posits that all possible alternative histories of a quantum system are equally real, each in its own parallel universe. These differences in interpretation have led to significant philosophical debates and have influenced how quantum phenomena are understood and explained, demonstrating the dynamics and continuous evolution within the scientific community.

- *Experimental character*: lies in the realization of practical and controlled actions in a laboratory to observe and measure the results. The experiment is an essential example of how scientific principles are tested by data collection and comparison with theoretical predictions, supporting the scientific method and understanding of quantum phenomena. In addition, it demonstrates both wave interference and electron and photon particle behavior and highlights the importance of direct observation and measurement in a controlled environment to validate scientific theories. The replication of these experiments in various laboratories and with different technological configurations has allowed to corroborate the predictions of quantum mechanics, emphasizing the value of the scientific method and the importance of empirical evidence in the understanding of quantum phenomena (Agazzi, 2000).
- *Absence of external influences to the scientific methodology*: the double slit experiment is related to the need to minimize any factor that is not controlled or measured in the experimental process, to ensure that the results accurately reflect the effects that are being studied. To ensure the validity of the results of the double-slit experiment, it is essential to minimize any uncontrolled or measured factors that may influence the experimental process. This involves rigorous control of the experimental environment, including removal of potential sources of

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interference and accurate calibration of measurement instruments. For example, when measuring electron interference, factors such as ambient noise and temperature variations should be monitored to ensure that observed patterns are effectively caused by the quantum phenomena being studied and not by external variables (Agazzi, 1996).

- *Replicability of methods and procedures*: evidenced through detailed documentation, use of standardized protocols, data availability, cross-checking by other researchers, scientific publication and review, conference communication, and collaboration. The ability to obtain consistent results in different contexts reinforces confidence in the validity and understanding of the quantum phenomena involved in the experiment (Agazzi, 2019). Replicability is a main milestone of the scientific method. In the case of the double-slit experiment, detailed documentation of procedures, the use of standardized protocols, and the availability of data for verification by other researchers are crucial. For example, experiments with electrons and photons have been repeated in multiple laboratories around the world, always obtaining consistent results that validate the theoretical predictions of quantum mechanics. This ability to reproduce results in different contexts and conditions reinforces confidence in the validity of observed quantum phenomena.
- *Valuation*: evidenced through comparison with theory, coherence with previous experiments, replicability, statistical analysis, discussions in the scientific community, exploration of alternative interpretations, and influence on theoretical development. Evaluation involves interpreting the results critically and reflexively within the existing scientific and theoretical context. The evaluation of the experimental results is carried out through comparison with theoretical predictions, coherence with previous experiments and statistical analysis. In the case of the double-slit experiment, the observed interference patterns have been critically analyzed in the context of quantum theory and shown to be consistent with mathematical predictions of wave functions. In addition, the ongoing discussion in the scientific community, including the exploration of alternative interpretations and their influence on theoretical development, shows a commitment to a critical and reflective interpretation of the results (Agazzi, 2012b).

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- *Interpretative neutrality*: evidenced through focus on empirical data, use of standardized methods, consideration of multiple perspectives, peer review, comparison with existing theories, transparency in methodology, and scientific debate. Scientists strive to minimize any subjective influence and personal bias on the interpretation of results to achieve objective, evidence-based understanding (Agazzi, 1977). Peer review, transparency in methodology and scientific debate are essential practices that help to maintain objectivity. For example, different interpretations of quantum phenomena are continually debated and reviewed, allowing for evidence-based understanding and avoiding personal or cultural biases.

For this reason, it could be said that both Galileo's free-fall experiment and the double-slit experiment meet the different criteria of rigor and objectivity that allow physics to be a true knowledge and consistent with experimental data, established scientific theories and logical principles, while offering a clear and predictable explanation of the observed phenomena.

Conclusions

Agazzi has pointed out that there are two fundamental requirements when explaining scientific rationality, these are rigor and objectivity.

The rigor (from the Latin *rigoris*, which relates to severity, accuracy and rigidity in respect of a norm) consists in that for a speech to be considered scientific, sufficient reasons must be given for the propositions that make it up in an argued way. An effective and effective way to do this is through mathematical calculation and demonstration, although it is not the only form of rigor. In the social sciences it is argued from the facts and the compatibility that one has with certain sources, and in the law the subtle logical rigor is used. The rigor requirements vary from science to science, without the essence of what rigor means varying or transforming.

The objective is what can be shared by a plurality of observers. In this way, the discourse of the different disciplines has elaborated criteria that allow specialists to reach shared statements and differentiate one science from another, obtaining from them certain aspects through cuts of reality, which is valid and necessary, as it allows to gain in objectivity from the specialized look of the sciences. It is thus held that each science is devoted to certain attributes or properties that are important and ignores others that will be considered by other sciences. In this way, each science

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has its criteria of objectivity which are, at the same time, criteria of referentiality and truth, which allow investigating certain aspects of reality, as well as achieving a consent from specialists in that specific field.

Scientific realism generally asserts that physical theories and entities refer to objects and processes of reality independently of human knowledge. According to Agazzi's realistic approach, it is possible to identify three essential features of the ontological status of physics: the structural nature of the real, the existence of physical entities, and the independence of theories.

The rigorous criteria in physics are logical coherence, which relates to the internal consistency and the solid logical structure that scientific theories and propositions must have; mathematical precision, which refers to the requirement that theories and claims in physics be formulated clearly and accurately; the empirical dimension, relative to the great importance of physical theories being based on empirical verification; the relationship with previous theories, i.e. the requirement that new theories be compatible with the corpus of scientific knowledge and not contradict it; *critical examination and control*, which highlights the importance of physical theories being evaluated in detail and *permanently contrasted; cultural independence and subjectivity*, since, for Agazzi, theories and assertions of physics must be universally applicable and cannot depend on cultural or personal interpretations.

The criteria of objectivity in physics are the agreement of the scientific community, since peer review and intersubjectivity are fundamental to ensure the objectivity and quality of scientific knowledge; the experimental nature, since theories must be able to verify with information collected from experience and based on what is observed; the absence of external influences to scientific methodology, because it is necessary that, in physical research, there are no factors of cultural, political, ideological or subjective order; the *replicability of methods and procedures*, since objectivity is promoted through the exact and detailed description of the method and process used in scientific research; *valuation*, since physicists must submit their theories and results to the review of experts and be willing to modify their conclusions to the role of feedback and new information received from peers; and, finally, *interpretative neutrality*, as physicists must strive to present information in a neutral and objective manner, so that the information presented allows other scientists to evaluate it impartially.

This paper could have different educational implications. Some possible are the training of teachers of physics and philosophy, contribut-

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ing to a more complete and contextualized presentation of physics and its philosophical foundations in the classroom; the design of educational programs, since research could inspire the design of educational programs in philosophy of science, specifically, teaching the scientific realism of Agazzi; the development of critical thinking, since, by delving into the onto-epistemological foundations of physics, students can develop critical thinking skills, which, in turn, would facilitate a better and deeper understanding of scientific research and its difficulties; and, finally, interdisciplinarity, since its subject promotes dialog and collaboration between experts in physics and philosophy.

Note

1 This article is the result of the research project "onto-epistemological foundations of physics: contributions from the scientific realism of Evandro Agazzi".

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