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Analysing the Errors of Renowned Scientists Throughout History and Those of Students After Learning About Science

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Abstract

In the present study, we will first clarify the concept of error as developed by scientists and by students before and after science instruction. A study of the history of science reveals two categories of errors that have shaped its development: those that have contributed to its progress and those that have hindered it. In this regard, we will see that many renowned scientists, such as Aristotle and Buridan, developed theories or put forward explanations of force and movement that later proved false. Also, we will see that some errors did not prevent scientists from advancing science. This research underscores the pivotal role of scientific errors in shaping the evolution of science throughout history, enlightening us about the scientific process and fostering an appreciation for the scientific community's resilience and adaptability as a key insight. The study also explores students' errors and their relevance to developing strategy-based teaching that enables meaningful learning of science. The study also delves into errors in students' reasoning, which can be attributed to distractions or unintentional mistakes, as well as to misunderstandings of natural and human-made phenomena. Finally, we will see that identifying the errors of scientists and those of students is crucial for creating teaching strategies that promote meaningful science learning.

Keywords: scientists' errors; students' errors; positive errors; negative errors; learning science; teaching; conceptuel conflict

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1. Theoretical framework

Science education researchers widely acknowledge that educators play a pivotal role in presenting to their students the fundamental conceptual difficulties that scientists face in their quest for scientific development [1–4]. Van Ravenzwaaij et al. [3] note that two types of errors are widespread among scientists, "One type of error results from bias and influences scientific output through factors not related to scientific content, but through extraneous factors such as career prospects, funding opportunities, and the peer-review process. The other type of error results from mistakes and influences scientific output through inaccuracies and mistakes in the research process itself." (p. 2)

These errors, despite their negative connotations, are rich in teaching the accurate Nature of science, both epistemological and sociological. Hacieminoğlu [5] summarized why teachers do not use the history of science in their teaching: "Teachers commented that since their curriculum was overloaded with topics, they did not attach importance to the inclusion of additional historical elements." (p. 355) However, it is crucial to understand that including historical elements in the curriculum is not just an option, but a necessity. It can ignite a deeper interest and investment in educators and students towards the Nature of Science, thereby inspiring a new generation of scientific minds.

Abimbola [6] and other constructivist scholars stress the essential role of students' contributions in science education. This perspective challenges the 'empty vessel' analogy, as it asserts that students are not passive recipients of knowledge but active contributors. Kaliampos et al. [7] further elaborate

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on this, stating that students are not 'empty vessels' devoid of understanding of physical systems. They actively contribute with their pre-existing ideas about various scientific concepts and phenomena, such as sharing their personal experiences or asking thought-provoking questions. These pre-existing ideas, often overlooked, are not just significant but essential in the construction of knowledge in science education, inspiring and motivating both educators and students.

What, however, are the errors that we must consider for learning and teaching? The French philosopher of science, Bachelard [8], explores the notion of an error in analyzing the evolution of scientific concepts. For him, the scientific spirit builds on a set of rectified errors. Indeed, he distinguished two error categories: negative error and positive error. An example of a negative error could be a student misinterpreting a scientific concept due to fatigue, while a positive error could be a student making a mistake in an experiment that leads to a new discovery.

The negative error results from a distraction of the tired mind and represents a transitory obstacle. As for the positive error, the helpful error represents an epistemological obstacle. Recognizing that positive error has its place in science teaching, Migne [9] views it as a source of inspiration for the researcher, rather than a state of stagnation. This understanding of positive errors and the distinction from negative errors can inspire and intrigue us, sparking curiosity and motivating us to engage in further research in our scientific pursuits.

Moreover, Rosmorduc [10] effectively uses historical examples to illustrate the constructive role of errors in scientific discoveries vividly. According to him, the notion of error in science should not be seen as a simple flaw, but rather as an essential driver of knowledge and scientific progress. He emphasizes that error, far from being an obstacle, is a central element in the process of constructing scientific knowledge. He highlights Newton's discovery of the reflecting telescope and Becquerel's discovery of natural radioactivity as prime examples.

These instances, when viewed from an epistemological and scientific perspective, illustrate how errors and false theories can contribute to the development of scientific knowledge. They show that errors are not setbacks, but rather transformative moments that can lead to significant advancements in our understanding of the world. In the realm of teaching and learning, Lévy-Leblond [11] extols the virtues of false theories and underscores the immense value of exploring a broader field than that typically outlined by official views in school curricula, thereby encouraging and motivating the reader to maintain an open mind in their scientific endeavors.

2. Scientist' Errors

This perspective emphasizes the importance of adopting a more open-minded approach to science education, one that fosters critical thinking, creativity, and the exploration of alternative scientific theories. This approach encourages teachers to transcend traditional curricula, inspiring students to think critically and creatively. From this viewpoint, the teacher's role becomes both challenging and rewarding, as they must be well-versed in accepted scientific knowledge, refute theories, and explain why the scientific community has discarded them. It is worth noting that on this topic, many researchers, including the historians of science Kuhn [12] and Bachelard [13], view such a shift as problematic because it challenges the epistemological foundations of scientific laws and theories. For instance, the relativistic conception of movement necessitates a reevaluation of the notions of time and space as defined in the Newtonian conception. Similarly, Galileo's conception of falling bodies represents an epistemological departure from Aristotle's. Below, we provide further details on the errors committed by Aristotle, Becquerel, Galileo, and other famous scientists, as well as their views on the role of errors in science.

2.1. Francis Bacon (1561-1626): Light and Heat

Bacon's persistent belief that light and heat are manifestations of the same force is a significant point of confusion. His failure to distinguish between these two fundamental phenomena, and his inability to differentiate between various forms of light, such as sunlight, reflected light, and light from natural phenomena like lightning, is a crucial aspect that needs to be understood [14].

Despite his pioneering role in the scientific method [15], Bacon's study of light was marred by a subjective and haphazard approach. This stark contrast to the controlled and precise experiments that are now the hallmark of scientific inquiry highlights the significant progress in scientific methodology.

In summary, although Francis Bacon contributed significantly to the development of experimental science, his ideas about light were marred by errors stemming from a still limited understanding of light phenomena and the significant influence of his own 'idols' (i.e., prejudices and misperceptions). The influence of personal biases on scientific research serves as a stark reminder of the formidable challenges faced by early scientists in their relentless pursuit of knowledge.

2.2. Georg Ernst Stahl (1659-1734): Phlogiston Theory

Georg Ernst Stahl's significant scientific error, rooted in his phlogiston theory, played a constructive role in the development of a new approach to chemistry, despite the scientific community's abandonment of his theory following experiments by the French chemist Lavoisier (see section 2.3). According to the phlogiston theory, combustion is a process in which a body loses a substance called phlogiston, a kind of igneous principle [16]. Stahl believed that combustible bodies were rich in phlogiston and that during combustion, they lost it, becoming ash. This theory was proven false when Lavoisier's discovery demonstrated that combustion involves a body combining with oxygen, not a loss of phlogiston [17]. Despite being superseded by Lavoisier's discovery of oxygen, Stahl's framework provided a basis for chemical studies and served as a foundation for a novel perspective on chemistry. It is important to note that, despite his mistake in postulating that the fuel contains phlogiston, which escapes during combustion, he laid the foundations for a new approach to chemistry, highlighting the constructive aspect of scientific mistakes. Stahl's theory, though ultimately incorrect, was a crucial stepping stone in the evolution of chemistry.

2.3. Antoine Laurant Lavoisier (1743-1794): Caloric Theory

The most notable scientific error attributed to Lavoisier is his adoption of the caloric theory to explain the heat released during combustion. Note that the concept of caloric, once believed to be a tangible and all-pervasive substance, was a cornerstone of Lavoisier's catalogue of chemical elements [18]. However, the revelation of the true nature of kinetic energy was a revolutionary moment in the history of science. It illuminated that heat is not a substance, but a form of energy, rendering the caloric theory obsolete. So, the caloric, an imponderable substance supposed to explain heat, turned out to be false.

Despite Lavoisier's research errors, his work was transformative, sparking a revolution in chemistry. He brought to light the crucial role of oxygen in combustion and pioneered the use of instruments like balances to establish quantitative methods for studying matter conservation [19,20]. His missteps were not setbacks but instead stepping stones to his discoveries. These developments underscore the transformative power of scientific progress, inspiring us with the potential of errors to lead to discoveries and advances.

2.4. John Dalton (1766-1844): Atomic Theory

Dalton asserted that atoms of the same element are identical in size, mass, and other properties. However, we now know this to be untrue, thanks to the discovery of isotopes, a crucial advancement in atomic theory. Isotopes are atoms of the same element with different masses, and their discovery has significantly enhanced our understanding of atomic structure. Dalton also believed that atoms were indestructible and could not be created or subdivided [21]. However, this notion was debunked when it was revealed that certain elements exist in molecules, such as gaseous oxygen, which is not O but O_2. He also believed that the simplest compound formed by the reaction of two elements contained only one atom of each species. For example, he thought that the formula for water was HO, not H_2O.

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Despite these errors, Dalton's theory was a crucial step in the development of atomic science, as it provided a conceptual framework for understanding the composition of matter and the nature of chemical reactions. Importantly, it was not just a theoretical construction, but was firmly grounded in experimental observations, leading to important discoveries, such as the law of multiple proportions. Thus, Dalton's atomic theory, a significant milestone in the history of science, was the first to describe matter in terms of atoms and to specify its properties. He based his theory on the laws of conservation of mass and of definite proportions. Dalton's atomic theory is considered revolutionary compared to that postulated by Leucippus and Democritus around 430 BCE [22].

2.5. Aristotle (384 BC-322 BC): Force and Movement

The renowned Greek philosopher Aristotle committed a fundamental error in his theory of motion. He argued that an external force is necessary to maintain an object's motion, a concept now referred to as Aristotle's fallacy. He believed that objects naturally tend towards a state of rest, and that motion would cease once the force was removed. This once-held belief, now recognized as a significant shortcoming, was later contradicted by Galileo's groundbreaking concept of inertia, a stark contrast to Aristotle's theory. This law states that an object in motion will remain in motion at a constant velocity unless acted upon by an external force, challenging Aristotle's theory of rectilinear motion at a constant velocity [23]. Also, he claims that the force is proportional to its speed, which is incorrect; it is proportional to acceleration in Newtonian mechanics.

Aristotle's flawed theory, which failed to account for an object's persistent motion in the absence of any discernible force, had a significant impact on the understanding of motion. He erred in thinking that only touching objects could exert force, and struggled to explain how a projectile, such as a thrown stone, could continue moving after leaving the hand. To explain this, he proposed that the air pushes the object forward. These developments highlight the need for further exploration and learning in the history of physics related to movement.

2.6. Galilei Galileo (1564-1642): Falling Bodies

The brilliant Italian physicist Galileo's attempt to explain the tides, while a significant step in the history of science, was flawed. He combined the Earth's rotational and translational motions to propose that variations in speed due to these motions created forces that caused the tides. However, his explanation was flawed due to his underestimation of the gravitational influence of the Moon and the Sun. He failed to consider the gravitational pull of the Moon, a force he did not fully comprehend, and even dismissed the Moon's influence on the tides [24]. This flawed conception highlights the urgent need for a more comprehensive understanding of the tides and underscores the importance of continuous scientific exploration and discovery.

When it comes to falling bodies, Galileo initially believed that in free fall, the speed of an object at a given point is proportional to the distance it has traveled. However, as we know today, this is not the case: the speed of a body in free fall is proportional to the time elapsed since the beginning of the movement. It is fascinating to note that this misconception led Galileo to the correct conclusion: that when an object falls, the distance traveled is proportional to the square of the time it takes to travel that distance. This correction of his initial belief is a testament to the thrilling evolution of scientific knowledge and the birth of modern physics. For further information, explore Galileo's experiments on falling bodies in Drake's book [23] and Bellone's [25].

According to Galileo, error in science lies not so much in poor observation or erroneous calculation, but instead in a misinterpretation of natural phenomena and an excessive attachment to prejudices and dogmas, especially those of Aristotelianism about movement, for example.

2.7. Isaac Newton (1643-1727): Light and Color

Newton's error in understanding the composition of white light, where he believed it to be a mixture of different colored rays, was a significant moment in the history of science [26,27]. This error, later corrected to be an electromagnetic wave with a continuous spectrum of wavelengths, underscores the importance of scientific progress.

Newton's unwavering belief in the importance of the scientific method, which involves observation, experimentation, and formulating hypotheses, then testing and correcting them as necessary, was unwavering. He viewed human knowledge as imperfect and saw science as a discipline that progresses through the correction of errors and the accumulation of empirical evidence.

2.8. Henri Becquerel (1852-1908): Fluorescence of Uranium

Henri Becquerel, the esteemed recipient of the 1903 Nobel Prize in Physics, discovered the instability of an atom's nucleus, which is at the origin of many revolutionary applications. While studying the fluorescence of uranium salts, he anticipated that these salts, when exposed to sunlight, would emit X-rays [28]. However, his findings fell short of his expectations. He discovered that uranium salts emitted rays even without being exposed to light, and that they could imprint photographic plates. This discovery, although the result of an initial misinterpretation, was a significant step towards understanding radioactivity and its applications. It serves as a potent reminder that even errors can drive progress in science. Becquerel's ability to observe, analyze, and capitalize on his erroneous interpretation, turning a mistake into a breakthrough, is a testament to the role of errors in scientific progress.

2.9. Alessandro Volta (1745-1827): Electric Battery-Metallic Electricity

The illustrious Italian physicist Volta, renowned for his work on electricity and the invention of the first electric battery, the «voltaic pile,» also advanced some erroneous explanations about the functioning of his pile. He mistakenly attributed the electricity produced solely to the contact between the metals (Copper/Zinc), neglecting the crucial and significant role of the electrolyte (the saline solution). The electrolyte is not just a simple passive conductor, as he had advanced, but a key player in the phenomenon that generates the current. Understanding the chemical reaction between copper, zinc, and the electrolyte is not only beneficial but also essential to fully comprehend the ionic current product in the solution [29].

2.10. William Gilbert (1544-1603): Earth Magnetism Electrification by Friction

It was the illustrious English physician and astronomer William Gilbert who first revealed, through conducting experiments, the secret of the compass, identifying the Earth as a mammoth magnet. However, his initial explanation of the origin of Earth's magnetism was flawed. He believed the Earth to be a stationary magnet, a view that has evolved. He believed also that magnetic forces kept the planets in their respective orbits. Later, Newton formulated the law of universal gravitation, refuting Gilbert's thesis.

Today, we understand that the convection movements of the liquid metal, where 'heated' material rises and 'cooler' material sinks, are responsible for generating the Earth's magnetic field in the outer core [30–32].

Gilbert, in his research on "electricity", erroneously believed that all substances that attract light objects after friction were "electric" in nature. He did not differentiate between "static electricity" and magnetism, instead lumping them together under the label of 'electric' occurrences. Gilbert's concept of examining the Earth's magnetism by studying that of a 'Terrella' (a miniature globe coated in magnetite) was groundbreaking in his era. He used modelling and analogical reasoning to demonstrate that the Earth behaves like a giant magnet, although he was unable to pinpoint its magnetic poles accurately. Additionally, he took on the centuries-old hypotheses about the allure of lodestones by resuming experiments on the phenomenon of attraction and repulsion between magnets, as conducted by Pierre de Maricourt in the Middle Ages [30]. This comparison with Pierre de Maricourt's work provides an intriguing historical context to Gilbert's research. It is important to note that Pierre de Maricourt's work did not receive the same level of enthusiasm among his contemporaries because there was no theoretical framework to interpret his groundbreaking observations.

2.11. William Thomson (Lord Kelvin) (1822-1873)

The greatest physicists William Thomson, known as Lord Kelvin, made notable scientific errors, most notably concluding that the Earth was only a few million years old [33], contradicting subsequent discoveries about radioactivity. He based his conclusion on Earth's cooling rates, without accounting for the heat generated by radioactive decay, and he rejected Maxwell's theory of transverse waves in the ether. In an article published in the journal American Scientist, Encland and his collaborators note that, contrary to what is reported in many references, Lord Kelvin was not wrong in his calculations because of his lack of knowledge of radioactivity: "Many people believe that Kelvin's calculation failed through his ignorance of radioactivity. Here, we examine Kelvin's approach and show that this was not where his error lay. The flaw in Kelvin's thinking was divined by one of his own assistants, a scholar, educator and inventor named John Perry, who attempted and failed to convince the establishment of the day that enhanced heat transfer in the Earth's interior—by convection or some other means—could reconcile the geological and the physical arguments. Today it is possible to see how Perry's ideas could have advanced the study of the Earth considerably, had geologists understood and appreciated them." [34]

He also denied the future of radio and heavier-than-air aircraft, stating that "heavier-than-air flying machines are impossible" and that radio had "no future." However, his resilience in the face of these errors is a testament to the power of determination in scientific pursuit.

Despite these errors, Thomson made significant contributions to physics, particularly in thermodynamics, by developing the second law of thermodynamics and by advancing electromagnetic field theory. His achievements in these areas, along with his excellence in engineering, where he invented the moving magnet galvanometer, the recording siphon, and the harmonic analyzer for predicting tides, provide a balanced understanding of his impact on science and engineering.

3. Student's errors

Numerous studies in science education have focused on the conceptual difficulties that students encounter when solving problems that require the acquisition of basic concepts in physics, chemistry, biology, and other subjects. First, it is important to note that the errors students make in this research are not trivial; instead, they reflect alternative theories and personal, preconceived ideas about the subjects they are learning. These alternative theories, often student-generated explanations of scientific phenomena, significantly differ from the official, accepted ones. This stark difference underscores the urgent need to address these misconceptions [11,35].

The following summarizes the most common mistakes students make in their science classes, based on a global literature review. These missteps correspond to the fallacious ideas that have arisen over time, as explored in the previous section.

3.1. Students' Errors: Force, Movement, Mass, Weight, and Gravity

Numerous studies demonstrate that many students who studied courses dealing with the laws of motion within the framework of Newtonian physics during their secondary and post-secondary education often hold incorrect understandings, despite this teaching [36–40]. The errors most shared by these students are: 1. The motion requires continuous application of force; 2. In the absence of force, the object is at rest; 3. Zero acceleration means zero velocity; 4. The notions of mass and weight are synonymous; 5. On the Moon, there is no gravity, so it is less heavy; 6. Weight is a property of a single object; 7. Weight is the quantity of matter in an object; 8. Velocity is proportional to applied force; 9. Acceleration implies increasing force; 10. A greater Mass implies a greater force; 11. Gravity

Increases as Objects Fall; 12. Motion occurs only when the active force "overcomes" resistance, and it occurs when the force becomes "too weak"; and 13. No motion Implies No Force.

3.2. Students' Errors: Shadow Formation, Light Reflection and Absorption

Researchers have conducted extensive investigations into learners' errors on optical concepts, from primary school to university. A review of academic articles in an international journal reveals that the most prevalent misconceptions among these students concern the formation of shadows, specifically [41,42]: 1. The position of the Sun determines the size of the shadow; 2. The size of our shadow changes during the day as the Sun moves; 3. The size of our shadow also depends on how intense the sunlight is. In addition, many people have misunderstandings regarding the phenomena of light reflection, absorption, and propagation. The most common misconceptions are [43–46]: 1. The glass surface of a mirror reflects light; 2. A mirror reflects all the light that hits its surface 3. A black object absorbs all the light that reaches it; 4. Black-coloured bodies absorb all light rays. 5. Light moves in a straight line before coming to a halt when it encounters a sheet of pristine paper. Mirrors reflect light, but do not absorb it 7. Coloured light gives an object its colour. 8. Color is an inherent property of an object.

3.3. Students' Errors: Electrical Circuits Functionality

In the field of physics, research into students' understanding of the principles of electrical circuit operation is extensive, and several erroneous models have been identified among many students. These misconceptions significantly impact student learning, particularly in explaining the brightness of light bulbs connected in series in simple circuits. The most widely used models that add complexity to the topic are the unipolar [47,48], sequential [49,50], and the weakening current [51,52]. The most frequent errors published in the international literature review related to these models are: 1. If two bulbs are connected in series with a battery and one bulb illuminates while the other doesn't, then the one that does not illuminate is burnt; 2. When one switches the position to "On" to light a bulb whose filament is broken, the electric current still passes through the bulb, demonstrating the predictable behavior of current flow in such a scenario; 3. If the potential difference across a component is zero, then the current is also zero; 4. Voltages flow across resistors and decay along the way; 5. When a circuit composed of a battery and resistors is modified, the current supplied by the battery remains unchanged, providing a secure and constant current because the battery is a constant-current source; 6. The value of resistance of a lamp is proportional to the filament thickness; and 7. The resistor consumes the current through it, so that the current passing through the resistor, it will be decreased.

3.4. Students' Errors: Static Electricity

There is less research on student misconceptions regarding static electricity than on functioning DC electrical circuits [53,54]. The errors identified in most students' work on phenomena related to static electricity [55–60] can be explained by their inadequate understanding of matter at the atomic and particle levels. This highlights the need for further research in this area. Below is a summary of some of the misconceptions identified in this study:

1. The friction between the comb and the hair causes a transfer of protons and neutrons.
2. Friction causes the transfer of either electrons or protons from one object to the other.
3. When we rub hair with a woolen cloth, we charge electrons positively.
4. A previously rubbed party balloon sticks to the wall because the balloon is negatively charged, and the wall is positively charged.
5. Lightning occurs when particles of hot and cold air collide: when warm air rises and meets cold air, it creates a turbulent environment that separates electrical charges. This separation of charges leads to the formation of lightning.

Note that these misconceptions can lead to misunderstandings of the fundamental principles of static electricity, hindering students' ability to grasp more complex physics concepts.

3.5. Students' Errors: Heat and Temperature Concepts

Most studies on students' understanding of heat and temperature often struggle to differentiate between these two concepts [61–64]. It is crucial to address these misconceptions, as they are prevalent among learners. According to these studies, the following are the most prevalent misconceptions:

1. The sensation of cold (or warm) is related to the difference in temperature.
2. Heat is a substance.
3. Temperature is a measure of the degree of coldness or warmth of a substance.
4. There are two types of temperature: cold temperature and hot temperature.
5. Heating always increases temperature.
6. The temperature of an object depends on its heat and not on its kind or size.
7. Cold is the opposite of heat.
8. Temperature is a measure of heat.
9. Temperature is a property of a material: some substances are 'naturally' warmer (e.g., wood) or colder (e.g., metal) than others.
10. Heat can be transferred from one object to another through the sensation of cold.
11. Certain materials attract or absorb cold.
12. As heat, the temperature can be transferred from a hot body to a cold body.
13. Materials such as wood can warm things up.
14. Water's boiling point is dependent on the quantity of water.
15. When we heat a metal, it expands because the particles of metal expand, and at the same time, the distance between the particles increases.

Several of these misconceptions are strongly influenced by everyday language and by many media outlets that provide weather information.

3.6. Students' Errors: Atomic Structure and Particulate Nature of Matter

Students' conceptions about atomic structure [65,66] have received far less attention than those in mechanics, optics, and electrical circuits, even though it is a key concept in physics. This contrast in research attention highlights the need for further exploration in this field. In contrast, the particulate nature of matter has been the subject of extensive research, particularly in chemistry [67–69], demonstrating the depth of knowledge available on this topic, especially regarding the continuity and rupture in the development of atomic theory [70]. The following is a synthesis of the most prevalent ideas among students about the atom concept and the particulate nature of matter, as revealed in various research:

1. The atom is the smallest part, the most minor division of matter.
2. The mass spectrometer, with its remarkable precision, allows us to manipulate and study atoms individually.
3. Therefore, we can understand matter as being composed of these particles, arranged in a specific order; to form the substances we encounter in our daily lives.
4. Atoms of a substance in the solid state cannot move.
5. Atoms are solid spheres, having different sizes and shapes.
6. Electrons, as point particles, move predictably around the nucleus in circular orbits at fixed radii, contributing to the stability of the atom.

4. Discution

As highlighted by research worldwide, these false conceptions should not be dismissed as mere errors, but rather as potential stepping stones towards a more comprehensive understanding of the subject. In this perspective, Students' alternative theories play a pivotal role in learning, significantly shaping how students perceive and interpret new information. It is worth noting that some of the students' errors were also made by renowned researchers.

Thus, recognizing and integrating errors made by well-known scientists into teaching is essential for meaningful science learning, as it acknowledges the significant influence of students' perspectives on the learning process.

Educators play a pivotal role in guiding students through these errors, fostering a sense of responsibility and engagement. They are not just instructors, but mentors who can help students navigate the learning process. Unfortunately, it is a common misconception that errors are a parasite, a failure, or a misunderstanding that is not worth dwelling on. However, errors are not to be eliminated after traditional teaching; they will dissipate when the student confronts their errors with those made by scientists.

Abimbola [6] has already pointed out the problem. He explains that the teacher's conception of error would lie within the model of philosophy of science to which he adheres. If conceptions are a barrier to learning, they are harmful; however, if viewed within an interpretative frame of reference, from which we can anchor the knowledge achieved, they are positive. Moreover, Astolfi [71] suggests the idea of error for mistakes that students recognize as "alternative conceptions", which are essentially misconceptions that students hold before they are taught the correct scientific concepts. This concept is both intriguing and engaging, sparking curiosity and active participation in the learning process. In this perspective, errors are considered a tool for teaching. Seeing errors as symptoms of obstacles facing students' thinking at the heart of the learning process as indicators of conceptual progress to be made, thereby reassuring us about the learning process and the role of errors in it. This understanding can provide a sense of reassurance about the learning process and the role of errors in it.

By recognizing the status of errors and assigning them meaning, science education acknowledges their epistemological foundations and the need to consider them for students to learn meaningful scientific concepts. The significance of errors in student understanding is a grave issue that educators must address. However, the complex and systematic process of bridging the gap between spontaneous and scientific conceptions for students is a challenge that educators must face [72]. Educators must address the significant resistance that students' spontaneous conceptions exhibit when they encounter scientific knowledge. Even those, according to Roth [73], who "have taken several high school courses in physics do not change their ways of talking, leading researchers to suggest that the (mis-, alternative, pre-instructional, prior, naïve, canonical, non-standard) conceptions have persisted.

This resistance has proven to exist even when extraordinary efforts have gone into constructing curricula based on analogies involving leading advocates of the approach in the design." (p. 46). At this stage, the science education community is actively exploring the integration of students' misconceptions into learning arrangements. This approach, pioneered by Piaget [74] (1992) and Vygotsky [75], among others, is rooted in cognitive and social constructivism. It underscores the crucial and intriguing relationship between spontaneous ideas and scientific concepts, a key aspect of this approach. Their works, inspired by the constructivist approach, highlight the active role of the learner in building knowledge and developing the intellectual tools necessary for understanding scientific concepts, thereby engaging the audience and encouraging their participation.

5. Conclusion and Didactical Impact

From the didactic perspective, science teaching should not be limited to teaching today's science by wiping the slate clean of theories abandoned following scientific revolutions in the sense of Kuhn [12]. Instead, the rich history of science should be the foundation of science teaching, enlightening us about today's science and the prevalence of students' naive theories despite formal teaching. According to Sudre [76], on science education, it is crucial to show students "science in its beginnings, humble, groping and full of errors, instead of revealing it completed and imposing, in this great decor of order and abstraction which discourages the apprentice. The path seems longer, but its slope is gentler." (p.8)

By studying the historical development of science, students not only enhance their understanding of the subject but also make it more relatable and accessible. They can appreciate the long, arduous journey of science, with its many setbacks and successes, that brought it to its current state. This collaborative effort, in which researchers build on each other's findings, exemplifies the ever-evolving, never-ending nature of science [77].

The historical approach will inspire us to value students' false conceptions, as several researchers have observed a reassuring parallelism between students' conceptions and those developed throughout history, which have been abandoned [78]. This emphasis on valuing students' false conceptions will make educators feel empathetic and understanding, fostering a more supportive learning environment. It also underscores the importance of the educator's role in the learning process, making them feel integral and important to the students' understanding of science. Such an approach, when embraced, will transform the school context, making adequate teacher training in the history of science in science teaching mandatory. It should be noted in this regard that in the training program of the Quebec school in Canada, teachers are encouraged to address historical considerations in their teaching with their students, which very few teachers do because of their gaps in this area.

Regarding pedagogy, science education should not only focus on imparting current scientific knowledge but also on understanding the historical perspective. As underlined in the theoretical framework, many distinguished scientists argue that the history of science should form the basis of science teaching. Let us recall in this regard that the history of science allows us to know how scientific knowledge has evolved, highlighting the research processes, debates, errors, and successes that have shaped our current understanding of the world. This historical perspective, which involves learning about the discoveries and theories of early scientists like Galileo and Newton, is equally important in shaping our present scientific ideas. It is also a powerful tool, convincing us of the need for its balanced inclusion in science education to address the persistence of students' misconceptions despite formal instruction, and garnering our support for this approach.

By exploring the historical construction of science, students gain a profound understanding of its development from its early, tentative stages, often riddled with errors, to its current state. This understanding is not just a historical curiosity, but a key to unlocking the deeper principles of science. This approach, though time-consuming, provides students with a less daunting learning environment in which they can see that even the most outstanding scientists make errors. Such a study fosters a deeper appreciation for the subject and can help in building students' resilience and perseverance in the face of scientific challenges.

Furthermore, incorporating a historical perspective not only allows educators to acknowledge students' misunderstandings but also empowers them to address these misconceptions effectively. Research has shown similarities between students' conceptions and the theories that were once widely accepted but have since been discarded. However, this method can only be effectively implemented in schools with proper teacher training. It is crucial to integrate the history of science into science education, as it gives educators the tools they need to make a significant impact on their students' learning, underscoring their responsibility and influence in the process.

Worldwide, scientists have underscored the importance of incorporating historical context in teaching biology, physics, chemistry, and medical science at university levels to study the errors made in research that contributed to the development of science and technology. This global consensus, to which we all contribute, underscores the importance of our role as educators in shaping the future of science education. Unfortunately, many educators from elementary school to the university do not follow this guidance due to a lack of knowledge [30].

To promote students' alternative theories, it is crucial for educators to guide them in understanding and confronting false theories developed by renowned scientists, such as those summarized in Section 2. Equally important to study with students the unfinished theories that we

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have not analyzed in this research, as corpuscular theory of light postulated by Newton considering, light as a stream of particles did not explain could not explain phenomena such as diffraction, where light bends around obstacles, or interference, where light waves combine to create interference patterns or even the motion Newton's laws which could not explain the motion of bodies moving at speeds close to light. To explain such movement we must refer to Einstein's theory of special relativity.

These studies should be done using references found in books dealing with the history of science, and also by consulting the documents written by scientists on their work. This approach empowers educators with a wealth of resources that are not commonly found in science textbooks, making them feel integral and influential in the learning process.

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