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Contrasting biology and physics in science education: Emphasizing the central role of evolution in teaching

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Abstract
This work aims to constructively use the differences between physics, as a typical representative branch of science, and biology, to enhance science education. It advocates for the use of a common science, technology, engineering, and mathematics teaching framework as a pedagogical tool for conveying concepts related to the epistemology of these two disciplines, highlighting their epistemological distinctions. Notable disparities include the absence of "universal" laws in biology, combined with the presence of a unifying theory in its instruction. Additionally, the differing roles of experimentation, mathematics, and history in these fields are examined. The text also addresses the distinction between the concepts of "social implications" and "social science," alongside a discussion of essentialism in physics compared to the non-typological "population perspective" in biology, where the constant interplay of random errors and mutations serves as the universal driving force behind all biological phenomena.

Keywords: differences, physics/biology, didactics, NOS

INTRODUCTION: THEORETICAL BACKGROUND

In recent years, there has been an increasingly prevalent perspective in the teaching of science in order to teach the latter under a common umbrella, that of STEM. The same perspective was previously proposed in the context of the AAAS (1990) "Project, 2061" program. The present work is a proposal that reinforces such a perspective, arguing that the knowledge and understanding of the differences between science (mainly physics), in one hand, and biological sciences (BS), on the other, can be a tool for their joint comparative teaching (Allchin, 2011; Clough, 2006).

Diversity in Teaching: The Existence of a Unified Theory in Biology

The theory of evolution by natural selection (ThENS) serves as the integrative theory of biology (Ross, 1984). It is pertinent to every facet of BS, illustrating the connections between various functions, structures, and fields of biology that might otherwise appear unrelated. Consequently, it unifies the field of biology and is recognized as its central unifying theory, capable of simultaneously explaining both the diversity and unity of life. In a previous paper, we explored the implications of teaching biology through the lens of evolution as a "unifying theory" and highlighted the benefits of such an approach (Athanasiou, 2015, 2022).

The distinction when comparing this to the teaching of physics is noteworthy: theoretical physicists have yet to establish a widely accepted, coherent theory that reconciles general relativity with quantum mechanics to formulate a theory of everything. The discord between these two theories poses a significant challenge in the field of physics. Even should a resolution be found, the difference lies in the fact that in biology, this teaching perspective is essential and universally applicable, whereas in physics, it may represent merely an alternative approach (National Association of Biology Teachers, 1995).

The existence and non-existence of laws

In science, theory and law are two different concepts that are connected but not identical.

1. **Law:** A law describes a phenomenon that is consistently observed in nature, without necessarily explaining the "why". Natural laws

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Contribution to the literature

- The study contributes to science education research by proposing a comparating epistemological framework that contrasts Physics and Biology to enhance teaching about the NOS.
- The study suggests how diffrrences in laws, experimentation,mathematics, and historical reasoning can be transformed into pedagogical resources.
- The study also offers practical implications for classroom implementation, linking epistemology with instruction design.

are usually mathematical formulas or simple statements that have been confirmed through observations and experiments (e.g., Newton's law of gravity).

2. **Theory:** A theory is a more comprehensive scientific explanation that includes the causes and mechanisms behind a phenomenon. Theories are based on data, observations, and experiments, and are flexible to evolve as we gain more knowledge (e.g., Einstein's, 1934 theory of general relativity). Therefore, a theory can offer an "interpretation" of a law or explain the phenomena that the law describes, but it is not simply its interpretation. It is more general and includes a framework for understanding the world more deeply.

The model of the scientific method derived from science and physics, gives the impression that the goal of science is to create "laws" (e.g., Newton's and Kepler's statements about general and planetary motion, respectively). Laws, in this sense, are statements about an event that has been proven to include all known cases. Biologists have at times suffered from a desire to imitate physics by enacting laws (e.g., Ernst Haeckel's biogenetic law that "ontogenesis recapitulates phylogeny") (Renard, 1981). However, the historical element and inherent variability of biological systems make such universal statements impossible (Mayr, 1982). BS advances by developing general concepts that are used to guide our approach to specific phenomena. Natural selection is an example of such a concept, and, while some have discussed the case of a law it is simply a typical generalization about the interactions between the environment, organisms, and the genotypes of those organisms in terms of the impact of these interactions on genotypic frequencies (Gould, 1981a). Official generalizations of biology always include exceptions that "confirm the rule" and may lead to the modification and clarification of concepts over time.

The role of the experiment: Similarities-differences

Of course, there have been, in the past, scientists and philosophers of biology who argued that the cell theory (CTh) is not a *theory* in the strict sense, since it does not possess universal application in the strong, exceptionless sense required by some accounts of scientific laws (e.g., Ponce, 2018; Sober, 2018). Specifically, the first cells that appeared on Earth did not satisfy the central condition *omne vivum ex vivo* (all life from life), because the earliest living cells must have arisen from inorganic or prebiotic matter through processes of abiogenesis (Harris, 1999; Miller & Urey, 1959; Oparin, 1938).

For cases like this, we suggest that the Duhem and Wiener (1982) principle applies: the validity of a scientific theory is not refuted when one of its subordinate propositions can be corrected or restricted without undermining the overall theoretical framework. In the case of CTh, its universality can be preserved if we explicitly qualify the principle as follows: *"All living cells arise from pre-existing living cells, except for the first living cells that appeared on Earth through abiotic processes."* This modification maintains the explanatory power of the theory while acknowledging the unique historical exception inherent in the origin of life.

Additionally, we may refer to Gould (1981b), who formulated the thesis that "data and theories are different things, not steps in a hierarchy of increasing certainty. Data are the information of the world; theories are structures of ideas that explain and interpret data" (quoted in Sosa et al., 2008). This distinction is relevant to the status of the CTh: although it contains empirical generalizations, its primary function is to provide a unifying explanatory framework for understanding living organisms in terms of their cellular organization. In this sense, CTh operates as a robust theoretical structure that integrates diverse biological observations, even if one of its propositions requires historical qualification (Schäfer, 1897; Wolpert, 1996).

Physics, Biology, and Mathematics

In the past, "scientific" was considered only some field that included mathematical interpretations, while their scientific characters of research practices were evaluated based on the degree of affinity with the language of mathematics. Mayr (1976, 2004) refers to the mathematician Jacob Bronowski as the proponent of the view that based on the content in mathematics, "true science is physics, followed by chemistry, then biology, followed by economics, and then by social sciences." The introduction of mathematical logic in combination with experimental practice were the main factors that led to the discovery and formulation of the laws of physics. That is, of the world's principles that govern the functioning of the world. According to Galileo, "the book of nature is written in the language of mathematics." A language of perfection governed by universal, stable and unalterable laws that have no exceptions. Newton's contribution was nothing more than the transfer of these laws to the world sphere (Einstein, 1934).

Essentialism and Teleological-Deterministic Logic

According to Mayr (1976), in the world of science (especially physics), we have a reformulation of Plato's ideas in another form: The discovery of universal laws that govern the functioning of the universe are principles that reflect the perfection of the world of ideas, i.e., we have Essentialism in practice. The only truth of the natural world is the truth of essentialism. That is why Whitehead (from Mayr, 1976) asserts that "the entire European philosophical tradition is nothing more than a footnote to Plato's work." In other words, the world of physics and astronomy is a world of perfect and stable structures (typology). A world governed by essentialism and teleological-deterministic logic. A world that comes into perfect antinomy with Darwin's world, which is the world of population-thinking, of non-typological, non-teleological perception and perspective (Gould, 2002; Mayr, 1982). A world in which errors in the genetic material, as constantly and universally occurring events (mutations) constitute the cornerstone on which the ThENS process acts (Hanscom & McVey, 2020).

Biology (and) as a social science

The comparative teaching of the two disciplines (physics/biology) can help the student to perceive the difference between the concepts: The *social* contribution of a science, on the one hand, and the concept *social science,* on the other. For example, a few years ago the scientific community was all against the use of nuclear reactors (NR), as well as the use of mutant organisms. Today, after global warming, the whole issue is being reformulated on a new basis, and there are more and more voices in the scientific community advocating the use of NR. The two examples concern the social role of science. However, the criterion of whether a science or a branch of it can be considered as "social science" or whether it is exclusively included in the science is something completely different and related to the tools it uses. That is, the mathematics/experiment in science (Gavroglou, 2003) in contrast to the historical study of the fossils in the foundation of the ThENS that we find in biology (Loewe & Hill, 2010).

EDUCATIONAL OUTCOMES

Teaching Biology Through Evolution as a Unifying Theory

Teaching biology through the lens of ThENS is not merely a philosophical preference; it is a pedagogical necessity rooted in the very character of the discipline. As noted by the National Association of Biology Teachers (1995), the integration of evolution into biology education is a "one-way street." Fragmented or postponed treatment of evolutionary theory risks producing scientific misunderstanding and biological illiteracy.

By adopting this strategy, teachers align their instruction with the structure of biological knowledge, promote meaningful learning, and cultivate students' ability to think biologically.

To support conceptual integration and authentic scientific understanding, biology teachers are encouraged to adopt a teaching strategy that positions the *ThENS* as the central organizing principle of the biology curriculum. This approach is not simply an alternative instructional method; it reflects the very structure and epistemology of the BS.

Implementation Strategy

Curriculum reordering

Restructure the sequence of instruction to begin with evolution, not as a concluding chapter, but as the foundation. Begin with core evolutionary concepts such as common ancestry, natural selection, variation, and descent with modification.

- **Example:** *Use evolution-based textbooks or re-sequencing activities:* Compare textbooks that open with evolution as a framing theme, such as *Campbell biology* (12th edition), where chapter 1 introduces "evolution, the themes of biology, and scientific inquiry."
- Alternatively, another approach is to use curricular re-sequencing: insert educators can integrate explicit evolutionary connections throughout the curriculum, rather than relying on when using traditional textbooks that isolate evolution as a final topic.

Thematic integration

In the field of genetics, it is essential to highlight how mutation, recombination, and selection drive changes at the population level. An illustrative example can be found in the work of Athanasiou (2022), where first-year Education students participated in an introductory course centered around evolution as a unifying framework. Accordingly, chapters on genetics, DNA, and classification were taught as processes influenced or driven by these evolutionary principles. Specifically, the chapter on genetics was presented as a teaching module aimed at explaining the emergence of *b-thalassemia* carriers in Mediterranean countries like Greece. This phenomenon, as established in previous studies (Flint et al., 1986), is rooted in the dynamics of natural selection.

In **physiology and anatomy:** use comparative anatomy to explain functional adaptations.

A teaching example

We have proposed a teaching intervention aimed at instructing students on the anatomy and physiology of the nervous system by exploring its evolution from protozoans to humans, particularly in a class that has not been previously exposed to this material (Athanasiou & Petromelidis, 2020). The main question posed to the students focused on the emergence of enhanced spatial memory in polygamous rodents and whether this trait, specifically the larger hippocampus—an area of the vertebrate brain associated with increased spatial demands—could be inherited (Jacobs et al., 1990). Following the teaching intervention, most students concluded that the enlargement of the hippocampus in taxi drivers is an acquired characteristic linked to their profession, rather than an inherited trait. They seem to overlook the idea that the development of larger hippocampi in these rodents results from random genetic mutations that, through the process of natural selection, favored the survival of individuals with larger hippocampi in species and sexes that faced greater spatial memory demands.

Assessment alignment

Design formative and summative assessments that require students to apply evolutionary reasoning—not just recall facts. For example, ask students to explain why certain traits persist in populations or predict outcomes of environmental changes using natural selection principles.

Didactic Examples: Comparative Pedagogical Applications

To meaningfully convey the differences in scientific reasoning between physics and biology, a comparative approach in the classroom can be particularly effective. The use of carefully selected historical examples—Galileo's experiments on motion and Mendel's (1866) work on heredity—provides an ideal framework for illustrating the epistemological and methodological contrasts between the two disciplines.

Galileo's Experiments: Universality and Mathematical Idealization

Galileo's investigations into the motion of falling bodies, whether through the legendary experiment from the Tower of Pisa or his inclined plane trials, epitomize the deductive and mathematical character of physics. From his observations, he derived a general law of uniformly accelerated motion, where all objects, regardless of mass, reach the surface of earth with the same acceleration: [= 9.8 m/s^2] and a velocity of [$v = gt$].

This mathematical expression encapsulates a universal principle: under ideal conditions, all bodies fall at the same rate regardless of mass. The experiment is abstract, repeatable, and intentionally stripped of historical or contextual detail. It exemplifies the physicist's essentialist goal of uncovering timeless, invariant laws of nature through idealized experimentation and mathematical formulation (Ruse, 2009).

Pedagogical implication: Students are introduced to the idea that, in physics, scientific knowledge often emerges from theoretical abstraction and mathematical reasoning. Controlled experiments are designed not to capture the variability of the real world, but to isolate and reveal underlying universal principles (Franklin, 1999, 2005).

Mendel's (1866) Experiments: Biological Patterns in Variation

By contrast, Mendel's (1866) experiments with pea plants illustrate a profoundly different scientific logic. Through meticulous counting of phenotypic traits across successive generations, Mendel (1866) identified regular statistical patterns—such as the 3:1 ratio of dominant to recessive traits—which led to the formulation of the laws of inheritance. Unlike Galileo's law, Mendel's (1866) findings are probabilistic and apply to populations rather than individual cases.

Mendel's (1866) methodology did include measurement, but the nature of that measurement—focused on counting and comparing frequencies—reflected the inherent variability and complexity of biological systems. His conclusions were not universal laws in the physical sense, but generalizations that describe tendencies within populations.

Pedagogical implication: Students should understand that in biology, variation is not a source of error but a fundamental aspect of the system. The scientific method here relies on statistical reasoning and population-level inference, rather than deterministic laws. This approach helps them appreciate the historical and contingent nature of biological explanation.

Historical Evidence: Fossils and Karyotypes in Biology

Another pedagogically valuable contrast lies in the type of evidence used in each science. In physics, experiments are typically replicable and predictive. In biology, however, many phenomena are accessible only through historical data. The study of fossils, for instance, or the analysis of karyotypes, provides insight into evolutionary processes that cannot be experimentally repeated. Such evidence is historical, and biological explanations often involve reconstructing past events based on present traces.

Pedagogical implication: This invites a broader understanding of scientific evidence. Students are encouraged to view biology as a science where narrative and historical reasoning are central, complementing their understanding of physics as a science of abstract universals.

Classroom Implementation: Integrating Comparisons

These examples can be integrated into classroom practice through the following strategies:

- **Parallel activities:** Have students perform simplified versions of Galileo's inclined plane experiment and Mendelian trait counting using simulated data sets.
- **Comparative discussion:** Facilitate reflection on how mathematics is used differently in each discipline: deductively to derive laws in physics, and statistically to reveal patterns in biology.
- **Evidence analysis:** Present fossil records or karyotype charts as forms of historical evidence, encouraging students to think about how time and variation play roles in biological understanding.
- **Epistemological framing:** Explicitly contrast *essentialist* reasoning in physics with *population thinking* in biology, helping students appreciate how different sciences construct and validate knowledge.

Through such a comparative pedagogical approach, students develop a deeper, more differentiated understanding of scientific reasoning. Rather than treating Science as a uniform method or body of knowledge, they are invited to recognize its internal diversity—its different languages, logics, and modes of inquiry (Driver et al., 2000; Hacking, 1983).

Verifiability vs. Falsifiability in Scientific Reasoning

To help students grasp the contrasting epistemological foundations of physics and biology, we propose a classroom activity centered on two core concepts: *verification* and *falsifiability*. The goal is for students to recognize that while both are valid scientific methods, they function differently depending on the nature of the phenomena and the type of generalizations sought in each discipline (Pantin, 1968).

Teaching verifiability through Newton's inductive-deductive method

Begin with a lesson on *Newtonian physics*, focusing on how scientific theories are developed through *observation*, *experiment*, and *logical deduction*. Present Newton's *second law of motion* (F = ma) as an example of a theory that has been verified countless times through controlled experiments. Guide students through a basic experimental setup where they vary mass and force using carts and weights and record the resulting accelerations. Their data should confirm mathematical prediction, reinforcing the process of theory verification through empirical testing (Matthews, 1994).

Key message: In physics, theories are often expressed mathematically and verified through repeatable, controlled experiments. This builds confidence in their universal applicability.

Teaching falsifiability through the theory of evolution by natural selection

Transition to biology by presenting the ThENS as a theory grounded in historical and population-level evidence. Rather than focusing on prediction in the same sense as physics, evolutionary biology gains strength by surviving repeated attempts at falsification.

Introduce the famous quote by J. B. S. Haldane, who stated that (the discovery of) a *"fossil rabbit in the Precambrian"* would falsify the theory of evolution (quoted from Dawkins, 2009). Discuss what this implies: that evolution is scientific not because it is endlessly confirmed, but because the core theory has never been refuted, despite over 160 years of testing. This is a key feature of *Popperian falsifiability*. Provide students with a simplified geological timeline and fossil record so they can reason through why such a finding would contradict everything we know about evolutionary history (Lakatos, 1970; Popper, 1959).

Key message: In biology, theories gain strength by remaining open to falsification. Their credibility increases not through absolute certainty, but through their ability to withstand potential refutation by new evidence.

Classroom activity: Compare and reflect

Divide students into small groups and assign each the task of:

- Describing the logic of verification (physics) or falsifiability (biology),
- Giving an example of a theory that uses each approach, and
- Explaining the strengths and limitations of each method.

Conclude with a class discussion reflecting on how these methods shape the different ways scientific knowledge is built and justified in each field.

Pedagogical objective: This intervention encourages metacognitive awareness of science as a pluralistic endeavor. It equips students not only with knowledge of content but with a critical understanding of scientific methodology, enhancing their scientific literacy and reasoning.

Implications for Science Education: Nature of Science and the Diversity of Scientific Methods

The comparative approach outlined above not only helps students differentiate between scientific disciplines but also serves broader educational goals. Two key outcomes of this method are:

Promoting understanding of the nature of science

By engaging students with historical and disciplinary examples—such as Newton's laws in physics and Darwinian evolution in biology, they are exposed to how scientific knowledge is constructed, justified, and evolved. This supports a deeper understanding of the nature of science (NOS) as a human, creative, and context-dependent enterprise (Lederman, 1992, 2007).

In this way, the students may realize that:

- Scientific theories are not absolute truths, but models that explain the world within certain limits.
- The standards of evidence and reasoning vary across disciplines.
- Scientific knowledge is both empirical and theoretical, shaped by experimentation, historical data, and conceptual frameworks.

In other words, the didactic usefulness of comparative teaching lies in showing that NOS is not a single thing, but a collection of evolving ideas and practices that reflect the diversity of scientific inquiry (Antonatou et al., 2024).

Challenging the myth of a single "scientific method"

The conventional depiction of a rigid, step-by-step "scientific method" is pedagogically limiting and epistemologically inaccurate. Through the comparison between verification in physics and falsifiability in biology, students begin to see that no single methodology can capture the full range of scientific practices.

In the classroom:

- Students working on Newtonian experiments follow a clear path of hypothesis → prediction → experiment → confirmation.
- When exploring evolutionary biology, students must reason from historical evidence, accept uncertainty, and engage with probabilistic models rather than deterministic laws.

This comparison powerfully illustrates that "there is no single scientific method, but many scientific methods, each adapted to the questions and phenomena of its domain." This insight fosters a more authentic view of science, encouraging students to approach knowledge with flexibility, critical thinking, and epistemic humility.

Conclusion of section: A comparative teaching approach—by highlighting methodological diversity, historical context, and conceptual differences—acts as a vehicle for students to better understand how science works, not just what science knows. It demystifies science without devaluing it, replacing rigid formulas with dynamic reasoning tailored to each discipline's nature.

PEDAGOGICAL IMPLICATIONS: MOVING FROM COMPARISON TO PRACTICE

A comparative approach to teaching science—highlighting the epistemological distinctiveness of disciplines like physics and biology—can do more than enhance content understanding. It offers a pathway toward cultivating a deeper, more authentic grasp of how science works. When students engage with the contrasting logics of essentialist, law-driven reasoning in physics and the historical, population-based reasoning in biology, they are exposed to the plurality of scientific thought processes and methodologies.

Rather than presenting science as a monolith governed by a single, linear method, this approach emphasizes the diversity of scientific inquiry. Physics often privileges control experimentation and mathematical deduction, while biology embraces probabilistic reasoning, historical contingency, and falsifiability—especially in the context of evolution. Presenting these as complementary rather than competing modes of inquiry helps displace the myth of a universal scientific method.

Two key educational goals are advanced by this strategy:

- **Fostering NOS understanding:** Students learn that science is not merely a collection of static facts, but a dynamic, context-sensitive enterprise shaped by both empirical rigor and theoretical innovation. They begin to see how knowledge is constructed differently across domains—sometimes through idealization, other times through interpretation and revision.
- **Developing epistemological sophistication:** Exposing students to methodological and conceptual diversity prepares them to engage with scientific issues critically and flexibly. This is especially important in an era where scientific literacy must encompass the ability to evaluate claims across fields ranging from climate science to genetics.

To translate this framework into classroom practice, educators might consider integrating cross-disciplinary case studies (e.g., Newtonian mechanics alongside Mendelian genetics), explicitly discussing how different sciences define "evidence," or encouraging students to reflect on the kinds of questions each discipline is best suited to answer.

Ultimately, by teaching students to compare rather than homogenize scientific disciplines, we not only foster deeper understanding but also equip them with the intellectual tools needed to navigate the increasingly complex scientific and societal challenges of the 21st century (Athanasiou et al. 2016).

CONCLUSIONS

These comparative examples do more than illustrate differences in scientific content; they illuminate fundamentally distinct worldviews—one characterized by abstraction, universality, and mathematical idealization (physics), the other by contingency, variability, and historical reasoning (biology). By making these contrasts explicit, science educators can cultivate deeper epistemological awareness and critical thinking in students. Such pedagogical strategies promote an understanding of science not as a monolithic method, but as a diverse, evolving set of practices tailored to different domains of inquiry. This kind of approach may prepare students to develop a higher commitment to the complexities of scientific knowledge and its implications in contemporary life.

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