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SI: NATURE OF SCIENCE

Towards a Refined Depiction of Nature of Science

Applications to Physics Education

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Abstract
This study considers the short list of Nature of Science (NOS) features frequently published and widely known in the science education discourse. It is argued that these features were oversimplified and a refinement of the claims may enrich or sometimes reverse them. The analysis shows the need to address the range of variation in each particular aspect of NOS and to illustrate these variations with actual events from the history of science in order to adequately present the subject. Another implication of the proposal is the highlighting of the central role of science educators who, facing various strong claims of researchers in education and philosophy of science, often have difficulty in making a choice of what to teach about NOS. It is suggested that a representative variation with regard to the traditional NOS claims may be appropriate for a genuine understanding of the subject. In that, using the discipline-culture structure of the fundamental theories of physics and addressing the plurality of scientific methods may be helpful in the actual teaching and learning of NOS.

Keywords Nature of science · Context of science education · Conceptual variation · Discipline-culture · Science epistemology and method

> *Everything should be made as simple as possible, but not simpler.*
> *Albert Einstein*
> *The truth is never univocal*
> *Andrei Sakharov*

1 Introduction

Clarifying the nature of scientific knowledge is a matter of special interest in educational research. Schwab (1978) and Shulman (1986) considered scientific knowledge as a

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curricular subject and pointed to its two major aspects—conceptual and methodological foundations (*substantive* and *syntactic* knowledge). The former obliges the educator to specify the major concepts and the latter defined the ways in which truth-falsehood and validity-invalidity are established. Considering these aspects in education has eventually produced a discourse described as Nature of Science (NOS). Describing NOS implies addressing the conceptual structure of disciplinary knowledge (content knowledge) and the methods of knowledge construction, a special type of inquiry which makes possible objective knowledge about nature, determines its features, the status of its elements, and their validity and reliability. Both aspects are inherently interwoven (Popper 1962; Lakatos 1980). The complexity of the subject stems from the fact that teaching science requires competence in several dimensions of contribution from independent disciplines (Fig. 1).

It is widely recognized that NOS enters the area of education each time a teacher asks him/herself "What kind of knowledge does science represent?," "What knowledge is considered to be scientific?," and "How should one present this knowledge in regular teaching?" Each of the disciplines in Fig. 1 provides a specific answer to these questions. Science educators, therefore, attain a unique role to be recognized, first of all, by themselves. They are challenged by the need to synthesize different aspects of knowledge posed by various disciplines. The question arises as to how to meet this challenge.

Vygotsky (1934/1986) provided a clue which may help. Scientific knowledge represents a particular culture, and there are two ways to learn a culture—from inside and from outside. Scientists perform specific, long-term, comprehensive, never fully accomplished studies, continuously raising new questions. They learn the NOS *from inside* throughout their professional lives. In contrast, introductory science education seeks the knowledge of the same subject *from the outside*. In school classes, we undertake short-term teaching activities combining the holistic with the selected specific perspectives. The knowledge of a novice is normally superficial, fragmental, selectively deep, pragmatic, and lacking a holistic view of science. Vygotsky represented the difference between learning from inside and from outside through contrasting learning to one's mother tongue, as opposed to learning a foreign language (pp. 190–208). In exact similarity, students experience difficulty with constructing knowledge of the general features of science and scientific method, which are seldom explicitly addressed in

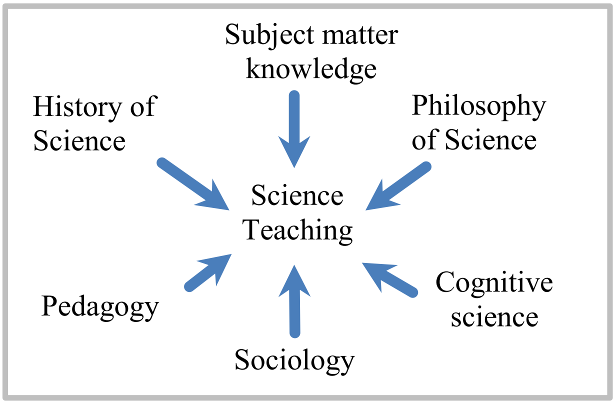

Fig. 1 Areas of competence required from science educators to comprehend and teach the features of NOS

regular teaching.[1] Science educators need the specific content of NOS knowledge to support an initial view of the subject matter from *the outside*. This implies clear and distinct statements on behalf of the teacher, rather than drawing on discoveries by students and their investigation of numerous fields. In our perception, the requirement is to enrich students' *disciplinary* knowledge of science with respect to its nature, while refraining from dragging them away to other fields, given the often very limited curricular slot devoted to learning science.

It seems plausible that the meaningful learning of science requires addressing the status of scientific theories, laws, models, principles, and experiments—constructs unavoidable in science classes (e.g., Berry & Friedrichsen, Berry et al. 2015). Such learning implies addressing history and philosophy of science (HPS) as recognized in several basic documents[2] (Matthews 1994/2015). In reality however, even basic knowledge of HPS is often lacking in teacher training programs,[3] pushing teachers to reinvent the fundamentals—which in turn provides a shaky ground for reaching genuine understanding.

Unlike the content-knowledge possessing clear standards of being correct and false, the features of NOS (epistemology and methods) emerge in a range of variation often including opposite claims, different ideas, and various methodologies. These variants often puzzle teachers (Clough and Olson 2004; Clough 2007). The challenge thus is twofold: first, with respect to the normative features that should be taught and, second, regarding the way of how to teach them (e.g., Duschl and Grandy 2013). In this article, we mainly consider the first aspect—the normative features of NOS, their clarification as required before teaching.

Being faced with a great number of relevant publications we were attracted by a short well-known list of NOS features introduced by Norman Lederman and his collaborators (Lederman et al. 1998, 2002, Lederman 2006, 2007, Lederman et al. 2004, 2015).[4,5] Through its analysis, we hereby present our views on the subject. The L-list is often regarded as a "consensus view" despite strong criticisms on theoretical grounds (e.g., Osborne et al. 2003; Matthews 2012; Kampourakis 2016; Wallace 2017). As such, it is frequently used in many studies addressing school practices and is cited in numerous studies, somewhat modified and moderated (e.g., McComas 1998; Niaz 2009; Abd-El-Khalick 2012; Duschl and Grandy 2013). As I intend to show in this study, the L-list deconstructed the traditional image of science (e.g., Merton 1973) and of scientific method (e.g., Hempel 1966, 1983), thus presenting a strong shift and challenge. Yet, the L-list is the only account of NOS in the *Encyclopedia of Science Education* (Gunstone 2015), as if justifying the status of the consensus view.

This study aims to contribute to the same dialog around the L-list of tenets. In our vision, a compact presentation of NOS features is not only valuable but essential for science education in practical aspects. Our view shares the items of the L-list; yet, we often disagree with the particular

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[1] The problem is that the science curriculum normally skips over the epistemology of science and does not elaborate on the difference between syntactic and substantive knowledge. The pivotal role of philosophy of science in science education often remains in shade (Tseitlin & Galili 2006).

[2] These are, for example, AAAS (1993)—Benchmarks for science literacy; NRC (1996)—National Science Education Standards; NSTA (2000)—National Science Teachers Association position statement.

[3] This is often the situation in many countries. Kampourakis (2017) pointed to the problem in a wider scope including faculty members in science departments.

[4] There is some similarity of the considered list to the list published in the past by Kimbal (1968). Erduran and Dagher (2014) mentioned other lists containing similar features. The list by Lederman and colleagues has been promoted since 1998 (Abd-El-Khalick, Bell, Lederman 1998).

[5] We coded them as L1-L5: L1—for Lederman et al. 2002; L2—for Lederman 2006; L3—for Lederman 2007; L4—Lederman et al. 2014; and L5—Lederman et al. 2015.

claims in it. Our analysis often draws on the specific theoretical platform of discipline-culture (Tseitlin and Galili 2005, Galili 2017) when addressing the epistemological foundations of scientific knowledge, its structure, and the meaning of its components (theories, principles, laws, models). While we do not neglect practical aspects of science, we do ascribe a central role to providing students with meaning and status of scientific constructs, the structure of scientific knowledge, and its epistemology.[6] We believe that this content should be explicit in science curricula rather than ignored and left for discovery by teachers and students. We believe that a compact account which could help teachers construct a more representative image of NOS could be reached through a refinement of the tenets of the L-list, its elaboration and modification. Based on such a refinement, one may proceed to the ways of teaching NOS, which will vary in accordance with the level and goals of instruction. We briefly address possible implications to teaching.

2 Refinement of the Problem

At first glance, science teaching can be considered an applied science, nourished by other disciplines. Schwab (1978) asked his famous “Who knows?” in relation to the structure of the disciplinary curriculum. He answered “Nobody,” pointing to the enormous variety of parameters in considering substantive and syntactic disciplinary knowledge. After years of study, science teaching may progress beyond this negation. Numerous bright minds from the distant and recent past have held very different, sometimes contradictory, views on science thus presenting a “deep truth” about its nature requiring complementarity (Bohr 1949, pp.199–241).[7] They are often cited in pairs: Aristotle-Plato, Descartes-Bacon, Galileo-Newton, for example (e.g., Losee 1993). Almost every one of these luminary figures presented a certain facet of science which was often problematic to adopt if taken univocally and literally.[8] Similarly, psychologists Piaget, Skinner, Vygotsky, and others have provided cognitive perspectives with apparently contradictory curricular implications. Educational experience testifies to the fact that teachers may need to draw on all of these approaches in making pedagogical decisions in each educational context (Clough et al. 2009).

Science practitioners may express views dependent on the area of their expertise which vary tremendously, drawing on their specific experience, interest, success, and failure. HPS was normally not a requirement of their training as students. Hence, episodic interviews on NOS

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[6] A clear complementarity of the two approaches to scientific knowledge—the worldview versus the practical importance—has accompanied science from its dawn (e.g., Matthews 2009). For a striking example, one may compare the intentions of Newton (1686/2016) expressed in his Preface to the *Principia* with its Marxist analysis by Hessen (1933). This opposition is permanently observed in science education: holistic conceptual understanding versus practical problem-solving; theory-based (“worldview”) versus modeling-based (“practical science”) curricula orientation; nominal versus operational concept definitions and so on.

[7] Bohr chose the claim “opposites are complementary” for his coat of arm. Since the Renaissance, complementarity has become emblematic of science (Galili 2013).

[8] Literal understanding may mislead regarding NOS. “Anything goes” by Feyerabend (1993, p. 241) in his “against method” critique does not mean a lack of any methodology. “How the Laws of Physics Lie” by Cartwright (1983) does not mean that physics laws are untrue. “Science without laws” by Giere (1988) does not presume that one may manage without laws. A close view in each case shows that they should be understood in a specific way. For instance, van Fraassen (1980, pp. 8, 12) defined scientific knowledge as *anti-realistic* (being empirically verified but not literally true). Scientists often disagree with the label “anti-realist,” and they often agree with constructive materialism when introduced to its claim. The difference between conceptual and material realisms is often not known to science teachers for whom the claim of scientists as being anti-realistic presents an oxymoron.

with practitioners of science may provide biased information regarding the holistic image of science[9] (e.g., Wong and Hodson 2009, 2010). Yet, highly valuable information was provided by prominent scientists who analyzed scientific knowledge and its methodology—Galileo, Descartes, Newton, Duhem, Einstein, Bohr, Heisenberg, Weinberg, to name a few.

Faced with this variety, it is upon science educators to recognize the range of argumentation around the univocal claims with respect to epistemological issues. We argue for the refinement in this sense. Variation of perspectives and conceptual width does not, however, exclude considering certain features as central and justifying a certain preference while preserving the range.

The scope of this study does not expand beyond the natural sciences. We contextualize our claims in physics and chemistry. This approach is justified by the increasing complexity of the systems dealt with by the disciplines of the natural sciences (the number of irreducible components and factors of influence; Schwab 1978). It is within this perspective that the following considerations arise.

3 Refinement of the NOS Features

3.1 The Feature of Objectivity

3.1.1 Objectivity Versus Subjectivity

The first and most problematic feature of science to consider is the claim of the subjectivity of scientific knowledge.[10] This claim initially appeared in L1 in the form “The theory-laden nature of scientific knowledge.” Yet, in L2 and later, it appeared as “Scientific knowledge is subjective *and* theory laden,” bringing subjectivity to the fore:

> …scientific knowledge is subjective and/or theory-laden. Scientists’ theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations actually influence their work. All these background factors form a *mind-set* that *affects* the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), and how they make sense of, or interpret their observations. (Lederman 2007, p.834)

> Scientific knowledge, owing to (based on) scientists’ theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations, is unavoidably subjective. (Lederman et al. 2014, p.976)

> Scientific knowledge is subjective and theory laden. Scientists’ beliefs, previous knowledge, training, experiences, and expectations, in addition to theoretical commitments, influence their work. (Lederman et al. 2015, p.695)

Here, the authors made two claims—subjectivity *and* being theory-laden.[11] Firstly, they consider idiosyncratic features that make scientific knowledge subjective. Indeed, people of

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[9] Einstein’s (1973) saying “do not listen to their words, fix your attention on their deeds” may be helpful but not sufficient. Practitioners are often not familiar with the pertinent conceptual discourse but may quickly be introduced into it being challenged by the claims regarding NOS.

[10] The L-list of NOS features was not hierarchical. Therefore, in order to simplify our treatment, we have made a single change in the original order—the fourth claim regarding the subjective nature of scientific knowledge is addressed here first for its central importance and implications for the rest of the features.

[11] Several authors, while citing the list, corrected this point without even mentioning the inaccuracy of the original claim. They stated subjectivity *as* being theory-laden. Here, we address both aspects separately as the L-lists deserve. The claim of subjectivity of physics knowledge contradicts the situation in introductory physics around the globe. We never saw such a claim in hundreds of physics textbooks and supporting materials examined.

different backgrounds and mind-sets have produced scientific knowledge. However, being objective normally presumes the knowledge being independent of a subject (producer), independent of human will, and constrained by reality as if it is "factual." Such status is traditionally ascribed to scientific knowledge.[12]

There is a special mechanism, a procedure by which fragments of scientific knowledge become objective. It includes (a) the hypothetico-deductive procedure; (b) the iterative, reciprocal, empirical, and many-faceted refinement and verification; (c) and the intersubjective agreement reached through synchronic and diachronic dialog of scholars causing continuous refinement and self-correction.[13] Scientific knowledge thus becomes an object possessing its own life.

In a sense, this procedure refines the statement by Russell: "The question whether objective truth belongs to human thinking is not a question of theory, but a practical question." (Russell 2009, p.169). Kuhn (1977, p.326) cited the common view: "Objectivity enters science… through the processes by which theories are tested, justified, or judged." He defined "subjective" as being a "matter of taste" and illustrated by considering the view of Einstein on quantum mechanics, who ascribed to nature certain features as he believed them to be. Kuhn mentioned (p. 337) that "Einstein was one of the few, and his increasing isolation from the scientific community in later life shows how very limited a role taste alone can play in theory choice."[14] Quantum mechanics was repeatedly proved to reflect objective reality.

Secondly, the claim of being theory-laden is separate and extremely important since the scientific knowledge is indeed *theory-based.* Physicists consider a big structure of science as established by a few fundamental theories—widely inclusive clusters of internally coherent knowledge elements, related and hierarchically organized (e.g., Heisenberg 1958; Bunge 1967a, 1973; Weizsäcker 2006).[15,16] Theories establish science as a "systematic knowledge of subject matter" also in science curriculum (Schwab 1978). However, a mere dependence on a theory does not imply subjectivity, because scientific theories can be objectively justified (e.g., Couvalis 1997, p.12). Such are the fundamental theories in physics: classical mechanics, thermodynamics, classical electrodynamics, quantum physics, the general theory of relativity, the quantum field theory (Fig. 2). They all are objective theories.

In teaching about NOS, there is a need to depict how human knowledge can be objective and how it may lose its idiosyncratic features and become impersonal. After being developed by, say, Aristotle or Newton, a theory is detached from them and proceeds with its independent

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[12] For example, Losee 1993; Longino 1990; Couvalis 1997; Godfrey-Smith 2003, pp. 6, 229.

[13] One may clarify here the difference between objectivity and inter-subjectivity. Some scholars do not grant scientific knowledge more than being intersubjective which literally means being a product of agreement among scholars, community ("conventionalism"). We consider this feature insufficient, since *being agreed* does not mean, although some might presume so, *multiple empirical many-staged verifications* on which such agreement draws in science and which present a core requirement of objectivity. The procedure of reaching objectivity must include both aspects—(b) and (c).

[14] Kuhn stated that the adopted theory may preserve some idiosyncratic features. He rejected, however, the claim that he deprived science of objectivity in its "standard application" as opposed to the "matter of taste" which is subjective and undiscussable (ibid. p. 336).

[15] The use of the notion *theory* in these resources is different from the meaning of theory as a counterpart to *practice*, *experiment*, and *experience*, and is neither a synonym for *abstract* nor *hypothetical*. Theory in science may signify an inclusive cluster of coherent knowledge elements organized in hierarchical structure. This use as a structural whole is close to that described by Giere (1985, p. 16; 1999, pp. 97–99) and is common in science and the philosophy of science (e.g., Chalmers 1976, Ch. 7, 8).

[16] Heidegger defined science as a theory of what is actually real (Kockelmans, 1985 p. 162) implying natural science to be a theory of nature.

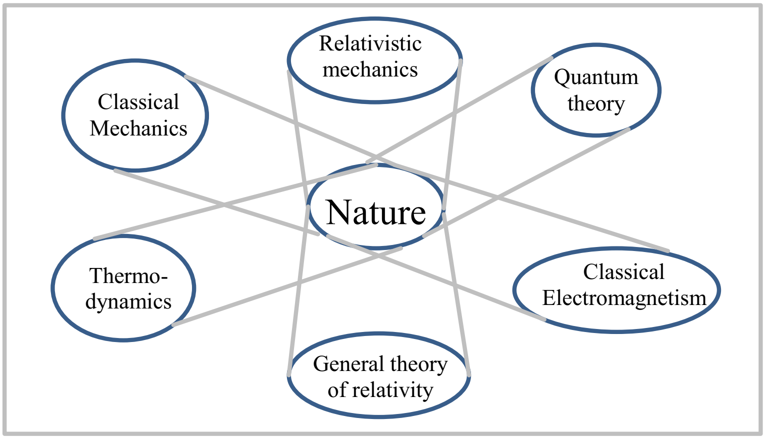

Fig. 2 Fundamental theories of physics present reflections of reality in its different aspects, the "Pictures of the World"

life. Popper (1975) epitomized this fact by introducing the concept of "the third world"—a virtual space of cultural products, collective knowledge free of supernatural and voluntary factors.

Scientific theories are often credited with the virtue of being "universal." The latter corresponds to the idea of being invariant and deserves clarification. Indeed, a scientific theory holds everywhere, at any time and regardless of the individual applying it. Yet, each scientific theory depicts nature only in certain aspects, creating a partial, specific picture, valid in a well-defined domain of parameters. Therefore, we have several fundamental theories.

The claim that scientific knowledge is subjective breaks with the tradition of science education and commonly surprises science teachers. It is, however, not new in philosophy where the concept of science ranges from the objective to a socially determined construct (e.g. Glasersfeld 1995). Historians assert that practitioners normally consider scientific knowledge objective (e.g., Holton 1985; Shapin 1996; Nozick 2000; Agazzi 2014). Philosophers emphasize that only such knowledge can be a subject of critical discourse and progress (Popper 1975).[17] Physicists seldom talk about objectivity, taking it to be a presumed norm (Di Francia 1976). Still, when they do, they normally firmly state the objectivity of the collective knowledge by being confirmed through multiple experiments, reproduction, and predictions, even if they mention their reservations regarding immediate specific products and personal limitations. The quantum field theory was confirmed with amazing accuracy in measuring the magnetic moment of the electron, up to 10^{-11}, which testified to its validity (Feynman 1985/2014, p. 7; Sokal and Bricmont 1998, p. 57). Weinberg (2001, pp. 91–92) argued:

> We [scientists] believe in an objective truth that can be known, and at the same time we are always willing to reconsider, as we may be forced to, what we have previously accepted.

He continued (ibid. p. 151):

> I have come to think that the laws of physics are real because my experience with the laws of physics does not seem to me to be very different in any fundamental way from my experience with rocks. For those who have not lived with the laws of physics, I can offer the obvious argument that the laws of physics as

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[17] It is helpful, in this regard, to see the contrast with such areas as religion where *to be subjective* is presented as a goal of mature knowledge (Kierkegaard 2009).

> we know them work, and there is no other known way of looking at nature that works in anything like the same sense.

Elsewhere, he stated (Weinberg 1974, p. 151):

> . . . there is an essential element in science that is cold, objective, and nonhuman . . . the laws of nature are as impersonal and free of human values as the rules of arithmetic . . .

Yet, *Stanford Encyclopedia of Philosophy* starts from the definition (Reiss 2014):

> It [scientific objectivity] expresses the idea that the claims, methods and results of science are not, or should not be influenced by *particular perspectives*, value commitments, community bias or personal interests, to name a few relevant factors. (Emphasis added)

The reference to a "particular perspective" as a feature of subjectivity (similar to that stated in L3) is inexact. The fundamental physics theories do provide particular perspectives while they constitute objective knowledge. They guide our successful interaction with reality, the planned products, the realized predictions within the range of predicted accuracy, and so on. Within such perspective, empirical data are interpreted attaining a specific meaning.[18]

Popper (1959, p. 22) followed Kant in the meaning of objectivity:

> … scientific knowledge should be *justifiable*, independently of anybody's whim: a justification is 'objective' if in principle it can be tested and understood by anybody. 'If something is valid', he [Kant] writes, 'for anybody in possession of his reason, then its grounds are objective and sufficient.'

Carnap was more precise (Weinberg, J. 1936, p. 215):

> …knowledge is objective insofar as it is limited or constrained by certain conditions (the facts) over which arbitrary will has no control.

The idea of science as the objective knowledge of nature was introduced in the epistemological evolution which replaced myths with the idea of cosmos—the universe organized in a stable order, independent of any personal will. For that, Carnap (1971, p. 206) praised Democritus:

> Democritus, for example, regarded the regularities of nature as completely impersonal, not connected in any way with divine commands. … this step from the personal necessity of divine commands to an impersonal, objective necessity was a great step forward.

Russell (1912/1990) summarized his rejection of subjectivity of scientific knowledge:

> There is a widespread philosophical tendency towards the view which tells us that Man is the measure of all things, that truth is man-made, that space and time and the world of universals are properties of the mind, and that, if there be anything not created by the mind, it is unknowable and of no account for us. This view, if our previous discussions were correct, is untrue; but in addition to being untrue, it has the effect of robbing philosophic contemplation of all that gives it value, since it fetters contemplation to Self.

In the context of education, however, we should be specific and proceed to the points deserving specific clarification, each addressing a certain aspect that may raise confusion with respect to establishing an objective knowledge of nature.

3.1.2 Deception by Perception

Objectivity could be affected due to deception by the senses. The Greeks talked about contemplation rather than observation in natural philosophy. In other words, their looking was interwoven with the analysis of the observed. Newton worried in 1670 about the validity

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[18] We address here neither the truth of the theory nor the certainty of scientific knowledge that is distinguished from the objective nature of the scientific knowledge as impersonal and involuntary.

of his claims regarding colors. What troubled him was whether colors obtained behind a prism were innate to sunlight (Shapiro 1984). Newton realized that white color can be reproduced by combining some, but not necessarily all, colors of the spectrum. The reason for that was shown later by Young, who, in 1801, introduced a theory of color *perception* based on three basic colors that corresponded to the three types of color sensitivity of the human eye.[19] According to that understanding, Young separated the *objective* (observer-independent) color from the *subjective* (psychological, observer-dependent) one. Generally, science does not rely on sense perception but transcends it through using instruments which probe, measure, and monitor reality in a variety of ways prior to reliable inference within the construction of objective knowledge.

3.1.3 Content/Mathematical Form Versus Interpretation

One can distinguish between the science content, depicting specific features of *objective* reality, and its interpretation. Consider the law of light reflection (the equality of the co-planar angles of incidence and reflection—a mathematical statement). Over the course of history, this law has been given different interpretations. While its empirical content remained, its interpretations varied from Heron's idea of nature seeking the shortest path to Fermat's interpretation of the path being *extremal* in time. Then, Newton interpreted the same form as conservation of the momentum component parallel to the surface, while Huygens (1912, pp. 22–28) showed the same regularity by interference among the secondary waves. Feynman (1985, pp. 37–47) transferred the wave account to the interference of the multiple paths involved in the motion of a single photon.

Over time, the objective empirical law of reflection obtained accounts in three theories of light (geometrical optics, physical optics, quantum optics)—all three correct in the realms of their validity. The mathematical form of the relationship between physics quantities not only was more compact and numerically accurate but also neutralized unsupported speculations. Newton understood this advantage and tried his best in providing physical theory with mathematical formulations (Shapiro 1984). He wrote (Newton 1670)[20]:

> But truly with the help of philosophical geometers and geometrical philosophers, instead of the conjectures and probabilities that are being blazoned about everywhere, we shall finally achieve a natural science supported by the greatest evidence.

The mathematical accounts of internal energy, heat and work, entropy, electric and magnetic fields, and wave function, all revealed a certain objective content of empirical reality whose meaning was clarified later. Even more, two different mathematical forms could appear later as equivalent in representing the same objective reality, as happened with the accounts of quantum phenomena by Heisenberg and Schrodinger (Dirac 1958, pp. 108–116).

Scientists joke that equations are smarter than people in their coverage of objective reality. Dirac's equation in relativistic quantum mechanics described the electron, but also provided additional states with negative energy. They were interpreted as corresponding to anti-particles of electrons—positrons, never observed until then. Since then, the *objective* existence of anti-electrons was experimentally confirmed and antiparticles were discovered.

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[19] RGB in modern terms

[20] We quote from the article by Shapiro (1984) depicting Newton's Optical Lectures of 1670–1672.

3.1.4 Objectivity Versus Correctness

It is common to equate objectivity and correctness. While both definitely represent goals of scientific knowledge, these characteristics do not coincide. Showing that a certain scientific theory was imprecise does not make it subjective. This is because being adopted by science means a certain impersonal, independent claim about nature, and its phenomena. The same claim could be later recognized as limited, less accurate, less effective, and erroneous and replaced by other knowledge.

The geocentric theories of the solar system by Ptolemy and Tycho Brahe were dismissed by Galileo, Kepler, and Newton. Yet, these theories were objective, providing accounts of a certain appearance, independent of anyone's will. Geocentric models remained valid and widely used in everyday navigation.[21,22]

Scientists suggest different working models of reality which vary in correctness and accuracy, providing accounts of certain aspects of nature. In the theory of electromagnetism, we use models of fluids and gas for the electrical current. Each model is successful in some aspects but fails in others. Both are objective, however. Ampere introduced microscopic electrical currents, never observed, but effective in uniform and inclusive phenomena explanations (e.g., Darrigol 2000). They provided mathematical accounts of and explanations for several physical phenomena. Over time, the limits of validity of this theory were revealed but the theory has remained objective. The model of a current within an atom provides a successful account for an orbital magnetic moment, even though there is no current in the classical sense in an atom as a quantum object and hence, in some sense, this model is incorrect. Scientific correctness is distinct from objectivity. The opposite of falsity is correctness, not objectivity.

3.1.5 Context-Dependence

Scholars have indicated the essential difference between the way that researchers develop knowledge and the way they argue for its acceptance. While knowledge construction may involve subjective ideas and beliefs, and reflect personal ideology, the subsequent acceptance of that knowledge requires argumentation and empirical verification of an objective nature (Reichenbach 1938, pp. 6–7, 381–382).[23] Reichenbach insisted that scientific epistemology and method cannot deal with the act of discovery but only with the procedure of justification, which does not, or at least need not, involve subjective factors.[24] Laudan introduced a parallel pair, *pursuit* and *acceptance* (Laudan 1977; Godfrey-Smith 2003, pp.108–109).

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[21] A very simple example: the claim that the "Sun is rising in the East" is an objective claim. Its correctness, however, depends on the frame of reference, geocentric or heliocentric.

[22] Here, the notions of theory and model are used within the discipline-culture framework (Tseitlin and Galili 2005, Galili 2017). As elaborated below, the notion of theory is often used in physics to represent an inclusive cluster of knowledge elements (e.g., the theory of classical mechanics). Possessing such a structure, theory includes models of different kinds in all areas of its structure. Considered as discipline-culture, the Geocentric Theory of the solar system includes various geocentric models.

[23] Goodman (1968, p. 251) put it as follows: "Indeed, in any science, while the requisite objectivity forbids wishful thinking, prejudicial reading of evidence, rejection of unwanted results, avoidance of ominous lines of inquiry, it does not forbid use of feeling in exploration and discovery, the impetus of inspiration and curiosity, or the cues given by excitement over intriguing problems and promising hypotheses." Nersessian (1992) termed this stage as the context of development.

[24] Laudan introduced a parallel pair, *pursuit* and *acceptance* (Laudan 1977; Godfrey-Smith 2003, pp.108–109)

Losee (1993, pp. 121–126) traced the recognition of the two contexts to John Hershel, who was impressed by Ampere's new theory of electromagnetism. Ampere did not draw on any specific data or inductive scheme, but his heuristic circular currents in the magnetized matter were much later shown to be real. Similarly, Maxwell derived his fundamental equations of electromagnetism using the heuristic model of elastic medium which remained merely imaginary (Nersessian 1992; Darrigol 2000, pp. 149–151).[25]

After theories are introduced, they become detached from their creators in the process of justification, analysis, development, and testing by other researchers on the way to becoming collective, objective knowledge—an item in the "third world" of Popper (1959, 1975). Such justification is never a single ("crucial") experiment but includes a variety of them by different researchers. It is a long process of rational elaboration which, in the view of Toulmin (1972, p. 105), invalidates the idea of "revolution" in science in favor of its evolution.

For instance, Einstein's ideas of relativity were not justified by Michelson-Morley or any other single experiment, but by a whole list of experiments.[26] The process of justification included the contest of six parallel theories: the ether theories by Lorentz and the ballistic theories by Ritz (Miller 1981, pp. 25, 280; Miller 1986, p. 2). Einstein's theory surpassed Fresnel's explanation by ether drag in accuracy (French 1968, pp. 131–132). The subjective inquiry of Einstein, his mental images of rods and clocks in a spacious lattice were left behind (Einstein and Infeld 1938; Miller 1984). From 1902 to 1909, Einstein's inquiry was out of the academic mainstream (Miller 1986), while the process of justification moved him to the center of scientific discourse, theoretical and experimental, eventually providing his theories with the status of objective knowledge about space-time.[27] Perhaps, the most convincing justification of objectivity was the atomic power technology and weaponry.

3.1.6 The Objectivity of Modern Physics

Modern physics, the theory of relativity and especially, the quantum theory, changed the status of the observer in physics theories, bringing it to the fore. Galileo, Kepler, Descartes, and Newton addressed reality presuming no intrusion by an observer, who was considered as a perturbation factor causing distortion of appearance. Such disturbance could be taken into account and ignored in an ideal experiment. This vision became a subject of a cardinal revision in the twentieth century. Multiple observers (frames of reference) and quantum measurement raised the doubt of subjectivity. It appeared, however, that the new physical theories remained objective. The theory of relativity draws on the strict rules of invariance relating all the accounts. In quantum theory, an observer may choose the kind of macroscopic apparatus

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[25] In contrast, Duschl and Granny (2013) stated that the two contexts might be interwoven: "What occurs in science is neither predominantly the context of discovery nor the context of justification but the intermediary contexts of theory development and conceptual modification." However, even their being interwoven does not dismiss the high validity of recognizing the two aspects of knowledge creation as different with respect to the status of objectivity.

[26] Panofsky and Phillips (1955, p. 240) illustrated the process of justification of the special theory of relativity. Five of the rival theories successfully accounted for the zero result of the Michelson-Morley experiment, but only Einstein's theory could explain all 13 different experiments performed by different researchers. Actually, criticism of the Einstein theory of relativity never stopped.

[27] Hodson (2011, pp. 111–112) quoted Mitroff who already in 1974 depicted science in terms of *Particularism*, *Solitariness*, *Interestedness*, and *Non-rationality* as better characterizing the reality than the universalism, disinterestedness, and rationality proclaimed by Merton (1973). The argumentation provided by Mitroff, however, addressed the context of inquiry.

and environment that determine possible states of a micro-object (as in classical theories). The new and subtle feature of micro-world reality—the *probability* of measurement results—is observer-independent. As Dirac explained, probability is made by Nature and not by the observer (Bohr, 1959, p. 223; Cushing 1994, p. 178). Modern physics thus remains objective in providing knowledge about reality, though different from the classical account.[28]

Summarizing our refinement, we argue for the objective nature of scientific knowledge though subjective elements may be present in knowledge construction and ongoing research. Einstein (Einstein 1934b, p. 57) expressed this aspect in the following manner:

> Science as something existing and complete is the most objective thing known to man. But science in the making, science as an end to be pursued, is as subjective and psychologically conditioned as any other branch of human endeavor…

Though objectivity of science presents a commonplace and the major scientific norm, there is a need for refinement in order to prevent its misinterpretation in science education.

3.2 Scientific Laws and Theories

The following item deals with the concepts of theory and law. L2 (Lederman 2006, p. 305) stated:

> Laws are statements or descriptions of the relationships among observable phenomena. Boyle's law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point. Theories, by contrast, are inferred explanations for observable phenomena (e.g., kinetic molecular theory provides an explanation for what is observed and described by Boyle's law). Scientific models are common examples of theory and inference in science.

The provided definition of laws is deficient, being not fully representative. Firstly, as Mach stated (Mach 1976, p. 140):

> All general physical concepts and laws, the concept of a ray, the laws of dioptrics, Boyle's law and so on, are obtained by idealization.

It is rather obvious that, in practice, we have a more or less good approximation of the claimed functional dependence and there is often the need of asymptotic consideration to state the law in its ideal form. Thus, Galileo never observed *simultaneous* falling of bodies with different masses (experimentation in a vacuum was not available) but derived his law through asymptotic consideration in a thought experiment (Galilei, 1638, p. 116). A similar procedure is required to reach the law of inertia and others.

Secondly, the concepts related through physics laws should not be necessarily observable/measured directly. Such are, for instance, *energy* in the law of its conservation, *entropy* in the Boltzmann law, *electromotive force* in the Kirchhoff laws, and *internal energy* in the First Law of Thermodynamics. In quantum mechanics, wave function is a non-observable quantity that determines observable ones (transition probabilities, particle interference, etc.). "Theoretical laws" are theory products, and they are not solely about observables (Carnap 1971, p. 305; Wilczek 2004).[29]

The meaning of the term "theory" is twofold. Only the first has been addressed in the L-list, that of the opposition of theory-practice. This meaning is common in everyday use, but it is not

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[28] There is an extensive discussion of the objective nature of quantum mechanics (e.g., Heisenberg, 1965; Popper 1967; Bunge 1967a; Cushing 1994; Agazzi 2014).

[29] Besides concepts, the *units* used to measure physical quantities do not draw any more on the directly measured *kg*, *m*, and *sec*. They have been elicited through sophisticated *theoretical* accounts from the world constants h, c, and e considered now as fundamental.

unique. The list ignores the meaning of theory in science as an inclusive cluster of coherent and hierarchically arranged knowledge. Starting from Plato (2003), theories became an agenda of scientific exploration; they present the fundamentals of science.[30,31] The ancient Greek term *theory* is elucidating in meaning since it emphasizes observing the replacement of reality by its representation with the knowledge of that reality—*theory*, as if it happens in *theater*.

Indeed, knowing a theory may help the understanding of laws. Even so, to define a theory solely as an explanation is not representative. We derive the law of mechanical energy conservation and the law of pendulum from Newton's second law, but this derivation does not explain those laws conceptually. The empirical laws such as Hooke's law of elasticity, da Vinci's law of sliding friction,[32] and Ohm's law of electrical circuits are not explained by the theories of mechanics and electricity, but belong to them, respectively.

Each fundamental theory of physics presents a "picture of the world" from a specific perspective (Fig. 2). Each such theory is very inclusive incorporating numerous elements—principles, laws, concepts, models, phenomena explanations, solved problems, experiments, and apparatus—in a self-consistent system.

Beyond consistency, a scientific theory is also hierarchically ordered. One may identify fundamental laws, principles, and basic concepts—the *nucleus* of a theory. Other elements would present its *body*. For instance, if the nucleus includes Newton's law of gravitation, the body includes Kepler's Laws of Planetary Motion which are derived from the law of gravitation, and if the nucleus includes Newton's Laws of Motion, its body includes the work-energy theorem and the law of conservation of mechanical energy (Fig. 3). As mentioned already, the important feature of a physical theory is that it is not valid universally, but only within a well-defined range of parameters (length, time, mass, particles, and type of interaction)—the area of validity. Thus, classical mechanics is not valid for black holes where the general relativity theory works. Yet, it does *not* imply that physical theories (and laws) "lie," nor that physics knowledge presents a "patchwork."[33] In Einstein's view, the splitting of one picture of the world to several theories is "not a matter of fundamental principle" (Einstein 1918/2002).

Consider the domain of optics. To account for image creation in a simple microscope, one may use geometrical optics, or the theory of light rays, and correctly predict the location and size of the image. However, the gradually increasing magnification blurs the image when it approaches the limit of resolution, indicating the invalidity of the ray theory and the need for the wave theory. Yet, besides the new outputs, the wave theory reproduces all the results of the ray theory regarding image creation.[34] Furthermore, by gradually reducing the light flux to

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[30] As mentioned already, Heidegger defined science (the whole science!) as a theory of what is actually real (Kockelmans 1985, p. 162) implying natural science to be a theory of nature.

[31] Kuhn (1969) used the terms *constellation* or *disciplinary matrix* when he addressed a theory.

[32] This law which states the friction between two surfaces to be proportional to the pressing force between them regardless the areas in contact was introduced by Leonardo but seldom called by his name. Instead, if at all, it may be attributed to Amonton, the French scholar of the seventeenth c. (e.g., Persson 1998, pp. 10–11)

[33] The nature of physics knowledge was addressed by the metaphor of "patchwork" (Cartwright 1994) and the claim of Giere (1988) "Close inspection, I think, reveals that they are neither universal nor necessary – they are not even true" (p. 128). Physics laws do not "lie" as Cartwright wrote (1983), but are valid each in their particular areas of validity (e.g., Heisenberg 1948; Einstein, 1989). The patchwork metaphor is inappropriate: the theory of general relativity is valid in the area of classical mechanics but not vice versa. Newton's law of gravitation works on the leaning tower in Pisa but not in quasars, while Einstein's theory of gravitation works in both. Quantum mechanics works in the macro-world but Newtonian mechanics does not work in the micro-world. In short, the scenario of simple division is wrong.

[34] This approach is termed Abbe optical theory (Hecht 1998, pp. 602–604).

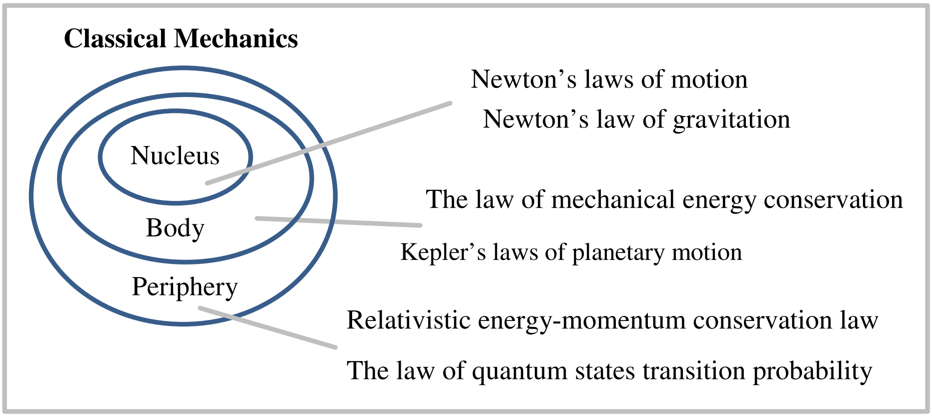

Fig. 3 Examples of laws in the theory of classical mechanics structured as a discipline-culture

very low intensities, one distorts the image again as, this time, it splits into light spots,[35] leaving the area of validity of the wave theory and indicating the need for yet another light theory, that of photons. The universality of scientific laws and theories is of specific kind.

The relationship between fundamental theories can be represented by placing the nuclei of Einstein's theory of relativity and quantum theory in the periphery of classical mechanics, and the nuclei of ray and photon theories in the periphery of the wave theory of light.[36] Organization of knowledge elements in the tripartite structure—nucleus, body, and periphery—can represent the normal scientific practice and "visualize" the process of theory exchange in scientific revolutions (Tseitlin and Galili 2005, Galili 2014). Theory structure incorporates laws (Duhem 1982). When laws belong to a nucleus (such as Newton's laws on classical mechanics), they are used as principles (Giere 1995). Theoretically established laws of the body of knowledge may be explained in the sense of being reduced to (or derived from) the elements of nucleus (e.g., energy conservation, laws of projectiles, planetary motion laws, the law of pendulum). Empirical laws, such as da Vinci's law of sliding friction and Hooke's law of elasticity, are affiliated to the body knowledge of mechanics, but are not explained by it.[37]

We have elaborated on the law-theory relationship using the context of physics, but we cited this relationship vis-a-vis natural sciences in general. While physics deals with the "simplest" material objects, its structural canon serves as desirable, though not always available pattern also in chemistry and biology. The pattern of discipline-culture for a fundamental theory remains valid in other natural sciences as well as the presented theory-law relationship. For instance, some chemistry laws (such as the law of periodicity in qualities of elements) can be derived from the electronic structure.[38]

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[35] For example, Tipler 1987, pp. 184–186; Serway et al. 2005, pp. 180–182. The reference to the original experiment by Taylor in 1909 is rare (Rabinowitz 2017).

[36] This model essentially refines the traditional claim (e.g., Nagel 1961) that a more advanced theory (such special relativity) subsumes, under ceteris paribus reservations, its predecessor (such as classical mechanics), and emphasizing *incommensurability* of the fundamentals (Kuhn 1970) in parallel with *commensurability* of the correspondent numerical accounts.

[37] Such elements as the friction, elasticity, non-conservative forces, and Ohm's laws are formally irreducible to the nuclei axioms. They appear as *emergent* properties, obtained as empirical laws. They point to the conceptual incompleteness of the particular theory but do not prevent its validity in the certain area of parameters.

[38] We teach theories in class not in the form that these theories were historically introduced. Indeed, Newtonian mechanics did not include energy, Mendeleev's periodic law did not draw on electronic structure, and Darwin did not justify selection of species by genetic rules (e.g., Dagher and Erduran 2014).

Chemistry, thus may affiliate the periodic law and the matter conservation principle with the nucleus. Then, the specific regularities of chemical reactions can be ascribed to the body-knowledge, and the alternative classifications of elements (by Mayer according to valences as well as that practiced by Lavoisier and in the medieval alchemy) will be identified with the periphery.

To summarize, the difference between law and theory should be refined and upgraded rather than oversimplified. Such a refinement is feasible in high school instruction of science (e.g., Levrini et al. 2014).

3.3 The Involvement of Creativity and Imagination

In L2 (Lederman 2006, p. 305), the authors stated:

> Even though scientific knowledge is, at least, partially based on and/or derived from observations of the natural world (i.e. empirical), it nevertheless involves human imagination and creativity

Although this statement regarding NOS is obvious, a refinement may make it more informative and specific for science. Einstein (1952) stated that concepts and theories are “free inventions of the human spirit.” Yet, he specified the place for imagination among other activities, testing the products of imagination—the invented constructs—to assess whether they fit the objective world in order to adopt or discard them (Fig. 4).

For Einstein, imagination is guided by reality and participates in a self-correction cycle of knowledge production: the intuitive move from experience (E) to creating fundamental axioms (A), rational deduction to statements (S), checking these statements against experience, and returning to further consideration. In a way, this process is reminiscent of the Aristotelian research cycle (Losee 1993, p. 6) and the procedure of deduction from phenomena which Newton placed against “hypothesizing” on possibilities (e.g., Shapiro 2004, p. 188). This circle continuously repeats itself as an iterative mechanism, making it spiral, that is, developing. In it, human imagination and creativity are empirically tested against the objective reality in a self-regulative process of scientific theory creation.

At the same time, however, one may contrast imagination and creativity with the equally correct complementary idea of the “economy of thought” suggested by Ernst Mach (1976, p. 354), implying scientific knowledge as a product to be consumed without repeating an in-depth analysis in each case. This reality countenances the whole industry of problem-solving and actually enables progress in science (as well as in technology). Thus, using Kepler’s laws of planetary motion does not require the ability of their derivation from first principles. One can design a flying apparatus without knowing the proof of the Bernoulli and Stock equations from theoretical aerodynamics; one can dismiss perpetuum mobile without the ability to demonstrate the laws of thermodynamics.[39] Within this perspective, there is a continuous spectrum to be exposed in science education (Fig. 5) precluding an extreme view of any kind and showing the importance of both virtues in describing NOS.

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[39] Of course, we are talking here about the cases of well-established theoretical knowledge and not about fundamental research. This fact, however, does not remove the validity of the claim of economy of thought in science: automatic repetitive use of scientific algorithms. Scientists can proceed with their research only because they do not check every product they use in their inquiry. In that, they draw heavily on the authority of the resource they use. The situation changes only in case of failure.

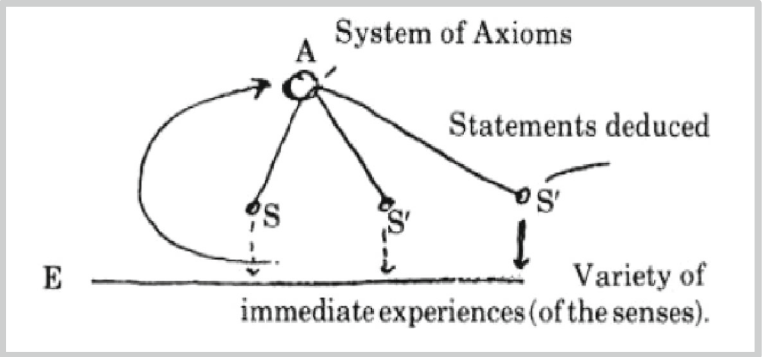

Fig. 4 The cycle of concept introduction and verification in scientific practice as explained by Einstein (1952)

3.4 The Empirical Nature of Scientific Knowledge (Observation-Inference)

The statement of L1 that scientific knowledge is empirically based is also correct. As stated by Einstein (1934a), "Pure logical thinking can give us no knowledge whatsoever of the world of experience; all knowledge about reality begins with experience and terminates in it." Yet, in the context of education, this claim is not sufficiently representative. There are other non-scientific domains of knowledge which are also empirically supported. For thousands of years, people have followed the paths of planets, registered the level of water in rivers, practiced traditional healing, and developed a wide variety of crafts. However, these systems of rich empirical knowledge (useful and viable as they are) do not constitute science. The major feature of scientific knowledge is its arrangement in accordance with especially inclusive, abstract, conceptual systems—objective *theories* of nature. Scientific knowledge is empirical, but nonetheless theoretical. Theory projects onto observations, implying the need to distinguish between *observation* and *inference*, which are interwoven, but different in nature. This difference is often subtle and is not always adequately presented in classes. For instance, the Primary School Curriculum of Ireland (Science 1999, p. 13) reads:

> A feature of the work in both the *middle* and *senior classes* is that pupils will investigate falling objects. They will discover that objects fall because of the force of gravity. They will measure force by constructing their own spring balances.

In fact, however, there is no way to "discover that objects fall because of the force of gravity."[40] Observation of falling bodies and the studies of gravity for thousands years did not lead to a concept of force. The concept of the force of gravitation was introduced, *invented*, by Newton as a part of his theory in the seventeenth century. Students may better appreciate this fact if they are taught that Aristotle and Einstein also explained gravity, each in his own way, with both explanations being different to the Newtonian force explanation (periphery elements of the classical mechanics). Just as theoretical and experimental activities are deeply interwoven, so too are observation and inference. The terms used for observation often depend on a particular fundamental theory (Kuhn 2000, pp. 246–247), and the involvement of tacit knowledge in the scientific observation is unavoidable.[41]

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[40] Ironically, the first critique of the "discovery" of the gravitational force instead of its invention as an abstract tool was due to the Irish philosopher Berkeley (e.g., Popper 1962, p.109).

[41] Kuhn (1969, pp. 197–198) discusses the same point when considering the pair of perception-interpretation of something, cemented together by the tacit knowledge of the explorer.

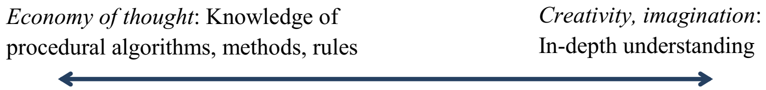

Fig. 5 The broad variation of cognitive activity with regard to scientific knowledge in different contexts. Each scientific activity (or product) can be "located" on this axis as combining the two complementary virtues

Summarizing this refinement, the nature of scientific knowledge combines empirical and theoretical aspects manifested in the distinction between observation and inference. Their connection surpasses a simple dichotomy to a symbiotic one. In a classroom, their continuous reciprocal influence should be contextualized in teaching with concrete examples of the iterative process of knowledge construction.[42]

3.5 The Social and Cultural Embeddedness of Scientists and Science

The text in L5 (Lederman et al. 2015, p. 695) [L2 (p. 306), L4 (p. 976)] reads:

> Science as a human enterprise is practiced in the context of a larger culture and its practitioners (scientists) are the product of that culture. Scientific knowledge affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded.

Indeed, scientific knowledge is a cultural-social product (e.g., Longino 1990). However, there is a need to refine this claim in regular teaching to distinguish scientific knowledge from other numerous knowledge systems produced by society. The central norm of scientific knowledge is its objectivity, being reduced to a few inclusive fundamental theories based on empirical verification, reproduction, and successful predictions. Different social environments definitely influence the manner in which scientists live, think, and work. Environment affects the agenda of the studies in form and content. Even so, despite the social impact, the essence of the products has to be objective in order to be scientific. This norm originally caused the split of science from mythology in ancient Greece, and it allowed continuity of the scientific discourse, dealing with the *same* fundamental questions and scientific problems through different societies and at different times.[43]

Consider the scientific knowledge of light. Its construction was maintained through the very different societies of Classical Greece, the Hellenistic civilization, Muslim and Christian medieval worlds, and seventeenth century Europe. Yet, despite striking social differences, the development of pertinent knowledge continued as a single process (e.g., Lindberg, 2007). Addressing the contribution of Muslim scientists in that regard, Wein(useful and viable as they are)(useful and viable as they are)berg mentioned that they (the Muslim, Christian, and Jewish scholars) saw themselves as refiners of Hellenistic thought and they promoted science much farther (Al-Khalili 2010). They "were not doing Islamic science. They were doing science" (Weinberg 2015, p. 70).[44]

Weinberg (2001, p. 158) related the cultural independence of physics laws to their objective nature:

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[42] Einstein (1934a) called it "the eternal antithesis of the two inseparable constituents of human knowledge, Experience and Rationale, within the sphere of physics." This symbiosis is epitomized in representative artistic images to show in science classes as a logo of science, its nature (Appendix 1).

[43] The further complexity of this claim we briefly address in Appendix 2.

[44] A very similar claim was made by another Nobelist, Leon Lederman (1998, p. 132), who stated categorically: "We believe that there is only one science, not Western, not indigenous, not even Maori. Its origins may be traced to the Ionian Greek civilization, and it flowered in Europe in the seventeenth century."

> One of the things about laws of nature like Maxwell's equations that convinces me of their objective reality is the absence of a multiplicity of valid laws governing the same phenomena, with different laws of nature for different cultures.

Similar examples can be provided from mechanics and astronomy developed in very different cultural milieu and by researchers holding a variety of worldviews.[45] Scientific knowledge was produced standing on the shoulders of scientists active in different societies regardless of social factors (values, ideology[46,47]). Once developed in one social environment, "science swept across the world as a forest fire" (Needham 2004, p. 231). Scientists may hold different views on the meaning of $E = mc^2$ but none of them replaces it with $E = mc^3$, regardless of any social factor.

Besides the social-political aspect, there are other aspects of social influences on science, its content and practice, including the practical and religious demands of each society at all periods of history (e.g., Lindberg 2007; Al-Khalili 2010). Another special issue is the social impact on scholars *within* scientific communities (e.g., Kuhn 1970; Latour 1987). All these, however important, do not change the aspect to be emphasized in introductory science education: that the objective meaning of the scientific contents is independent of social environment because its origin is in nature itself.[48]

Without such refinement, a mere claim of scientific knowledge as dependent on social environment might be greatly misleading. Actually recalling the social constructivist perspective on scientific knowledge threatens to reduce science to ideology and pedagogy—that is, merely propaganda (Slezak 1994).

3.6 The Tentative Nature of Scientific Knowledge

In L1, the text relating to the next item is especially short: "scientific knowledge is tentative". L2 and L3 expanded and claimed that scientific knowledge was "never absolute or certain." It is not difficult to trace this claim to the Popperian perspective (Popper 1959, p. 22)[49] described as follows (Thornton 2016):

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[45] Here is a contemporary example. A vast body of literature documented the tragic reality of Soviet science during Stalin's regime and the brutal pressure of the social environment, including physical elimination, torturing, and imprisonment of numerous scientists (Gorelik and Frenkel 1994; Gorelik and Bouis 2005; Ginzburg 2005). In spite of this, the scientists there managed to produce results universally valid regardless of the nightmares they faced, being committed to the universal scientific norms for argumentation and creating objective, socially independent products (Josephson and Sorokin 2017). By contrast, when the subjective social demand penetrated scientific content, as happened in the Lysenko case (Lamarckian paradigm) where Stalin destroyed the opponents, the product was pseudoscience, not science (Birstein 2001). In an interesting parallel with education, the entrance of social, subjective factors may cause pretending social behavior and pseudoconceptual understanding on behalf of students (Vinner 1997).

[46] In Soviet Russia, genetics and cybernetics were considered to be bourgeois pseudoscience or "capitalistic" products. The development of these areas of objective knowledge was thus suppressed in Russia for many years but eventually overcame.

[47] We limit our discussion to science, arguing using scientific theories, but technology is not different in this perspective. Think about the striking difference in all aspects of social environment and ideology between the USA, USSR, China, Pakistan, and Northern Korea. Despite the differences, practically the same scientific and technological products were created—the atomic weapon and rocketry, for instance.

[48] We skip here another important claim of cultural influence on scientific content, for instance, in Marxist perspective. To illustrate, it was claimed that Newton's *Principia* was actually the answer to the needs of England in constructing canals and locks, problems of chronometry in navigation, etc. (Hessen 1933, p. 30, 62). In our view, it does not change our argument of social independence of the scientific contents.

[49] We refer to Popper in this regard and not to other philosophers of the past, such as Hume (1739/1978), who expressed a similar criticism to replacing the cause-effect based necessity relationship in human claims with experience based inferences of merely probability. Popper addressed science in a more inclusive and mature way.

> Scientific theories, for him [Popper], are not inductively inferred from experience, nor is scientific experimentation carried out with a view to verifying or finally establishing the truth of theories; rather, *all knowledge is provisional, conjectural, hypothetical* – we can never finally prove our scientific theories, we can merely (provisionally) confirm or (conclusively) refute them.

In his comments, Popper (1970, p. 35) was clear:

> … in general, with the exception of comparatively trivial theorems, the truth of a statement of a theory *cannot* be proved; which means that even if we should ever arrive at a "final description of nature", we could not know it.

L5 (Lederman et al. 2015, p. 695) repeats and strengthens:

> …scientific knowledge is never absolute or certain. This knowledge, including "facts," theories, and laws, is inherently tentative or subject to change.

This perspective of Popper, however, belongs to the dialog on the continuous and unlimited progress of scientific understanding of nature taken holistically, across domains and theories. It looks as if the knowledge is addressed there, by Popper, in the *metaphysical* sense with respect to the *ultimate all-inclusive* truth of nature—*gnosis.*[50] This philosophical perspective is distant from science and science education. Teaching and practicing science addresses knowledge in the essentially different sense of *episteme—rational understanding*, created and structured in a scientific discourse, a subject for demonstration (theoretical and experimental), replacement, and refinement. The Popperian negation of "being proved" as a possible characteristic of science products clearly contradicts the scientific practice, the normal activity of science (Weinberg 2015, p. 24) which presents the agenda of science education. Leon Lederman (1998, p. 132) stated in presenting a novel educational program: "We believe that science is tentative at its frontiers, but that there is a large body of knowledge that is objective truth for all practical purposes."[51]

In fact, there is no need to wait until the scientific theories we teach are falsified and replaced by more advanced, but also "provisional", theories. Scientific knowledge is already organized in a family of fundamental theories none of which is all-inclusive in validity.[52] Each such theory represents a specific aspect of reality, valid within a certain area of parameters. In the tripartite structure of a theory, the limits of the validity of its nucleus are indicated by the periphery. The status of *proven* regarding a scientific statement implies demonstration of its coherence with the nucleus of certain adopted theory, being verified empirically and theoretically. It is in this sense that a scientist never claims "absolute proof"—any proof draws on the nucleus of certain theory (principles), but it does not make the claim tentative. To call the myriad of products of classical mechanics, thermodynamics, and electrodynamics "tentatively

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[50] In religious Judeo-Christian literature, the knowledge of ultimate truth is labeled *gnosis*. In similar sense, in Soviet Russia, all students learned *gnoseology* that apparently replaced *epistemology*.

[51] It is, however, not a divorce from philosophy but rather a recognition of complex relationship (Russell 1912/1990). Bunge wrote: "What is obvious to the practitioner of a science may be problematic to its philosopher" (Bunge 1973, p. 28). Why, then, not ignore philosophy? Bunge answered, "Ignore all philosophy and you will be the slave of one bad philosophy" (Bunge 1967b, p. 261) and elaborated (Bunge 2000, p. 461), "Physics cannot dispense with philosophy, just as the latter does not advance if it ignores physics and the other sciences. … Science and sound (i.e., scientific) philosophy overlap partially and consequently they can interact fruitfully. Without philosophy, science loses in depth; and without science philosophy stagnates." The clarification of the difference between episteme and gnosis may illustrate the importance of philosophy for science education and the different context of their activity.

[52] This perspective may resolve the confusion of those who do recognize the progress of science but do not see it approaching the truth about nature (Kuhn 1970, p. 170). The approach of science is not linear but multifaceted in different aspects of truth revealed in greater and deeper extent by several fundamental theories.

correct" presents a highly misleading assertion erasing the meaning of being erroneous and incorrect. All the discoveries and inventions rewarded by a Nobel Prize were *proved* to be true.[53] Furthermore, to *explain* a natural phenomenon scientifically means in physics to demonstrate its coherence with the tenets of a certain fundamental theory. Proving is a working norm in a scientific laboratory as well as in school science classes.[54] Researchers often deal with tentative knowledge in the course of their exploration of new objects, but in this process, they draw on the enormous amount of *certain* knowledge previously established as factual.

Science textbooks and teachers tell their students that Aristotle proved[55] the spherical shape of the Earth and Archimedes proved the law of the lever and the law of buoyancy. Galileo proved that Venus rotates around the Sun and not around the Earth. Pascal and Boyle proved the existence of atmospheric pressure and vacuum. Newton proved the oblateness of the Earth globe and that tides are due to lunar attraction. All these facts are taught not as *tentative* but as *certain* results derived through drawing on scientific theories and verified by corresponding experiments and predictions. The certainty of science reached tremendous accuracy on molecular, atomic, subatomic, and cosmic scales. How can a teacher, following Popper's claim (above), declare that all scientific knowledge is tentative while presenting numerous factual discoveries and products of our knowledge about nature? Is the word "tentative" sufficiently representative in the context of education for the numerical accuracy of 10^{-11} reached in the experimental approval of the advanced physics theories (e.g., Feynman 1985/2014, p. 7; Sokal and Bricmont 1998, p. 57)?

No doubt it is not easy to establish certainty. It may require much time and effort, often complex technology and a variety of experiments carried out by independent research groups. During the ongoing inquiry, which can take years, the scientific claims under investigation could be addressed as *tentative*. Therefore, in the context of education, to avoid confusion and to distinguish science from other areas, one should present the variation of tentativeness between its extremes: from an argumentative hypothesis to certitude (Fig. 6). Each scientific result or claim should be considered within this span from hypothetical and tentative to certain and accurate. The atomic structure of matter may illustrate the historical change of knowledge status along the time axis, from a speculative hypothesis to the objective fact to be taught as such.

Let us further exemplify through the knowledge of the electron as an elementary particle. An electron, within the theory of classical electromagnetism, presents a particle with certain, clearly determined characteristics (mass, charge, spin). Within quantum theory, the electron becomes a Quanton (quantum particle, Lévy-Leblond 2001), which in addition to the old possesses new features corresponding to the nature of the quantum world (includes non-classical "wavity," manifested in diffraction). Physics, as a subject of education, does not

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[53] As a rule, the Nobel Prize is not provided for a theoretical contribution, unless it was proven empirically: thus, in Medicine of 1945, awarded for the discovery of penicillin and its curative effect that saved the lives of millions and proved the theory of immunology; likewise, the Nobel Prize in Physics of 2017, given for the observation of gravitational waves that added another proof of correctness of the Theory of General Relativity.

[54] Physics teachers prove Kepler's laws, work-energy theorem, Bernoulli equation, Galileo's claims regarding projectiles and so on and so forth from the endless list of examples of proving in physics class. Physics textbooks are abundant with proofs/demonstrations.

[55] By being proved the textbooks (and so the teachers) normally mean revealing the mechanism by which the considered claim is coherent with certain fundamental physical theory, its principles (nucleus). The proving procedure may include theoretical and/or empirical activities. The textbooks apparently aim to the *context of disciplinary education* addressing the established rational knowledge (episteme) rather than *philosophical debate* regarding the absolute truth (gnosis).

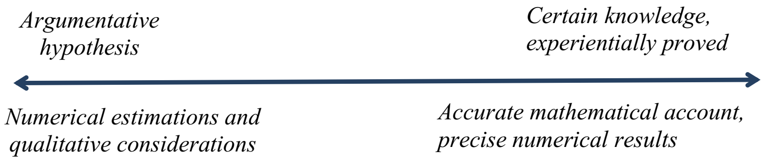

Fig. 6 Span of variation of tentativeness of scientific claims in the context of science education

address concepts, such as electron, in their absolute universal amorphous sense, but within specific fundamental theories. Physics theories, classical and quantum, were produced in historical sequence. One may see them holistically as a development of knowledge, its progression. Yet, in each of the two fundamental theories, classical and quantum, the electron presents a well-defined object explaining a vast amount of natural phenomena and revealing new facts about nature, not merely tentatively but with certainty. The perspective which does not recognize the theory-based structure of science may bring the learner to the claim of the all-tentative nature of knowledge, which makes sense as *gnosis* but senseless as *episteme* adopted by science.

3.7 The Myth of the Scientific Method

Considering the topic of scientific method, L1 (Lederman et al. 2002, p. 501) states:

> One of the most widely held misconceptions about science is the existence of the scientific method.

In the following, the authors moderated this claim which could be understood as dismissing any canon of the scientific method contrasting it with other approaches to knowledge production:

> The myth of the scientific method is regularly manifested in the belief that there is a recipe-like stepwise procedure that all scientists follow when they do science. This notion was explicitly debunked: There is no single scientific method that would guarantee the development of infallible knowledge.

This formulation might be misleading regarding constantly applied specific knowledge (*techne*)—method—of production the scientific knowledge (*episteme*), continuously developed and meticulously refined throughout the history of science. The method included logical proof, measurement, mathematization, modeling, scaling, systematic observation, and specific types of experiment through which scholars act and produce reliable knowledge. The scientific method was, and is, what makes knowledge scientific and distinguishes it from other kinds of knowledge.[56]

Addressing the scientific method often alludes to a certain sequence: (a) defining the problem; (b) gathering background information; (c) forming a hypothesis; (d) making observations; (e) testing the hypothesis; and (f) drawing conclusions (Hempel 1966, p. 11). Though one may consider this list schematic and requires refinement, it indeed characterizes the specific approach of science which is different from other non-scientific approaches used in problem-solving (intuition, traditional knowledge, magic, etc.).

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[56] For example, Losee 1993, pp. 120–136; Gower 1997; Lakatos 1999, pp. 19–108; Betz 2011. See Appendix 3 for an artistic illustration of the scientific method as emerged in antiquity. Furthermore, the well-defined scientific method does not imply a simple demarcation in any scientific context. Thus, the context of inquiry may violate the strict rules, which, however, emerge later on as unavoidable in the context of justification, considered above.

A close look reveals, however, that denying a "recipe-like stepwise procedure" does not imply a lack of method. In the much-quoted critique of the scientific method in *Against Method*, Feyerabend (1993) wrote: "I argue that all rules have their limits… I do not argue that we should proceed without rules and standards" (p. 231). Scientists normally practice "methodological pluralism" (Feyerabend 1999, p. 216) showing an amalgam of philosophical approaches. Feyerabend's "anything goes" (p. 296) apparently addressed the context of inquiry rather than the context of justification. Einstein (Einstein 1949/1979, pp. 683–684) elaborated on the former:

> He [the scientist] therefore must appear to the systematic epistemologist as a type of unscrupulous opportunist: he appears as *realist* insofar as he seeks to describe a world independent of the acts of perception; as *idealist* insofar as he looks upon the concepts and theories as free inventions of the human spirit (not logically derivable from what is empirically given); as *positivist* insofar as he considers his concepts and theories justified *only* to the extent to which they furnish a logical representation of relations among sensory experiences. He may even appear as *Platonist* or *Pythagorean* insofar as he considers the viewpoint of logical simplicity as an indispensable and effective tool of his research.

Importantly, scientific knowledge itself serves as a tool for achieving new results and so presents a methodology (Popper 1962). Lakatos considered fundamental physics theories, such as Newtonian mechanics, as a methodology calling it a *scientific research programme* (Lakatos 1980). Rephrasing Engels' maxim of 1876 in *Dialectics of Nature* regarding hand and labor, we may say scientific knowledge is not only the product of a certain method, but that the certain method is the product of scientific knowledge. The role of a specific method is especially striking in modern physics, quantum and relativistic. Heisenberg defined scientific knowledge as nothing but the knowledge that obtains its substance and meaning through specified tools (Heisenberg 1958, p. 58, 81).

In specifying the scientific method, we draw on the inclusive, empirically tested fundamental theories structured hierarchically and on the specific mechanisms of knowledge production.[57] The features of the scientific method include *mathematization* of the account of reality (seeking numerical accuracy), theory-based *modeling*, *experimentation*, testing through *prediction and reproduction*, and *statistical analysis*—all highly developed in science. One may consider, as evidence of a specific method, the fact that its violations lead to the fiasco of pseudoscience—the cases of systematic violation of certain aspects of the scientific method (astrology, alchemy, Lysenkoism, cold fusion, creationism, etc.).[58] While the historical offshoots of science contributed in observation, experimentation, terminology, data classification, and conceptualization (e.g., Hoskin 1997; Glashow 1994; Lindberg 2007), their separation from science illustrated the inadequacy of "anything goes."[59]

The components of the scientific method comprise an inquiry, not as a protocol procedure, but logically related components that contribute to the continuous process. Imagination and

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[57] We consider as important pedagogy the strengthening of the *specific* features of the scientific approach to knowledge production rather than stating that "the same methods are used by all effective problem-solvers" and that "science is no different from other human endeavors when puzzles are investigated" (McComas 1998). Similarity and adoption of scientific method in other areas of activity should not bring the learner to missing the identity of the scientific method.

[58] See Kuhn (1957) and Lakatos (1998) with regard to astrology, Read (1995) for alchemy, Birstein (2001) for the Lysenko case, Huizenga (1993) for cold fusion, and Roob (2001) for mysticism. Each case was analyzed and contrasted with the scientific methodology. The split from science often followed periods of interwoven activities. Astrology and mysticism went a long way with astronomy. The claim of correspondence and relationship between macro-cosmos (the world) and micro-cosmos (the human organism) considered scientific for centuries.

[59] A special issue we should mention here is the violation of ethics in medical investigations such as Nazi medical experiments which led to the establishment of the Nuremberg code for such experimentation (https://encyclopedia.ushmm.org/en).

creative leaps provide variation but do not change the idea of an inquiry loop. Newcomers join research projects at any stage within the process termed *enculturation*.

Mathematization appeared to be among the most distinctive features of the scientific method first proclaimed by Plato (2003) as the way to reveal truth, despite deception by the senses. Mathematics followed the scientific enterprise through all its history until it became a requirement of modern science.[60] Mathematization is observed in the history of natural sciences as a tool for breakthrough achievements.[61] It thus presents an indicator of maturation, providing clarity and distinctness of scientific statements which through becoming quantified are easier to critique and falsify.

Modeling is another central feature of the scientific method. The replacement of reality by conceptual or mathematical models enables its effective representation and treatment through simplifying both the subject (to be simpler than reality) and its investigation (to be simpler than applying a full-scale theory). Within the conceptual model of discipline-culture, one may distinguish between three basic kinds of models—paradigmatic, working, and heuristic—ascribing them to nucleus, body, and periphery of a theory respectively.

Scientific method obliges "gathering information" and selecting a proper theory prior to any problem-solving, searching for similar problems discussed and solved. Solving problems starts with copying others, learning and applying the known methods in a new context. Kuhn (1970) stated normal science as "puzzle-resolving" within certain paradigm, following standard prescriptive and prohibitive rules and norms. Objectivity is one of them (Popper 1959, p. 34).

Teaching the scientific method may start from simple cases of a logical Hempel-like procedure including observation and empirical verification of a spontaneously emerged hypothesis (e.g., Khan Academy 2017). Yet, seeking representative inclusiveness, a science teacher should proceed to refinement. With regard to content, effective instruction can use a contrast with the cases where violating the scientific method led to failure.

4 Summary of the Refinement

Table 1 reproduces our results of refinement of the L1-L5 lists. In most cases, the univocal tenets were replaced by a range of variations, including opposites, thus providing a more adequate account of NOS features.

5 Discussion

Our review of the L-list has touched on the essential aspects of NOS and showed that, behind each of its items, there is a non-trivial facet of science and a range of meanings. Univocal tenets, seeking so-called golden middle, are usually non-representative, missing important aspects of NOS. Refinement appears to be essential.

Indeed, the L-list succeeded to capture seven central epistemic aspects of the scientific knowledge—the status of knowledge, its features of accuracy, dependence on the producers

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[60] See, for example, Neugebauer (1993) for Babylonian and Egyptian science, Berry (1961) and Dreyer (1953) for Hellenic astronomy, Russo (2004) for Hellenistic science, Pedersen and Pihl (1974) for medieval science, and Kepler (1621/1972) and Gorham et al. (2016) for modern science. Galili (2018).

[61] It is clearly observed in the actively progressing disciplinary areas such as quantum chemistry, physical chemistry, and molecular biology.

and their environment, the method of construction. These aspects naturally attract curiosity. We argue that meaningful investigation of such issues implies addressing the range often including opposites—objective-subjective, tentative-certain, socially dependent–independent, creative-algorithmic, theoretical-empirical, unique-plural and so on. This reveals the complex reality, prepares for adequate understanding and allows refinement which widens the sense, context, and the depth of coverage of each claim. Such expansion often reconciles different univocal claims which appeared addressing different meanings, contexts, and levels. Such is, for instance, the issue of objectivity of scientific knowledge. If the meaning is not placed against the context (inquiry or justification), the claim can easily be misleading, as it was in the L-list. Specific knowledge is required to cope with this challenge implying familiarity with the complexity and the conditional preferences made.

We argue that complementarity of opposites in the NOS features requires simple illustrations in actual teaching. Rather than claiming overall tentativeness of all products, one should specify the changing status in this regard. The discipline-culture structure provides an adequate platform for making explicit the areas of validity of different theories and laws and the relationship between them. In the triadic structure of a theory (nucleus-body-periphery), the meaning of the nucleus is emphasized by contrasting it with peripheral elements. Cognitive psychologists argue that variations of the subject learned, especially in the negative sense (emphasizing "what it is not"), are preferable to resemblance and stipulate meaningful learning (Marton and Pang 2006, 2013).

Comparison between the opposites in the range of NOS features stimulates the learner to realize a very important feature—the stipulated nature of all scientific claims. It upgrades the naïve ideas of univocal claims of subjective, tentative, universally valid "laws" often erroneously ascribed to science. Students will reveal the validity of asking "In what sense? Under what conditions? How do we know that?" *before* providing an answer realizing that it is valid in the particular circumstances and invalid in others. They will reveal that the non-specified, in this sense, claims with regard to the features of NOS might look vague and dubious.

Furthermore, we bring attention to the reciprocal relationship among complementary pairs of NOS features. Observations and inferences, theoretical (conceptual) and experimental (practical) activities, and rationalism and empiricism in the method show *continuous reciprocity* producing *iterative evolution* in science.[62] This feature belongs to the mechanism of reaching objectivity of scientific knowledge. Iterative reciprocity seems to us elucidating in understanding conceptual progress, the mechanism of complementary and evolutionary epistemology.[63] Such a relationship between science and the philosophy of science clarifies the naturalized philosophy of science (Godfrey-Smith 2003, pp. 149–150), as well as the continuously interchanging leadership between physics and mathematics (Galili 2018).

Our refinement addressed *physics* in the first place. Only a few examples touched on chemistry. This is because the NOS characteristics are easier to introduce in their simplest forms.[64] This vision echoes Schwab's (1978) recommendations to teach disciplines starting from that which draws on a

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[62] It is different from Darwinian evolution (Toulmin 1972, pp. 140–141) and rather corresponds to the perspective of historical materialism elucidated by Popper's vision of sequential dialectical conjectures and refutations. The *reciprocal evolution* changes the participants, the researchers, and their knowledge, in the process of conceptual progress. To describe such reciprocal change, Paget introduced the complementary aspects of assimilation and accommodation.

[63] This way, Mach (1883/1989), Einstein and Infeld (1938), Taylor (1941), Glashow (1994) depicted the history of science.

Table 1 Summary of refinement for the considered list of NOS features

#	L1-L5 lists	Suggested refinement
1	Scientific knowledge, owing to scientists' theoretical commitments, beliefs, previous knowledge, training experiences, and expectations, is unavoidably *subjective*	Scientific knowledge is *objective* as collective knowledge essentially independent of personal will and values. Scientific inquiry may include subjective elements in form and interpretation. Exclusion of subjective aspects takes place in the context of knowledge justification, through the continuous many-faceted experimental verification, iterative steps of exploration, and community discourse of scholars.
2	The distinction between *theories and laws*. Laws are statements or descriptions of the relationships among observable phenomena. Theories, by contrast, are inferred explanations for observable phenomena.	Scientific knowledge is comprised of fundamental *theories*—inclusive clusters of various knowledge elements, coherent and hierarchically organized. Each theory is valid in a certain area of validity. A fundamental *theory* is structured in a *nucleus* (basic concepts and principles) and a *body* containing derived and associative elements of knowledge coherent with the nucleus. *Periphery* may be added to include the elements of pertinent knowledge at odds with the nucleus. *Laws* present stable functional relationship among the characteristics of natural phenomena in a variety of settings valid in a certain area of validity. Laws are normally affiliated to a particular theory. Laws of different status (theoretical and empirical) belong to all three areas of theory structure.
3	The development of scientific knowledge involves human imagination and creativity	The development of scientific knowledge draws on a continuous disciplinary discourse within the scientific community. It involves imagination and creativity while drawing on the previously developed knowledge taken as given.
4	The empirical nature of scientific knowledge. The distinction between observation and inference	Scientific knowledge is essentially theoretical and draws on empirical verification. Observation and inference differ, but they are intrinsically interwoven as are empirical and theoretical aspects of scientific knowledge.
5	The social and cultural embeddedness of science. Scientific knowledge affects and is affected by the various elements and intellectual spheres of the culture	Science presents the objective theory of nature and at the same time, it is a cultural product. Social and cultural environments affect scientists in their activities, agenda, forms and ways of knowledge production. Yet, the practical content of scientific knowledge, its essence, conceptual and operational meanings can be independent of social and cultural environment. Committed to objectivity, science products and knowledge can be valid across different societies and independent of them.
6	The tentative nature of scientific knowledge; scientific knowledge is never absolute or certain. This knowledge, including "facts," theories, and laws, is inherently tentative or subject to change	Science continuously advances, producing knowledge of different status of validity and reliability ranging from hypothetical and tentative to certain and accurate. Proving claims in science presumes demonstrating their coherence with a certain theory, theoretical and/or experimental verification using scientific methodology. All fundamental scientific theories are empirically proved and valid in certain areas of basic parameters (such as length, time, mass).

Table 1 (continued)

#	L1-L5 lists	Suggested refinement
7	Myth of the scientific method (absence of unique recipe-like stepwise procedure)	The scientific method possesses a plurality of specific norms, procedures, and prescriptive and prohibitive rules. Scientific inquiry unfolds in a spiral sequence of repeating components. It includes iterative hypothetico-deductive cycle, experimentation, modeling (idealization), mathematical account, logical rules, and qualitative and quantitative analysis of the collected data, seeking causal stable relationships between the characteristics of natural phenomena and material systems. Fundamental theories serve as methodological programs of knowledge production.

minimal number of irreducible substantives, that is, from physics to biology, or vice versa, from more holistic accounts to the fundamentals (from biology to physics). In fact, facing the need to reduce also the time of instruction, the school curriculum of sciences traditionally goes both ways simultaneously even within each scientific discipline. This awareness is required for curricular decisions in secondary schools to prevent excluding some of the science disciplines from the requirement.[65]

6 Possible Implications to Teaching NOS

Duschl and Grandy (2013) reviewed relevant studies and stated the advantage of long-term courses (“weeks and months long”) adopting *naturalized* epistemology to teach NOS features.[66] A similar suggestion was to learn from, about, and with scientists (Hodson and Wong 2017). This approach goes against the direct teaching of the tenets as a list of features. In our view, dealing with isolated practices of “doing” science can be informative about the context of inquiry, but is only evidentially and fragmentally suggestive regarding the norms, the big picture of the scientific knowledge. The context of the regular teaching of science, the learning *about* science “from outside” (Vygotsky 1934/1986), is different from practicing science. In regular teaching, science teachers might introduce short discussions on this or that aspect of NOS as is relevant to the subject being learned, but they, the teachers, need to know their goals, the concepts they aim to teach clearly and distinctly (e.g., Osborne et al. 2003; Osborne 2017), and for that, the list of tenets, as presented in Table 1, is of high validity. It directs and stimulates consideration, suggests conceptual framework, and offers variations of each idea to be contextualized as was illustrated above. Such content is not likely to be

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[64] An anecdotal evidence is due to George Feher, Wolf Prize winner for understanding photosynthesis. Answering why he was successful where others failed, Feher said that, as a physicist, he carried out his study with the simplest bacteria instead of investigating the emblematic object performing photosynthesis—a tree leaf, which is a much more complex.

[65] If natural sciences present elective courses in high school curriculum, students often chose one of the science disciplines, sometimes, excluding physics. Such arrangement contradicts the presented perspective on the required complementarity of simple and complex to appreciate NOS.

[66] Duschl and Grandy (2013) mentioned the development of the philosophy of science as possessing three periods focusing on (1) epistemology, (2) scientific knowledge as social phenomenon, and (3) scientific practices—naturalized epistemology. Apparently, all three perspectives are required in constructing the big picture of science.

arrived at by novices if not explicitly guided. Special teacher training is required to know and to preserve the values and norms of science clearly and distinctly.

In the past, we introduced HPS-based materials in a yearlong course on optics in high schools, in keeping with a discipline-culture curriculum. We observed a clear, positive impact on students' content knowledge (Galili and Hazan 2000). Though our assessment showed positive impact on students' ideas about NOS (Galili and Hazan 2001), they learned less than they would have had if we had stated explicitly the set of NOS tenets of Table 1.

Furthermore, in the spirit of naturalized epistemology, it seems that dealing with HPS for teaching science is preferable in the form of historical *excursus* (Galili 2012) rather than isolated *case studies.* Excursus better reveals concept consolidation within "evolutionary perspective" (Giere 1985). We aimed at the construction of cultural *content* knowledge (CCK) in students. In a similar manner, we may expect that excursus addressing of NOS tenets in their range of variation may promote cultural *epistemic* knowledge (CEK).

Another approach suggested for reaching CCK was a summary lecture as a delay organizer of knowledge in a discipline-culture format (Levrini et al. 2014; Goren and Galili 2018). Significant improvement of CEK was also observed there. We may suggest that the summary lecture will emphasize the items of NOS list in parallel with the disciplinary concepts, drawing on the just constructed content knowledge in the regular disciplinary course.

In applying any of the three suggested ways of teaching, one may direct and stimulate students' learning of NOS while engaging them with the following questions:

1. How are humans, each a *subjective* individual, able to create *objective* knowledge about the world? How is objective knowledge possible and how can it be preserved through the history of different societies?
2. How do scientific products, created as tentative accounts, transform and develop into a certain and accurate knowledge of science?
3. How does scientific knowledge arrange its numerous elements (theories, laws, concepts, models, principles, experiments, explanations) in coherent and hierarchical systems of knowledge?
4. In what way is scientific knowledge universal?
5. How does the cultural social environment influence the scientific activities and products? What are the limits of that influence?
6. What are the constraints of creativity and imagination in establishing the scientific knowledge of nature?
7. What are the specific rules, tools, activities, and restrictions in the creation of scientific knowledge? What is not considered as science?

7 Conclusion

The NOS features of the L-list deconstructed the holistic account of science and the scientific method as depicted by Merton (1973) and Hempel (1966, 1983), among others. However, the major benefit of the L-list is its focus on the collection of central features of NOS feasible to consider in a regular teaching of science in school classes. In our view, a significant expansion of the list to a more inclusive but a much longer one could blur the major features of science and diminish the ability of students to distinguish scientific knowledge and method from other kinds of cultural products. Equally, avoiding to state NOS features explicitly and leaving their discovery to the teachers in schools may easily cause inadequate and fragmentary knowledge of NOS. Therefore, we argue for teaching the list of NOS tenets, refined, illustrated, and contextualized explicitly.

It is suggested to expand each traditional univocal tenet of NOS with a range of its variation, that is, consider “deep truth” concepts, in order to prevent oversimplification and one-sidedness of teaching and learning. Scientists and philosophers can contribute to constructing more mature curricula of science disciplines clarifying the fact that NOS tenets cannot be too simple (Einstein’s epigraph to the paper) nor univocal (Sakharov’s epigraph). Within this perspective, a discipline-culture framework of scientific knowledge can be of essential and efficient support.

Compliance with Ethical Standards

Conflict of Interest The author declares no conflict of interest.

Appendix 1

Images may effectively facilitate science teaching and presentation to wide audience. Art provides appealing images of the symbiotic relationship of Reason and Experience as the essential feature of knowledge and method in science (Galili 2013). Such is Rafael’s renowned collective portrait of *The School of Athens* (1501). The fresco in the Vatican has as its focus two figures of the founders of natural philosophy, Plato and Aristotle, who present through their gestures Reason (Rationality) and Experience (Empiricism) symbolizing their symbiosis in science (Fig. 7a).

Another image of Far East art is on display in the National Museum of Seoul. It employs similar symbolism of the idea of cosmic complementarity in a no less appealing way (Fig. 7b). The two components are represented by the interwoven figures symbolizing the Earthly and Heavenly origins, rationality and experience. The right-angle tool symbolizes the Earth, considered to be of rectangular shape by Eastern scholars in the past. The compasses represent rationality since the Heavens were considered to be of a round shape. The Korean image is even stronger, showing the intertwined basis of the two figures possibly referring to the emergence in process.

Appendix 2

The essential independence of social environment does not dismiss the question why, despite the international nature of scientific enterprise at the present time, it was invented in Greece and nowhere else; why modern science was developed in Europe two thousand years later, not in other places. Why the long intellectual tradition of interest in nature in China and India did not achieve a similar outcome? This question is known as the Needham Question (Needham 2004; Sivin 2005; Gorelik 2012; Goren and Galili 2018). As a possible answer, we may mention that human history, being one whole comprised of interacting components, prevents isolated paths of development which could need more time for otherwise independent growth. It is enough for one trend to develop faster than another, for any reason, that its products would influence scholars in other societies preventing their original inventions and thus dragging them to adopt the trend of others with respect to consolidation of specific scientific knowledge. Adoption, repeating and copying methods and discoveries through learning from others, are much easier way than developing original conceptual construction. This reality can

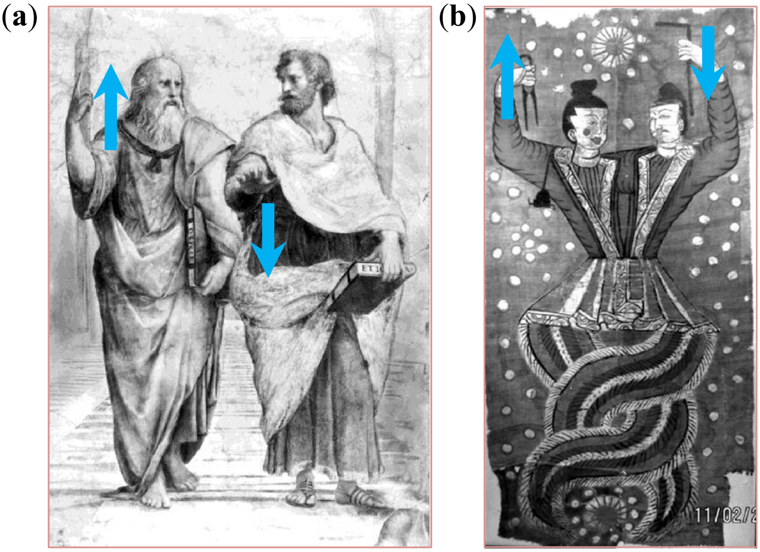

Fig. 7 **a** schematic reproduction of the fragment of Rafael's *The School of Athens* (1501) in the Vatican. **b** Knowledge creation in the anonymous picture in Seoul National Museum. (Arrows are added for emphasis)

undermine cultural originality and can cause a collective universal mode of scientific knowledge development by humankind.

Appendix 3

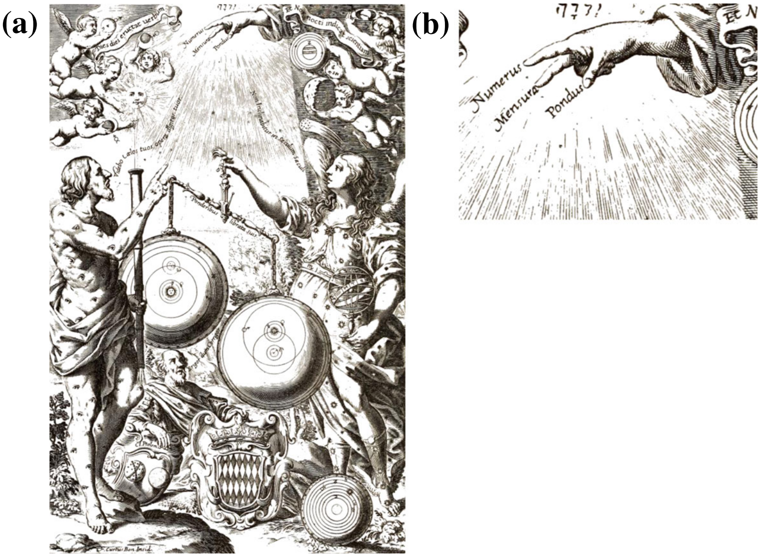

Fig. 8 (**a**) Representation of a theories contest in cosmology as depicted on the front page of the book by Riccioli (1651). (**b**) The fragment presents the scientific method "Numerus, Mensura, Pondus" (Number, Measure, Weight) adopted from the *Book of Wisdom* (11:21) of the 1st century

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