Chapter 8
Scientific Knowledge as a Culture: A Paradigm for Meaningful Teaching and Learning of Science

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8.1 Introduction

Science education research in part studies the ways in which scientific knowledge is represented for teaching and learning purposes. Such a goal naturally seeks to be informed by the most representative and essential features of scientific knowledge as established by research in history and philosophy of science (HPS). Though educators share many views in this regard, there is controversy regarding some features which are of principal importance (Matthews 2012; Lederman et al. 2014): objectivity-subjectivity, theory-experiment, theory dependence of observation, tentativeness-certainty, theory-model and theory-law relationships, etc. A recently published HPS&ST *Handbook* (Matthews 2014) represents the wide breadth of the pertinent discourse in this regard, and this essay touches on some of it in relation to the new inclusive framework of curricular contents oriented to Cultural Content Knowledge (CCK).

The problematic of this discourse stems from the complexity of science teaching and the multidisciplinary nature of research in the field. Science teachers require knowledge of subject matter, pedagogy, cognitive science, history and philosophy of science (Fig. 8.1). Commonly, the first three are addressed in pre-service programs of teacher training. Yet, even a basic knowledge of history and (especially) philosophy of science is very often totally lacking in such programs.[1] In such a situation, teachers' knowledge of the philosophy of science is inevitably superficial and this makes them an easy prey of various trends of superficial philosophical thought.

Seeing frequent confusion regarding epistemology among teachers encouraged us to look for a curricular framework, which could protect the practitioner providing

[1] For instance, this is the situation in Israel.

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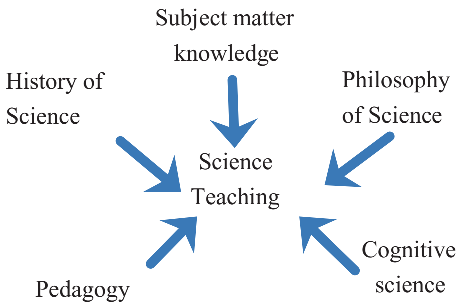

Fig. 8.1 Areas of proficiency required from science educators

a wider a more mature representation of scientific knowledge – metaknowledge, drawing on basic aspects of HPS. The core idea of the suggested change is to consider *scientific knowledge* as a kind of *cultural system*, a discourse of ideas rather than a univocal discipline. This perspective mediates between scientific knowledge and the learner constructing understanding of science.

In the following, we will first depict science knowledge composed of a few fundamental theories as a special type of culture, so that disciplines become discipline-cultures (Tseitlin and Galili 2005). We will review applications of this paradigm to the contents of science curriculum: presenting scientific revolutions, involvement of HPS, conceptual change of students learning science and their interests in science. The essay proceeds and depicts the implementations of CCK (Cultural Content Knowledge) perspective in three curricular approaches: CCK based curriculum, conceptual excursus and summative lecture. Finally, the cultural perspective expands on some epistemological issues suggesting complementarity and integrated account in order to clarify and refine such epistemological oppositions as theory-model, objective-subjective in scientific knowledge.

8.2 Knowledge as a Culture

The term *culture* is extremely inclusive. It designates the entirety of human products (Tylor 1871/1920). Hofstede (1991) reduced it to a subset of material and spiritual products with the productive activities distinguishing one group from another. Thus, science is clearly distinct from history, religion, philosophy, arts, even if it is often interwoven with them. It employs a different methodology, possesses different goals and values. It is common to consider science as interacting *with* culture in specific social aspects (e.g. Bevilacqua et al. 2001). Other researchers elaborate the features characterizing the activities, behavior, internal relationships of scientists as a social group (e.g. Latour 1987). Still another popular meaning of culture considers ethnical traditions, habits of different civilizations in the ways they accounted for nature, the kind of knowledge and knowledge production different from those adopted in the western science (e.g. Aikenhead, Aikenhead 1997; Ma 2012; Liu 2015).

Physics knowledge, as we know it, is composed of a few fundamental theories, each presenting an organized and internally coherent set of interrelated concepts, principles, laws and their derivatives all together describing and interpreting features of world organization in a unified structure (Heisenberg 1959/1971; Weizsacker 1985/2006; Weinberg 1992).[2] Each such theory presents a "picture of the world" (Einstein 1918), valid not globally but in a certain area of experience and degree of accuracy/reliability.

There is a specific perspective in which knowledge itself is considered as a culture (Lotman 2010). Lotman distinguished two types: the culture of rules and the culture of texts. Within the first type, the well-defined rules regulate relationship among knowledge elements in certain area, making clear their correct-incorrect status (e.g. jurisprudence). The culture of texts allows grouping knowledge elements around canonical exemplars (e.g. art). One may consider scientific knowledge as a *culture of rules* composed of disciplines such as mechanics, electromagnetism, thermodynamics, etc. Each group of knowledge elements affiliated with a discipline can be represented by a fundamental theory structured in terms of nucleus-body-periphery – "discipline-culture" (Tseitlin and Galili 2005). Such representation is not only hierarchical but also reflects scientific knowledge as inherently discursive, yet specific in validation in terms correct-incorrect and including epistemological norms. Considering scientific knowledge as a culture creates an encompassing and adequate picture of such knowledge. It may serve as a guidance in the selection relevant HPS materials in the curriculum design, clarifying their role and possible involvement. This approach was exemplified in developing the historico-philosophical perspective on teaching optics (Galili 2014).

Discipline-culture codifies scientific theory in a tripartite structure (Fig. 8.2). Its first area, *nucleus,* includes fundamentals – the principles of ontological and epistemological nature, paradigmatic model and basic concepts. The second one, *body knowledge*, includes the elements subdued to the nucleus. They could be derived from and reduced to the fundamentals as well as being empirical and non-contradictive with the nucleus. *Body knowledge* incorporates more specific laws, secondary concepts, explanations of particular phenomena, experiments (actual and

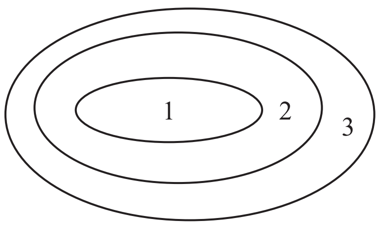

Fig. 8.2 The structure of discipline-culture: *1*-nucleus, *2*– body knowledge, *3*- periphery

[2] Though we address the fundamental theories of physics, the stated regarding theory representation holds also regarding theories in biology (e.g. theory of evolution) and chemistry (e.g. classification of elements).

thought), technology, etc.[3] To better represent the nature of scientific knowledge as a culture, one should, however, expand and include elements of a third type – *periphery*. The elements of periphery are at odds with the pertinent nucleus. Periphery includes challenging problems and alternative accounts. By challenging certain nucleus, the periphery of the correspondent theory determines the meaning of the nucleus as well as informs about the boundaries of the theory so often remained implicit and not known to the novice. In that, periphery touches on the tradition of apophatic and comparative approaches in philosophy (e.g. Libbrecht 2009). Scientific knowledge codified and structured in terms of discipline-cultures, is defined as cultural content knowledge (CCK) and establishes a framework of the new type of science curriculum (Galili 2012).

Furthermore, since learning scientific concepts could be considered somewhat similar to the process of learning of a foreign language (Vygotsky 1986) – the learning "from outside" – identifying scientific knowledge as a culture cannot be left for students to discover; instruction should introduce the codification of knowledge and its structure.

8.3 Cultural Content Knowledge Advantages

8.3.1 Scientific Revolution and History of Physics

We can apply the introduced structure to representation of conceptual change taking place in science during scientific revolution, replacement of the fundamental theory. Instead of seeing this process as a sequential exchange of theories, each dismissing the previous, CCK suggests an inclusive and more realistic image incorporating competitive ideas. This is because:

> At almost any period in history, one can find a vast range of ideas existing simultaneously. The important question is which of the variety of ideas available at an earlier period got adopted and transmitted to later periods, and thus shaped later interpretations. (Giere 1999, p. 88)

Consider, for example, the theory of how the world is organised. Its first scientific account took the form of the geocentric theory. Its *nucleus* included principles of Aristotelian physics, the paradigmatic model of concentric spheres, fundamental concepts (circular motion, spherical universe, the basic elements, etc.). The *body knowledge* of that theory included working models of Eudoxus and Apollonius,[4] auxiliary concepts (epicycle, equant), accounts of seasons, equinoxes, eclipses and other

[3] This definition excludes identification of a theory as either syntactic (based on axioms and theorems) or semantic (based on models) type (van Fraassen 1980, p. 44; Giere 1988, p. 48), incorporating knowledge elements of both types in addition to principles, concepts, experiments, epistemological rules, etc. In fact, it depicts a theory as it is used and taught in physics class: classical mechanics, electromagnetism, thermodynamics and so on (Tseitlin and Galili 2005).

[4] For simplicity, we may ignore here the mismatch of epicycle-based model with Aristotelian principles, which caused Lakatos to introduce *protective belt* around the core of the theory (Lakatos 1978).

phenomena as depicted in Ptolemy's *Almagest*. The body knowledge included collected data, instruments (quadrant, Jacob's staff) and methods of measurement (parallax, shadow patterns). Importantly, however, the rival (heliocentric and Earth spinning) accounts of Pythagoras, Heraclites, and Aristarchus were present from the beginning establishing permanent debate (Ptolemy 1952, pp. 6–14; Heath 1966). Various scholars continuously introduced new elements of periphery through the period of two millennia. The increasing tension between the nucleus and periphery caused the revolutionary change, a breakthrow and rearranging of elements: during the Copernican revolution, the heliocentric model moved to the nucleus, and the geocentric model – to the periphery. The body elements transformed to adjust the new nucleus.

Importantly, the elements of the new and old knowledge were interrelated within one system. One may get this spirit of conceptual unity and continuity from Einstein's perception of his contribution to physics theory. He wrote to his biographer (quoted in Miller 1986, p. xx):

> With respect to the theory of relativity, it is not at all a question of a revolutionary act, but of a natural development of a line which can be pursued through centuries.

CCK-based description visualizes this pursuit in the space of scientific discourse, displaying the meaning of crisis and following revolutionary change as described by Kuhn (1957, 1970). Yet, in the *cultural* perspective, the knowledge elements of the old nucleus are preserved after being refuted. They remain within the horizon of the new theories of the world organization.

8.3.2 Theories Relationship

The controversy of fundamental physics theories is often addressed by claiming their *incommensurability* – an essential mismatch of the scientific paradigms (Kuhn 1970). The tripartite model of discipline culture allows clarification of this relationship. In particular, the nucleus of one fundamental theory ought to be located in the periphery of the other (Fig. 8.3). Yet, at the same time, the body areas of these theories may overlay representing the cases where the same phenomenon or problem is treated by the two theories producing *commensurable* results.

For example, in the limit of low velocities both classical and relativistic mechanics provide physically equivalent results despite the essential contradiction between the nuclei of these two theories. The tripartite structure illustrates the meaning of the

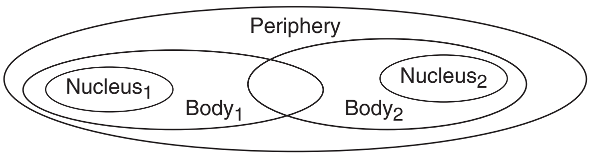

Fig. 8.3 Representation of relationship between two fundamental physical theories that contradict each other with respect to their fundamentals but may consider the same subject matter

principle of correspondence in physics knowledge. It is in this sense that continuity of scientific knowledge is maintained in science showing its cumulative nature as one of its major characteristics. Physics knowledge includes different theories, complementing each other. They establish relationship known as family resemblance, sharing some features and different in others. It allows to more advanced theories, to draw on the old accomplishments, problem solutions, rather than replacing altogether the previous knowledge. CCK envisions this type of relationship clarifying the nature of scientific holism and refining the metaphor of "patchwork" for scientific knowledge (Cartwright 2005). It is inadequate to represent scientific knowledge as a collection of non-related different pieces. Structuring the multiplicity of knowledge elements in a conceptually related web leads students to establishing *metaknowledge* defined as the knowledge of science as an organism in terms of its global features (Novak and Gowin 1984). CCK does it in terms of the tripartite structure.

8.3.3 Students' Learning

The tripartite structure of CCK suggests ways of representing individual conceptual change in learning science. Posner and associates (Posner et al. 1982) saw this process as similar to conceptual change in science and stated the epistemological conditions for that process to go – dissatisfaction, ineligibility, plausibility and fruitfulness. The individual conceptual change will be represented, then, in similar way to the change of the collective knowledge, as an exchange of contents between nucleus, initially containing naïve conceptions, and the peripheral contents created by the instruction. The implementations of students' naïve conceptions create corresponding body knowledge, which serves as a barrier for any change of the nuclear contents. The new knowledge due to instruction enters the periphery first. During the required conceptual change, the new concepts penetrate the nucleus and the naive ones move to the periphery.[5] Yet, facing a novel situation, students may retrieve the old contents and apply them again (Galili and Bar 1992). The metaphor of a breakthrough through the barrier of body knowledge may explain the difficulty of conceptual change, its essential difference from replacement as old software in a computer.[6]

Furthermore, periphery knowledge stipulates meaningful learning by creation of a "space for learning" (Marton et al. 2004). The periphery creates conceptual variation with respect to the goal of instruction. For instance, the genuine understanding of Newton's First Law as the cornerstone of mechanics[7] requires addressing alternative

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[5] Since 1982, the conditions for conceptual change were revised to include other factors. This, however, does not change the idea of using triadic structure to visualize the conceptual change as a breakthrough and elements transfer between nucleus and periphery.

[6] The factors instigating the breakthrough are compared, thus, to the difference of potentials between nucleus and periphery.

[7] Beyond being a special case of the Second Law, as often stated in disciplinary instruction (e.g. Galili and Tseitlin 2003).

accounts for motion – those by the Aristotelian and impetus theories. It is through identification of nucleus contents and their comparison with alternatives that conceptual change takes place both in the history of science and in individual learning.

In other words, by comparison of conceptual accounts, students may learn through considerations similar to those of scientists who changed their mind in the past (e.g. Galili 2015). The awareness of such changes is metalearning. CCK stimulates students' metalearning due to the created metaknowledge:

> Learning about the nature and structure of knowledge helps students to understand how they learn… Metalearning and metaknowledge are two different but interconnected bodies of knowledge that characterize human understanding. (Novak and Gowin 1984, p. 9)

8.3.4 Physics Curriculum

The CCK paradigm transplants easily to physics curriculum. In common teaching, the theory-based superstructure of physics knowledge is often barely emphasized. Instead, a sequence of concepts, laws, models, instruments, experiments, problems to solve and phenomena to explain flood the learners with a flux of knowledge elements without clear organization in a hierarchical structure, in effect promoting the image of a toolbox, or even a "patchwork" (Cartwright 2005). Physics educators often unfold the knowledge from simpler to complex as if building a unique and homogeneous construction.

The learner often gets an impression of a proportional accretion: the more one learns, the more one knows – more models, solved problems, explained phenomena, concepts and laws. Principles are often barely distinguished from laws which endlessly multiply themselves along the course. This perspective in which the laws might appear as "…neither universal nor necessary – nor even true" (Giere 1999, p. 90) is refined by discipline-culture organization. Indeed, physics laws are not universal and hold in specified areas of validity. Yet, the physics knowledge is composed of a few fundamental theories, structured hierarchically. They are much more than "rules for model construction".[8] Although different, they are related, epistemologically and ontologically. The diminished status of a theory in science curriculum may impede adequate appreciation of scientific knowledge as a culture.

Instead of a sequential presentation of non-interrelated contents, curricular designers may point to the triadic affiliation of each element of knowledge. We may learn of such approach from Newton. Dealing with specular reflection and refraction laws, he placed them in the nucleus of his *Opticks*. At the same time, in his *Principia,* the same laws appeared as elements of body knowledge: they were derived from the general principles of mechanics. Similarly, presenting thermodynamics one may place the state equation (Mendeleev-Clapeyron) in the nucleus as an empirically

[8] van Fraassen (2008, p. 266) says: "A well-constructed scientific theory will tell a story, a narrative in which the *why* is as clearly explained as the *what*, and we come to understand not only 'what happens' but 'what is really going on'".

based law, whereas in statistical physics the same law would be affiliated with the body knowledge backed by its microscopic underpinning.

The CCK approach emphasizes the nucleus in each theory, often missed in physics class. Thus, such contents of mechanics as space and time, relativity, interaction, inertia being ignored may mask the essential difference with their counterparts in electromagnetism.[9]

An important feature of the CCK based curriculum is inclusion of knowledge elements usually considered to be wrong or external, they are in the periphery of the considered theory. For instance, the curriculum of classical mechanics would incorporate the obsolete conceptions of Aristotelian violent and natural motion, medieval impetus. Moreover, such curriculum would point to *how* classical mechanics essentially is different from relativistic and quantum. It is also emphasized that the classical account is valid in the particular span of space, time and mass magnitudes. By variation, these extensions provide the meaning of the classical conception of motion in the unified picture of physics knowledge.

The appeal to the alternative ideas specifies HPS involvement surpassing a mere enrichment and scientific literacy. By bringing conceptual alternatives to the fore, the curriculum reveals diachronic and synchronic conceptual debates thus promoting meaningful learning of scientific disciplines.

8.3.5 Students' Typology

The tripartite structure of discipline-culture suggests a new typology of students with regard to their potential, interests and intentions. Instead of the division between scientists and non-scientists ("good" and "bad" in science) as reflecting "two cultures" (Snow 1959), students may be distinguished in their cognitive preferences towards the three facets of scientific knowledge corresponding to the three types of knowledge elements of discipline-culture. Some students may show interest in the rules of the world order (the nucleus), but remain reluctant towards their applications, problem solving, and are satisfied by being informed of the science fundamentals. Other students may prefer solving practical problems (body) taking general principles as given. Such individuals are focused on certain problems that attract them either by challenging their ambition of mastering scientific knowledge or being encouraged by their needs of different nature (e.g. social or techonological). Becoming a competent practitioner implies seeking proficiency in modeling and problem solving. The third type of students is interested in a different aspect of scientific knowledge. Facing the authoritative claims, they raise, however, a question why these laws and not others govern reality.[10]

[9]The contrast between nuclei of classical mechanics and classical electromagnetism is striking, since electromagnetism is essentially relativistic theory and employs field interaction.

[10]Allegedly, this was the question Einstein mentioned as the one he would ask God if a chance were granted.

The students of the first type – "observers-philosophers" – often meet teachers' remarks of being superficial, not practical and not serious enough. They are advised to engage in more practice, problem solving, and mastering of mathematical formalism. They are urged not to be "childish dreamers". Taking seriously such critique, such students often leave their science class and move over to humanities. This presents a real loss for our society that badly needs an enlightened population literate in science in order to make educated decisions in a modern democratic society. Worth listening to is one of the leading physicists of our time who said:

> What is important in science (I leave philosophy to others) is not the solution of some popular scientific problems of one's own day, but understanding the world. (Weinberg 2015, p. 24)

The students who are attracted to the body knowledge – "engineers" – do not need to be pressured. They often please their teachers and are usually supported by the school administration. Such students are often shown in media as easy to present and appreciate. Indeed, they comprise the great reserve for the practitioners, normal scientists and people of technology.

The third and most controversial type of student is attracted to the periphery knowledge – where there is debate over ideas. Such students – "investigators" – often challenge the teachers with philosophical questions. "Correct" and "incorrect" subject matter becomes equally interesting and deserve attention. Since such students may impede the flow of instruction, they might face not a favorable attitude. Yet, before they are called to order, one may recollect that the archaic "philosophical" ideas of *potentiality* and *actuality* in Aristotelian physics inspired the founders of quantum mechanics, students of classical gymnasium. It was the antique idea of the Cartesian plenum that led physicists to the introduction of the field concept to account for interactions in electromagnetism. The twentieth century introduction of photons was informed by the seventeenth–nineteenth centuries debates about the particle-wave nature of light in. Recycling of ideas is a norm in physics research and virtue of intellectuality. Therefore, the students of the third type deserve support and encouragement, as they will nourish the new generation of researchers, the science pioneers producing essentially new knowledge – the extremely important role.

It is important therefore that science curriculum speaks in three voices corresponding to the three aspects of CCK, matching the interests important for the society in wider perspective. Moreover, given that people are not born with clear self-identification of their cognitive preferences, each of us must try all three aspects of scientific knowledge to detect and make the correct choice of his/her preference for future occupation, leaving aside the special value of holistic knowledge and the pleasure people receive from multi-faceted intellectuality. The evidence of relevance of the tripartite typology of students' preferences emerged from a study introducing discipline-culture in a summative lecture (Levrini et al. 2014) that will be addressed in the following.

8.4 The Ways to Provide Cultural Content Knowledge

After a certain innovation is theoretically considered, the ways to implement it become a subject of experimentation. Feasibility and the nature of impact of any innovation can be checked only through real teaching. We have explored three ways to facilitate construction of CCK in students. Their brief account follows.

8.4.1 CCK-Based Curriculum

The *first* and the most comprehensive way is a production of a CCK-based curriculum in a certain area of knowledge. We produced a new curriculum for teaching optics – a theory of light and vision – in high school and developed a special textbook (Galili and Hazan 2004). A yearlong teaching experiment was performed (Galili and Hazan 2000). The new curriculum included the unfolding discourse with regard to the nature of vision and light, the debate of competitive accounts throughout the history of science (Lindberg 1976; Galili 2014).

Our experience in teaching optics and research in students' knowledge found evidence of certain recapitulation. Recapitulation implies similarity of ontogeny of knowledge, individual development, and correspondent phylogeny, the development of the pertinent collective knowledge. In the domain of optics and vision such parallelism is presented in Table 8.1.

Optics teaching involving the diachronic discourse on the nature of light and vision caused resonance with students' ideas and beliefs. The teachers drew on this similarity in addressing the known misconceptions of students. In a way, CCK of

Table 8.1 Conceptual parallelism in optics knowledge

Historical conceptions	Students' conceptions
Pythagorean active vision (5th c. B.C.)	Active vision scheme
Euclidean dichotomy of vision and light rays (Ptolemy – 2nd c., Alkindi, 9th c.)	Rays of sight and rays of light
Atomists' conception of Eidola (moving replica, simulacrum, from the observed object) (5th c. B.C.)	Conception (scheme) of Holistic Image moving in space
Biblical dichotomy of light as an entity and light as perception (lumen-lux Latin and in photometry)	Conception of static light located in/around light sources (halo, bright sky) and illuminated surfaces and moving light
Ibn al-Haytham's theory of light and vision (11th c.)	Light comprised of rays and image projection scheme of account for optical image observed by means of light rays
Pure (white) light and colour as a pigment, attenuation/pigmentation	Pure (white) light and colour as a pigment, attenuation/pigmentation

Galili and Hazan (2000)

the subject matter vaccinated the learners through their appreciation of the evolving scientific views. We believe that even if the particular student did not develop a particular alternative conception, the learning about such was beneficial. Students' naïve ideas are often less well reasoned in comparison with historical conceptions. Therefore, comprehension of the pertinent historical debate enriches students' knowledge instigating conceptual learning. The usually vague intuitive alternative ideas become distinct in their meaning and that helps to analyse them, reveal their rationale and facilitate their refutation. This process may be compared with increasing the potential difference between the nucleus and periphery leading to a breakthrough – the required conceptual change. Our experiment showed that the suggested curriculum had strong remedial effect on students' misconceptions (Galili and Hazan 2000).

8.4.2 Conceptual Excursus

The *second* way to provide CCK we explored does not require changes in the regular curriculum and facilitates the cultural upgrading of conceptual knowledge by means of complementary studies. It suggests performing a conceptual excursus[11] to the historical consolidation of a particular concept that took place in the history of science, identifying the major steps in such process and thus establishing the space of variation of that concept in order to be truly understood. This genre is common in historical studies often focused on certain concept (e.g. Jammer 1957; Lindberg 1976). It, however, is marginal in regular disciplinary teaching-learning. We have produced several such HPS-based excursuses to illustrate the idea in educational perspective (Galili 2012). Excursuses may support students' learning in classes and teachers' training, in- and pre-service. We picked up several concepts that were interesting and relevant to illustrate this new genre. The problematic nature of the chosen concepts (collision, motion, image, weight and inertial force) calls attention and invites changes in teaching practice. In the following, we briefly illustrate a couple of them.

8.4.2.1 The Concept of Weight

The concept of weight is of special interest in science education because it belongs to a cluster of concepts interwoven, interchangeably used and badly distinguished: weight, mass, heaviness, gravity, gravitation. Moreover, there is no consensus among physics educators regarding how this concept should be defined. In many countries weight of a body is defined as the gravitational force exerted on it

[11] The meaning we address in the notion of *excursus* is stepping aside of the major line of teaching for elaborating on a certain subject.

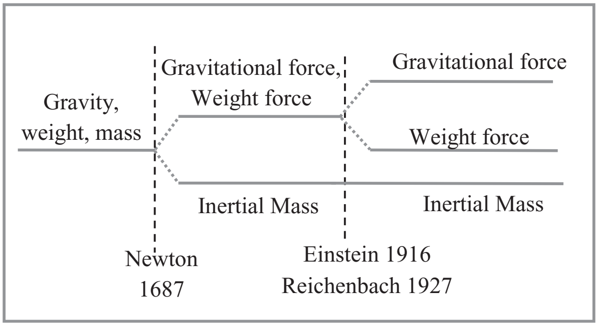

Fig. 8.4 Flowchart of the conceptual change of meaning in the conceptual cluster of mass-weight-gravitation throughout the history of science (Galili 2012)

(e.g. Young and Freedman 2004, 2012),[12] while in others, weight is defined as a result of standard weighing.[13] Physics educators argued for the latter followed Reichenbach (1927/1958, p. 223) in his epistemological analysis in light of the Einstein principle of equivalence. The debate in physics education started after King (1962) who argued for changing the definition of weight toward the operational one. The concept of weight was discussed (Galili 2001), checked in students' and teachers' knowledge (Galili and Kaplan 1996; Galili and Lehavi 2003, 2006) and experimentally tested in teaching (Stein and Galili 2014; Stein et al. 2015; Galili et al. 2017) showing numerous advantages of the operational definition of weight. Textbooks slowly change in the account of weight and weightlessness towards the operational definition of weight.[14]

Importantly, however, physics textbooks avoid discussing the available choice in the definition of weight, and do not compare between the two options, regardless the way they chose to present the weight concept and related issues (weightlessness, weight changes, etc.). The CCK orientated excursus to the subject suggests an explicit comparison between the approaches. In contrast to disciplinary teaching, the excursus followed the evolution of the pertinent conceptual understanding (Fig. 8.4), displayed the debate of scientists, their discourse and in this way revealed to the learners the rationale underpinning concept definitions in general, the need of

[12] Such is the definition adopted in the majority of the "Western" world countries (also in Australia, South Korea and many others). This approach culminates in the famous definition: "The weight of a body is the total gravitational force exerted on the body by all other bodies in the universe" (Young and Freedman 2012). The latter has no sense in modern physics epistemology being impossible either to measure, or estimate, or use in solving any problem (Galili 2001).

[13] For instance, Baruch and Vizansky (1937) in Israel, Chaikin (1947/1963) in Russia; Marion and Hornyack (1982) and Knight (2013) in the US.

[14] Hewitt 1992, pp. 176, 179–180, versus Hewitt 2002, pp.159–160; Knight 2004, pp.131–132, versus Knight 2013, pp.146–147; Resnick and Halliday 1966, p. 93 versus Halliday et al. 2001, pp. 80–81

a pair of definitions for each: nominal and operational (Margenau 1950). This requirement presents a new epistemological framework of physics knowledge introduced in the modern physics, and it is illustrated by the case of weight.

8.4.2.2 The Concept of Optical Image

This excursus lays out the genesis of physics knowledge regarding optical imagery and vision. The subject is usually studied at the beginning of optics course. The account for optical images developed in classical Greece, in parallel with the views about the nature of light. Several conceptions of optical image coexisted for years, remaining a subject of a continuous discourse[15] (Fig. 8.5). The excursus traces the evolution of understanding from the Hellenic conceptions (Pythagorean active vision, Atomists' eidola, Plato's hybrid understanding, and Aristotle's medium through transmission), to the Euclidean rays of vision, and the medieval theory by Ibn Al-Haytham (11th c.).

These accounts preceded the theory of Kepler (17th c.) and thus belong to the periphery of the currently taught light theory of rays – Geometrical Optics. The concept of light rays developed in parallel, changed its status from being the effective cause of vision, in the Hellenistic and Medieval physics, to a mere descriptive tool, in Kepler's ray and Huygens' wave theories of light. The important opposition between the intromission and extramission theories of vision held for more than 1500 years, until Ibn Al-Haytham refuted the extramission theory in the eleventh century. His own theory of image creation though was also erroneous but served as

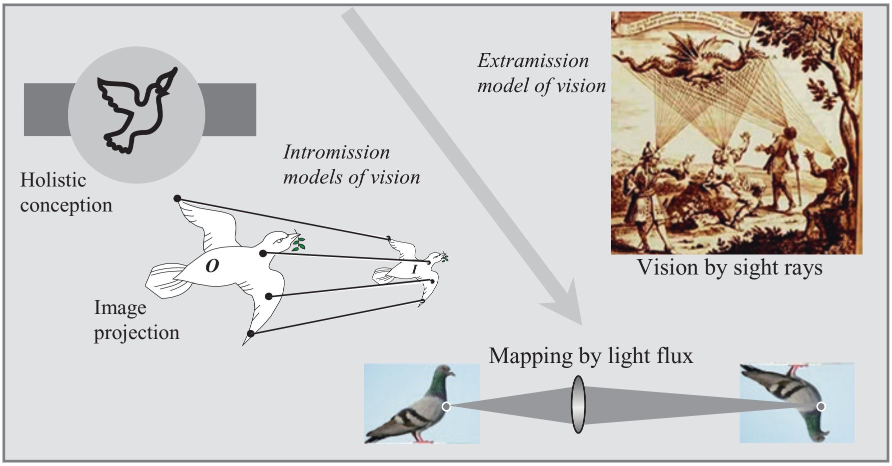

Fig. 8.5 Historical conceptions with respect to understanding of optical image (Galili 2012)

[15] Ronchi (1970, 1991), Pedersen and Phil (1974), Lindberg (1976), Russo (2004)

a vital intermediate stage before Kepler who resolved the problem within Geometrical optics – image creation by light flux, instead of single rays tracing the points of an object to its image replica (Lindberg 1976).

Similar to mechanics, it appeared that the historical conceptions are relevant for physics education. Several researchers reported and analyzed conceptions possessing clear similarity with the historical models (Table 8.1) (Guesne 1985; Bendall et al. 1993; Galili and Hazan 2000).[16] Thus, prior to optical instruction, students often show holistic understanding of optical images travelling through space, reminiscent of eidola of Greek Atomists, as well as the understanding by active vision, visual rays, similar to that by the scientists of Alexandria (Euclid, Ptolemy) and medieval Arabic scholars (Alkindi). Novice learners, after initial instruction, often show the misconception similar to Ibn al-Haytham's account for vision. It stated that "relevant" light rays, one per image point, create the image. Light rays enter the eye, refract in multiple layers and construct an image on the surface of the eye's-lens. This process often seems reasonable to learners (Galili et al. 1993; Galili and Hazan 2000; Kim 2011).

The excursus to imagery in optics creates a space of learning and furnishes genuine understanding of geometrical optics by conceptual variation and comparison amidst a range of possibilities of image creation. The excursus shows the progress of physics theories: holistic and descriptive (Hellenic), structural and mechanistic (Hellenistic and medieval light rays). The account for image changed from pure qualitative (by means of eidola) to quantitative mathematical providing image construction and a formula for its location (by means of light rays flux).

The story of the optical image touches on the nature of science with respect to its identification as a sub-culture of Western culture (Aikenhead 1997). In any event, after the first steps in Hellenic science of Greece the knowledge was promoted in Hellenistic mixed society of the middle East, and then by scientists of Muslim countries (Arabs, Jews, Christians) before its arrival to the medieval Europe (Al-Khalili 2010).

The important inference here is that different scholars, regardless their ethnicity shared a specific trend of thought and inquiry of the same subject matter. They drew on the previous research, adopted its results and further developed the relevant knowledge. The optical excursus refines the Kuhnian claim about the incommensurability of physics theories. Muslim scholars adopted Hellenic and Hellenistic science and saw it as their own. They "were not doing Islamic science. They were doing science" (Weinberg 2015, p. 70). Science clearly appears here as cumulative and continuous, preserving and developing a universal culture with no ethnic, racial or religious essence.[17]

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[16] For a more inclusive list of citations, see Galili (2014).

[17] This claim also touches on the important trend of science education considering Western culture seeking the way to present scientific knowledge in developing countries of the post-colonial world.

8.4.3 Summative Lecture

The third way to provide CCK, *summative lecture*, though lacking the inclusiveness of the novel curriculum and the depth of historical excursus, might be, however, the most affordable and easily implemented.

In the past, David Ausubel suggested a special tool – *advance organiser* – to facilitate and fortify learning (Ausubel 1968). Before teaching a new topic, students are instructed regarding the framework of the knowledge to be considered. The instruction may include the tools to be used, such as the required mathematical formalism. Yet, the major goal in such an approach is displaying the overall idea, the concept. For example, in a biology course, introducing at the beginning the concept of natural selection may serve as an advance organizer. In physics, the big picture of the course would require addressing fundamental theories. Providing such metaknowledge as an advance organiser looked problematic in physics as there were too many unknown specific concepts. Therefore, we tried the reversed order. We designed a summative, reviewing lecture, which might be considered as an *a posteriori* or *delayed organizer*. The lecture addressed the students after they learned the contents in a traditional course.

This special type of lecture is designed to rearrange the learned materials in a theory-based structure, identifying the elements of knowledge as affiliated to three types: nucleus, body, and periphery of a certain theory. Though the lecture addresses the already known to students contents, to reach CCK, one should, besides the hierarchical classification, provide, even if only qualitatively, certain elements for the periphery of the considered theory in order to address the pertinent historical discourse. Such a lecture should create a holistic view on the course, its essential content and unifying structure, rearranging the learned mosaic of knowledge elements.

As a teaching experiment, we provided a summative lecture to three high school classes at Liceo Scientifico in Rimini, Italy (Levrini et al. 2014). Optics was chosen as an especially convenient area for testing the discipline-cultural organization since the school curriculum employs three basic theories learned in different depth: ray theory of light (geometrical optics), wave theory of light (physical optics) and photons theory of light (modern physics). To these basic theories, we added Newton's particle theory addressed at a conceptual level (Galili 2014). The four theories together created a panoramic image of optics development as shown in Fig. 8.6.

To depict the scientific discourse on light and vision a few fragments were added. Such was Newton‘s treatment of interference patterns (Newton's rings) within the theory of rays and without the interference principle (not known to Newton). He developed the ray theory and stretched it in order to include colors and color bands in thin films (Shapiro 1993). Another historical fragment added was Huygens' treatment of double refraction in crystals. It showed where Huygens was stuck, unable to recognise the transverse nature of light waves. Newton only qualitatively resolved that problem by ascribing sides to a light ray.

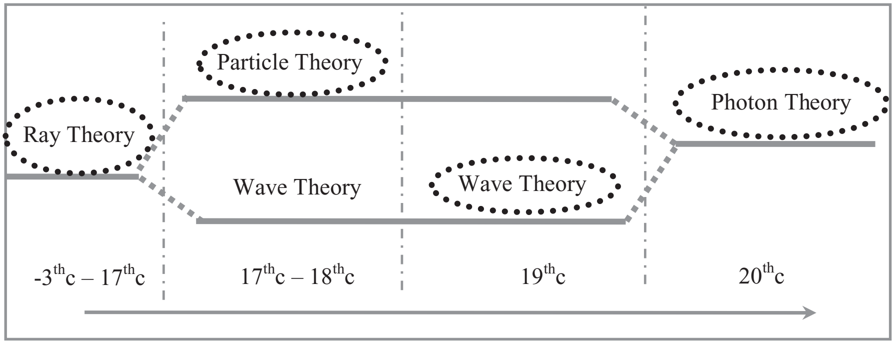

Fig. 8.6 The big picture of the development of the knowledge of light. The theories dominated in each period are marked by a point frame (Galili 2014)

The elements of optics knowledge learned and new, were affiliated in according to the tripartite codification and filled the diagrams of the kind shown on Fig. 8.7. This way a competition of basic theories was visualized: the debate on color, the account of reflection and refraction, Snell's law and double refraction, diffraction and other items populated different areas of the structure. The diagram facilitated explanation of the preference given in the eighteenth century to Newton's theory of light particles over the theory of ether waves of Huygens.

In the following, a pertinent diagram illustrated the victory of the Fresnel-Young wave theory over the Newton‘s theory of light particles in the nineteenth century. Finally, the wave theory succumbed to the modern theory of photons in the twentieth century. This review showed that each topic and feature of light the students had learned could find its location in the suggested structure and participate in a dynamic picture – recognizably human, often contentious, conditioned by context and environment, and producing a stream of knowledge development arranged in different theories.

The big picture of optical knowledge emerged in its full stature. In the case of optics, all three learned theories of light preserved their validity and coexist in present practice. Each of the basic models – ray, wave and photon – is valid in certain area of parameters (light intensity, wavelength) and level of accuracy. They serve for producing the simplest and efficient accounts, products and useful devices. The idea of knowledge progress was thus refined. Despite the confidence that the quantum theory is the most general, we account for spectacles by ray optics and for microscope resolution by light waves.

8.4.3.1 Findings of the Experiment

We applied the lecture, pre- and post- questionnaires and following class discussion (Levrini et al. 2014). We found that the tripartite organization of knowledge elements within theories was appreciated by students as helpful and informing. Novel

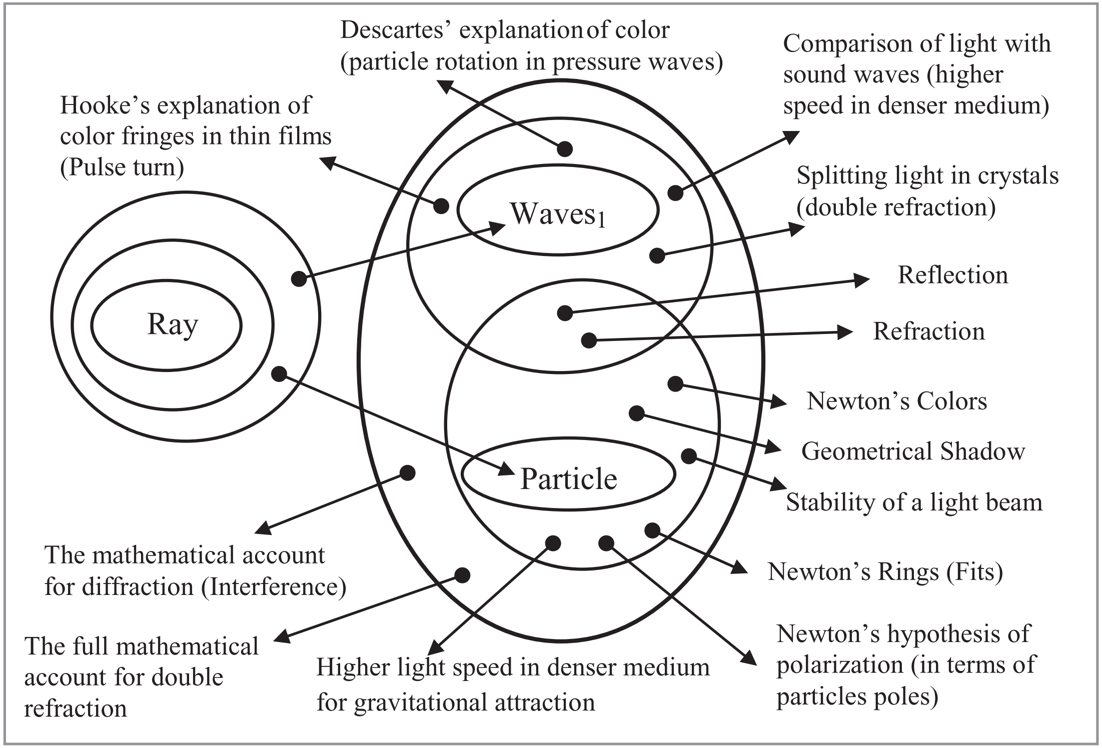

Fig. 8.7 Representation of the development of optics knowledge in the seventeenth to eighteenth centuries in the CCK perspective. It represents the competition of two theories of light stemmed from the ray theory (Levrini et al. 2014)

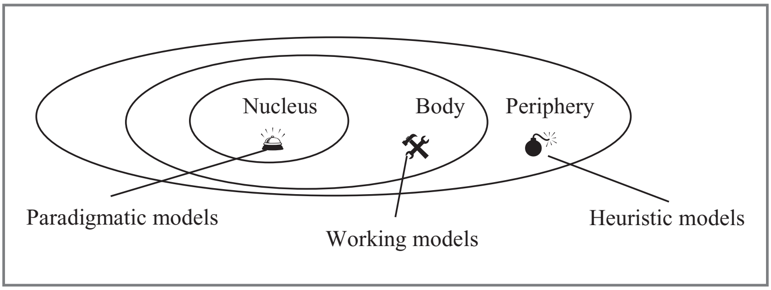

Fig. 8.8 Models may appear in all areas of theory structure

for all, it matched students' intuition. Many of them (2/3, 1/3, 1/3 in the 3 classes) said "it was not new for me…" indicating closeness to intuition and their naïve attempts to organize the multitude of laws, principles, models, concepts that they learned.[18] Students debated the relative importance of the three types of knowledge elements. They were interested in the hierarchy of the theories and their possible unification in one inclusive theory of all.

Lacking initial understanding of theories and the related role of models, the students asked for clarification of theory-model relationship. In responding to this question, different models of optical theories were affiliated to the three areas of the corresponding theories (Fig. 8.8). The models of ray, wave, photon were attributed to the nuclei as paradigmatic models. The models of thin lenses, paraxial rays, point sources were identified as working models located in the body of ray theory. Finally, the models from periphery were exemplified by photons in the wave theory used as a heuristic model.

Some students, who usually remained outside of discussions in physics class, mentioned that they were interested in the big picture of optics knowledge. Refutation of some conceptions and explanations, and adoption of others, as shown in the history and philosophy of science lessons, attracted them to physics.

The image of the subject matter as a cluster of several theories allowed consideration of the relationship of physics knowledge with the real world: does physics knowledge mirror nature exactly? Facing several valid theories of light led students away from the idea of a unique reflection toward the more adequate view of physical theory as representing a certain perspective – useful, and valid, but not identical to nature leaving space to other accounts, quite in harmony with the view that the "scientific knowledge is not absolute, but perspectival" (Giere 1999, p. 150).

Student interest and engagement that was apparent in the discussion indicated the strong appeal of the new perspective on physics knowledge applied in the experiment and its beneficial impact. Students thought about whether they wanted

[18] One may interpret this reaction to the triadic organization as a sort of cognitive resonance with the immature ideas located in the Vygotskian Zone of Proximal Development (ZPD).

to be physicists and if so, of what type – dealing with the nucleus, body or periphery of physics.

When interviewed, the teachers of the experimental classes expressed appreciation of CCK as a framework of the subject matter, unifying various knowledge elements – models, laws, experiments, etc. – in a related web. They mentioned that such inclusion of history and philosophy of science infused new meaning into the regular teaching. In particular, they pointed to the ability to display the progression of physical theories, the conceptual change in science and transitions from one theory to another. Frequent use of representative graphical, artistic, and allegorical images in the short summative lecture was seen as an appealing pedagogical tool (Galili 2013).

8.5 Epistemology and Considering Knowledge as a Culture

The impact of a cultural knowledge approach to science curriculum with respect to the epistemological aspects is of different nature because philosophy itself corresponds to a different type of culture. While the content knowledge of science comprises a culture of rules, the epistemological knowledge of science is rather a culture of texts, implying a more flexible perception of correct-incorrect opposition. Different epistemological approaches often complement each other rather than exclude.

In particular, the history of science illustrates the continuous contest of rationalist and empiricist methods of knowledge construction. Aristotle combined them in an inductive-deductive circular procedure of scientific investigation drawing on contemplation and logical analysis (Losee 1993). Platonic-Pythagorean rational analysis preceded Aristotelian. It drew on the idea of transcendent order and mathematical logic to uncover the hidden forms projecting to the perceived reality. Theory was introduced to account for and represent reality. The scientific method developed and was modified. Initially focused on theory-based speculations it was reinforced by experimentation in Hellenistic and Muslim sciences.

In the following elaboration of scientific method, medieval science introduced "prerogatives of experimental science" on top of the further developed rationalist apparatus clearly prevailed. The medieval resolution-composition method as well as nominalist-realist opposition regarding scientific concepts prepared both Baconian empiricism and Cartesian rationalism. Science always kept both approaches towards their synthesis by Galileo and Newton who produced the integrated account (Fig. 8.9). This is different from the clear hierarchy of content elements in the discipline-culture structure. For instance, in classical mechanics, the rectilinear uniform motion is affiliated to the nucleus whereas its counterparts in the Aristotelian (state of rest) and quantum (state of definite momentum) mechanics belong to the periphery.

Fig. 8.9 Plato and Aristotle in the center of Raphael fresco *The School of Athens* in Vatican (c. 1511). This image became emblematic of the Western science as having two images in its focus. The gesturing of the two philosophers is interpreted as representing integration of rationalism ("theory first") and empiricism ("experience first") (Galili 2013). (*arrows added*)

The cultural perspective unifies the accounts of discovery in the Baconian "interrogation of nature" with the constructivist creation in the scientific research program (Lakatos 1978). The combination of both approaches more adequately represents scientific practice as in Fig. 8.10.

Scientists are often inconsistent in their methodology. They may employ empiricism, rationalism, constructivism in different combinations while remaining committed to the standards of empirical verification, drawing on theory, objectivity, and open discourse. The teaching drawing on discipline-culture idea displays this plurality claiming their complementarity. The epistemological plurality influences on science curriculum as may be represented with a semiotic triangle (e.g. Löbner 2013, p. 24). In it, the disciplinary contents of a theory constitute the object vertex. The chosen philosophical dictum creates the concept vertex thus providing the object with conceptual meaning (Fig. 8.11). The object – disciplinary contents – is signified by science curriculum, the sign vertex, which features are determined by the chosen philosophical framework of the concept vertex (Tseitlin and Galili 2006). This dependence manifests itself in the emphasis and preferences given to empirical versus theoretical fundamentals,[19] deductive versus inductive organization of materials,[20] etc.

[19] Thus, one may compare the introductory physics textbooks of the Nuffield project in UK strongly emphasizing laboratory work and less the elaboration of theoretical aspects with other physics textbooks of the same level, for instance, Harvard Physics Project in the US.

[20] Introductory courses of physics are often framed in inductive organization while the corresponding advanced courses of theoretical physics are usually deductive.

Fig. 8.10 Images representing two scientific methodologies. (**a**) Discovery taken as emblematic for physics on the Nobel Price medal (names of the figures emphasized); (**b**) Constructivism as the method of modern science might be represented using the images of Pygmalion and Galatea

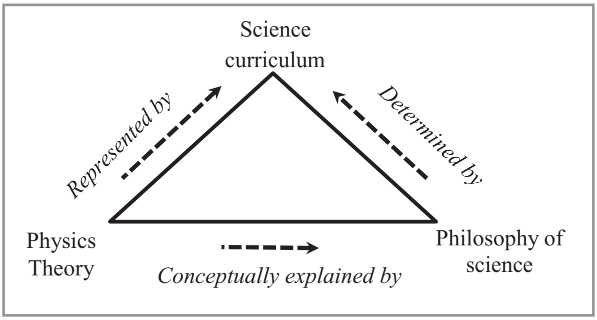

Fig. 8.11 Semiotic triangle of physics education

A discipline-cultural curriculum suggests a combined methodological perspective in exact parallel with scientists who cannot afford being restricted to one epistemology and combine philosophically different and even opposite approaches (Einstein 1949, pp. 683–684).[21]

[21] Einstein explained there: "He [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."

Pragmatic, instrumental philosophy, such as that by Dewey (1938), would emphasise problem-based curriculum, learning by doing, drawing on personal experience and initial conceptions of the learner (educational constructivism) as the ways to mastering and understanding scientific knowledge. This perspective may miss the overall view, the epistemological status of knowledge elements in the theory-based structure of physics, identification of fundamentals, concept definitions, principles, and interrelations of the constituents. Those contents would come to the fore in the curriculum based on the rationalistic account of science (e.g. Frank 1957). The latter comprise metaknowledge which cannot be created in practicing standard problems, but should be explicitly taught, illustrated and discussed.

As an example, within the curricular perspective of modelling, one considers theory merely as a set of models constructed according to certain rules (semantic view). Addressing classical mechanics such approach pointed to the set of basic models (e.g. Giere 1999, pp. 110–111; Halloun 2006, pp. 140–141). However, the other contents of theory, its nucleus may be missed. Among them, the relativity principle, concepts of absolute time and space, state of motion, force definition, central interaction of point masses, etc. Thus, the mentioned set of useful models includes the uniform motion (rectilinear with constant velocity) as *one of* the basic models, next to circular and oscillatory motions. Yet, the uniform motion is much more than that. It presents a fundamental state different from all other types of motion (e.g. Galili and Tseitlin 2003, 2013). It served as one of the revolutionary claims of Newton's *Principia* following the discourse on motion of two thousand years.

As already specified (Fig. 8.8), theoretical models contribute to all three areas of theory structure. *Paradigmatic* models of nuclei may reveal the analogy underpinning the formalism of the whole theory (in Newton's mechanics: point particles in a void under central force interaction). Models in the body area, *working* models, mediate between the theory and reality (Morrison and Morgan 1999) as simplified subsets of the theory enabling precise account of chosen ideal systems (e.g. mathematical pendulum). Models of the periphery may be of *heuristic* type for the account of a system without conforming to the nucleus. Such models may pave the way to a new theory (Bohr's model in quantum theory or Plank's account for blackbody radiation in classical electromagnetism).

Missing fundamentals, converts teaching of physics to instruction of a craft. Ironically, such teaching could well serve prospective physicists who will construct an adequate image of physics knowledge for themselves later. Yet, the others, the much wider audience, will miss the holistic picture of mechanics, its ideas – the cultural heritage.

Similar critique could address the model-based curriculum of introductory quantum mechanics often focused on Schrodinger equation and its solutions in simple cases. Ignoring the nucleus of quantum theory, its central principles, basic concepts and specific epistemology, so much different from classical mechanics, implies students' missing the quantum picture of the world.

Apologists for a pragmatic curriculum sometimes quote Einstein (1934/2011):

> If you want to find out anything from the theoretical physicists about the methods they use, I advise you to stick closely to one principle: don't listen to their words, fix your attention on their deeds.

One may, however, pay attention that this advice addresses the *methods* used by practitioners, not the *meaning* of the theory to develop the methods on the first place. That aspect presents a goal specific for science *education*. For that, one has no other way but address both rationalist and empiricist approaches.

Another epistemological aspect is the need of integrated concept definition. We have addressed above the concept of weight in that respect. Historically, Mach was the first who emphasized the need to draw on the operational definition of concepts. He introduced a new definition of inertial mass through the measurement of accelerations in an interaction (collision) of two bodies (Mach 1883/1989, p. 218). Einstein followed him with regard to simultaneity in his theory of relativity (Reichenbach 1927/1958).[22] Yet, the initial claim of operationalism that any "concept is synonymous with the corresponding set of operations" (Bridgman 1927) was transformed to the more recent philosophical account requiring a pair of definitions: nominal and operational of the same concept (Margenau 1950). This approach might be viewed as integration of empirical and rational approaches in physical method.

8.6 Objectivity of Scientific Knowledge

Lastly, we touch on the epistemological claim of science being *subjective* which presents a cardinal attack on the traditional presenting scientific knowledge as objective in science education.[23] Normally, physicists state (Hestenes 1993)[24]:

> What makes knowledge scientific? Scientific knowledge is distinguished from ordinary knowledge by its *objectivity, precision and structure.* These distinctions are erratically maintained and sometimes missing altogether in introductory science textbooks and programs.
>
> Students cannot be expected to comprehend the structure of science until they have learned to think objectively, in the sense that they can readily distinguish between "objective" properties of physical objects and their own subjective perceptions of them.

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[22] In physics education, the introduction of operational definitions was advocated by Karplus (1981) and Arons (1990). Essential changes might follow such change as illustrated by the case of weight concept.

[23] Though clearly a philosophical topic, it entered educational discourse as an item of NOS (nature of science). As mentioned above, the implied complexity stems from the need to learn about the pertinent accomplishments in philosophy of science and science itself in order to avoid naïve opinions regarding the nontrivial arguments of another discourse.

[24] This claim presents a commonplace in physics (e.g. Weinberg 1992, 2001), philosophy of science (e.g. Popper 1979), history of science (e.g. Holton 1985; Russo 2004; Jaroszyński 2007).

In a sharp contrast, Lederman and colleagues assert that:

> …scientific knowledge, owing to scientists' theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations, is *unavoidably subjective.* (Lederman et al. 2014, p.976. Emphasis added)

The subjectivity of scientific knowledge was argued for because of its dependence on scientific theories which were considered as subjective constructs (Lederman et al. 2015, p. 695):

> …scientific knowledge is *subjective and theory laden*. Scientists' beliefs, previous knowledge, training, experiences, and expectations, in addition to theoretical commitments, influence their work. (Emphasis added)

Steven Shapin (1996, p. 165) wrote as if in answer:

> …much recent history and sociology of science that seeks to portray science as the contingent, diverse, and at times deeply problematic product of interested, morally concerned historically situated people is likely to be read as criticism of science. It may be thought that anyone making such claims must be motivated by a desire to expose science to say that science is not objective, not true, not reliable or that such accounts will have the effect of eroding respect for science.

While Lederman talks about the personal perception of scientific knowledge and individual inquiry, Shapin addresses the collective scientific knowledge, the product of inquiry process. If taken as is, Lederman misinterprets the unifying role of theory in the scientific knowledge providing an inadequate image of science as activity of separate individuals or groups in workshops, a picture reminding more art (the culture of texts) rather than science (the culture of rules) which draws on a few fundamental theories shared by the whole community. In another perspective, Lederman's confusion stems from missing the difference between the context of inquiry and the context of justification in science (e.g. Losee 1993). To avoid confusion, one needs to address the conceptual pair objective-subjective in science curriculum, exposing and refining both aspects – discipline-cultural approach.

Historically, objectivity was preserved as a norm in science.[25] It was about the account of regularity and features of Nature (object) independent of our (subject) wish. Since its foundation in Classical Greece, natural science considered objectivity as the genus of scientific knowledge and its differentia from mythology and the knowledge in other areas of intellectual activity, history, literature, etc. (Sarton 1948, p. 170). Yet, despite the long tradition, the opposite claim of science being subjective has been univocally appeared in the voluminous *Encyclopedia of Science Education* (Gunstone 2015). Critique came from Matthews (2012) who demonstrated that the claim was dubious (mixing contents) and contradicted the actual status of scientific *knowledge*. Yet, the claim of subjectivity is not new in philosophy and sociology of science revealing non-trivial subtleties. It is therefore cannot be ignored.

Commonly, the objectivity of knowledge presumes its essential independence from psychological and social factors; the latter are germane to the creation of knowledge (the context of inquiry), and even to its form of expression, but not to the

[25] See Elkana 1981; Hempel 1966; Polanyi 1962; Popper 1979; Weinberg 2001.

epistemological status of what is created (the context of justification). Scientists explain: "the way whether and how the dropped object falls is independent of our attitude to that" and such should be any scientific account. In this sense scientists state physics theories (classical mechanics, electromagnetism, thermodynamics, quantum theories, general relativity) being *objective* and dismiss their relativism (Weinberg 1992, 2001). Each of the theories is valid in certain area of parameters and depicts a certain aspect of reality; a sort of approximation in depicting reality. Yet, their objectivity suggests understanding of the stated *tentativeness* of scientific knowledge: "the approximate theories are not merely approximately true" says Weinberg (2001, p. 208). They adequately account for certain aspects of reality. *Only* such objective knowledge can be a subject of any critical discourse stipulating its *reliability* and "health" (Popper 1965, 1978, 1979; Elkana 1981; Holton 1985), providing a pledge for progress and adequate world view − much more than new devices, medicine, and weapon (Weinberg 2001, p. 106).

Commonly objective–subjective disputes regarding scientific knowledge are sometimes interwoven with true-false claims about the putative knowledge (e.g. Agazzi 2014). In their products, scientists might be wrong or leave explanation unknown, but seeking objectivity and excluding of voluntary factors in scientific theory present a common norm. The *theory-laden* analysis is intrinsic in any scientific inquiry. However, stating analysis being *theory-laden* is not equal to voluntarism. It is as correct in science as stating *experiment-laden* theory. Both comprise complementary aspects of a *reciprocal* process of scientific inquiry essential in knowledge construction in science.

The subtlety of science is in the fact that in their account of nature scientists use associative imagination in creating a system of concepts − a "free creation of the human mind" (Einstein and Infeld 1938, p. 33). Yet, those enter into a *continuous* inquiry loop in which the chosen (subjectively) concepts are going through refinement and correction drawing on experiments. Awareness of the circular iterative construction of scientific knowledge may resolve the confusion between scientific *inquiry* and scientific *theory (subjective* and *objective* aspects of science). Indeed, inquiry relies on the individual and group views, hypothesis, interpretations, and style, and therefore, it might *include* subjective or intersubjective elements. However, the scientific theory consolidates in an iterative process of evolutionary construction, empirical corroboration in the professional discourse.[26] Multiple studies independently test theory in a variety of dimensions and in back and forth interaction with reality. Together with continuous versatile attempts of falsification, theoretical and experimental, they provide objectivity of the product. As Gerald Holton wrote:

> …the metaphysical tenets of individual scientists, though often quite strong, are generally so varied, so vague, and technically inept that in a sense they cancel out, made ineffectual by the lack of a basis for general acceptance and agreement of such tenets. (Holton 1985, p.193)

[26] The problem arises when the process of scientific inquiry is presented being listed as a sequential procedure (e.g. Hempel 1966, p.11). Missing *circularity* and *iterative* self-corrective nature of scientific inquiry makes it vulnerable to the claims of subjectivity or intersubjectivity (e.g. Husserl 1978).

Therefore, inclusion of the specific historical contents in education is essential for appreciation of objectivity as emerging from the melting pot of scientific discourse. This is the approach of CCK-based curriculum, in which scientific theories appeared not as useful opinions or dogma but as products distilled in the discipline-cultural discourse. Inclusion of diachronic discourse allows tracing the arguments on the way, compare and complement theories in contest. The mentioned excursus to the conceptual history of weight and optics may illustrate such process (Galili 2014).

In our optics materials, we considered, for instance, the path of light. Heron of Alexandria in his *Catoptrics* demonstrated the rule of specular reflection: the light path presents the shortest trajectory between any two points including mirror reflection (Cohen and Drabkin 1966, p. 263). This was a piece of objective knowledge. However, the interpretation of this result by Nature seeking the most "economical" way to go, or by Nature that does nothing in vain *(natura frustra nihil agit*) was mystical. Fermat in the seventeenth century used the method of *Maxima and Minima* and advocated for the *extreme* temporal rather than spatial path (Ross 2008, p. *v*) – the objective truth. Yet, he claimed that such path expressed the "natural intention" – a mystical view. The actual measurement confirmed the Snell law of refraction as sine ratio of incident and reflection angles – the objective truth. Descartes believed that this empirical law is insufficient, as it did not *explain* the phenomenon. He provided an *ad hoc* mechanism of analogy between light and the motion of a ball being hit downwards at the surface of water (Descartes 1637/1965, p. 79). The artificial and subjective nature of this analogy was obvious. Mach called it "unintelligible and unscientific" (Sabra 1981, p. 104).

The approach of Fermat was unsatisfactory too: how and why does light "decide" in advance (!) about the extreme path? Scientists continued to seek for an objective account. Only in the nineteenth century, following the account of wave interference by Fresnel, were the subjective speculations regarding light propagation removed. Raleigh by covering odd (or even) Fresnel zones demonstrated that light did not "decide" which way to go but goes in all ways between any two points. The interference of all these beams produces the apparent light path and destroys all others. Feynman (1948, 1985) further expanded this account to massive particles. Summarizing, the *subjective interpretations* associated with the understanding of light path through the history "cancelled out" and the *objective* account emerged. At no stage, however, were scientists seize trying to reveal the objective truth about Nature. Individual scientists are not purely subjective; their "personal knowledge" incorporates *both* subjective and objective components (Polanyi 1962).

For Karl Popper, the objectivity of physics knowledge was framed using the idea of the "third world"[27] – a virtual intellectual space incorporating physical theories (Popper 1978). Possessing its own existence (spiritual reality shared through generations), somewhat reminiscent of Plato's transcendental world of forms and the realists' view of concepts in the medieval science, it contains objective knowledge of science:

[27] To be distinguished from the real world (the first one) and the personal world (the second one).

> Without claiming to solve such ancient philosophical problems, I would argue that scientific theories share those properties of rocks—stability and independence of societal setting—that lead us to call rocks real (Weinberg 2001, p. 269).

Holton (1985) introduced ideas of science-1 and science-2 for the same purpose – to distinguish between the objective core and subjective associative ideas of physical knowledge. We used this metaphor in addressing optics as a cluster of a few theories of light complementary and objective, dwelling in the "third world". Valid in different areas of space-time and energy scales, they share the objective genus.

8.7 Conclusion

Altogether, considering scientific knowledge as a culture displays the discourse of science revealing its characteristic structural features – ontological and epistemological – which are often missing in strictly disciplinary teaching. For the ontological disciplinary contents, CCK approach suggests the curriculum displaying the tripartite hierarchical structure of a *few* fundamental theories: nucleus-body-periphery, whereas for the epistemic contents, an integrated presentation is suggested addressing a *few* principal accounts as complementary instead of claiming only one view as legitimate. Such CCK curriculum reveals a big picture and broader context of scientific knowledge. It provides metaknowledge of science appealing to the broad population of learners of different interests and preferences beyond the audience of disciplinary oriented students. It frames and specifies the involvement of HPS contents, making them a curricular necessity. In doing this, it provides a paradigm matching the historical tradition of dissemination of scientific knowledge and cultural enlightenment.

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