The Story of the Light Ray and Vision as a Story for Teaching Optics as a Discipline-Culture

IGAL GALILI
Science Teaching Department, The Hebrew University of Jerusalem, Israel. email: igal@vms.huji.ac.il

Abstract. Light and Vision are addressed in any introductory physics curriculum for high schools and colleges. Research results inform us that learning these topics, for their being abstract and confusing sense evidence, are accompanied with great difficulties on behalf of the students who develop a variety of alternative conceptions. At the same time, one finds a rich conceptual history of light and vision. Teaching physics as a discipline–culture advocates for the inclusion of pertinent historical models, surpassed by science, into science instruction. We developed a new textbook in optics for high schools, which reflects this culturally oriented education. To exemplify its rationale I picked up the contents comprising a "Story of a Light Ray". It follows this concept from its introduction by Euclid in the IIId century B.C., through its climax in the optical theory of Al-Hazen in the Xth century and its central role in the theory of perspective, during the Renaissance, to a total ontological "devaluation" (getting the status of a mere technical tool) in the optics of Kepler and thereafter. Testing these materials indicated their high educational efficiency in supporting the construction of adequate content knowledge, as well as providing students with an adequate image of the nature of science.

Introduction

It is currently possible to better support the call for a renewed effort into the production of case studies of the History of Science which can be used to design educationally appealing units of instruction based on historical episodes (Stinner *et al*., 2003). The positive effects of such exposure to case studies was for educational purposes was anticipated in the past (e.g. Conant, 1957) and may have inspired the designers of the Harvard Project Physics Course (Rutherford, 1970). Now in the post-behaviorist era of science education, it is understood that even a detailed explanation of the formal content of the scientific curriculum cannot guarantee successful learning by the students. In order to learn science there is often a need, not only to adopt new knowledge of certain phenomena but to replace existing knowledge, which is often the product of previous misunderstanding. Learning is often a matter of changing one's personal intuition and beliefs or one's personal interpretation of laws provided by a teacher. Educators call this process *conceptual change*, rather than the mere accretion of knowledge imprinted on the tabula rasa of human mind (e.g. Carey 1990, Galili, 1990). Much effort has been invested in learning how to encourage such a change. The strategy initially suggested, *cognitive conflict,* was later generalized into the fulfillment of four conditions[1] (Posner *et al.*, 1982), these still reflected a belief in need to persuade the learner, almost as though the learner presents one side of a debate of scholars during a disciplinary discourse[2]. A more careful approach (Strike and Posner, 1992) also took account of important social factors, which may influence conceptual change. Nevertheless, in light of the great variety of misconceptions and types of students, it is difficult to believe that this theory can account for all learners' conceptual change. Our understanding of the reality of a physics class suggests that we moderate the analogy of student as a *scholar* in debate with an opponent. We propose exposing students to views and theories taken from the history of science which might remind them of their own beliefs, which are considered *misconceptions* from the point of view of modern science (Galili and Hazan, 2000). In this case the students initially take on the role of observers, rather than participants in the debate, they may then change their neutral stance to become engaged when certain views of a scientist from the past remind them their own. We called this positive reaction of the learner "cognitive resonance" (Galili and Hazan, 2001). This understanding leads to the analogy of the learner to a person listening in to a discussion of people standing a small distance away. An initial lack of

Fifth International Conference for History of Science in Science Education
Keszthely, Hungary, 2004: 37–48

attention to the talk of unknown people may switch instantly to very high attention if a word is uttered which possesses special meaning for the occasional listener, for example, his/her name. This analogy may only be able to explain the students interest in the subject but it is well known that the state of heightened interest is a necessary, if not sufficient, condition for meaningful learning such as conceptual change.

Thus we have arrived at the conditions for development of new curricula using the history of science. One should first study students' conceptions in the area of the subject for instruction. In addition, one should learn the history of science in the particular area of the subject matter. Given both these conditions, one is in a position to scan history for the theories (views, beliefs) which might cause cognitive resonance to the learners. As an example of this method, we bring here the story of a *light ray,* one of a series of stories organized in an innovative high school textbook for optics, which is heavily based on the materials of historical and philosophical nature (Galili and Hazan, 2004).

The Story Line Used in School Teaching

1ST STAGE, HELLENIC SCIENCE

It is important to note that the study of light and vision were inherently interwoven from the beginning of the study of the Natural Sciences (Natural Philosophy). The study was lead by the interpretation of vision. During the first period, known as Hellenic, classical Greece provided at least four competing theories of vision (e.g. Ronchi[3] 1970, Lindberg[4] 1976).

The *first* one was practiced in the school of Pythagoras. It stated that an internal fire is radiated by observer's eyes, reaching the objects observed and causing them to be seen (extramission theory – Fig.1).

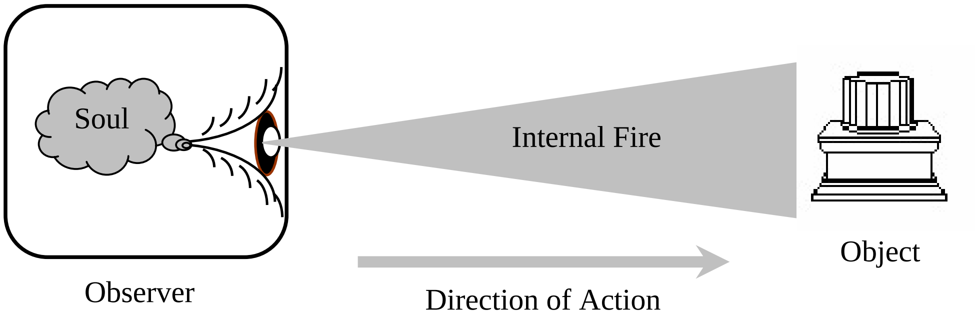


Figure 1: Schematic representation of the Pythagorean extramission theory of Vision

The *second* theory was due to the school of Atomists. They stated that each body around produced a sort of its replica, an image (*eidolon*). Comprised of atoms of that object, eidola leave it in all directions, traveling in space until entering the eye of an observer, causing the effect of vision (intromission theory – Fig. 2).

The *third* theory is usually referred to Plato. It synthesized the ideas of the two first theories, suggesting the meeting of the internal fire emanating by the observer with external fire given off by the observed objects, to be responsible for vision. Unlike previous theories, the process takes place only due the influence of ambient light interwoven with the internal fire (Fig. 3).

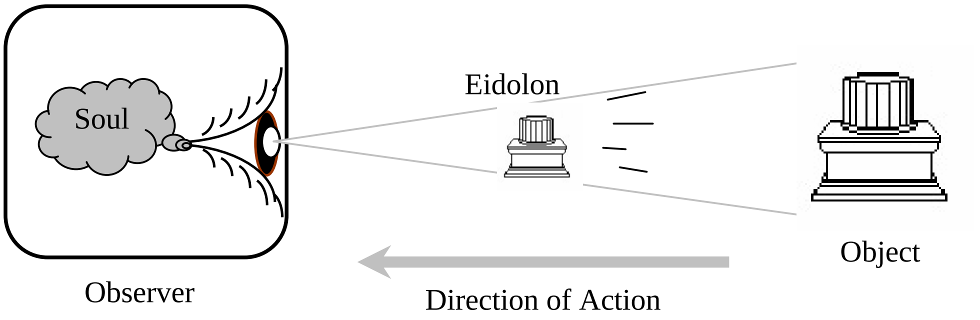


Figure 2: Schematic representation of the Atomists' intromission theory of Vision

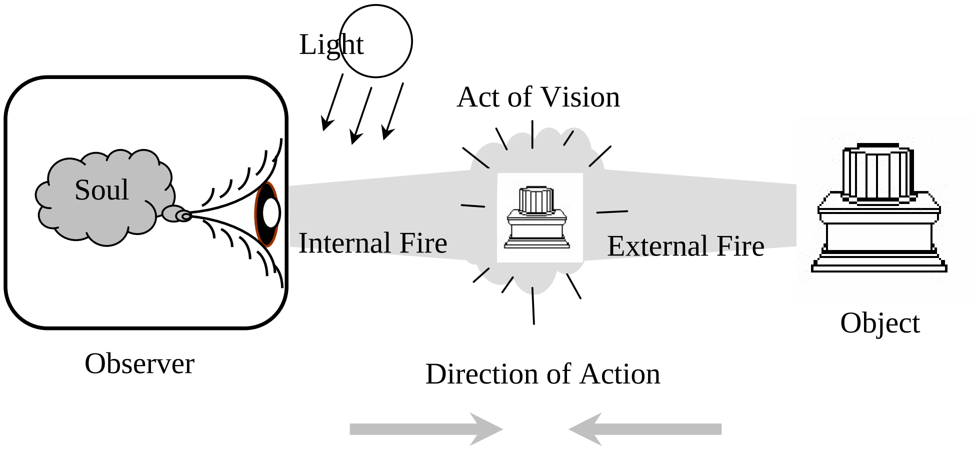


Figure 3: Schematic representation of the Plato's hybrid theory of Vision

The *forth* theory was also extremely creative. It was the intromission theory of vision due to Aristotle himself[5]. He suggested the color of the object to cause a special compression in the medium between the object and the observer. Light causes the medium (air, glass, water) to be transparent and allows the mentioned compression to reach the observer and proceed within the eye to the soul, providing the act of vision (Fig. 4).

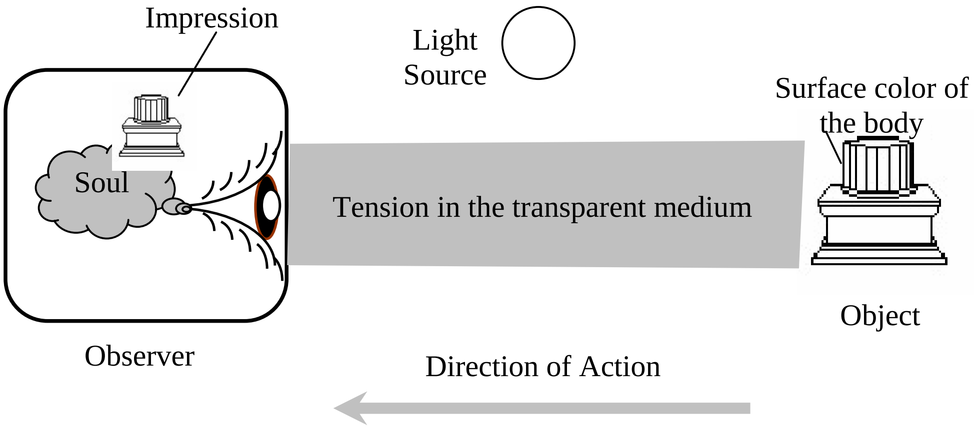


Figure 4: Schematic representation of the Aristotle's intromission theory of Vision

2ND STAGE, HELLENISTIC SCIENCE

Although these four theories appear to address all possible relationships between the observer, the medium and the object seen, the progress during the next period of Hellenistic culture was remarkable. Hellenistic culture in general presented a sort of rebellion against the Hellenic holistic, qualitative, “philosophical” account for the Cosmos. Scientists of this period inquired more about the detailed mechanisms, particular facts and more specific descriptions and measurements[6]. In optics, Euclid’s contribution was revolutionary. Having adopted the framework of Pythagorian extramission theory, he essentially refined it by introducing the concept of the Ray (Fig. 5). Euclid introduced two types of ray simultaneously, Visual and Light Rays, these presented the fundamental concepts for the Euclidean theory of light and vision. Euclid postulated that rays of light and vision obey the same laws of behavior and stated a theory explaining the experience of vision which is very similar to his famous geometry. The ray concept refined in clear terms the Pythagorean vague “internal fire” and provided a powerful tool for the diagrammatic account of vision, enabling the establishment of a theory of perspective. Using the concept of ray, Heron, Archimedes and Ptolemy formulated an account for light and vision rays reflection and refraction.

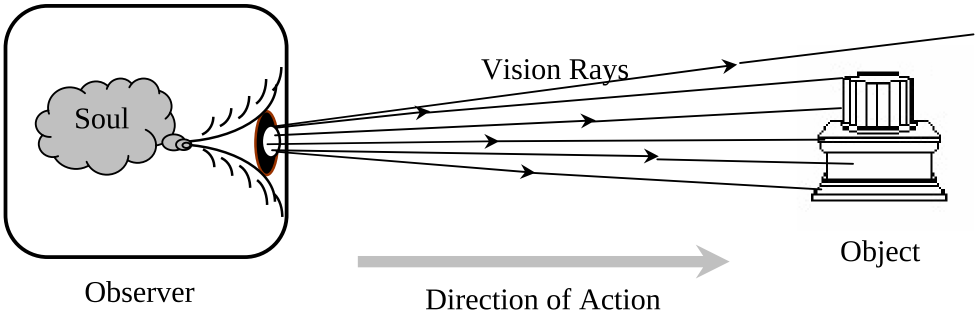


Figure 5: Schematic representation of the Euclid’s refinement of extramission theory of Vision. Observer’s eye scans the object by visual rays.

3RD STAGE, MEDIEVAL ARABIC SCIENCE

At this stage of history, one can mention a remarkable progress in the account for vision and light. First, Alkindi in the 8th century stated an important principle, according to which, light emanates from each point of a source or is reflected from each point of an illuminated object in all possible directions. Second is the great contribution of Alhazen, who reviewed the Greek ideas, analyzed and criticized them, and through a creative synthesis and his own ideas further promoted the theory of light and vision. Alhazen unified light and vision rays. Using Alikndi’s principle he explained the image observed in Camera Obscura, thus resolving the paradox mentioned by Aristotle. According to Alhazen’s theory of vision, an abundance of light rays leaving each point of the observed object fall on the surface of the eye. Only those perpendicular to its surface enter the eye without weakening. The process repeats itself at several inner layers of the eye, until the rays reach the surface of eye-lens. By that time, each point of the object is represented by a single ray causing the replication image to appear on the surface of the eye-lens. This image is sensed by the observer (Fig. 6). Therefore the theory stated that the observed image of the object outside is efficiently mapped to the image inside the eye by point-to-point mapping of single rays.

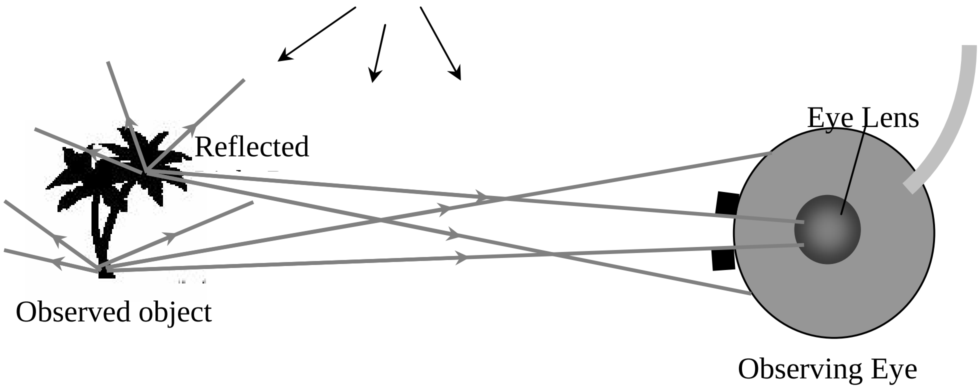


Figure 6: Schematic representation of the Alhazen's extramission theory of Vision. Straight image is obtained on the surface of the eye lens.

4TH STAGE, EARLY MODERN SCIENCE

We now reach the interesting period of high medieval and Renaissance science during which the Euclidian theory of light perspective and Alhazen's theory of vision were assimilated by European science[7]. In the 13th century, the circulated manuscripts of Witelo's *Perspectiva* and Pecham's *Perspectiva Communis* textbooks on optics made these theories known to the educated people throughout Europe[8]. Perspectivists in Renaissance Italy applied Euclidian perspective to the fundamentals of architecture and painting (Fig. 7). The ray became a central concept in these domains.

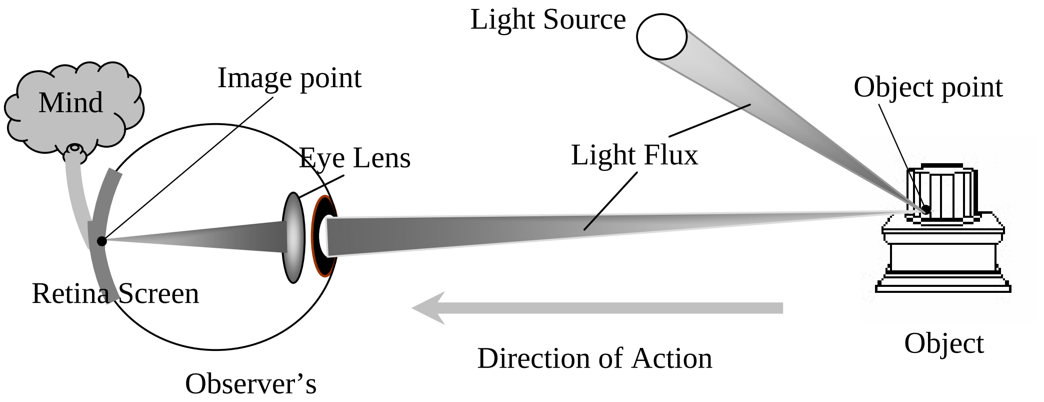


Figure 7: Schematic representation of the Kepler's solution of the problem of Vision. Mind inverses the inverted image obtained on the retina of the observing eye.

Leonardo was among the first who counted light rays to evaluate the intensity of light and shadow[9]. Copernicus had to do the same while being pushed to explain the phenomenon of season and erroneously introducing the third annual rotation of the Earth. Galileo perhaps reproduced his explanation of seasons by counting rays (Galilei, 1632/1967)[10] and through counting rays anticipated the renowned cosine law for the illumination of an area by the light flux[11]. Similarly, Kepler related the rate of rays to the illuminated area and stated the $1/r^2$ law for the light intensity reduction with the distance to the light source[12].

The major development of light and vision theory during the scientific revolution was due to Kepler. He explained the construction of optical image tracing light rays in ray diagrams and resolved the enigma of vision by introducing a new stage in the process of vision: image interpretation by human conscious in the mind (Fig. 8). Lacking this understanding made it impossible to adopt the creation of an inverse image on the retina of observers' eye. However, it was also Kepler who subverted the grand status of the light ray to a mere tool, albeit useful to represent light, but lacking any meaning as a physical entity. The light ray was finally understood to represent a perpendicular to a wave front of light in the Huygens' undulatory theory of light or a trajectory of light particles in Newton's conjecture regarding the nature of light.

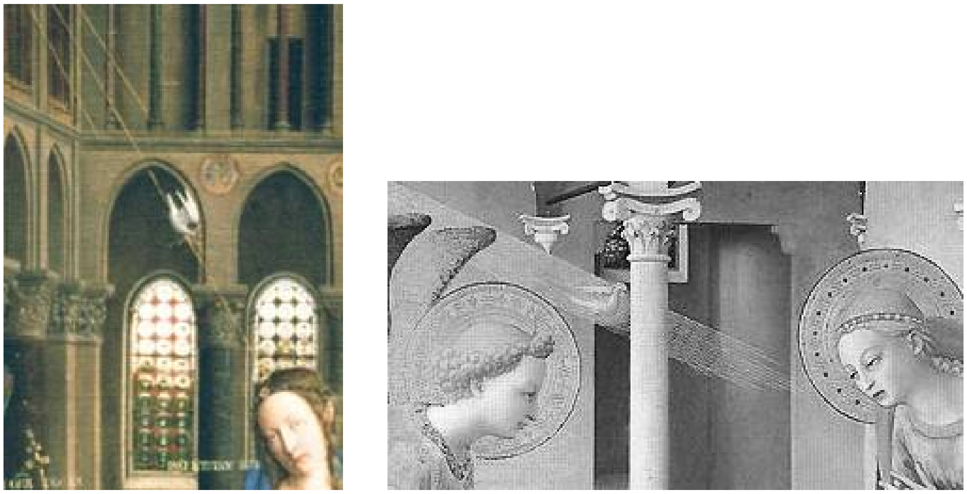

(a) (b)

Figure 8. Artistic manifestation of image transferring by light rays in beginning of the Renaissance. (a) a fragment of Annunciation by Van Eyck (1450) (b) a fragment from Annunciation by Fra Angelico (1452).

Relevance of the Story for School Teaching

This brief account of the evolution of knowledge about vision does present historical facts but it is not a complete history, much interesting and important physical content is skipped over. In order to cover the extreme broadness of the topic it is clear that many of the events and theories which contributed to this story are left without mention in any class presentation by a teacher or student.[13] Nevertheless a meaningful and *conceptually* complete coverage is created. We start with the first scientific theories of vision and light (if not all of them) and stop at the scientific revolution of the 17th century. By this time, the knowledge normally presented within the physics instruction of the 10th grade, usually labeled as Geometrical optics, was consolidated.

What then was the educational rationale behind this presentation of physics development? Our guiding principles reflect the teaching direction as understood in the context of the importance of (1) *cognitive resonance* in learning (Galili and Hazan, 2000), (2) learning by *variation* (Marton, 2003) and (3) teaching science as *discipline-cultures* (Tseitlin and Galili, 2005). These guided our design and are all represented in the new textbook for optics instruction in high school (Galili and Hazan, 2004).

1. STUDENTS' COGNITIVE RESONANCE IN LEARNING

Several studies during the last twenty years explored students' conceptions regarding light and vision[14]. It appeared that the structure of this knowledge could be represented by schemes-of-knowledge, cognitive constructs relating several concepts in a sort of explanatory pattern of context independent content (Galili and Hazan, 2000a, b). In a particular context this knowledge usually manifests itself as a facet-of-knowledge affiliated to a certain scheme. The advantage of such representation is that schemes are relatively few. They should thus be a goal for a constructivist type of instruction seeking learning as a conceptual change (Duit and Treagust, 1998).

If one compares the knowledge of students learning optics with the scientific theories in the course of the history of science, the similarity of characteristic features between the models of vision and light becomes obvious (Table 1).

Table 1: Examples of conceptual parallelism in optics knowledge used in the experimental course.

Historical conception *practiced in the past science*	*Student's conceptions* *practiced in course of learning*
Pythagorean conception of vision Extramission theory	Active vision scheme
Atomists' conception of ''Eidola''	Image Holistic scheme
Euclidean visual and light rays	Scheme of reified rays (Students' rays of sight and light)
Biblical–Medieval dichotomy of light lumen–lux, as a resolution between the light as entity and the light as perception	Scheme of static light (reified light). Light is located in/around the light sources, in halos, in bright sky, on the illuminated surfaces
Al-Hazen conception of vision by means of light rays	Image Projection Scheme (image moves point by point by means of a single ray)

Given this closeness, the working hypothesis of our course in optics was that the exposure of the historical materials which correspond to the parallel beliefs of the students and especially the historical debate between the theories, with the refutation of some and the dominance of others may cause cognitive resonance. This would then capture the interest and attention of the students, which could lead them to replace their initial knowledge by the scientifically preferable conception. The experiment we performed in which, among other materials, we presented and discussed the old theories of vision, supported our expectations (Galili and Hazan, 2000b) causing students' higher quality of content knowledge when compared to students who learned in accordance with the regular curriculum.

2. LEARNING IMPROVEMENT DUE TO THE CONCEPTUAL CONTRAST

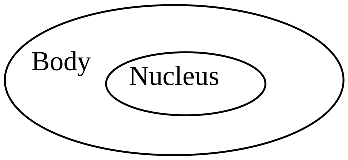
Recent studies in educational psychology stress the advantage of learning by *variation* of the teaching content as being of an especially powerful strategy (Marton, 1997). This approach states that, in order to acquire certain knowledge, skill or problem solving ability the educator should first identify the central feature of the subject and prepare learning material which would present the learner with variations of this target feature. This exposure puts the learner in a position from which it is possible to discern this feature due to the variation and therefore meaningfully assimilate this element of knowledge. If so such variation could well be provided by our presentation of the variety of theories regarding vision and light, which replace one another during the course. Moreover, the very refutation of the alternatives, which initially appeared much more “logical” and grounded in common sense, than the central statements of the theory of vision ultimately adopted, can become more reasonable, intelligible and plausible. For example, the scheme of “direct” transmission of image points by single rays seems much more plausible to the students than the creation of an image by diverging-converging light flux. Instead of ignoring it, it is better to consider it as a “variation” of the true theory, analyze the difference between them and refute the former.

We, thus, consider *variation* to be too weak a term for learning science. In learning science, the important activity is criticism and refutation[15]. This aspect of the approach of comparison between various theories actually resembles Popper’s philosophy of science, with a much milder version of his principle. In our instruction, we did not talk about *total* refutation and reserved the validity of ideas and importance of their memory even when the theory as a whole was discarded (see the next section).

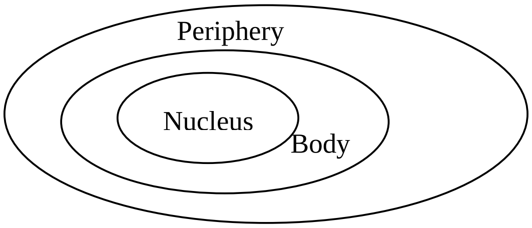
In fact, learning by contrast is not a new idea. Its origin can be traced to the ancient debates between philosophical schools, the dialectic approach in philosophy and debates on controversies and the seeking of truth in Jewish, Christian and Eastern theologies[16],[17]. However, as a reflection of the prevailing philosophy in the 19th century, when science was first introduced into public education, the presentation of rejected theories was dismissed. In this sense, the call to compare theories, does present a serious innovation deserving of the discussion of science educators. Some steps in this direction have been made in the discourse of science educational (Schecker and Niedderer, 1996).

3. TEACHING SCIENCE AS DISCIPLINE-CULTURES

As mentioned earlier, the tendency initially prevalent in science education was to teach scientific theories as they were evaluated at the time. So, for example, when teaching classical mechanics the teacher may mention that the theory is not currently considered correct but it is still useful for practical purposes. “Non-useful” theories, such as Aristotelian mechanics, impetus mechanics, Galileo’s and Descartes’ mechanics, are not normally even mentioned. The subject matter in science class is taught as a *discipline*, which means, presentation of certain theory and its applications. A more rigorous structure can be suggested for the scientific discipline, as a *nucleus* containing the fundamental principles, and the body, containing all possible statements derived from the nucleus (also a variety of solved problems, invented contrivances and so on). As it stands the structure skips over many variations which do not directly change it, this is a common mode employed in science education (Fig. 9a).



(a)



(b)

Figure 9. (a) The structure of a scientific discipline, (b) The structure of discipline-culture.

Within the new approach to presenting science for educational purposes the concept of discipline culture was introduced (Tseitlin and Galili, 2005). To represent the new structure one should add a new area to the diagram, the periphery (Fig. 9b). This area includes the theories, beliefs and ideas which deal with the same subject matter but contradict the contents of the nucleus. Thus, in presentation the theory of Geometrical optics, one finds in the periphery all the theories of vision and light prior to Kepler's, together with their concepts and beliefs. There one finds vision rays, the light rays as the fundamental constituents comprising light and so on. Moreover, if the nucleus incorporates Kepler's theory, the periphery of such a discipline-culture also incorporates all phenomena and concepts belonging to physical optics which surpassed the geometrical optics. One can immediately draw the connection between the peripheral elements with the need for learning by variation, as discussed above. Although this structure does, of course, support the educational goal of variation, its role surpasses mere learning by variation. The new structure represents a fundamental code of the nature of scientific knowledge. This is the picture possessed by an experienced practitioner who has constructed it following years of diverse applications and fragmentary learning of science in that particular domain. This picture represents scientific culture, organized in a hierarchical manner. If the goal of teaching is to provide such a worldview regarding the discipline, the curriculum should be structured in accordance with this model. Culture, then, obtains a modern meaning according to which to be cultural means to include more than one view (concept) on the same subject[18]. Science possesses this feature inherently. Therefore, adopting a curriculum based on the discipline culture view makes science-education closer to science *per se*. In contrast, to teach a discipline (that is to expose solely a nucleus and the body of knowledge corresponding to it) creates an artificial extract out of the scientific knowledge, which is as close to science as dried herbs are to living grass.

Finally, we assert that optics presents a particularly appropriate scientific domain for the application of the discipline-culture approach. Optics is actually as old as science itself, and its history is rich with alternative ideas and concepts. Its evolution started from natural philosophy in Greece and has come all the way to relativity and quantum theories, which both lead inevitably from the very nature of light. Moreover, optics allows for qualitative representation using rather simple mathematics within the introductory course. This conceptual account of competing theories and knowledge dependence on epistemology provides an opportunity to demonstrate the features of the scientific method, providing students with more mature views on science (Galili and Hazan, 2001b).

Conclusion

Albert Einstein once suggested teaching science through impressive experiments which might mean for a novice more than many theories. We may extend this suggestion to teaching physics by means of an impressive story, the kind possessed by the history of light and vision as it emerges in a science curriculum based on a modern cultural approach. Furthermore, several ideas add legitimacy to the incorporation of historical cases into physics curriculum: cognitive resonance in the learner, conceptual-contrast teaching and teaching physics as discipline-cultures.

Notes

[1] Those were dissatisfaction with the old knowledge, plausibility, intelligibility and fruitfulness of the new knowledge.

[2] Indeed, the reported study of Posner investigated students learning a rather advanced material – the special theory of relativity.

[3] It was seemingly suggested by Empedocles. Ronchi, Vasco, 1970, *The Nature of Light – A Historical Survey*. London: Heinemann Newnes.

[4] Lindberg, David, 1976, *Theories of Vision Form Al-Kindi to Kepler*. Chicago: University of Chicago.

[5] Aristotle was not consistent in his theory of vision. Thus, explaining the rainbow he clearly used the extramission theory.

[6] The Hellenistic culture provided an impressive array of names: Aristarchus, Euclid, Archimedes, Heron, Ptolemy, Hyparchus, Eratosthenes and others. They all contributed a lot by scientific enquiry, through observing, analyzing, measuring, inventing, constructing, but not suggesting new philosophical accounts of the Nature.

[7] Relevant to our story of the development in Europe was the first adoption of Alhazen's Optica, the theory of image observation by Roger Bacon in the 13th century in Oxford.

[8] An interesting evidence of the new theory of image transfer one may see in the pictures of Annunciation, where showing the holy image transferring from God to St. Mary was required. Annunciation by the famous artists Fra Angelico (1450) and Van Eyck (1452) show moving of image "on the rails" of the divine light rays. This type of depicturing was not shown in the orthodox pictures of the same event. Witelo's and Peckham's textbooks were available only in Latin and probably used mainly in the Catholic world.

[9] See for example Leonardo's consideration of circular aberration degree as dependent on the curvature of the parabolic mirror (Walles, R., 1966, *The World of Leonardo*, Time-Life Books, Alexandria, Virginia, p.104).

[10] Galilei, G. *Dialogue Concerning the Two Chief World Systems.* Berkeley: University of California Press, 1967.

[11] This is Lambert's Law of Illumination $E=E_0 \cos \alpha$ established in photometry in the 18th century (Wolf, A. A History of Science, Technology, & Philosophy in the 18th Century, Harper Torchbooks, NY).

[12] This is Bouguer's Law of Illumination $E=E_0/r^2$ established in photometry in the 18th century (Wolf, A. A History of Science, Technology, & Philosophy in the 18th Century, Harper Torchbooks, NY).

[13] For instance, we did not mention the theory of vision by Galen and the interesting theory of vision suggested by Stoics. We did not mention many developments of Hellenistic and the early medieval period in Byzantine Empire. We remained silent about the views of distinguished many Arabic scholars and so on and so forth.

[14] Studies on students' knowledge in optics were reviewed by Galili and Hazan (2000).

[15] Thus variation in learning history, geography, literature, art do not imply refutation even if they include critique and statements of preference.

[16] Expressions "We could not have the glory and the light without first knowing the contrast" could be found in numerous religious texts.

[17] Another close technique of dialectical debate is the idea of learning using anti-examples, especially easy to illustrate by introduction of special kind of geometrical figures.

[18] In fact, this presents a definition of pluralism.

References

Galili, I. and Hazan, A.: 2000a, 'Learners' Knowledge in Optics: Interpretation, Structure, and Analysis', *International Journal in Science Education* **22**(1), 57-88.

Galili, I. and Hazan, A.: 2000b, 'The Influence of a Historically Oriented Course on Students' Content Knowledge in Optics Evaluated by Means of Facets - Schemes Analysis', *American Journal of Physics* **68**(7), S3-15.

Galili, I. and Hazan, A.: 2001a, ‘Experts’ Views on Using History and Philosophy of Science in the Practice of Physics Instruction’, *Science & Education,* **10**(4), 345-367.

Galili, I. and Hazan, A.: 2001b, ‘The Effect of a History-Based Course in Optics on Students’ Views about Science’, *Science & Education* **10**(1-2), 7-32.

Galili, I. and Hazan, A.: 2004, *Optics - the theory of light and vision in the broad cultural approach*, Textbook for high school, Science Teaching Center, the Hebrew University of Jerusalem, Israel.

Marton, F. and Booth, S.: 1997, *Learning and Awareness,* Lawrence Erlbaum Assoc.

Schecker, H., and Niedderer, H.: 1996, ‘Contrastive Teaching: A Strategy to Promote Qualitative Conceptual Understanding of Science’, In Treagust, D., Duit, R., and Fraser, B. (eds.): *Improving Teaching and Learning in Science and Mathematics*, Teacher College Press, New York, pp. 141-151.

Tseitlin, M. and Galili I.: 2005, ‘Teaching Physics in Looking for Itself: From a Physics-Discipline to A Physics-Culture’, to be published by *Science & Education*.