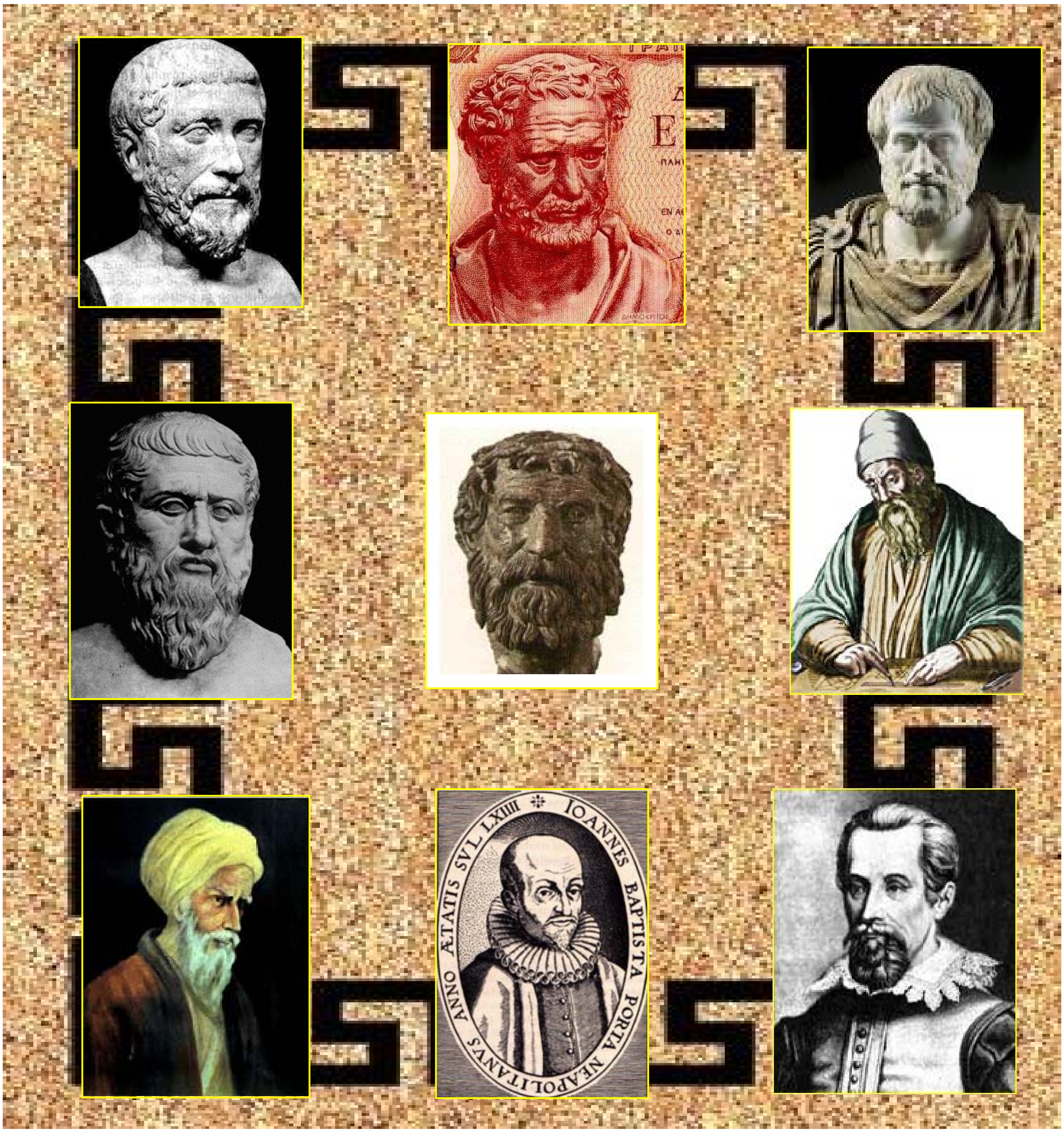
# EXCURSE TO THE HISTORY OF IMAGE CONCEPT AND VISION: FROM PYTHOGARS TO KEPLER

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***Keywords:*** Optical image, light ray, vision, eidola, extramission, intromission, image transfer

## Abstract

We address teachers and students of high school physics course with this excurse which deals with the concept of image in optics. The excurse starts from the classical Greece where scientists suggested several theories of vision. These theories provided qualitative accounts for the optical imagery. These were holistic theories that considered the optical image of an object as a whole. Hellenistic optics of Euclid was already not holistic, but suggested erroneous "active vision" by visual rays that scan the world around the observer. During the mediaeval era, Al-Hazen – a distinguished Arabic scholar – disintegrated image into points each "transmitted" to the eye by the relevant light ray. The further progress was reached in the Renaissance, stating similarity of human eye to the Camera Obscura but leaving open the question of inverted image. Al-Hazen's mechanism (splitting image into points) promoted understanding of optical image, but the solution came only during the scientific revolution of the 17th century. It was due to Kepler in Germany that the role of light flux was understood in the creation of image in the eye. It was also understood that human cognition presents a separate stage in vision, during which the image inversion takes place. By displaying the whole history of optical image – from holistic image to the image comprised by light flux and interpreted by brain – we present the physical theory of vision and shed light on the nature of science, the scientific progress taking place in a discourse between competitive theories. Physics knowledge grows in a complex cumulative process and does not present a simple multiplication. It includes modification of the central idea (basic model) which causes the reconstruction of the theory through a *conceptual change*. Researches on students' knowledge revealed certain similarity of students' accounts for vision with the old ideas in science of the past: the contest between intromission and extramission understandings of vision, between holistic and differential understanding of image creation, between the image created by light flux versus the same by single rays. The similarity between the central historical ideas and those by the contemporary learners suggests using the debate in science resulted in converging in the currently adopted knowledge in order to cause remedy of common misconceptions. This makes the historical excurse relevant in promoting effective teaching and learning optics at school.

* * *

> And God said, let us make man in our *image*, after our likeness: and let them have dominion over … every creeping thing that creepeth upon the earth.
>
> (Genesis 1:26[1])
>
> Thou shalt not make thee [any] graven *image*, [or] any likeness [of any thing] that [is] in heaven above, or that [is] in the earth beneath, or that [is] in the waters beneath the earth.
>
> (Deuteronomy 5:8[2])

So we all were instructed, first, that each of us, presents an image of somebody, and second, that we are prevented from making the same, that is, from producing an image of something. This is a very heavy statement, which at least implies to know what image is and which way it is given to our perception through vision… It, however, appeared to be not a simple matter for people to reveal what image is. To understand this we will follow its history.

* * *

# I. Understanding of vision

## *Introduction*

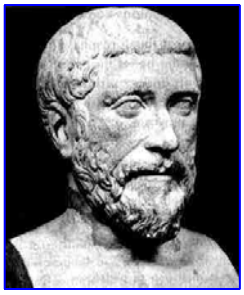
Reconstruction of an object appearance by means of light constitutes optical imagery and is a subject of optics – the physics theory of *light and vision*. The idea of *optic image* was central for people's understanding of light and vision in the course of a long history. Understanding of image, its origin and the ways it is created occupied human mind long before science was established. Myths and tales incorporated various images but the *scientific* inquiry of image is unique in the kind of knowledge it provides and the way that this knowledge was established. This we will demonstrate here. The investigation of light and vision were inherently interwoven from the beginning of Natural Sciences (Natural Philosophy) in classical Greece. It was only much later, not before the scientific revolution of the 17th century, that they split into physics of light and psychophysics of vision, as we know them on our days. In

[1] http://www.bible-history.com/kjv/Genesis/1/

[2] http://www.bible-history.com/kjv/Deuteronomy/5/

accordance, our tracing the growth of image understanding will mingle the major ideas invented by people to account for the nature light with those trying the same regarding vision.

## *Hellenic Science*



Pythagoras

Natural science was established in Classical Greece in the course of evolution from the knowledge in the form of myths. The first scientists of the Hellenic cultural period provided at least four competing theories of vision. The first one was introduced by the school of Pythagoras. Hippocrates of Chios (5th century B.C.) and Archytas of Tarentum (4th century B.C.), explained vision by some sort of radiation, *opsis*, an *internal fire*, emanating from observer's eyes, reach the observed objects and cause the observer to see them (Fig. 1). For the direction of activity in the process of vision, this theory was termed *extramission*.

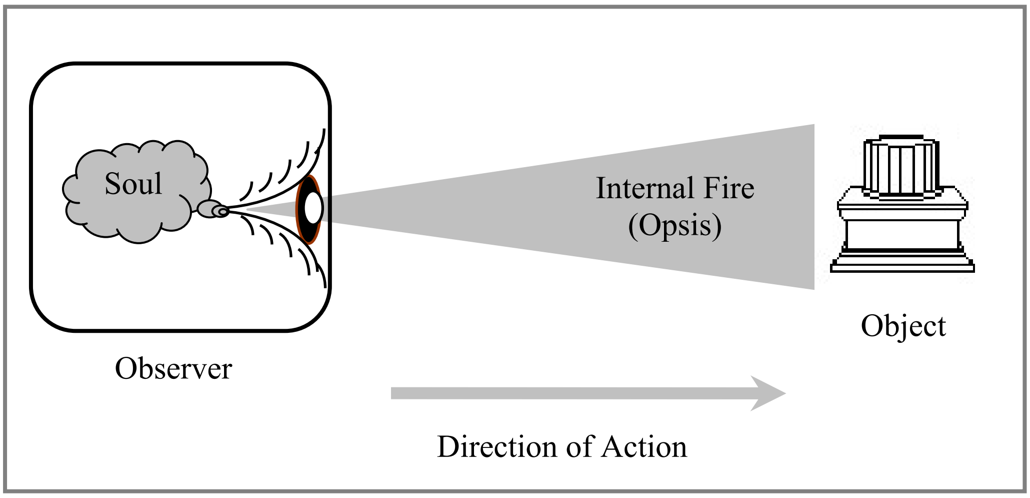



**Figure 1.** *Schematic representation of the Pythagorean extramission theory of Vision*

One may see the rationale of this conception. Indeed, the interpretation of vision as a sense of touch in the observer, in parallel with other human senses: smell, hearing, touch, and taste (Fig. 2a). This understanding might be observed in the much earlier understanding

**Figure 2a.** *Most of our senses presume touch. Is vision like this? The drawing from the text of Descartes of the 17th century*.

of light in the Ancient Egypt. Much before science was established, about 3500 years ago, Sun was conceived as sending its "hands" to touch and heat things around (Fig. 2b).

**Figure 2b.** *Egyption pharaoh worshiping Sun-God. The picture of the 14th century B.C.*

Pythagorean theory of vision was of extramission type. It stated that vision is a perception of touch which is realized by the vision flux coming out of the observer eyes.

This understanding looked reasonable. Indeed, the initiative of vision definitely belongs to the observer who turns his head and eyes to the object in order to see it. We "focus" our sight on the object. Strangely enough for the modern thinking, the adherents of "active vision" reasoned also by the *convex* surface of eyes: organs of other senses, like hearing and smelling, show a kind of *concave* surface. So, since eye possesses convex surface, they thought, it must radiate, not adsorb. They also appealed to the observation of animals, especially cats, who are known by their sparkling sights at night.

The opponents of this theory, however, argued by questions "why don't we see at night? or "Why do we see immediately after opening eyes the distant stars?" Both questions had no answers within this theory.

The *second* theory was due to the school of Atomists of Democritus. They stated that each body around us produced a sort of its replica, an image (*eidolon*) (Fig. 3). Comprised of atoms of that object, images (eidola) leave the object traveling in all directions in space until they enter the eye of an observer, causing the effect of vision. Opposite to Pythagorean theory, this theory should be considered as *intromission* theory since the process of vision presumed entrance of some physical entity into the eye of the observer.

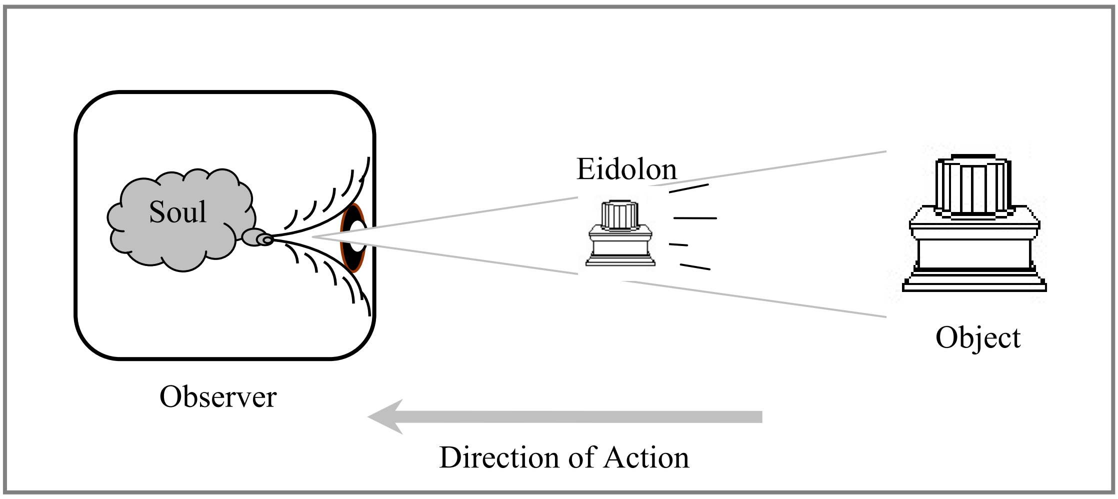
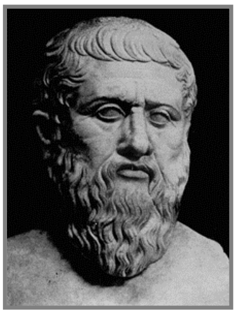
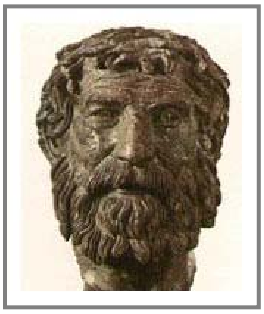



**Figure 3.** *Schematic representation of the Atomists' intromission theory of vision*

The opponents of Atomists' theory, argued by questioning, "how the eidola of big objects around, such as mountains, for instance, succeed to enter into a small eye" or "why do not we see images of things on walls?" Moreover, the same question that Pythagoreans could not answer was asked again: "why don't we see at night?" Atomists could not answer either.



Plato



Empedocles

The *third* theory is usually referred to Empedocles (a distinguished philosopher from Elea – the Greek colony in Sicily) and Plato (427–347 B.C.) in Athens. This approach in a way combined the two previous ideas, suggesting understanding of vision as resulting from a meeting of three fires (Fig. 4). Firstly, the "pure fire" of the ambient daylight "not admixed with other primary bodies". In contrast with flame, it "flows off flame, and does not burn but gives light to the eyes". Secondly, "*internal fire*" – the visual stream of the same kind as daylight, contained in the eyeball and capable of issuing out as a flow (emanating from the pupil) towards the object seen by the observer. Thirdly, the "*external fire*" radiated by the observed objects, which was related to their colors. Comprised of particles it propagates towards the observer and meets the visual current to yield sensation.[3]

[3] Conford, M. (1937). Plato's Cosmology. The Timaeus of Plato. The Bobbs-Merrill Co., Indianapolis, New York, p.152.

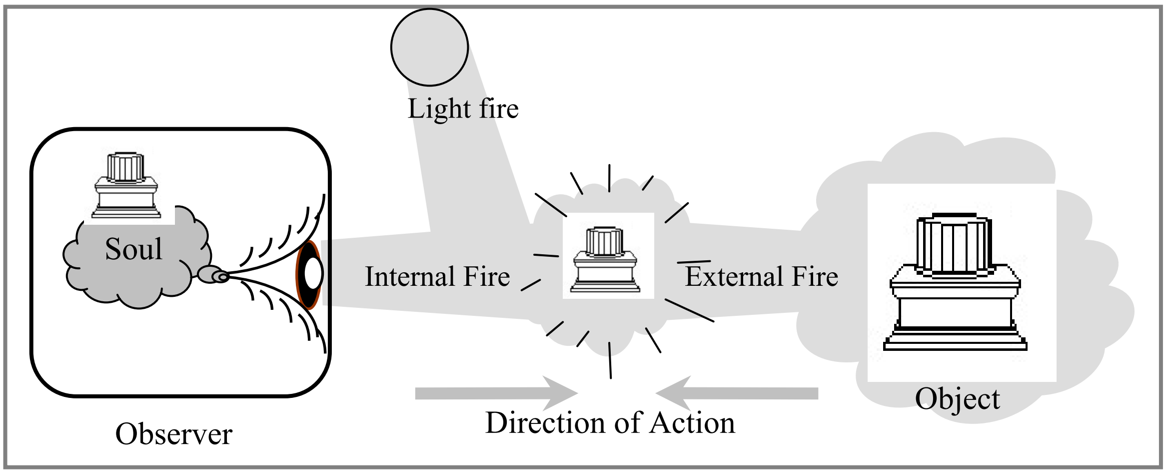



**Figure 4.** Schematic representation of the Empedocles-Plato's hybrid theory of Vision.

Unlike the previously mentioned theories, in the theory of Empedocles-Plato, the vision process takes place only under the influence of light ("pure fire diffused in the air by Sun") interwoven with the internal fire of the observer. It is the ambient light that somehow induces the radiation of the fire by the illuminated objects.

Aristotle

The *forth* theory was also extremely creative. It was an intromission theory of vision (the activity is from outside the observer into him, through his sense organ – the eyes) and was suggested by Aristotle (384–322 B.C.)[4]. He distinguished color – an inherent feature of objects – from *light*, which he understood as a non-material agent, a trigger for the medium (air, glass, water) to be transparent and allow the process of vision to take place (Fig. 5).

It is the *color* of the observed object, in view of Aristotle, that causes a special compression in the medium between the object and observer (usually the air), which reaches the observer and is perceived by his eyes. Indeed, it seems plausible to accept that the absence of color means being transparent, not seen. Colour is what lays on the surface of the object and it sets the transparent medium in a state of tension.

[4] Aristotle was not consistent in regarding vision. It is a rather strange fact since consistency was his central commitment in establishing scientific knowledge. In explaining rainbow, he clearly employed visual rays of the extra-mission theory. Perhaps these pieces were due to somebody else from the school of Aristotle.

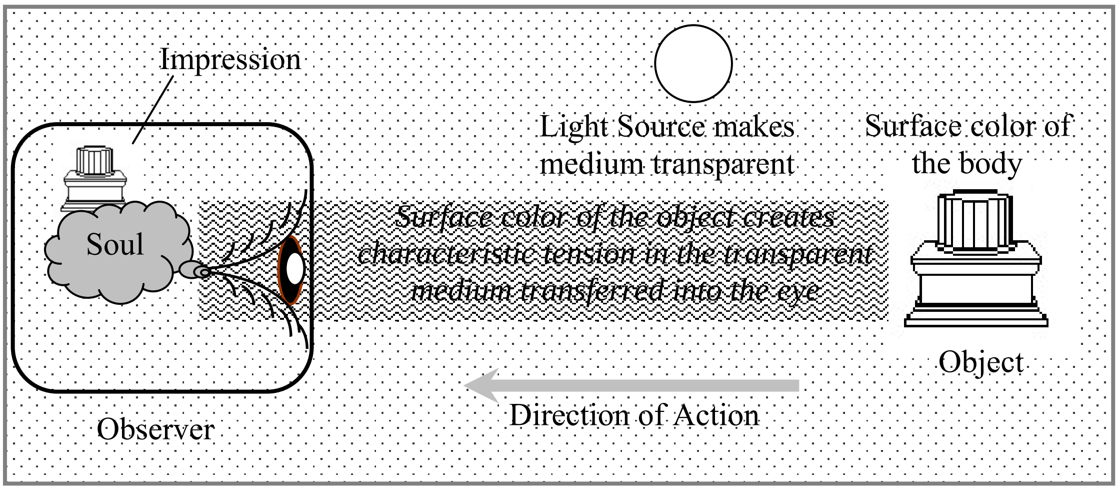



**Figure 5.** *Schematic representation of the Aristotle's intromission theory of vision*

The process proceeds within the eye and reaches the soul of the observer, causing the act of vision – the visual perception of the original object. All together, this theory should be an intromission theory with a mediator. The proof of the need of mediator Aristotle saw in the fact that we cannot see an object we approach our eye too close to it. Therefore, we need some space of air in between.

Hellenic optical theories stated the eye to be made of fluid, yet the lens was never identified.

**Questions to reflect**

1. Discuss the arguments if favor of each of the four Hellenic theories of vision.
2. Bring reservations with regard to each of the theories.
3. Was it possible to make a unique preference in favor of one of the theories and to refute the others? Explain.

## *Hellenistic Science*

The four Hellenic theories described various types of relationships between observer, medium and the object seen. During the next period, that of Hellenistic culture, scientists proceeded this exploration of vision, but sought a more detailed picture, refined mechanism of vision. This tendency brought new investigations and theories of more sophisticated description of vision and eye.

Hellenistic culture, in general, performed a sort of revolt against the general philosophical preference of the Hellenic science. The scholars were not satisfied with holistic, qualitative account of vision and reconsidered it. Scientists of Hellenistic world sought for a more concrete information about light behavior and vision process.

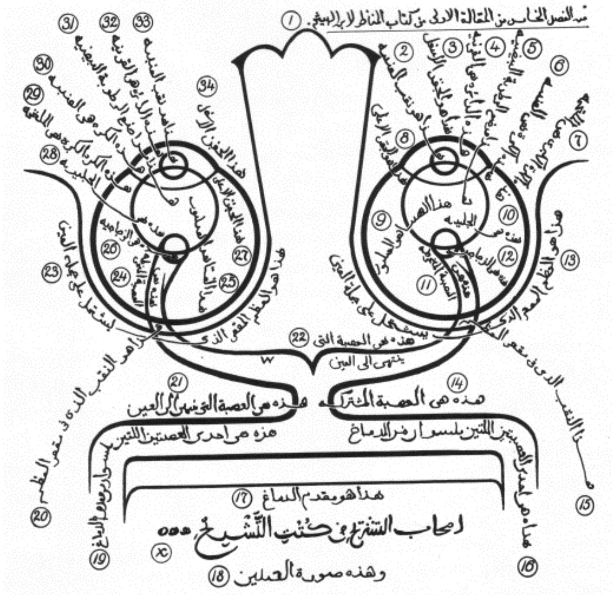
This ambition required a more active exploration and new methodology to perform a more precise elaboration of natural phenomena.[5]

* * *

Galen was a famous Greek physician in the Roman empire of the 2nd century. He accumulated a vast experience in making surgery to sick and injured people. Seemingly, he was the first to describe correctly the anatomic structure of the human eye and identified its components: cornea, iris, pupil, crystalline lens (or humor), aqueous and vitreous humor, and retina. He identified the humors that filled the eye organ (vitreous and aqueous) and ascribed to the lens the vital role in vision process, as seemed to him evident from his surgery practice.

Claudius Galenus
(129-199)

Among the most important findings was the established connection of the retina to the brain. This way, for the first time, brain was included to the process of vision – the seat of the vision perception.



*The structure of eye as established by Galen and described in Arabic manuscript few hundred years later*

In understanding the vision process, Galen adopted the new for his time approach of Stoics philosophers who ascribed the central importance to a special medium – pneuma, an all-pervasive active agent composed of air and fire that fills the whole universe. With regard to vision, it was, in a way, similar to the Aristotelian theory in which the medium, that became transparent, also played a central role. However, in Stoic physics, pneuma was a more active medium, possessing a feature of perception.

[5] The Hellenistic period provided an impressive array of scholars: Aristarchus, Euclid, Archimedes, Heron, Ptolemy, Hipparchus, Eratosthenes and many others. They all essentially contributed through scientific inquiry, analyzing, measuring, inventing, constructing. They, however, generally kept within the Hellenic philosophical framework from the previous period.

In the view of Galen, visual pneuma emanates from the brain and comes to the eye through the visual nerve (Fig. 6). When visual pneuma touches the air it goes through a transformation and obtains the virtue of visual perception, which was similar to what happens with the sense of touch. Although the scenario included a mediator, pneuma, it still was closer to the extramission process. Galen rejected the intromission idea of an image of the observed object that physically goes to the eye. He reasoned by incompatible sizes of the pupil and the big objects: how could possibly an image of a mountain enter the small opening of the observer's eye?

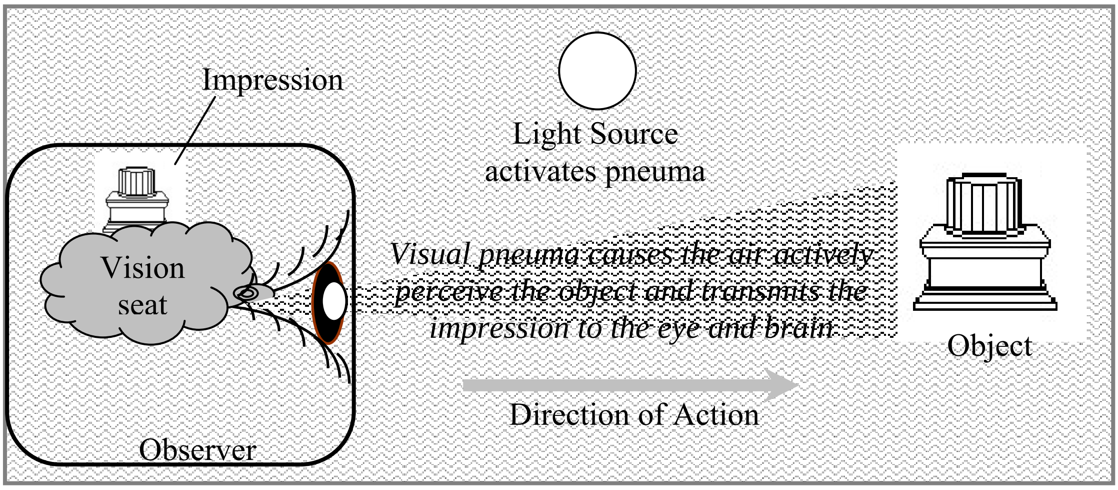



**Figure 6.** *Schematic representation of Galen's extramission theory of vision*

Euclid – the renowned mathematician of the Hellenistic science, whose geometry we all still learn at school, made his own contribution to the understanding of light and vision process. In fact, his contribution was revolutionary. Having adopted the extramission framework by means of vision flux he refined it by introducing the concept of *ray*. Euclid introduced two types of rays: visual and light. Both served as fundamental concepts for his theory of light and vision. Light was considered as comprised of light rays, and vision – as a process of searching the environment by the observer who emanates rays of vision. Euclid postulated that rays of light and rays of vision obeyed the same laws of behavior. His theory that explained the experience of vision by its structure reminded his famous geometry. The observer scanned the environment by visual rays (Fig. 7). The ray concept structured the "internal fire" of Pythagorean philosophers and provided a powerful tool for the graphical account of vision. In fact, it is the account by means of rays that established the theory of perspective – the flat, two-dimensional representation of the three dimensional reality.

This approach explained, for example, why we see all remote objects smaller, and how one should draw the observed reality on paper in the way that the drawing will appear to the observer as three-dimensional, and not flat.

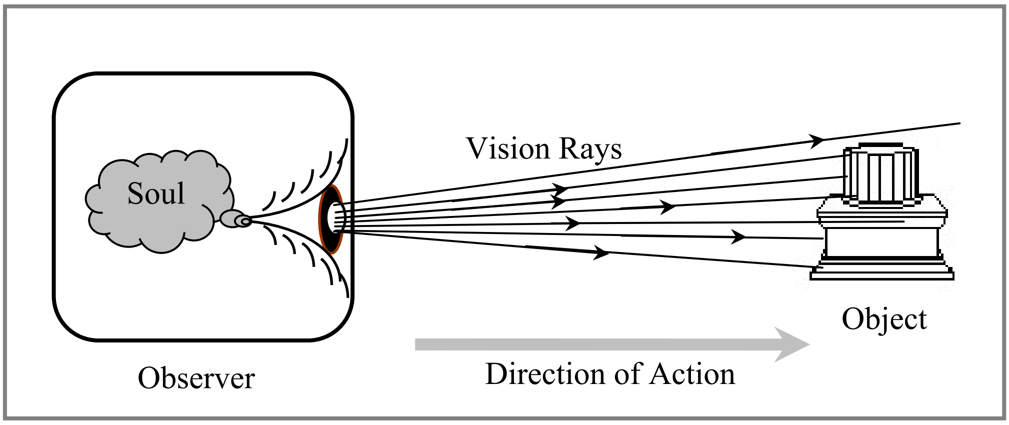



**Figure 7.** *Schematic representation of Euclid's refinement of the extramission theory of vision. Observer's eye scans the object by visual rays.*

The great minds of the Hellenistic science – Heron, Archimedes and Ptolemy – investigated the rules obeyed by light and vision rays in the phenomena of reflection and refraction. Thus, Heron and Archimedes formulated and proved (basing on postulating the trajectory to be minimal – Heron, and be reversible – Archimedes) the law of reflection: on the trajectory of light and vision to lay in one plane and the angle of incidence and the angle of reflection must be equal (Fig. 8a). Ptolemy, who also adopted the idea of visual rays, was the first who experimentally investigated the rule of vision (and light) rays refraction – the change in the direction at the boarder between two different transparent materials. Although Ptolemy could not establish the correct functional dependence between the angle of incidence and the angle of refraction of light and vision rays, he could state that at comparatively small angles they keep their ratio constant, and its magnitude depends on the kind of the materials the light leaves and enters to (Fig. 8b).

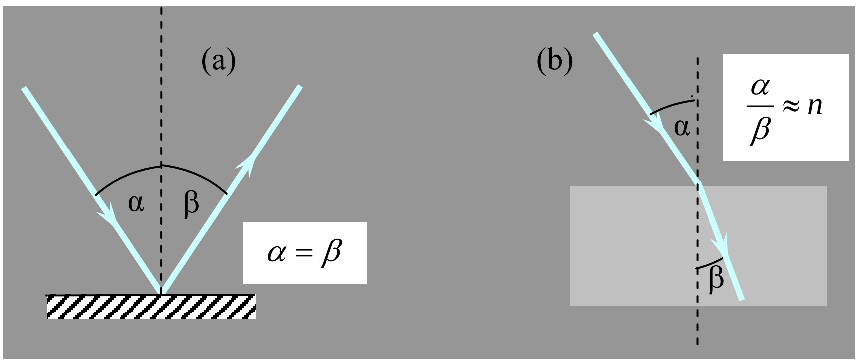
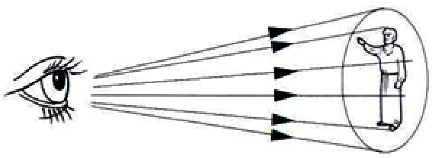


**Figure 8.** *The established regularity of vision and light rays at the processes of their reflection (a) and refraction (b).*

However, even that the behavior of rays (of light and vision) outside of observer was investigated nobody asked what exactly happened with the rays inside the eye of the observer that caused the image to emerge.

**Questions to reflect**

1. Discuss the features of Hellenistic theories of vision (Euclid, Galen, Ptolemy). In comparison between them and those Hellenic theories, previously described? Formulate the rationale and central features of these theories.



2. Discuss the justification of and reservations against with regard to each of the Hellenistic theories of vision.

* * *

## *Medieval Muslim Science*

During the 9th century the center of scientific research activity moved to the Muslim world. Europe by this time was deeply immersed in numerous wars and suffered from no stability. The remarkable progress in the account for vision and light imagery took place at this time.

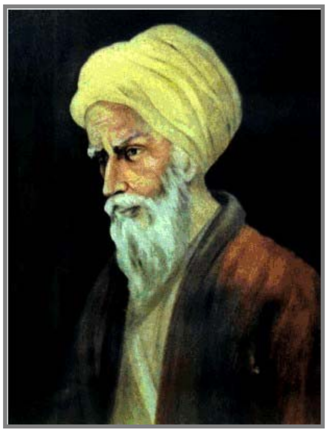
It started by Al-Kindi, a distinguished Arabic scholar in the 9th century, stated an important principle, according to which, light emanates from each point of a source in all possible directions. This claim was seemingly not obvious in the past (Fig. 9a).

**Figure 9a**. *Violation of the principle of Al-Kindi for light radiation in the old Egyptian drawing of the Sun.*


Al-Kindi

An important extension of this principle was made by another great Arabic scholar – Abu Ali al-Hasan ibn al-Haytham – in the 11th century. He stated the same claim regarding any observed object (Fig. 9b), that is to say:

*Each object, whether radiating or reflecting light, causes light radiation in all directions from each its point*



Al-Hazen
(965-1039)

This principle might be confused as presenting a contradiction to the law of light reflection (Fig. 8a), but can be explained by the roughness of surface of regular bodies that causes multiple reflections from each tiny piece which all together, in a big scale, appear as radiation of light in all directions (Fig. 9b). This understanding was very important for the further progress in resolving of the enigma of vision.

A breakthrough in the understanding of vision took place in the 11th centuries due to the contribution of Abu Ali al-Hasan ibn al-Haytham, or Al-Hazen, as he was known in Europe.

Firstly, Al-Hazen very seriously adopted the concept of light ray and considered light as abundance of light rays, which was a powerful approach to account for optical phenomena in a more accurate manner. Secondly, he dismissed the idea of visual ray and thus took a clear position in favor of the intromission theory of vision. He stated that our vision is due to the light that enters to the eye of the observer.

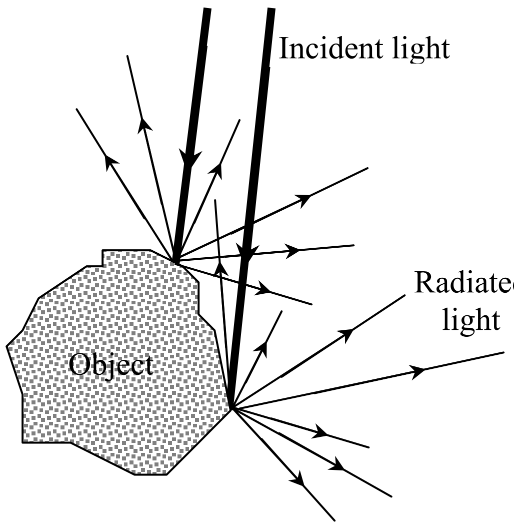



**Figure 9b**. *Illustration of the principle of Al-Kindi –Al Hazen: light is emanating from each point of any observed object in all directions.*

He reasoned by the fact that it is painful for us to look straight at the strong source of light, such as the Sun (looking straight to the Sun is very dangerous!). Furthermore, he mentioned the known effect of after-image (if one looks at an object for about a minute and then closes her eyes, she still has a feeling of an image observed).

So, considered Al-Hazen, no visual rays radiated from the eyes.

Light traveling in all directions from each observed object is sufficient to allow our vision, and to account for that process one can render with light rays. However, how exactly to do that?

To be convincing Al-Hazen had to proceed beyond a mere idea and to suggest a mechanism of vision. To understand the nature of his analysis, in which Al-Hazen adopted drew on the knowledge established before him in Alexandria by Euclid, Heron, Archimedes and other Hellenistic scholars. Those all stated and used the fact of the rectilinear expansion of light. Al-Hazen started with confirming it empirically by using a special instrument – Camera Obscura – a darken room with a small opening in one of its walls (Fig. 10).

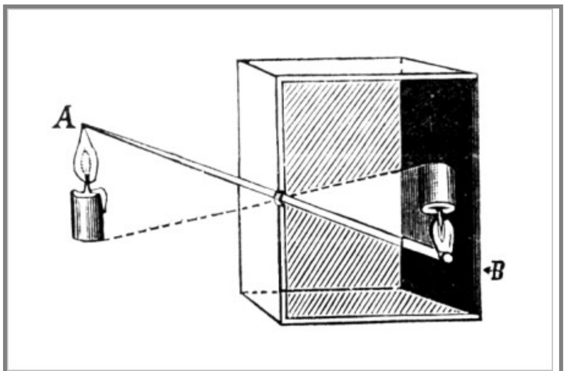



**Figure 10**. Schematic representation of Camera Obscura.

From the time of Aristotle it was known that on the wall opposite to a pinhole one can observe an image of things placed in the space before the wall. Al-Hazen understood that this image can be explained by using two prepositions:

1. Each point of any illuminated object sends light to all directions and

2. Light rays are straight lines only. Indeed, each point of the object radiates light in all directions and only a fraction of this light succeeds to enter through the pinhole in the wall (Fig. 10). It creates a light spot on the opposite wall of the camera.

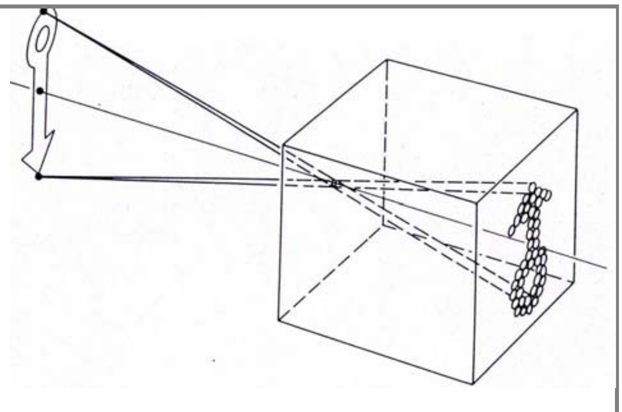


**Figure 11**. *The image observed in the Camera Obscura is comprised of spots of light each coming from a point of the object.*

All the spots together comprise the observed image (Fig. 11). Here was the new point: image should not travel in space *as a whole* in order to be seen. It is enough that each point of the object will cause an illuminated spot. All the spots together create an illuminated area of the wall that presents a replica of the object – the optical image.

Basing on this idea Al-Hazen considered the process of vision and faced an immediate problem. If each point of the object sends many rays to the eye, how could it be all that these rays do not cause a chaos of illumination inside the eye? After all, we have an impression of a very clear and focused image. There is, Al-Hazen thought, a sort of selection among the rays of light, and he speculated regarding such.

Al-Hazen knew that when light that entered the transparent medium of any material it changes its direction (Ptolemy of Alexandria, known to Al-Hazen, reported about the *refraction* of light and even provided numerical data about it). However, all light was deflected aside but the one traveling perpendicular to the surface. Al-Hazen assumed that only such rays (at right angle to the surface) were relevant for vision: they entered the eye through the cornea (convex eye surface) and proceeded towards the crystalline lens. Here, on the lens, an image is created, as on the wall of the Camera Obscura (Fig. 12). This way rays 1 and 2 map points **a** and **b** of the object to points **a'** and **b'** of the image. We may summarize:

> *During the image creation, in fact (in the view of Al-Hazen), the points of the object are "transferred" by light rays to the points of the image on the surface of eye lens, point to point by means of a single light ray for each point.*

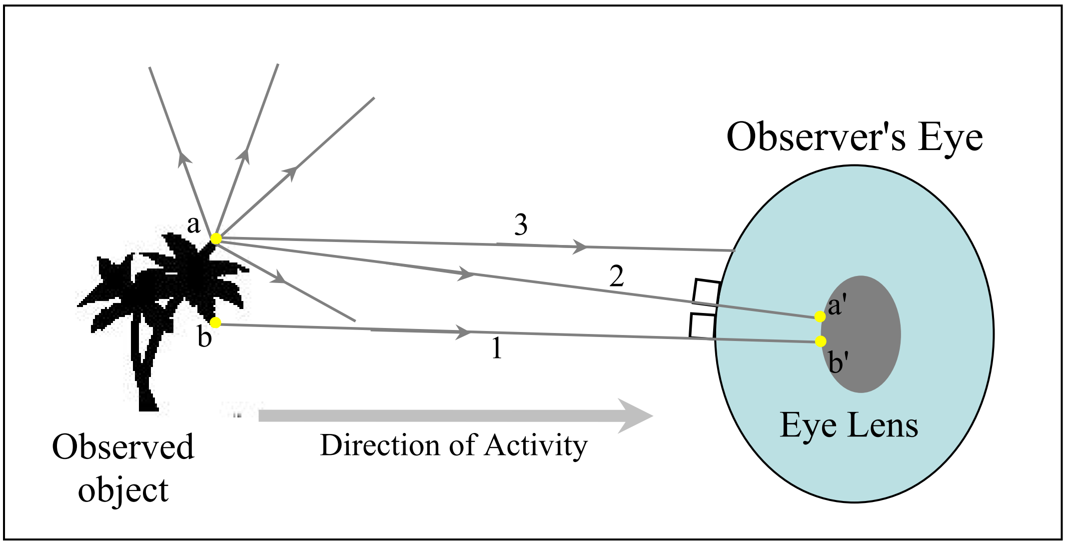



**Figure 12.** *Schematic representation of the mechanism of vision according to Al-Hazen. Ray selection: rays 1 and 2 are perpendicular to the eye surface and enter the eye, ray 3 is oblique and is irrelevant for image construction in the eye.*

The question remains, however, why Al-Hazen stopped this scenario of image creation on the lens, making it a sensitive organ of human sight and did not proceeded with the rays crossing the lens and coming to the retina.

Seemingly, one of the reasons for that, if not the reason, was the usually observed up-side down inverted image observed after the lens, as well as in Camera Obscura. This fact could puzzle Al-Hazen, looking as contradicting the actual experience of observation: regular right side up images of the observed objects.

The optical treatise of Al-Hazen: *Kitab al-manazir* (*The Book of Optics*; *De aspectibus* or *Perspectivae*), reached the scholars of the Western Europe. In the 13th century, Roger Bacon in Oxford was inspired in his optical explorations by Al-Hazen. The treatise was translated into Latin and became known to the scholars during the Middle Ages. They not only adopted this new knowledge of Al-Hazen, but also reproduced it experimentally and disseminated the new knowledge of Optics by writing textbooks, in the 13th century: the manuscripts of *Perspectiva* by Witelo (Fig. 13) and *Perspectiva Communis* by Pecham.

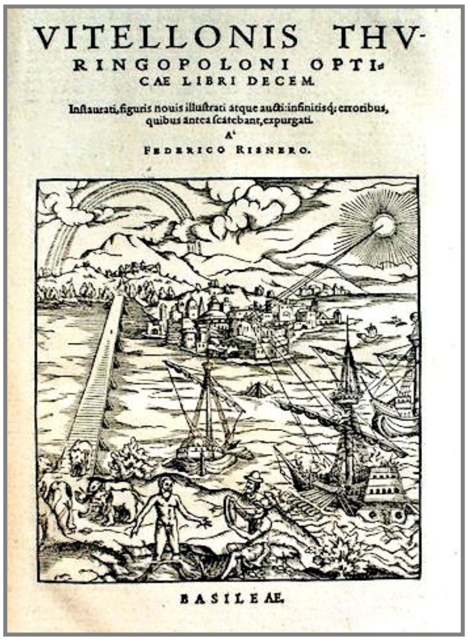



**Figure 13**. *The front page of Witelo's tractate Perpectiva as a textbook published in Basel in 1572. It was largely based on the Al-Hazen's optics and introduced it to Europeans.*

The book of Witelo was especially popular and dominated in the education of the medieval Europe for more than four hundred years. This regarded the knowledge of eye structure (Fig. 14) and the process of vision. The light ray became a central theoretical concept of optics.

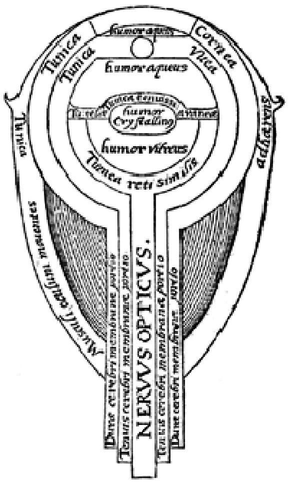



**Figure 14**. *Alhazen's view on the structure of eye as depicted in Witelo's Perspectiva. See the eye lens ("humor crystalling") erroneously located in the center of the eye.*

### Questions to reflect

1. Which way Al-Hazen reasoned for the intromission theory of vision?

2. Al-Hazen stated that light was reflected from any point of

the illuminated object in all directions. Did this claim contradict the law of light reflection (equality of the angles of incidence and reflection)?

3. What kind of light ray selection did Al-Hazen apply? What for?
4. Al-Hazen placed the image on the surface of the eye lens. What was the reason for that?

* * *

## *Early Modern Science*

During the time of Renaissance, scholars continued to think about vision. Al-Hazen sounded convincing but his theory still was too qualitative, no mathematical account, no ability to make any practical implementation. This did not match the intention of the newly coagulating science. The major reservation against Al-Hazen's mechanism of vision was that he drew only on the *relevant* rays (those that stroke the eye surface at right angles), and what about those rays that were very close to the relevant ones? Can the Nature be so selective in preferring one ray to its adjacent one? These questions kept to bother scholars. One may say that they, the unanswered questions, remained in the periphery of the optical theory that explained vision since the 11th century.

Leonardo da Vinci
(1452-1519)

In the 15th century, Leonardo da Vinci contributed a lot to the creation of the human ability to represent reality observed by eye on the surface of a flat page – marvelously reproducing reality. The theory of perspective became central in this endeavor:[6]

> *Perspective, which shows how linear rays differ according to demonstrable conditions, should therefore be placed first among all the sciences and disciplines of man, for it crowns both mathematics and the natural sciences and is adorned by the flowers of one as well as of the other.*

Leonardo counted light rays to estimate the intensity of light and shadow. In the Renaissance Italy of the 15th century, the group of artists and architectors – "Perspectivists" – Brunelleschi, Alberti and others in Florence, revived the Euclidian theory of perspective for the needs of architecture and painting. In this activity, it was not important whether light come into eye or from it, as a well as what happens inside

[6] Leonardo da Vinci, Atlanticus, 203. In Leonardo da Vinci (2002). *Leonardo on Art and the Artist*. Dover, New York, p.101

the eye of the observer. Alberti wrote, showing his knowledge of the old debate in optics[7]:


Leon Battista Alberti
(1404 – 1472)

> *Among the ancients, there was no little dispute whether these rays come from the eye or the plane. This dispute is quite useless for us. … Nor is this the place to discuss whether vision, as it is called, resides at the juncture of the inner nerve or whether images are formed on the surface of the eye as on a living mirror.*

**Figure 15.** *This flat artistic composition aims to generate a perception of depth in the observer visiting the church of San Giacomo Maggiore in Bologna. The perspectivist tradition was very strong in the classical painting.*

Leonardo and others of his time (like the quoted Alberti) continued to believe in mapping of the observed object by means of light rays, which transfer the image into the eye. In fact, this understanding corresponds to the functioning of the Camera Obscura in creation optical images. It is in accordance with this understanding that we read in Leonardo's notebooks:[8]

> *…the larger the pupil the larger will be the appearance of the object it sees…. All things seen will appear larger at midnight than at midday and larger in the morning than at midday. This takes place because the pupil of the eye is considerably smaller at midday than at any other time….at night it [pupil] sees things larger than by day.*

Unlike Al-Hazen, Leonardo did not suggest any selection among the multitudes of rays emitting by the object and reaching the eye. He focused on another problem.

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[7] Alberti, L. B. (1436/1970) *On Painting* Translated by J.R. Spencer. New Haven: Yale University Press. http://www.noteaccess.com/Texts/Alberti/1.htm

[8] Leonardo da Vinci (1955). *Notebooks.* In E. MacCurdy (Ed.), Optics, Ch. IX, Georger Braziller, New York, p. 251.

Leonardo did not agree with Al-Hazen on the image location in the eye: not on the lens, which only refracts rays, but further inside the eye, on the extremity of the optic nerve.

It is interesting to follow the conceptual struggle of Leonardo to discover the mechanism of vision. Image (in terms of that time: *similitudine*, *spetie*, *impressione*, *forma*, *eidolon*, *simulacra*) travels through space by rays. Leonardo knew the principle of Camera Obscura and the analogy of vision with Camera Obscura obliged him to include inversion of light rays when they enter the small opening of the pupil in the eye (Fig. 16a).

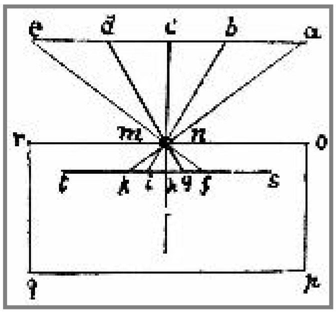


**Figure 16a**. *In this sketch, Leonardo explains the first inversion of image in the eye.*

This, however, implied immediately the image to be, inverted or up-side down. This inversion puzzled Leonardo as it apparently contradicted to the fact that we see objects right side up. He thus suggested the existence of the second crossing of the rays that took place inside the eye, the one, which could cancel the first inversion of the image on its way to the optic nerve (Fig. 16b).

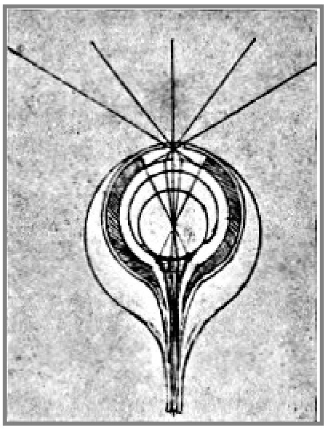


**Figure 16b**. *In this sketch, Leonardo showed two consecutive inversions of the image in the process of vision.*

The ideas of Leonardo did not have a big impact, perhaps, because he did not want this to happen: he codified his comments and those often remained only for the use by the reader in future to read and be impressed.

It is indicative for the conceptual history of image understanding to mention the views on vision by two more heroes from Italy of the 16$^{th}$ century: Francesco Maurolico and Giovanni Batista Della Porta.

Maurolico, a professor in Messina, Italy, understood that one should not forget what a transparent concave lens – and such is the inner crystalline lens of the eye – makes to light rays: their convergence. This account explains the function of spectacles for far-sighted defected vision that requires convex lenses to compensate for the insufficient power of eye lens.

Francesco Maurolico (1494-1575)

However, Maurolico did not lengthen the rays to their crossing, the rays, "properly arranged" after refraction in the lens, reached the extension of the optic nerve – the retina, which covers the inner surface of the eye. Retina presented, in the eyes of Maurolico, the destination of the image travel (Fig. 17). In fact, Maurolico's picture remained coherent with the medieval paradigm of vision by Al-Hazen: point to point mapping the object to the image by single ray.

Although Maurolico rejected the claim of Al-Hazen that only perpendicular rays constitute the image and called this claim absurd, yet, he did not provide any other, new mechanism of image creation. He just mentioned that the central ray in the relevant pyramid of rays coming from the object point make the major contribution, while the others yield "less certitude", that is to say, play a minor role – quite an obscure claim.

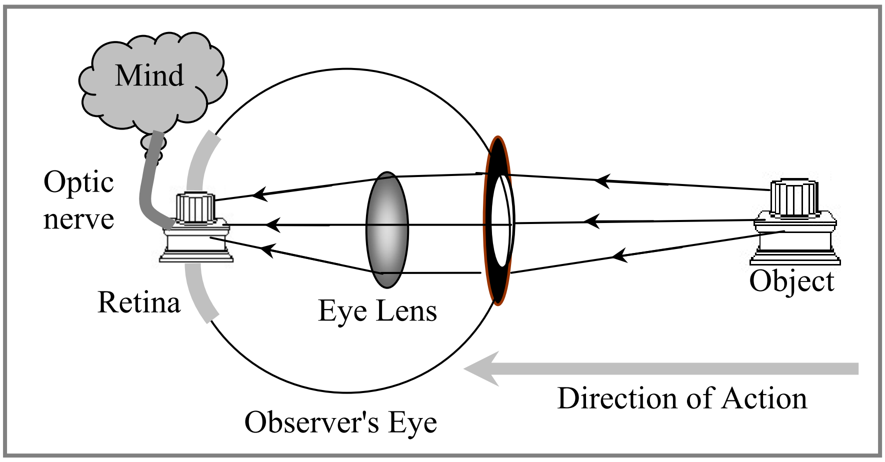



**Figure 17.** *Schematic representation of Maurolico's understanding of vision. Single rays projected each point of the object to its image in the eye.*

Maurolico still regarded the crystalline humor not merely as a refracting device, but also as an instrument of perception, where the visual power resides.[9]

We may mention one more explorer from the Renaissance Italy – Giambattista della Porta who was a scholar and polymath, working mainly in Naples. His major

[9] Lindberg, D. (1976). *Theories of Vision Form Al-Kindi to Kepler*. University of Chicago, Chicago, p. 182.

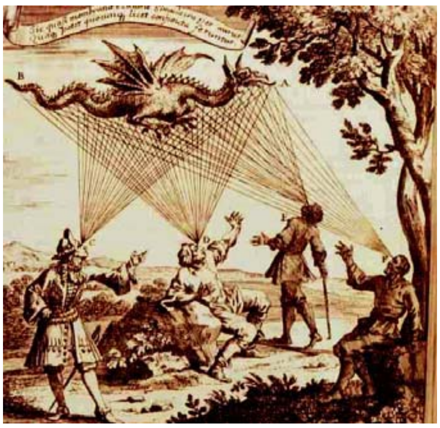
interest was to discover new phenomena what he considered as revealing secrets of the Nature without providing them with theoretical account.

Della Porta
(1535-1615)

Within this activity, Della Porta once found that if one placed a convex lens in the opening of the *Camera Obscura* the image in the camera became much brighter. Not only so, if the image in the regular camera was practically not sensitive to the distance of the wall to the opening, in the camera with a lens, a clear edge image was observed only at a certain distance between the lens and the wall of the camera.

We know today that by placing a convex lens into the opening of the Camera Obscura della Porta converted it into a regular camera in which the focused images can be obtained only at a certain distance after the lens. Much brighter, the image in the camera with an incorporated lens became blurry and disappeared at the whole range of distances. For the distant objects the distance for the focused image to be observed was equal to the focus distance of the lens.

Although della Porta speculated that eye was a tiny *Camera Obscura* it did not shake the main erroneous conception of vision reigned in the science of optics for about six hundred years (the one originally established by Al-Hazen). The history of vision was going to enter the revolutionary conceptual change with regard to understanding of the optical image creation.



**Questions to reflect**

1. What problem did Leonardo try to resolve with regard to vision? What preposition obliged Leonardo to tackle this problem?
2. What was the similarity between Al-Hazen and Maurolico in understanding of vision?
3. What was the contribution of Della Porta to the understanding of vision?
4. The presented figure from the old book of optics regards the process of vision. To what theory of vision does it fit?
5. Should we consider Della Porta to be a scientist? Discuss this question.

* * *

## *Modern Science*

The major breakthrough in the development of vision theory took place during the scientific revolution of the 17th century, when science performed a transition to the Modern Science period. Johannes Kepler, a genius scholar, was one of the actors of this process. He explained the course of action taking place in vision in a essentially new manner. At its first stage, the construction of optical image was compared with the way it takes place by a convex lens (Fig. 18).

While doing so, Kepler reconsidered the role of the light ray to be a mere representation of light flux with no other function in transferring optical image: "lines [of light] infinite in number issue from every point" in visual field. This was important, since instead of explaining image creation in terms of rays, one may do the same in terms of light or light flux: each visible point completely bathes the eye with rays, which create a cone with the apex on this point and the base on the eye surface (Fig. 18).

Exactly in accordance with the Al-Kindi–Al-Hazen principle, light flux emanates from each point of the object and expands in space in all directions. Then, the flux that meets the convex surface of cornea enters the eye which parts (including the crystalline lens inside the eye) serve a system that causes the flux to converge. Due to the refraction in the eye lens, the light flux converges exactly on the retina, creating an image point. This point of illumination corresponds to the particular point of the object. The cluster of created image points comprises an illumination pattern reproducing the object – the optical image.

The fundamental conceptual change introduced by Kepler was the replacement of point-to-point mapping of object to its image by means of *single rays* to the point-to-point mapping of the object by means of *light fluxes*, converging by the eye on the retina. Thus, Kepler dismissed Al-Hazen's idea (known to him from Witelo) of discrimination between rays, perpendicular and oblique: [10]

> *I refute Witelo by this very confusion of rays. For, as he says, oblique radiation too is seen insofar as oblique rays intersect perpendicular rays [within the eye]; therefore the same point [of the eye] receives both oblique and perpendicular radiation. Consequently, two things [the oblique and perpendicular radiation] will be judged to be situated in the same place.*

[10] Kepler, J. (1604). *Ad Vitellionem paralipomena, quibus astronomiæ pars optica traditur*, in Lindberg (1976), *op. cit.* p. 189.

Here Kepler faced the same problem that many years challenged the scientists, as Al-Hazen, Leonardo, Maurolicus and many others. The aforementioned image on the retina was inverted, exactly like the real image produced by lens in a camera, or Camera Obscura. This fact, however, did not stop Kepler. He pointed to the next, after image stage in the process of vision: interpretation of the retina image by human conscious:[11]

> *I say that vision occurs when the image of the whole hemisphere of the world that is before the eye… is fixed on the reddish white concave surface of the retina. How the image or picture is composed by the visual spirits that reside in the retina and the nerve, and whether it is made to appear before the soul or the tribunal of the visual faculty by a spirit within the hollows of the brain, or whether the visual faculty, like a magistrate sent by the soul, goes forth from the administrative chamber of the brain into the optic nerve and the retina to meet this image, as though descending to a lower court – this I leave to be disputed by the physicists.*

Unlike Al-Hazen who followed light rays only up to the lens in order to prevent the image to be inversed; and unlike Leonardo who looked for additional intersection of rays in the eye to compensate for he first and cause the regular image, Kepler left to the human consciousness to treat the upside down image on the retina. It is in the human mind that the image was interpreted and "recognized" as right side up image of the reality. In a sense, Kepler ascribed to the consciousness an additional inversion of the image.

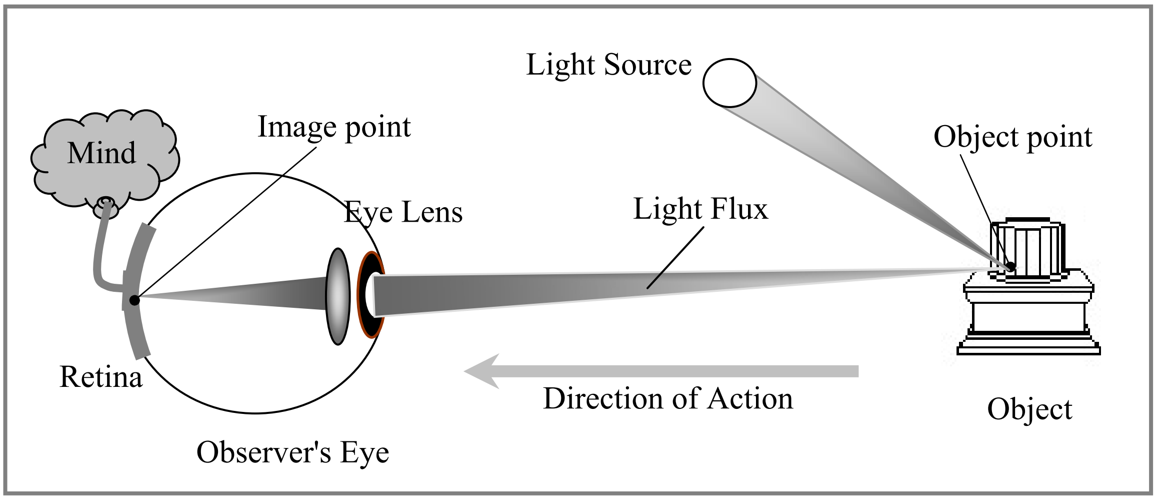



**Figure 18a.** *Schematic representation of Kepler's solution of the problem of vision. Mind interpretes the inverted image obtained on the retina of the observing eye. The image is obtained through the point to point construction of the real image by means of a diverging-converging light flux.*

[11] *Ibid.* p. 203.

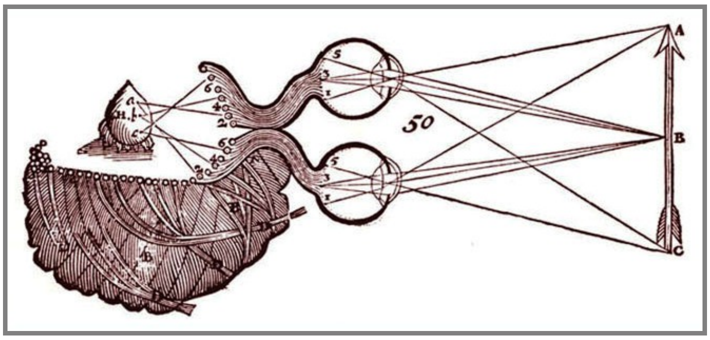


**Figure 18b.** *The sketch from Descartes' Dioptrics (1637) in which he represented Keplerean understanding of vision: mapping by light flux and connection to the brain. Descartes believed that image is interpreted in the pineal gland which is the seat of vision and common sense.*

Within this understanding, Kepler dismissed the whole idea of image transfer through space, the ancient idea of Atomist eidola and the transfer by disturbance in the medium (Aristotle). Al-Hazen disassembled the eidolon into points transferred by relevant rays, and in a sense, addressed an image transferred through space. In the new scenario, the optical image did not potentially exist anywhere between the object and the screen.

As to the light ray, it went through a significant change of role: from the essential element of optical process, an "atom of light", to an auxiliary tool, useful representation, lacking uniqueness. Light ray remained in service of all theories of light produced in the 17th century: that of Huygens and the one by Newton. Within the wave theory, light ray was understood as a set of points, each representing a perpendicular to the wave front at different moments. In the corpuscular interpretation of light, light ray represented the trajectory of light particle. And in the careful representation of light by Newton, who tried to avoid any speculation, light ray signified *the smallest amount of light that demonstrated the features of light behavior*.[12] In all cases, it was not more than a representative tool.

**Scholium**

It took people more than two thousand of years to understand the process of vision correctly. It started from the debate between intromission and extramission theories, which corresponded to the debate about the existence of visual rays radiated from the eyes of the observer and the eidola that enter the eye of the observer. The debate decreased mainly after the contribution of Al-Hazen in the 11th century, the intromission theory was preferred. Visual rays were dismissed in physics.

[12] Although Newton made a conjecture of particle nature of light, which would correspond to rays as trajectories of tiny particles, in his *Opticks* treatise, Newton did not define ray as a trajectory of light particles.

Al-Hazen disassembled optical image (eidolon) into points and treated the correspondence between each point from of the observed image to the correspondent point of the object related by means of one relevant ray. He insisted on the visual image to be obtained as we perceived it, that is, in right side up position. Therefore, the upright image was placed by him on the surface of eye lens which considered being the sense organ of vision.

In the following progress (Fig. 19a, b), this understanding was replaced by Kepler in the 17$^{th}$ century by mapping the object to its image by means of light flux emanating from each point of the object, entering the observer eye and converging by the eye lens to a point on the retina. It was understood that the obtained real, reversed and inverted (as in a convex lens) image, is subsequently interpreted by the mind of the observer to provide the familiar to us visual sensation of image of an object.

Kepler's understanding of optical image was a part of the Geometrical optics (the domain of optics that treats light as straight rays), which is learned since then in all physics courses. The further developed physical optics, the optics of waves, did not dismiss geometrical optics description of image because at the case of very small wavelength of light, comparative to all parts of the eye, and one can neglect the limitations implied by the wave nature of light.

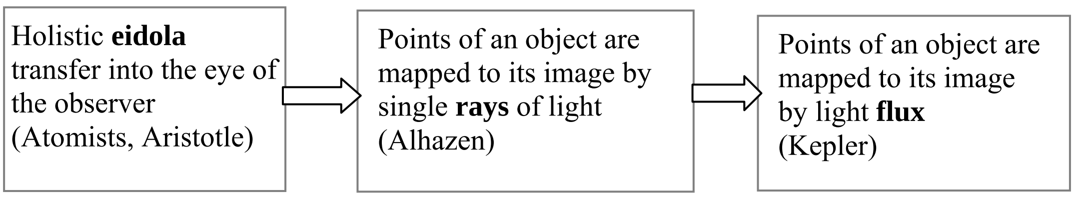



**Figure 19a.** *Flowchart of intromission the theory of optical image.*

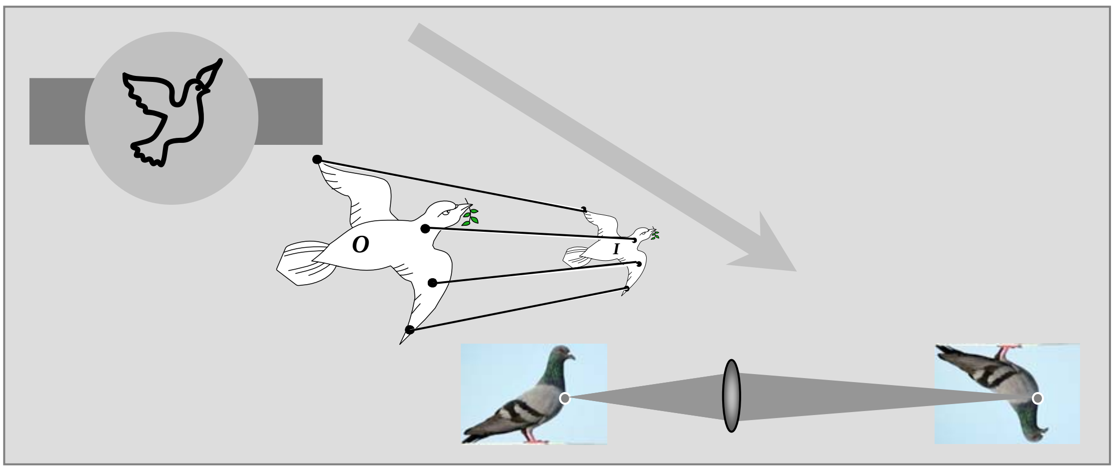
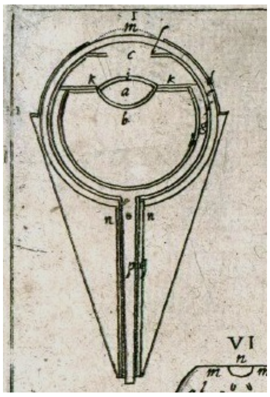



**Figure 19b.** *Symbolic presentation of transformation of the theory of optical image.*

**Questions to reflect**



1. What was the solution of Kepler to the mechanism of vision? In what way was it different from the theory of Al-Hazen?
2. What was the novelty of Kepler's theory of vision? Why was it preferable to Al-Hazen's one?
3. Compare the structure of eye by Kepler (on figure) with the same by Al-Hazen (Fig. 14). What is different?
4. What is the meaning of the image in the eye to be inverted and inversed? What feature of mind does it imply to the interpretation of visual image?
4. What was the change in the role of the concept of ray in the course of the history of optics?

* * *

## Historical and philosophical background including nature of science

The excurse into the concept of optical image crosses about two thousand years. It started with the foundation of science in Classical Greece and came to solution at the beginning of the scientific revolution of the 17th century. During this time several paradigms of science and scientific method exchanged coming to the cannon of modern science. Following the concept of optical image, therefore, may represent the fundamental changes in the scientific ontology and epistemology.

The first optical theories of Pythagoras, Atomists, Empedocles, Plato and Aristotle were developed during the period of Hellenic science which was rather close in form to the Philosophy of Nature. The major features of science at that time were seeking universal regularity and objectiveness. This was represented in the paradigm of cosmos (the universe organized by objective laws) which contrasted to the previously prevailing form of knowledge in the form of myths, non-consistent variety of subjective (voluntary) statements regarding the order of things. The latter is known to us from the epic poems by Homer and Hesiod, and myths of other ancient peoples. They all were characterized by voluntarism and subjectivity. Hellenic scientific theories mainly used qualitative reasoning by principles and formal logic. They certainly preserved traces of previous non-scientific knowledge, mainly in the fact that their concepts were vague, not well explained (no detailed mechanism), and not well defined (not empirically determined meaning). These theories may seem solely descriptive to the modern learner, lack of practical use. However, they sought the objective truth about the nature, independent of any personal will or mood. In this sense it was a scientific revolution.

During the following Hellenistic period, science became more pragmatic and concrete, less interested in philosophical and qualitative claims, which it kept from the previous period. Such were the optical theories of Euclid, Galen, and Ptolemy. Euclid developed the theory of perspective, Galen established the structure of eye, Heron and Archimedes investigated the law of reflection of light and vision, and Ptolemy was the first who empirically investigated the phenomenon of refraction in order to establish the quantitative dependence between the angles of incidence and refraction.

The scientists of the Medieval Muslim science usually proceeded with Hellenistic heritage and further developed the empirical epistemology of the Hellenistic scholars. Such was Al-Kindi who proceeded in the trend of Ptolemy optics. Al-Hazen, however, was original in ontology. He adopted the intromission idea of Aristotle, the rays of Euclid, refraction of Ptolemy and the anatomy of eye by Galen. This synthesis of conceptions was powerful in optics (he could explain the functioning of Camera Obscura) and in vision theory (he provided a new more detailed explanation). Although not elaborated in précised terms of mathematics, his vision theory was more advanced than any other of his period. It preserved its leadership for about 600 years until was replaced by the optics of Kepler.

In the following historical period the center of scientific activity moved to the medieval Europe. The progress in understanding vision and optical image was slow. One may explain this by the fact that the emphasis of scientific exploration was again in qualitative philosophical realm rather than in empirical investigation. Yet, there were attempts to bring the empirical method to the research agenda. Robert Grosseteste (1168-1253) and Roger Bacon (1214-1294) in Oxford stated so called the "prerogatives of experimental science"[13] that required experimental testing of the scientific claims. Within this framework, Grosseteste could arrive, for example, to the understanding of light refraction in a spherical lens and its converging into a point in

[13] Losee, J. (1977). *A Historical Introduction to the Philosophy of Science.* Oxford University Press, Oxford, p. 35.

passing through a convex lens (Fig. 20). The point was termed *combustion point*, which hints to the method he used in his research.

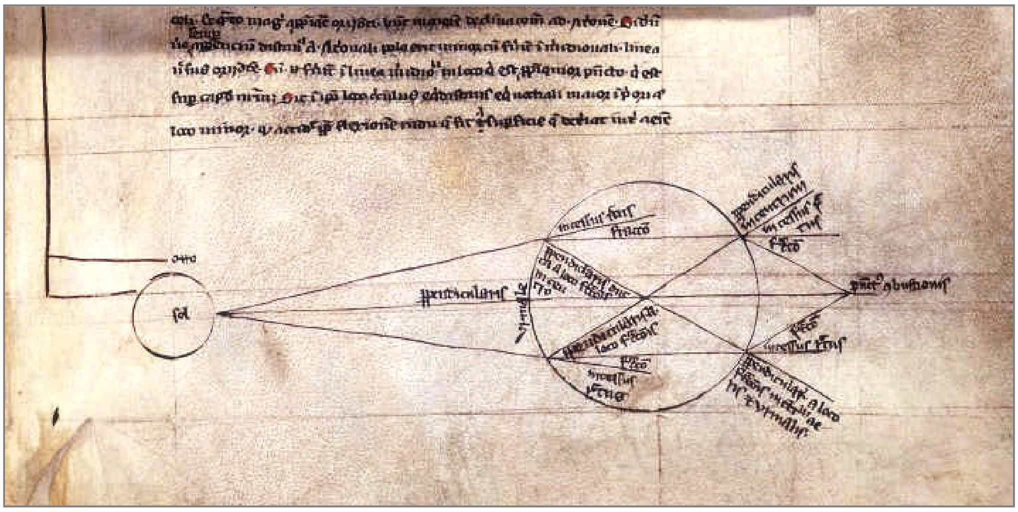


**Figure 20.** *Sketch by Robert Grosseteste explaining lens functioning as causing refraction to light rays from the Sun to converge into the point that he called "point of burning".*

However, there was no further steps in the way to understand the creation of optical image, and first of all, no experimentation in this domain. Therefore, although Grosseteste understood the importance of mathematics in the scientific account of phenomena[14]:

> *The usefulness of considering lines, angles and figures is very great since it is impossible to grasp natural philosophy without them. They are absolutely important both in the universe as whole, and in its individual parts.*

nobody at that time, including Grosseteste and Roger Bacon, adopted this trend beyond geometry, which served as the method to investigate image creation and vision. The development of this approach took place for the scientific revolution when the corpus of knowledge known to us as Geometrical Optics was established.

It was Kepler who made the breakthrough. In his activity one may see the meaning of the scientific revolution with regard to the nature of science. It was the synthesis between the rationalistic (deductive-inductive) method with the empiricist one (controlled variable experimentation). It is within this framework that Kepler resolved in 1604 the problem of construction of the optical image and the enigma of vision.[15]

[14] Pederson, O. & Pihl, M. (1974). *Early Physics and Astronomy.* Macdonald & James, London, p.196.
[15] Kepler, J. (1604). *Op. cit.*

Two major discoveries of Kepler regarding the optical image in the process of vision may illuminate on the nature of physics.

1. Mapping the object to its image by means of light flux instead of single relevant rays. Neglecting the rest of the light in the image creation looked artificial and contrary to physical intuition (the "oblique" rays, very close to "perpendicular" ones, had to contribute to image formation). Kepler wrote:[16]

> *The reception or sensing of the perpendiculars and the rays adjacent to them [should be] almost equal.*

2. There is no prerogative of common sense in physics, despite its role of a driving force in scientific exploration: the reality may be complex and not coinciding with intuitive thinking. Thus, for centuries scholars rejected any thought that the optical image in the eye is inversed. Al-Hazen, Leonardo, Maurolico and others were convinced in this conception. It seemed ridiculous to suggest anything else. In reality, however, it appeared that this was exactly the case. Kepler made the transgression of common sense when he introduced the role of cognition in the interpretation of optical image.

Optical knowledge was not isolated from social environment of scholars. It influenced beyond scientists, the wider population of people educated in science and occupied in other fields. Evidence of this fact one may find in the pieces of art preserved from different times and places.

As was shown, the Egyptian drawings of the Sun (Fig. 9a.) showed their premature understanding of light radiation that ignored the principle established in the Muslim science – the principle of Al-Kindi.

The influence of the new theory of image transfer, due to Al-Hazen that came to the Medieval Europe, could be observed in the pictures representing light not as a flow but as a collection of light rays and image transfer related to these rays. Such were the pictures depicted the religious context of Annunciation (Fig. 21a).[17] Artists tried to show the holy image traveling to Virgin Mary. In the picture of Fra Angelico (1450) in Florence, for example, one may see the divine image moving "on rails" of the light rays. Similar context was depictured differently in the Eastern Christian

[16] *Ibid.*

[17] Galili, I. & Zinn, B. (2007). Physics and Art – A Cultural Symbiosis in Physics Education, *Science & Education*, 16, 441–460.

canon (Fig. 21b). The reason could be that Witelo's and Peckham's optical treatises were available only in Latin and studied in the Western Europe.

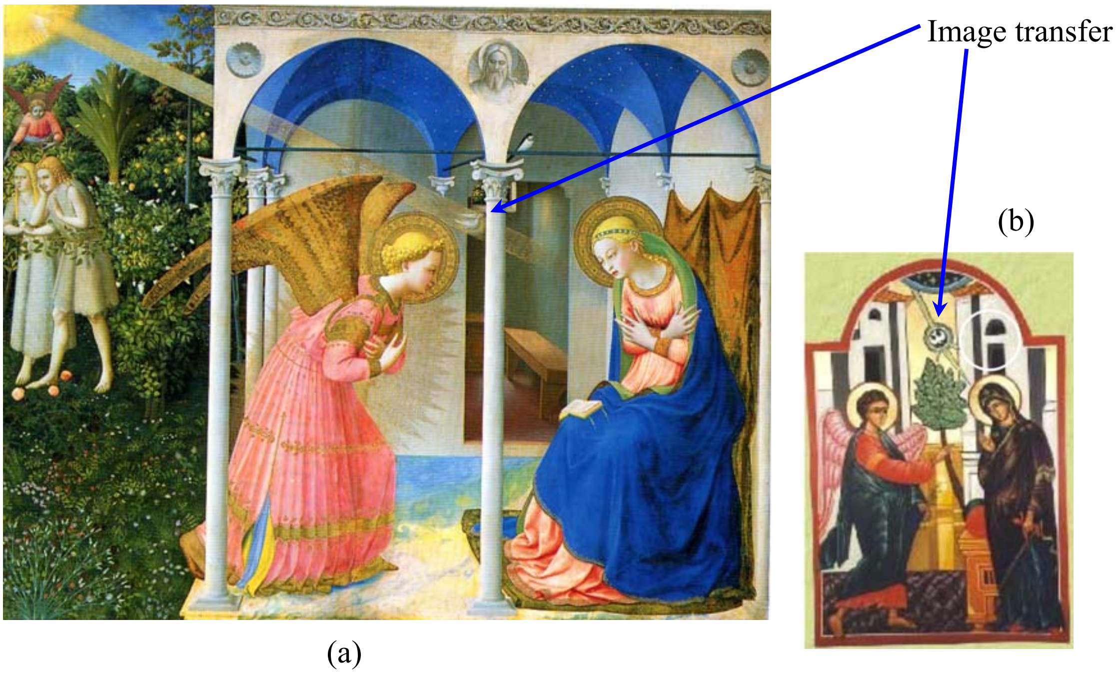



**Figure 21.** *(a) The artistic representation of the event of Annunciation from the New Testimony. The picture Annunciation by Fra Angelico (1450) represents the optics knowledge in the Western Europe during the late Medieval Age. It illustrates the idea of light as composed by light rays and the image transfer by light rays. (b) The holistic understanding of image transfer is usually depicted in the representation of the same event in the icons of the Orthodox canon corresponding to the knowledge in the Eastern Europe during the early Medieval Age.*

**Questions to reflect**

1. Try to identify each theory of optical image in terms of rationalist and empiricist approach to the account of reality by means of a physics theory.
2. Discuss the reason for us to consider the presented knowledge of optical image scientific. In what way was it different from mythological, religious, and traditional?
3. Discuss the correspondence between the features of each of the optical theories (Pythagorean, Atomistic, Plato-Empedoclean, Euclidean, Al-Hazen's, Keplerean) and the nature of science: the commitment of each theory of optic image to the correspondent ontological and epistemological conceptions as existed at the time the considered theory was introduced.

* * *

## Target group, curricular relevance, and didactical benefit

The developed unit addresses first of all physics teachers, pre- and in-service. This is because the regular curriculum does not include the physics knowledge that is considered today obsolete and erroneous. Indeed, the presented excurse to the development of physical understanding of optical image and vision process includes earlier views and conceptions, changed and replaced with the modern view currently taught at schools. Teachers may transfer and mediate these contents to their students in a variety of didactic ways.

Numerous researches in physics education demonstrated that image and vision process present a difficult subject for students who are often confused, and develop/hold numerous misconceptions.[18] The analysis of these misconceptions and their comparison with the historical development of optical knowledge revealed a clear parallelism. This true even if a single person in his/her learning path did not show all historical conceptions.[19] The conceptions relevant to the subject of image and vision are presented in Table 1.

**Table 1.** *Conceptual parallelism in optics knowledge regarding image and vision.*

| ***Historical conceptions*** *practiced in the past science* | ***Students' conceptions*** *manifested in the course of learning optics* |
|---|---|
| Pythagoras-Plato conception of vision (Extramission theory) | Active vision scheme ("touching by sight") |
| Atomists' conception of *Eidola* (Intromission theory) | Image Holistic scheme (the whole image is traveling to the eye or screen/mirror where it is later observed) |
| Euclidean visual and light rays | Light rays as the entity comprising light Vision rays as the entity performing sight |
| Al-Hazen's conception of visual image mapping by means of light rays. | Image Projection Scheme: image is mapped point to point by means of a single ray from the observed object to its image in the eye or on the screen. |

[18] e.g. Galili, I. & Hazan, A. (2000a). 'Learners' Knowledge in Optics: Interpretation, Structure, and Analysis'. *International Journal in Science Education,* 22(1), 57-88. This paper includes numerous references on other research reports.

[19] Galili, I. & 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.

The clear conceptual parallelism suggests the relevance of historical conceptions to the process of science education.[20] In particular, one can show that curricular relevance, and didactical benefit of this knowledge for a teacher or student of physics class can be reasoned by the following arguments:

(1) *cognitive resonance* in the learner,

(2) learning by *variation* of the conceptual subject,

(3) teaching science as a *cultural knowledge*, and

(4) exposure of the *nature of the scientific knowledge*.

We briefly address each of these aspects in the following.

### *1. Cognitive resonance*

Within the widely accepted constructivist theory of learning the process of learning is considered as a conceptual change, which should be encouraged by the teacher.[21] The mentioned above parallelism (Table 1) implies that addressing certain historical conceptions by the teacher which may cause a *cognitive resonance* – exceptional sensitivity of the learner to certain conceptions that indicates the cognitive background of the learner in the particular topic.[22] The latter might be related to the zone of proximal development[23] of the learner. This effect may enhance students' attention, interest and success in overcoming misconception. The possible teaching strategy is to expose the historical theories in context of the historical debate that accompanied them, exposing the arguments in favor and against these theories.

### *2. Learning by variation of the conceptual subject*

Recent studies in educational psychology stressed the advantage of learning conceptions by *variation*.[24] This approach states that in order to stimulate meaningful assimilation of certain conception the educator should prepare the learning material which would present this goal feature in conceptual variation. The learner is thus

[20] e.g. Matthews, M. (1994). *Science Teaching.* Routledge, New York.

[21] e.g. Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66(2), 211-27.

[22] Galili, I. & Hazan, A. (2001). Experts' Views on Using History and Philosophy of Science in the Practice of Physics Instruction, *Science & Education,* 10 (4), 345-367.

[23] Vygotsky, L. (1994). *Thought and Language.* MIT Press, Cambridge, Mass.

[24] Marton, F., Runesson, U. & Tsui, A. B. M. (2004). 'The Space of Learning.' In F. Marton, & A.B.M. Tsui (Eds.), *Classroom Discourse and the Space of Learning* (pp. 3-40). Lawrence Erlbaum, Mahwah, New Jersey.

guided and encouraged to discern and adopt the target conception through comparison, analysis and contrasting it.[25] The presented here historical conceptions regarding optic imagery and nature of vision provide the required conceptual variation. The process should be supported by teacher's mediation clarifying historical and philosophical contents in light of cultural historical differences of concepts and lacking specific knowledge in the philosophy of science. The mediation should lead to the adoption of the scientific conception. For example, the scheme of "direct" transfer of points of the object by single rays to points of the correspondent image (Al-Hazen's conception) might initially seem plausible to the students, but eventually, under the influence of the historical arguments, it could be refuted by using arguments of Kepler and later scholars.

### *3. Teaching science as a cultural knowledge*

Teaching the disciplinary contents without any conceptual variation (as commonly prevails at schools) may adequately represent the particular disciplinary knowledge, but not the science as a living body of knowledge. Science is a culture and its knowledge possesses hierarchical structure. Thus, in any fundamental scientific theory one may identify *nucleus* containing fundamental principles, the *body*, containing applications of the principles (a variety of solved problems, explained phenomena, invented devices, apparatus and so on), and *periphery* – the knowledge elements contradicting the particular nucleus.[26] Within this framework, the periphery of the classical optics includes the old theories of vision, their concepts (visual rays, image transfer, etc.) Besides, the periphery incorporates the principles of the more advanced theory (e.g. the physical optics – the wave theory of light). All these together, may create the space of learning which adequately represent the cultural content knowledge (CCK) in optics. Learning this material performs enculturation of the learner into physics in general, its basic principles, norms and standards of knowledge, as well as its ramifications. This is a cultural approach to science education which addresses wide population of school students, not necessarily intending to choose physics as a profession.

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[25] Schecker, H. & 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.* New York: Teacher College Press, 141-151.

[26] Tseitlin, M. & Galili I. (2005). Teaching physics in looking for its self: from a physics-discipline to a physics-culture, *Science & Education,* 14 (3-5), 235-261.

***4. Nature of the scientific knowledge***

The history of optical image and vision spreads over two thousands years of scientific endeavor. During this long period science changed not once its features, passing through different periods: Hellenic, Hellenistic, Muslim and European Medieval, and finally reaching the scientific revolution of the 17th century. The presented excurse to optical theories provides an opportunity to illustrate the *changing features of science,* such as the variance in its epistemology: the varying preferences of rational and empirical approaches in science research, as well as ontology: changing concepts, basic conceptions in the content knowledge.

At the same time, one may observe *the invariant features of science*, such as the commitment to seeking objective truth about the nature, revealing the general principles and laws that govern the reality. By comparison between the scientific knowledge at different historical periods of its genesis one may better appreciate the essential features of the modern science – a well balanced synthesis of rationalist and empiricist approaches together with the necessary use of mathematical tools in knowledge codification. Our application of the presented excursus to the history of image and vision was tested in a year long application in a representative sample of school students of the 10th grade. Various benefits to students' knowledge about science were observed and documented.[27]

* * *

## Activities, methods and media for learning

The major mode of presenting this excurse, as prepared above, could be a series of interactive lectures incorporating discussions. It is recommended to precede the discussions with a questionnaire asking students for (1) their account for the way people see objects and (2) the evidence they can bring for their understanding. The answers to this pair of questions should facilitate the dual approach to science teaching, addressing ontological as well as epistemological aspects of physics knowledge. The questions to ask could be taken from the published researches that investigated students' knowledge regarding optical image and vision.[28]

[27] Galili, I. & Hazan, A. (2001). The Effect of a History-Based Course in Optics on Students' Views about Science, *Science & Education,* 10 (1-2), 7-32.

[28] See the list of references at the end of the unit.

The instructor should elaborate the results of the questionnaire and recognize the major schemes (conceptions) the learners hold on the subject. These schemes of alternative to the scientific knowledge should be addressed in the course of teaching, possibly by the excurse to the past, choosing the relevant optical theory. Such as the scheme of active vision invited presentation of the views of Pythagoreans, Euclid and Ptolemy, as well as their critique by Al-Hazen. Similarly – the scheme of holistic image transfer etc.

The context of mirror image is extremely effective in revealing students' views on image formation and its nature. For example, the question where is the image that we observe in the mirror is located, or whether there is an image when we do not look in the mirror but remain in front of the mirror, or why we observe multiple images (Fig. 24) present a powerful instrument in revealing the schemes of knowledge of ontological and epistemological nature, which students hold and apply in their account of the optical reality.

The following activities could expand teaching optics to the general cultural knowledge beyond scientific.

**Figure 21a**. *The head of Medusa as a basis of a column in a water pool in Istanbul. What was the reason for the inverted position of Medusa's head?*

1. In the old water pool from Byzantine period in Istanbul, one may observe the sculpture of the head of the mythological Gorgon Medusa (Fig. 21a). It is placed just above the water level in up-side-down position. The teacher may invite students to interpret this orientation of the sculpture. To interpret this fact one need to know the myth of Medusa, the believe that one could not look at her face directly. The relevance to optics may be established through the reconsideration of the mirror image transformation.[29] It is well documented misconception of students to ascribe the plane mirror the feature to transform right to the left, instead of the direction "from the mirror" to the direction "to the mirror".[30] This discussion may naturally expand to observation of a written text in the

[29] Galili, I. & Zinn, B. (2007). ‘Physics and Art – A Cultural Symbiosis in Physics Education.’ *Science & Education*, 16 (3-5), 441-460.

[30] e.g. Galili, I. Goldberg, F. & Bendall, S. (1991), ‘Some reflections on plane mirrors and images’. *The Physics Teacher*, 29 (7), 471-477

mirror and the fact that signs on the front of emergency cars are written backwards (Fig. 21b).


**Figure 21b**. *The inscription on the car "Ambulance" is inverted. Why is it usually done with emergency cars? Many students believe that it is because the mirror, by which the driver of the car moving ahead observes the ambulance, "transforms right to left". Is it so?*

2. Another culturally rich activity regarding understanding optical image could follow the question what could be the reason of the fact that in the artistic representation by Giotto of St. Francis stigmatization (Fig. 22a) the correspondence between the hands and feet of the two figures is left hand/foot to the right hand/foot, while other later artists usually made a regular correspondence[31] (Fig. 22b)?

**Figure 22**. *(a) Stigmatization of St Francis by Giotto, c.1300. (b) Stigmatization of St Francis by the Master of the Legend of St. Ursula, c. 1500.*

* * *

[31] Galili, I. & Zinn, B. (2007). 'Physics and Art – A Cultural Symbiosis in Physics Education.' *Science & Education*, 16 (3-5), 441-460.

## Obstacles to teaching and learning

1. The presented excurse to the history of optical image and vision spreads over two thousands years and therefore deals with conceptions of the old physics presented in a different style and arguments, using unusual archaic and foreign language (terminology) and manners of presentation. All these make practically impossible direct use by contemporary school students and teachers of the original treatises (often survived only partially). Therefore, it is recommended to use secondary literature produced by historians of science who translate and employ modern language as well as provide interpretations. To a certain extent, the presented above excurse to the conceptual development of the optic knowledge may be initially used as a teaching resource. The further learning can make use of the following resources:

Lindberg, D. (1976). *Theories of Vision Form Al-Kindi to Kepler*. The University of Chicago, Chicago.

Lindberg, D. (1992). *The Beginnings of Western Science*. The University of Chicago, Chicago.

Ronchi, V. (1970). *The Nature of Light – A Historical Survey*. London: Heinemann, Newnes.

Ronchi, V. (1991). *Optics. The Science of Vision*. Dover, New York.

Park, D. (1997). *The Fire within the Eye. A Historical Essay on the Nature and Meaning of Light*. Princeton University Press, Princeton, New Jersey.

2. One of the major obstacles in teaching the subject is the resistance to the contents which are obsolete in science and therefore may confuse instead of teach. The answer to this reservation may draw on the same arguments used and elaborated above in order to justify the *relevance* of historical materials:

- Stimulation of learning by *cognitive resonance* and *learning by variation*, causing remedy of the misconceptions possessed and developed by students. Their conceptions are often similar to the scientific ideas from the past.
- Genuine knowledge of science is usually cultural in the sense that it is discursive and incorporates alternative scientific accounts for the same subject as it took place in the scientific debates;
- The knowledge of "what" is not sufficient in science. The essential is also "how do we know?" The acquaintance with the historical genesis of knowledge, the ways its parts were introduced, criticized, and refuted are essential for understanding.

* * *

## Pedagogical skills

The excurse presents the unfolding story of scientific understanding of optical image and vision. It practically does not use any mathematical formalism beyond simple ray diagrams and laws of light reflection and refraction. Two major pedagogical skills are required from the teacher:

- to perform mediation of knowledge, meaning the ability to encourage construction of knowledge in a educational dialogue converging to the goal scientific concept through comparative analysis of several alternative options. The teacher should be sensitive to his/her students' ideas of the subject and should serve as an agent of the physics culture, much in accordance with the ideas of Lev Vygotsky[32] and the concept of CCK (defined above)[33]. One needs a skill of performing a diachronic dialogue between the scholars of different times and places (Fig. 23).

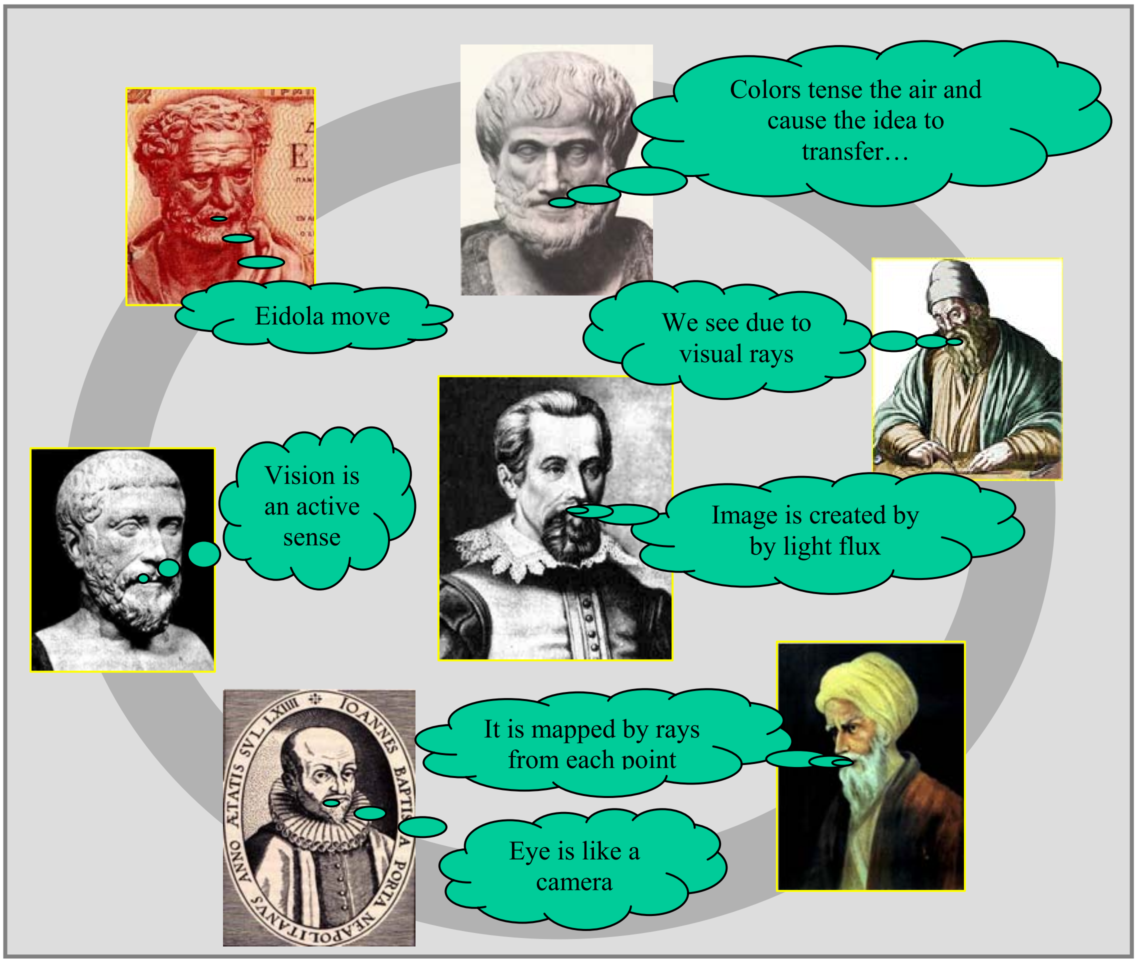


**Figure 23**. *Symbolic presentation of the diachronic dialogue on the nature of vision.*

[32] Vygotsky, L. (1934/1986). *Thought and Language.* The MIT Press, Cambridge, Mass.

[33] Tseitlin, M. & Galili I. (2005). Teaching physics in looking for its self: from a physics-discipline to a physics-culture, *Science & Education,* 14 (3-5), 235-261.

- to present an unfolding story of knowledge consolidation requires teachers' narrative skill, to tell stories, much in like to the teachers of humanities (history and literature) in addition to the regular skills of a physics teacher. One may illustrate this skill by presentation of optics history by Park.[34]

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**Studies on optical knowledge of students**


Galili, I., Goldberg, F. & Bendall, S. (1993). 'Effects of prior knowledge and instruction on understanding image formation.' *Journal of Research in Science Teaching*, 30(3), 271-303

Bendall, S. Goldberg, F., & Galili, I. (1993). 'Prospective elementary teachers' prior knowledge about light.' *Journal of Research in Science Teaching*, 30 (9), 1169-1187.

Galili, I. & Hazan, A. (2000). 'Learners' knowledge in optics: interpretation, structure, and analysis'. *International Journal in Science Education*, 22(1), 57-88.

Galili, I. & Hazan, A. (2000). '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. & Hazan, A. (2001). 'The effect of a history-based course in optics on students' views about science.' *Science & Education*, 10 (1-2), 7-32.


* * *

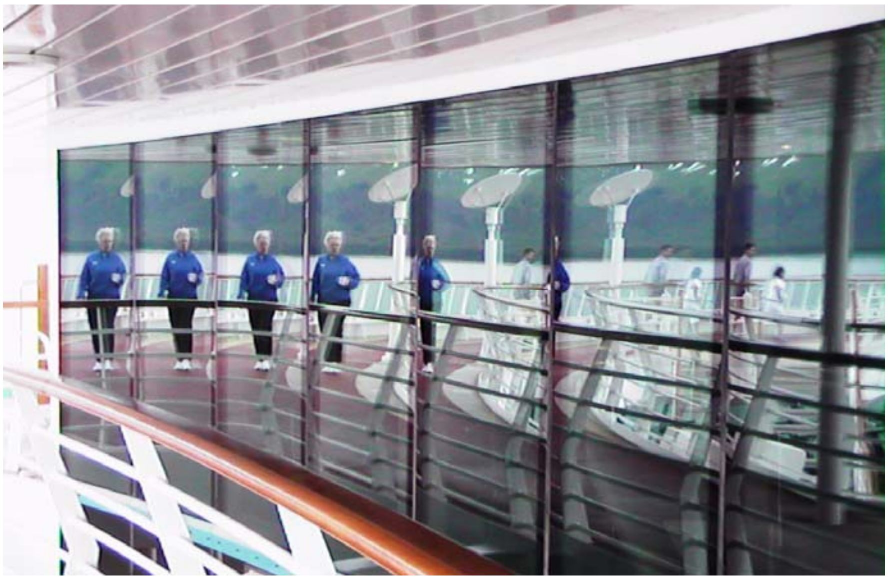

**Figure 24**. *Multiple images can be used to illustrate the principle of Al-Kindi–Al-Hazen: light expansion to all directions.*

[34] e.g., Park, D. (1997). *The Fire within the Eye. A Historical Essay on the Nature and Meaning of Light.* Princeton University Press, Princeton, New Jersey.