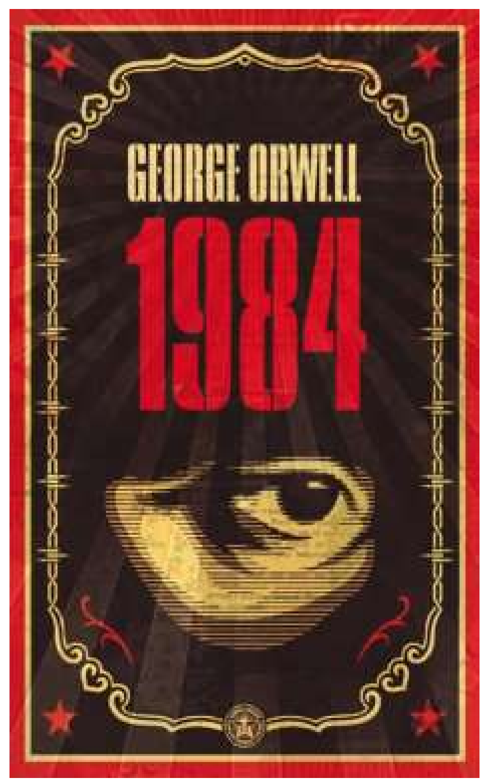
Light and Vision: There is more than meets the eye—an historical introduction to the elements of vision

Science is a way of looking at the world around us in order to make sense of who we are, where we came from, and to help us understand and plan where we are going. Erwin Schrödinger stated that the value of natural science "*is the command of the Delphic deity…get to know yourself.*"

We study humans to help understand who we are. We study plants, animals, microorganisms, rocks, stars, air, and water to understand the biotic and physico-chemical world we live in and our relationship to that world. We gather **data** using our five **senses** and even more data that are **invisible** to our senses by using technology based on past scientific advances. We use these data to construct **models** of the world, in an **analogous** way to how our minds create models of the world using the visual information captured by our eyes. When many minds agree on the validity of the model, we call that model a **theory** or a **law of nature**. The laws of nature are **valuable** in helping us understand and appreciate the world around us and to understand our place in the universe. There are also **limitations** in the observational and experimental evidence that contribute to the natural law. As scientists we should realize that the laws are provisional and each of us must make a personal choice about how reliable they are. For example, I think that the laws of thermodynamics are more reliable and fundamental than Einstein's Theory of Relativity and the Uncertainty Principle of Quantum Mechanics.

There is currently a national trend to teach only the **value** of current scientific theories and not their **limitations**. The National Center for Science Education (http://ncse.com/creationism/general/academic-freedom-legislation) is fighting "academic freedom bills" that ask teachers to teach "the full range of scientific views regarding biological and chemical evolution," and to help students develop "critical thinking skills" on "controversial issues" by permitting teachers to discuss "the scientific strengths and scientific weaknesses of existing scientific theories."

While there is a movement to teach "*the state of the scientific consensus on the issues*" remember what George Orwell wrote in his book, *1984*:

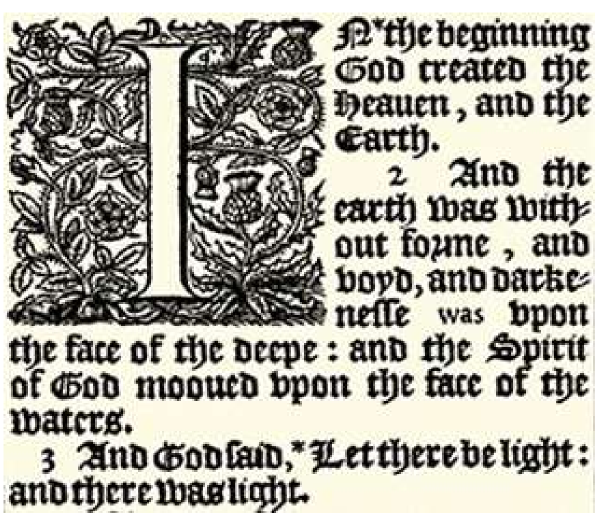


"*Being in a minority, even a minority of one, did not make you mad. There was truth and there was untruth, and if you clung to the truth even against the whole world, you were not mad. A yellow beam from the sinking sun slanted in through the window and fell across the pillow. He shut his eyes. The sun on his face and the girl's smooth body touching his own gave him a strong, sleepy, confident feeling. He was safe, everything was all right. He fell asleep murmuring 'Sanity is not statistical,' with the feeling that this remark contained in it a profound wisdom.*"

I love science and the ability of the scientific method for helping us to question, understand, and appreciate the world around us. I am a staunch supporter of questioning any and all authority in order to help us understand and appreciate the world around us. On that note, I will try to provide you with as much personal experience as possible concerning light and life so that you do not have to believe a single thing I say but have enough experience to trust your knowledge while understanding both the **value and limitations** of what you and others know.

Johann Wolfgang von Goethe coined the phrase ***Thatige Skepsis***, which according to Thomas H. Huxley means, "*An Active Skepticism is that which unceasingly strives to overcome itself and by well directed research to attain to a kind of conditional certainty*" or "*A state of doubt which so loves truth that it neither dares rest in doubting, nor extinguish itself by unjustified belief."*

Let's begin talking about light from the beginning. In the Old Testament, Moses (ca. 1500 BC) wrote, *God Said, "Let there be light," and there was light* (Genesis 1:3).

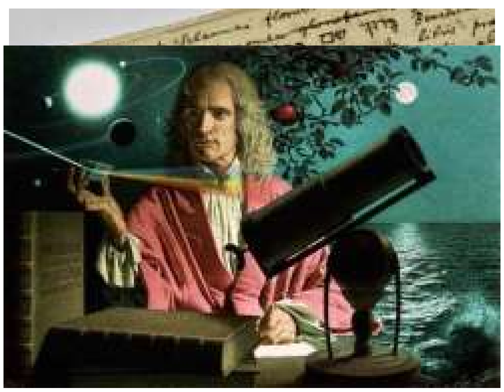


IN* the beginning God created the Heauen, and the Earth.
2 And the earth was without forme, and voyd, and darkenesse was vpon the face of the deepe: and the Spirit of God mooued vpon the face of the waters.
3 And God said,* Let there be light: and there was light.

According to the Turin papyrus (ca. 1300 BC), for those who lived in Heliopolis in the New Kingdom of Egypt, light was the Sun God Ra seeing: "*I am he who opens his eyes and there is light, who shuts his eyes and there is darkness*." For Zoroaster (ca. 500 BC), God was Ahura Mazda, whose name literally means light wisdom.

Historically, and in many cultures, light has been associated with God and good, and with truth and knowledge. The ancient Hindu festival of lights, known as Diwali, celebrates the victory of light over darkness, good over evil, knowledge over ignorance.

Historically, much of science has been derived from a religious quest to understand the wisdom of God and promote a virtuous world. Isaac Newton, for example, did not make a clear distinction between science and faith. For Newton, light, both particulate and real and symbolic and divine, held a central place in science and theology. In *The First Book Concerning the Language of the Prophets*, Newton wrote, "*Light—for the glory, truth and knowledge wherewith great and good men shine and illuminate others*." What kind of knowledge did Newton illuminate? Newton (1687) wrote in the General Scholium of his *Principia*, "*This most beautiful system of the sun, planets, and comets, could only proceed from the counsel and dominion of an intelligent and powerful being…and from his true dominion it follows that God is a living, intelligent, and powerful being."*



This does not sound like the same Isaac Newton described by scientists today. For example, Johnjoe McFadden (2008) wrote in an article entitled, Survival of the Wisest, published on the 150th anniversary of the *Origin of Species*, "*Quite simply, Darwin and Wallace destroyed the strongest evidence left in the*

19th century for the existence of a deity. Two centuries earlier, Newton had banished God from the clockwork heavens. Darwin and Wallace made the deity equally redundant on the surface of the earth." Had McFadden not read Newton? Darwin or Wallace did not see the deity as being absolutely redundant. Not able to see evidence of a material solution to origins, Charles Darwin (1958) wrote that "*The mystery of the beginning of all things is insoluble by us: and I for one must be content to remain an Agnostic*" and Alfred Wallace (1871) not seeing the application of natural selection to mankind wrote that the "*faculties which enable us to transcend time and space…, or which give us an intense yearning for abstract truth…, are utterly inconceivable as having been produced through the action of a law which looks only, and can look only, to the immediate material welfare of the individual or the race."*

We will begin with an historical account of light and life that is not exclusively **materialistic**, does not marginalize the theological component, and emphasizes the importance of questioning authority, no matter who the authority is (including me).

According to one Greek legend, **Prometheus** formed men out of clay and Athena gave the clay figures life by putting a fire within their clay bodies.

Ovid (43 BC-18 AD) wrote that Prometheus "*gave human beings an upturned aspect, commanding them to look towards the skies*." Prometheus then brought to men the gift of fire from Mount Olympus so that they could warm themselves and illuminate the darkness. The Olympic torch lighting ceremony at the Temple of Hera is a reminder of Prometheus' gift of fire.

While fire can warm and illuminate the darkness, it also casts **shadows** of things. In the ***Allegory of the Cave***, Plato tells us of men imprisoned in a cave and chained to a wall so that they cannot see the fire behind them. They also do not know that there is a puppeteer behind them that is casting shadows of puppets and other things on the opposite wall. The prisoners can only see the shadows and they imagine that the sounds they hear come from the shadows themselves. The prisoners only have reason to believe that the shadows are the real and only entities of the world. One prisoner escaped from the cave and while he was above ground, he found truth and enlightenment in the heavens. He saw shadows of real objects and realized that what he had seen in the cave were only shadows of real objects. Then he realized that the position of the life-sustaining sun, which changed throughout the day and throughout the year, influenced the nature of the shadows.

And he came to know the relation between what we see and reality and understood from his path of knowledge, the idea of good and inferred that there is an author of good.

When he returned to the cave to tell his fellow prisoners about his newfound knowledge, they laughed at him as though he had gone mad. Indeed in the meantime, they had set up contests, where the person who could predict the actions of the shadows would win a prize. Plato tells us that we all live in a cave and it is incumbent on us to learn the laws of optics so that we will be able to understand the relationship between what we see and the true and real object.

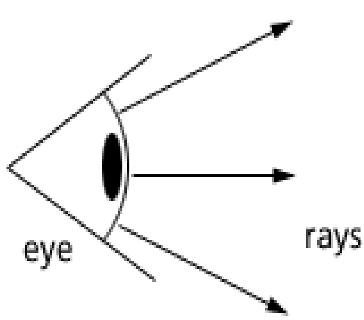
The ancient Greeks realized that in order to see an object, there must be some kind of **contact** between the eye doing the seeing and the object being seen. They developed several theories of light and vision to explain the nature of the contact. These theories can be reduced into two main opposing classes:

-**Extramission** theories, championed by Empedocles, Euclid and Ptolemy, state that vision results from the emission of visual rays from the eye to the object being viewed.

-**Intromission** theories, championed by Lucretius and Democritus, state that vision results from light in the form of a minute replica (eidola) or a thin film (simulacra) of atoms that is emitted from the object and enters the eye.

Both theories relate the sense of vision to the sense of **touch**. However, the extramission theory is analogous to the act of **touching**, while the intromission theory is analogous to the act of **being touched**.

Extramission theory is based in part on the belief that the gods endowed us with the "**fire in the eye**." However, the extramission theory was robust enough to explain why we see "stars" when someone strikes our head, why we see light or phosphenes when we rub our closed eyes, why we see images when we sleep in the dark, why we "feel" it when someone stares at us, why we see only the surface of objects and why more than one person can see the same object at the same time. The intromission theory, by contrast, could only explain why we cannot see in the dark.



Euclid (300 BC) **mathematized** the extramission theory to explain why distant objects appear to be smaller than nearer objects. Euclid used the **geometry of straight lines and angles** to describe how we see the world. To use geometry to explain vision, Euclid demands (or postulates) that we accept certain assumptions. Euclid's postulates can be summarized like so:

-Infinite straight lines, known as visual rays, proceed from the eye, forming a cone such that the vertex is at the eye and the base is at the surfaces of the objects being seen.

-Objects touched by the visual rays are visible; those untouched by the visual rays are not seen.

-Objects seen through a larger angle appear larger, those seen under a smaller angle appear smaller, and those seen under equal angles appear equal.

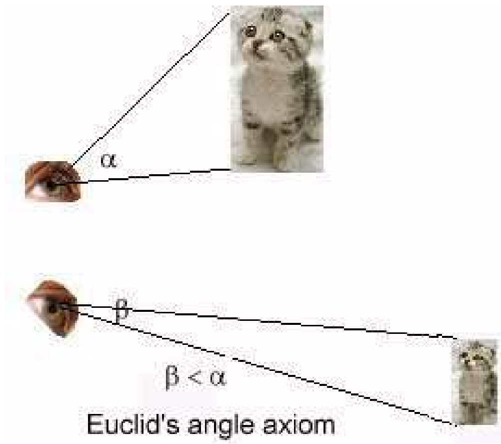
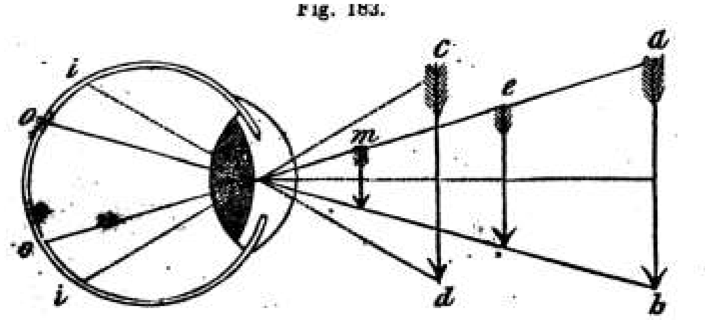


Fig. 183.



Note that the visual angle cannot tell us whether an object is naturally small or naturally large but far away. We are fooled by **forced perspective** photography to see large objects that are really farther away to be as close as the near object, but smaller.

http://digitalphotopix.com/unbelievable/brilliant-examples-of-forced-perspective-photography/

-Objects touched by visual rays coming from more angles, or a greater angle, are seen more clearly.

The visual rays cease to travel in straight lines when they encounter an **opaque** object, which stops them. Euclid's geometrical optics is also useful in describing the shadows and images produced in these cases.

Visual rays also cease to travel in a straight line when they strike a shiny object such as a **mirror** that reflects them. Hero of Alexandria used Euclid's geometry to describe the images formed by reflection and stated that the position of the image can be determined by using the Law of Reflection, where the angle of reflection equals the angle of incidence. The image is formed by the convergence of apparently straight visual rays.

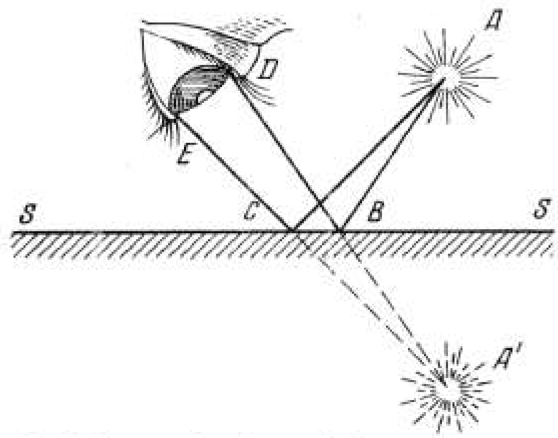
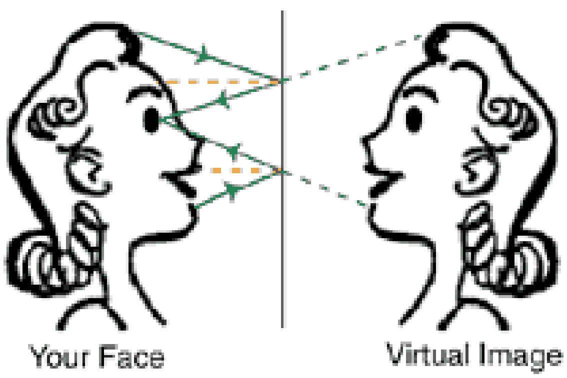
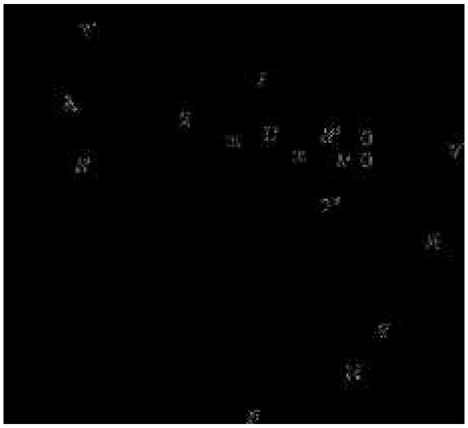
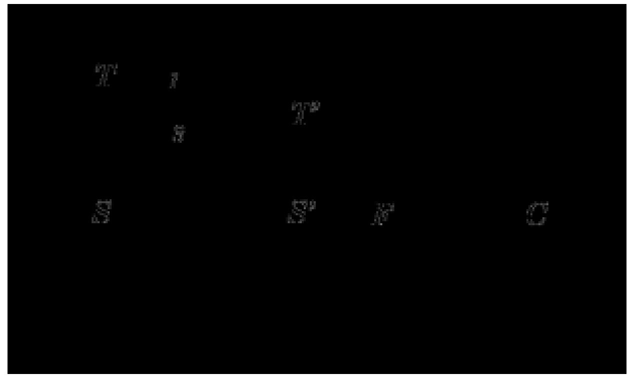


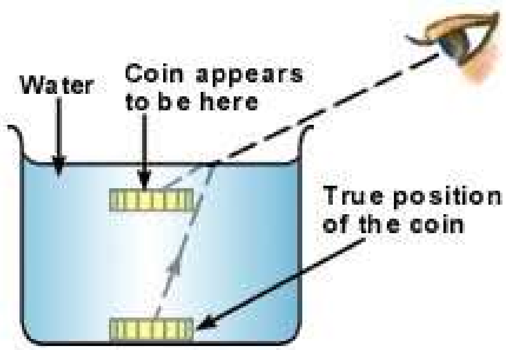
FIG. 3. Observing the reflection of a luminous point in a mirror.



The Law of Reflection can also be used to find the image in concave and convex mirrors. We will go into the geometrical laws of image formation in the next lecture.



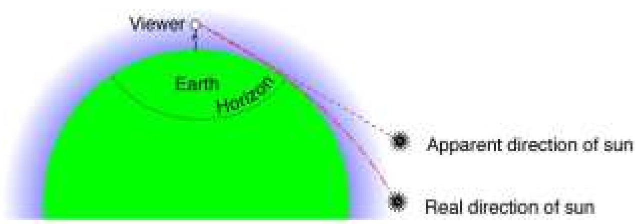


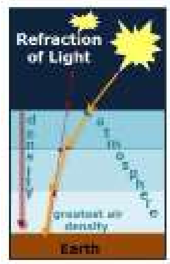


Visual rays also cease to travel in a straight line when they pass through a **transparent** medium such as water or the atmosphere that bends them. Euclid knew that "*If something is placed into a vessel and a distance is so taken that it may no longer be seen, with the distance held constant if water is poured, the thing that has been placed will be seen again.*" Ptolemy used Euclid's geometry to explain the position of an image that is refracted or bent by a transparent medium.

Ptolemy (90-168 AD), realized that the position of light had a powerful effect on the bending of plants. In the days when astrology and astronomy were not differentiated, he realized that the **actual** position of the stars at the time of one's birth, and not their **apparent** position would be important for constructing accurate horoscopes. He incorporated the concept of refraction of starlight by the earth's atmosphere to determine the true positions of stars at the time of one's birth in order to construct accurate horoscopes and the true positions of the heavenly bodies which allowed accurate navigation.

Ptolemy knew that when a visual ray passed from a less dense medium to a denser medium, it did not travel in a straight line but was bent toward the perpendicular (e.g. looking at a coin in water) and as it passed from a denser medium to a less dense medium (e.g. seeing a star in the heavens), it bent away from the perpendicular. Ptolemy realized that this meant that we see a star higher in the sky than it really is because our **mind's eye assumes that the visual rays travel in straight lines**. Based on the same assumption, we think that the sun is setting long after it has already set.





Ptolemy did not figure out the ratio of the angles, even though he knew trigonometry. The effect is roughly proportional to the obliquity of the visual rays and the difference in the densities of the media. Next week, we will see that the ratio of the sine of the angles of the incident and transmitted light is equal to a constant.

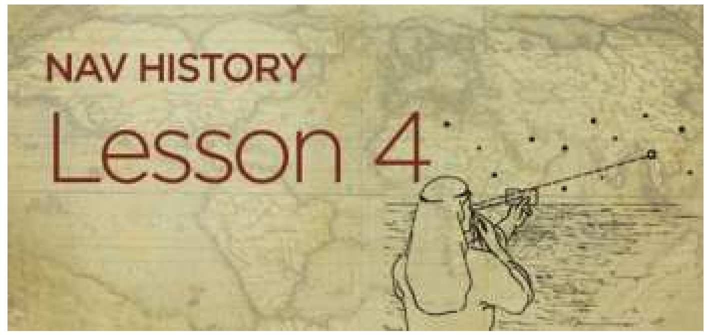
Demonstration: Make a table of the relationship between the angle of incidence and the angle of transmission. Check out these two formulaic models:

(angle *i*)/(angle *t*) = n

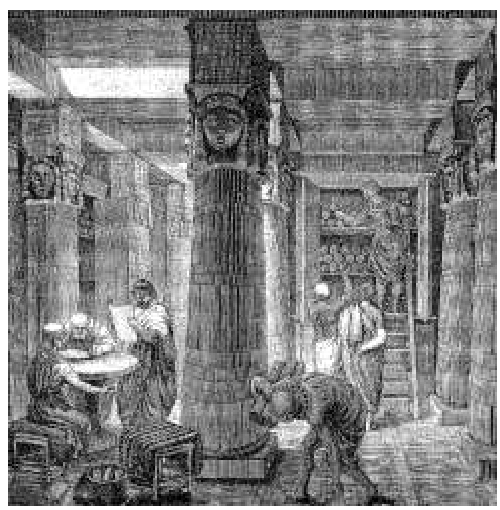
(sin angle *i*)/(sin angle *t*) = n

Which formula seems to be correct and why does it seem to you to be correct?

While Euclid's and Ptolemy's assumption of the reality of visual rays may seem **reasonable** to little children who cover their eyes when playing hide and seek or peek-a-boo, they seem absurd to us. Nevertheless Euclid's geometry, which was based on his theory of vision, became very successful when extended to distant objects like the sun and moon because it made **navigation** to distant places possible. There seemed to be no reason to consider further the **limitations** of the extramission theory, such as why can't we see in the dark, especially at a time when Greek science was in jeopardy.



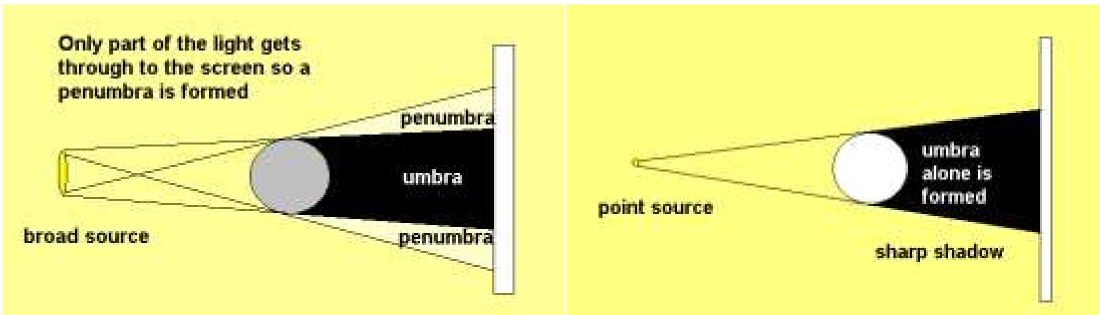
In 391, under the rule of Emperor Theodosius I, who made Christianity the official religion of the Roman Empire and made pagan thought illegal, Pope Theophilus of Alexandria (385-412) ordered the burning of the last vestige of the great library in Alexandria, which had existed for almost seven centuries and which contained Euclid's texts. Thankfully this was not the end of Greek Scholarship since the Greek scholars who were displaced from the centers of learning found sanctuary in Persia and Constantinople. They brought their manuscripts with them and Greek cultural thought persisted. http://www.wilbourhall.org/index.html#euclid



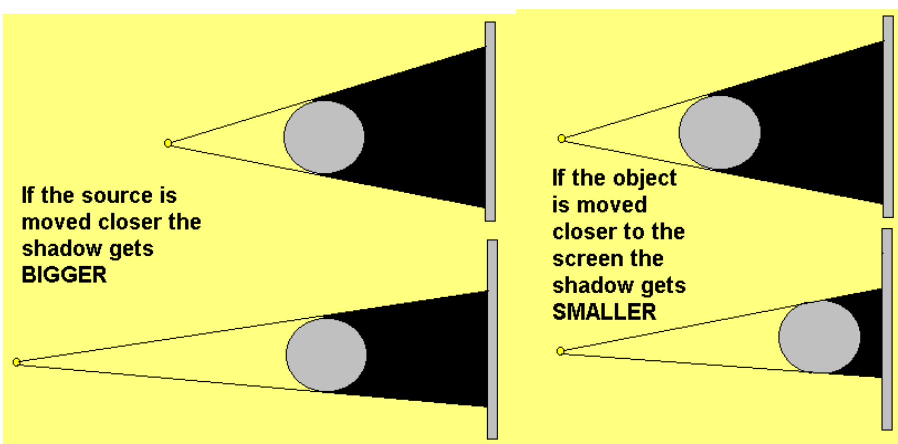
Unfortunately Greek scholarship suffered again in 529 when Justinian I (482-565), the Byzantium Emperor who also outlawed pagan thought, shut down the Platonic Academy in Athens. At the margins of the Roman Empire, including Sicily, Greek culture also survived because the scholars were left alone.

Sicily, a center of Greek science, was conquered by the Muslims from North Africa in 965, and Euclidean texts became available to Ibn Ishak al-Kindi, Abdullah ibn Sina (Avicenna) and Ibn al-Haytham (Alhazen), who sought to assimilate and further develop Greek Science. **Alhazen** (965-1040), who lived in Cairo, began to study Euclid's theory of light and vision under the Caliph Al Hakim. Alhazen, perhaps a little too full of himself, figured that he could solve any problem with mathematics and so the Caliph ordered Alhazen to stop the Nile from flooding. Unable to carry out the Caliph's request, Alhazen was thrown in prison. Sitting in the dark in prison, Alhazen began to question Euclid's assumption that we could see because light emanated by the eye. Alhazen realized that he could only see when the sunlight entered the dark prison cell. He also wondered, if light emanated from his eye, why would looking at the sun cause pain? Alhazen resuscitated the intromission theory and concluded that we see not because visual rays extend from our eyes in straight lines but because light from **luminous** objects or light reflected from **nonluminous** objects follow **straight lines into the eyes**.

What evidence do we have that light travels in straight lines? The shape and size of shadows produced by **opaque** objects tells us that light travels in straight lines. To make the geometry simple, consider the source to be a point source.

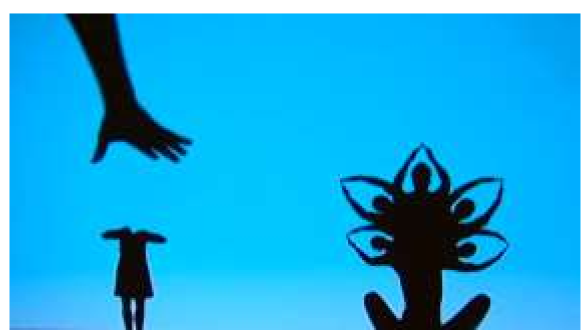


The size of the show depends on the relative distance between the object, the light source and the screen.



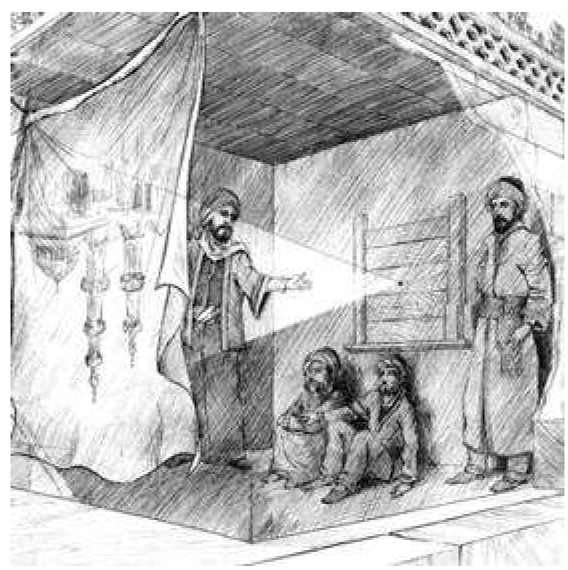
The fact that light travels in straight lines is used by the Pilobolus Dance Troupe to create their shadow dance.

https://www.youtube.com/watch?v=Znb3lpPnoXc



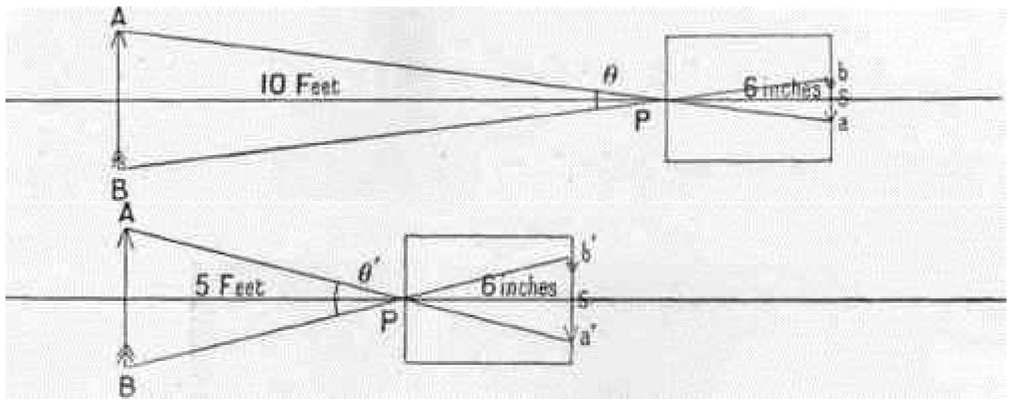
After 12 years in prison, the Caliph died and Alhazen was freed. Alhazen continued making observations and performing experiments and then published a text on optics. In his *Optics*, Alhazen wrote, "*Light emanates in every direction from any luminous body, however it is illuminated. Thus, when the eye faces any visible object that shines with some sort of illumination, light from that visible object will shine on the eyes' surface. And it was shown that it is a property of light to affect sight, while it is the nature of sight to be affected by light. It is therefore fitting to say that sight senses the luminosity of a visible object only through light that shines from it upon the eye.*"

Alhazen used **analogy** (degree of similarity; relevance of similarity) to suggest that the eye formed an image the same way that a ***camera obscura*** (dark room) or pinhole camera formed an image. Alhazen pierced a tiny hole in the wall of a dark room and placed three lamps outside the room and saw that three light spots appeared on the wall across from the pinhole. By placing an obstacle in front of a lamp, he saw that the image of that lamp disappeared and reappeared when he removed the obstacle. The image of a given lamp was always aligned with a straight line from the object to the image. Moreover, obscuring one lamp had no effect on the images of the others. Alhazen described vision, not as the complete transfer of the surface of an object, but as the **transfer of light rays emitted in all directions from individual points on the external surface to the crystalline humor of the eye**. Only the rays that stuck perpendicular to the crystalline humor in the eye were powerful enough to form an image. Thus if image formation by eyes is

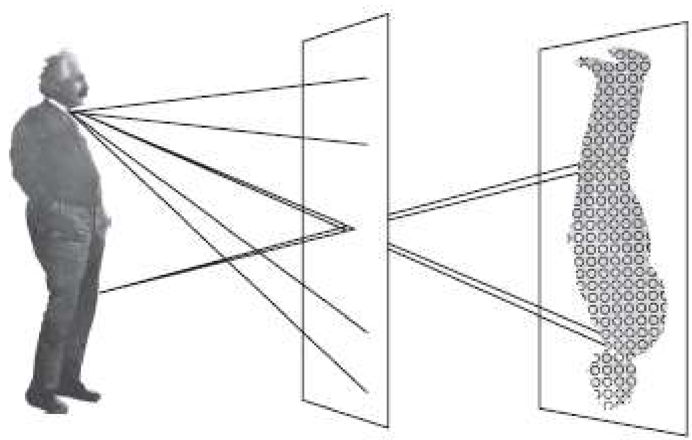


analogous to image formation by pinholes, **the image on the crystalline humor would be a point-by-point representation of the surface of the object**.

By eliminating the visual rays, Alhazen nullified the foundation of geometrical optics, which has been so successful in understanding vision and so useful for navigation. Consequently, he reformulated geometrical optics to account **for light rays radiating in straight lines from the object to the eyes** instead of visual rays extending out to the objects.



Demonstration: Turn room into camera obscura. See the effect of aperture size on the image. See the **tradeoff** between brightness and resolution. See how a lens affects this tradeoff and introduces a plane of best focus for an object at a given distance. See that for a pinhole, some information is more valuable than all information. See that **image formation can be explained only if light travels in straight lines**. This valuable truth that light travels in straight lines will find its **limitations** when we study the interaction of light with **small microscopic objects**.



Around 1100, Muslim-ruled Sicily and Toledo, Spain became Christian-ruled and scholars of every religion lived side-by-side peacefully in these linguistic borderlands that became multicultural cities. One of the Toledo translators, known as Gerard of Cremona (1114-1187), translated Alhazen's *Optics* into Latin.

Roger Bacon (1214-1294), a Franciscan monk who taught at Oxford, studied the works of the Islamic scholars such as Alhazen which had recently been translated into Latin. He realized how useful this knowledge was and like Augustine of Hippo (354-400), wanted to reclaim scientific knowledge for the service of the Christian faith. Roger Bacon asserted that the science of vision (**perspectiva),** which had been neglected by the Latins, was the noblest of the sciences and invaluable for biblical exegesis in the pursuit of wisdom since it offered "**sure experiences** of all that is in the heavens and on earth." After all, light, color, vision and mirrors were frequently referenced in the Scriptures. For example, In John 8:12 it is written, *When Jesus spoke again to the people, he said, "I am the light of the world. Whoever follows me will never walk* ***i****n darkness, but will have the light of life"* and in I Corinthians 13:12 it is written, "*For now we see through a glass, darkly; but then face to face: now I know in part; but then shall I know even as also I am known"* or *"For now we see in a mirror dimly, but then face to face. Now I know in part; then I shall know fully, even as I have been fully known*."

Bacon felt that the **truth** given by the Bible could be grasped though the development of **reason**, made precise by **mathematics** and confirmed by **experience**. He thought that an understanding of the natural world would lead to knowledge of its Creator. According to Roger Bacon, "*in the things of the world, as regards to their efficient and generating causes, nothing can be known without* *the power of geometry*" and that "*it is necessary to verify the matter of the world by demonstrations set forth in geometrical lines.*"

Geometric optics tells us that as objects become more distant, their visual angle decreases and this is why they appear smaller to us. This is why the distance between two parallel railroad rails seems to vanish at the vanishing point. It is sometimes useful to think of the vanishing point, not only as the limit of objects of constant size seen at greater distances, but in terms of binocular vision, where the vanishing point is the intersection of visual rays from each eye. By studying geometrical optics or perspective as it was known, Roger Bacon could use **lenses**, from the Latin word for lentil, to increase the **visual angle**.

Fig. 173.

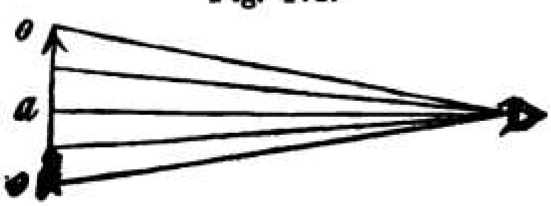
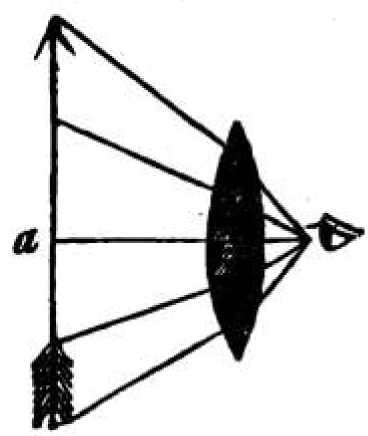


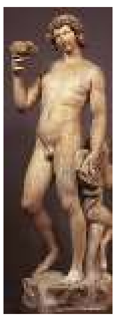
Fig. 174.



To build his knowledge of geometrical optics, Roger Bacon took a new look at **burning glasses**, which had been used since ancient times to light fires.

Aristophanes documents the use of burning glasses in *The Clouds* (423 BC):

Strepsiades. "I say, haven't you seen in druggists' shops That stone, that splendidly transparent stone, By which they kindle fire?"
Socrates. "The burning glass?"
Strepsiades. "That's it: well then, I'd get me one of these, And as the clerk was entering down my case, I'd stand, like this, some distance towards the sun, And burn out every line."



Clear glass was also developed to drink and appreciate wine. Aristophanes documents this too. He wrote in *The Acharnians* (425 BC): "*And then they feasted us, and would insist all That we should drink from cups of gold and crystal Their strong sweet wine."* It seems likely that happy and playful wine drinkers would have looked through the glass, that was geometrically similar to burning glasses, and seen small objects magnified.

Roger Bacon studied **refraction** or bending of light and thought that lenses that bent or refracted light might be useful for helping old men read the Bible. Roger Bacon wrote, "*If the letters of a book or any minute objects be viewed through a lesser segment of a sphere of glass or crystal, whose plane base is laid upon them, they will appear far better and larger…And therefore this instrument is useful to old men and to those that have weak eyes. For they may see the smallest letters sufficiently magnified… also that the most remote objects may appear just at hand…."*

For Roger Bacon, light also became a way to dramatize the teachings of the church. The churches and cathedrals were illuminated with candlelight and stained glass windows that illustrated bible stories for the illiterate and were sermons that "*reached the heart through the eyes instead of entering at the ears*."

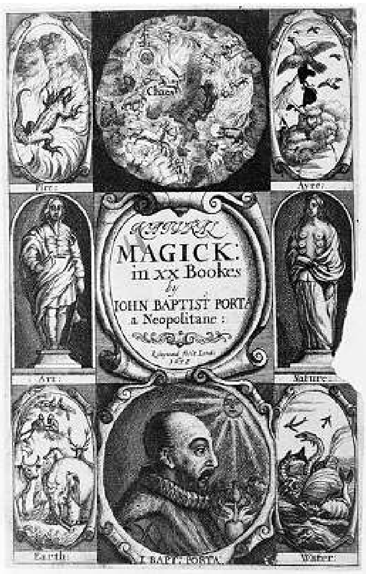
Roger Bacon saw knowledge such as the study of optics as a **handmaiden to theology** and not valuable for its own sake. He wrote that "*For every investigation of man that is not directed toward salvation is totally blind and leads finally to the darkness of hell.*" However, Roger Bacon also emphasized the importance of questioning and experimental science in searching for truth. He began his *Opus maius* by discussing **four obstacles to realizing the truth**; obstacles that Moses and Jesus also faced when presenting their message to pharaoh and to the Pharisees, respectively. Bacon also pointed out that, men such as Jerome, who were originally thought of as heretics, were later shown to be right and were made saints.

According to Roger Bacon, **the first obstacle is adherence to flawed and unworthy authority**. **The second obstacle is the persistence of custom, which often favors the false over the true. The third obstacle is popular prejudice, which produces obstinacy and confirms men in their error. The fourth and most serious obstacle error is the tendency to cloak ignorance in a show of wisdom.** Roger Bacon stated that "*Although argument does not suffice for the certification of truth, authority suffices far less….Therefore this [experimental] science wishes to teach that nothing is to be examined by argument or authority* *unless there is some [confirming] experience.*" I want you to provide you with experience and want you to learn to question authority (including me).

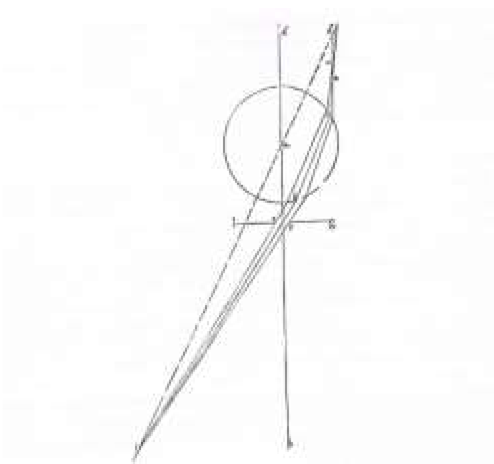
Knowledge of **perspective**, as geometric optics was called, allowed later painters, such as Andrea Pozzo (1642-1709), to mathematize the intuitive techniques of *trompe-l'oeil* (using optical illusion to depict objects as three dimensional) or *di sotto in sù* (seen from below) and include architectural elements to develop the technique known as *quadratura* (opening up walls through visual illusion), which creates an imaginary focal point to paint ceilings in churches that appeared to extend to the heavens.



On the right is a beautiful *Trompe l'oeil* of a violin and a bow hanging on a door in Chatsworth painted by Jan van der Vaart (1653-1727). We will hear more about Chatsworth and its gardener Joseph Paxton later in the semester.



Following work by Alhazen, Leonardo da Vinci (ca. 1500) and others, Giovanni Batitista della Porta (1535-1615), in his book *Natural Magic*, promoted the comparison between the eye and a *camera obscura*. He also popularized the addition of a converging lens to the *camera obscura* in order to maximize the brightness and resolution of the image. This made the *camera obscura* more useful. Johannes Kepler (who actually coined the term *camera obscura*) used the *camera obscura* to survey land and to observe the sun.

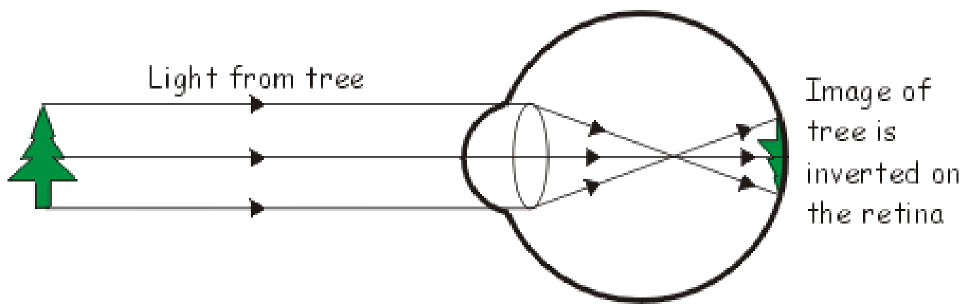


Felix Platter (1583) saw that retina was connected to the brain through the optic nerve and suggested that that the cornea and crystalline lens produced an **erect image** on the retina (from the Latin meaning net, which describes the net-like blood vessels). **Johannes Kepler** (1604) suggested that convergent light rays were bent by the cornea and the crystalline lens together so that an **inverted image** was produced on the retina. Kepler wrote,

"Vision takes place by a painting of the visible object on the white and concave wall of the retina; the leftward objects are the right side of the wall, the rightward on the left side, the upward on the lower side, the downward on the upper side;

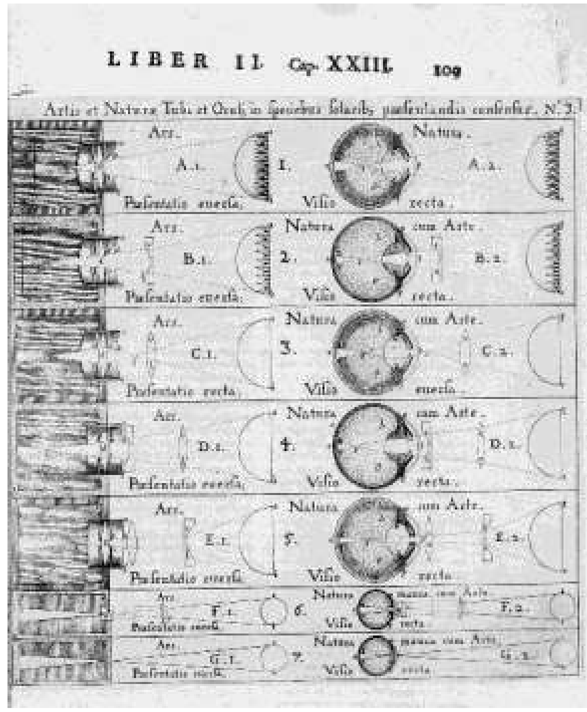
green is painted with the same green color, and in a general manner every object is painted with its original color; so that if this painting on the retina could be exposed to daylight by removing the interposed parts of the eye that serve to form it, and ***if there were a man with sufficient visual acuity****, he could recognize the identical figure of the hemisphere [of vision] on the tiny inside of the retina. Proportions are indeed conserved: the angle under which lines drawn from a given point of the visible object would reach a certain point within the eye is about equal to the angle under which these points are depicted; even the smallest points are not omitted; the sharper is a man's vision, the subtler is this painting in the eye."*

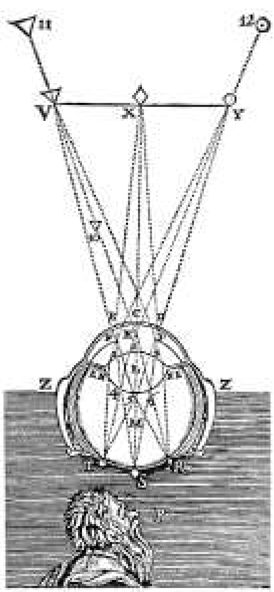
About the inverted image painted on the retina, Johannes Kepler wrote, "*I leave it to the natural philosophers to discuss the way in which this image or picture is put together by the spiritual principles of vision residing in the retina and in the nerves, and*



whether it is made to appear before the soul or tribunal of the faculty of vision by a spirit with the cerebral cavities, or the faculty of vision, like a magistrate sent by the soul, goes out from the council chamber of the brain to meet this image in the optic nerves and retina, as it were descending to a lower court."

Christoph Scheiner (*Rosa ursina*; 1630) tested Kepler's theory by placing the eye of an ox and many other animals, including cows, sheep, goats and pigs in which the **sclera** and **choriod** covering the back of the retina had been removed, in the aperture of a *camera obscura,* and saw that an inverted image was formed on the retina the same way it was formed on the wall opposite the pinhole and lens by the *camera obscura* itself. He suggested that the human eye worked the same way.





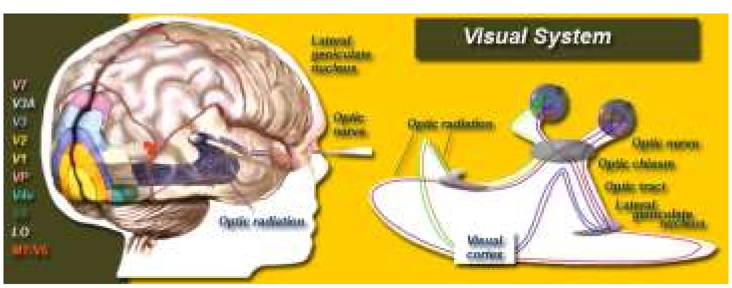
Rene Descartes (1637) repeated Scheiner's experiment and illustrated it in his Optics book taking into consideration the Snel-Descartes Law of refraction when drawing the light rays. Considering that the image on the retina was inverted, the **mind** must interpret the image and invert it again, indicating that **image formation requires more than optics. It requires the mind**. Descartes wrote, *"…we should consider that there are many things besides pictures which can stimulate our thought, such as, for example, signs and words, which do not in any way resemble the things which they signify….It is only a question of knowing how the images can enable the mind to perceive all the different qualities of the object to which they refer; not how they hold their resemblance."*

Bishop **George Berkeley** agreed that vision was not solely the result of angles and lines. Indeed the **mind**, with all its experiences, was involved in making

judgments about the nature of the image projected on the retina. He suggested that the inverted image on the retina was judged by the mind to be an erect object, consistent with ones experience with touching the object. According to Berkeley, even the size and distance of objects were not seen directly using lines and angles, but judged by the mind. He came to this conclusion after considering the **moon illusion**. That is, even though the moon has a constant size and distance from the earth, it seems larger when it is on the horizon than when it is at its zenith. Berkeley suggested that, just like a word does not have the same significance in our mind when heard in different contexts, an object placed in different contexts will not produce the same image in our mind and an object placed on high will seem smaller than an object placed at an equal distance at eye level. Berkeley showed that an object placed on the top of a one hundred foot high steeple seemed smaller than the same object placed the same distance at eye level. In *An Essay Towards a New Theory of Vision*, Berkeley (1709) concluded that it was the orientation of the head and eyes that determined the apparent size of the object. Bishop Berkeley emphasized that there is a difference between the optical processes of **seeing** in the eye and the final process of **perceiving**, or seeing with the mind's eye. Consequently, vision cannot be left to the simplifications of the mathematicians, but must take into consideration the complications of the mind.

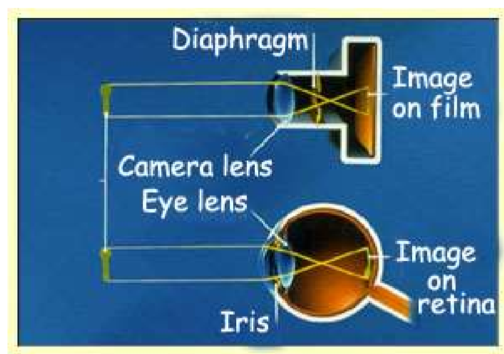
The mind has the ability to correct the image formed on the retina in order to bring it in alignment with reality. In the late 19th century, George Stratton showed that the mind could also learn not to invert an erect image projected on the retina. Stratton wore inverting glasses that produced an erect image on his retina. For four days he saw the world as **upside down** but by the fifth day, his mind brought the visual information in alignment with the tactile information and he began to see the world **right-side up** again. The role of the mind in mediating competing sensory information is known as **perceptual adaptation**.

The parts of the brain involved with vision were discovered **serendipitously** as a result of wartime **brain injuries**. People with brain injuries can be blind even though their eyes are perfectly healthy. Following the Russo-Japanese War (1904-1905), Tatsuji Inouye created a map of the visual cortex by correlating **visual field deficits** with regions of the **occipital lobe** of the brain that were damaged by bullets. Gordon Holmes and William Lister (1916) studied the relationship between visual field deficit and regions of the brain that were damaged by bullet wounds in World War I. The spatial resolution of their map compared with Inouye's map was improved because they used X-rays to localize the bullets and the damage was more localized



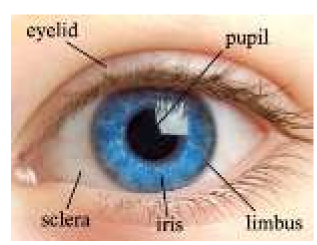
as a result of rifles with greater muzzle velocity and bullets that were smaller and less deformable. Holmes and Lister studied over 2000 soldiers because the WWI British Brodie helmet (as well as the USMC Doughboy helmet) unlike the German (Stahlhelm) helmets did not protect the occipital lobe and the cerebellum.

During WWI, George Riddoch noticed that some soldiers could still perceive **motion** even though they were blind as a result of bullet injury to the visual cortex meant that other regions of the brain were involved in vision. We now know that loss of color vision can occur when there is a lesion outside the visual cortex.



The eye itself can be considered to be an image-capturing, mechanical device **analogous** to a modern day camera. The cornea is the major factor in image formation because of the great difference in the refractive index of the air (n = 1) and the cornea (n = 1.376). The cornea has its own lens cap and lens cleaning system too. The eyelid shuts to protect the cornea; the eyebrows and eyelashes keep out sweat and dust, respectively, and the tears wash the cornea. The light rays are refracted toward the perpendicular by the cornea are slightly refracted away from the perpendicular by the aqueous humor (n = 1.336) on the way to the crystalline lens (n = 1.386-1.406).

The crystalline lens is composed of over 2000 microscopically thin layers. The crystalline lens, with the help of the cilary muscle, fine-focuses the image first made by the cornea. In a human, the distance between the crystalline lens and the retina is fixed, and the crystalline lens, which is elastic, focuses on nearly objects by increasing its



curvature and decreasing its focal length. This process is known as **accommodation**. The inability to accommodate is known as **presbyopia** and can be corrected with reading glasses. In a camera, focusing of nearby objects to take a close-up is effected by moving the lens farther from the CCD chip or film plane.

The color of the eye is determined by the color of the **iris**, named after the goddess of the rainbow. In a later lecture, we will discuss the **inheritance of eye color**. The muscles of the iris control the opening of the pupil. This allows the

amount of light that enters the eye to vary much like the **aperture diaphragm** of a camera lens varies the amount of light that reaches the film. The f-number (focal length/diameter of aperture) of the eye varies from f/8.3 to f/2.1. A larger aperture favors a brighter image with greater **spatial resolution** and less **depth-of-field**, while a smaller aperture favors a dimmer image, with less **aberration** and more depth-of-field. Squinting accomplishes the same results consciously.

The excitation of **photoreceptor cells** captures the image on the **retina** much like a **CCD chip** in a camera captures the image in a camera. In bright light, the retina is analogous to a high resolution color CCD chip or film, while under low light conditions, the retina is analogous to a monochromatic, black and bluish-white CCD chip or film. We will talk more about the development, anatomy and physiology of the eye and color vision over the next two weeks.

The **photoreceptors** that capture the image the retina of the eye are proteins known as **opsins**. The photoreceptor proteins are determined by genes and we will discuss them in terms of **sex-linked inheritance**. When the **chromophores** of the photoreceptors are excited by light, a signal transduction chain is stimulated so that the **radiant energy is transformed into electrical energy** that travels as nerve impulses through the **optic nerve** to the **brain**. The image we perceive however depends on the **mind**, which does the **image processing**. The images captured by digital cameras can also be processed.

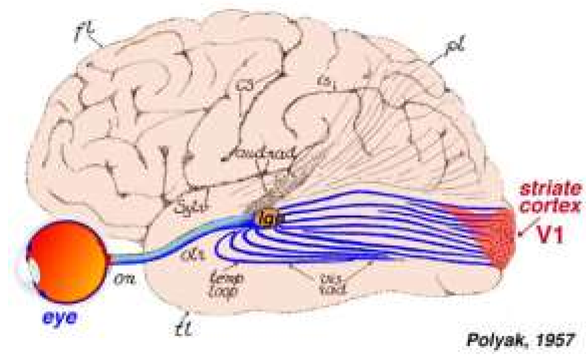
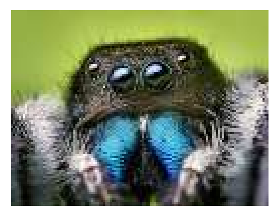


Figure 8. Visual input to the brain goes from eye to LGN and then to primary visual cortex, or area V1, which is located in the posterior of the occipital lobe. Adapted from Polyak (1957).

Our two eyes, which give us **binocular or stereoscopic vision**, are analogous to a stereo camera, which produces two images observed at slightly different angles that the mind processes into a three dimensional image in the minds eye. By taking into consideration the positions of the eyeballs that are creating the visual image, the mind helps us to **judge distance**.

Animals that have two eyes will only have stereoscopic vision that allows them to judge distances if the two eyes are in the same plane so that the two visual fields overlap. This is important for **predatory animals** such as cats and wolves. Primates have stereoscopic vision that allows them to use their hands and to jump from branch to branch. Flounder, which have two eyes in a single plane, also have stereoscopic vision. This helps these bottomdwelling predators to catch their prey. Squirrels have eyes that are intermediate between being on the same frontal plane and on opposite sides of their head. There is sufficient overlap of the two visual fields to produce stereoscopic vision which allows depth perception to catch branches and use their hands and also keep a wide angle of surveillance. Small birds that flit through shrubbery have similar eye geometry. Most birds, including the chicken and pigeon, have eyes on the sides of their heads to give them a wide angle for surveillance but must judge distance by moving their heads and focusing with each eye independently. Owls, which are predatory birds, have both eyes in the frontal plane. This gives them stereoscopic vision and the depth perception they need to capture their prey. **Browsing animals** have their two eyes on the sides of their head because surveillance with an all-around view is more important than depth perception. They can see in all directions without moving their head.

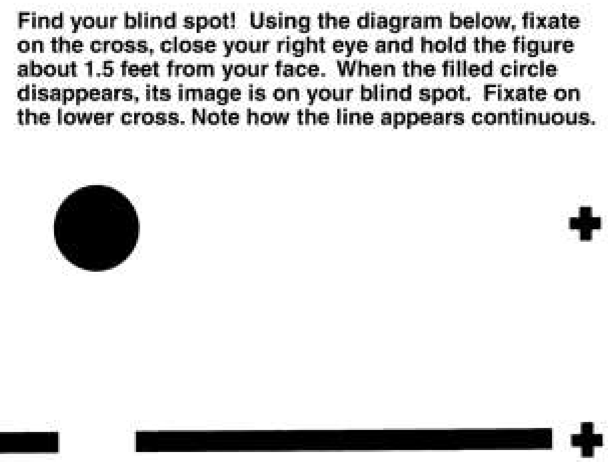
While most animals have two eyes, other animals, like *Cyclops* (a Copepod) have one eye while spiders may have eight.

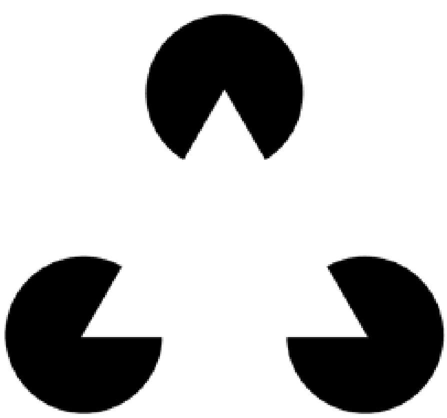


Light, in the form of **photons**, carries **information** about the external world to our retina. The photoreceptors in the retina absorb the photons and transform the spatial information into electrical signals that are encoded by the neural cells of the retina, which include the bipolar cells and the ganglion cells. The electrical signal is then transmitted along the optic nerve and it is further processed by various regions of the brain ultimately forming our **perception**, an image in the mind's eye.

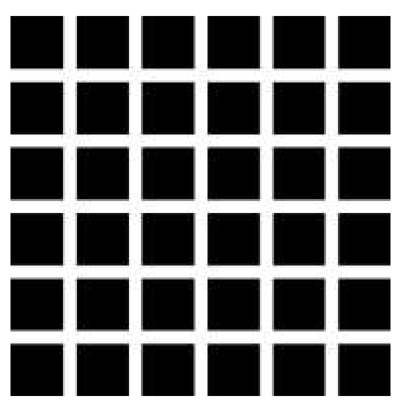
Perception is not determined solely by the physical distribution of light energy in space, but by our mind that searches for the best interpretation of the distribution of light energy in space. That is, our mind combines the sensory information with our knowledge of the world to make the best possible interpretation of the world within a reasonable time. ***Thus we do not perceive the world directly since what we perceive goes beyond the sensory experience of what we see***.

This is clearly demonstrated by the **blind spot test**, in which the way the mind "**completes**" the missing information. As we will see next week, the retina has a region devoid of photoreceptor cells where the optic nerve enters the nasal side of the eye, resulting in a blind spot. **Demonstration**: Close your right eye and hold the test pattern 18 inches in front of your eyes. Focus your left eye on the plus sign and move your eye back or forth until the dot disappears.



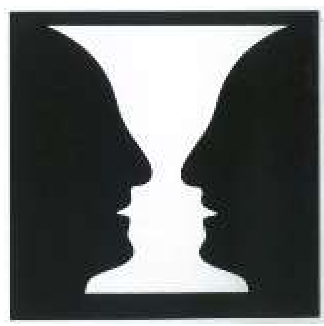


Usually our perceptions are correct in the way they illustrate the natural world to our mind's eye, but **optical illusions** remind us that this is not always the case. Do you **see** the photons that make up a triangle? Do you **perceive** a triangle? Is a triangle there in reality? What we **perceive** with our mind's eye is not the **real world**, but is a **testable hypothesis that can be confirmed by experience**. Are we any different from the prisoners in **Plato's cave**?



When we look at the Hermann grid we see the invisible phantom dots at the intersections that are not really there. Again, are we any different from the prisoners in **Plato's cave**?

When we see an **ambiguous image**, which consists of two separately valid images, each of which conforms to a realistic picture of the world, our mind makes a choice between the two i**nterpretations**. We typically cannot see the two interpretations simultaneously, although one can learn how. Do you see a woman sitting at a vanity or a skull in Charles Gilbert's (1920) "All is Vanity?"

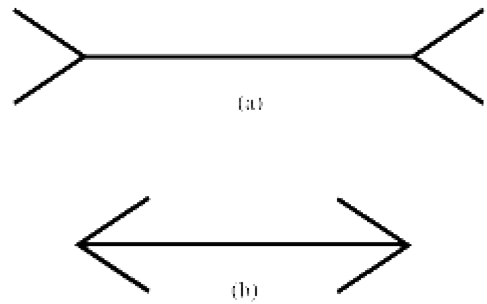


Do you see a goblet or two faces in Edgar Rubin's (1915) "Hidden Faces and Goblet?"

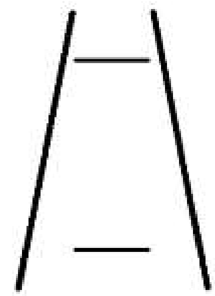
Do you see a young woman or an old woman in this picture on an old German postcard from 1880?

We will use optical illusions to document that we do not perceive the world directly as a camera does because the mind processes visual images. The mind makes certain logical and reasonable assumptions such as the influence of distance on size and that there is only one source of light illuminating the object. In everyday life, the processing gives a rapid and realistic view of the world with a modest number of photoreceptors and neurons. We can confirm the limitations of the mind's image processing capability when we study objects that we do not realize are optical illusions until we investigate the image using rulers, light meters or touch.

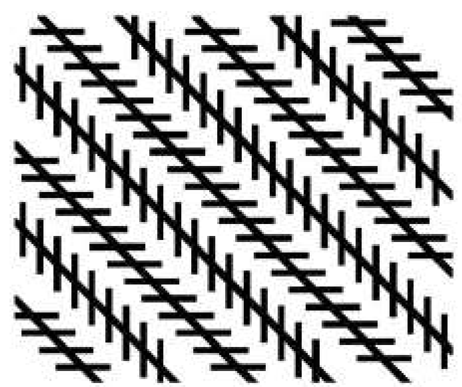
In the Müller-Lyer illusion, the lengths of the horizontal lines in figures (a) and (b) are the same, yet our minds trick us in seeing the line in (a) longer than the line in (b). Even after we measure the lengths of both lines, we still see the line in (a) longer than the line in (b). Why can't our minds fix the illusion in the same manner it erects the inverted image on the retina, to give us the right answer?



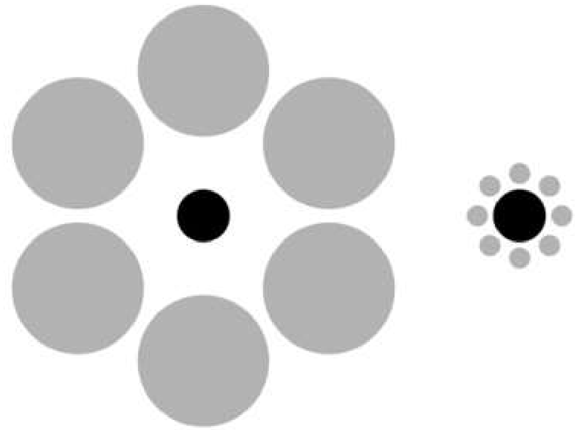
In the Ponzo illusion, the lengths of the two horizontal lines are the same, yet our minds trick us in seeing the upper line as longer than the lower line. Again, even after we measure the lengths of both lines, we still see the upper line as longer than the lower line. Why can't our minds fix the illusion and give us the right answer?



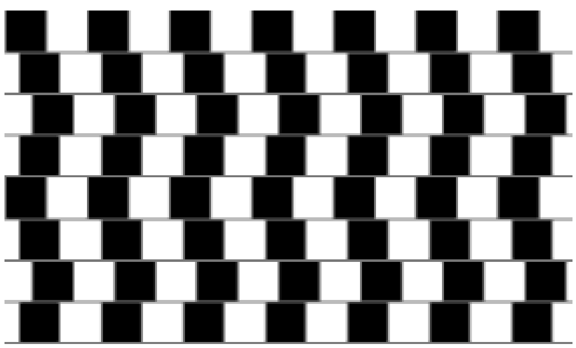
In the Zöllner illusion, parallel lines appear to diverge or converge when the lines are crossed by short lines that appear to be a part of an arrowhead or a barb, respectively. Why can't our minds fix the illusion to give us the right answer?



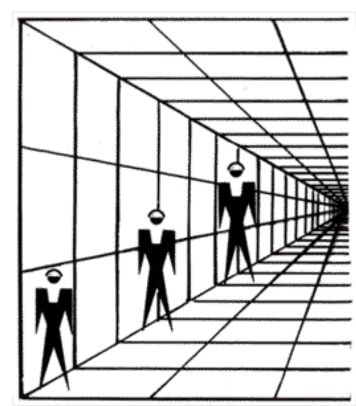
In the Ebbinghouse illusion the central spots are the same size even though the one on the right looks larger. Why can't our minds fix the illusion and give us the right answer?



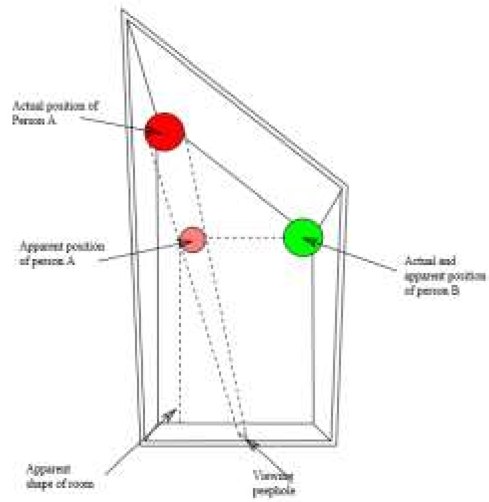
The mind cannot make the horizontal lines in the figure below straight,



nor perceive the people in the figure on the right to have the same height.



In the **Ames Room illusion**, which is an architectural illusion, we **think** that the room is a cube, even though, in **reality**, it is trapezoidal. Consequently, we **perceive** that a person standing at position A is tiny and a person standing at position B is a giant. A single person walking between position A and position B seems to grow and shrink. Are we any different from the prisoners in **Plato's cave**? What if the cave were trapezoidal shaped?



We discussed **spatial information** that contributes to optical illusions. What about **temporal information**? **When** do we see? Light takes time to travel from an object to our eye, but more importantly now, it takes time to process the visual information. Under low light conditions, it takes more time before a neural cell is sufficiently stimulated to fire. The dimmer the light, the more time it takes to process the image. **Demonstration** of the **Pulfrich Pendulum Effect:** Look at the apple pendulum swinging back and forth in a straight line. When you look with both eyes at the pendulum swinging perpendicular to your line of sight, it appears to move in a straight line. When you put a neutral density filter in front of your left eye, the apple will appear to move clockwise in an ellipse and when you put the neutral density filter in front of your right eye, the apple appears to move counterclockwise in an ellipse. **Try this at home** using sunglasses that only cover one eye at a time.

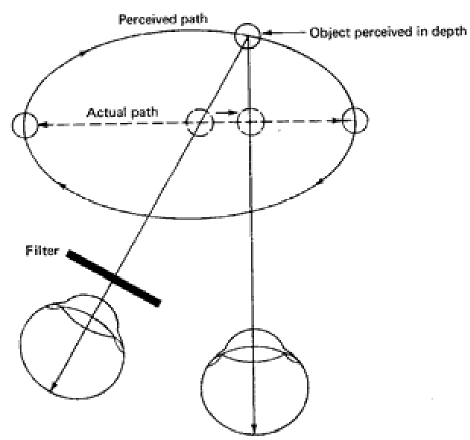
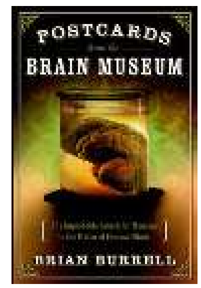


Fig. 13.7. The Pulfrich phenomenon. The attenuated eye perceives the pendulum ball as lagging behind the position as seen by the unattenuated eye. This is consistent with the ball actually traveling in an elliptical path, as shown.

The **waterfall illusion** observed by Robert Addams (1834) at the Falls of Foyers in Scotland is another **temporal** optical illusion. You can observe the waterfall illusion at Taughannock Falls. When one stares at a waterfall for a period of time and then looks to the side; the stationary rock face beside the waterfall appears to move up. Also after stopping a video of a waterfall, it looks like the water goes up!



In the "**Allegory of the Cave**," **Plato** warned us of the discrepancy between perception and reality and presented an example of how one man learned the difference. Later on, **Roger Bacon** warned us not to blindly accept any authority's view of reality. It is unlikely that we will ever see true reality, but we can do our best to understand it, and the laws of nature can help us with this.

All too often we take the world around us for granted as we quickly and effectively go from all the point A's in our life to all the point B's. The reason we are able to take the world around us for granted is because our visual system, composed of our eyes and mind, is so effective in creating a seamless and accurate representation of the world in our mind's eye. The mind usually creates seamless and accurate perceptions in real time because most of the assumptions, upon which the image processing takes place, are justified.

However, our creative mind is also **playful** and plays tricks on us. This can be joyful and fun, especially when looking at optical illusions. The playfulness may be a design feature or an evolutionary adaptation to remind us not to take ourselves too seriously. But if we really want to know something about the **natural and objective world** around us, and this applies especially to natural scientists (Tolansky, 1964), we have to get to know the value and limitations of our **assumptions** and how we use our minds to construct our personal hypotheses about the natural world, and how these personal hypotheses can be **generalized** into **laws of nature**. It is the human condition (Magritte, 1933) that we have an amazing ability to distill out the **laws of nature**, which is a shared image of the world, from the paintings on our retinas and the images created immediately by our mind's eye.

The mind is a *sine qua non* for seeing the world in a meaningful way. **Do you *see* what I mean?** The image in our mind's eye of reality is much like a scientific theory used to describe and explain reality. Both must be considered provisional and both must be tested by experience. According to Joseph Priestley (1787), "*The great superiority of man over brutes consists in the greater* comprehensiveness of his mind*, by means he is, as it is commonly expressed, capable of* reflection*....*" In *The Everlasting Gospel*, William Blake wrote about the importance of the mind/soul in seeing:

This life's five windows of the soul
Distorts the heavens from pole to pole
And leads you to believe a lie
When you see with, not through, the eye.

I'll end with a reference to divinity. Ken Knowlton (1999) (http://www.knowltonmosaics.com/pages/AEdice.htm) created a mosaic out of dice called, "**God Does Not Play Dice with the Universe**" that is now in the collection of Al Seckel (http://www.ted.com/talks/al_seckel_says_our_brains_are_mis_wired.html) . When you stand back from the mosaic, Albert Einstein's face appears. In contrast to many of his contemporaries and almost all current scientists, Einstein did not believe that the Uncertainty Principle of Quantum Mechanics was fundamental.