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Cartesian Lumière and Newtonian Light

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Cartesian Lumière and Newtonian Light

Dr. Disaster's Completely Cataclysmic Collection of Colorful Catastrophes

An Honors Thesis
College of St. Benedict/St. John's University

In Partial Fulfillment of the Requirements for the Distinction of "All College Honors" and the Degree Bachelor of Arts in the Department of Physics

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Then God said, "Let there be light," and there was light. God saw how good the light was. (Genesis 1: 3-4)
Abstract
I examine the optical methods employed by René Descartes and Sir Isaac Newton. I also present my results after performing selected experiments recorded by both of them. These experiments show that light follows strict patterns of behavior. I compare the results that I obtain to the results of Descartes and Newton and report whether their explanations are still accepted or rejected. I also examine selected queries posed by Newton to answer his unanswered questions with modern knowledge of light.

Introduction

Light has fascinated human curiosity for thousands of years. Beginning with the ancient Greeks, many scientific minds have since developed theories considering the composition and behavior of light. Some maintained that light consisted of tiny particles; others believed light was a wave. Some thought light traveled from its source to the eye instantaneously, or at infinite speed; others later determined that light moves at a finite, measurable speed. Although many theories preceded his, René Descartes looked upon light in a new and promising manner: "Cartesian theory was the first clearly to assert that light itself was nothing but a mechanical property of the luminous object and of the transmitting medium" (Sabra, p. 48). Before Descartes, scientists had adopted the Aristotelian view of light. Aristotle did not consider light as a separate, mechanical entity apart from its source and the substance, or medium, between the source and the eye: "light for Aristotle was a state or quality which the medium acquired all at once from the luminous object" (Sabra, p. 46). Hence, Aristotelian light was transmitted instantaneously between the source and the eye. Descartes also believed that light traveled instantaneously, but his concept of light required that the transmission of light itself involve motion. After Descartes, light no longer existed simply as a property the medium acquired from the source. Separating light from the medium allowed one to examine the properties of light as mechanical events that could be explained with known mechanical concepts. A mechanical system would be easier to understand and experiment with than Aristotle's abstract concept.

With this novel conception of light, Descartes opened the door for his successor, indisputably one of the greatest scientific minds in human
history: Sir Isaac Newton. Newton took the mechanical concept of light to
new levels of sophistication. He believed light was a particle that
traveled at a finite speed. Through careful study and experiment with this
mechanical concept in mind, Newton determined many properties of light
still accepted today. His work confirmed some of Descartes' observations
and disproved others. Cartesian theory fell by the wayside. It provided a
revolutionary starting point for understanding the nature of light, but it
was far from complete or even well supported. Where Descartes merely
described his beliefs, Newton labored hard to support his. Where Descartes
cleared the way for study, Newton laid the foundations of modern optical
knowledge.

For this thesis I will examine the methods employed by both Descartes
and Newton in their search for the nature of light. I will then report the
results I obtained by reproducing some of Newton's experiments. I will
compare my results to his to understand better the nature and behavior of
light as known in the time of Descartes and Newton. I will also examine
selected Queries from Newton's work concerning ideas on the behavior of
light. Newton never fully addressed these questions. By employing modern
knowledge of light, I will prove or disprove Newton's claims. Finally, I
propose to present this material in a clear, concise, and simple form so
that even the reader unfamiliar with optics may also understand.

The Men Behind the Methods

Let us first acquaint ourselves with these two great scientists. René Descartes was born on March 31, 1596 at La Haye in the Touraine region of France. He was the third child of Joachim Descartes and Jeanne Brouchard. His mother died a year later. Descartes was then raised by his maternal grandmother, Jeanne Sain. He most probably entered the Jesuit-founded Collège de la Flèche when he was 10, although the exact time is uncertain. He left in 1616, at the age of 19, "after completing the normal cycle of studies that comprised six years of high school followed by three years of college" (Shea, p. 2). In 1617, Descartes joined the
Hollander army, but within several years he turned to a scholarly life after having three dreams in 1619 which he believed were sent by God for just such a purpose. During the following ten years he traveled over much of Europe. In 1629, Descartes moved to Amsterdam and spent the next 20 years of his life living in various places in Holland.

Descartes wrote *Le Monde ou Traité de la lumière* in 1633, which supported the Copernican theory that the Earth was not the center of the universe. However, he delayed publication upon hearing of Galileo's condemnation for the same offense. In 1635, a daughter, Francine, was born to Descartes and a servant named Hijlena (or Hélène) Jans, who was probably his housekeeper. Descartes cherished his daughter for the short time he was to know her: "Descartes was greatly attached to his daughter, whom he referred to as his 'niece,' and the saddest moment of his life was her untimely death at the tender age of five on 7 September 1740" (Shea, p. 326). Afterwards, Descartes busied himself with the original publications and Latin and French translations of the *Méditations métaphysiques* (1641), *Principes de la philosophie* (1644), and *Discours de la méthode* (1636). In February of 1649, Queen Christina of Sweden invited Descartes to Stockholm to instruct her. He soon discovered that the job was far from ideal. Christina desired to study at five in the morning, much to Descartes' chagrin: "Descartes was in the habit of staying in bed until noon, but he accepted with good grace" (Shea, p. 339). Along with the cold carriage rides to court, the early risings led him to catch pneumonia. After a short illness, René Descartes died on February 11, 1650, at the age of 54.

Isaac Newton was born prematurely on Christmas Day, 1642 (Julian Calendar) in the house of Woolsthorpe in Lincolnshire, England. He was small enough to fit into a quart pot (Westfall, p. 49), and was not expected to survive. His father, also named Isaac, died before he was born. His mother, Hanna Ayscough, remarried to Barnabas Smith, a wealthy clergyman, less than two years after his birth. Newton's grandmother then raised him, but the loss of his mother's attention, being fatherless, and hating his stepfather likely traumatized the boy: "Newton was a tortured man, an extremely neurotic personality who teetered always, at least through middle age, on the verge of breakdown" (Westfall, p. 52). Newton
showed great mechanical skill even as a child, and loved to read, having
inherited a theological library from his stepfather. He entered Trinity
College, Cambridge, at the age of 18, where he devoted himself to study:
"The capacity Newton had shown as a schoolboy for ecstasy, total surrender
to a commanding interest, now found in his early manhood its mature
intellectual manifestation" (Westfall, p. 103). He earned his master’s
degree in 1668 and became a fellow of the college. In 1669, he succeeded
to the Lucasian professorship in mathematics vacated by the death of Isaac
Barrows, Newton’s mathematical mentor. However, in order to remain a
fellow, he would have to be ordained in the Anglican church by 1675, a
vocation which he did not desire. Fortunately at the last moment, a royal
dispensation exempting the Lucasian professor from the ordination require-
ment "rescued Newton from threatened oblivion" (Westfall, p. 333). The
dispensation had come about through Barrow’s influence before he died, for
Barrow "understood Newton’s worth, and he valued learning" (Westfall, p.
333). Newton was free to devote himself to his studies.

Throughout the course of his life, Newton’s interests would captivate
his attention for a time; then he lost interest. It happened suddenly, as
if his interest and work were a source of light turned off: "the light went
out, as suddenly and totally as if Newton had extinguished a candle"
(Westfall, p. 134). These interests included alchemy, mathematics,
theology, and, of course, optics. Through his interests Newton either met
or corresponded with notable scientists such as Robert Hooke, Edmond
Halley, and Gottfried Wilhelm Leibniz. When Hooke criticized Newton’s
optical paper of 1672, he earned Newton’s disfavor. In 1686, with the
imminent publication of Newton’s *Philosophia Naturalis Principia Math-
ematica*, Hooke demanded credit for his part in the Principia’s creation,
and charged Newton with plagiarism. Newton was outraged: "Apparently nothing
galled him as much as the demand for acknowledgement" (Westfall, 449). The
disfavor quickly inflated to enmity: "The charge of plagiarism in 1686 was
the final straw. He never forgot it, and he never forgave it. Hooke
remained his enemy until Hooke’s death in 1703" (Westfall, p. 451). Newton
eventually eliminated all references to his adversary, Hooke, in the
Principia.
Newton suffered a breakdown in 1693. He soon recovered, and accepted the position of Warden of the Mint in 1696. He also continued to hold the fellowship at Trinity and the Lucasian chair and receive their incomes for another five years. By the end of 1699, Newton was Master of the Mint. From 1701-05, Cambridge elected him to Parliament. When Hooke died in 1703, Newton succeeded him as president of the Royal Society, and retained the position until his death. Newton published his second great work, the *Opticks*, in 1704. Queen Anne knighted him in 1705. In his last few years, Newton suffered recurring illness and succumbed to bodily weakness, perhaps as a result of earlier exposure to poisonous chemicals in his alchemical experiments. After a final painful bout with illness, Isaac Newton died on March 19, 1726, at the age of 84. He was honored with interment in Westminster Abbey.

**Cartesian Lumière**

The Aristotelian concept of light dominated scientific thought on the subject for nearly two thousand years prior to Descartes. Through the centuries, many notable scientists supported Aristotle's view of the medium instantaneously acquiring a luminous property: "From the second to the twelfth [sic] century it was adopted by such influential writers as Galen, Philoponus, al-Kindi, Avicenna, and Averroës...and [up to the 17th Century] it was shared by Grosseteste, Witelo, and Kepler" (Shea, p. 46-7). Then along came Descartes, who proposed a different kind of light: one where mechanical motion gained importance.

Descartes still maintained that light was transmitted instantaneously.¹ His conception of light as a separate entity, however, was an entirely new twist on old theories; one that soon became and remains a standard accepted concept. Descartes was very confident that he possessed the correct theory of light. He also had great, albeit misplaced, confidence in his ability to relate his theory to others in a clear manner. At

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¹ That light traveled at a finite speed was finally determined in 1676 by the Danish astronomer Ole Roemer. Roemer discovered that the speed of light was finite by observing time inconsistencies during eclipses of Jupiter's moons (Jaffe, p. 24-29).
the beginning of his work, *La Dioptrique*, he writes, "I will try to make myself understandable to everyone, and to omit nothing, nor suppose, that one must have learned other sciences" (Descartes, p. 100). On the contrary, I found several places where Descartes' explanation is at best inadequate or confusing. I will point out these occasions as I come to them.

The method Descartes employed to determine the nature of light and color consists mainly of analogies between the behavior of light and observations completely unrelated to optics. He begins by calling light the movement or action propagated through the ether between a luminous body and our eyes. The concept of an ether pervaded science until the early twentieth century when modern physics finally ended the need for ether. Scientists used ether to account for many phenomena they could not readily explain, such as the movement of light and planets, the effects of electricity and magnetism, etc. Definitions of ether varied extensively: "Ether had the properties of a solid of great rigidity, said some. It was thin and tenuous, argued others. That at different times under different conditions, the ether, like cobbler's wax, had different characteristics, was a common analogy used by others" (Jaffe, p. 62). Whatever it was, scientists assumed ether filled the universe. For Descartes the ether was a very subtle or rarefied fluid, composed of very tiny, invisible particles that made air look like cold molasses in comparison but yet was nearly as viscous itself. He believed it caused planetary motion by swirling in elaborate vortices. He also used it to account for the transmission of light.

Descartes compares the movement or action of this ether to the information passed through a blind man's cane when it strikes something, say a rock (Descartes, p. 101). Descartes theorized that the ether transmitted light as an "instantaneous communication of movement" (Sabra, p. 50), not as motion itself. This communication occurred as the particles bumped and pressed each other: "This would make the action of light consist

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2 For those not acquainted with the French language, I have translated the quotes I obtained from French literature. To signify that the translations are my own, these quotes appear henceforth in the following manner: "<<translated quotation>>."
in a succession of shocks received and transmitted by the particles" (Sabra, p. 54). One might note that this observation sounds curiously similar to a description of waves, even though Descartes never thought of light as a wave. Today we understand the structure of waves both in theory and experiment. A wave would actually move, whereas Descartes' idea would not require actual movement. Because each particle of ether would merely shove its neighbor around a bit but not vacate its position, it would not actually move even though light still propagated instantaneously. In the blind man's cane, the information travels from the end which strikes the rock to the end in the man's hand (we now call the transmission a shock or sound wave), just like light from a luminous body to our eyes. By rubbing the end of the cane against the rock, the blind man can determine the rock's texture. In comparison, the sighted view colors. Descartes writes, <<You believe perhaps that these colors are nothing else, in bodies one calls colored, than the various ways in which these bodies receive it [white light] and send it to our eyes>> (Descartes, p. 101-02). From this analogy, Descartes determined that the speed of light was infinite because the information that passes through the cane appears to do so instantly.

At first this reasoning may seem silly, but we must consider the level of science in Descartes' time, when sophisticated measuring means were not available. We know today that sound travels approximately $344 \text{ m/s}$ in room temperature air and slightly faster in denser materials. Assuming the cane to be 1 m long, the time the wave takes to pass through the cane from one end to the other is then about 3 milliseconds, which is quite fast to human perceptions. In contrast, we now accept that light travels approximately $3 \times 10^8 \text{ m/s}$ based on many experiments, including the early 20th Century research by Michelson. Considering these facts, Descartes' observations have at least a little merit. Descartes did not intend this analogy to state that light was a wave, though. He wanted to

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3 The appendix contains a table of abbreviations and relevant scientific information.

4 For more information on the history behind the determination of the speed of light and especially Michelson's research, refer to Jaffe's book.
show only that light corresponded to an instantaneous tendency to movement or "action" of the ether.

From another analogy, Descartes determines that rays of light move in straight lines (through his ether), and do not interact with one another. Descartes compares rays of light to squashed-grape juice (Figure 1) flowing through two holes K and M in the bottom of a wine vat (Descartes, p. 103). He observes that the juice from A and that from B tend to move towards both holes simultaneously, although a given quantity of juice can pass through only one hole. However, according to Descartes, the juice from A moving towards M and that from B moving towards K do not prevent each other from flowing. Here Descartes' explanation becomes confusing. It appears that Descartes only saw in the vat what he wanted to see: "he seems unconcerned about the concrete physical situation and only interested in the pictorial suggestiveness of straight lines drawn across the vat" (Shea, p. 232). Descartes concludes that since the straight lines do not prevent each other from lying between the points, light rays do not interact or collide. This analogy also supports the notion that the transmission of light is the tendency to motion rather than motion itself, just as the juice tends to flow towards both holes. In fact, Descartes compares the transmission of light itself to the straight lines: "<the rays of this light are nothing other than the lines which this action tends to follow>" (Descartes, p. 104). Since the particles of ether did not really move but merely pressed against each other to transmit light instantaneously, Descartes avoided instantaneous motion of substance (which he did not believe possible) but still retained instantaneous transmission of light. That light rays do not bounce off each other is an important fact. Otherwise, we would see little
but a haphazard mess of randomly scattered rays. The very important observation that light travels in straight lines in a homogeneous medium (meaning all its parts are the same) leads to observations concerning reflection and refraction.

To examine reflection, Descartes once again employs an analogy. This time he compares the potential motion of light rays to the motion of a little ball. He writes: "These rays must always be imagined to be exactly straight when they pass through but a single transparent body which is everywhere the same; but when they encounter some other bodies, they are subject to being turned away by them, or absorbed, in the same manner as is the movement of a ball. . .by those bodies which it encounters" (Descartes, p. 105). Descartes then studies the reflection of a ball on flat, hard ground and compares it to the behavior of reflecting light. He ignores the ball's size, shape, and weight; only its motion is important to him. He observes that the ball bounces off at the same angle, the angle of reflection $r$, as at the angle it hits, the angle of incidence $i$ (Figure 2).

![Figure 2](image)

We measure these angles from the line BH perpendicular to the surface at the point of incidence, B, to the ray's path AB and BF. We call the line BH the "normal" to the surface. The motion of the ball can be divided into horizontal and vertical components. Descartes assumes the ball to be perfectly elastic so that it does not lose any speed when it hits the ground, and therefore it always travels with the same speed in both directions. When it encounters the ground, though, its vertical speed is reversed. The ball intersects the circle first at A then at F. Because it
travels horizontally at the same speed, the same amount of time passes for the ball to travel between A and C as between E and F, and thus the distance CB equals BE and AC equals FE. The ratio CB to AB yields Sin i and the ratio BE to BF yields Sin r. Since these ratios are equal, the sines are equal, and thus i equals r. This result is known as the law of reflection—the angle of incidence equals the angle of reflection.

Descartes compares the effects of the ball reflecting off different surfaces to the formation of colors. Colors for Descartes are not inherent properties of light, but instead depend on changes in its action. Once again, he provides only a sketchy explanation. For instance, the flat, hard ground corresponds to a plane mirror. The mirror reflects light rays at the same angle as it receives them. However, the ball does not bounce on soft cloth. According to Descartes, the soft cloth acts in the same way as the color black absorbs light rays: by removing from them all their force>> (Descartes, p. 107). The explanation for other colors such as red, blue, or yellow becomes perplexing. Apparently, Descartes believes these colors form due to the speed at which ether particles rotate and affect their neighbors' rotations when light reflects. Perhaps one way to understand this explanation is to envision different sizes of cogs turning each other successively. Each cog rotates at a different speed depending on how fast its neighbors rotate. Various changes in rotational speeds then yield various colors. White is a special case, though; when light reflects, the rotational speeds of the ether particles do not change and thus do not introduce an intermediate color. Descartes pondered briefly proving that what he believes about colors is true. Unfortunately, he does not pursue the topic: <<I think I can determine the nature of each of these colors, and show it by experiment; but this surpasses the limits of my subject>> (Descartes, p. 107). This quote illustrates the one great failing of Descartes: a lack of experimentation. Although he identified several important properties of light, he failed to properly test their validity by experimentation.

Descartes gives no indication of what sort of experiments he might have had in mind to prove his theory of color formation. However, his theory does attempt a new, mechanical explanation of color. Earlier
theories considered colors as qualities that objects possessed, not as a property of light dependent on the object. Descartes' theory that objects cause colors to form by the way they reflect light does not really challenge this notion, but the theory does suggest a mechanical interaction between an object and light that results in the formation of color. The concept of color as a property of light escaped attention until Newton proved it studying refraction: "his [Newton's] theory is distinguished by taking into account the experimental fact of unequal refractions of different colors which had escaped everyone before him" (Sabra, p. 68). Color became more directly associated with light.

Curiously, Descartes introduces a discrepancy in his considerations of reflection, and later, refraction: instantaneous transmission of light versus the temporal motion of the bouncing ball. He attempts to dispel the doubts, however, by assuming that a potential movement or tendency to movement (such as light) should follow the same laws of motion as actual movement: "Thus he implied that in investigating optical reflection and refraction, one may forget about the actual mechanism of light for a while and study the reflection and refraction of moving bodies" (Sabra, p. 79). Descartes assumed that if he considered the tendency to motion indicated by the path of his ball, he could trace out the path of a light ray as a similar tendency to motion and thereby justify his comparison.

Figure 3

Next Descartes studies refraction, the bending of light rays, by letting his ball strike and pass through water (Figure 3). As in the case of reflection, the motion of the ball can be divided into horizontal and
vertical components. Once again, the ball travels horizontally at the same speed, because the surface of the water is not opposed to the ball's movement in this direction. Descartes again ignores any characteristics of the ball and considers only the path created by its tendency to motion. This time, however, the ball continues in the same direction vertically but loses some of its speed in this direction at the water's surface CBE. For Descartes, only the surface affects the ball's motion; whatever lies below does not continue to affect the ball. The ball thus moves towards I, not D. Since it travels slower vertically but at the same speed horizontally after B, the distance IE is smaller than AC. Figure 3 may be confusing in this respect. If Descartes had considered the same time interval for the ball to travel from A to B as from B to C, he should have drawn a smaller circular quadrant BID with a radius equal to CB. Instead, Descartes argues that if the ball slowed at CBE to one-half of its initial speed, then it would take twice the time after B to travel the vertical distance equal to AC. He seems to ignore how long the ball takes to travel from B to I and simply allows the ball to intersect the circle with radius AB.

Descartes believed that the refraction of light was greater if the angle of incidence was greater. In other words, the more horizontally the ray strikes the water (the greater the angle of incidence), the more the ray bends from its original direction (the smaller the angle of refraction). In water, a ball's path bends towards the surface, but the path of a light ray bends away from it towards the normal. Descartes explains this discrepancy with his ether. Ether fills the "pores" or holes between particles of matter. The pores in air, he reasons, are soft and poorly held in place, since air is so rarefied; the pores in a denser material are harder and more firmly held in place by the surrounding matter. Because the ether pores of the air are so spongy, the potential movement of light in air is hindered. When the light encounters the denser medium, such as water, the matter resists the pores of ether more. The pores then allow the light to travel more readily (recall that sound waves travel faster in denser materials. Because the matter particles are closer together, they do not have to move as far to jostle each other, and the sound wave thus travels faster than in air. For light, the ether pores act analogously to
the matter particles.) The ball, on the other hand, must "chase" parts of matter out of its way in order to move. Therefore, it is much easier for the ball to move in air, which has little matter in the way, than in water, which has more matter in the way. On the other hand, the light ray travels in the more densely-packed ether of the water more easily than in the loosely-packed ether of the air. Descartes signifies this difference when comparing the ball's path to a ray's path by assuming the ball speeds up at the water’s surface due to a swat from a racket.

It might appear that Descartes believed light traveled faster in denser materials. This would be contradictory, since Descartes believed that light propagated instantaneously. How can "instantaneous" be faster or slower? However, Descartes did not explicitly consider changes in the speed of light when he examined refraction. He instead employed the words "plus aisément" (Descartes, p. 118) meaning "more easily," to describe how light travels in water compared to air. Unfortunately, the concept of "ease" compared to speed is almost as confusing. Descartes probably recognized the paradox of faster/slower speeds versus instantaneous propagation and dodged it as best he could. Since light was only a potential movement, he believed that it could potentially move easier depending upon the rigidity of the ether pores. Like much of his method, he avoided detailed analysis in favor of a general, simplistic argument.

![Figure 4](image-url)

Descartes continues his reasoning with a mathematical account of the refraction of light (Descartes, p. 116). In Figure 4, let AB be a ray incident from air on the surface of a transparent material CBE (water, glass, etc.). Descartes assumed that if he gave his ball a little boost
(the racket swat) at the surface CBE, then its path would also bend towards the normal. Since the ball travels slower vertically before the swat and intersects the same circle, the horizontal distance CB would be greater than the horizontal distance BE after the swat, when the ball travels faster vertically. He then concluded that the ratio of the original vertical speed to the final vertical speed of the ball would be given by the ratio of CB to BE. This ratio signifies the "ease" with which air transmits light compared to the "ease" with which a denser material transmits it. This result is known as the law of refraction. Descartes appears to have discovered it around 1625 or perhaps a little earlier. A more familiar version states that the ratio of the sine of incidence $i$ to the sine of refraction $r$ equals a constant proportion, $n$. We can easily obtain this version from Descartes' formulation. In Figure 4,

$$\frac{AM}{AB} = \sin i \quad \text{and} \quad \frac{IG}{BI} = \sin r$$

If we let our circle have a unit radius, then both AB and BI have lengths of 1 unit. Our equations become $AM = \sin i$ and $IG = \sin r$. However, $AM = CB$ and $IG = BE$, so we can write $\sin i = CB$ and $\sin r = BE$. Between these two lengths exists a proportion which we now call $n$, the index of refraction:

$$\frac{CB}{BE} = \frac{\sin i}{\sin r} = n \quad \text{or} \quad CB = n \cdot BE$$

Descartes continues that, using rays incident at different angles, one always finds the same proportion between these two sines. However, this proportion remains constant only in the same material; it varies among different materials. For instance, for practical purposes, from vacuum to air, $n = 1$; from air to water, $n = 1.33$; air to different types of glass yield different values ranging from $n = 1.5$ to $n = 1.7$; and for air to diamond, $n = 2.42$.

It is interesting to note that scientists often refer to the law of refraction, perhaps erroneously, as Snell's Law. Wilibrod Snell, a Dutch mathematics professor, formulated the law as the ratio of the cosecant of $r$ to the cosecant of $i$. He discovered this law at roughly the same time as Descartes, but never published his result. Snell died in 1623. It was not
until 1628, when Isaac Vossius first charged Descartes with plagiarism, that Descartes would have learned of Snell’s work: "Descartes had formulated the law of refraction before 1628, the earliest date when he could have been apprised of the different route Snell had followed" (Shea, p. 149). As a consequence, scientists have disputed the originality of Descartes’ finding, and some have even called him a plagiarizer who copied Snell’s work and took the credit. However, since Snell never published his result, no one knows for certain who found the law of refraction first: "neither the question of Descartes’ originality nor that of priority can be settled on the evidence available" (Sabra, p. 103). I personally think that Descartes should receive the credit for the law of refraction. No one can prove the plagiarism claim either way, and Descartes, unlike Snell, published his result.

Descartes postulates that the refraction the light ray undergoes upon leaving a material should be the same as when it enters that material, because if one reverses the path of the ray, it must follow the same path in reverse. He also writes that some materials the path of the ray curves. He gives no explanation why this curving occurs, other than to consider that because weight of a ball causes its path to curve, something might also occur with a light ray. Today we know some materials have indices of refraction which actually increase through them and thus cause light rays to refract continuously, in effect curving the rays. An example of this latter case is rising warm air which produces mirages. However, in agreement of Descartes' observation, the path would still be reversible. Descartes also believed that refraction at a curved surface occurs as if the light ray encountered a flat surface touching the curved surface at the same point. This observation is true. We call the flat surface the tangent plane to the normal at that point (meaning the plane touches the surface only at that point). We can then treat refraction as if it happened at this flat plane instead of at a curved surface.

The Cartesian theory of light contributed much to the development of modern optical theory. Descartes considered light as an entity separate from the medium, unlike Aristotle’s luminous property. He still held to the doctrine of instantaneous transmission but studied examples that
required finite time to gain insight into the behavior of light. This separation of light and medium, along with his explanation of colors, brought a mechanical explanation and understanding of light closer to reality. Abstract concepts might account for the behavior of light, but they would be very difficult to prove. Mechanical properties, on the other hand, could be more easily examined and supported by experiments, as Newton would demonstrate. Although his actual methods were at times rather dubious, Descartes managed to arrive at some very important conclusions, most notably the law of refraction. He made comparisons only to affirm one or two points while dismissing the importance of other factors, such as a ball (size, shape, and weight ignored) traveling at finite speed as compared to a light ray of infinite speed. However, he did not intend to incorporate his entire theory into each comparison, although he may have thought that his readers would understand much of it: "We cannot avoid the impression, however, that Descartes was hoping that his analogies would convey much more to his perceptive readers" (Shea, p. 228). Unfortunately, for all of his theorizing, Descartes never attempted to prove any of it. He even stated, as with his thoughts on color production, that experiments were beyond the scope of his work. For this reason one may call his methods into question. Undoubtedly a brilliant theorist, Descartes' one great failing was his lack of support by experiment. Had he attempted to support at least some of his conjectures, he might have contributed far more to optical knowledge during his time. He might have discovered that light travels at a finite speed, as does sound. He might even have discovered that color was actually a property of light. As it turned out, the world eventually received support. It simply had to wait a few years for the advent of one of the greatest scientists of all time: Isaac Newton.
Newtonian Light

Not long after the death of Descartes, Isaac Newton began his distinguished career. Although the first edition of the *Opticks* was not published until 1704, Newton had already begun studying colors in the 1660's: "He had the theory fully elaborated before January 1670 when he lectured on it" (Westfall, p. 158). However, Newton's progress was hindered by the novelty of his work: "Newton had to grope his way forward as he denied a tradition two thousand years old which seemed to embody the dictates of common sense" (Westfall, p. 161), and "When we follow his papers, we realize what hard work it was to cast off the dictates of common sense embodied in a tradition two thousand years old. His ultimate theory did not reveal itself all at once" (Westfall, p. 169). Most of Newton's scientific progress in optics occurred by 1670, with only slight modifications in the following years: "Though he would devote considerable time to the exposition of his theory, first in 1672, later in the 1690s, and carry out some minor experimentation, he had effectively exhausted his interest in the subject" (Westfall, p. 222). The light went out for a time.

Evidence points to Newton's planned publication of his early optical theory around 1678, but a fire appears to have destroyed part of his work. He temporarily gave up: "Though he tried briefly to get new copies, he finally abandoned the project" (Westfall, p. 277). The enmity between Hooke and Newton caused another obstacle: Newton's difficulty handling criticism. Newton intensely disliked criticism of his work and lashed out harshly at anyone who criticized him: "He feared criticism. He preferred silence to the risk of controversy in which he might find himself an object of ridicule" (Westfall, p. 643). Since Hooke was one of Newton's staunchest critics, his death removed the greatest obstacle blocking Newton's publication of the *Opticks*.

Newton wastes no time in stating his objectives. He commences, "My Design in this Book is not to explain the Properties of Light by Hypotheses, but to propose and prove them by Reason and Experiments" (Newton, p.
1. Newton readily states that his work will be thorough and scientific, involving propositions followed by proof through repeated experiments. Unlike Descartes, Newton provides experimental support of his theories. Like Descartes, Newton also draws some erroneous conclusions about light. However, most of these erroneous conclusions require modern knowledge of light for correction. We must also realize that experiments can often support more than one theory, even incorrect ones. Some of Newton's theory may be wrong now, but at least he tried to prove it and show that it could work.

Immediately following his objectives, Newton includes some definitions which he intended to clarify his methods and make his work more understandable. I include here a partial list of those definitions which relate to my thesis:

(1) a ray of light is the smallest, indivisible part of light;
(2) refrangibility is the tendency of a ray to bend from its original path upon passing from one transparent medium to another; refraction is the bending itself;
(3) reflexibility is the tendency of a ray to be reflected back into the same medium from the surface of any other medium upon which it falls; reflection is the act itself;
(4) the sines of the angles of incidence, reflection, and refraction will be abbreviated as the sines of incidence, reflection, and refraction;
(5) homogeneal light consists of rays which all possess the same degree of refrangibility; heterogeneal light is compounded or consists of rays of mixed degrees of refrangibility.

I will also include, for the would-be experimenter, a short list of helpful axioms that Newton uses:

(1) the angles of incidence, reflection, and refraction are coplanar (this allows us to work in just two dimensions, instead of

5 Quotes from Newton appear exactly as he wrote them. I will also attempt to use the same terminology Newton uses so that the quotes and my writing discuss the same topics.
three. Geometrically, two lines, the incident and reflected/refracted paths, form a plane);
(2) the angle of reflection equals the angle of incidence (the law of reflection);
(3) a refracted ray, if returned to the point of incidence, follows the line it described as the incident ray;
(4) the angle of refraction, from a rarer medium to a denser, is less than the angle of incidence;
(5) the sine of incidence is in a given ratio, namely, the index of refraction, to the sine of refraction (the law of refraction).

The contents of these statements have been routinely proven for at least the 350 years since Descartes' time, and some for much longer. They form the basic precepts of geometrical optics. On this point Newton writes:

I have now given in Axioms and their Explications the sum of what hath hitherto been treated of in Opticks. For what hath been generally agreed on I content my self to assume under the notion of Principles, in order to [proceed to] what I have farther to write. And this may suffice for an Introduction to Readers of quick Wit and good Understanding not yet versed in Opticks: Although those who are already acquainted with this Science, and have handled Glasses, will more readily apprehend what followeth. (Newton, p. 19-20)

Now that Newton has introduced us to the working concepts of optics, we are ready to delve into Newton's experiments.

I selected a small assortment of the many experiments and observations described by Newton in the Opticks to reproduce. This assortment includes Experiments 2, 5, 6, 11, 14, and 15 from Book I; detailed observation of Newton's rings in lenses and bubbles, described in Book II; and construction of a reflecting telescope following Newton's instructions, also in Book I. Each experiment is designed to prove or support Newton's propositions concerning the nature of light. I chose most of these experiments because they sounded intriguing and perhaps even fun. For each experiment I will state both Newton's reason for performing it and my reason for reproducing it.
EXPERIMENT 2

The first experiment I performed was Experiment 2 (Newton, p. 23). Newton used this experiment to prove that blue light is more refrangible than red light. In Figure 5, ABEF is a piece of stiff paper with the half ABDC colored blue and CDEF colored red. Black thread is wrapped around ABEF several times, forming the uneven lines in Figure 5. A candle or other suitable light source illuminates ABEF. I used a candle to follow Newton's procedure as closely as possible. The black thread serves as fine lines which help distinguish when the image of the paper is focused. Lens MN, in my case a large magnifying glass, focuses the light reflecting from ABEF, forming an image of the blue half ABDC at hi and an image of the red side CDEF at HI, due to the different refrangibilities of red and blue light. Newton worked with a distance of about six feet on both sides of his lens, which then had a focal length of three feet. He found that ABDC focused an inch and a half nearer the lens CDEF. He concluded that blue light is more refrangible, or refracts through a greater angle than red light, since the blue side focuses closer to the lens. When I performed the experiment, I arrived at the same conclusion. However, I used a distance of about one foot on either side of the smaller lens I used. This smaller lens had a shorter focal length than Newton’s lens. I found that ABDC focused just under an inch nearer MN than CDEF. The image of ABDC was rather dim, but I could still determine when the lines formed by the black thread focused. I picked this experiment because I was interested in seeing if the blue side really did focus nearer the lens than the red side.
After Experiment 2, I decided I needed to build a special experimentation laboratory to perform the other Experiments. Newton performed his experiments in a large room about 20 feet long. He also had a window, covered except for a small hole to admit sunlight. Newton wanted his room as dark as possible to avoid unwanted light affecting his experiments. Although with Descartes we observed that light rays do not interact and therefore extra light would not ruin Newton's results, a dark room does render fainter spectra much easier to see. I, on the other hand, had a small, windowless room for a laboratory. This situation was unfortunate, since I lacked sunlight. A beam of sunlight consists of a continuous spectrum of all colors in fairly parallel rays that do not spread noticeably over short distances and thus produces a clear image. I was forced to use simulated sunlight instead: a 250 watt light bulb, shining through three small holes in screens made from cardboard and adjustable metal apertures. The bulb was a poor source of parallel rays, but the apertures effectively cut down most of the spreading of the light from the bulb, leaving me a small beam that did not spread too much over the short distances I used. My first experimental setup is depicted in Figure 6. Because the bulb had such a high wattage, it produced an incredible amount of

![Diagram of experimental setup]

**Figure 6**

heat. I had to use ceramic bricks to insulate it. However, soon after finishing Experiment 5, a minor disaster struck: my bulb burnt out. I had to find another light bulb: an inch high, 50 watt halogen bulb. This new, smaller bulb produced much less heat, so I was able to do away with the bricks. In addition to my light sources, I also used lots of rods, clamps, and movable tracks and mounts to hold everything where I wanted it.
Finally, my viewing screen consisted of several large sheets of white computer paper taped to some of the aforementioned rods. During the experiments, my lab looked like a Tinker Toy nightmare.

I performed the experiments over a total distance of about five or six feet compared to Newton's 20 feet, mostly because I had access to lenses with shorter focal lengths than Newton did. I also wanted my light rays to remain parallel. This requirement thus constrained my work to smaller distances. My spectra were smaller than Newton's because they did not have as much distance in which to spread after the prism refracted the rays. Because the light from my light bulb was not exactly the same as sunlight, my spectra may have contained different proportions of certain colors (for example, less orange or more red), but as far as I could tell, all of the important colors were there. Normal incandescent light bulbs also produce continuous visible spectra, so my simulated sunlight spectra were probably very similar to Newton's genuine articles.

**EXPERIMENT 5**

![Figure 7]

Having created this technological terror, I performed Experiment 5. I chose this experiment because it shows that rays of a certain refrangibility always maintain it. In Figure 7, let S be the sun or other light source along with a screen with a small round hole admitting a small amount of light, ABC and DF two prisms whose axes are at right angles to each other, PT the spectrum of the first prism, and pt the spectrum of the second prism (blue at P and p, red at T and t), as they appear on a white screen. Without DF, ABC refracts the light upwards and produces the elongated spectrum PT indicated by the dashed lines. If DF is placed after ABC and refracts the light sideways as indicated by the solid lines, one
should expect the breadth of the resulting spectrum to increase, as the length increased after ABC. However, I found, as did Newton, that the spectrum merely inclines. The light which undergoes the greater refraction after ABC undergoes the same process after DF; likewise for the less refrangible light. These repeated processes cause the more refrangible blue light p to translate further from P than the less refrangible red light t translates from T, resulting in the inclined spectrum. This inclination shows that certain rays (blue) are always more refrangible than others (red) in any direction. Should this condition not be true, DF would form the square image π in Figure 11, as red light would undergo the greater refraction in the new direction after DF, having undergone the lesser refraction after ABC.

Newton concludes from this Experiment, that, due to a round hole, "Rays which are equally refrangible do fall upon a Circle answering to the Sun's Disque... By a Circle I understand here not a perfect geometrical Circle, but any orbicular Figure whose length is equal to its breadth, and which, as to Sense, may seem circular" (Newton, p. 38). What Newton means is that each color of homogeneous light creates a circular image of the shape of the light source’s aperture. Without prisms, the resulting image on the screen is a round white spot of heterogeneous light, which contains every color of homogeneous light. However, since each of the numerous colors of homogeneous light possesses a different refrangibility, a prism separates the heterogeneous light into overlapping circles of homogeneous light, resulting in an elongated spectrum. If the shape of the hole were changed, the corresponding image would mirror the new shape. Consequently, a rectangular hole will produce overlapping rectangles of colors, or a triangular hole will produce overlapping triangles of colors, as will be seen in Experiment 11.
Experiment 6 also demonstrates the different refrangibilities of certain colors of light and also shows that white light consists of a mixture of many colors of light. I wanted to do this experiment to see how well I could separate the colors. In Figure 8, S is once again the light source, ABC a prism refracting the light sideways, DE a screen with a small round aperture G mounted on a sliding track, and abc a second prism refracting the light from G upwards. The use of DE on the sliding track allowed me to separate the light into specific colors, which abc then refracted upwards. Newton, on the other hand, turned ABC about its axis to refract the different colors of light towards G. We both discovered that ABC refracts blue light the furthest sideways and red light the least sideways. The second prism abc refracts the blue light separated by DE the furthest upwards to M and red light the least upwards to N, as indicated by the dotted lines in Figure 8. The second prism does not produce new spectra from the light refracted by ABC; it simply refracts each color to a certain spot on the screen. The other colors fall in-between accordingly. My colors were probably a little more dilute or mixed than Newton’s due to the shorter distances I used (the colors refracted by ABC would not have separated as much as Newton’s), but this mixing would only affect the purity of adjacent colors like red and orange, or yellow and green. I should also point out that blue is not the most refrangible color—violet wins that distinction. However, the violet in my spectra was always rather faint, while the blue was in comparison much brighter. I will continue to use blue in comparisons of refrangibility, unless otherwise stated.

Experiment 6 has come to be known as the experimentum crucis (meaning "crucial experiment"), a phrase introduced by none other than Robert Hooke.
Newton only used the phrase in 1672 (Westfall, p. 214), but its implications remained valid. This experiment was crucial for several reasons (Sabra, p. 239-44). First, it showed that white sunlight consisted of rays of many different refrangibilities; it was not homogeneal, but heterogeneal. White was not a homogeneal color, as had been thought for many years. It was a mixture of colors! Experiment 6 showed that one color always had the same degree of refrangibility. It also demonstrated that one color did not change to another after refraction. According to this experiment, colors were an inherent and immutable characteristic of light. Most importantly to Newton's contemporaries, though, Experiment 6 determined the nature of colors not by considering the colors themselves, but by examining the different refrangibilities of light. Newton's experiment refuted the contemporary theory that colors were "modifications" that supposedly homogeneal white light underwent during refraction and reflection.

**EXPERIMENT 11**

![Figure 9](image_url)

Experiment 11 appealed to me because of its means of obtaining differently shaped spectra and producing the greatest separation of colors. Figure 9 depicts the setup for this experiment. S once again represents the light source, MN a lens as in Experiment 2, ABC a prism, and PT the spectrum produced. I first used a round hole about one-third inch in diameter for the aperture in the screen of the light source. The spectrum which ABC produced without MN contains colors which blur into one another. The boundaries between them are indistinct, as indicated by the overlapping lines in Figure 10. However, with MN immediately in front of ABC as in Figure 9, the colors are brighter, and more sharply defined. Using a triangular hole an inch high, apex pointing towards the ceiling and with a
base about one-third inch wide, yielded a larger spectrum height, since the aperture was larger.

\[
\begin{array}{ccc}
\text{P} & \text{without MN} & \text{P} \\
\text{round hole} & \text{P} & \text{P} \\
\text{triangular hole} & \text{with MN} & \text{with MN}
\end{array}
\]

**Figure 10**

Again, without MN the colors were blurred together, and the top and bottom edges of the spectrum were indistinct (Figure 10). With MN, however, the top part of the spectrum, which corresponds to the base of the triangle since MN inverts its image, was quite a bit brighter than the bottom, which corresponds to the apex of the triangular hole. Consequently, more light was able to pass through the base than the apex, resulting in the differing brightness. The top edge was also very sharply defined. If I looked closely, I could almost distinguish the overlapping triangles of various colors, as was previously explained to occur. Considering my results, I agree with Newton that the combination of MN to focus the light and ABC to separate it results in the greatest separation of heterogeneous light into homogeneous light. Also, the shape of the spectrum depends on the shape of the aperture used.

**EXPERIMENT 14**

Experiment 14 employs the setup for Experiment 11 to prove one of Newton's Propositions. This Proposition states that since heterogeneous light consists of rays of many different refrangibilities, objects appear confused or indistinct when viewed through a refracting substance in heterogeneous light. This confusion results because the substance refracts different colors through different angles and produces overlapping images of different colors, like the spectrum of Experiment 11. I used a second aperture following ABC in Figure 9 to obtain separate, individual colors of homogeneous light. By regarding small objects in these homogeneous lights through a second prism abc, and comparing the results to their appearance through the prism in white, heterogeneous light, one finds that they are indistinct in heterogeneous light but clearer in homogeneous light. Newton
used "Flies, and such-like minute Objects...[and] the Letters of a small print" (Newton, p. 74). In the homogeneous light, he "saw their Parts as distinctly defined, as if I had viewed them with the naked Eye" (Newton, p. 74). However, in white light, he "saw them most confusedly defined, so that I could not distinguish their smaller Parts from one another" (Newton, p. 74). For small objects I used a small screw, tiny 6-point size writing produced by a computer and laser printer, a dead beetle, an electronic chip, and small metal spheres contained in a tube of clear rubber tubing (Figure 11).

Figure 11

I could clearly see the screw's threads in homogeneous light, but not in white light. I could also read the tiny writing fairly easily in homogeneous light, but it appeared indistinct and unfocused in white light. I found the dead bug very difficult to see clearly in either white or homogeneous light. However, I could distinguish some of the bug's features, such as its legs, better in white light. I think that because the bug was very dark, homogeneous light did not illuminate it well enough for me to see it clearly. The electronic chip, little more than a plastic dead beetle in shape, appeared the same in white and homogeneous light. I could see it clearly. Finally, the edges of the small spheres in the rubber tubing appeared indistinct in white light, although I clearly noted shiny spots on the spheres where they reflected whatever color light illuminated them. In homogeneous light, the spheres were quite distinct, and appeared sharpest when viewed in red light. I found that the tube especially reflected blue light, so that I had to twist and turn the tube in order to clearly see the spheres. I also noted throughout this Experiment that in heterogeneous
light the objects tended to possess blue and red shadings to their edges, a result of the white light being marginally refracted by the prism.

EXPERIMENT 15

The last Experiment I performed was Experiment 15. This Experiment proposes proof that refraction involves the normals to surfaces and that the sines of incidence and refraction are in proportion to one another. It involves using first one prism of a certain angle to refract the light upwards and then other prisms of differing angles to refract it sideways. The angle of a prism is the angle between the two sides through which light passes. Newton used a 60° prism for his first prism and either a 20° prism, a 40° prism, or another 60° prism for the second prism. I used a 45° prism for the first prism, and then a 22°, another 45°, and finally a 60° prism for my second prisms.

Figure 12

In Figure 12, according to Newton, S is the image of the light source formed without a prism, PT represents the spectrum produced by the first 60° prism, pt the spectrum of the 20°, 2p2t the spectrum of the 40°, and 3p3t, the spectrum of the second 60° prism. Newton writes that the lines through the axes of the second prisms' spectra intersect the line through PT in various points. For instance, the lines pt and 2p2t should intersect the line PT below the center of S, at M and N respectively. The line 3p3t, produced by a prism of the same angle, should intersect line PT at the
center of $S$. The lines $pP$, $tT$ (and higher numbers) are, according to
Newton, the tangents of refraction. He writes:

by this Experiment the Proportions of the Tangents of the
Refractions are obtained, from whence the Proportions of the
Sines being derived, they come out equal, so far as by viewing
the Spectrums, and by using some Mathematical Reasoning I could
estimate. For I did not make an accurate Computation. So then
the Proposition holds true in every Ray apart, so far as
appears by Experiment. And that it is accurately true, may be
demonstrated upon this Supposition. That Bodies refract Light
by acting upon its Rays in Lines perpendicular to their Sur-
faces. (Newton, p. 79)

How Newton determined his relationship between the tangents and sines is
unclear, since he gives no further explanation. If he simply used a table
of trigonometric values, it would have been a simple matter to determine
the angle given the tangent of the angle of refraction, and from that value
find the sine. His purpose in this experiment was to show that each degree
of refrangibility obeys the law of refraction individually.

When I performed this experiment, the lines $pt$ and $3p3t$ both inter-
sected the line $PT$ a little above $S$, while the line $2p2t$ (the spectrum made
by the prism of the same angle as the first prism) went through $S$ a little
below its center. I admit that my measurements were not very accurate. As
a result of my sometimes inadequate equipment and the space in which I was
confined to experiment, I had some difficulty in obtaining good spectra and
tracing them to examine the lines. I have no doubt that Newton was able to
determine tangents and sines, although I was at a loss to do so myself.
Since I was at least able to reproduce a similar set of spectra, I feel
that the experiment had a valid purpose even if I could not reproduce the
exact method. The conclusion that each degree of refrangibility obeys the
law of refraction is certainly valid.
I chose Experiment 15 because Newton uses its results to derive the law of refraction. In Figure 13, let MC and AC be two rays incident from air on the surface RS of water, and let them be refracted along CN and CE respectively. Let MC and AD be the sines of incidence of angles DCA and DCM, and let NG and EF be the sines of refraction of angles GCN and FCE. Then let the incident motions of the rays be represented by the equal lines MC and AC, where MC is parallel to RS. AC consists of component AD, which is parallel to RS, plus component DC, which is perpendicular to RS. Newton believed that light rays traveled faster in denser media, so accordingly the perpendicular motions of the refracted rays are greater than the perpendicular motions of the incident rays by the proportions of sines:

$$\frac{MC}{NG} \text{CG for } CN \quad \text{and} \quad \frac{AD}{EF} \text{CF for } CE$$

Newton states that the parallel components of the motions are unchanged since the refracting plane does not act on the rays in the parallel direction, only in the perpendicular direction. Using a little geometry, CD^2 = MC^2 - AD^2, since MC = AC. Also, CF^2 + EF^2 = CG^2 + NG^2, since both sides equal the length of the radius squared. Given the perpendicular motion of CN, we can then write the perpendicular motion of CE as the square root of

$$CE^2 = \frac{AD^2}{EF^2} CF^2 = CD^2 + \frac{MC^2}{NG^2} CG^2$$

Replacing CD in the above equation and rearranging distributive terms on both sides, we obtain

$$\frac{MC^2}{NG^2} (CG^2 + NG^2) = \frac{AD^2}{EF^2} (CF^2 + EF^2)$$
Dividing out the equal quantities in parentheses and taking the square root of both sides, we are left with the proportion

\[ \frac{MC}{NG} = \frac{AD}{EF} \]

which shows that sines of incidence and refraction are in a given proportion to one another.

Now we know, of course, that light travels significantly slower in denser materials, and that the index of refraction from air to denser materials generally increases with increasing density. However, Newton assumed that these denser materials exerted a "force" acting perpendicular to their surfaces on the light rays, causing the rays to travel faster when refracted. He reasoned that, like the index of refraction, the force also increased with density, so that the light rays traveled faster accordingly. On the other hand, the light rays would slow down when traveling from water to air, or from more force to less force. Although Newton had the speed of light in water versus its speed in air backwards, he still found the correct index of refraction: "this Sine EF is...in Proportion to the Sine of Incidence AD as 3 to 4" (Newton, p. 7). The index of refraction from air to water is therefore $4/3$, or 1.33. It may appear odd that with the speeds reversed Newton found the correct index of refraction. However, recall that for Newton the light ray travels faster vertically in water due to the perpendicular force acting on it. The ray will then intersect the circle nearer the normal, refracting through a smaller angle measured from the normal. The ratio of sines thus yields the correct index of refraction. More importantly, Newton showed that the ratio was constant for a given refrangibility with this experiment.

**NEWTON'S RINGS**

After finishing the experiments, I examined the phenomena of Newton's Rings. These rings appear as concentric light and dark rings when one traps a thin film of air between transparent surfaces, at least one of which is curved, such as glass lenses. Newton used a variety of different lenses together such as two double-convex lenses (both sides curve
outwards), or a double-convex lens and a plano-convex lens (one side flat). He used the latter combination for his Observation 4 (Newton, p. 197-200). I based my examination on this Observation, using a large, double-convex lens and a flat glass plate for this experiment (Figure 14). Newton's explanation of this phenomenon consisted of his complex "fits of easy reflection and transmission." Newton thoughtfully provides a definition: "the disposition of any Ray to be reflected I will call its Fits of easy Reflexion, and its disposition to be transmitted its Fits of easy Transmission" (Newton, p. 281). The rings result, according to Newton, because the light rays are disposed to be reflected and transmitted alternately by the lower air film surface at progressive distances measured from the center of contact.\footnote{The modern explanation of Newton's rings is that the rings form as a result of constructive and destructive interference in the light waves partially reflected at the film surfaces. See the appendix for an explanation of interference and electromagnetic waves.} When light rays encounter the lower surface of the air film in Figure 14, the film alternately reflects and transmits rays, forming the colored circles. At one distance, for instance, rays will be reflected; at twice the distance they will be transmitted; at three times the distance, they are again reflected, etc. Newton does not concern himself with how these fits happen: "Whether it [the mechanism of the fits] consists in a circulating or a vibrating motion of the Ray, or of the Medium, or something else, I do not here enquire. . . I content myself with the bare Discovery" (Newton, p. 280-81). Newton could not readily explain how the fits occurred, although he does concede the possibility, however slight it may be in his own opinion, that some sort of vibration or wave theory might account for the fits. He still remained convinced that light was a particle, though.
Once again, I had to settle for simulated sunlight in the form of a large-panel fluorescent overhead light in the hallway, where people could walk by and watch me sitting at a table in the hallway staring at pieces of glass. (The things we do in the name of science.) I checked the spectrum produced by this fluorescent light using a monochromator, a device that allows one to look at a roughly .2 nm range of visible light wavelengths at a time. I then compared it to the solar spectrum. I noted that both sources produced a continuous spectrum of visible colors, but some colors were brighter in sunlight than in the fluorescent light. I did not therefore expect to observe the same sequences of colors that Newton did. Under this lighting, I saw a darker bluish gray spot of the same size in the middle, surrounded by several dozen colored rings in the repetitive order yellowish-tinged white, red, black, and blue. Newton, using actual sunlight, reports the following succession of "circuits" (ending with the colons) from a central black spot: "blue, white, yellow, red: violet, blue, green, yellow, red: purple, blue, green, yellow, red: green, red: greenish blue, red: greenish blue, pale red: greenish blue, reddish white" (Newton, p. 199-200). Newton must have had pretty good eyesight to see all those colors. I could barely make out the ones that I saw, especially in the smaller rings. I noticed that when I moved my head directly over the plate so that my shadow covered it, the dark rings turned light and the light rings turned dark. Only about the nine largest rings were then visible. Under either amount of light, the rings themselves became thinner as their radii increased. By moving my point of view towards the side of the plate, the rings began to expand and distort, an effect of having to pass through the glass more obliquely to reach my eye, as was stated earlier in trying to look at things through a prism.

Next, I pressed down on the edges of the lens to see what changes the rings would undergo. I noted that the dark spot in the center expanded, as did all the rings, but it became lighter the harder I pressed. Lifting up slowly, I watched the rings converge into the central spot, following the pattern yellow, red, purple, black, blue, green, yellow, etc. Newton writes that by pressing down the top lens slowly and by lifting it up again, he was able to discern the above pattern of colored rings he
recorded. Newton must have also had a pretty steady hand. I had a hard
time trying to hold the lens steady while slowly easing the pressure on it
because the lens tended to wiggle around on the plate.

I then turned my attention to rings in soapy bubbles. Newton studied
soapy bubbles in Observations 17-20 (Newton, p. 214-21). He concluded that
these rings also form due to fits of easy reflection and transmission at
the bubble's interior surface. The thickness of the bubble increases down
its sides from its top, like the air film thickness increases the further
from the center of contact in Figure 14. I used the glass plate from the
earlier experiment, a bell jar to protect the bubble from stray air
currents and other unwanted disruptions, and Wonder Bubbles® solution. I
blew a fairly large bubble onto the plate, covered it, and commenced bubble
watching. I could see multicolored swirls on the bubble immediately, as
the fluid of the solution flowed around the hemispherical bubble and
gravity began to affect it. The colors quickly flowed into rings stacked
up the sides of the bubble, with an enlarging white spot on top. Then a
completely clear spot began to grow in the center of the white spot after
about five minutes. Meanwhile, the colors on the sides had arranged
themselves, starting below the now white ring in the order black, purple,
blue, green, yellow, red, black, purple, etc. All of these rings slowly
flowed down the sides of the bubble towards its base. New white spots
appeared in the clear spot on top after about ten minutes. At fifteen
minutes, the top of the bubble had become almost invisible, requiring one
to look through the bubble from the side to see it. The white spots
disappeared and the colors were fading. In another seven minutes, the
colors had faded save a narrow band at the base, visible only at the edges
of the bubble. The bubble itself was practically invisible except when
seen head on from the same level. Eventually the bubble burst, but it
existed for an amazing 35 minutes. Too bad bubble bath does not last that
long.

Newton recorded a process very similar to the one I described. He
also included a detailed list of the colors he saw from sunlight: "red,
blue; red blue; red, blue; red, green; red, yellow, green, blue, purple;
red, yellow, green, blue, violet; red, yellow, white, blue, black" (Newton,
p. 216). This time, however, light sources might not be the only cause of
the different colors; the soapy water we used was likely quite different.
The different chemicals in each of our solutions could easily have
reflected different colors. I do not believe that Newton had any Wonder
Bubbles® solution. If he had, he might have had some fun blowing bubbles
and watching them drift around his room. It might have cheered him up
some. It worked for me.

NEWTON’S TELESCOPE

The final part of my experimentation with Newton’s work involved
constructing a reflecting telescope following his instructions. Newton
advocated reflecting telescopes instead of refracting telescopes for a
couple of reasons. First, the lenses in a refracting telescope need to be
large to collect enough light. Consequently, they become very heavy and
cumbersome. Secondly, the refracting telescopes of his time produced
images with chromatic aberrations, or colored distortions. Because a lens
refracts white light consisting of many colors of differing refrangibili-
ties, blue and red light, for example, would refract slightly differently
and focus in different places. The image would appear distorted due to
overlapping colored images, similar to the overlapping colors in the
spectrum of Experiment 11. Since a mirror reflects, not refracts, a
reflecting telescope would eliminate chromatic aberration. However, Newton
did not know that using multiple lenses of different focusing abilities,
such as a convex/concave combination, each with different refractive
indices, would also solve the problem. The result would focus enough of
the light at the same point to virtually dispose of chromatic aberration.
Unfortunately, in order to collect enough light to produce good images,
refracting telescope lenses have to be very large and consequently are very
heavy. They become difficult to support without deforming. Mirrors, on
the other hand, can be much larger and easier to support without being bent
out of shape. Hence, most modern astronomical telescopes are reflecting
telescopes.
Figure 15 shows the schematic of Newton’s Telescope (Newton, p. 107-11). AB is a concave (curved inward) second surface mirror (meaning that the back of it is silvered, not the front) which reflects parallel rays through its focal point, C is a right (45°-45°-90°) prism which redirects the rays at a right angle to the axis of the telescope, and D is a plano-convex lens. The focal points, or where the light focuses, of AB and D coincide at F. In my version, AB has a diameter of 216 mm and a focal length of 500 mm; C is a pentagonal prism which performs the same job as a right prism; D has diameter 13 mm and focal length 20 mm; and the telescope’s body consists of a 620 mm long section of stove pipe painted flat black on the inside to absorb scattered rays that do not enter the mirror. AB is held in a hand-scraped styrofoam brace with adhesive clay and glue. I glued the brace to the stove pipe’s end. After a lengthy bout with various adhesives, I managed to use Elmer’s® Glue-All to hold the prism to the end of its supporting rod. The eyepiece consists of a black rubber stopper cut in half, with a hole approximately the same size as the lens drilled in it. The lens fits snugly into the hole. The stopper fits into the end of a short tube which then slides into a slightly larger tube. This combination forms an adjustable-focus eyepiece. The magnification of the telescope is given by \( M = \frac{f_m}{f_l} \), where \( f_m \) is the focal length of the mirror and \( f_l \) the focal length of the lens. This should give a magnification in my telescope of \( M = 25 \).

I wanted to reproduce Newton’s reflecting telescope for a couple reasons. First of all, I found Newton’s reflecting telescope such a great
result of his study of refrangibility that I felt my experimentation would be incomplete without trying to make one. I was also intrigued by the possibility of constructing a small working telescope. I hoped that I could actually use it to see some heavenly phenomena. Unfortunately, Newton possessed much greater mechanical skill than I do. My telescope does not work quite as well as I had hoped. It is also a little on the ugly side. My mirror is subject to spherical aberration, a condition where different radii of the mirror (or of a lens) have different focal lengths, causing an indistinct image. Newton never addressed this other problem of refracting telescopes lenses; he thought the blame for poor images from refracting telescopes rested with the differing refrangibilities of light alone. To correct this problem, I covered the open end except for a small aperture. Less light reaching the mirror results in reduced, but not eliminated, spherical aberration. I could then read the license plate on a car about 50 m away using the telescope. Without it, I had to approach the car to within half that distance to read the plate. On the plus side, my telescope forms images without chromatic aberration. In that regard, Newton's reflecting telescope design is a success. I have no doubt that Newton's telescope was probably a bigger success than mine. It probably looked better, too.

Newton's Queries ??

At the end of Book III of the Opticks, Newton lists a series of questions concerning the nature of light, questions that he never experimentally answered. He hoped instead that others after him could examine them and reach certain conclusions. He posed these speculations in a manner indicating that he expected the answers to be yes. However, should the answer be no, the form he used also avoided claiming something to be true without proof: "The fact that they appear in the Opticks as Queries and not as Propositions means that they do not form part of the asserted doctrine of light and refraction" (Sabra, p. 312). Of the 31 Queries recorded at the end of the Opticks, I chose Queries 1, 13, 17, 21, 26, and 29 to examine and discover if Newton's suppositions survive in light of
modern optical knowledge. Each of these particular queries presented a
difficult problem for early 18th Century science to resolve. Each also
concerns, in accordance with the topics I have presented, either refraction
or the composition of light itself.

Query 1 states, "Do not Bodies act upon Light at a distance, and by
their action bend its Rays; and is not this action (ceteris paribus)
strongest at the least distance?" (Newton, p. 339). This question follows
from Newton's belief in forces causing refraction, as explained after
Experiment 15. Newton vacillated between believing in an ether like
Descartes and explaining things without ether. With the Principia he
destroyed the need for an ether like Descartes', but he also destroyed his
explanation for the cause of refraction resulting from vibrations in ether.
He then turned to forces acting at a distance (Westfall, p. 522). However,
acknowledging that some of the properties of light could not be explained
by his ether-less mechanics alone, it appears that he settled for an
amalgam of ether and force: "Queries 17-24 assert the existence of a
universal aether and offer an explanation of forces in terms of such"
(Westfall, p. 641). Newton suggested that ether still existed and treated
it as a sophisticated mechanical system. The ether's sad demise at the
hands of scientists like Michelson refutes Query 1. Without ether and
forces acting at a distance, modern electromagnetic wave theory soon
explained optical processes like refraction.

Query 13 postulates that colors result from light rays making
"Vibrations of several bignesses" and exciting "Sensations of several
Colours" according to their bignesses when they strike our eyes (Newton, p.
345-46). It continues that the most refrangible rays cause the shortest
vibration, resulting in the color violet; the least refrangible rays cause
the longest vibration, resulting in the color red; and other colors fall
in-between accordingly. Proving that color is an innate property of light
rays in Experiment 6, the experimentum crucis, Newton attempts to explain
how we perceive these colors in Query 13. Today we know that visible light

7 The original set of Queries of 1704 ended at 16. The Queries comprising
numbers 17-24 were added and the set renumbered in the second English
comprises a small part of the electromagnetic spectrum. Colors depend upon the wavelength of light waves and range from deep violet at the shorter wavelength of 400 nm to deep red at the longer 700 nm. In a footnote, Sabra states, "I have argued elsewhere that by "bignesses of vibrations' Newton meant wave-lengths" (Sabra, p. 278). Newton refused to accept a wave explanation of light. However, he conceding the possibility of vibrations in ether in connection with optical phenomena. Despite his rejection of wave theory, Newton appears to have determined the proper relationship between color and wavelength as a consequence of the vibrations in his ether. The basic premise of color formation in Query 13 thus still holds today.

Query 17, added in 1717, presupposes the existence of an ether to explain his fits of easy reflection and transmission (Newton, p. 347-48). Newton writes that light rays falling on a transparent material excite vibrations in the ether in the material just as the rays caused vibrations in our eyes to form colors in Query 13. He proposes that these vibrations overtake the rays and put them into the fits by alternately accelerating and retarding them. Recall that when Newton first named the fits to explain ring formation, he did not consider their cause. With Query 17, he tried to find a satisfactory reason for ring formation. Although we can now explain Newton's rings without ether and fits, Newton made a valiant, albeit insufficient, attempt in this Query to explain the problematic fits.

In Query 21, Newton provides information leading to an approximation of the speed of light (Newton, p. 350-52). His intent in this Query is to determine the elasticity of ether by comparing the speed of sound in air to the speed of light in ether. He considers the how elasticity of air in proportion to its density affects the speed of sound. Newton concludes that the elasticity of ether compared to its density must be $4.9 \times 10^{11}$ times greater than the elasticity/density proportion in air. We already know the fate of ether. Concerning the speed of light, however, Newton states that light takes about seven or eight minutes to travel from the sun to earth, and that this distance is about $1.13 \times 10^{11}$ m (the modern accepted value is approximately $1.5 \times 10^{11}$ m). Choosing eight minutes (480
s) as an upper limit on the time (and therefore a lower limit on the speed), and seven minutes (420 s) as a lower time limit, the speed of light is then between $2.35 \times 10^8$ m/s and $2.69 \times 10^8$ m/s according to Newton. This approximate calculation is not too bad for Newton's time. His radius is a little small, but the time is quite accurate. In 1676, Roemer estimated that light took around 11 minutes (660 s) to travel the radius of Earth's orbit (Jaffé, p. 24-8). Roemer believed that this radius was about $1.47 \times 10^{11}$ m. He then calculated the speed of light to be approximately $2.22 \times 10^8$ m/s. Roemer's radius was closer to the accepted value, but his time was a little long. In 1717, Newton surely knew of Roemer's work and even agreed with it: "Isaac Newton... did support the Dane" (Jaffé, p. 28). Newton's finite approximation differs substantially from the instantaneous light accepted by Aristotle and Descartes.

Newton turns his attention to the corpuscular nature of light in Query 26: "Have not the Rays of Light several sides, endued with several original properties?" (Newton, p. 358-61). Newton poses this question to explain the occurrence of double refraction in Iceland Crystal (also called Iceland crystal or Iceland spar, and better known as calcite), described in Query 25 (Newton, p. 354-58). This crystal forms two images of objects viewed through it, a result of two different refractions. Newton discovered that, depending on the way two crystals were turned with respect to each other, light rays would either be refracted the same way in the second crystal or a different way. He realized that some inherent property of light rays caused them to behave thus. Because he thought of light as a particle, he gave the particle a shape with several types of "sides," opposite pairs being the same type of side. The calcite crystal affected two types of sides differently, causing the double refraction. Newton used Query 26 to illustrate again that light rays have innate properties that cannot be changed, such as color, refrangibility, and their "sides."

We know now that the double image results from the atomic structure of the calcite crystal affecting the electric and magnetic field oscillations of an electromagnetic light wave in slightly different manners. The crystal behaves as if it possessed two different indices of refraction, one
which affects the component of the incident wave parallel to the optic axis of the crystal and one which affects the perpendicular component. The optic axis follows the direction of symmetry of atoms in the crystal. The sides of Newton's particles would correspond now to the electric and magnetic fields of the wave. In calcite, the emergent beam affected by the parallel index of refraction contains only the electromagnetic components parallel to the optic axis, and likewise for the perpendicular emergent beam. This result is known as linear polarization. Calcite acts as a type of polarizer, a material which separates the electric and magnetic components of light. While some polarizers actually eliminate one component, calcite simply causes them to follow two different paths (Figure 16) through the crystal, which results in the double image.

![Figure 16](image)

Newton once again supports the corpuscular nature of light in Query 29. He writes, "Are not the Rays of Light very small Bodies emitted from shining Substances?" (Newton, p. 370). He then proceeds to list some properties of light that his corpuscular theory can explain. One such property is that particles "will pass through uniform Mediums in right [straight] lines without bending into the Shadow" (Newton, p. 370). Newton illustrates one of his major arguments against a wave theory of light with this passage about bending into shadow: like water waves bending around a large rock or sound waves being heard around a corner, he believed that light waves would also bend around objects. Light, he observed, did not bend around large objects; therefore, he reasoned that light was not a wave. Newton could explain reflection, refraction, and color with his particles. He writes, "it's difficult to conceive how the Rays of Light,
unless they be Bodies, can have a permanent Virtue in two of their Sides which is not in their other Sides, and this without any regard to their Position in the Space or Medium through which they pass" (Newton, p. 374). Newton steadfastly stuck with his particle theory.

Newton was partially correct about the particle nature of light. We now consider light to be fundamentally a wave, but it also exhibits some properties of particles. It is true that light does not bend noticeably around large objects. However, when a light wave encounters a small enough object or aperture, it bends around it. This small-scale bending is called diffraction and cannot be explained by a particle theory where the particles only travel in straight lines. In Figure 17, a light wave of parallel rays (indicated by the plane wavefront) and wavelength $\lambda$ is incident on an aperture approximately

![Figure 17](image)

the same size as $\lambda$. At such small distances, the wave nature of light causes it to bend around the corners. Most of the light continues straight ahead, but some rays follow other paths as indicated by the dotted lines connecting successive arcs. Because light waves bend around small obstacles, the edges of shadows are indistinct if viewed closely enough. On the other hand, Compton scattering, where x-rays bounce off electrons, is an example of the particle nature of an electromagnetic wave. Both energy and momentum are conserved. This fact requires that the x-ray possess momentum, a particle characteristic. Although the nature of light since Newton has sustained some very important changes, Newton’s tenacious grasp of a particle theory has never been completely discarded.
Concluding Thoughts

René Descartes and Sir Isaac Newton possessed two of the greatest scientific minds in history. By examining their methods and their work, we can easily see that they contributed greatly to optical science. Along with his ether, Descartes formulated a complex theory of the nature and behavior of light. Unfortunately, his methods were often superficial and lacked support. Descartes would use an analogy that was completely dissimilar to an optical situation simply because some part of the analogy favorably demonstrated a principle he maintained. The analogy of the straight lines in the wine vat indicating that light traveled in straight lines through a uniform substance without interacting manifests this conclusion. He also failed to give substantial support for his hypotheses. Even though his methods were questionable, he was a prominent contributor to the advancement of optics. Descartes was the first to challenge Aristotle’s concept of light as a property that the transmitting medium instantaneously acquired from the luminescent object. By taking a more mechanical view of the behavior of light, Descartes started a process that continues through the 20th Century. He removed some of the mystery behind the action of light and prompted scientists after him to continue a mechanical approach. Through mechanics, the electromagnetic wave theory of light developed. Mechanics also led to the downfall of ether. Descartes also derived, perhaps controversially, one of the most important results in optics: the law of refraction. By applying this law, he was the first to explain why one saw rainbows only at certain angles (Descartes, p. 185-99). Descartes’s work brought one of the biggest leaps of progress to optical theory in nearly 2000 years. Soon afterward, optical theory made yet another giant advancement with Newton.

Newton’s achievements continue to have their impact today. Unlike Descartes, Newton offered support by experiment for his suppositions. Some of his suppositions were wrong, but he nevertheless attempted to support them with experiments. He studied light in-depth, explaining such behavior as blue light always being more refrangible than red light. He showed that
materials refract light rays by acting on them in lines perpendicular to their surfaces. He discovered that thin films of air or soapy water produce colored rings. Of course, some of his explanations no longer hold true, like his fits of easy reflection and transmission. Had he accepted a wave explanation, he might have been able to explain the rings in thin films without the fits. Newton provided an improvement over refracting telescopes with his design for the reflecting telescope and opened the heavens to amazing new discoveries. Through his efforts Newton not only provided support of his theories about light which everyone could reproduce, but he also provided a basis for improvements of many optical devices.

Voltaire includes some interesting thoughts on Descartes and Newton in his work, *Lettres Philosophiques*, a collection of philosophical discussions composed between 1726 and 1730. Voltaire's writings include biographies of both men and his own opinions concerning their works on gravity, optics, and time. Recalling that, for the most part, instantaneous Aristotelian light thrived under Descartes but had died out by Newton's time, Voltaire illustrates a basic difference between Descartes' and Newton's theories of light: "Light, for a Cartesian, exists in the air; for a Newtonian, it comes from the sun in six and a half minutes" (Voltaire, p. 70-71). Here Voltaire also compares the more scientific and precise nature of Newtonian theory to the more abstract Cartesian theory. Whereas light is something mysterious that just seems to exist all around us according to Cartesian theory, Newtonian theory announces where light comes from and how fast it travels. Voltaire continues that very few people in London read either Descartes or Newton. He believed that Descartes' work had become useless, while Newton was too smart for most people to understand. He points out the popularity of Newton over Descartes in England: "however, everyone speaks of them; one accords nothing to the Frenchman and gives everything to the Englishman" (Voltaire, p. 74). Voltaire himself was a strong supporter of Newtonian theory, and was well-versed in the works of Newton. However, he did not neglect the contributions of Descartes.
When focusing on Descartes, Voltaire sees a man with an active mind and imagination: "Descartes was born with a strong and vivid imagination which made of him a man as singular in his private life as in his manner of reasoning" (Voltaire, p. 72). It certainly appears that some of his optical analogies came from his imagination. Voltaire recognized that Descartes may have made lots of mistakes, but due to his steadfast study he made great contributions not only in geometry and mathematics, but also in optics. He deserved credit for his discoveries:

"He carried this spirit of geometry and invention in la Dioptrique, which became in his hands a wholly new art; and if he deceived himself in something, it is that a man who discovers new worlds cannot know all their properties right away: those who come after him and render these worlds fertile owe him at least the discovery." (Voltaire, p. 75)

Voltaire concludes that Descartes was fallible but that even his mistakes were useful to the advancement of knowledge and reason: "He made mistakes, but they were at least methodical, and in consequential spirit; he destroyed the absurd chimeras with which one infatuated our youth for two thousand years." (Voltaire, p. 76). Although Voltaire strongly supported Newton, he not only recognized but praised the important contributions Descartes had made to science and philosophy.

Like Voltaire, I admire Newton and his discoveries. Yet it was Descartes who first began to chip away at the crude Aristotelian concept of light and who offered the world the law of refraction, even if he made mistakes along the way. Perhaps Descartes was simply better suited to intellectual pursuits and philosophical matters than scientific experiments. Of course, both René Descartes and Sir Isaac Newton made mistakes. Some required centuries before they were rectified. However, we all make mistakes (some of us make more than others). I think that Descartes and Newton appear more accessible to us and more human because of their mistakes. And if two of the greatest scientists in history make mistakes, there is still hope for the rest of us.
I will conclude with a little rhyme that I found about Newton and light. It contains a bit of conceited praise, probably exaggerated, for Newton from Alexander Pope:

Intended for Sir Isaac Newton  
In Westminster Abbey

Nature and Nature's laws lay hid in Night:  
God said, "Let NEWTON be!" and all was Light.

∞
Appendix

Table of Abbreviations and Conversions

\begin{align*}
m & = \text{meter(s)} & 1 \, m & = 1000 \, mm \\
mm & = \text{millimeter(s)} & = 10^9 \, nm \\
nm & = \text{nanometer(s)} \\
s & = \text{second(s)} \\
sin & = \text{sine} \\
\text{scientific notation: } & 1 \, m = 1 \times 10^9 \, nm
\end{align*}

exponent "2" indicates # of zeros following 1, i.e. \( 4 \times 10^2 = 4 \times 100 = 400 \)

Pythagorean Theorem: \( a^2 + b^2 = c^2 \)

Trigonometry:

\[
\sin \alpha = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{a}{c} \quad \tan \alpha = \frac{\text{opposite}}{\text{adjacent}} = \frac{a}{b}
\]

Cosecant \( \alpha \) = \( \frac{1}{\sin \alpha} = \frac{\text{hypotenuse}}{\text{opposite}} \)

Light is an electromagnetic wave. The wave is formed by oscillations of electric and magnetic fields which are perpendicular to each other. As a wave, light has a wavelength that determines what type of light it is; it has an amplitude; and a phase. Depending upon their phases, the amplitudes of two or more light waves can add or subtract. They then interfere either constructively (add) or destructively (subtract):

In Phase \( \Rightarrow \) Constructive

Out of Phase \( \Rightarrow \) Destructive
Bibliography


