2016

A Low-Cost Apparatus for Laboratory Exercises and Classroom Demonstrations of Geometric Optics

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A Low-Cost Apparatus for Laboratory Exercises and Classroom Demonstrations of Geometric Optics

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An undergraduate honors thesis submitted in partial fulfillment of the

requirements for the degree of

Bachelor of Science

in

University Honors

and

Biomedical Physics

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Acknowledgements

I would like to thank my mother for the support she gave me through my undergraduate degree. My thesis advisor Ralf Widenhorn for the project idea and the resources to complete it. Alex Chally for his assistance in developing and fabricating all the various components. Finally, the entire Physics Department at Portland State University for the instruction and the opportunity to explore projects, experiment and teach.

Executive Summary

A Low-Cost Apparatus for Laboratory Exercises

And Classroom Demonstrations of Geometric Optics

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Current trends in research towards the teaching of geometric suggest a constructivist approach. Student experimentation dealing directly with student misconceptions through repetition of examples in many contexts to confront conflicting reasoning allow students to construct definitions with their experiences and observations. Developing the scientific method of observation, prediction/experimental design, conducting experiments and repeating is reinforced with these techniques. Cataloguing misconceptions, designing course material and laboratory experiments is called for throughout the literature. Furthermore, application of the constructivist theories towards teaching and laboratory experiments has only begun to be developed.

Use of technology is also shown to increase student interest in course material. 3D printers have become common tools in schools; by designing a set of 3D printable components, experimental design is disseminated more easily, improved upon more easily and the overall cost of the system is decreased. Constructing the apparatus allows students to design simple circuits and mechanical components and apply general physics concepts to real world systems. Experiments that lend themselves towards computer modeling are sought after as an interface to reconcile conflicting reasoning in student misconceptions.

The questions I intend to answer are:

1. What is the evolution of constructivist theories to teaching physics?
2. Are student misconceptions towards geometric optics universal or unique to a particular group?
3. Is it possible to design a set of laboratory experiments that deal directly with these possible universal misconceptions, guided by constructivist theory and using an apparatus with 3D printed components to decrease the cost?

To answer these questions, I will review the relevant scientific literature and detail how thought has developed towards constructivist theory in physics education. Additionally, I will research student misconceptions in geometric optics and catalogue common naïve ideas. I will review commercially available laboratory apparatus and experiment to design a contemporary set of experiments, guided by constructivist theory, and constructed using 3D printed components. I will test and optimize the apparatus and refine the experiments to be used in future general physics optics curriculum at Portland State University. Finally, I will review the successes and limitations of the system and document the development process to serve as a template towards developing future constructivist course material.

Table of Contents

List of Figures:

Abstract

Current trends in research towards the teaching of geometric suggest a constructivist approach. Student experimentation dealing directly with student misconceptions through repetition of examples in many contexts to confront conflicting reasoning allow students to construct definitions with their experiences and observations. Developing the scientific method of observation, prediction/experimental design, conducting experiments and repeating is reinforced with these techniques. Cataloguing student misconceptions and redesigning course material and laboratory experiments in their context has only recently begun. Use of technology has also been shown to increase student interest in course material and 3D printers have recently become common tools in schools. Additionally, experiments that lend themselves towards computer modeling are sought after as an interface to reconcile conflicting reasoning in student misconceptions.

An apparatus and set of experiments is described that deal with student misconceptions in iterative experiments. Overall cost of the system is decreased by 3D printing expensive optical components. The system highlights complex interactions of propagating light waves and seeks to explain the effects of media on image formation.

I. Introduction

1. Overview

The history of optics itself is full of poor theories, false explanations, misconceptions of its basic properties and conflicting theories.[16] Development of these theories took a long time and were met by opposition from learned scientists; for example, Descartes and Kepler did not believe the proposed speed of light; Newton rejected the wave-like nature of light; Plack and Einstein only recently proposed the discrete nature of light (1905), something never conceived of in Aristotle's time (2300 years earlier). The complexity of the subject of light is related to its interdisciplinary character. Understanding of light is deeply connected to the vision process, which is interpreted as biology, chemistry, physiology and psychology, not physics. Many of the optical phenomena widely observed in everyday reality cannot be treated without taking into account the media through which it travels. Teachers often fail in attempts to reduce the complexity of the optical phenomena in a way that remains accurate in all contexts, but plausible to the novice learner. The result is students' constructing their own definitions, reasoning, understanding and belief of natural phenomena. Terms such as misconceptions, preconceptions, alternative frameworks, children's science, naïve concepts and so on, are used to describe such beliefs.[1]

Student misconceptions develop with their experiences and are not limited to information given to them in the classroom. As such, many develop hybrid relationships and explanations from their experiences and what they have been taught. Common student misconceptions are as follows:

1. Students do not recognize light as an electromagnetic wave propagating through space or the wave-particle duality of photons. [1,2,13,14,15,17,22,23,34,35,40]

2. A holistic view of images and light as consisting of constituent "light rays" that travel parallel to one another through space, from one point of the source to one point of observable interaction. [1,2,14,15,17,18,22,34]

3. Misuse and misinterpreting the language of scientists; students construct their own definitions, leading to a separation of words' 'meaning province' between novices and experts, and may misuse language to "prove" their false claims.[22,34]

4. Vision; students believe the eye is "active" in "seeing" things, using "vision rays" to see, and fail to recognize the image formation process in vision. [1,2,14,18,22,23,35,38,40]

5. Color is a property of objects, not light, light is usually absent from students' explanation; "brightness" is a property of the "color" itself, again no relation with light or photonic flux is expressed. [2,17,22,23,38,42]

6. "Illuminated" is a passive environmental state; light constantly fluxing through the system is not seen as the cause.[14,22,23]

7. Mirrors are special objects; images form on a mirrors' surface and this property of the material is not due to their high reflectance of visible light, it is attributed with the object itself. [1,2,13,14,15,22,23,38,40]

Constructivist understanding of the teaching-learning processes makes this knowledge relevant and valuable to science educators. Misconceptions are consistent and transnationally held by students in regard to light and optics principles.[23] Misconceptions are described as part of students' initial learning and they should be given as much emphasis as the final examination.[2] In fact, history is filled with an assortment of false theories on the structure and properties of light; misconceptions therefore have historical relevance and should be regarded as part of a process of scientific inquiry. Modifications to course curriculum suggests encouraging students to make their schemes explicit, in order to recognize the eventual conflicts with their observed experiences.[23] Devising simple laboratory experiments to demonstrate these conflicts explicitly to students then follows. Finally, appreciation of the abstraction from the wave-like nature of light with respect to everyday and laboratory experiences cannot be underrated; it is present in the students' language, mental constructions and anthropocentric schemes like "vision rays."

The nature of reality is complex, therefore experiments and lectures should be structured around non-trivial examples.[2] Simplified instruction is to be avoided; for example 'light propagates in a straight line and is not able to overcome obstacles,' is not incorrect but neglects the dynamic propagation of light and the effects of mirages (light is bent and images appear distorted).

Stephan[32] recommends these six considerations for teaching-experiment design:

1. Students become aware of their own preconceptions about a concept by thinking about it and making predictions before any activity begins.

2. Students expose their beliefs by sharing them, initially in small groups and then with the entire class.

3. Students confront their beliefs by testing and discussing them, initially in small groups and then with the entire class.

4. Students work toward resolving conflicts (if any) between their ideas and their observations, thereby accommodating the new concept.

5. Students extend the concept by trying to make connections between the concept learned in the classroom and other situations, including their daily lives.

6. Students are encouraged to go beyond, pursuing additional questions and problems of their choice related to the concept.

A summary of these findings is followed by a review of the advantages of 3D printing in prototyping and production of apparatus.

2. Pre-University Students' Misconceptions

To begin to understand common student misconceptions about geometric optics, previous literature was reviewed seeking differences between age groups and locations throughout the world. Pre-university student understandings are considered first. The perspectives and conclusions that form the logical framework of pre-university students' are what they composite new information with as university students.

Tan[37] conducted a series of interviews in order to survey qualitative experiences of fifty high school students' conceptions of physics throughout a year of instruction at two schools in Ithaca, NY. The study acknowledges the work of Ausbel (1968), Novack (1977) and Gowin (1981) in describing "meaningful learning" as a process in which new information is linked to old information in a *meaningful way* by the student. The students' autonomous role is emphasized; it is the instructor's role to introduce progressively more abstract concepts beyond mere constructions of old information. Students' active constructive role is derivative of their experiences that support the multiplicity of students' conceptions of the subject matter and the fact that learners have their own techniques for learning based on their context. Based on these three theories and studies on misconceptions, a questionnaire interview with expounding to allow students to describe their experience was designed. Students' responses to four prescribed questions sought to answer three questions:

1. What is happening when students try to understand physics in the high school classroom?

2. What do they mean by 'understanding'?

3. How are they trying to understand the lesson?

Four non-exclusive domains of students' understandings are then described deriving from the results of these interviews:

a. Of relating physics knowledge to prior knowledge and experiences in reality.

b. Of being able to "work" inside the classroom, i.e. carry out experiments and solve problems.

c. Of interrelating new physics knowledge with knowledge and experiences in the classroom.

d. Of being able to use physics concepts to correctly explain a broad range of everyday experiences outside the physics class.

This study raises the question of how to include "everyday experiences" into the physics course and transcend the barriers to students understanding of concepts and theories. Furthermore, it asks the following questions of teachers: What kinds of knowledge and experiences are we using to help students build the concepts and understandings of physics? How are students constructing their meaning? What kinds of understandings are they achieving (based on the four domains of student understanding presumably)? What kind of concepts are we building for our students? Should understanding physics mean achieving all four domains of understanding?

Rice and Feher[34] used individual interviews of 110 children ages 9-13 at a local science center in San Diego to deduce common misconceptions about the nature of light, its propagation through space and the formation of an image. Students were asked to graphically represent their results as a diagram, common errors included:

a. Parallel lines spanning the size of the hole in question, going from the source through the hole and on to the screen, forming an image the same size as the whole.

b. Parallel lines from the source to the hole and diagonal lines after the hole to the screen.

c. Diagonal lines from the source to the hole and then again from the hole to the screen, 2/3 were divergent rays, 1/3 were crossed over beams.
d. Single line diagrams that only indicate directionality.
e. Shadows are "reflections" as are images.

It can be seen from the errors in the diagrams that children hold a holistic model of light that explains that light from the source travels as a whole and preferentially in the direction that matters. Furthermore, it was noted the misuse of language in constructing a false reality was common.

Jung[22] performed concentric studies on students, 10-14 years old, in Frankfurt, Germany on their conceptions of light properties and general optics in order to catalogue student understandings and descriptions. They were asked to perform written tests, draw pictures, use real optical setups, and describe their reasoning. The results of interviews are discussed and it's noted that it isn't easy for a physicist to understand a students' descriptions due to the disjunction between the "meaning province" of optical language for a novice and expert (scientist). A novice lacks the conceptual framework to understand terms like "light ray" used in a scientific as opposed to colloquial setting. The students' basic phenomenological perspective is summarized as follows:

a. A luminous body ("source") shines light on an object which gets brighter, the "source" illumination is the cause and the "brightness" is the effect, however "shining-on" is a direct uninterruptable action with no intermediate step where the light is travelling.

b. The object is a passive receiver of illumination, to be illuminated is a state of the object.

c. The observer directs their attention and observes the object with their eyes open.

d. The observer "sees" the object "there", indicating the observer is actively involved in the process of seeing rather than passively taking in information similar to the object being passively illuminated.

Students' misconceptions are summarized as follows:

a. White objects, or "bright colored" objects, can be seen without a source of illumination. To be "bright," is synonymous with being visible. Objects undergo illumination, but their "brightness" is a property of the object, therefore they can be observed without a source.

b. A "source" can be seen at any distance without the light travelling between the source and observer. The effect is instantaneous and "illuminated" is an instantaneous state of a system or environment. The source is observed to be "light" misidentified with the property of being "bright"; propagating electromagnetic waves are disassociated with light, an observer hence does not "see" incoming light the object is "seen" an active enterprise.

c. "Illuminated" objects cannot "illuminate" other objects. The illuminated object is understood as a passive receptor, "mirrors" or objects that reflect light are a special kind of object. Most teachers were shown to hold similar misconceptions.

d. Students shown conflicting experimental results from their preconceived notions initially integrate this new information into their old logic framework, a common compromise for students admitting an object reflects light is because, "light reflects light." Thus the conception that the object itself is "bright" is preserved.

e. Light stays on the surface of objects, "illumination" is a state of the environment and inevitably the "brightness" of the surface of an object makes the object "visible."

f. "Light" is not continuously emitted from a source to "illuminate" the environment, illuminated is a state of the environment. An object painted red with paint does not need to have paint continuously added to it to remain red, similarly a source need not continuously "illuminate" an object.

It can be seen from Jung's analysis that students' phenomenological perspective lacks a comprehensive understanding of light as a traveling electromagnetic wave produced by a source, or that the interaction of the wave with matter and self-interference is never even considered. Similarly, the observer is disconnected with passively observing this wave, an observer actively "sees" the "brightness" of objects.

Watts[40] conducted a series of informal interviews with Collin, a student in his fourth year of secondary school, informal discussions developing from a series of sketches representative of situations or concepts. Collin held two views of light, that it could be a single composite entity or a noun for a variety of forms. Uncertain of what composes light, he describes, "…light from an electric light is virtually pure. But light from the sun is mixed up with all other lights, you know, ultraviolet light and radioactive light…" He describes images as forming on the mirrors surface, without any reference to the light that reaches the eye. He further suggests that you can see your reflection even in a dark room, it's a "product of the quality of a person's eyesight."

Collin perceives that light from a source is ejected at the speed of light but then becomes trapped by the screen, this frozen image can be seen by anyone in the room. The argument he posits is that the light must stop at the screen otherwise you would see the image move. Watts concludes by suggesting that the issues should be approached through actual experiences, students' need to encounter and confront their logical contradictions, not merely dismiss the phenomena as an "anomaly." It is not enough for students to merely become dissatisfied with their current view, fruitful discussion from intelligible and plausible arguments presented in a compatible language are necessary to comprehensive change of firmly held misconceptions. Principles like superposition and electromagnetic waves must be introduced in such a way to seem like a reasonable trade for their own theories of how light works.

Saxena, et. all,[35] even suggest that student misconception can form the basis of general physics course curriculum in secondary schools. Their study was designed to assess secondary school students' misconceptions in geometric optics prior to course design. The multitier questions were designed around subjects common to optics courses in India (also common to course material across the world), like reflectance, shadow formation, refraction and the color of light. The study found that in general, students understood the rectilinear propagation of light, the constituent colors of white light and the action of a lens in image formation. However, misconceptions were held on how filters effect white light and the formation of shadows by opaque objects. Students were uncertain about the process of image formation and less than a third could describe the effect of covering half a lens on the formation of an image. Observation of these effects was also poorly understood, students believed it wasn't necessary for light to enter the eye, it was an active process of the eye to "see" objects. The study suggests that students lack opportunities to apply the concepts of physics to real life situations where they must describe and defend their reasoning.

La Rosa, et. all,[23] studied the conception of light for non-science teachers, non-physics science teachers and students without a prior course in physics, at a secondary school in Italy. It was noted that the importance of optical phenomena as they appear in nature is important to common sense schemes of interpretation and the interference with scholastic-scientific themes of course material. Concerning "personal construct theory" the organization of concepts in students "common sense knowledge" is 'scientific' in their coherence of relations among facts and explanations. This knowledge differs from the acknowledged scientific theories only in the nature of relationships established among facts, observations and concepts. The study found common misconceptions included an understanding that "light" is a static property of space, if a source is present, the environment is "illuminated," light does not need to propagate through space and reflect off objects.

Students also claim eyes are active in the in the process of "seeing" which is attributed to "vision rays." Color is a property of the object and may be effected by low light levels. Reflectance is a property of mirrors, or special objects, light is absent from the model except in the static condition that is "illuminated." Light intensity from dim to bright is correlated with "light colors," like azure, and "dark colors" like navy blue, for example. These results are consistent with transnational misconceptions held by students in regard to light and optics principles. Suggested modifications to course curriculum include encouraging students to make their interpretive schemes explicit, in order to recognize eventual conflicts with their observed experiences; devising simple laboratory experiments to demonstrate these conflicts explicitly to students; finally, appreciation of the abstraction from the wave-like nature of light with respect to everyday and laboratory experiences cannot be underrated, it is present in the language, mental constructions and anthropocentric schemes like "vision rays."

Favale and Bondani[13] relate their study of misconceptions of light and geometric optics in high school students (sample size 200) in Italy. A questionnaire and set of experiments was presented to students before and after their study of geometric optics to determine common misconceptions and beliefs held by students about light. Only 17% of students could successfully predict the effect of covering half the lens used to form an image. 16% of students were able to correctly describe where the image of an object forms for 3 separate observers (the same location) due to a mirror; most described the image as being contained on the mirrors surface and none could successfully reproduce a technically correct ray diagram. This result is reinforced when students were asked to predict the image location if the single light source, held in front of the mirror and behind the object, is moved vertically up; less than 60% were able to answer correctly, most believing the image shifts up or down. Students held the common beliefs that light does not propagate and the eye actively "sees" objects. More than half of students did not believe the speed light travelled varied or that it always took the shortest path available from source to observation or that air was not necessary for light to propagate.

Some answers students gave were in direct contradiction with their other predictions. Moreover, students could not relate their life experience to predict results; for example, it would be easy to remember light does not need air as a medium to travel if one recalls observing the stars from the vacuum of space. Students were unable to predict color as the result of subtraction from white light by absorption, color due to illumination with colored light and the meaning of appearing "black" colored. The authors propose that by identifying student misconceptions, instructors can create a dialogue to raise awareness and prepare students for the difficulties arising from firmly held naïve beliefs. The nature of reality is complex, not necessarily complicated, therefore experiments and lectures should be structured around non-trivial examples. Simplified instruction, for example the statement that light propagates in a straight line and is not able to overcome obstacles, is not incorrect but neglects the dynamic propagation of light and the effects of mirages (light is bent and images appear distorted) and should therefore be avoided.

Bouwens[2] studied Dutch high school students with a written questionnaire designed to elicit the students reasoning to geometric optics and their misconceptions. Recently Dutch schools have recommended less time be spent teaching optics, specifically excluding two lens systems, which neglects traditional aspects like microscopy or telescopes. The author believes ray diagrams, Snell's Law and other mathematical abstractions remove students from the practical applications like lasers or cd players. Misconceptions are described as part of students' initial learning, approaching them should be given as much emphasis as the final examination. History is filled with an assortment of false theories on the structure and properties of light; misconceptions therefore have historical relevance and should be regarded as part of a process of scientific inquiry. Common misconceptions included:

a. Notions about the nature of light, for example, light is purely static phenomena, a condition of the environment. Like air, light fills up space; if there is much of it, it is "bright" and otherwise it is "dark". Light is identified with its source (lamp or sun) or with its effect (a spot of light on a wall), propagating waves is not a feature of their descriptions. The author was surprised that students are confused about the nature of light, because history contains an infinite range of hypotheses, falsifications and theories about this subject, starting with Aristoteles' ideas and continuing up to the wave-particle-duality of this century.

b. Rectilinear and dynamic properties of light, for example, the distance light can travel is limited by the extent of its visible effect (only a few meters unless it is a very bright light source like the sun). Or that light travels at an infinite speed (a result of the misconception of light as a static phenomenon), or has no speed at all. Light can bend round a corner, hence a room with only a small window is illuminated entirely and not just the narrow strip in front of the window itself. Historically, it was Newton who became first aware of the finite speed of light and it was not until 1854 that Foucault was able to measure its velocity accurately.

c. Interactions of Light with matter or objects, for example, light rays can be seen from any distance if they are strong enough. Confusion about the difference between specular and diffuse reflections. Light was conceived to 'contain' warmth and transfers it to any object that it hits.

d. The concept of vision. The dominating misconception in students' minds is the decoupling between light and vision: although they know that light near an object is the minimum condition for seeing it, they do not think it necessary for light rays coming from the object to enter the eye. Most of the investigators previously mentioned inquired into the concept of vision, often reporting things similar to this decoupling concept.

e. Color, for example objects can be seen only when they have a color different from the background. All colors together form a range of light intensities from black to white or that color is purely a property of an object, not of the light itself. Light passing through colored glass, is 'painted' by that glass; therefore, it must be effected by some sort of pigment. Most of the students' misconceptions about colors relate to their inability to distinguish physical color properties in the environment from physiological properties of the color perception by the brain.

f. Formation of an image, for example the location of an image behind a plane mirror or the understanding of a virtual image. Most students think of images in terms of a 'one-to-one journey' from light point to image point by only one ray, a holistic view that negates the propagation of light as waves. This idea of the 'travelling' image without light propagating as a wave from every point and then recollected to form an image seems to be a rather persistent one and it appears in many different situations. students having this idea will answer incorrectly to the traditional question: what happens to an image if half of the lens is covered by an opaque material?' A quite extreme appearance of this misconception is the idea that in the middle between an observer and an object there has to exist an image half the object size according to the laws of perspective.

Fetherstonhaugh, et. all,[14] summarizes common student misconceptions concerning light in a comparative literature review of views held by students in France, New Zealand, Sweden and the United States. Using results from these studies, a questionnaire of multiple choice as well as open ended questions was designed to probe high school students in Perth in Western Australia conceptions about the nature of light. The results of this study report similar misconceptions to other studies performed in the world. Misconceptions include believing light does not travel, the well represented belief "illuminated" is a passive environmental state. Other students believe light travels variable distances. Most 11th year students believe light travels until it strikes an opaque object, whereas 8-10th year students believe that only if the room is dark will the light continue to travel; reasoning linked "brighter" light to "stronger" light and therefore able to travel greater distances. Students also held the common belief that the image existed on the mirrors surface; this misconception produces large numbers of students unable to correctly locate the image or explain the image formation process.

Students held many misconceptions similar to those shared by students throughout the world of the image formation process. Half of Australian students believed the lens to be unnecessary to image formation. This misconception is tied to students not recognizing the wave-like nature of light, constructive interference and the effects of light passing through media. It was shown that this misconception of a complex set of phenomena was pervasive even in students who had recently studied light. Many students understood light was necessary for humans to see, but firmly held the belief that cats could see in absolute darkness. The implications of students' conceptions of a given property of light is that reasoning is multi-tiered and tied to the context of the phenomena. The affect of colloquial language on students' reasoning of scientific situations lends itself towards misunderstanding basic properties of light and moreover a multitude of meanings attached to scientifically strict terms. It is proposed that teachers design student-student interactions to bring about dissatisfaction with students' experientially derived misconceptions.

3. University Students' Misconceptions

Many common misconceptions of the properties of light have been shown in pre-university students throughout the world and that these misconceptions remain after students have taken courses in physics. To assess if these misconceptions remain imbedded in students during their studies at university and the implications to potential future teachers, the literature was again reviewed for relevant studies.

Blizak, et. all,[1] conducted a study of 246 first year university students in Algeria, all of whom had previously studied optics. A questionnaire consisting of 12 items was taken by students in a regular class environment, prior to optics instruction without a time limit. It was found that less than half of the students could properly describe the process of vision, one quarter of them described the eyes as "active" in the process. Nearly half of students believed light will not propagate in a vacuum and 21% believed the vacuum had a fundamental affect on a camera obscura. Students commonly misunderstood the formation of a shadow and lacked the concept of a penumbra. Students had the misconception that the image forms on the surface of a mirror. One third of students also misunderstood the formation of an image by a lens and nearly half believed half the image would disappear if half the lens was covered, nearly a third believed the image would be half as large. 22% believed covering the center of a lens will produce a half image, 43% however believed the entire image would disappear.

Yalcin, et. all,[42] studied misconceptions held on light by 100 first year undergraduates enrolled in general physics in the science teacher training department in Ataturk University in Turkey. Four questions were developed from previously tested student misconceptions of university physics students elsewhere in Turkey and prior literature to test students' beliefs on the properties of light. Students believed that all objects emit light and related color to "brightness." Half of students reasoned that the speeds at which light from different sources travels is different depending on various factors like the nature of its source, its power, its frequency or the number of photons. Students held misconceptions about light travelling in day as compared to night, objects are night were conceived to reflect less, night was presumed to "use up" light, or that light is difficult to "perceive" at night. When asked about a bulb in daylight, some students reasoned that destructive interference from the suns light nullifies the bulbs light, misapplying the wave-like nature of light. Finally, a third of students held the misconception that different sources of light cannot emit the same kinds of light, suggesting that the type of light is completely dependent upon the source. The study concludes by recommending that teachers prepare course material that deals directly with student misconceptions and relates everyday experiences to the phenomena being described.

Galili[15] studied pre-elementary school teachers in Israel who previously had optics instruction conceptions of the properties of light. Interviews with 27 students were conducted with a real optical system consisting of converging lenses and mirrors, observations of phenomena, ray diagrams and verbal reasoning was used to assess students' conceptions. Two thirds of students were unable to represent the image formation process with ray diagrams or accurately describe it. The students carried a holistic view of the image travelling through space, flipping over at some point between the lens and the focal point and able to form wherever the screen is placed. Each unique point in the object is then mapped by a single unique ray to an equally unique single point in the image, students who drew diverging and converging rays often failed to recognize the importance of this feature in a lens. Students also failed to understand how the image formation process plays a role in vision and none successfully represented the image formation due to observing an objects reflection in a mirror. Misconceptions were summarized as being an intermediate step between naïve concepts and formal scientific understandings. He concludes by stating strong concept restructuring is necessary to progress between each of these "well defined" states of understanding. This implies that alternative instructional strategies built on students' misconceptions and addressing the aforementioned intermediate state of understanding.

Goldberg and McDermott[18] conducted an investigation of university students at University of Washington that sought to identify and address conceptual difficulties with optics encountered by students taking introductory college physics. Students tested with real optical set ups after the instruction of image formation in geometric optics were found to be not consciously aware that given an object distance from a lens or mirror the position of the image is fixed. Students misunderstood the focal point to be the point of inflection in the image or where the image converges. Many students failed to use the concepts, principles, or techniques that they had recently studied. Students perceived the role of the lens as inverting and maybe magnifying the image; if the lens were removed it was believed the image would still exist, right side up on the screen, although maybe 'fuzzy.' This is because the light rays would extend outward nearly parallel from the bulb. If half the lens were to be covered, half the image would disappear corresponding to how the image inverted in the lens. The ray diagrams students drew further obfuscated the problem by reinforcing their ideas when they inaccurately applied the technique. Students commonly misunderstood the difference between a real narrow beam of light and the concept of a 'light ray.'

It was clear from the interviews that it was probable that students emerge from their physics course without understanding the essential role of the converging lens or concave mirror in image formation. Students could recite answers but were in general unable to apply the information to a simple and real optical system. The author's call for a greater emphasis on developing the qualitative understanding of the basic ideas of geometric optics which on the surface appear to be trivial.

Galili and Hazan[17] studied college students' in teacher-training knowledge of light, vision and related topics before and after instruction. The study was carried out with a written questionnaire consisting of thirteen items addressing conceptual understanding of the act of vision, general properties of light, shadow formation, imagery in reflection and refraction, color resulting from radiation and reflection. The study noted that students find the subject of optics to be obscure and difficult and teachers' help often insufficient. Similarly, scientists have also considered light and vision to be troublesome subjects through a 2500-year long history. Peculiarities of light are summarized as follows:

a. The physical parameters associated with light, e.g. its speed, wavelength, pressure and discrete nature, are all far removed from the range of perception of the human senses, the range of an individual' s experience.

b. Optical phenomena are commonly observed in media (air, water) which often greatly modify the behavior of light from that in vacuum.

c. The observer in optics is an inherent part of the optical system.

d. Language brings problems of a psychological nature.

e. Optics instruction is heavily based on graphical symbolism, whose definition is subject to the novice's interpretation.

Students' responses often poorly reproduced memorized ray diagrams, reinterpreted and modified in keeping with their misconceptions regarding the nature of their constituents. Indeed, the 'Image Projection Scheme' is based on an erroneous ontology of the light ray, which maps the object into its image, whereas the scientific model of image formation operates with object-image mapping by means of light flux, instead of single rays. This alternative understanding of image formation has historical context in the development of the scientific definition of light and reflects the Alhazanian view of the tenth century. Other implications of the deficiency of instruction were noted in connection with understanding seasons and illumination. The assertion that a color corresponds to a unique frequency in the electromagnetic spectrum to students seems a hollow account for a variety of observed phenomena. Full elaboration of color perception, at least a simplified qualitative model, must be introduced to explain the trichromatic model of primary colors and the simple rules of colors addition and subtraction based on it, to account for many everyday experiences.

Taslidere and Eryilmaz[38] conducted a survey of 317 junior and sophomore level science and computer science pre-service teachers in Turkey conceptions of light, shadow and mirror images before they learn geometrical optics. A three-tier (correct answer, reasoning and confidence in answer) questionnaire consisting of 16 items designed to identify student misconceptions. They found many errors in students' ideas and reasoning pertaining to plane mirrors; many students believed that the image would move if the observer was to move; only 8% affirmed their correct conceptions at the third tier. When presented with a single source of illumination, a plane mirror and an object, 61% of students believed the image moves when the source changes location. Many students believed the system to be optimized when the source is oriented toward the mirror first, rather than the object, showing a strong misconception about the propagation of light and the image formation process. Students were sometimes similarly confused between properties of shadows and lenses; 20% predicted the image would change location if the source of illumination moved. One third of students were unable to predict penumbra, 17% of them approved their misconceptions at the third tier. Many students believed vision to be an "active" process of the eye. Some students held the common misconception that color is related to "brightness." These findings were intended to be used in designing course material for the general physics course.

Foucher[12] sought to define a new class of students' understandings observed in advanced physics students, 'pragmatic conceptions,' which is essentially non-constructivist. Pragmatic conceptions differ from misconceptions in that beliefs are adopted after a short incubation period since theories are often considered "fact." Theories concerned with an assumption based model, like Rutherford's Atomic Model, are reduced to their postulated mathematical relations, like Rutherford's Scattering Formula, and their assumptions ignored. Accepted theory is successful theory, it has been peer reviewed and its conclusions verified; whatever it says must be true.

The difficulty encountered in conceptualizing wave-corpuscle duality is common: In the macroscopic world we deal with visible effects with waves which extend in space. When the electron is introduced, it is classified as a particle or point-particle, neglecting that it might also be a wave, which seems absurd from the macroscopic point of view. The dilemma will be solved when we accept that the macroscopic entities, wave and corpuscle, cannot be transposed to the microscopic domain. When asked if nuclei are solids, liquids or gases, some students believed that they are solid, since they are compact or liquid, because of the liquid-drop model. They could not see that nuclei and electrons are constituents; being a solid or a liquid involves a relation between the constituents, like the individuals which are united in a family. Concepts and definitions are involved frequently by students with pragmatic conceptions without apparent understanding, in a kind of jargon.

By attaching less importance to the assumptions, concepts and models in theory, one is more likely to believe that discoveries are made only experimentally. The important things will be the facts and the verifiable conclusions, which are considered more or less equivalent. This is a mistaken opinion however, because when we make an observation, we must have at least some a priori idea of what to observe. Experiment does not tell us which concepts must be used to explain a phenomenon; experiment may indicate which one of two or more concepts is more descriptive, but we must create them ourselves. The whole area of conceptualization is reduced to a minimum in a quite restricted view of science. The role of logic and problem solving in science is reduced to a minimum by the student with pragmatic conceptions. That is why they frequently show incorrect logic, like contradictory explanations.

4. Constructivism & The Multiple Experiment Approach

Druit and Treagust[7] reviewed how the notion of conceptual change has developed over the past three decades. This has led to alternative analytical techniques for conceptual change and a multi-perspective view of science learning creating a powerful framework for improving science teaching. Beginning in the 1970's, with the investigation of students' pre-instructional conceptions on various science content domains such as the electric circuit, force, energy, combustion, and evolution, the analysis of students' understanding across most science domains has been comprehensively documented. Continuing in the 1980's, research showed that children are not passive learners and the way they make sense of their experiences led to 'children's science' based on intuitive knowledge. Findings from many studies from 1970-2000 show that students are not 'blank slates' without any pre-instructional knowledge or beliefs about the phenomena and concepts to be taught. Rather, students already hold deeply rooted misconceptions and false ideas of science definitions and are even in stark contrast to them. It is remarkable the number of studies on students' learning in science that primarily investigate such students' conceptions at the content level. Since the middle of the 1980s investigations of students' conceptions at meta-levels, namely conceptions of the nature of science and views of learning also have been given considerable attention. Research shows that students' conceptions here are also rather limited and naive.

Since the 1980s research on students' conceptions and conceptual change has been embedded in various theoretical frames over the past decades. Initially, Piagetian ideas were applied that drew primarily on stage theory and on the clinical interview. Also, basic frameworks of the emerging theories of cognitive psychology were quickly adopted. Later, constructivist ideas developed by merging various cognitive approaches with a focus on viewing knowledge as being constructed, such as with the Piagetian interplay of assimilation and accommodation. Kuhnian ideas of theory change in the history of science and the radical constructivist ideas of people like von Glasersfeld.

However, what becomes increasingly evident in reviewing the literature on conceptual change is the general polarization of the dichotomy of researchers in science education and cognitive psychology. Certain limitations of the constructivist ideas of the 1980s and early 1990s led to their eventual merger with social constructivist and social cultural orientations. More recently this resulted in the author's recommendations to employ multi-perspective epistemological frameworks in order to adequately address the complex process of learning. Studies by Sinatra and Pintrich also emphasize the role of the learner's intentions in conceptual change. This unifies the ideas of the intentional learner and those emphasizing that conceptual change is more than conceptual. The notion of intentional conceptual change is similar to a "construct which reflects a voluntary state of mind, and connects among motivation, cognition and learning."

The most common analysis is that there are two types of conceptual change, variously called weak knowledge restructuring, assimilation or conceptual capture and strong/radical knowledge restructuring, accommodation or conceptual exchange.

Models of every kind are used to communicate scientific outcomes, plan and implement its methods, and models are science's major learning and teaching tools. However, many students find the diverse models that are used to explain science challenging and confusing; researchers argue that learning with diverse models prevents students developing imbedded misconceptions that are hard to change. This problem led to a classification of students' ability to model:

Level 1 modelers are students that believe that there is a 1:1 correspondence between models and reality (models are small incomplete copies of actual objects).

Level 2 models remain real world entities rather than representations of ideas, and a model's main purpose is communication rather than idea exploration.

Level 3 is achieved only by experts, models have multiple meanings and contexts, are thinking tools and can be manipulated by the modeler to suit his/her epistemological needs.

Some students fell into mixed level 1/2 and 2/3 classifications. Because the levels are derived from the way students describe, explain and use models, the levels provide information about the status of students' conceptions and modelling level changes that may provide useful evidence for conceptual changes.

There is ample of evidence in research on learning and instruction to important an aim of science instruction to develop interest and students' awareness of pre-instructional conceptions towards the intended science concepts. Briefly summarized, multi-perspective frameworks have to be employed in order to adequately address the complexity of the teaching and learning processes. Only such frameworks allow researchers to model teaching and learning processes sufficiently and to address the ambitious levels of scientific literacy briefly presented in the preceding review.

Parker[30] sought to analyze conceptual change and effective learning and teaching in primary science education. Drawing on Piaget's ideas, initiated in the early 1980s and later refined, conceptual change identifies two patterns in students: assimilation and accommodation. The former concerns the use of existing concepts to deal with new phenomena, whereas accommodation requires their radical reorganization or replacement. Such research tends to concentrate on conceptual change within particular domains of subject knowledge. Conceptual change is a process of cognitive repair of misconceptions. Addressing misconceptions becomes concerned with the recategorization of concepts and the cognitive repair taking place within learners' minds. Learners as organizing from fragmented to structured complex knowledge systems is not a simple process of deletion or replacement but rather a complex cognitive process of integration and reorganization. Vosnaidou depicts conceptual change as a process of synthesis. As such, learners seek to build a coherent explanatory framework through attempting to reconcile inconsistent explanations and models by integrating new information from experiences with existing frameworks. This is a gradual process resulting from a progression of mental models rather than involving a sudden replacement of misconceptions. A central tenet of conceptual change is predicated on learners becoming dissatisfied with their existing conceptions. An instructional strategy for promoting such disaffection is that of introducing cognitive conflict. Cognitive conflict delineates the usefulness of the learners' understanding and allows students to reconstruct conceptions and models to better reflect these new experiences.

Additionally competing concepts proved to be highly effective in generating discussion and fueled the need to resolve uncertainties. It enables students to frame questions that could be explored to further modify their understandings. The value of being able to formulate predictions and test their ideas through practical investigations engendered a more sophisticated perception of investigation as an integral part of inquiry and provided the opportunity to review and reformulate thinking: "The investigation let us test to see which of our ideas worked, I could see why mine didn't."

Next Generation Science Standards: For States, By States[29] is a cumulative document presented as the national stance on science standards from many disciplines. Physics falls under the title "Physical Sciences" along with chemistry. Historically the college board emphasized content; this calls for a goal of establishing lines of evidence and using that evidence to develop and refine testable explanations and make predictions about natural phenomena. Lack of current content on the wave-particle duality, electricity and simple circuits, the fundamental forces and in general content on the atomic scale. They list several "performance expectations," only some of which apply to the subject matter presented:

> 1: Explain the structure, properties and interactions of matter "plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current." (High School, Physical Science, concept 2, standard 5.) In other words students need to know how to design an experiment to produce desired evidence. This is not a traditionally assessed aspect of learning physics.

Furthermore, the following eight directives should guide science teaching content:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence

8. Obtaining, evaluating, and communicating information

Etkina and Planinšič[11] further expounded on the science practices goals or "requirements" of the NGSS to refine the "fuzzy" language presented from a perhaps novice perspective. Developing sound conceptions and logic based understanding are best developed in the devising and testing of multiple predictions. These predictions come in the form of proposed explanations to observed phenomena and are cultivated in an open forum where all perspectives are considered equally. Experiments are then devised to test the proposed theories leading to new observations and refinements to prior explanations and proposals of new explanations. This cycle is facilitated by experiments designed to phenomena in multiple contexts to reinforce the constructivist experience. In their experience the following themes should guide the student experimentation experience:

1. Students need to observe a simple phenomenon that they can describe in simple words.

2. The students need to work in groups and share what they think with the group first, discuss it, and come to a consensus before sharing the ideas with the whole class. White-boarding is very useful here.

3. The students need to notice all relevant aspects of the phenomenon. Noticing is greatly enhanced if the students do not predict the outcome before they watch the phenomenon, but instead are encouraged to say everything they observed and to use simple language (no science terms) when doing it. Making no predictions and using simple terms are crucial for the success of the process.

4. The students need to devise explanations that could explain important features of the phenomenon (here the teacher helps focus on the important features). While devising explanations, the students need to think of multiple explanations that need to be experimentally testable ("little invisible men did it" is not a testable explanation) and to be tolerant of their peers' explanations. These multiple explanations naturally appear as students work in groups.

5. The students need to accept all explanations as "correct" for the time being even if they do not like some of those, and then design experiments whose outcomes they can predict using all of the explanations (testing experiments). Thus, they need to learn to differentiate between the explanations and the predictions of the outcomes of the experiments.

Etkina shared an approach to learning and teaching physics that engages students the processes that physicists use to construct physics concepts, physical quantities and equations at the Millikan award lecture.[10] This document restates the guiding systems toward student inquiry and experimentation and formally titles them. ISLE (Investigative Science Learning Environment) is a learning system that engages students on the reasoning processes and has five principles:

a. Observational experiments should be simple and "clean" enough that students can infer a pattern. No predictions are required before making observations. In fact, the more "open" the students are to their observations, the better.

b. Students are encouraged to propose as many possible explanations as they can. Sometimes multiple explanations are easy to devise, sometimes not, but the goal should always be to encourage as many as possible. Explanations can be causal and/or mechanistic.

c. All explanations are considered to be equally valuable until the testing experiments are performed. Testing experiments can be designed by the students (this is the best way) or suggested by the instructor. In any case, students should not rush to perform the experiments and "see what happens." They need to first make predictions based on each proposed explanation and only then conduct the experiments. Predictions should not be based on their intuition or gut feeling, they should be carefully based on the explanations. This is the most difficult part of the cycle.

d. The outcomes of the testing experiments matching the prediction do not prove the explanations correct, they merely fail to disprove them. The experiments with outcomes that contradict the predictions are in a way better as they allow students (physicists) to think about rejecting an explanation. And this is where the assumptions are important. Checking assumptions that went into the prediction in addition to the explanation is the step whose value cannot be overestimated.

e. Students read the textbook after they have devised ideas in class. This is in contrast with some other curricular approaches where students are expected to read a textbook or watch an instructional video before they come to class so they are ready to discuss the new material with their peers and the instructor. As ISLE's goal is students learning to think like physicists, listening to a lecture or reading a text before having an opportunity to explore, to create explanations, to connect them to existing knowledge and to test them does not help achieve this goal.

The science of teaching is knowing how to approach complex problems, create experiential definitions and practice the spirit of science that is creativity, the uncertainty in the answer, and the tolerance of the ideas of others. Specifically, the teacher has to make sure that the students spend time and effort noticing things; that all predictions and reasoning are initially accepted as equal prior to testing; that students are testing the predictions themselves and not their intuition; finally, that they distinguish between the hypotheses and predictions of the experiments. These steps can guide the development of science teaching material.

Etkina, et. all,[9] applies these principles in an experiment designed to illicit multiple explanations of an optical phenomena. A laser pointer shines through the water in a tank of water onto a white piece of paper upon which the tank is sitting and a backscattered cone of light is observed. Students can understand the optical principles producing this cone by constructing multiple explanations, then proposing and designing experiments to test their explanations. This process is the foundation of the aforementioned ISLE framework and designed to engage students reasoning with experiences similar to those that physicists encounter and use to construct their definitions. They described typical student ideas, provided a short list of equipment and suggestions for facilitating student exploration. Key features of these suggestions are summarized as follows:

1. Perform the observational experiment and draw a clear picture of what you see.

2. Propose different explanations for how the light cone is formed and suggest experiments to test each of your explanations.

3. For each of the testing experiments use, the explanation being tested to predict the outcomes of the testing experiment.

4. Perform the testing experiments, record the outcomes, and make judgments about the explanations you proposed.

5. Based on the results of your testing experiments and using a ray diagram, explain how the cone is formed.

6. Prepare group report about your investigation.

Wesley[41] reported on the insights gained from restructured course material that sought a more cognitive approach. Most students were observed to come to class with a fairly well developed, partially contradictory, conceptual system relating to the physical world. Research on student experiences demonstrate that these student views are highly resistant to change. It was also observed that students try to learn physics completely or partially by rote. The traditional organization of physics texts and courses follows the historical development of the discipline, but it does not approach the instruction psychologically functionally. Major concepts, such as fields or waves, are usually discussed in fragments separated by several hundred pages in the text and months of class time. Cognitive scientists have investigated how information is organized and processed, meaningful learning must focus on concepts and their relations. Concepts are organized in our memories into a hierarchical cognitive structure. New concepts are most efficiently learned when they are related to existing concepts already present in the cognitive structure of the learner. Students do not learn the conceptual structure of physics implicitly, rather they must have explicit instruction about the structure of knowledge. Since the introductory course is the only exposure to physics for many of the students, it is imperative that some modern physics be included to gain some appreciation for the complex theories presented by this relatively new subject.

Perkins and Grotzer[31] sought to emphasize the role of complex casual models in students' understanding of science. The development of constructivist pedagogy in science education has fostered students' inquiry by encouraging them to reason, test predictions and seek consistency through multiple applications. Conceptual change theories of learning encourage reflection on students' initial and evolving conceptions throughout the teaching process. They summarize four dimensions of complex causality and argue that the increasingly complex examples designed along these dimensions present challenges that delineate students' misconceptions.

> Mechanism: This dimension refers to the causal mechanisms invoked in an explanation. At their simplest, they take the form of surface generalizations from experience. Scientific explanation typically involves one or more levels of underlying mechanism involving properties, entities, and rules that underpin the surface situation; i.e. DNA shape and folding or electrons and the complex systems governing them. Often the deep explanation infers or posits entities that are part of a model and scientifically accepted explanation, not easily verifiable by nonscientists.
>
> Interaction Pattern: This dimension refers to the patterns of interaction between causes and effects. At their simplest, such patterns take the form 'A causes B,' as in, 'Electricity makes the bulb light.' In contrast, Ohm's Law is a constraint-based system and accurately describes the electric circuit. Increased complexity along this dimension can also entail movement from sequentially towards simultaneity between causes and effects and from linear towards nonlinear patterns.
>
> Probability: This dimension refers to cognition of the level of certainty held in causal relationships by students. Ohm's Law treats electrical circuits as a deterministic system, but it is the averaging effects of innumerable counts that smooth out uncertain, atomic-level events into large-scale, orderly patterns.
>
> Agency: This dimension refers to the capacity of constituents to affect observations and to the compounding of agents within a system that lead to new and unanticipated outcomes. The simplest level involves central agents with immediate influence: the battery makes the current move. Electrical circuits display self-organizing characteristics yet circuit configurations can yield unexpected large-scale irregularities, as in oscillations. Increased complexity along this dimension can also entail increasing spatial distance or temporal delay between causes and effects and forms of agency that are non-intentional or passive.

Clement[5] argued that overcoming students' misconceptions in physics is a multi-tiered problem that requires presenting repeated evidence anchored by experiences to create faceted models to be analogous complex phenomena. The experimental teaching method described attempted to ground the student's understanding on physical intuition. Which led to an unforeseen paradox: in order for difficult conceptual material to make sense to the student, it is necessary to connect somehow with the student's existing knowledge; but the student's existing intuition in the area is incorrect. A way around this paradox was proposed by using "anchors."

“Anchors” are based on experiential results from observations of phenomena that tie that unique scenario to the model that relates all related phenomena. This method relies on the fact that students are generally inconsistent in their understanding from a physicist's point of view; the student can simultaneously harbor in memory an “anchored” fact and a misconception that are diametrically opposed. The suggested cause is the student's knowledge schemas are packaged in much smaller pieces than the complete model physicists' acknowledge and because each schema is activated only in certain contexts (presumably tied to the experience defining the anchor). The teaching strategy uses discussion and bridging to promote dissonance in the students’ comfort between the anchor and the misconception, thereby encouraging conceptual change. The notion of searching for anchoring intuitions opens up a complimentary field for the ongoing research effort on misconceptions in the following ways:

a. Anchoring intuitions can be used as starting points for lessons which attempt to overcome misconceptions in physics.

b. Forming analogies between more difficult examples and an anchoring situation is an important instructional technique. When a misconception leads to false reasoning, the problem is that students will often not be able to understand how the unique experience is analogous through the model to the familiar anchoring case. Presenting the right analogy is not enough - the student must also construct their own definition from the analogy.

c. The technique of bridging by using structured chains of analogies combined with discussion to encourage active thinking appears to be helpful for this purpose. Bridging is an important tool for stretching the domain of an anchor to a new situation, constructing a more accurate understanding through generalizing models.

d. Many anchors and bridges can be introduced as thought situations or thought experiments. Thus, thought experiments are potentially powerful tools in instruction, as has been noted by Helm and Gilbert.

e. Misconceptions can be used to advantage in instruction. Topics where students feel that the accepted theory is counter-intuitive are sometimes frustrating to them, but such topics are also potentially more interesting because of their complexity. Constructing a satisfactory definition of a difficult topic becomes its own reward when understanding is achieved. When a misconception can be brought into conflict with another conviction within the student's head, dissonance can be potentially harnessed in a more impactful experience than ordinary topics, which do not threaten beliefs held with conviction. Students should be presented with experiences that internally motivated them to understand the issue and resolve the conflict.

f. Socratic discussions can help students achieve conceptual change. One encourages controversy centering on opposite views and the inherent tension between proposed theories. These tensions have the potential to create some unusually exciting and motivating discussions in the classroom that should act to increase student involvement and retention. Skillfully led classroom discussions appear to be the most effective vehicle for fostering dissonance, internal motivation, and conceptual restructuring.

Pompea, et. all,[32] outlined their use of misconceptions in the design of instructional materials for teacher and professional development programs. Hands-On-Optics is a national science foundation funded program designed to address the disconnect between ideas held by young children about light and basic optical concepts. Unfortunately, approaching the field of optics from an expert's perspective does not always serve the educational process. One must appreciate the approach of a novice to light and color and the perspective a child brings to the learning process. A student does not necessarily reason like a scientist and misconceptions may impede progress to learning. Novices differ from experts by not immediately notice meaningful patterns in a given field of study. Novices do not have a multifaceted, organizational structure of the content knowledge that an expert possesses. The knowledge of an expert has a sense of context, conditions or assumptions; it is not a set of facts, propositions, or theorems. Experts are very flexible in their thinking processes and also have the ability to make analogies with complex models. They are comfortable in the extents of their knowledge and they have an intuitive feel for their subject. The following fifteen misconceptions or "myths" were used as a basis for their material:

1. Light only reflects off mirrors and other smooth surfaces.

2 Objects are black because they do not reflect any light.

3. If you are five feet tall, you need a five-foot tall mirror to see your entire body at once.

4. You can see more of yourself if you move farther away from a mirror.

5. Light stays on a mirror during reflection (light doesn't travel).

6. The image you see forms on the surface of the mirror.

7. An object is "seen" because light shines on it.

8. Mirrors reflect all light that shines on their surfaces.

9. Light always travels in a straight line.

10. Light travels infinitely fast.

11. You can use a telescope to magnify objects as much as you desire.

12. An image is always formed at the focal point of the lens.

13. Polarizing filters are just dark plastic or glass.

14. All radiation is harmful.

15. Lasers emit tight, parallel beams of light.

Activities were structured on Stepans' six step model:

1. Students become aware of their own preconceptions about a concept by thinking about it and making predictions before any activity begins.

2. Students expose their beliefs by sharing them, initially in small groups and then with the entire class.

3. Students confront their beliefs by testing and discussing them, initially in small groups and then with the entire class.

4. Students work toward resolving conflicts (if any) between their ideas and their observations, thereby accommodating the new concept.

5. Students extend the concept by trying to make connections between the concept learned in the classroom and other situations, including their daily lives.

6. Students are encouraged to go beyond, pursuing additional questions and problems of their choice related to the concept.

They note that misconceptions and naïve theories held by students are valuable to the educational resource designer. Additionally, an understanding of research on misconceptions and conceptual change has been extremely valuable to the Hands-On Optics project and in the creation of instructional materials and related programs.

Pompea and Carsten-Connor[33] believe a wide variety of optics concepts can be taught using the overall perspective of the "colors of nature" as a guiding and unifying theme. This approach is attractive and interesting with a wide appeal to children, nature enthusiasts, photographers, and artists. It also encourages a deeper understanding of the natural world and the role of coloration in biology, remote sensing, the aurora, mineralogy, meteorology, in human-made objects, and astronomy, to name a few. Instructors can provide students encouragement to:

• Pay attention to things that most people ignore

• Touch what other people won't

• Compare things

• Ask questions

• Experiment to test ideas

• Make predictions prior to testing guesses

• Bring lab partners

• Measure and count

• Keep track of discoveries and write them down

• Explain what they see

• Share their experiences

5. 3D Printing & Technology

3D printing was developed by Charles Hull, who started engineering apparatus to fabricate plastic devices from photopolymers in the early 1980's.[19] From the applications of this idea stereolithography, 3D printing (first patented by Michael Cima and Emanuel Sachs, henceforth to be used synonymously with all forms of additive manufacturing), and other types of additive manufacturing using photopolymers to fabricate plastic components developed. The idea of rapid prototyping, where ideas are quickly brought to reality and, by ease of production, rapidly developed through many successive iterative models was a consequence of the ease of fabrication.

The technology has found applications in automotive and aerospace technology, architecture, consumer goods, research, as well as education. The system reconstructs a three dimensional path in space prescribed by a computer assisted design with a tip extruding photosensitive plastic that melts when exposed to heat or a UV laser. Successive layers fuse to prior and harden quickly. Limitations exist on the total size of printable object (which cannot exceed printer dimensions); in the microscale due to the size of extruded polymer which is related to macroscale limitations in layer strength; and the speed, by the time it takes for the polymer to fuse to previous layers before the tip moves on and by the time it takes a layer to harden before another can be applied. Designs can be easily copied and shared instantly through computer networks, offering an unprecedented opportunity for collaborations. Schubert[36] notes that recent advances in printing materials have now enabled 3D printers to make objects that have detail comparable to traditionally manufactured items. Further development of materials with which to print renders new aspects of design possible. Canessa, et. all,[4] related the history of materials from printed wax material to other materials like acrylate photopolymers or metals. A method of recycling plastics into thin wires of plastic suitable for thermal deposition 3D printers exists.[22]

The Strategic Foresight Report[3], a document assembled for the Atlantic Council, seems mostly interested with the advent of 3D printing and concerns surrounding manufacturing commodities. However, their shrewd assessment of the possibilities of 3D printing is enlightening: 3D printing offers a new paradigm for engineering design and manufacturing, which will have profound geopolitical, economic, demographic, environmental and *security implications*. Recent reports and developments suggest that 3D printing development is gaining momentum and could be reaching a take-off point within the next decade. The easy dissemination of designs, growing ubiquity and applications to manufacturing creates instant production on a global scale.

An immediately apparent benefit is the ability to create complex shapes that cannot be produced by any other means. For example, curving internal cooling channels can be integrated into components. 3D printing allows designers to selectively place material only where it is needed, limiting waste (in one sense, rapid prototyping is also prone to rapid creation of waste). Designers taking inspiration from nature mimic cellular materials that are strong, stiff and also lightweight. Increasing complexity is effectively free: In metal casting and injection molding, a new product requires a new mold to cast the part. In machining, several tool changes are needed to create the finished product. However, 3d printing is a "single tool" process, no matter the design, there is no need to change any aspect of the process. The process is automated which saves time from fabrication for development of successive models and allows prints to be performed overnight and printing of individually unique items as if they were a batch.

The method is being developed in biomedical engineering as tissue scaffolding[19], which is deposition and designed growth of tissues. Tissues and organs grown in this manner still face bioresorption and biocompatibility when grafted to patients. Fairly common is their use in teaching for creating 3D models of anatomical models or polypeptide chains.[19] Eisenberg[8] called for more intricate designs to be implemented for children to work with; and summarized, if the child is no longer assembling the legos and instead 3D printing models, the design should then have complex parts or novel print designs to encourage "discovery" and "creativity."

Kostakis, et. all,[22] note that learning processes based on constructivism are championed by the implementation of 3D printing into curricula. They observed that students, who were otherwise indifferent (according to the students and their teachers) about their class projects, when given proper stimulation and the necessary tools, can choose what to learn themselves through exploration. Thus addressing the initial question, 3D printing can help in creating a classroom environment supportive of students truly engaging the whole process by materializing an artifact out of a mere idea. Students can proudly share their results with others while they acquire applicable knowledge instead of dry information out of textbooks. Canessa, et. all,[4] describe the design process for students:

1. The first step is to create a computer-assisted design (CAD) of the idea, a digital "alter ego" of the object.
2. The design is then exported in a usable file format particular to the model. There is a shortcut for the two previous steps: simply download a design from the internet (https://github.com/PSUScience/universal-optics, can be used to print our aparatus).
4. The model is printed and defects or non-functional aspects are assessed and corrected in the CAD.

They note that repositories of 3D printable models for education have recently emerged and technology has been used for K-12 education in STEM projects, mathematics, geographic relief maps, the arts, sciences and music (printing simple instruments) education. The authors are optimistic that it will have a large impact in education. A Fab Lab is a high-tech workshop where students can find equipment, such as 3D printers, laser-cutters and CNC-machines. The first Fab

Lab has been initiated in the year 2002 by Neil Gershenfeld at MIT. At this time a multitude of those Fab Labs exist worldwide, providing access to this modern production processes to all interested students.

Customized implants and prosthetics are one of the other widely explored areas for application of rapid prototyping. 3D prototype models may be beneficial for the communication between clinicians and patients for demonstrating required treatment and consenting for the procedure and manufacturing commercially available implants are suitable for most patients. The application of rapid prototyping in surgery is also valuable for diagnosis, treatment planning, intra-operative surgical navigation and for training surgeons simulating surgical procedures. Limitations of 3D objects in this application regard not adequately simulating human tissue and surrounding structures. The process chain from imaging to 3D prototype modeling is a multidisciplinary field involving knowledge ranging from acquisition of imaging data, image post-processing and manufacturing of the prototype models by various techniques.[25] Radiologists play a pivotal role in this process chain by connecting engineering to health care, images to 3D models in these applications.

II. Similar Apparatus

1. Overview

It has been shown that iterative experiments based on common experiences in nature lend themselves to constructivist learning in geometric optical physics. Exploration of geometric optical phenomena in the classroom is guided by experiments with different light sources and optical components. Many such apparatus exist[43-52] to explore the various principles of geometric optics and the transmission of light. The cost of these many sometimes overlapping systems ranges from simple components less than $30,[43] to light sources closer to $100,[44-46] and full systems from one to several hundreds of dollars.[47-52] As such, less funded institutions and high schools may only have a few systems for demonstration and limited access for in class experimentation.

2. Pasco

Pasco has several designs for experimentation to offer.[43,44,46,52] The adjustable lens[43] is useful for studying how the radius of curvature of a lens and the index of refraction of the compositional material effects focal length. In addition, this small component is relatively inexpensive and made from readily available parts.[26] The basic light source[44] supplies a quartz-halogen bulb as a point source, or split into 1, 3 or 5 parallel beams of white light, the primary colors (red, green and blue) and a scaled crosshair. The parallel beams are useful for experiments concerning focal length of lenses, the effects of mirrors and prisms. The scaled crosshair is useful to relate magnification with focal length, object and image distance. The point source can be used to demonstrate the formation of shadows. The usefulness of supplying the primary colors with this source is unclear; the colors cannot easily be mixed since the source of all three colors is the bulb, with a single transparent plastic filter with coatings for each color. Pasco's color mixer[46] does allow the tuning of three, colored LED's to investigate color mixing.

Pasco also offers a model human eye[52], which combines plastic 1" lenses or the adjustable lens with an "eye shaped" tank to discover how the eye forms images and explore the effects of deformations like astigmatism and near and far-sightedness. The model is a fine representation because the lens in the human eye has an index of refraction similar to oils (n = 1.396[36]) and is sandwiched by the aqueous and vitreous humour, media of similar optical properties to water. The model is designed to fit the adjustable lens filled with corn starch or vegetable oil submerged to simulate the eyes lens. The only defects are the curved surface of the cornea, bordering the aqueous humour, is flattened in the model and the cost of the system ($235) makes it a bit prohibitive.

3. SEOH

SEOH is also a prolific company when it comes to experimental setups.[48-51] Their laser refraction set[48] features a circular plate with angular markings to mount magnetic optical components and a red laser source. The setup works nicely vertically for demonstrations and can be used horizontally with water and a scattering agent. The ray optics kit[49] consists of large incandescent lamps cast in alloy with various planar lenses and lamp shields also made from alloy. The kit is expensive and cumbersome to use and the list of experiments is unsubstantial. The advanced placement light and waves kit[50] includes the laser refraction set, a tabletop red laser source, optical table with lightbulb, lenses and holders, and a ripple tank for demonstrating mechanical waves. The kit has many experiments relating to optics and waves and is the most expensive set offered. Additionally SEOH offers a color mixer for demonstrations[51]. This setup is overpriced and very limited in its experimental scope.

4. Arbor Scientific

Finally, Arbor Scientific offers two designs.[45,47] The laser ray box with lenses[45] offers 3 or 5 parallel red beams with a circular plate to measure angular changes due to refraction. The laser viewing tank[47] is a vertical, rectangular tank to be used with water and a scattering agent to demonstrate refraction, critical angle, diffraction gratings and gradual refraction, related to the formation of a mirage (which will be discussed in a later section in thorough detail).

III. Design

1. Guiding Processes

In constructing the apparatus, constructivist themes were prioritized in the context of iterative experiments studying similar facets of the same optical phenomena seen in nature. Many aspects from commercially available models were synthesized into an easily interchangeable system for hands-on experimental use by students and demonstrations in conjunction with a document camera by teachers. Student misconceptions have been condensed into the following list:

1. Students do not recognize light as an electromagnetic wave propagating through space or the wave-particle duality of photons. [1,2,13,14,15,17,22,23,34,35,40]

2. A holistic view of images and light as consisting of constituent "light rays" that travel parallel to one another through space, from one point of the source to one point of observable interaction. [1,2,14,15,17,18,22,34]

3. Misuse and misinterpreting the language of scientists; students construct their own definitions, leading to a separation of words' 'meaning province' between novices and experts, and may misuse language to "prove" their false claims.[22,34]

4. Vision; students believe the eye is "active" in "seeing" things, using "vision rays" to see, and fail to recognize the image formation process in vision. [1,2,14,18,22,23,35,38,40]

5. Color is a property of objects, not light, light is usually absent from students' explanation; "brightness" is a property of the "color" itself, again no relation with light or photonic flux is expressed. [2,17,22,23,38,42]

6. "Illuminated" is a passive environmental state; light constantly fluxing through the system is not seen as the cause.[14,22,23]

7. Mirrors are special objects; images form on a mirrors' surface and this property of the material is not due to their high reflectance of visible light, it is attributed with the object itself. [1,2,13,14,15,22,23,38,40]

These misconceptions were given special attention in the design of the optical experiments available to the aparatus. The components were sourced such that everything is easily available for purchase by the general public, the nominal cost of the system being less than $100. The price was decreased by using 3D printed components when feasible. Thus construction of the apparatus provides a project in 3D-printing with designs posted on an open source website[55] available to modify and update with reviewed consent.

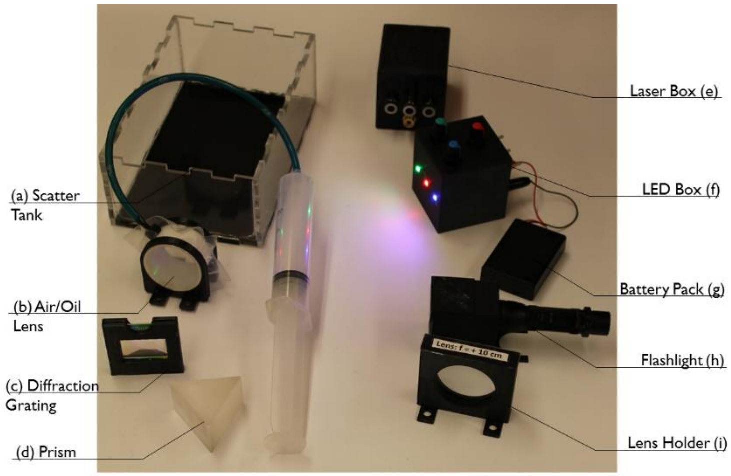

Figure 1 The complete apparatus with various optical components.

The system consists of a scatter tank (a), a flexible membrane air/oil lens (b), a diffraction grating and 3D holder (c), a glass prism (d), laser box (e), LED box (f), battery pack (g), flashlight with single and five beam slit apertures, and lens holders for use with various lenses; the various components are shown in figure 1. The scatter tank is filled with water and a scattering agent (we used very dilute, water soluble metal cutting oil, two or three drops per tank volume; milk or sugar are commonly used agents as well, though many exist[25]) to scatter a portion of the impinging light from the source making the path visible from all angles. The various optical elements (b-d, i) are either used inside or outside the tank to effect the projected light.

2. Scatter Tank

Construction of the apparatus began with determining the size of scattering tank to be used. The design had to be easily managable and observable under a document camera, as well show all the intended effects. The effect we were most concerned with was image formation, it was therefore necessary to optimize the system to illustrate this effect. The Gaussian Lens Formula[36]was used to determine possible configurations:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

where f is the focal length of the lens, d_o is the distance from the object to the lens and d_i is the distance from the lens to the image. Therefore, if a 5 cm focal length lens was used, the shortest total pathlength would be 20 cm (d_o = d_i = 10 cm, it can be seen from figure 2 that path length is minimized when d_o = d_i), a managable length for a document camera; whereas if a 10 cm focal length lens were to be used, the shortest optical path would be 40 cm, too great for a document camera to capture the entire system. A commercially available, 50 mm diameter, 5 cm glass lens was found and a 13 x 21 cm scatter tank was decided upon. By extending the scatter tank length to 21 cm, object distances as close as 6.56 cm could be used to produce images within the tank (neglecting the effects of changing from media of low index of refraction, air, n = 1.0003, to that of acrylic, n = 1.4896 or water, n = 1.330. This is discussed in the section titled "Image Deformation and the Effect of Media"). The thinnest scrap acryillic we could find was used for the walls of the tank to limit the effects of chaning media on image formation. Pieces were chosen and laser cut with square-wave shaped edges to allow overlap and strengthen the bond of the glue used to make the chamber water tight. The bottom was painted matte black to increase contrast and decrease reflected light.

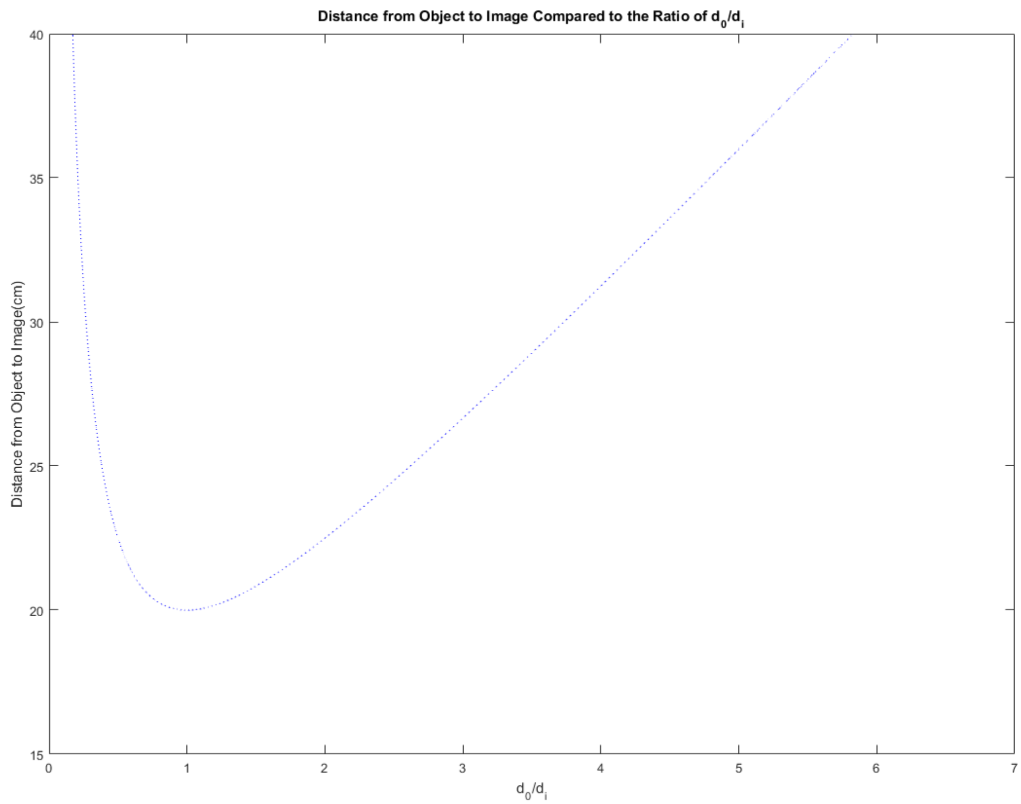

Figure 2 Distance from the source to the image compared to the ratio of the distance from the source to the lens and the image to lens.

3. Air/Oil Lens

The flexible membrane air/oil lens was developed using a similar design as created before[26], with different dimensions to produce the intended effects. It was the desire of the lens to form images within the tank when filled with air as a concave lens and show focal length when filled with vegetable oil as convex lens. In order to accomplish this, the Lens-Maker's formula was used[36]:

$$\frac{1}{f} = \frac{n_l - n_m}{n_m}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

Where f is the focal length of the lens, n_l index of refraction of the lens, n_m is the index of refraction of the media the lens interfaces with, R_1 is the radius of curvature of one side of the lens, and R_2 is the radius of curvature of the other side of the lens. The equation was simplified by setting $R_1 = R_2$, using n_l = 1.0003 and n_m = 1.330, air and water respectively, the following result is obtained:

$$f = -2R$$

To insure that the image would be formed within the tank ($d_i = d_o$ = 10 cm) a focal length of 5 cm was chosen, thus a radius of curvature of -2.5 cm was necessary to the design. Working backwards from this result in the case of a vegetable oil filled, convex lens, n_l = 1.467 and n_m = 1.330 respectively, produces this result:

$$f \approx 5R = 12.5\ cm$$

Although the lens in this case cannot form images within the tank ($d_i = d_o$ = 25 cm), the focal length can be determined within the space of the tank. The lens was made from commercially available 2" PVC pipe (diameter = 5.08 cm), 2" long to adequately form the concave lens and squares of 0.02" thick latex for the membrane. The membrane was sealed to the pipe with 3D printed lids; these lids have "feet" on one side to stabalize the lens, height match the center of the lens with the center of the tank and provide an attachement point for magnets. When the lens is filled with media less dense than water and submerged, the bouyant force makes the lens unstable, this was overcome with a submerged, black metal plate and magnetic feet on the lens holders. A barbed hose attachment and a 1' length of 1/8" ID tubing was used to connect a 60 ml syringe, the resevoir for either air or oil.

4. Diffraction Grating Holder

Diffraction gratings are prevalent optical components with fairly common dimensions (2" x 2"). A 3D holder was printed for the diffraction grating to stabalize and height match the center of the aperture with the center of the tank. The diffraction gratings chosen were a 500 lines/mm and 1000 lines/mm slide, this allows one to see the difference of effect in varying the distance between slits.

5. Laser Box

The laser box was developed to illustrate two concepts: the focal length of lenses using three horizontallly parallel red lasers or the effect of monochromatic light passing through a diffraction grating with three vertically parallel lasers, the primary colors. When parallel beams pass through a lens normal to the plane separating the two radius' of curvature, the "object" can be said to lie "infinitely far away" from the lens. In the Gaussian Lens Equation d_o becomes infinity and a simplification takes place:

$$\frac{1}{f} = \frac{1}{\infty} + \frac{1}{d_i} \Rightarrow f = d_i$$

Thus the focal length of any lens can be determined by passing beams in this orientation through the lens and measuring the distance from the lens to the beam crossover point. When passed through a diffraction grating, monochromatic light destructively interferes producing split beams at an angle dependant on the spacing between the slits of the grating and the wavelength of light used. When the three primary colors pass through the diffraction grating they are split at differing angles, this angle can be compared and accurate predictions made using the equation for double slit interference and considering the influence of the scattering tank:

$$d sin\theta = m\lambda$$

Where d is the seperation between slits, θ is the angle of seperation, m is an integer representing the order of maxima the equation refers to and λ is the wavelength of light.

A 3D printed housing was designed with holes drilled and tapped for set screws to keep the lasers positioned and height matched so the middle beam is centered on the scatter tank no matter what orientation the box is in (ie, positioned such that the red lasers are vertically parallel and the primary colors are horizontally parallel). The 3D printed housing also served as a faceplate to the box used to mount the small circuit board, five switches and banana plug jacks for power. Power was supplied with a battery pack equipped with three AA batteries, supplying 4.5 volts. The three horizontal red beams positioned closely together so as to pass through the lenses; the three vertical beams were more closely spaced to fit all three beams through the diffration grating.

Since the intended purpose of the source is to be used as an in class demonstration, precautions had to be taken with the optical power of the lasers. Laser safety[32] requires that monochromatic beams in the visisble range be limited to 5mW or less optical power to be rated class 3R lasers, the highest rating for laser lights without necessitating interlocks for demonstrations. As such, each laser was tested with an optical power meter (THORLabs PM200[33]) and constant current source to determine the current at which each lasers total optical power (no filter for monochromatic light was used) was less than 5 mW. By using the experimentally determined current, the known maximum voltage supplied by the battery pack and the known voltage drop of the laser module, the adequate current-limiting resistance was determined through the following relationship:

$$I = \frac{V}{R}$$

$$V = V_0 - V_{drop}$$

$$\Rightarrow R = \frac{V_0 - V_{drop}}{I}$$

where, I is the experimentally determined current, V_0 is the battery pack's voltage, V_{drop} is the voltage drop across the laser module (given in the factory specifications), and R is the applied current-limiting resistance. A table of this calculation is given in figure 3, resistance used was calculated by using the list of know resistor values and the relationships of resistors in series and parallel:

Series: $$R_{total} = R_1 + R_2 + R_3 \ldots$$

Parallel: $$R_{total} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots\right)^{-1}$$

#	Color	Beam Appearance	Voltage Drop	Current @ 5 mW	Use?	Resistor Value	Resistance Used
1	Green	Nice round beam		Built in Potentiometer	Laser Box	0	
2	Red	Rectangular poor beam	2.3	0.02	Laser Box	110	135.71
3	Red	Rectangular poor beam	2.3	0.01	Laser Box	220	257
4	Red	Rectangular poor beam	2.3	0.01	Laser Box	220	257
5	Blue	Rectangular poor beam	5	0.05		-10	
6	Blue	Rectangular poor beam	5	0.04	Laser Box	-12.5	None
7	Red	Rectangular poor beam	2.3	0.01		220	
8	Red	Rectangular poor beam	2.2	0.03		76.67	
9	Red	Rectangular poor beam	2.3	0.06		36.67	
10	Green	Nice round beam - No Adjustment Lens	2.3	0.18		12.22	
11	Green	Poor round beam	2.3	0.22		10	
12	Blue	Poor rectangluar beam	1.7	0.22		12.73	
13	Blue	Poor rectangular beam	1.5	0.15		20	
14	Red	Poor rectangular beam	3.3	No Resistor necessary	None, very low power ~1.3 mW	0	
15	Red	Poor rectangular beam	2.2	0.04		57.5	
16	Green	Nice round beam - No Adjustment Lens	2.2	0.12		19.17	
17	Green	Nice round beam - Adjustable	2.2	0.23	Interferometer	10	10
18	Green	Nice round beam - Adjustable	2.3	0.28		7.86	
19	Green	Nice round beam - Adjustable	2.4	0.33		6.36	

Possible Resistors
10
22
47
68
150
470
1000
4700
10000
15000
100000
1000000

Figure 3 Table of lasers, their voltage drops and current at < 5 mW optical power.

6. LED Box

The LED box consists of the three primary colors as point sources to explore image formation with the various lenses provided or color mixing. The tips of the three LEDs were ground down and polished to provide point sources with minimal distortion. A 3D box was designed to mount the LEDs, four switches and banana plug jacks for power; a lid was also designed that has mounts for 1 kiloohm potentiometers to limit LED power output for color mixing. An extra resistor (10 Ohms) was used with the red and green LEDs to equalize the brightness of their beams with the blue LED. The LEDs mounting slots were height matched to be centered on the face of the scatter tank whichever orientation the source is in. This allows image formation to be viewed from the top when the LEDs are positioned horizontally parallel, or color mixing when the box is rotated 90° and the LEDs orientated vertically parallel.

7. Flashlight

A white LED flashlight (Coast HP1) was modified with a 3D printed mount with space for acrylic planar lenses and metallic aperture slides. This design takes an unfocused point source, focuses the light rays through a single or five slit aperture to produce one or five parallel white beams. The five beams can be used with any of the lenses for determing the focal length of the lens. The single beam is to be used with the prism to show dispersion: because of the frequency dependence of the index of refraction in some materials, as white light passes through the interface between air and glass, different wavelengths of light are bent at different angles according to the Lens-Maker's Equation, this serves to separate by angle the constituent wavelengths of light.

8. Lens Holders

Finally, 3D printed lens holders were designed to "snap together" allowing 50 cm diameter lenses of various focal lengths and thicknesses to be used. The lens holders have feet on one side for stabillity, to allow the lens to be brought nearly into contact with the scatter tank and provide a point to attach magnets to be used inside the scatter tank itself.

IV. Experimental Operation

1. Constructing Iterative Experiments

It has been shown that children, secondary school and university students all show similar preconceived notions of how light behaves in geometric optics. These misconceptions are summarized in the following list:

1. Students do not recognize light as an electromagnetic wave propagating through space or the wave-particle duality of photons. [1,2,13,14,15,17,22,23,34,35,40]

2. A holistic view of images and light as consisting of constituent "light rays" that travel parallel to one another through space, from one point of the source to one point of observable interaction. [1,2,14,15,17,18,22,34]

3. Misuse and misinterpreting the language of scientists; students construct their own definitions, leading to a separation of words' 'meaning province' between novices and experts, and may misuse language to "prove" their false claims.[22,34]

4. Vision; students believe the eye is "active" in "seeing" things, using "vision rays" to see, and fail to recognize the image formation process in vision. [1,2,14,18,22,23,35,38,40]

5. Color is a property of objects, not light, light is usually absent from students' explanation; "brightness" is a property of the "color" itself, again no relation with light or photonic flux is expressed. [2,17,22,23,38,42]

6. "Illuminated" is a passive environmental state; light constantly fluxing through the system is not seen as the cause.[14,22,23]

7. Mirrors are special objects; images form on a mirrors' surface and this property of the material is not due to their high reflectance of visible light, it is attributed with the object itself. [1,2,13,14,15,22,23,38,40]

These naïve ideas present logistical barriers for students to predict phenomena and accurately describe the process. University students tested during optics coursework often showed an inabillity to confidently connect ray diagrams and the reasoning behind their use to experimental setups.[1,15,17,18] Synthesizing this information into a working mental model is a continuous process of observation, prediction and experimentation to present the mind with enough conflicting evidence to dispel the belief in preconceived ideas in the constructivist theme.

In conjunction with the apparatus, a set of experiments have been designed more closely aligning with the current trends in physics education and keeping these misconceptions in mind. These experiments repeatedly investigate of a wide variety of optical phenomena, building from simplistic to more complicated models. The experiments deal directly with many common student misconceptions, allowing them to interact with the problem, without relying on misleading descriptions of the optical process. By exploring these effects at work while using a hands on setup, students can explore optical principles like refraction, lensing, focal length, image formation, light scattering, color mixing, diffraction and dispersion. Each activity (instructions found in the supplementary material) can be done individually or scaffolded.

Inherent in the design are the commplications of projecting light through dense media.[36] The scatter tanks' effect on the propogation of light leads to complications even in simple applications like the Gaussian Lens Function. A full discussion of the effects of the tank, rayleigh scattering and mirages is given in the following section. These effects can be understood and naturally lends themselves to computer modeling.

2. Color Addition

How the human eye derives color from the broadband signal of white light is complicated[39], the combined effects of hue, saturation and luminosity on image formation are the colors that define our reality and ourselves[35]. A focus on the "colors of nature" is called for in guided scientific inquiry.[33] The experiment investigates the effect of varying the relative intensities of monochromatic light sources, changing the luminosity, and superimposing the light to create hue. The effects of saturation are negated due to the fixed colorfulness of the LEDs. By turning the LED box so the lights are vertically parallel, two or three colors are combined and 1 KΩ potentiometers vary their relative intensity. The effect is illustrated in figure. Since the two beams are scattered by the oil diffused in the tank, when viewed from above the colors overlap. Red, green and blue combine to form white light (a), green and blue make cyan (b), red and green make yellow (c), and red and blue make magenta (d).

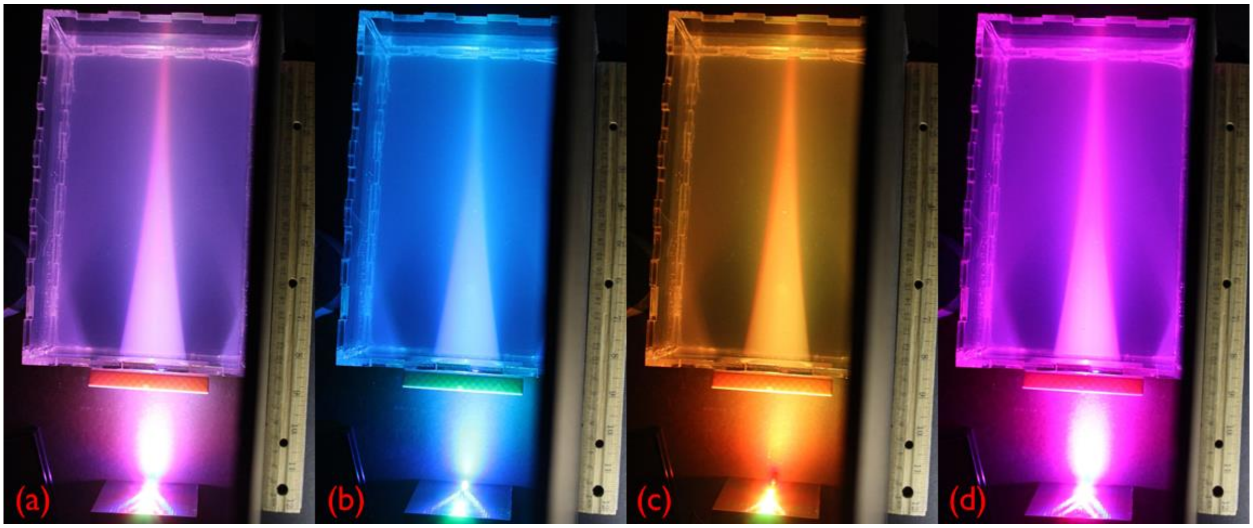

Figure 4 (a) White light is produced from combining all colors. (b) Cyan is made from blue and green. (c) Yellow is made from green and red. (d) Magenta is made from blue and red.

3. Dispersion & the Constituents of White Light

The effects of combining multiple wavelengths to produce white light is further investigated in this experiment. White light is passed at an angle through a glass prism, the effect of a frequency dependent index of refraction is that red light ($\boldsymbol{\lambda} =$ 640 nm; $\boldsymbol{n} =$ 1.50917) is deflected at less of an angle than blue light ($\boldsymbol{\lambda} =$ 434 nm; $\boldsymbol{n} =$ 1.51690) and the wavelengths become separated enough to be viewed by the naked eye (figure 5). The angle which light is deflected is governed by Snell's Law:

$$\boldsymbol{n_1 sin\theta_1 = n_2 sin\theta_2}$$

Where n_1 is the index of refraction of the media the light is originally in (ie, air, water), θ_1 is the angle between the impingent light and the line normal to the prism face, n_2 is the index of refraction of the prism and θ_2 is the angle the light passes through the prism with respect to the line normal to the prism face. By rearranging this equation,

$$\boldsymbol{\theta_2 = sin^{-1}(\frac{n_1 sin\theta_1}{n_2})}$$

And noting,

$$\boldsymbol{\theta_2 \propto \frac{n_1}{n_2}}, \qquad \boldsymbol{for\ 0 < \theta_2 < \frac{\pi}{2}}$$

It can be seen that by varying $\boldsymbol{n_2}$ there is a nearly inverse effect on the angular displacement of the beam.

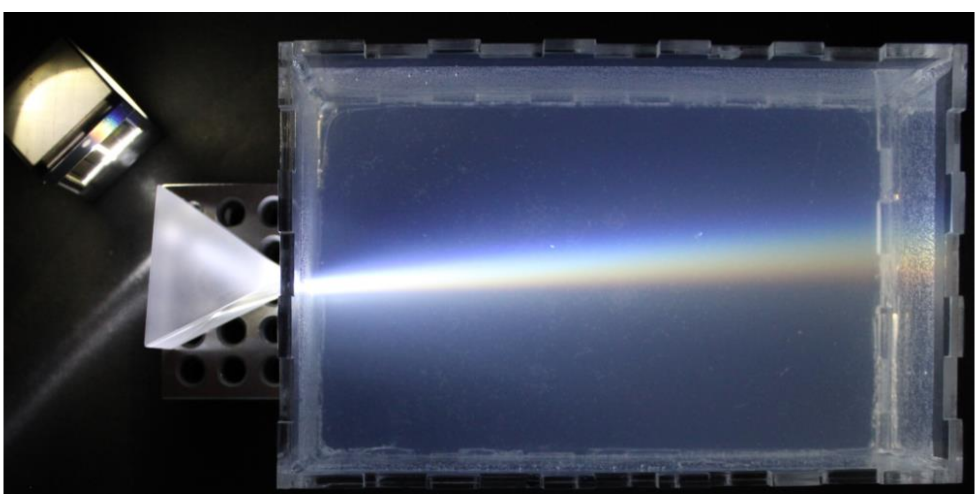

Figure 5 White light is dispersed after passing through a crown glass prism.

4. Diffraction

This experiment again enforces that white light is made up of all colors by exploring the frequency dependence of the deflection angle as light passes through a diffraction grating. When a plane wave of monochromatic light is incident upon a diffraction grating, the multiple slits are illuminated and each acts as a coherent linear oscillator producing wave interference.[36] This pattern is seen as 0th order maxima beams, 1st order maxima beams and occasionally 2nd order maxima beams in the apparatus. The effect is an example of Fraunhofer diffraction:

$$\boldsymbol{\theta = sin^{-1}\frac{m\lambda}{d}}$$

where $\boldsymbol{\theta}$ is the deflection angle, $\boldsymbol{m}$ is the order of maxima, an integral number, $\boldsymbol{\lambda}$ is the wavelength of light, and $\boldsymbol{d}$ is the distance between slits. It can be seen that longer wavelength light is deflected at greater angles and slit spacing is inversely proportional to the deflection angle. Therefore, as white light passes through the diffraction grating, the constituent colors become "fanned out" based on their wavelength. The vertically parallel, primary color beams produced by the laser box are used to study this effect more closely. Angular measurements can be made from above the scatter tank and the diffraction approximation verified (this approximation is made more accurate by considering the effects of the tank on the angles).

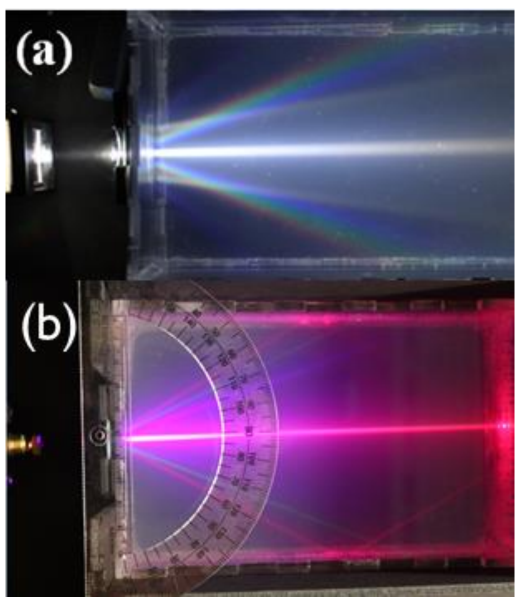

Figure 6 Different wavelengths cause constructive interference at different angles.

5. Focal Length

The effects of concave and canvex lenses are investigated in this portion of the lab. Focal length is often confused with 'the point of image formation' or the place where 'the image flips over' by students. It is a property of lenses that wave fronts impingent upon their surface are reshaped and either convergent or divergent from the lens.[36] The focal length of a lens is an intrinsic property that is used to relate the radius of curvature to the materials index of refraction to the optical power and ability of the lens to focus light. This effect is explored by using any of the sources producing parallel beams and passing them through a lens to verify the focal length of the lens using the Gaussian Lens Formula:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

where f is the focal length of the lens, d_o is the distance from the object to the lens and d_i is the distance from the lens to the image. If the incoming parallel rays were from the same "object," that object could be said to lie "infinitely" far away, and the Gaussian Lens Formula simplifies:

$$\frac{1}{f} = \frac{1}{\infty} + \frac{1}{d_i} \Rightarrow f = d_i$$

Using this relationship, the focal length can be locating the crossover point of parallel rays impingent orthogonally to the plane that seperates to curatures of the lens. This is illustrated in figure 6 where parallel red lasers are used to show the focal length of a 5 cm lens (a), a 10 cm lens (b), and a -10 cm lens (c). Measurements made using the apparatus will suffer from the effects of the scatter tank and can be made more accurate by considering the angular changes due to the tank.

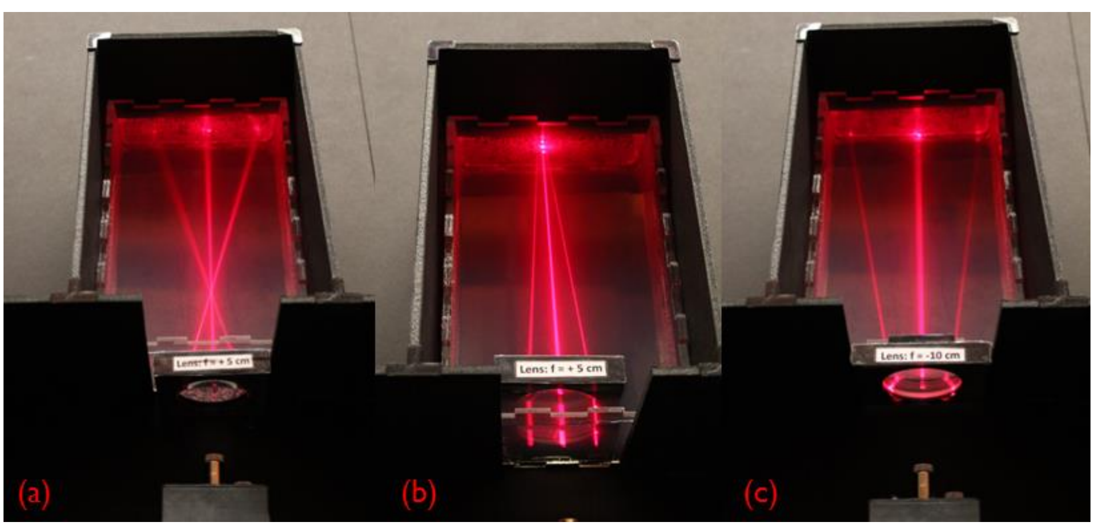

Figure 7 (a) Parallel lasers pass through a +5 cm lens. (b) Parallel lasers pass through a +10 cm lens. (c) Parallel lasers pass through a -5 cm lens.

6. Image Formation

Image formation is an effect of lenses, intrinsic to human vision,[36] and very poorly understood by students. Confusion stems from misinterpreting ray diagrams, misunderstanding how the image becomes reflected, what effect partially covering the lens has and the "path" that the light takes. In this experiment the phenomena is demonstrated with the LED box. The 5 cm lens is placed close to the scatter tank and the LED box is placed 10 cm away from the lens plane, an image without the effects of the tank will form at 10 cm. Experimentation with arranging the various pieces is encouraged, recreating the observation as the students see it is imperative to the constructivist learning process.

Observe the system in figure 7. (a)The images are noticeably beyond 10 cm and the image plane is distorted, the projection of the LED point sources is out of focus. Many of the central rays also terminate and do not continue beyond the point of focus, only the outer rays tend to continue creating a "haze" beyond where the image appears to form. Moving the LED box backwards moves the image forward and it becomes more focused. Then by moving the lens further from the scatter tank, the image again sharpens and moves farther forward. The conical projection beyond the image also becomes more evident. Expectedly the LED projections have reversed position from the box upon exiting the lens. Studying the ray diagram of the experiment reveals that the linear displacement of the LEDs from the lens center line leads to a change in the angle the plane waves strike the lens surface leading to the image appearing with a related angular displacement in the opposite direction.

Consider the LED as a fixed point source of light that projects a spherical wave front. Only a portion of the expanding wave passes through the lens and focuses to form the image. This is an important feature of the lens: projecting the entire wave through the lens is not necessary to image formation. If half the lens were covered, the overall effect is that less of the wave is focused and the image appears dimmer. Observe figure 7, (a) is the normal image, whereas in (b) the half of the lens closest to the observer is covered. Notice the images are dim, less intense. Compare the upper half, (c), and the lower half, (d), of the lens obscured, note the difference in sizes of the green and blue projections. This is an effect of the LEDs position, the images are formed from planar waves traveling at very different incident angles to the lens surface. The effect is further distorted due to the water in the scatter tank. Note the differences in distortion of the red beam to itself and the other two beams.

Furthermore, imagine that each LED is now a fixed point that can project any hue, saturation or luminosity; this is the concept of a pixel. Each pixel similarly projects a spherical wavefront that expands to eventually form a plane wave. If there were many more LEDs in a two dimensional panel, it can be imagined that any sort of image can be formed from the overlapping projections, a human face for example, and the definition or quality is related to the pixel size in relation to image size. For the same reason the LED positions are reversed in the projection, any pixels angularly displaced from the lens center line have some related displacement and the whole image would appear reversed. The human lens projects a reversed image onto the cornea, image processing done by the brain inverts the image for you.[20] Movie theatres work under a similar principle, light is focused by a condenser lens through a series of upside down images passing from the top to the bottom of the focused light. The light then passes through the projection lens, which magnifies and inverts the image; the actors appear upright and the film appears to pass from the bottom of the screen to the top. It should be noted the scatter tank would likely provide a poor method for projecting films, the images of each LED suffer many obvious defects.

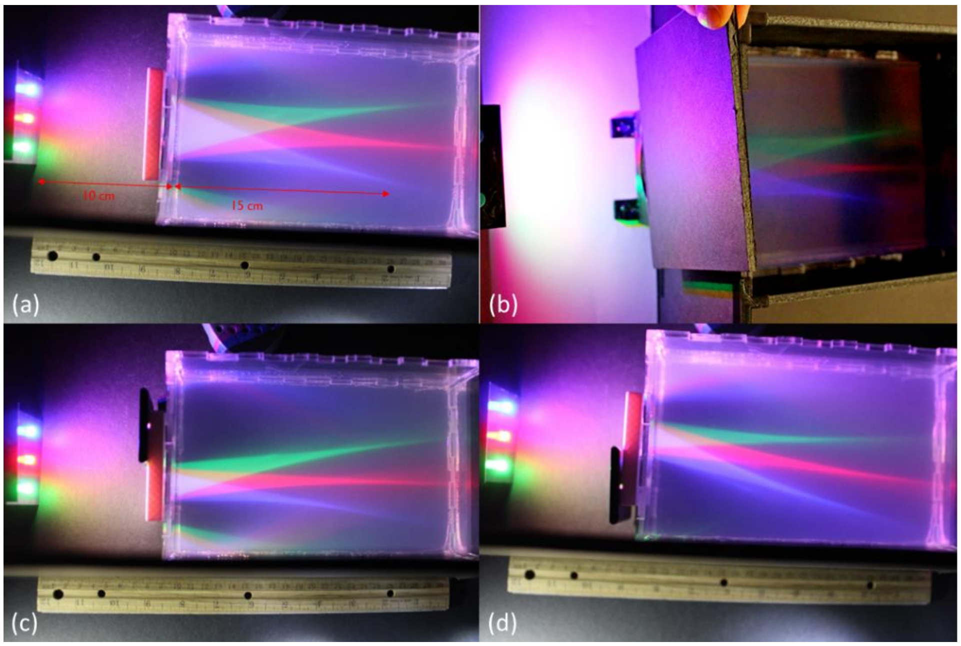

Figure 8 (a) Images are formed using a +5 cm lens. (b) Half the lens closest to the observer is covered. (c) The upper half of the lens is covered. (d) The lower half of the lens is covered.

7. Index of Refraction, Focal Length & the Radius of Curvature

To investigate the effects of changing the media within a lens and the radius of curvature has on the focusing power of a lens a series of experiments has been developed. Until this point students have been working with lenses made from fused silica glass, $n_l = 1.458$, in air, $n_m = 1.003$. The flexible membrane lens is a versatile component and useful to student exploration of these effects. The lens is first filled with water and the focal length approximated using the Gaussian Lens Function:

$$\frac{1}{f} = \frac{1}{\infty} + \frac{1}{d_i} \Rightarrow f = d_i$$

The radius of curvature is approximated from the focal length using the Len's Makers Formula:

$$\frac{1}{f} = \frac{n_l - n_m}{n_m}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

where $\boldsymbol{n_l} = \boldsymbol{n_{water}} = \mathbf{1.330}$, $\boldsymbol{n_m} = \boldsymbol{n_{air}} = \mathbf{1.003}$, and $\boldsymbol{R_1} = \boldsymbol{R_2}$. Without changing the location of the light source, the lens is then filled with oil ($\boldsymbol{n_l} = \boldsymbol{n_{oil}} = \mathbf{1.471}$) and the effect is compared by noting the difference in the radius of curvature between the two lenses. Without altering the radius of curvature, the oil lens is then moved into the tank, removing the distortion due to the air/acrylic/water interface. The actual radius of curvature recalculated from the undistorted focal length and the results compared by calculating the error. This number can be used to more accuately estimate the actual radius of curvature of the water lens.

Students should be encouraged to predict what would happen if instead of a media with a larger index of refraction, one with a smaller index is used. The lens is then filled with air and set in the scatter tank, the effect of a convex lens is reversed in this case and beams will diverge, whereas a concave lens is convergent. Adjust the air lens to a suitable focal length to form images, keeping in mind the minimum distance is $2f$. Using the LED box, an image is formed within the scatter tank. Observe that the image doesn't *obviously* suffer from the distortions due to the tank. The expanding spherical wave is somewhat distorted as it enters the scatter tank. Attempt to form the images against the rear wall of the scatter tank, then vary the object and image distance to observe the image growing or shrinking. This change is size is governed by the magnifying power:

$$M = \frac{d_o}{d_i}$$

The effect of changing the radius of curvature of the oil lens submerged in the tank is very similar to the function of accommodation the lens undergoes within the eye; differences arise when the scatter tank wall is compared to the cornea and more acutely the lack of pupil and actual media composition. Although the average index of refraction of the eyes lens is nearly that of oil, 1.396, and the aqueous and vitreous humours nearly that of water, the lens is complex fibrous mass coupled with elastic fibers, the aqueous humour is similar to blood plasma and the vitreous humour is a thick gel).

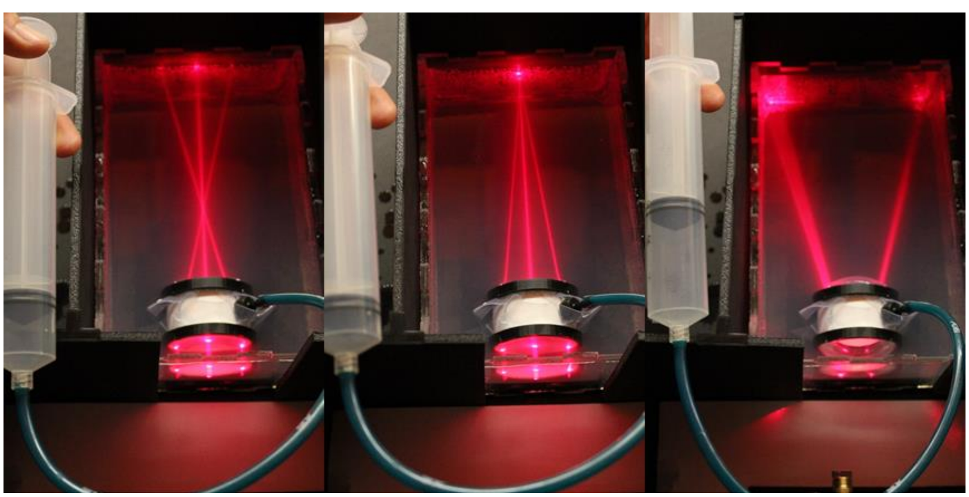

Figure 9 Focal length changed by altering the radius of curvature.

8. Exploration

Given all the components and variability of the system, experimental setups are nearly limitless. Iterative experiments have been designed for specific phenomena, but these are by no means the only phenomena illustrated by the system. The following activities are short, novel experiments without supplemental material.

Using the magnetic lens holder, observe the effects of parallel beams reflecting from the surface of a curved mirror; compare concave to convex mirrors; does the focal length of the mirror submerged in water change?

Use the prism to split an image: arrange the prism outside the tank such that the tip touches the 5 cm focal length lens and the opposite face is parallel to it. Use a beam light source normal to the prism face to find the focal point from the beam crossover. Use a single LED as a point source and form an image, add more LED's to study the effect further.

Add sugar cubes or corn syrup to the bottom of the scatter tank before filling it slowly with warm water. The effect is an index of refraction dependent on the depth of water, the effect of this gradient can be used to study the phenomena of mirages.

V. Image Deformation and the Effect of Media

1. Observed Effects

The many image deformations have been discussed in the previous sections. A summary of the effects can be seen in figure 8. Light passing at an angle into the tank is bent according to Snell's law at the air/acrylic/water interface (a). Water scattering light can be modelled as a packed volume of coherent oscillators according to Mie scattering. The scattering agent is diffused in a much larger volume of water forming a micellar solution and is in general, smaller than the wavelength of light ($\boldsymbol{d} < \frac{\lambda}{15}$);[57] therefore the Rayleigh scattering approximation governs the effect. Rayleigh scattering is highly dependent on wavelength (c,d,e) and particle size. Mirages are complicated deformations that are due to Snell's law applied to graded indexes of refraction, most commonly seen from temperature fluxes, and in (f) as light passes through water with a corn syrup gradient.

These phenomena effect the image formation process by creating distortions in the image plane. Students can see the obvious effects and begin to find reasons for the causes of image deformation, a commonly misunderstood topic by students. Similar effects are under play in the function of the eye, in the blue sky, in swimming pools and all around us. By approaching these complications to image formation in a constructivist format, repeating experiments, students have the opportunity to define the effects for themselves. These effects are due to the wave-like nature of light, a subject that is under scrutiny for improved methods of teaching.

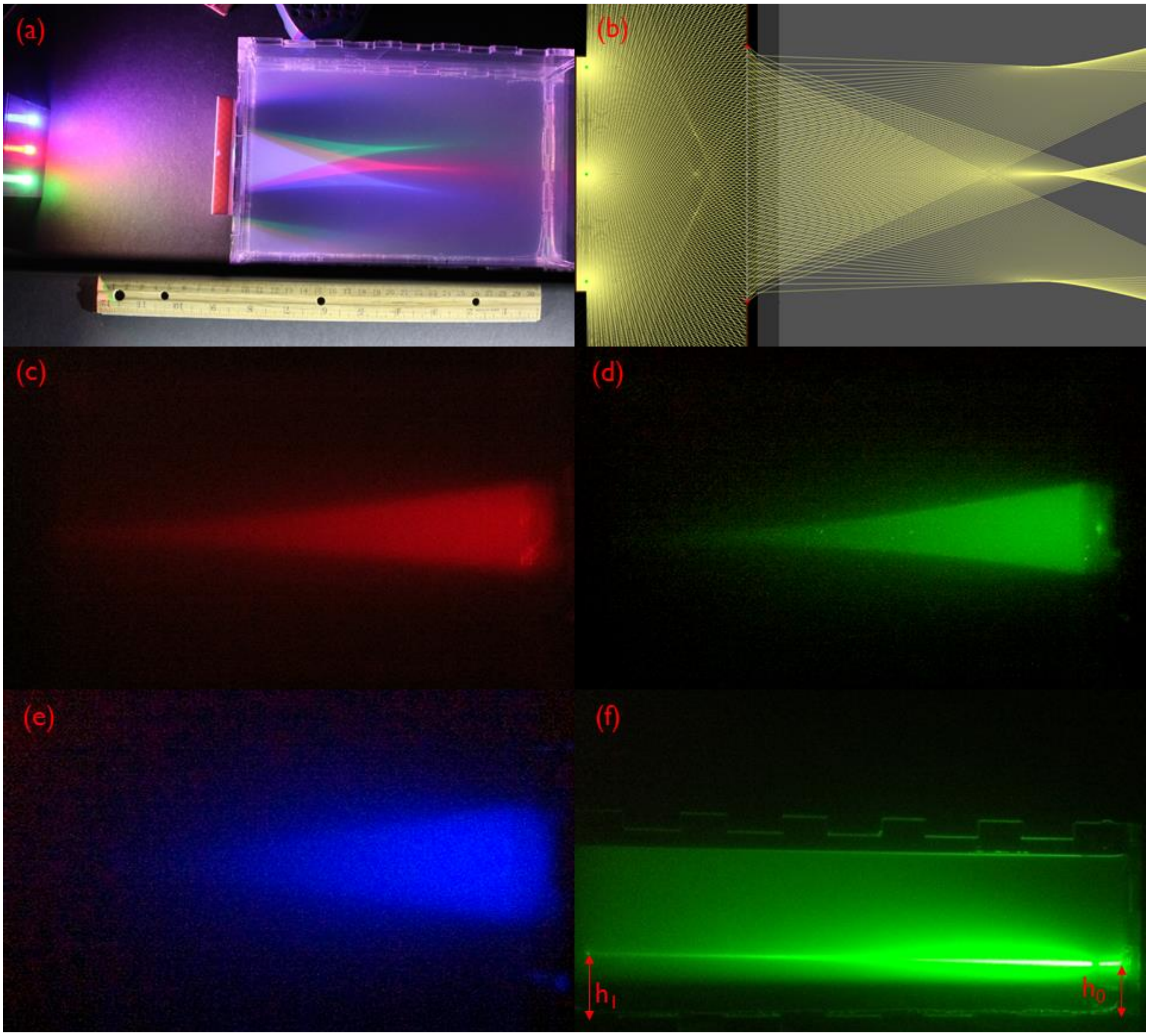

Figure 10 (a) Images are formed, the image plane is distorted. (b) The effects of the tank are modelled with a computer simulation. (c,d,e) Red, green and blue light, respectively, effected by Rayleigh Scattering. (f) Mirage formed in graded corn syrup solution.

2. Effects of Air/Acrylic/Water Interface on Image Formation

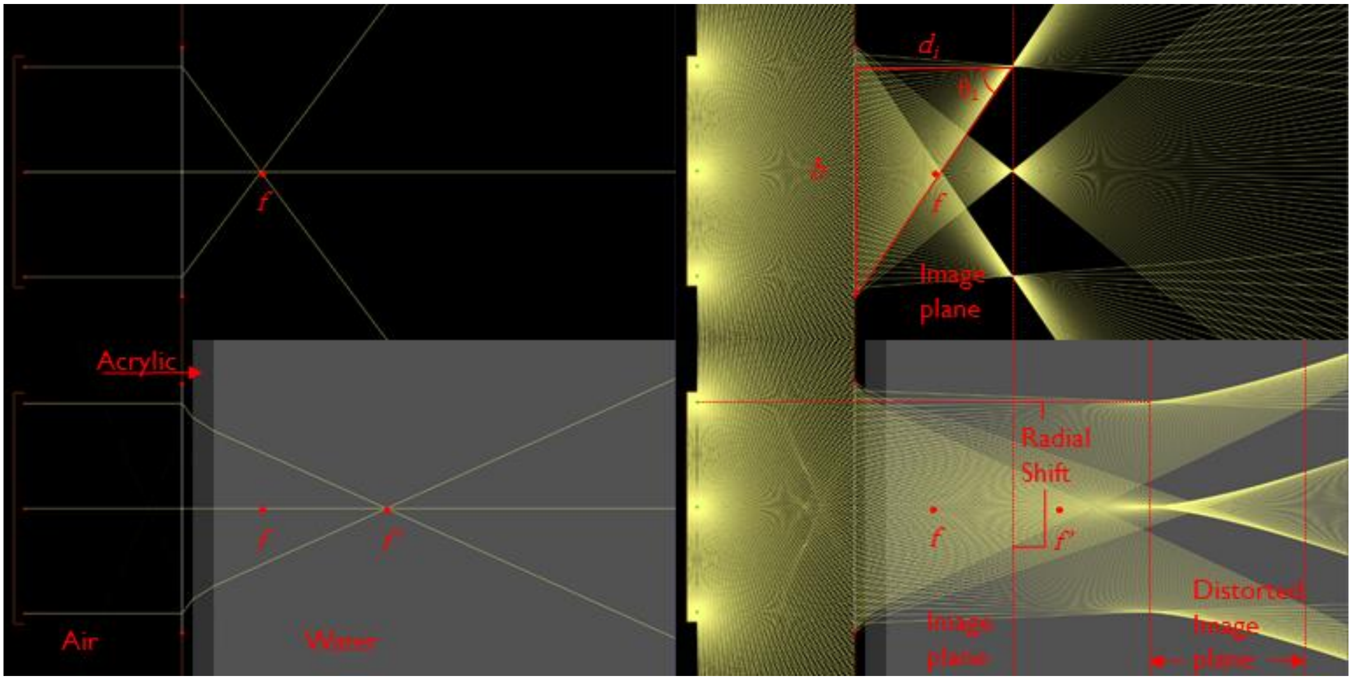

Figure 11 Computer simulations modelling the effect of the acrylic tank.

Light rays passing from one media into a second are bent closer towards the normal line if the second material has a larger index of refraction and further away if the index of refraction is smaller. The effect is governed by Snell's Law:

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

Light that is focused through the lens is often impingent on the air/acrylic barrier at an angle not equal to 0. As previously shown from the Gaussian Lens Equation, if we are using the 5 cm focal length lens and the source is 10 cm away from the lens, images should then form 10 cm on the other side of the lens. If we assume the LEDs make perfect point sources, in the ideal case all rays originate from the same point, pass through the lens and form an image at the same point. It can be seen in figure 9, using a computer simulation of the media effects on light rays, the rays with the greatest angle are those that extend from one edge of the lens to form an image across the midline of the lens (highlighted) analyzing the problem geometrically in two dimensions, it is found that the maximum angle is determined by:

$$\theta_1 = \tan\left(\frac{h}{d_i}\right)$$

Impingent light then enters the tank between -θ_1 and θ_1.The effect of the tank due to Snell's Law is angular dependent. Rays at larger angles will be bent more toward the normal inside the tank, leading to some rays focusing to a point behind the image plane. Shifts due to material composition are determined independently and combined, a summary of these effects can be seen in figure 10.

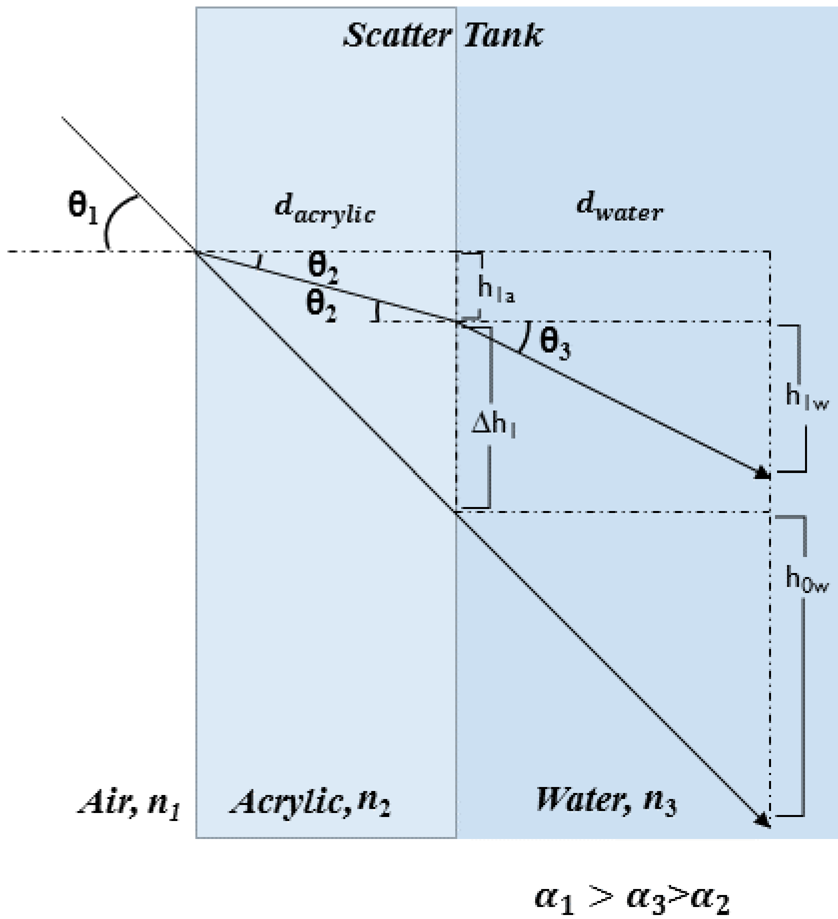

Figure 12 Drawing used to analyze the effect of the Air/Acrylic/Water border.

To determine the effect the acrylic, $n = 1.4896$, following relationships are noted:

$$d_{acrylic} = 0.5\ cm$$
$$h_{0a} = d_{acrylic} tan\theta_1$$
$$\theta_2 = \sin^{-1}\left(\frac{n_{air}\sin\theta_1}{n_{acrylic}}\right)$$
$$h_{1a} = d_{acrylic} tan\theta_2$$

$$\Delta \boldsymbol{h_1} = \boldsymbol{h_{1a}} - \boldsymbol{h_{0a}} = \boldsymbol{d_{acrylic}}(\boldsymbol{tan\theta_2} - \boldsymbol{tan\theta_1})$$

where $\boldsymbol{d_{acrylic}}$ is the thickness of acrylic, $\boldsymbol{h_{0a}}$ is expected change in height without the presence of acrylic, $\boldsymbol{\theta_2}$ is the shifted angle of the light passing through the acrylic, $\boldsymbol{h_{1a}}$ is the change in height with the presence of acrylic and $\Delta\boldsymbol{h_1}$ is the difference between these calculated changes in height.

The effect is further exacerbated by the light then entering water following the acrylic barrier. Following a similar logic, the height shift in water is taken into account using the following relationships:

$$\boldsymbol{d_{water}} = \boldsymbol{d_i} - \boldsymbol{d_{acrylic}}$$
$$\boldsymbol{h_{0w}} = \boldsymbol{d_{water}tan\theta_1}$$
$$\boldsymbol{\theta_3} = \sin^{-1}\left(\frac{\boldsymbol{n_{acrylic}}\sin\boldsymbol{\theta_2}}{\boldsymbol{n_{water}}}\right) = \sin^{-1}\left(\frac{\boldsymbol{n_{air}}\sin\boldsymbol{\theta_1}}{\boldsymbol{n_{water}}}\right)$$
$$\boldsymbol{h_{1w}} = \boldsymbol{d_{water}tan\theta_3}$$
$$\Delta\boldsymbol{h_2} = \boldsymbol{h_{0w}} - \boldsymbol{h_{1w}} = \boldsymbol{d_{water}}(\boldsymbol{tan\theta_1} - \boldsymbol{tan\theta_3})$$
$$\Delta\boldsymbol{h_t} = \Delta\boldsymbol{h_1} + \Delta\boldsymbol{h_2}$$

where $\boldsymbol{d_{water}}$ is the distance the light travels in the water, $\boldsymbol{h_{0w}}$ is the expected change in height without the presence of water, $\boldsymbol{\theta_3}$ is the shifted angle of the light passing through the water, $\boldsymbol{h_{1w}}$ is the change in height as the light passes through the water and $\Delta\boldsymbol{h_2}$ is the difference between these calculated height changes. The cumulative effect of this shift in height from acrylic and water is the sum of the difference from water and acrylic, $\Delta\boldsymbol{h_t}$.

The height shift of individual rays is related to the angle they impinge upon the tank, the beam height at any point inside the tank can be estimated. Figure 11 shows the height shift of the rays relative to their impingent angle. (a) is the angular dependent displacement of rays from the point they are supposed to focus to give an image, 10 cm from a 5 cm focal length lens that is flush to the tank. Rays impingent upon the tank surface at angles greater than 25° are shifted more than a centimeter from where the image is being formed. This leads to a greatly distorted image. If the source is moved 5 cm further from the lens and tank the maximum angle of light impingent on the tank increases, however the distance travelled through the water is also decreases. The angular dependent displacement of this setup is shown in (b). If the object and lens are then shifted 5 cm further from the tank such that $\boldsymbol{d_o}$ remains 15 cm and the lens is 5 cm from the tank, the angle is still increased, however the distance travelled through water is less than before. The angle dependent displacement of this setup is shown in (c). A comparison of the effect of these different setups is given in in (d). This data compliments the observations made during the image formation exercise: decreasing $\boldsymbol{d_i}$ and/or the distance the focused rays travel in the scatter tank results in sharper image formation.

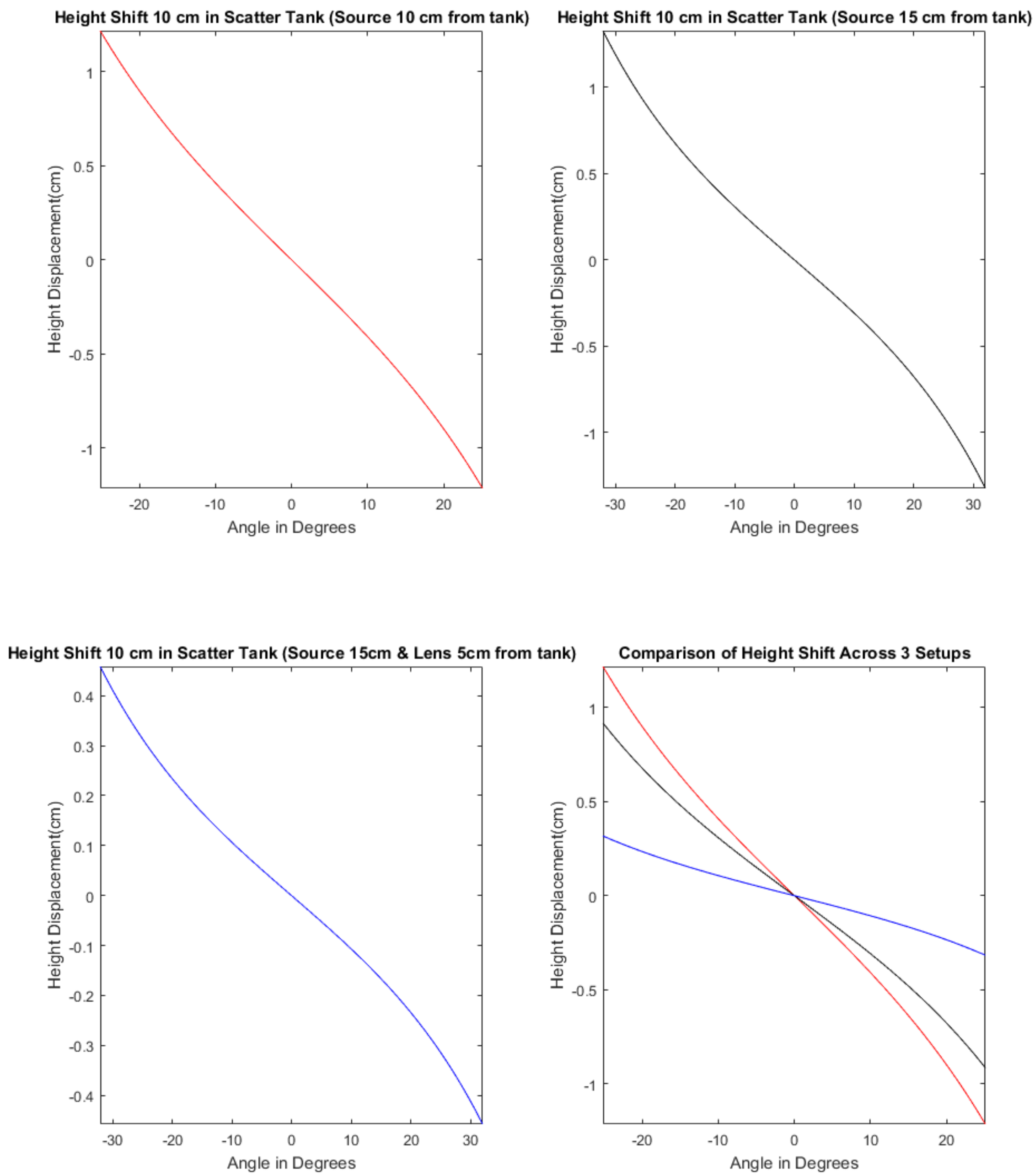

Figure 13 Height shift due to the scatter tank under various conditions analyzed at 10 cm from the lens.

3. Scattering Agents, Mie Scattering, Rayleigh Scattering & Blue Skies

The distortion of an image due to the scatter tank is an unintended side effect of using a dense medium suspend small particles to scatter and trace the path of the propagating light waves. The intended consequence, scattering for ray tracing, is an effect ubiquitous in everyday experiences of blue skies and sunsets. An effective scatter agent was chosen for the experiments, metal cutting oil; it readily forms micelles and dissolves in water and has a long shelf life. There are many such agents however, each having its own set unique properties of scattering.[29,30] The effect of the scattering agent is governed by Rayleigh scattering, caused by *diffuse* particles oscillating and elastically scattering light waves in every direction rather than in the direction of the wave propagation from the source[21]. The effect is wavelength dependent and is the cause of blue skies, sunrises and sunsets. The effect is governed by the following equation:

$$\boldsymbol{I} = \boldsymbol{I_0}\frac{\boldsymbol{1+cos^2\theta}}{\boldsymbol{2R^2}}\left(\frac{\boldsymbol{2\pi}}{\boldsymbol{\lambda}}\right)^{\boldsymbol{4}}\left(\frac{\boldsymbol{n^2-1}}{\boldsymbol{n^2+2}}\right)^{\boldsymbol{2}}\left(\frac{\boldsymbol{d}}{\boldsymbol{2}}\right)^{\boldsymbol{6}}$$

which can be broken into the following proportionalities:

$$\boldsymbol{I} \propto \boldsymbol{R^{-2}}$$

$$\boldsymbol{I} \propto \frac{\boldsymbol{1+cos^2\theta}}{\boldsymbol{2}}$$

$$\boldsymbol{I} \propto \boldsymbol{\lambda^{-4}}$$

$$\boldsymbol{I} \propto \boldsymbol{d^6}$$

where the initial intensity, $\boldsymbol{I_0}$, of a wave of light, $\boldsymbol{\lambda}$, traveling $\boldsymbol{R}$ meters to a particle of size, $\boldsymbol{d}$, with an index of refraction, $\boldsymbol{n}$, is scattered at an angle $\boldsymbol{\theta}$, resulting in a continuum of intensities, $\boldsymbol{I}$. From the related equations it can be seen that the distance traveled by the wave decreases the intensity by an inverse squared relationship; which is to be expected by from the spherical expansion of the wavefront. Waves scattered at 0° loose no intensity and are half as intense when scattered perpendicularly. The intensity is related to the inverse of the wavelength to the fourth power, thus longer wavelengths loose much more intensity due to scattering than shorter wavelength light. This is due to the dipole moment of molecules and the oscillation of their magnetic field and why many molecules have resonant frequencies in the ultraviolet spectrum. As well, larger particles scatter light more effectively to a point, they must remain much smaller than the wavelength of the light ($\boldsymbol{d} < \frac{\boldsymbol{\lambda}}{\boldsymbol{15}} \approx \boldsymbol{270}\text{Å}$); micelles sizes range from 20-200 Å and are dependent upon the constituent monomer size.[59] This is why as a beam of white light passes through the scatter tank it appears to be tinged blue or the relative "fuzziness" of the colored LEDs increases from red to green and green to blue.

Mie scattering is a generalized type of scattering that occurs from a homogenous sphere. A dense material can be modeled as a densely packed collection of homogenous spheres, the scattering of light traveling through such a material is the effect of the superposition of *many* coherent oscillators. The propagation of light through dense media can be seen as light passes through water or other liquids for example. The effect is that light waves are scattered preferentially in the forward direction and undergo destructive interference in lateral directions and increases the more dense, uniform and ordered the atoms or molecules are.

4. Mirages

Mirages are another set of distortions common to human experience and can be seen in figure 8 (f) temperature fluxes from surfaces or in our apparatus when sugar is dissolved in the tank and forms a gradient solution. Snell's Law dictates that the angle of light rays passing through an interface of two media will be proportional to the sine of the angle and the ratio of indexes of refraction. Now consider the case where the indexes of refraction are variable at different points in space. The effect would be similar to a heterogeneous scatter tank and images would be subject to any number of distortions. This appears to be in direct contradiction to Fermat's Principle of Least Time[20], which states that light always takes the short path between two points. It has been shown that,

$$(n-1) \propto \rho$$

and that density is related to changes temperature by changes in volume. Air directly above a hot road surface is hotter than air further away from the surface, the air can be viewed as thin slices of media of ever decreasing indexes of refraction the closer to the road surface the slice is. The effect is that light impingent at a shallow angle to the road surface will be bent upwards and appear to be coming from below the surface like a mirror. A similar effect can be seen in conjunction with the use of a gradient sugar solution. As the beam passes laterally through the solution that is concentrated corn syrup at the bottom, it is slowly bent upwards. The height of the beam above the scatter tank bottom was measured as the beam enters the tank and just before it exits. The beam was bent 5 mm higher before exiting the tank than after entering (2.5 cm and 2 cm respectively).

VI. Conclusions

It has been shown from the literature that there are common misconceptions in students' understanding of light. Misconceptions are held by students of all ages, from all backgrounds. These misconceptions prevent students from accurately describing many optical phenomena and are difficult to change. These misconceptions are summarized as follows:

1. Students do not recognize light as an electromagnetic wave propagating through space or the wave-particle duality of photons.

2. A holistic view of images and light as consisting of constituent "light rays" that travel parallel to one another through space, from one point of the source to one point of observable interaction.

3. Misuse and misinterpreting the language of scientists; students construct their own definitions, leading to a separation of words' 'meaning province' between novices and experts, and may misuse language to "prove" their false claims.

4. Vision; students believe the eye is "active" in "seeing" things, using "vision rays" to see, and fail to recognize the image formation process in vision.

5. Color is a property of objects, not light, light is usually absent from students' explanation; "brightness" is a property of the "color" itself, again no relation with light or photonic flux is expressed.

6. "Illuminated" is a passive environmental state; light constantly fluxing through the system is not seen as the cause.

7. Mirrors are special objects; images form on a mirrors' surface and this property of the material is not due to their high reflectance of visible light, it is attributed with the object itself.

Similar apparatus' and experiments were analyzed for their experimental value and focus on these misconceptions. A contemporary apparatus was designed and built using 3D printed components to decrease the overall cost. Experiments were designed to highlight some of the common misconceptions of students. The experiments were designed to build from simplistic to complex models and focus on the effects of light waves passing into media. The effects of image deformations were considered analytically, emphasizing the effects of media and giving a more complete explanation to the propagation of light than usually provided from university optics experiments.

Further improvements on the system can be made. Providing a media that effectively scatters light without noticeably distorting the image plane is theoretically possible, gasses are of interest. The drawbacks of such a system is that lenses cannot easily be used or exchanged within a sealed scatter tank (necessary to prevent diffusion of gasses. Many misconceptions can be highlighted and discussed more thoroughly through design of more experiments. The experiments detailed within this paper are only some of the possible experimental designs. By making the system inexpensive and easily assembled and modified, other users have the opportunity to optimize the system for their own uses.

Additionally, it should be noted this system does not claim to dispel student misconceptions. The constructivist approach to dealing with student misconceptions is considered appropriate, but by no means perfect. It is the student who needs to become dissatisfied with their own explanations and seek to reform their misconceptions, providing this experience is up to the teacher. Providing complex examples that force students' to predict outcomes is the achievable goal of the described apparatus.

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