Apparatus Competition

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Universal Apparatus to Demonstrate Optics Phenomena

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Abstract
An apparatus to demonstrate optics phenomena using relatively inexpensive commercially available components and 3D printed parts is presented. It consists of an array of color LEDs, an array of diode lasers, a white light source, lenses, diffraction gratings, a prism, and a scatter tank that holds a colloidal solution for ray tracing. The apparatus is designed to be used in lab courses, for in class demonstrations, and is particularly well suited when used with a digital document camera for larger audiences. The apparatus facilitates visual student learning of optics principles such as: refraction, color mixing, light scattering, focal length, image formation, diffraction and dispersion.

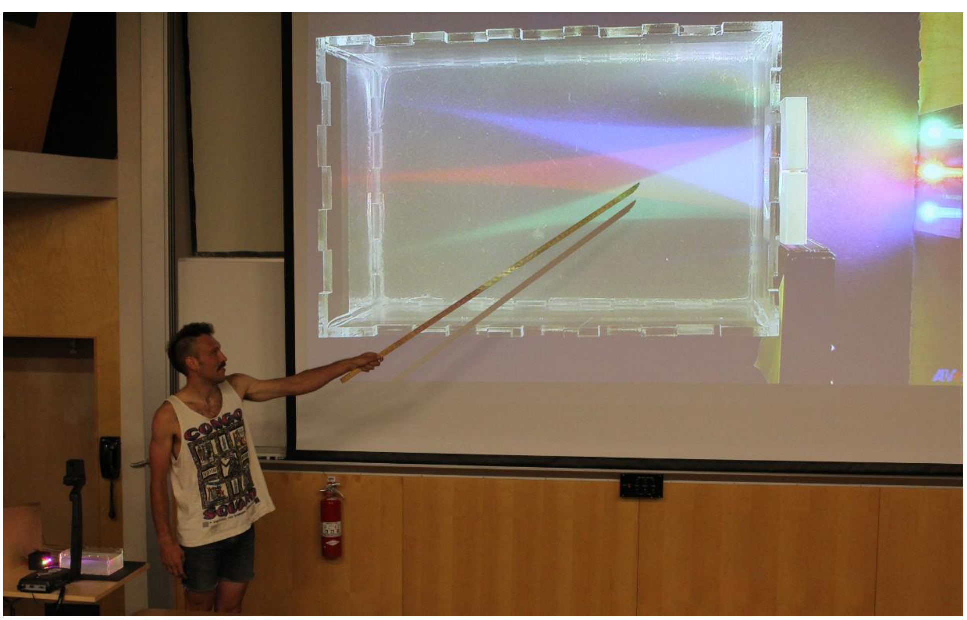

Fig. 1: The apparatus being used in classroom (with room lights on) in conjunction with a document camera (lower left of the image) to present image formation and color addition.

Construction of the Apparatus

The apparatus is designed to visually demonstrate optical phenomena common to optical physics problems in physics and optics courses. The individual components are not new or unique by themselves;[1-10] however, the ease of use, interchangeability of the system, and the ability to visualize different phenomena from many previously separate experiments in one system makes it a unique setup that is not currently available to teachers and students.

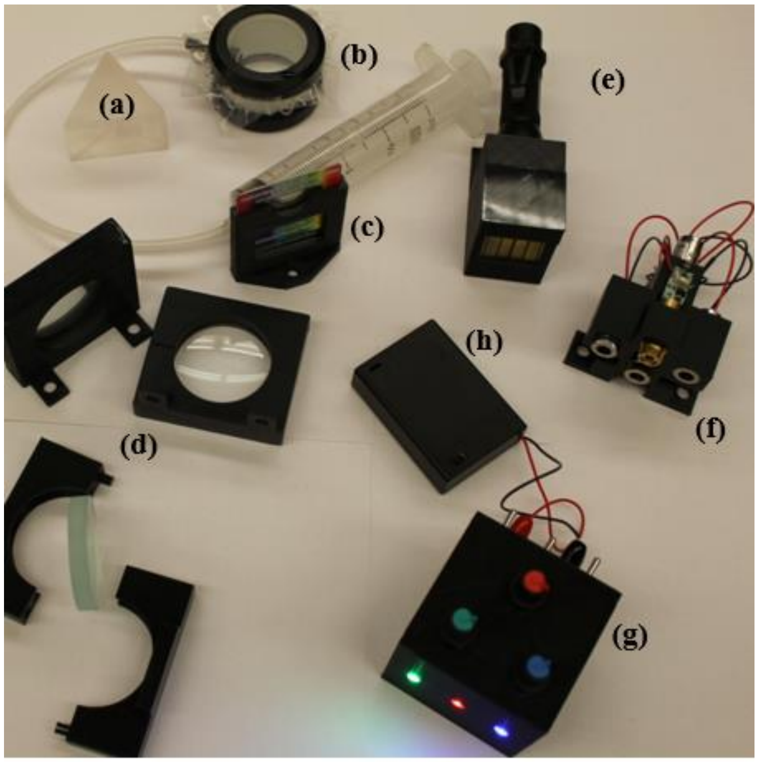

Fig. 2: Equipment used with the scatter tank: (a) glass prism, (b) air lens, (c) diffraction grating and holder, (d) lens holders with concave and convex lenses, (e) white light source with flashlight, (f) array of green, blue, and three red lasers, (g) red, green and blue LED box, (h) battery pack.

The apparatus requires a variety of light sources and optical elements. Unless otherwise indicated the holders of the optical components and light sources are 3D printed. Current 3D designs are available online at https://github.com/PSUScience/universal-optics and can be reproduced by anybody with a 3D printer. Here is a list and description of the major components of the apparatus:

- The light scatter tank (see Fig. 3 (a) for side view or Fig. 4 for top view) is constructed from laser cut pieces of optically transparent recycled acrylic glued together to form a watertight seal. The solution within the scatter tank is water with a few drops of metal cutting oil, milk or sugar. Added drops increase the scattering of light, which makes the light visible to an observer in any direction, but decrease the transmitted light intensity.

The bottom surface is black to get the best color contrast. Using black painted steel as a bottom plate allows the placement of optical elements with magnets in the tank.

- White light source using high intensity white LEDs. This source provides a single or five parallel beams similar to the Pasco ray box.[3] A similar light source can be built with a single, high intensity, neutral white LED (CREE XLamp XP-G2) flashlight powered by one AA battery (Fig. 3 (e)). The single beam can be used with a prism to show dispersion or with a diffraction grating. The five parallel beams can be used with any combination of lenses or mirrors to determine their focal lengths.

- Array of either three horizontally aligned red diode lasers or three vertically aligned blue, red and green diode lasers (Fig. 3 (f)). The 5 mW lasers were chosen such that they do not exceed the Class 3R rating (note: frequently the power ratings of lasers are incorrect and one needs to measure their power output and limit the supplied current). Direct exposure of laser light to the eye needs to be avoided, thus the sides of our scatter tank can be blocked to limit exposure. We recommend that only individuals with appropriate training use them in the classroom.
  The three horizontal beams can be used with combinations of lenses to investigate the focal length of lenses (an alternative to the white light source). The three vertical beams can be used with a diffraction grating to demonstrate the wavelength dependence of the location of side maxima for different colors of light. The scatter tank allows tracking the beams through the medium rather than just showing the transmitted location as a bright dot on a piece of paper.

- Light box with three high intensity blue, red and green LEDs (Fig. 3 (g)). This source is designed to be used with lenses to demonstrate image formation of point sources and color mixing. The LEDs are mounted in a box, which is height matched to all optical components to work both horizontally and vertically. The LEDs work as sold by the vendor, but we filed and polished the lenses to create a flat surface for a better point source. Other devices present color mixing[7,8] or image formation,[9] however our apparatus is unique in its ability to visualize the path the light takes.

- Lens holders designed to open and close over 50 mm diameter concave and convex lenses of various thicknesses (Fig. 3 (d)). The lens holders can hang from the side of the light scatter tank, be screwed down to an optical table, fixed with magnets to a steel surface or standalone outside or inside the tank.

- Air lens made from PVC pipe with flexible latex membranes and 60cc syringe to adjust the radius of curvature (Fig. 3 (b)). The air lens is similar to previous designs,[10,11] but has a larger diameter to capture more light.

- Additional designs include holders for diffraction gratings (Fig. 3 (c)) and commercially available parts like the prism (Fig. 3 (a)), battery pack (Fig. 3 (h)), lenses, mirrors, and diffraction gratings.

Parts list

Device	Component	Cost	Source
Laser Stand	1 x 532MD-5-1250-BL Green Laser	$13.99	http://www.amazon.com/product/dp/B018ASBZQQ
	1 x d611111111 Blue Laser	$10.01	http://www.amazon.com/gp/product/B014WZV9DA/ref=s9_dcacsd_bhz_bw_c_x_1
	3 x FH0054 Red Laser	$19.43	http://www.amazon.com/gp/product/B01CH53Y08/ref=olp_product_details?ie=UTF8&me=
	1 x MTS-202 Switches	$0.63	http://www.amazon.com/TOOGOO-125V-Position-Toggle-Switch/dp/B00IIDY49E
	2 x cess-bn15*12 Banana Plug Female	$0.88	http://www.amazon.com/12-Banana-Plug-Socket-Female/dp/B01690VADK
	5 x 8-32 x 1/8" Set Screws	$0.22	http://www.mcmaster.com/#92311a188/=12u4srp
Color LED Box	1 x C5SMF-BJS-CS24Q4T2 Blue LED	$0.22	http://www.mouser.com/
	1 x C5SMF-RJS-CU34QBB2 Red LED	$0.20	http://www.mouser.com/
	1 x C5SMF-GJS-CV0Y0792 Green LED	$0.23	http://www.mouser.com/
	3 x MTS-202 Switches	$1.90	http://www.amazon.com/TOOGOO-125V-Position-Toggle-Switch/dp/B00IIDY49E
	3 x s15072400am2613 Potentiometers	$4.66	http://www.amazon.com/uxcell%C2%AE-Linear-Taper-Rotary-Potentiometer/dp/B00X73X67Q
	2 x cess-bn15*12 Banana Plug Female	$0.88	http://www.amazon.com/12-Banana-Plug-Socket-Female/dp/B01690VADK
	2 x P100BACT-ND 100 Ohm Resistor	$0.18	http://www.digikey.com/
	1 x S68CACT-ND 68 ohm Resistor	$0.10	http://www.digikey.com/
White Light Source	15 x C503C-WAS-CCADB231 White LED	$3.60	http://www.mouser.com/
	15 x S68CACT-ND 68 ohm Resistor	$1.50	http://www.digikey.com/
	1 x MTS-202 Switche	$1.90	http://www.amazon.com/TOOGOO-125V-Position-Toggle-Switch/dp/B00IIDY49E
	1 x 20382 LED Flashlight	$16.14	http://www.amazon.com/gp/product/B00IEMUOWU/ref=olp_product_details?ie=UTF8&me=
Power Supply	1 x B00SUVOIO0 3 x AA Batteries Battery Holder	$3.23	http://www.amazon.com/gp/product/B00SUVOIO0/ref=olp_product_details?ie=UTF8&me=
	2 x B00APVQZ8U Banana Plug Male	$0.73	http://www.amazon.com/product/dp/B00APVQZ8U
	3 x ALK AA48FFP-U AMZ AA Batteries	$0.80	http://www.amazon.com/product/dp/B00MNV8E0C
Optics	1 x PH0534GCV 50 mm Lens 50 mm FlDouble Convex	$7.88	http://www.amazon.com/gp/product/B0193K6010/ref=olp_product_details?ie=UTF8&me=
	1x LI220-0100 Prism	$4.90	http://www.amazon.com/dp/B00EPQAE88
	1 x 01603-50 1000 lines/mm Diffraction Grating	$0.40	http://www.amazon.com/product/dp/B00K6K3Q50
	1 x PH0536HCC 50 mm Lens 50 mm FlDouble Concave	$5.12	http://www.amazon.com/dp/B01F9KXT62/ref=olp_product_details?_encoding=UTF8&me=
	Mirrors	Optional	http://www.arborsci.com/concave-convex-mirror-set
	1 x 50 mm 100 mm FL Double Convex Lens	Optional	https://www.amazon.com/product/dp/B0088AQYBI/
	1 x 50 mm 100 mm FL Double Concave Lens	Optional	https://www.amazon.com/product/dp/B00EPQ961O/
Air Lens	1 x 2" PVC Coupling	$1.02	https://www.grainger.com/product/LASCO-PVC-Coupling-22FJ50?functionCode=P2IDP2PCP
	.020" thick Silicone Sheet	$1.26	http://www.mcmaster.com/#86915k12/=12u4tst
	1 x Barbed Hose Fitting	$0.75	https://www.amazon.com/Eldon-James-A2-2PP-Non-Animal-Polypropylene/dp/B017VNO32O/
	1 x 1' length of 1/8" ID Tubing	$0.74	https://www.amazon.com/dp/B000FMWW72/ref=biss_dp_t_asn
	1 x 60 mL Syringe	$0.60	https://www.amazon.com/Syringe-60cc-Luer-Lock-Sterile/dp/B000FN897I/
Scatter Tank	Scrap Acrylic	Negligible	
	Acrylic Glue	Negligible	
	Black Paint	Negligible	
	Steel sheet	Negligible	
Misc.	Wire	Negligible	
	Solder	Negligible	
	1/4"x1/8" Magnets	$3.44	https://www.kjmagnetics.com/proddetail.asp?prod=D42B-N52
Total		$93.55	

Use of the Apparatus

Students' naive ideas concerning image formation and the effects of lensing are not inherently dispelled through the general physics optics coursework.[12-16] Students are often able to recall facts, but are frequently unable to apply that knowledge to actual optical experiments. Applying their developing skills of drawing ray diagrams, using the lenses, Snell's law, and Lens-Maker's equation with real world situations may be integral to synthesizing information into a working mental model. Furthermore, repeatedly experimenting and contextualizing similar models helps make a concrete, lasting impression on learners.[17] Demonstrating optical phenomena in a classroom to multiple students can be challenging and often requires various sets of equipment.[1-10] This equipment is used successfully by many instructors, but has the disadvantage of being at times difficult to handle, may not work in some classrooms, and can be expensive.

An alternative method is proposed more closely aligning with the current trends in physics education.[18-20] We have constructed an apparatus that allows the demonstration and investigation of a wide variety of optical phenomena, building from simplistic to more complicated models. The experiments deal directly with many common student misconceptions, without relying on misleading descriptions of the optical process. The apparatus is inexpensive, portable and easy to use by either individual students or with a document camera in a large classroom. The visual focus of the apparatus is a water-tight acrylic container that holds a colloidal solution to scatter light. The chamber is transparent to visible light and therefore transmits beams into the colloidal solution that effectively traces the beam pathway by scattering the light. While the interface between air and the water tank can cause some distortion, it can be modeled or minimized if one keeps the light rays close to the main axis. The chamber is used in conjunction with various light sources, lasers and diodes, as well as common optical elements, lenses, slits and diffraction gratings, to illustrate the principles of optical effects.

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 can be done individually or scaffolded. For example, Activities 1-4 nicely build on each other. Activity 4 is especially rich in physics content, taking advantage of the apparatus to visualize various optics concepts and phenomena. Further exploration with modeling the experiments can be taken by tracing light rays using one of the many online apps for ray tracing, for example the one we used to design our ray diagram (Fig. 7 (b)).[22] This free app for Google Chrome allows students to recreate the effects they are seeing in the experimental design.

1. Color addition

This experiment illustrates how the three primary colors, green, red and blue, combine to produce the different colors of the rainbow. Green, red and blue LED's can combine to make white light, they can be turned on or off and 'mixed' by adjusting their intensities up or down. It is worthwhile discussing why the light is not easily visible in the air before entering the scatter tank. In the tank, due to the large number of small particles of the colloidal scatter agent, the light is scattered and easily observable. One can observe that blue light is scattered more than red light due to the wavelength dependence of this scatter phenomena.[23,24] One can discuss with students that this causes the sky being blue during the day and red during sunset.

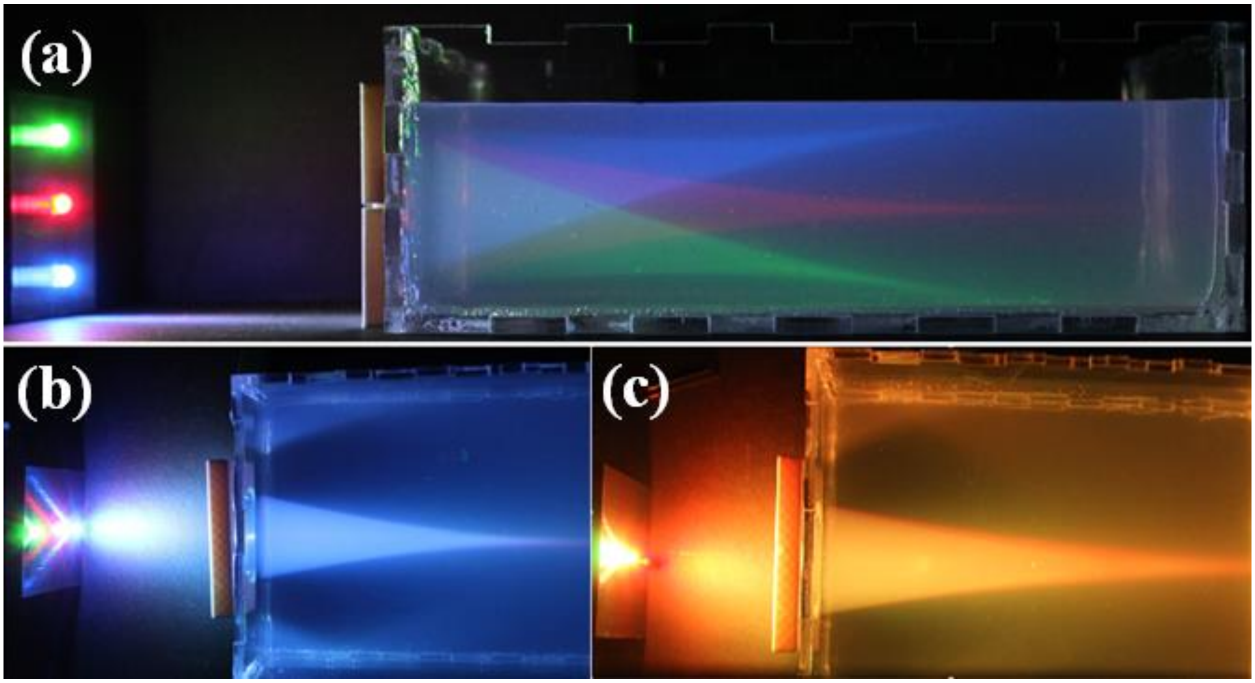

Fig. 3: (a) (Side view) Light from the LEDs traveling through a convex lens into the scatter tank. (b) (Top view) Light from vertically arranged green, red, and blue LEDs entering the scatter tank through a convex lens. With all three LEDs on, the colors mix to white with a bluish hue. (c) (Top View) The blue LED is turned off and *light from vertically arranged green and red LEDs entering the scatter tank through a convex lens mix to a yellow color. The light intensity of the LEDs can be adjusted with potentiometers to mix the different colors of the rainbow.*

2. Dispersion of light travel through a prism

This experiment utilizes the white light source to emit a single beam that, when refracted at the appropriate angle, is dispersed through a prism. Due to the wavelength dependence of the index of refraction red light is deflected less than blue light as white light passes through the prism, effectively separating the various color constituents of white light.

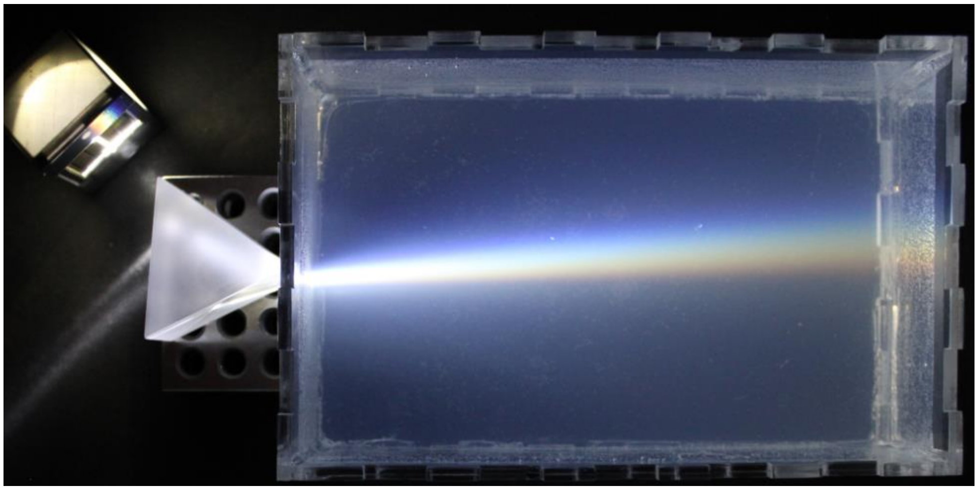

Fig. 4: White light from the LED disperses as it goes through a glass prism, showing a rainbow in the scatter tank. Note that the color spectrum of a white LED would be different from an incandescent light bulb.

3. Focusing with convex lens outside the scatter tank

This demonstration shows the focusing of light as it passes through a convex lens and then travels into the scatter tank. Either one of the two light sources producing three/five parallel beams, red lasers or white light, can be used in conjunction with a 5 cm focal length convex lens. The beam crossover point can be measured and the focal length determined.

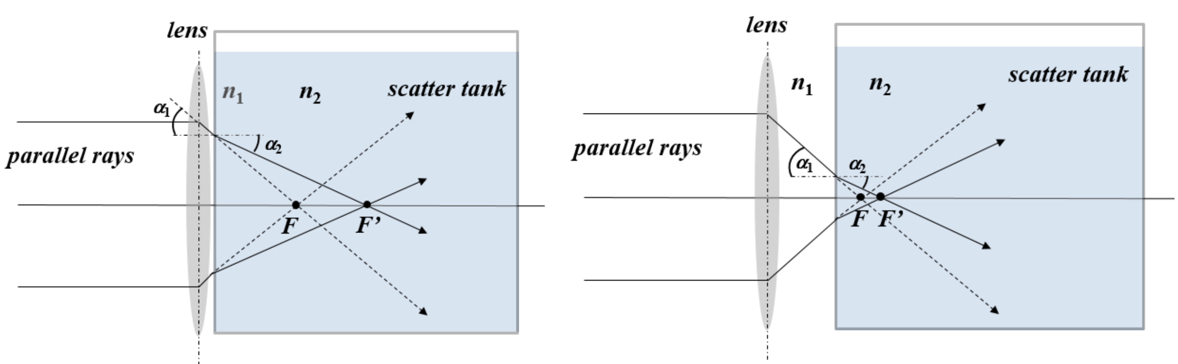

Fig. 5: Parallel rays get focused by the convex lens and enter the scatter tank. F indicates the focal point if the lens is used in air, F' when used with the scatter tank. Note that the light gets refracted as it passes from the air, to the lens and into the higher index of refraction water in the tank. Note that the focal point F' is always to the right of F and moves further away when the lens is closer to the scatter tank. The acrylic wall and the water in the tank will cause the focal point to be slightly less defined resulting in some distortions when the setup is used to investigate image formation. These distortions can be modelled well with a ray tracing app.[22]

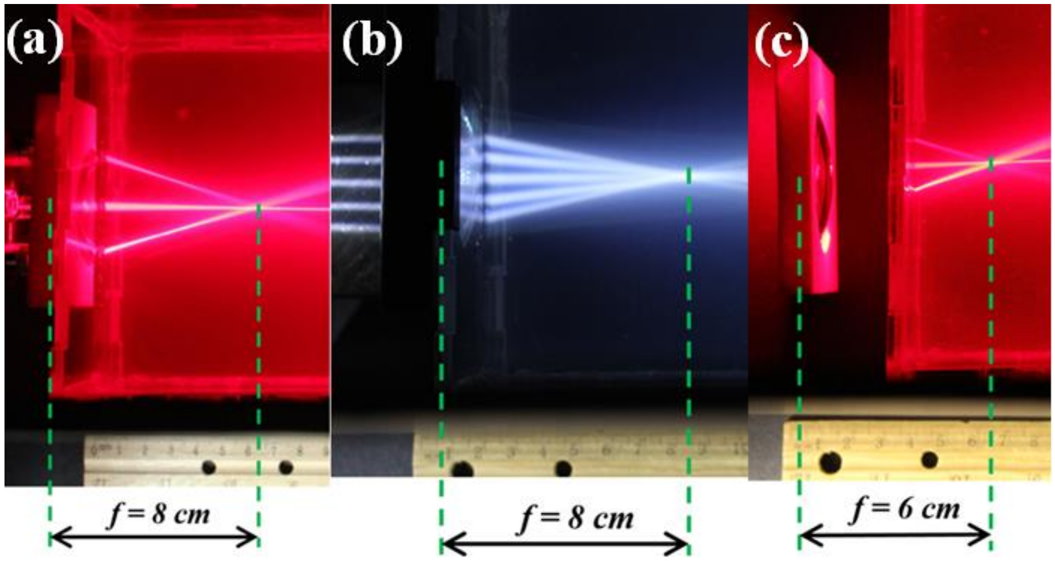

Fig. 6: Picture of three/five parallel rays with a 5 cm convex lens in front of the scatter tank using the red lasers (a) and white light ray sources (b). As expected from the ray diagrams in Fig. 5, the focal point is closer to the 5 cm convex lens when the lens is further away from the scatter tank (c).

4. Image formation with a convex lens

This experiment is related to image formation and uses the three LEDs as approximate point sources with a convex lens. When the emitted light is focused by the lens, the image of the point sources is formed. By this demonstration it can be seen that the point sources emit light in all directions, not merely along the principle rays path, a common misconception of students. Additionally, it can be shown that covering half the lens will not omit half the image, another common misconception of students, but merely decrease the brightness of the image formed.

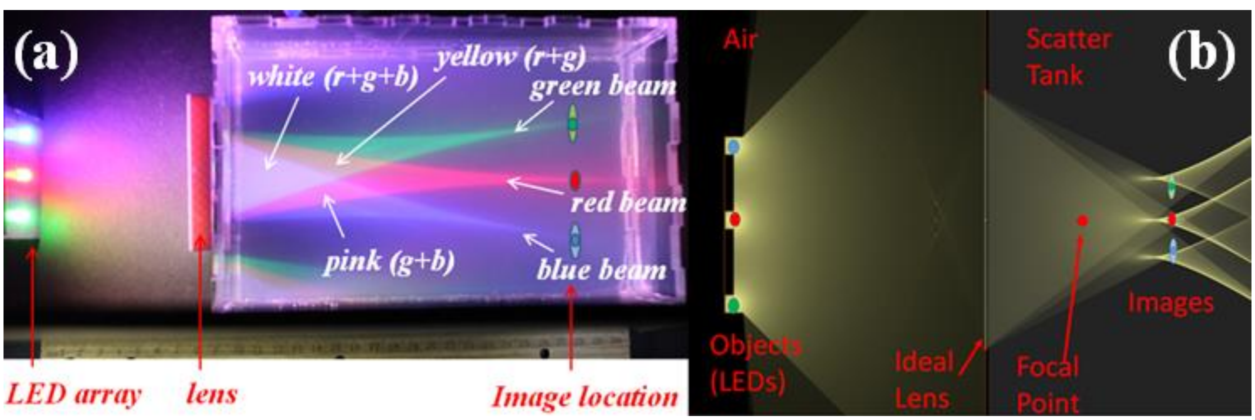

Fig. 7: (a) Picture of the setup with light from the red, green, and blue LEDs going through a convex lens (f=5 cm) into the scatter tank. (b)Simulation of the optical system assuming n_{air}=1 and n_{water}=1.33 in the scatter tank, the LED as point sources, an ideal 5 cm focal length lens, and ignoring the acrylic walls using the free ray tracing app.[22]

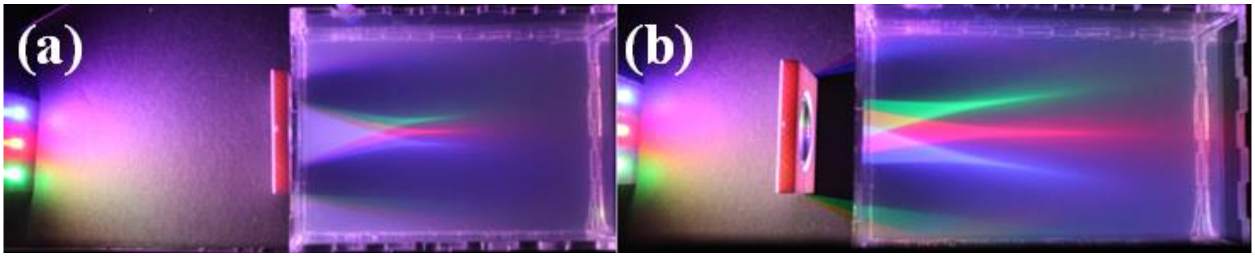

Fig. 8: (a) Setup with increased distance of the LEDs from the lens (object distance). Note that the image distance (the distance between lens and where the beams converge) and size (the distance between the green, red, blue beams at the convergence point) decreased. (b) Setup with the lens further from the scatter tank. Notice that the rays do not converge precisely for the outer LED's due to the interface between air and the scatter tank; this leads to a slightly out of focus and distorted image.

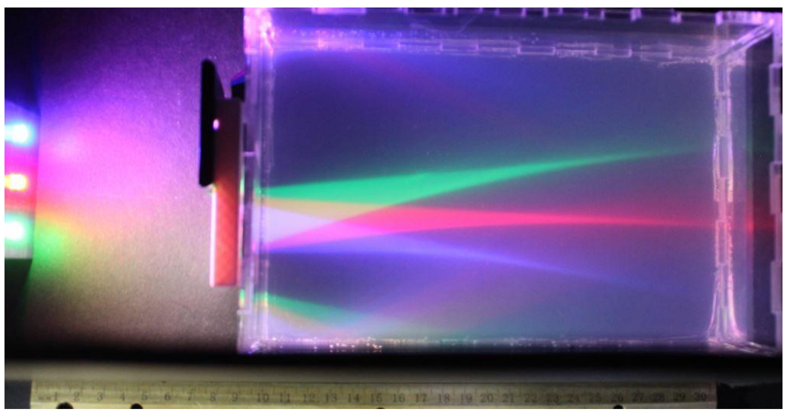

Fig. 9: (a) Picture of setup with light from the top half of the lens blocked. Note that the intensity decreases, but there is still an image formed. Note that blocking some of the light makes the image distortions due to the air/scatter tank interface more visible. This can be explored experimentally or with a ray tracing app.[22]

5. Diffraction of light through a diffraction grating

This experiment illustrates the effect of using a diffraction grating to separate different wavelengths of light or taking measurements with a diffraction grating to analyze the wavelength of emitted light. The three parallel lasers of different colors are passed through diffraction gratings (e.g. 1000 lines/mm) diffracting at larger angles for increasing wavelengths (Fig. 10 (b)). Similarly, the white light source can be used and its light broken into its components (Fig. 10 (a)). Measuring the angle of the maxima can be used to quantitatively estimate the wavelengths of light.

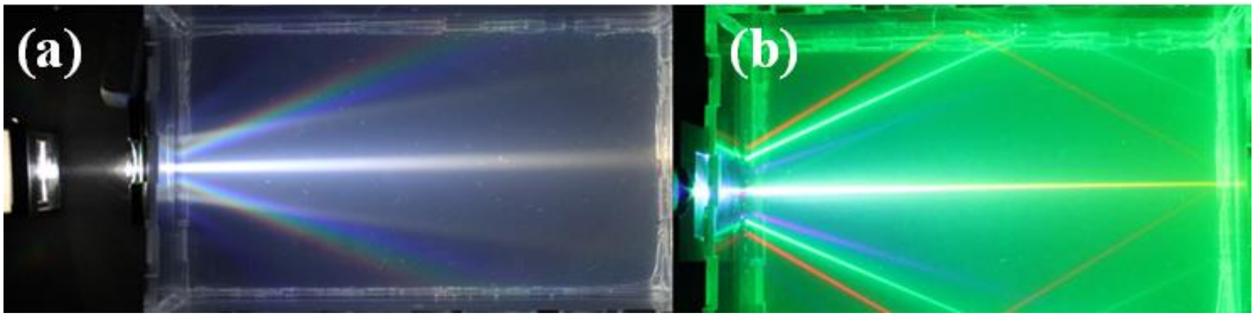

Fig. 10: (a) White light diffracted by a 1000 lines/mm diffraction grating, (b) red, green and blue laser light diffracted by a 1000 lines/mm diffraction grating.

6. Air lens

A classic optics question that challenges students to think about Snell's law of refraction at the interface of a curved surface is reversing the indexes of refraction of a lens and the medium it is in. For example, a spherical air bubble will act like a diverging lens in a liquid which has an index of refraction larger than air. An empty glass will also serve as a diverging lens if placed in the scatter tank (Fig. 13 (b)). We used standard PVC piping and sheets of latex adapted from a previous design[10,11] to make an adjustable surface to form convex and concave lenses. The convex lens acts as a diverging lens (Fig. 13 (a)) and the concave lens acts as a converging lens (Fig. 11 (b)) when placed in the scatter tank. The concave lens can form an image (see light paths in Fig. 12) and students can apply Snell's law in conjunction with measurements of the focal length (through Fig. 11 (b) or from the Lens-Maker's equation) to calculate object and image distances for a thick lens.

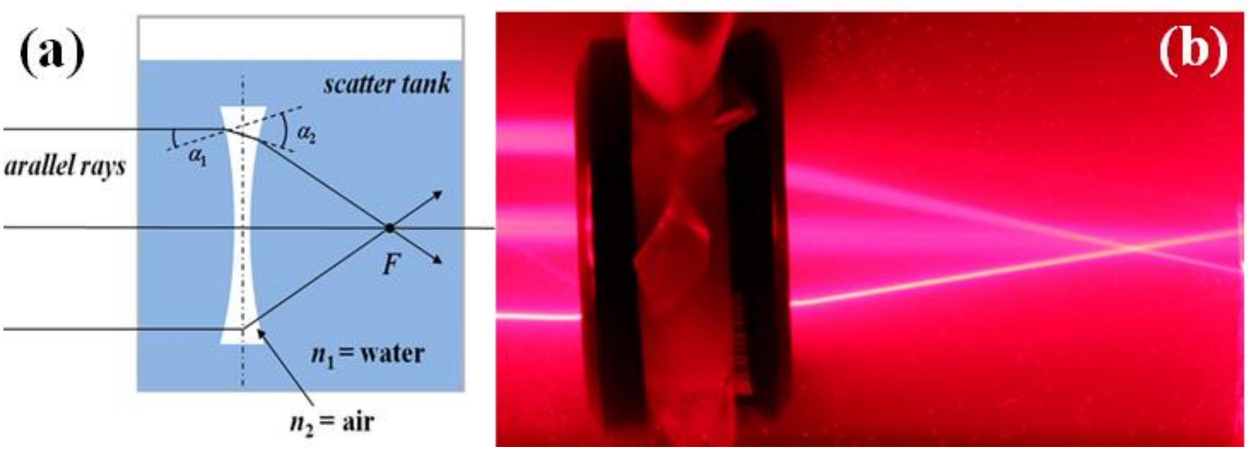

Fig. 11: *Concave air lens serving as a converging lens in the scatter tank. (a) Schematic* ray *diagram of concave air lens (b) thick concave air lens converging the red laser beams*

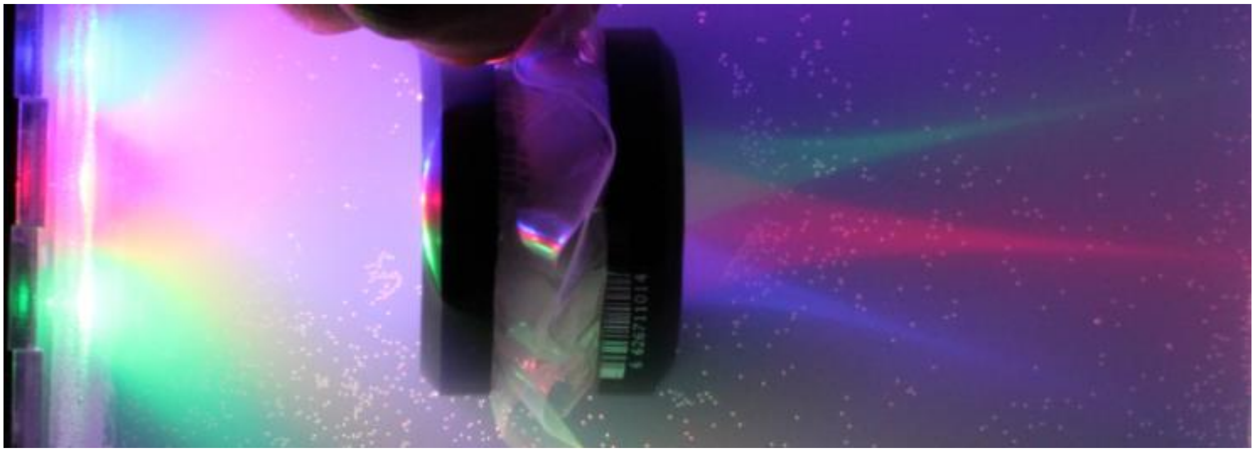

Fig. 12: The red, green, and blue light from the LED array passes through the concave air lens. The light gets focused and an image of the color LEDs is formed to the right of the concave air lens. There are some distortions since the LEDs are outside the tank.

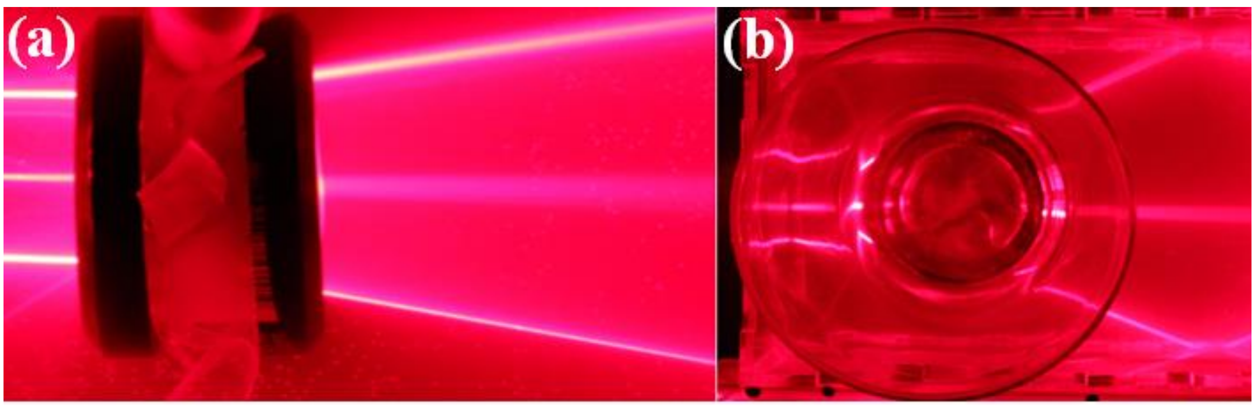

Fig. 13: Laser beam enters from the left onto: (a) Convex air lens serving as a diverging lens in the scatter tank. (b) Empty drinking glass serving as a diverging lens in the scatter tank.

7. Further experiments: Prisms, curved mirrors, lens combinations, concave lenses, and lenses in the scatter tank

The scatter tank setup with the laser or white LED light sources allow the visual exploration of many other optical phenomena and concepts. Below are just a few examples of experiments or demonstrations that can be setup.

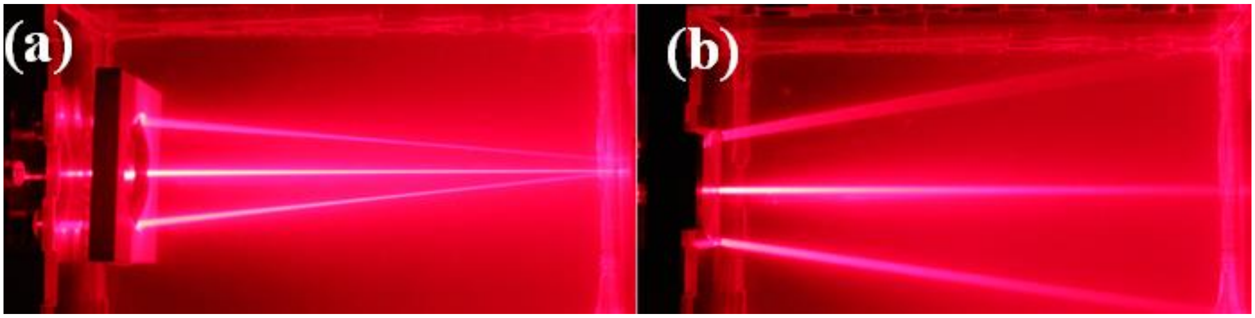

Fig. 14: (a) The 5 cm convex lens in the scatter tank. Since the ratio of the index of refraction of water and the lens is smaller compared to the lens and air, a larger focal length occurs when the lens is placed inside the scatter tank as opposed to outside. One can use the Lens-Maker's equation to calculate the focal length in water. (b) Light rays diverge due to a concave lens in front of the scatter tank.

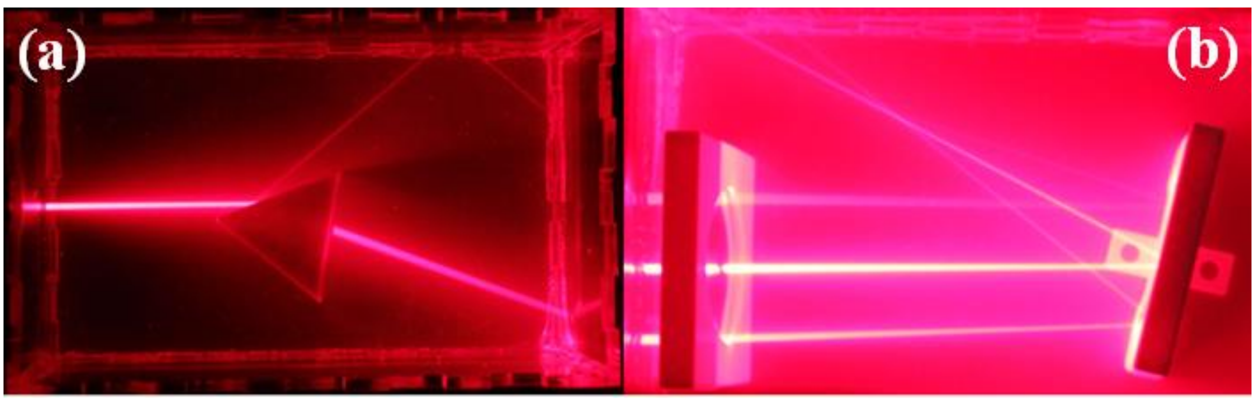

Fig. 15: (a) Red Laser beam getting refracted by a prism in the scatter tank. Note the part of the beam that is reflected at the prism interface. (b) Combination of a 10 cm focal length convex lens and a 10 cm focal length concave mirror placed in the scatter tank.

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