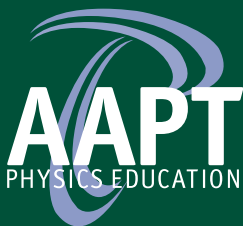# Apparatus Competition

AAPT PHYSICS EDUCATION

2016 SUMMER MEETING
JULY 16-20 SACRAMENTO, CA

American Association of Physics Teachers

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Low-Cost Interferometer Experiment with 3D Printed High Precision Tilt Adjustable Lens Holders and Flexure Stage

Abstract

Michelson-Morley interferometers are classic experimental devices in optics and are used in many college level experimental physics courses. Various commercial apparatus exist that demonstrate interference of two coherent beams of monochromatic light. Other inexpensive self-made setups exist, but are often imprecise and difficult to use or build. Our 3D printed lens mounts and high precision lens holders and flexure stage lowers the cost of important precision optical components, ubiquitous to many optics experiments. Our setup demonstrates interference patterns generated from Michelson-Morley interferometers and allows students to measure the wavelength of lasers. The necessary parts are commercially available, relatively inexpensive and can be printed by anyone with a 3D printer.

Construction of the Apparatus

The design is an iteration of the famous Michelson-Morley interferometer. It uses a beam splitter and two mirrors to form two orthogonal beam paths and create interference patterns between the two monochromatic beams after recombination. Precision adjustment of the mirrors to be able to determine time zero (when the differences in path lengths between the two beams is an integer number of wavelengths) is crucial. Many such interferometers exist,[1-9] however there is a large gap between inexpensive, non-precision models[1-3] that have long setup times and more expensive, precision models[4-9] that can measure the wavelength. This apparatus aims to bridge the gap, offering students a low cost method for viewing interference patterns and measuring wavelength of the laser.

The setup requires a few precision components to visualize interference patterns and measure wavelength. The design of the lens holders and flexure stage are the heart of this apparatus and can be built using standard optical components attached to a frame which can be printed by any student or instructor who has access to a 3D printer. Current 3D designs are available online at: https://github.com/PSUScience/low-cost-interferometer.

- Three lens holders that have mounts for an optical table and one adapter for holding a standard inexpensive red diode pumped solid state laser. The lens

holders adjust planar tilt for two mirrors and the red laser. The version of the lens holder seen in Figure 1 was assembled with homemade ¼-100 screw bushings to reduce cost. These parts can be easily sourced online if fabrication facilities are not available.
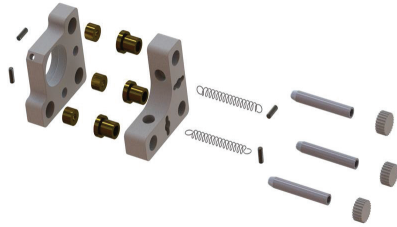
Figure 1: Exploded diagram of the lens holder.

- Flexure stage for precision linear translation of one of the mirrors.
- Beam splitter to split the beam into two orthogonal paths to the mirrors and recombine them before projection onto a screen. A holder was designed to height match the lens holders.
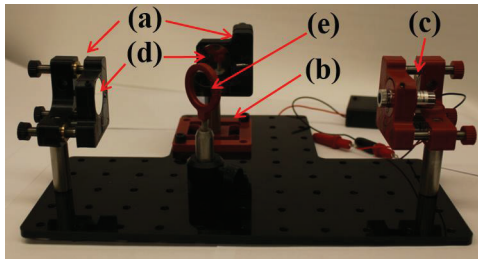
Figure 2: Picture of experimental setup. (a) Lens holders. (b) Flexure stage. (c) Laser in Laser holder. (d) Mirrors. (e) Beam splitter.

Use of the Apparatus

Adjustable lens holders are necessary in optical setups in both research and educational use. One often needs multiple holders for one experiment and the cost can add up for multiple experimental setups in an undergraduate laboratory course. This can be prohibitive in the design of some experiments at less funded institutions. 3D printers are becoming common tools at many high schools, two-year, and four-year colleges. They provide the ability to repair broken parts or build new equipment. They also provide a learning opportunity and let students actively participate in the design process. We have designed precision adjustable lens holders and a flexure stage to be used as a Michelson-Morley interferometer and other optics experiments that utilize these components.

Using these components, in conjunction with a beam splitter, mounted to an optical bench, one can observe interference patterns and measure the wavelength

of the laser. By understanding the scale of such measurements, one can begin to discuss the use of setups like a Fourier Transform Infrared Spectroscopy (FTIR) or even the Laser Interferometer Gravitational-Wave Observatory (LIGO).

The experimental setup can be viewed in Figure 2. The beam splitting surface is positioned at an angle $\pi/4$ to the beam pathway. Two lens holders with mirrors are positioned equidistant (on a macro-scale using the optical table) from the splitter along the perpendicular split beam pathways. By micro-adjusting one mirror, the two beam pathways are aligned and interference patterns produced.

Using the movable mirror on the flexure stage, the adjustment screw is turned a known amount (e.g. integer rotations). This causes the interference patterns to oscillate between dark and light fringes at any given location as the two waves move in and out of phase. By marking the interference fringes and counting the number of times the patterns cycle, the wavelength can be determined from the linear translation of the mirror on the flexure stage.

References

1. http://www.instructables.com/id/Desktop-Michelson-Morley-Interferometer/ (accessed 06/15/16)
2. http://i-fiberoptics.com/laser-kits-projects-detail.php?id=2130 (accessed 06/15/16)
3. https://www.amazon.com/product/dp/B008DWLESE/ (accessed 06/15/16)
4. https://www.pasco.com/prodCatalog/OS/OS-8501_introductory-michelson-interferometer/ (accessed 06/15/16)
5. https://www.thorlabs.de/NewGroupPage9_PF.cfm?Guide=10&Category_ID=138&ObjectGroup_ID=6635 (accessed 06/15/16)
6. http://www.thorlabs.us/NewGroupPage9_PF.cfm?Guide=10&Category_ID=117&ObjectGroup_ID=6957 (accessed 06/15/16)
7. https://www.amazon.com/product/dp/B00ES2PLZA/ (accessed 06/15/16)
8. https://www.a3bs.com/interferometer-u10350,p_647_719.html (accessed 06/15/16)
9. http://www.global-optosigma.com/en_us/interferometers/ifs2mi25.html (accessed 06/15/16)

Parts list

Item	MFG part #	# of Units	Price/unit	Total Cost /Set	Address
1/4-100 screw	F25US150	5	$6.21	$31.05	https://www.thorlabs.com/thorproduct.cfm?partnumber=F25US150
Extension Spring	9654K971	6	$0.64	$3.84	http://www.mcmaster.com/#9654k971/=12urqm9
Dowel Pin	98381A470	6	$0.10	$0.60	http://www.mcmaster.com/#98381a470/=12urq8h
.375" brass rod for screw seats and bushings*	8953K149	4.5	$2.74	$12.32	http://www.mcmaster.com/#8953k149/=12uruxo
Beam Splitter	EBS1	1	$31.40	$31.40	https://www.thorlabs.com/thorproduct.cfm?partnumber=EBS1
Mirrors	LOALMS25.4/18.3-1.1	2	$7.00	$14.00	http://www.aliexpress.com/item/25-4-18-3MM-Thickness-1-1-MM-Aluminium-Front-Surface-Reflected-Mirrors/32648784014.html
Red Laser	FH0054	1	$6.48	$6.48	http://www.amazon.com/gp/product/B01CH53Y08/
8-32 x 1/8" Set Screws	92311A188	4	$0.04	$0.18	http://www.mcmaster.com/#92311a188/=12u4srp
Total cost				$99.86	
* 1/4-100 bushings can also be purchased	F25USN2P	5	$5.18	$25.90	https://www.thorlabs.com/thorproduct.cfm?partnumber=F25USN2P

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Universal Apparatus to Demonstrate Optics Phenomena

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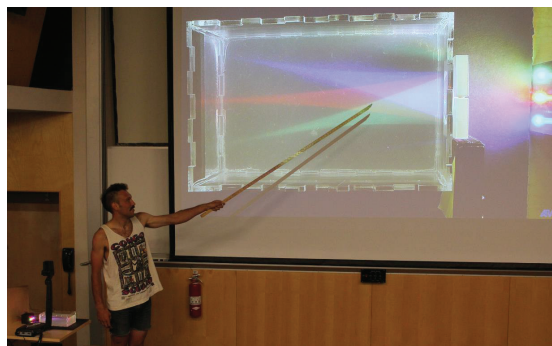
Figure 1: The apparatus being used in classroom (with room lights on) in conjunction with a document camera (lower left of the image) to present image formation and color addition.

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.

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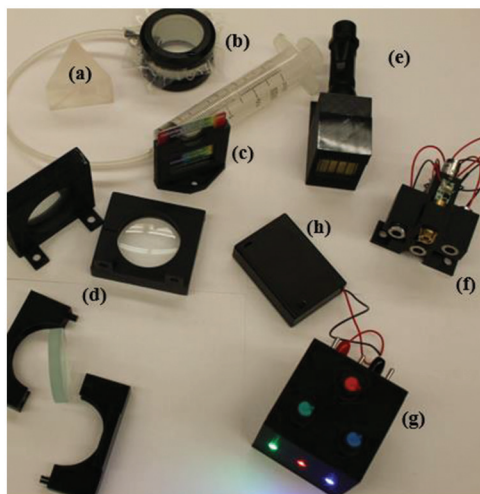
Figure 2: Equipment used with the scatter tank: (a) glass prism, (b) air lens, (c) diffraction grating and holder, (d) lens holders with concave and convex lenses, (e) white light source with flashlight, (f) array of green, blue, and three red lasers, (g) red, green and blue LED box, (h) battery pack.

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 train-

ing 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.
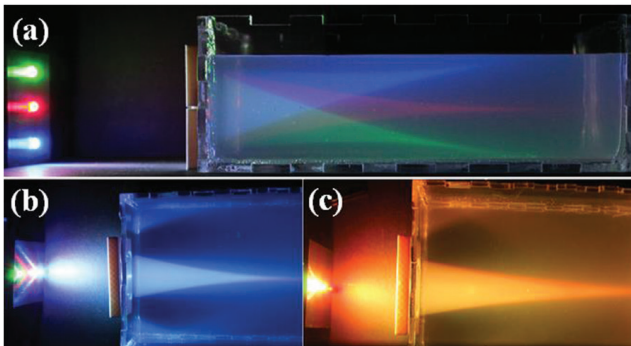
Figure 3: (a) (Side view) Light from the LEDs traveling through a convex lens into the scatter tank. (b) (Top view) Light from vertically arranged green, red, and blue LEDs entering the scatter tank through a convex lens. With all three LEDs on, the colors mix to white with a bluish hue. (c) (Top View) 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.

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/#92311a18&l=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 Fl Double 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 Fl Double 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/B00EPQ9610/
Air Lens	1 x 2" PVC Coupling	$1.02	https://www.grainger.com/product/LASCO-PVC-Coupling-22F-J507/functionCode=P21DP2PCP
	.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.

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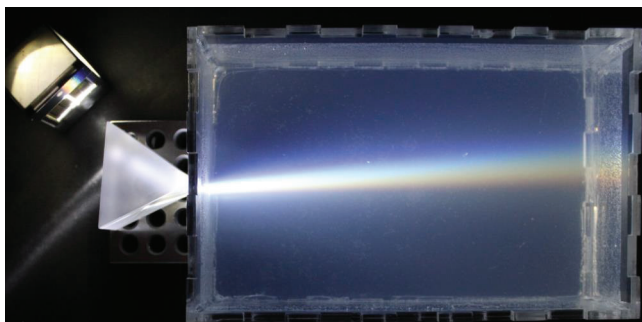
Figure 4: White light from the LED disperses as it goes through a glass prism, showing a rainbow in the scatter tank. Note that the color spectrum of a white LED would be different from an incandescent light bulb.

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.
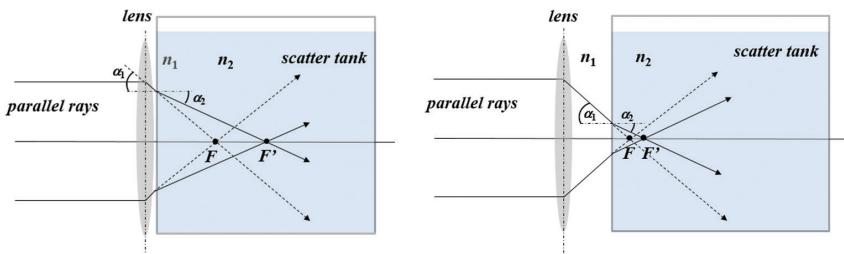
Figure 5: Parallel rays get focused by the convex lens and enter the scatter tank. F indicates the focal point if the lens is used in air, F' when used with the scatter tank. Note that the light gets refracted as it passes from the air, to the lens and into the higher index of refraction water in the 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]
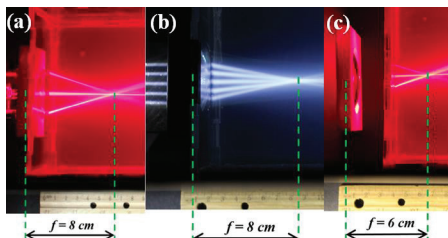

Figure 6: Picture of three/five parallel rays with a 5 cm convex lens in front of the scatter tank using the red lasers (a) and white light ray sources (b). As expected from the ray diagrams in Fig. 5, the focal point is closer to the 5 cm convex lens when the lens is further away from the scatter tank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

Figure 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]
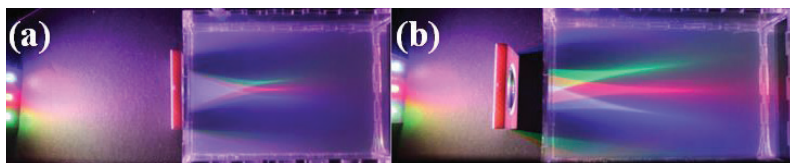
Figure 8: (a) Setup with increased distance of the LEDs from the lens (object distance). Note that the image distance (the di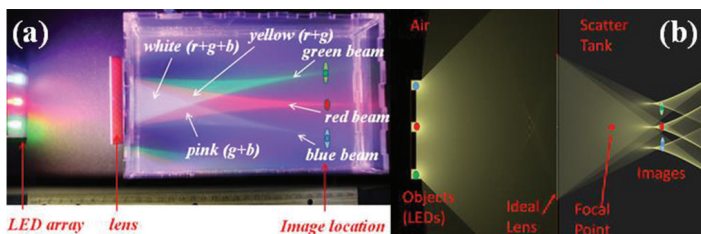stance between lens and where the beams converge) and size (the distance between the green, red, blue beams at the convergence point) decreased. **(b)** Setup with the lens further from the scatter tank. Notice that the rays do not converge precisely for the outer LED's due to the interface between air and the scatter tank; this leads to a slightly out of focus and distorted image.
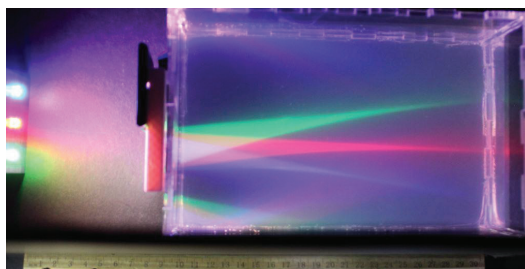
Figure 9: (a) Picture of setup with light from the top half of the lens blocked. Note that the intensity decreases, but there is still an image formed. Note that blocking some of the light makes the image distortions due to the air/scatter tank interface more visible. This can be explored experimentally 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)). Mea-

suring the angle of the maxima can be used to quantitatively estimate the wavelengths of light.
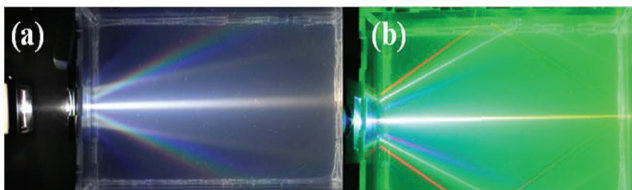
Figure 10: (a) White light diffracted by a 1000 lines/mm diffraction grating, (b) red, green and blue laser light diffracted by a 1000 lines/mm diffraction grating.

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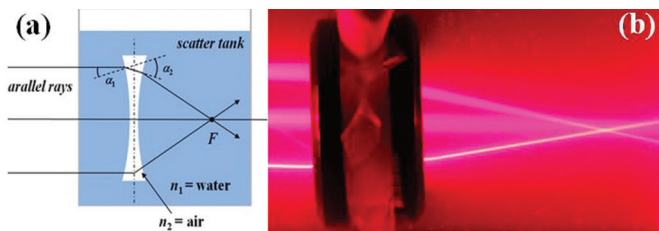
Figure 11: Concave air lens serving as a converging lens in the scatter tank. (a) Schematic ray diagram of concave air lens (b) thick concave air lens converging the red laser beams.

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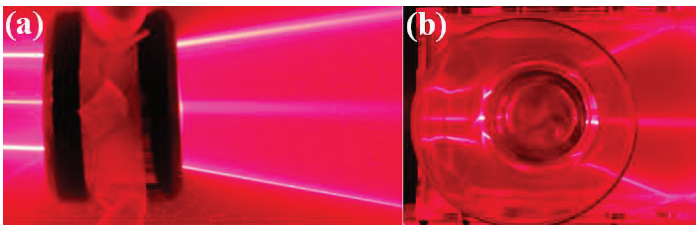
Figure 13: Laser beam enters from the left onto: (a) Convex air lens serving as a diverging lens in the scatter tank. (b) Empty drinking glass serving as a diverging lens in the scatter tank.

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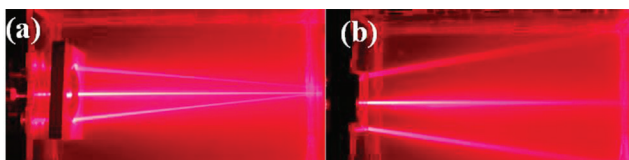
Figure 14: (a) The 5 cm convex lens in the scatter tank. Since the ratio of the index of refraction of water and the lens is smaller compared to the lens and air, a larger focal length occurs when the lens is placed inside the scatter tank as opposed to outside. One can use the Lens-Maker's equation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

Figure 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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Angle of Repose

Abstract

Angle of repose, an important characteristic of granular flow, is demonstrated with this thin enclosure, which contains sand and air. Multiple rod segments or partitions divide the enclosure into several rows. When the enclosure is turned upside down, the sand flows down and through the gaps between the partitions. Because the partitions are staggered, piles of sand are formed on them, clearly demonstrating the angle of repose. The enclosure has a simple design; requires no electricity or maintenance and can be used repeatedly with insignificant set up time.

Construction of Apparatus

The enclosure is made entirely of acrylic sheet and rod stocks. The front and back are 1/8" thick and cut to desired size. Black acrylic is used for the back to increase contrast. Four 1/4"-wide strips cut from thin, 1/16" thick, acrylic sheet serve as spacers around the enclosure. Thin rod, 1/16" thick, cut to 2" long pieces serve as partitions. A small portion of one of the edge strips is cut, but saved, to provide an opening to fill the sand. All parts, except the small cutout, are glued together with acrylic cement. The sand is carefully poured into the enclosure through a trough made of folded paper and partially inserted in the opening. The saved cutout piece is placed and glued in the opening. Acrylic paste-like glue is used to further reinforce all joints.

To fabricate this enclosure one needs to know basic fabrication techniques. Online resources to help with the fabrication techniques are available. For example, view instructional videos at tapplastics.com and type "Acrylic Sheet Fabrication Manual" in your search engine to download a 36-page manual. Special care is also required to glue the small partitions in place. Practice on scraps before final fabrication.

Use of Apparatus

It is easy to use the enclosure to demonstrate angle of repose. Pick the enclosure up from its cardboard stand, turn it 180-degree CW or CCW, and observe the resulting flow of sand and formation of sand mounds on the partition , exhibiting the angle of repose. Sample images are shown in Figure 1.
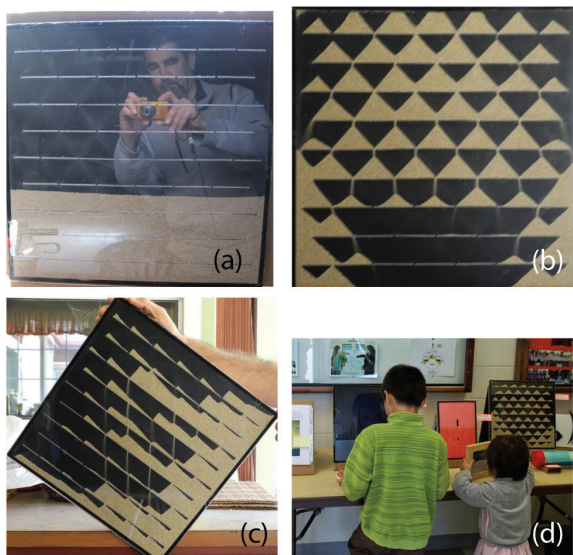
Figure 1. (a) Enclosure shown after several rocking motion to bring all sand to the bottom, (b) following turning the enclosure 180-degree sand flows through partition gaps and form mounds on partitions, clearly exhibiting the angle of repose, (c) enclosure turned to a different angle, and (d) these sorts of demonstrations, even though they show scientific principles, are attractive to children. Image (c) appeared in Visual Physics of *The Physics Teacher,* March 2016 issue.

Materials List:

Item	Quantity	Size	Source	Price, $
acrylic sheet, 1/8" thick	2	12 x 12"	plastic supplier[1]	2@ $10 each
acrylic sheet, 1/16" thick[2]	1	12 x 6"	plastic supplier	5.00
acrylic rod, 1/16" diameter	1	6 ft long	plastic supplier	<1.00
acrylic cement	1	4-oz can	plastic supplier	7.25
acrylic paste-like glue	1	5-oz. tube	plastic supplier	9.25
sand	1	small bag	home center	<5.00
Total				**47.50**

1. An example of plastic supplier TAP Plastics (tapplastics.com).
2. The supplier may cut the 1/4"-wide strips upon request; otherwise you would need a table saw with fine tooth blade to cut the strips.

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Flow Instability in Thin Enclosure

Abstract

Flow instability is demonstrated with this enclosure, which contains dyed glycerin and air. At idle, glycerin, the heavier fluid, rests at the bottom and air is at the top. This stable condition can easily be changed to unstable condition when the enclosure is turned upside down. Now the glycerin is at the top, and gravity causes it to flow down while air has to flow up, creating a dynamic interaction between the two fluids and demonstrating flow instability. The enclosure has a simple design; requires no electricity or maintenance and can be used repeatedly with insignificant set up time.

Construction of Apparatus

The enclosure is made entirely of acrylic sheet stock. The front and back are 1/8" thick and cut to desired size. (Colored acrylic could be used for the back to increase contrast.) Four 1/4"-wide strips cut from thin, 1/16" thick, acrylic sheet serve as spacers around the enclosure. A small section of one of the strips is cut, but saved, to provide an opening to fill the glycerin. All parts, except the small cutout, are glued together with acrylic cement. Glycerin is dyed with cake icing dye, and injected into the opening with a hypodermic needle. The saved cutout piece is placed and glued in the opening. Acrylic paste-like glue is used to further seal and reinforce all joints.

To fabricate this enclosure one needs to know basic fabrication techniques, and especially how to make leak proof joints between acrylic parts. Online resources to help with the fabrication techniques are available. For example, view instructional videos at tapplastics.com and type "Acrylic Sheet Fabrication Manual" in your search engine to download a 36-page manual.

Use of Apparatus

It is easy to use the enclosure to demonstrate two flow instabilities. Simply pick the enclosure up from its cardboard stand, turn it upside down (180-degree turn CW or CCW), place it back down on the stand, and observe the resulting flow and instabilities. The two fluid instabilities of interest here are: (1) Rayleigh-Taylor instability — When a heavier fluid is above a lighter fluid, an unstable situation is created. This gives rise to Rayleigh-Taylor instability and the resulting undulation at the interface of the two fluids as they exchange their places. (2) Saffman-Taylor instability — When the two sides of the enclosure are pressed together near the fluids' interface, the glycerin is forced out from the pressed area. ***Please pick up the enclosure to press the two sides as not to damage the cardboard stand.*** Upon releasing the pressure, air, which is the lesser viscous fluid,

rushes in and gives rise to fingering pattern called Saffman-Taylor instability. Sample images appear below in Figure 1. (Type "Flow Instabilities" in your search engine to download an 8-page pdf document titled "Flow Instabilities – MIT" to learn about the subject. There is also available a video in conjunction with the document.)
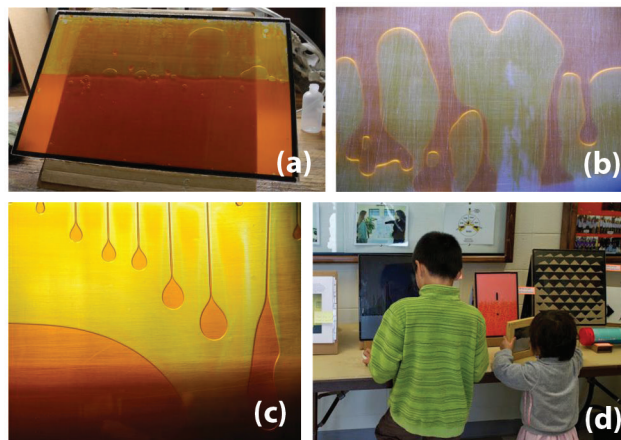

Figure 1. (a) Enclosure on its stand (at the end of a prior demonstration as a few air bubbles are still rising through glycerin), (b) close-up of undulation at the fluids' interface after the enclosure is turned upside down, (c) drops break away from the top edge near the end of a demonstration, and (d) these sorts of demonstrations, even though they show scientific principles, are attractive to children. A further cropped version of image (c) appeared in Visual Physics of *The Physics Teacher*, January and February 2016 issues.

Materials List:

Item	Quantity	Size	Source	Price, $
acrylic sheet, 1/8" thick	2	12 x 12"	plastic supplier[1]	2@ $10 each
acrylic sheet, 1/16" thick[2]	1	12 x 6"	plastic supplier	5.00
acrylic cement	1	4-oz can	plastic supplier	7.25
acrylic paste-like glue	1	5-oz tube	plastic supplier	9.25
glycerin	1	small bottle	drug store	<7.00
icing dye	1	1-oz can	art supply store[3]	2.29
dispenser with hypodermic needle (blunt tip)	1	2-oz bottle	plastic supplier	3.50
Total				54.29

1. An example of plastic supplier TAP Plastics (tapplastics.com).
2. The supplier may cut the 1/4"-wide strips upon request; otherwise you would need a table saw with fine tooth blade to cut the strips.
3. An example of art supply store is Michaels (michaels.com).

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Soap Bubbles in Thin Enclosure

Abstract

Soap films/bubbles obey specific arrangements called Plateau laws; the third law of which is demonstrated with this thin enclosure, which contains liquid soap and air. The third law stipulates that soap films meet in threes along an edge called a *Plateau border.* At idle, soap, the heavier fluid, rests at the bottom and the air is at the top. When the enclosure is turned upside down, the soap flows down and air flows up, creating random patterns of soap bubbles. Since the enclosure is thin, soap bubbles are formed in one layer and clearly seen. Plateau borders can be observed once the flow stops. The enclosure has a simple design; requires no electricity or maintenance and can be used repeatedly with insignificant set up time.

Construction of Apparatus

The enclosure is made entirely of acrylic sheet stock. The front and back are 1/8" thick and cut to desired size. (Colored back can be used for better contrast.) Four 1/4"-wide strips cut from thin, 1/16" thick, acrylic sheet serve as spacers around the enclosure. A small portion of one of the strips is cut, but saved, to provide an opening to fill the soap. All parts, except the small cutout, are glued together with acrylic cement. The soap is injected into the opening with a hypodermic needle. The saved cutout piece is placed and glued in the opening. Acrylic paste-like glue is used to further seal and reinforce all joints.

To fabricate this enclosure one needs to know basic fabrication techniques, and especially how to make leak proof joints between acrylic parts. Online resources to help with the fabrication techniques are available. For example, view instructional videos at tapplastics.com and type "Acrylic Sheet Fabrication Manual" in your search engine to download a 36-page manual.

Use of Apparatus

Plateau borders are demonstrated with the enclosure. The operation is easy. Simply pick the enclosure up from its cardboard stand, turn it 180-degree (upside down), set it back on its stand, and observe the interaction between downward flow of soap and upward flow of bubbles. Once the flow ceases, the Plateau borders can be observed. Sample images are shown in Figure 1.

As a companion, an annulus enclosure is also presented. The above description for flat enclosure equally applies to the annulus enclosure as well. The only difference is the geometry. The annulus is made of a section of PVC pipe as the inner cylinder (capped at both ends by gluing acrylic disks) and a plastic storage tube as the outer cylinder. Plastic caps (sold with plastic storage tube) seal the an-

nulus enclosure. The soap was dyed with food color. Sample images are shown in Figure 2.
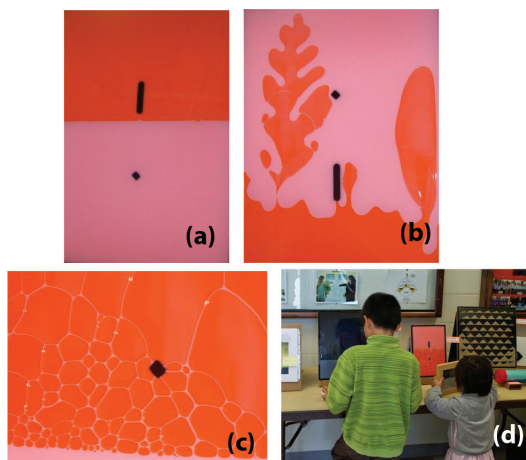
Figure 1. (a) The soap is at the bottom of the enclosure at rest, (b) after the enclosure is turn upside down interaction between downward flowing soap and creeping up air creates visually engaging pattern, (c) Plateau borders, and (d) these sorts of demonstrations, even though they show scientific principles, are attractive to children.

Figure 2. (a) Interaction of soap and air bubbles in annulus enclosure, (b) Plateau borders seen in annulua enclosure. Blue food color was added to the white soap.

Materials List:

Item	Quantity	Size	Source	Price, $
acrylic sheet, 1/8" thick	2	12 x 12"	plastic supplier[1]	2@ $10 each
acrylic sheet, 1/16" thick[2]	1	12 x 6"	plastic supplier	5.00
acrylic cement	1	4-oz can	plastic supplier	7.25
acrylic paste-like glue	1	5-oz tube	plastic supplier	9.25
white liquid dish washing soap	1	small bottle	grocery store	<5.00
food coloring	1	small bottle	grocery store	<3.00
dispenser with hypodermic needle (blunt tip)	1	2-oz bottle	plastic supplier	3.50
Total				**53.00**

1. An example of plastic supplier TAP Plastics (tapplastics.com).
2. The supplier may cut the 1/4"-wide strips upon request; otherwise you would need a table saw with fine tooth blade to cut the strips.

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Trailing Vortices in a Tube Filled with Water

Abstract

Trailing vortices that form behind an object moving in a fluid are demonstrated with this sealed tube, which contains water and an air bubble that serves as the object. Special crystals added to the water allow vortices to be observed. The tube rests in a V-shaped groove in packaging foam. The bubble is large enough to be clearly seen. The bubble is set in motion by pressing down the end of the tube near it. Trailing vortices are formed as the bubble moves across the tube and are visualized by the additive in the water that is sensitive to local shear force. The tube has a simple design; requires no electricity or maintenance and can be used repeatedly with insignificant set up time.

Construction of Apparatus

Using acrylic paste-like glue fix a cap on one end of the tube. Fill the tube with rheoscopic fluid but leave about 1/4” of air space. Glue the other cap to seal the tube. Rheoscopic fluid is water mixed with a pearl-like additive and is available for purchase. A sharp knife is used to cut the V-shaped groove in the packaging foam.

Use of Apparatus

It is easy to operate the tube. If the tube has been idle for a while, pick it up from its foam base and give it a good shake to remix the content as some settling takes place in rheoscopic fluid. Wait a few seconds and set it back into the foam. With your finger/thumb Gently press down on the end of the tube near the air bubble and watch the trailing vortices as the bubble moves across the tube. If the bubble is made to move *very* slowly, by applying very gentle pressure to the tube’s end, no trailing vortices will be observed. However, as the bubble is made to move a little faster, trailing vortices are formed and clearly seen. By controlling the applied pressure (in separate attempts), the number of trailing vortices can be changed from none, corresponding to laminar flow, to several and onto fully turbulent flow. Sample images are shown in Figure 1.
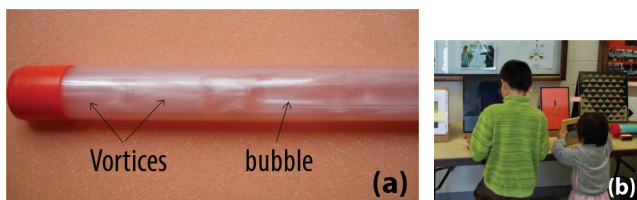
Figure 1. (a) Trailing vortices shown behind air bubble moving from left to right in a tube containing rheoscopic fluid (finger pressing the left end was just removed), **(b)** these sorts of demonstrations, even though they show scientific principles, are attractive to children. Here, the child in green shirt is playing with the trailing vortices demo to see if he could get the laminar vs. turbulent flow situations.

Materials List:

Item	Quantity	Size	Source	Price, $
10" acrylic tube with 2 caps	1	~1" OD	plastic supplier[1]	<10.00
acrylic paste-like glue	1	5-oz tube	plastic supplier	9.25
rheoscopic fluid	1	1 liter bottle	educational supplier[2]	16.95
Packaging foam	1	~1 ft^2	office supply	<10.00
Total				**46.20**

1. An example of plastic supplier on the West Coast is TAP Plastics (tapplastics.com).
2. An example of educational supplier is found at www.enasco.com.

Acknowledgement

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Random Number Generator with Radioactive Isotopes

Abstract

Radioactive isotopes decay at random time. We constructed a random number generator that is driven by the random delays between consecutive radioactive decays. We not only demonstrate the random nature of nuclear decay but also show its potential applications in scientific computing (such as Monte Carlo methods) and data encryption. Our generator was improved from John Walker's HotBits project.

Construction of Apparatus:

Figure 1 (a_d) depicts the parts and the assembled unit.

To construct the apparatus, you need the following parts:

Item	Qty	Unit price	Subtotal
Raspbery pi 2 B	1	$35	$35
3.5" LCD	1	$26	$26
Arduino nano, MAX3232 board, RJ11 board, breadboard	1	$30	$30
Aware RM-80 Radiation Sensor	1	$329	$329

Raspberry Pi set up

If you don't have "screen", install it by entering "sudo apt-get install screen" in a terminal. Once you have screen, type "nano .bashrc" and scroll to the end of the file. Add a new line "screen /dev/ttyUSB0". Your Arduino may have a different serial port name. If you want Raspberry Pi to automatically shut down, add "sudo shutdown -h now" on the next line.

To make a demonstration unit, you need to have raspberry pi automatically log on in order to show the random numbers on screen upon startup. Use "sudo raspi-config" and select option 3 with Boot. Then select B2, auto log in with command line.

Follow the instruction of the LCD vendor to set up the screen:

http://forum.banggood.com/forum-topic-109744.html

Arduino set up

1. Load the program in Appendix I to Arduino using Arduino IDE.

2. Connect Arduino to a MAX3232 board.

3. Connect RJ11 breakout board to Arduino and connect Aware RM-80 sensor.

Use of Apparatus

The values of the apparatus are:

1. The unit can be readily used to demonstrate radioactivity to the general public without the attached stigma (radiation noise). Use a more intense source ("Fiesta ware", Cs137 etc.) and see random numbers come out more quickly than just the background radiation.

2. The unit also demonstrates randomness of radioactive isotope decays by generating random numbers and displaying them along with average and counts on screen.

3. Remove the Raspberry pi and you can use the stream of random numbers for scientific computing (such as Monte Carlo methods) or data encryption.

4. One can easily modify the Arduino code to turn the unit into a digital radiation counter with computer interface, which is usually several times the cost.

5. The unit can output the delays between consecutive decays. A student may use the delays to test the probability hypothesis of exponential relation between the delays and their occurrences. Many commercial counters don't output the pulses or the delays.

6. The difficulty level of constructing this apparatus and analyzing data is appropriate for an intermediate to advanced level lab. A student will learn radiation counting through hands-on experience with basic electronics, programming, statistics, and seeing pulses.

Theory

Radioactive decays are naturally occurring events and happen at random times. We can use the randomness of radioactive decays to generate pure random numbers for scientific computing and data encryption. Unless you have a special device, your computers and phones only generate pseudo-random numbers through algorithms. Here is how radioactive decays are used to generate random numbers:

Assume you observe a delay t1 between two consecutive decays and another delay t2 between two other consecutive decays. Equal chances exist for t1>t2 and t1<t2. We constructed a random number generator that generates ones (t1>t2) and zeros (t1<t2) from these decays. Once there are enough bits (8-bit for 0-255), the number is printed out, ready for use. Figure 1 E and F depict the bipolar output pulse from the detector and the converted 0-5V clean digital pulse (via MAX3232) ready for Arduino to detect. We tested the randomness of the number and are planning on more tests. Figure 2 shows the distribution of 63,000 random numbers between 0 and 255.

This apparatus was improved from John Walker's HotBits project:

https://www.fourmilab.ch/hotbits/

According to the website, the HotBits project has not been updated for 10 to 20 years. The improvements are done to remove several of its shortfalls and bring it up to date with current software, hardware, and future proof it:

1. Using more appropriate hardware, a microcontroller instead of a computer

2. Compatible with any microcontroller instead of only designed for 1990's OS and CPU

3. Program easily understandable, PC assembly language knowledge no longer required

4. Small profile, minimal power consumption and mobile compared with a desktop PC

To turn on the device:

1. Connect Arduino box with detector via phone cord.

2. Connect Arduino box with raspberry box via USB-mini cable (any USB port will do)

3. Connect Raspberry box to AC adapter via USB-micro cable

4. Wait for 30 second and the demonstration will start automatically, showing the most recent random numbers on screen along with total numbers generated and the average.
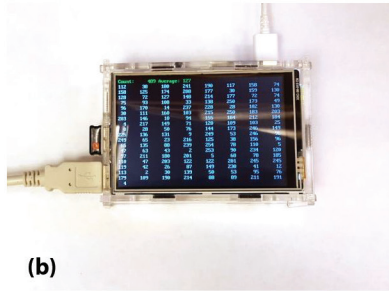
To turn off the device:

1. Disconnect Arduino box from raspberry pi. Raspberry pi will start the shutdown process.

2. Once the screen goes white, wait for 30 seconds before powering down Raspberry pi.
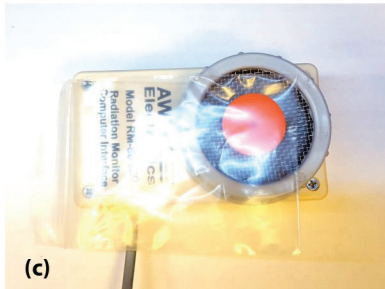
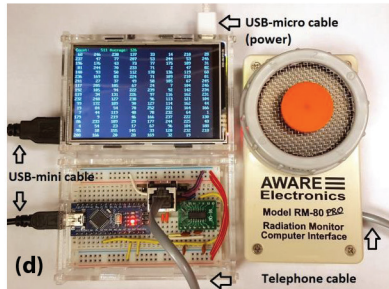3. Disconnect Arduino from detector.
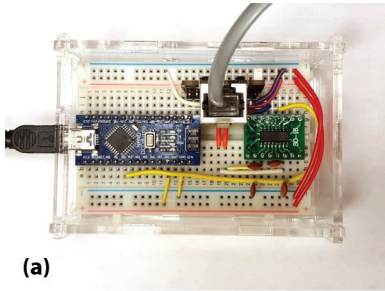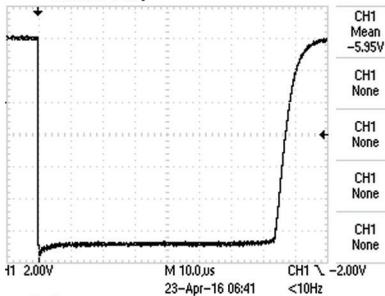
(a) Arduino box

(b) Raspberry Pi box

(c) Sensor with a Cs137 source on top (in a plastic bag for easy removal)
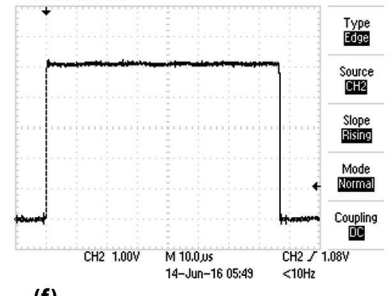
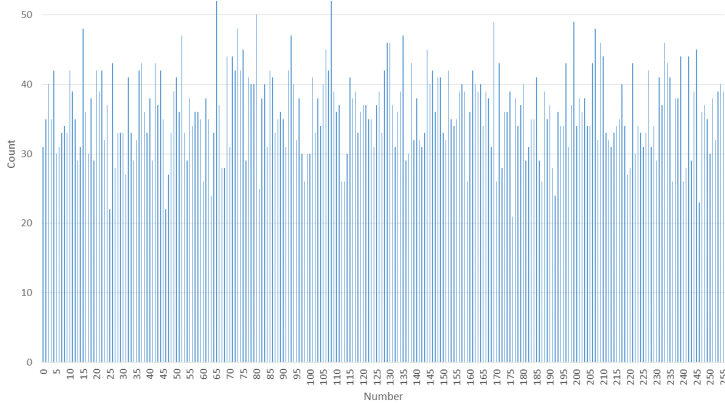**(d)** Unit connected and powered up. Raspberry Pi displays the random numbers

(e) Bipolar pulse generated by the detector

(f) 5V pulse converted by MAX3232

Figure 1. Random Number Generator With Cs137.

Figure 2: A plot of the occurrence of random integers between 0 and 255 from 9,000 samples.

Appendix I: program code for Arduino

```
// Within 3 second of opening the serial port, send any character, the printed values will be plain,
i.e. number followed by new line.
// If no character is sent to the serial port, numbers are printed with formatting to fit on a 3.5"
screen of a raspberry pi.
#define rand_bit_len 8 // Generate 8-bit random numbers
#define dead_time_us 100 // The pulse is about 75us long. Then entire transition is less than
100us
int print_plain=0; // Don't print CSI, instead, print new lines after each number.
unsigned long total=0;
unsigned long count=0;
int avg=0;
char settingup[]="\x1b[2J\x1b[1;1H\x1b[?25l\r\n";
char formatting1[]="\x1b[1;1H\x1b[32mCount:%8ld Average:%4d\x1b[0K\x1b[m";
char save[]="\x1b[s";
char restore[]="\x1b[u";
char buf[81];
void output_to_console(int num) {
static byte start=1;
static unsigned long counter=0;
const int num_per_line=8;
if (total>total+num) start=1; // Sum is overflowing, reset.
if (start) {
start=0;
Serial.print(settingup);
}
sprintf(buf,"%3d",num);
Serial.print(buf);
counter++;
if (counter==num_per_line) {
counter=0;
Serial.println();
}
else Serial.write('\t');
```

```
    total+=num;
count++;
avg=total/count;
sprintf(buf,formatting1,count,avg);
Serial.print(save);
Serial.print(buf);
Serial.print(restore);
}
int generate_bit(int later_longer) {
static unsigned int rand_byte=0;
static byte bit_cnt=0;
if (later_longer) bitSet(rand_byte,bit_cnt);
else bitClear(rand_byte,bit_cnt);
bit_cnt++;
if (bit_cnt==rand_bit_len) {
bit_cnt=0;
if (print_plain)Serial.println(rand_byte);
else output_to_console(rand_byte);
Serial.flush();
rand_byte=0;
return true;
}
return false;
}
void setup() {
pinMode(A2,INPUT);
Serial.begin(9600);
unsigned long start_ms=millis();
while(millis()-start_ms<3000) {
if (Serial.available()) {
Serial.read();
print_plain=1;
break;
}
}
}
void loop() {
int cnt_decay=0;
unsigned long time_us[4];
while(cnt_decay<4) {
if ((PINC&(1<<PC2))) {
time_us[cnt_decay]=micros();
delayMicroseconds(dead_time_us);
cnt_decay++;
}
}
if (time_us[1]-time_us[0]==time_us[3]-time_us[2]) return;
else generate_bit(time_us[1]-time_us[0]>time_us[3]-time_us[2]);
}
```

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Sonic Levitator

Abstract

You can demonstrate the existence of a standing sound wave by floating small pieces of Styrofoam or paper at the pressure nodes. An upward facing ultrasonic transducer driven at resonance creates the wave with metal plate above it acting as a reflector. At this frequency, the wave nodes are separated by just over a half-centimeter.

Construction

To build this apparatus four main parts are needed, a transducer, a signal generator, an amplifier, and a reflector. If you have a function generator and a 30 W amplifier (with a 70V output), the quickest way to build it is to drive the transducer at the resonant frequency through the amplifier. Use a flat sheet of metal on a lab stand directly above the transducer as the reflector. To build this as a stand-alone unit, two methods were pursued. One can drive it with a square wave and a single transistor amplifier, or use a Wien bridge oscillator with a push pull amplifier (both of these methods work). Due to the nature of the transducer, the push pull amplifier also needs an impedance matching circuit. In the interest of keeping costs low, the square wave method will be presented.

The square wave generator is an ordinary 555 timer in astable mode with a potentiometer (10 turn) to make small frequency adjustments (see fig 1). One should be aware that the transducer will have a much higher impedance and heat up if the system is not at the resonant frequency.
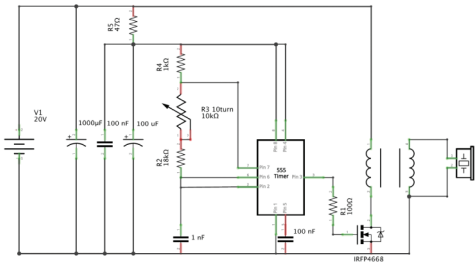
Figure 1: Circuit schematic for signal generator and amplifier.

The amplification is accomplished with a single mosfet with heatsink and then stepped up with a transformer. The power supply should be between 9-20 V and have a maximum power output of 30-50 W. The voltage should be stepped up to 70-110V with a transformer rated for at least 50 VA. The heatsink should have high power dissipation (20 W at 60°C). To monitor the frequency a set of panel

mount female banana jacks are connected through the case (fig. 2) to the output of the 555, and to read the current from the power supply, a set was placed on the back. The current will be highest at resonance which helps when tuning the circuit. The transducer is kept in a separate box with a cutout that allows the horn to move freely (fig. 2). Sticky tack is placed on the bottom of the transducer to prevent vibrational chatter. The reflector, held up with friction is mounted on a smooth rod (see fig 2). The transducer used will produce up to 90 dB at resonance (28 kHz). This is only at its surface and is highly focused, so poses little hearing risk. The acoustic energy leakage outside of the area between the reflector and transducer is about 60 dB.
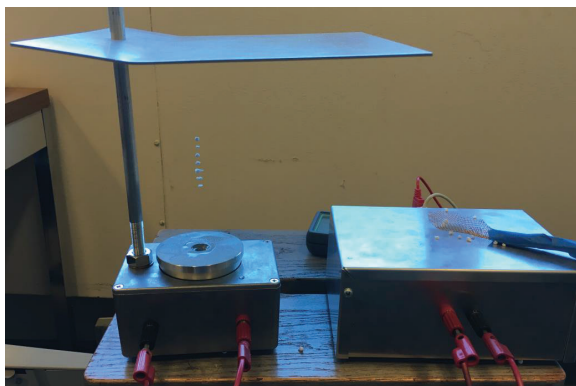
Figure 2: The transducer and control box hooked up and operating with a few floating Styrofoam balls.

Name	Qty	Cost	Total	Link
Transducer – 100W 28KHz	1	26.16	26.16	amazon
MOSFET – IRFP4668P	1	6.87	6.87	digikey
IC – 555 IC	1	0.33	0.33	digikey
Cap – 1 nF	1	0.1	0.1	digikey
Cap – 100 nF	2	0.12	0.24	digikey
Cap – 100 uF	1	0.2	0.2	digikey
Cap – 1000 uF (50V)	1	0.23	0.23	digikey
Res – 1 Kohm	1	0.04	0.04	digikey
Res – 18 kohm	1	0.04	0.04	digikey
Res – 100 ohm	1	0.04	0.04	digikey
Res – 47 ohm	1	0.04	0.04	digikey
Transformer – step up	1	23.24	23.24	digikey
20V DC power supply	1	20.27	20.27	digikey
project box	2	3	6	digikey
Pot – 10K 1 turn	1	1.29	1.29	digikey
Heatsink	1	1.65	1.65	digikey
Al rod (1 ft)	1	1.65	1.65	MMC
Al plate (1 sqft)	1	3.12	3.12	MMC
Total			**$91.51**	

Use

This is a demonstration, meant for small groups or for large lectures with the aid of a camera. This will allow students to visualize longitudinal standing waves in a fun and different way. Several activities can be imagined:

- Students, knowing the resonant frequency can calculate the speed of sound by measuring the distance between nodes
- By adjusting the position of the reflecting plate students can see how the standing wave is brought in and out of resonance
- Given the mass of the suspended objects, students can estimate the amplitude of the pressure fluctuations

To operate, plug the output of the control box into the transducer box. Short the black and red terminals in the back together unless you are using an ammeter there to monitor the current. Place the metal plate above the transducer and plug in the power supply. With a syringe, place a drop of water and spread it around on the surface of the transducer horn and watch for it to vibrate as you make adjustments. Place one styrofoam sphere in the copper mesh spoon and move it up and

down, while adjusting the height of the metal plate. The spheres will be sucked into the area of rarefaction when the standing wave is formed. The spheres can then be placed one after another without any adjustments.

A grid or small object can be passed between two adjacent spheres as long as the aperture of the grid is large enough or the cross-sectional area is small enough. A copper mesh spoon and wire can be provided to show this effect. Dry ice can also be used to show the nodes and antinodes.

Tuning

To tune to the correct frequency, connect an ammeter to the ports that monitor the current from the supply (on the back of the control box in the photograph), then adjust the potentiometer until you reach the maximum current. Due to heating effects, the device is best run for no more than 15 minutes at a time, with a rest time of 2-5 minutes in between uses.

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