Simple Creative Projects from an Optics Teaching Laboratory

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Abstract: The core educational program of the Stony Brook Laser Teaching Center is learning through the collaborative development of individualized projects. Many of these projects, especially with students new to research, are simple explorations or demonstrations of everyday devices or phenomena related to light, optics, or sound that have some creative component. Often the topic is suggested by something the student is just curious about or 'invents,' or by a chance observation or news article. This paper will describe a number of these 'simple, creative' projects, and relate the discovery process by which each came about and the results obtained.

Keywords: Active learning, project-based learning, collaborative learning, individualized research experience

1. Introduction

As described in a separate paper at this conference [1], the core educational activity of the Stony Brook Laser Teaching Center (LTC) is learning through the development of individualized hands-on projects; one such project was discussed in detail in a second separate paper [2]. Some of these projects can be described as fairly standard exercises explored in greater-than-usual depth over weeks or months [1]. Other projects relate to topics of current research interest, such as optical tweezers or optical vortices, and can be quite involved and open-ended. A third project category, which is described and illustrated through the various examples presented in this paper, consists of mostly simple explorations or demonstrations of everyday devices or phenomena related to light, optics, or sound that have some novel or creative component. This component could be related for example to the way the project topic was picked, or how the project was carried out with the simple tools and materials on hand in the laboratory or readily available. In some projects there is a 'Eureka!' moment of discovery when the student working alone has a significant insight, makes an unexpected observation, or invents something. More often the creativity arises in some way from the special chemistry between student and mentor that gradually develops as they communicate about and collaborate on the project over an extended period of time.

The students involved in these 'simple, creative' projects are mostly new to research and generally have had at most a very limited exposure to optics in a high school physics course. When they enter the LTC they are introduced to various optics phenomena and concepts through seeing demonstrations and participating in informal discussions. Except during the full-time summer program there are no classes or lectures and the unstructured discussions all take place in the small laboratory discussion area. The detailed optics knowledge and laboratory skills needed for each project are acquired on a need-to-know basis, through self-study and informal discussions with mentor(s) and more experienced students. The main requirement for success on the part of the student is ample interest and curiosity and an ability and willingness to collaborate with the mentor. Students and mentors become in effect partners in a unique shared experience, and the synergy of their interaction leads to the new ideas and insights not otherwise possible. The student-mentor partnership extends to the all-important writing process that concludes the project, as the mentor guides the student as closely as necessary to create a thorough and convincing written description of the project.

The projects described are not meant to be duplicated, although some of the ideas and 'tricks' might be useful to others. They are presented simply to provide examples of what's possible through relaxed one-on-one student-mentor interactions in a supportive learning environment. We hope that others will be inspired by these stories to explore opportunities to incorporate such unstructured project-based learning into their own educational programs.

2. Representative Projects

In the following I will describe eight representative projects of the type described above. Most of the students involved were university freshmen (age 18 or 19) from the Introduction to Research course (WSE187) in the Women in Science and Engineering (WISE) program [3]. Several others were high school students, and one was a high school physics teacher in training. In many cases the creative component was the idea for the project, how it came about, or what was studied. In another case a simple but very effective technique for nanometer motion control was invented in the course of a much more involved project. Several projects involved interesting or unusual optical properties of everyday objects. Studies of this type have a grand history and can be very open-ended indeed, see for example Michael Berry's "Reflections on a Christmas-Tree Bauble." [4]

The duration of the projects ranged from a few weeks to a full semester. Those by WISE students are documented in straight-forward (hand-coded) web reports that are freely available on the WISE Programs portion of the Laser Teaching Center web site [5]. Learning to create such hand-coded html reports is an essential part of the WSE187 course, and the collaborative writing involved reinforces understanding as well as writing skills. The project by the prospective high school teacher is also described in a web report. Other projects are documented on the web site in pictures, abstracts, Powerpoint slides and full-length written reports prepared in LaTeX. Web reports typically include many photos, drawings and graphs. The drawings could be done on a computer (we use the Linux program xfig) or could simply be a photo of a hand-drawn sketch on the white board or in the student's notebook. Graphs and numerical simulations are typically made using the 1980's era DOS spreadsheet program QuattroPro, the ultimate simplicity of which is a valuable feature to students new to this type of analysis.

2.1 Light decay of 'Glow in the Dark' materials

My partner in this project was Jill Chen, a mechanical engineering major who was one of six students in my spring 2002 WISE class [6]. Jill was the unusual student who not only had an excellent idea for a project ("can we study those glow-in-the-dark stars?") but also suggested it almost immediately. As a young child, Jill had enjoyed the comfort of falling asleep in a room with a light on, and had also enjoyed seeing stars in the sky at night. At some point she had been introduced to glow-in-the-dark decorative stars and had ever since displayed these in her room at home and later in her college dormitory. This turned out to be an excellent project: one that could be effectively performed with very simple equipment already on hand, but which was also very open-ended. The following summarizes the shared adventure that is better described in Jill's own words on her project web page [6].

We started with some internet research about glow-in-the-dark (phosphorescent) materials, and soon learned about a company (Shannon Luminous Materials) that markets such materials for a range of applications [7]. A person at the company was interested to hear about the project and quite willing to help. He provided samples of Shannon's state-of-the-art 'Super Phosphorescent' material based on rare-earth-activated strontium aluminate (SRA) [8] as well as a more traditional zinc sulfide (ZnS) screen. Although a photomultiplier was available, one of our standard Thorlabs silicon photodetectors (model DET-210) proved to be adequate for observing the light decay for several hours, and had the advantage of simplicity and stability. No amplifier was used, but a high value resistor (10^5 to 10^6 ohms) was placed across the output of the detector to convert the small current signal to a voltage in the 0.1 - 100 mV range.

In projects that involve taking a modest series of readings I typically guide students to record readings by hand in their notebook and then type these data into a spreadsheet program for plotting. This manual technique has worked well for numerous laser beam profile measurements and the like, but in this case a very simple automated method based on the serial interface port in the Radio Shack Model 22-805 digital multimeter was employed instead. The software provided with the meter transferred one reading per second into a text file, which could then be imported into our QuattroPro DOS spreadsheet environment for plotting. This scheme was very simple, effective and economical (US $50 for the meter), and also pedagogically more transparent than using a less familiar device for an interface. To record data the materials were 'charged' by exposure to a bright desk light, the detector was set on top, and this package was quickly placed in a dark environment.
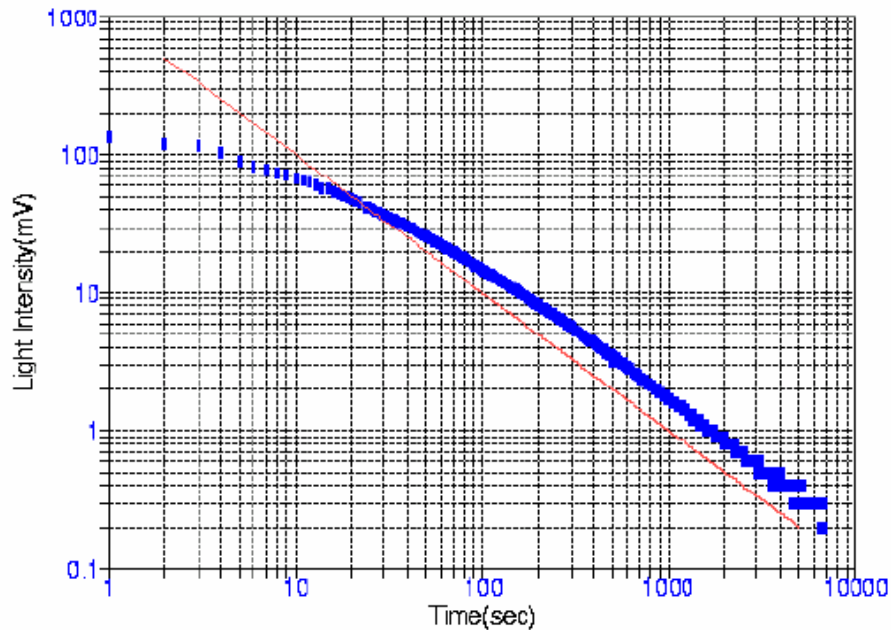
Fig. 1. Light decay curve for a sample of a commercial 'glow-in-the-dark' (SRA) material. The >6000 solid points (blue) are light intensity readings at 1-second intervals. The red line with slope -1 illustrates a power law of the form $I \sim t^{(-1)}$.

Our expectation was that the light decay curve would be exponential in form, and thus characterized by a 'half-life.' Such data, when plotted on a semi-log plot, would appear as a straight line. Much to our surprise, when we plotted the two hours of useful data obtained we did not obtain a straight line at all! By chance the data were then plotted on a full log-log plot, and this revealed the astounding result shown above. The recorded light intensity drops relatively slowly at first, but at a gradually increasing rate. Then from about 100 seconds on the intensity I drops steadily in inverse proportion to the elapsed time, $I \sim t^{(-1)}$. This type of behavior is known as a 'power law' (the exponent can be any constant) and turns out to be quite common in nature and statistics [9]. Familiar examples from physics are the inverse-square law for optical radiation or gravitation, and the `1/f law' that describes the intensity distribution of random noise. It was a surprise to learn that power laws also describe seemingly-unrelated phenomena such as the frequency of occurrence of words in a book (Zipf's law).

While this project went on for more than a full semester the key result (the figure above) came early on and many questions (such as how the decay curve varies with temperature) were left unexplored. We were however able to confirm by more sensitive measurements that the power law decay continues for at least ten hours. We also learned from reading and conversations with others that delayed light emissions arise from triplet spin states, and that a random distribution of the triplet state lifetimes can explain the power law behavior of the composite decay curve.

2.2 Multiple reflections in a decorative lamp
A decorative glass candle lamp with interesting optical properties was the topic of two similar but independent student projects five years apart. The lamp was a table decoration at a local Indian restaurant [10], which was happy to donate one to our lab. The flame in the candle lamp is surrounded by four tinted glass panels whose inside surfaces have a partially reflective coating; these panels are arranged in the form of a rectangular prism, with opposite faces parallel to each other. When the flame is viewed from outside the lamp at eye level a sequence of flame images of gradually diminishing luminosity is seen. These are clearly due to multiple reflections and 12 or more images can be counted in a darkened room (see figure below). The goal of the measurements and analysis performed was to determine the relative luminosity of the images. This is interesting in part because the luminosity ratio between the first image and the last visible image is a direct measure of the visual sensitivity range of the eye.

Fig. 2. Multiple reflections of the flame in a decorative lamp. The eye can perceive several even weaker reflections that the camera can't register.

After seeing a demonstration of the lamp Victoria Bonvento (WISE program, 2001) decided to study it for her project. She found the 'one way mirror' aspect of the lamp's metallized partially-reflecting surfaces especially appealing [11]. Hamsa Sridhar, a sophomore high school student, returned to this topic in spring 2006 for her initial research experience in optics. She was not aware of the earlier project at the time and made an independent and more complete analysis based on new and more careful measurements [12].

Victoria and I soon realized that the high reflectivity surface was the inner one, and that the luminosity ratio between successive images was simply equal to the reflectance r of this surface. We measured r directly by reflecting a HeNe laser beam against the inner surface on to a photodetector. While this direct method involved little analysis the geometry was awkward and our result $r = 36 \pm 4 \%$ had a relatively large uncertainty.

The subsequent experiments with Hamsa involved more analysis but gave more information and a more certain result for r by two different methods. Since Hamsa was quite comfortable with math, but had not yet studied physics or optics, this was a pedagogically quite appropriate project for her. In the first experiment the He-Ne beam was directed toward the glass lamp from the outside at a slight angle. Using a photodetector, the intensity of the initial beam and the three beams that either reflected from one of the two surfaces of one glass panel, or passed completely through it, were measured. These values were analyzed through a series of equations to obtain the reflectance values of the inner and outer surfaces and the absorption in the tinted glass between. In the second experiment, the laser beam was allowed to travel through the glass lamp to a screen. Five spots of decreasing intensity were visible when the lamp was rotated slightly; they were consecutively isolated by an iris and their relative intensities measured using the photodetector. In this case the ratio between the spot intensities is r^2, and this value could be accurately determined by a graphical analysis, as shown in the figure below.

The reflectance results from the two experiments were in good agreement and we took their average, $43.0 \pm 0.5 \%$ as the final result. It follows that the nth visible image must be $(0.43)^{(n-1)}$ times as bright as the first (unreflected) image, or 1/4,627 times as bright for n = 11. Thus the human eye can perceive an intensity range of about 5,000 – 10,000 at a single instant. (The eye can of course adapt to a much wider brightness range given time to adjust.)
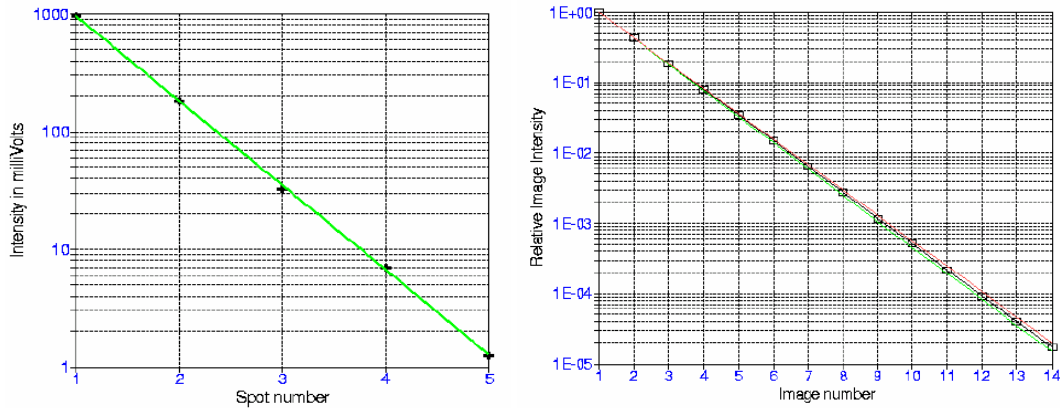
Fig. 3. Measurements and analysis on multiple reflections in the decorative lamp [12]. Left: measured intensities of multiply reflected laser beams. Right: predicted relative luminosity of the flame images.

2.3 Frequency response of the eye

The creative aspect of Meruba Anwar's project [13] derived from her strong native curiosity and ability as an observer. This was a short project for the WISE Introduction to Research course, about a third of a semester. The actual observations took just an afternoon or two, while learning html and writing a web report took a few days longer. Unlike Jill Chen (Section 2.1 above) Meruba struggled at first to find a suitable topic. I encouraged her to just pay attention to things around her that she was curious about and that seemed interesting. After several weeks she reported that while shopping at the mall that weekend she'd seen an unusual clock in which numbers and letters appeared to float in space [14]. She soon learned that the operating principle of the clock is the persistence of vision effect. By chance Meruba had stumbled upon a topic that was an excellent match to her interest in neuroscience.

I gave Meruba an assortment of LED's (purchased from the local Radio Shack store) and set up a square-wave generator to pulse them at any desired frequency. My intention was for her to explore how the threshold for visually detecting flicker (the Critical Fusion Frequency or CFF) depends on parameters such as the LED brightness and color [15]. After a few hours of investigation Meruba reported with great excitement an observation that was obvious in retrospect but which neither of us had anticipated – the threshold for detecting flickering depends significantly on whether one is looking directly at the LED (direct vision) or looking to the side (peripheral vision). By chance Meruba had discovered an essential feature of vision, the two types of cells (rods and cones) in the retina! An understanding developed in this way through self-discovery will certainly endure. Meruba went on to carefully record a variety of CFF observations and write an excellent web report that includes these [13].

Fig. 4. Demonstrating the principle of the Fantezein clock.

2.4 A variable water drop lens

Scott Huang was a high school student in summer 2006 [16]. After some exploration of possible project topics he developed an interest in techniques or devices that measure or correct for wavefront aberrations, and we worked together to find a project related to this interest. One such device, the Shack-Hartmann wavefront sensor, is based on an array of small lenses ('lenslets') that create a corresponding array of focal spots on a CCD-detector. While discussing this idea I showed Scott an image I knew of that depicted droplets of water trapped in the openings of a window screen (see figure below). We considered making a lenslet array of fluid droplets, but it was soon evident that it would be difficult to make the lenses sufficiently small and uniform enough to create a useful lenslet array. While playing with water-drop lenses Scott happened to place a droplet of water into the opening of an iris diaphragm, a common object in our lab. He was fascinated by the way the focal properties of the lens could be varied simply by varying the opening, and decided to investigate this 'variable water-drop lens.' Scott soon learned that variable fluid lenses are a topic of considerable recent interest, with important potential applications [18].
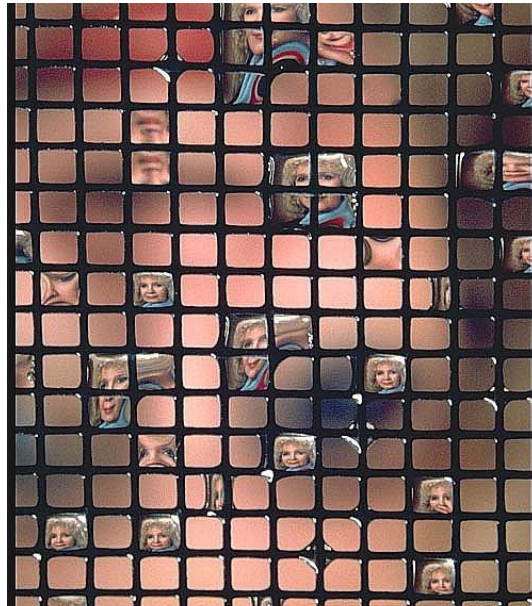

Fig. 5. Face viewed through water drop lenses in a screen [17].

Using a simple setup he devised, Scott measured the focal length of various water-drop lenses. These varied over a wide range (5 to 80 mm) as the droplet diameter varied from about 3 to 8 mm, and the droplet deviated more and more from a spherical shape [16]. Scott also made a simple microscope from the water-drop lens and recorded the image below and others with our Electrim 1000N CCD detector [1].
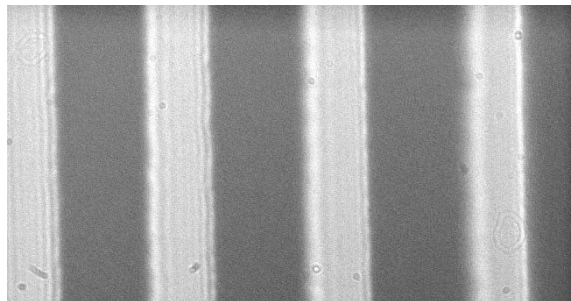

Fig. 6. Partial image of a Ronchi grating (pitch 150 μm) recorded through the water drop lens.

2.5 Color patterns in soap films

My student partner in this project, Eric Tompkins, was just completing an MAT (Master of Arts in Teaching) program at Stony Brook to be certified as a high school physics teacher [19]. He needed a course credit to complete his degree and so undertook a semester-long project. Eric and I started by looking at various simple demonstrations of optical phenomena. One of these was the demonstration of colors in soap bubble films illustrated in Figure 7 below. The small bottle holds a mixture of roughly of equal parts water, glycerin, and Dawn dishwasher detergent. (The bottle originally held the glycerin.) When the bottle is tipped over with its cap in place, and the cap is then removed, a soap film can be seen across the mouth of the bottle. If the bottle is held in a nearly horizontal position as shown for a few minutes the film is affected by gravity and develops a distinct black band at the top. In a location free of air currents a white area and horizontal colored bands form below this. The colors on the soap film are most distinct in an area well lit by diffuse bright light, preferably indirect sunlight. Coincidentally, the opaque container does more than provide a convenient way of creating the film – it keeps the back side of the film in darkness and thus allows the black area to show up distinctly.

Fig. 7. Interference patterns of reflected light in soap films. Note the 'black' film at the top, and the white area and horizontal colored bands in the right-most picture.

Eric was familiar with the way soap film colors arise from interference of light, but he had never seen a black soap film before. It was apparent to him immediately that this effect and the horizontal colored lines must be somehow related to the way film thickness must vary due to gravity, with the thinnest film at the top. We decided to focus the project on developing a mathematical model of the way the film colors vary with thickness. As described in Eric's research journal and report [19], the key concept is that a 180° phase shift occurs at the front surface of the film but not at the rear. Light reflected from the rear surface is however phase-shifted by its passage (twice) across the film. If the film is very thin, much thinner than a wavelength of light, the latter phase shift is negligible and one has purely destructive interference. To quantify this Eric derived an expression for the intensity of the reflected light, which was in turn used to create the graphs of intensity versus wavelength or film thickness shown in these figures.
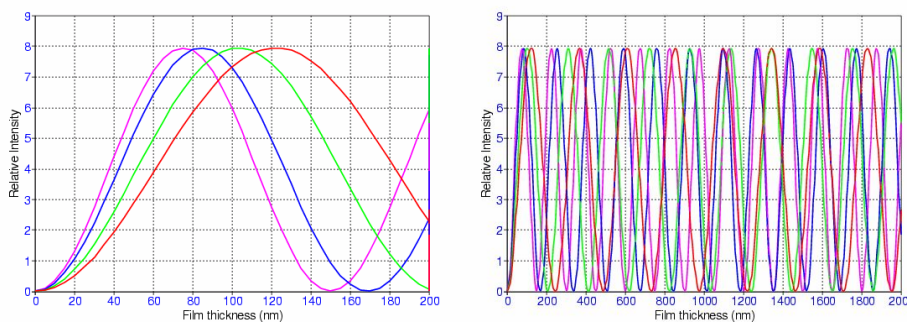

Fig. 8a. Calculated relative intensities of four colors (violet, blue, green and red) as a function of soap film thickness [19]. The plot at the left is just an enlarged view of the one at the right. It is apparent that the black soap film must be no more than about 10 nm thick. The fact that intensities for all colors peak around 90 nm explains the white region below the black band. Using these predictions reflectance measurements for monochromatic light could be used to map the film thickness as a function of position.
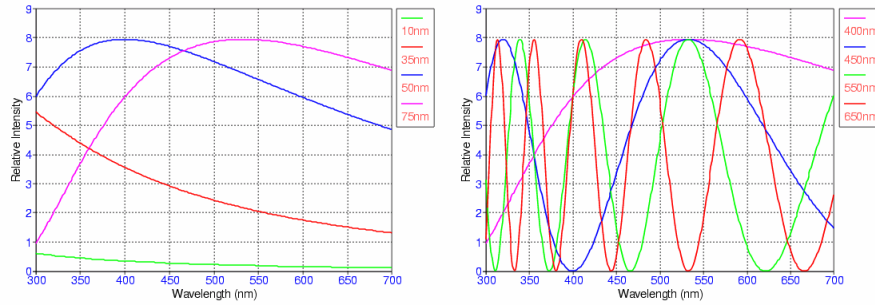
Fig. 8b. Calculated relative intensities of reflected light as a function of wavelength, for eight different film thicknesses. Note that the colors of the lines in this case relate to thickness, not wavelength. These predictions could be compared to spectrometer measurements of reflected white light to uniquely determine the film thickness.

2.6 Point spread function (PSF) of a consumer CCD camera

Marissa MacDonald (WISE program, 2007) carried out the first astronomy-related student project in the LTC [20]. It was one of several projects over the last decade that utilized the lab's simple Sony Mavica FD73 camera as a quantitative tool, not just for documentation. An important concept in observational astronomy is the point spread function or PSF. This can be described as the response of an imaging system to the light from a point source such as a star. The figure below shows the setup we used to create and photograph a simulated star. The angular size of the pinhole at the camera (2.2 arc seconds) was not nearly as small as even the 'largest' star Betelgeuse (0.045 arcsec), but it was comparable to the diffraction limit of the camera and therefore adequate.
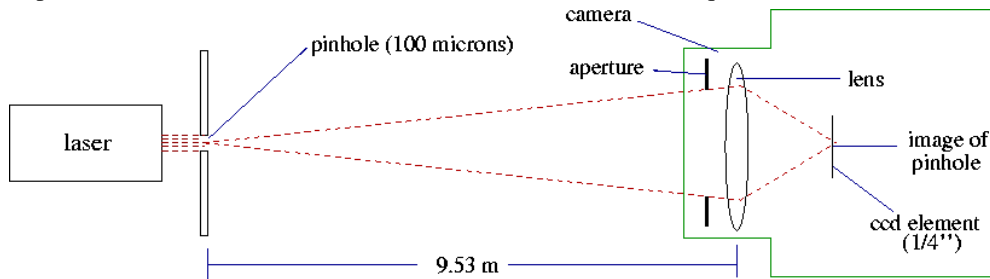

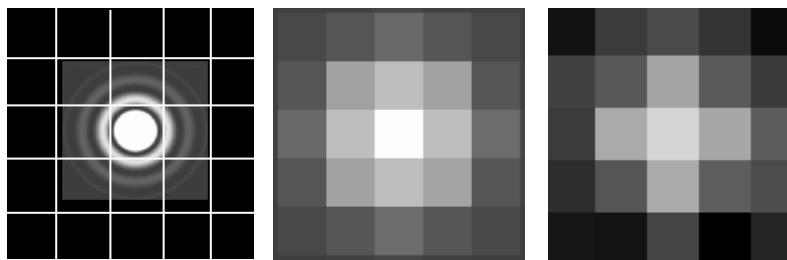Fig. 9. Setup for the point spread function experiment.

Fig. 10. Simulated (left and center) and observed (right) PSFs for the Mavica camera. The image at the far left shows the predicted Airy pattern corresponding to the camera's aperture superimposed on a grid of 5.6 μm square camera pixels. In the center image the same Airy pattern has been 'pixelated' in the xv program. Far right, the observed PSF is compact and comparable in size to the diffraction limited spot.

2.7 Noise cancellation and the velocity of sound

Yu Fen (Jen) Hwang (freshman WISE course, 2004) was inspired to this project by late-night noise in her dorm room [21]. She had seen my demonstration of two tuning forks 'beating' against one another, and thus knew that one sound could cancel another. She wondered whether arbitrary sounds could be canceled in a similar way. (Jen was not aware at the time that noise cancellation was already an off-the-shelf consumer technology.) An important consideration in noise cancellation is the wavelength of sound. We decided to try to visualize the wave properties of sound with a small handheld loudspeaker and microphone. A 2.00 kHz sine wave was fed to the loudspeaker and also to one channel of our dual-channel oscilloscope, which controlled the oscilloscope trigger. The microphone signal was fed into the second channel. Figure 11 below shows 9 consecutive images recorded over 3 seconds as the microphone and speaker were steadily moved apart. The phase shift of the received wave (fuzzier trace) is apparent, as well as its diminishing intensity. After this we established the distance corresponding to a 2π phase shift as 17.8 ± 0.5 cm. This wavelength value together with the known frequency implies a sound velocity of 356 m/s, in good agreement with the accepted value at 25 C. Even more interesting was the result when both loudspeaker and microphone were pointed at the adjacent wall. Now moving the microphone caused no phase shift, but did cause a periodic intensity modulation. We had inadvertently created a standing wave! All in all, this simple impromptu project, which took just part of an afternoon, was quite successful at making sound waves a familiar entity.
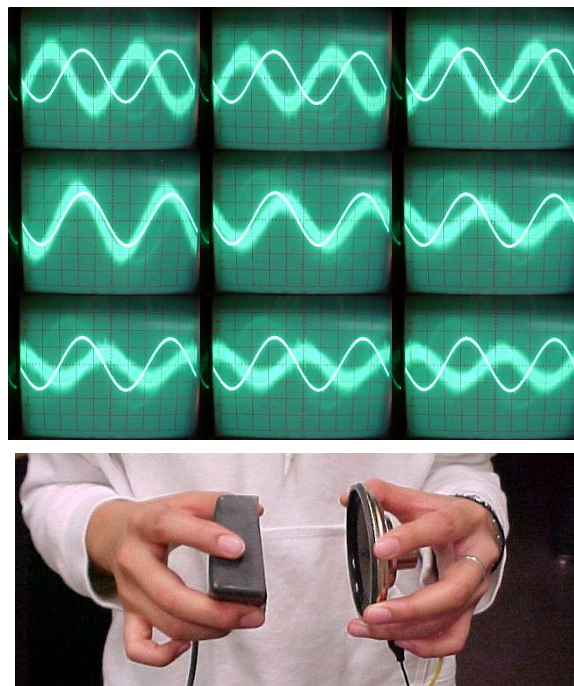

Fig. 11. Demonstrating the wavelength of sound (see text).

2.8 Nanometer motion control with a rubber band

The most creative aspect of Jon Wu's project [22] was a very simple yet quite effective technique for ultra-high-resolution motion control in a scanning optical interferometer. The path that led to this novel development was long and complicated. Jon was a high school participant in our 2004 full-time summer program. He expressed an interest in medical optics, so we looked at possible project ideas in this area. After considering various possibilities we focused on optical-coherence tomography (OCT), a technique for achieving micron-scale depth resolution within turbid media such as tissue by utilizing the limited coherence length of an broadband light source [23]. The idea gradually emerged of demonstrating the concept of OCT by observing interference fringe visibility as a function of path length difference. Similar to Fourier Transform Spectroscopy (FTS) the interferogram contains information on the wavelength components (spectrum) of the light, or in this case the spectral width of the broadband light source.

It was soon apparent from preliminary experiments in an interferometer that Jon put together that the challenge of the project was to achieve sub-micron resolution in the mirror movement over a range of thousands of fringes. (The difficulty of doing this is why FTS is rarely done at wavelengths shorter than the IR.) Jon experimented for some time with levers and the like that would scale down the motion of the mechanical translators available to us, which are graduated in relatively coarse 25.4 micron steps. His devices worked but were plagued with mechanical noise and backlash. While pondering these difficulties the idea came up of simply pulling on the mirror mount in a controlled way to gently deflect it . When an ordinary rubber band was used as the coupling device the result was amazingly successful (Figs. 12 & 13). Of course the range of mirror motion is quite limited, but the precise motion control provided by this simple trick has proven very useful for demonstrations and some other experiments.
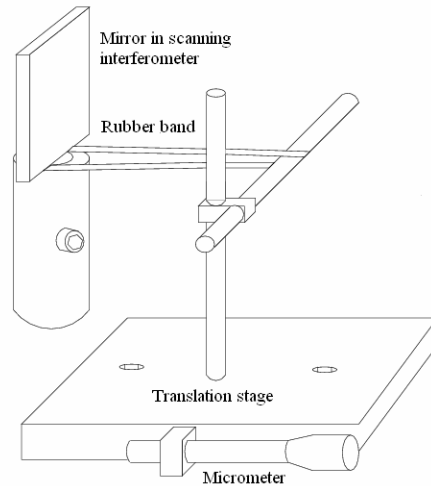

Fig. 12. A rubber band attached to the 25.4 mm translation stage pulls on the Thorlabs mirror mount to create reproducible nanometer-scale deflections.
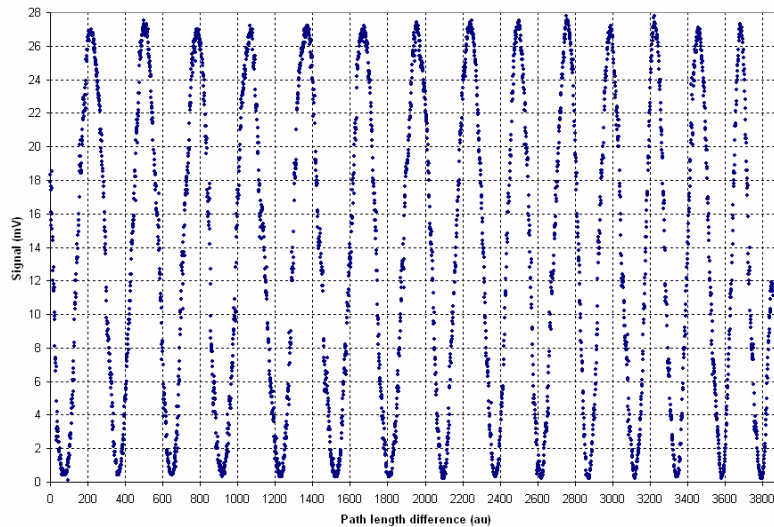

Fig. 13. Interference fringes from a HeNe laser recorded with the rubber-band translator as the micrometer was turned by a stepping motor. The step size is approximately 1.2 nm.

3. Conclusion

The response of the many students involved in these projects has been overwhelmingly positive, and the creative educational approach illustrated here has been enthusiastically endorsed by our university and many visitors. A great deal of time and effort is required to work individually with each student, but the resulting projects and educational experiences are often quite original and invariably of significant and lasting value.

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