Seeing the light: Introducing optics/photonics through middle school mathematics

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ABSTRACT

Over the course of an academic year, middle school students engaged in an exploration of some of the mathematics used in optics through hands-on inquiry-based experiments and exercises in problem-based learning. Goals were to introduce students to optics/photonics while demonstrating the relevance of math to the "real world". The program concluded with a capstone activity in the form of an art project celebrating “Light in Our Life”. Pre- and post surveys were conducted to determine changes in attitudes towards mathematics education. The year-long program was funded through an SPIE outreach grant.

Keywords: middle school, math education, outreach, K12 education, inquiry, Dumpster Optics, STEM education, Problem-Based Learning

1. INTRODUCTION

In previous math and optics high school projects, the authors developed lessons to introduce high school pre-calculus and calculus students to optics/photonics applications illustrating the math topics they were studying. Our goal was to answer the perennial question of math students, "Why do I have to learn this?" and to introduce them to STEM topics not normally studied in high school.

In the 2017-2018 project, we worked with middle school students at Saint Bernard School (Uncasville, CT) enrolled in 6th Grade Mathematics (33 students), 7th Grade Pre-algebra (26 students), and Integrated Mathematics I (18 8th and 9th grade students) to see if we could influence attitudes and improve problem solving at the beginning of their mathematics "careers". St. Bernard School is a Catholic co-educational 6th to 12th grade school co-sponsored by the Diocese of Norwich and the Xaverian Brothers. The school's math program is individually tailored to students' ability with offerings ranging from introductory algebra to multivariable calculus and differential equations.

Students in the math and optics program ranged in age from 10 to 14 years old. The 68 students were distributed among five classes, 2 6th grade, 2 7th grade and on 8th and 9th combined. Prior to the start of the program students filled out an informal questionnaire on attitudes toward mathematics education, problem solving and teamwork. Students were also asked if they had heard the term "photonics" and if they could explain what it means. Not one student had heard the term and none could guess at a definition.

Project goals were to increase students' appreciation for the applications of mathematics and to introduce them to the science and technology of optics/photonics and the basics of structured problem solving. Over the course of the academic year math students engaged in optics lab activities, using math to analyze data and solve problems. At the conclusion of the project, students had the opportunity to participate in a photo contest to celebrate the International Day of Light (May 16). In this paper we will describe the lessons and activities and present the results of our informal survey.

2. MATH AND OPTICS ACTIVITIES

2.1 Project planning and implementation

Originally, we had planned on monthly activities to be delivered over two days in the mathematics classrooms and the Math Lab, a separate classroom being modified into a space for active learning of mathematics. Missed days due to snowstorms and other scheduling anomalies required that we limit our program to six activities in fall and spring. See Table 1 for a list of program activities.

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The optics lessons were developed in part from the Dumpster Optics lessons, a program supported by SPIE.[1] In addition, an outreach grant from SPIE awarded to St. Bernard School allowed us to purchase equipment not in the "dumpster" category, such as gas spectrum tubes and light meters. We also adapted one lesson from the Hands-On Optics program and two of the Problem-Based Learning Challenges developed by the New England Board of Higher Education.[2,3] We chose lessons and activities that illustrated mathematics concepts from the middle school curriculum. Because of the short (42 minute) class period, some activities took three days to complete.

Table 1 Illuminating Math with Light Schedule of Activities.

Date	Activity	Duration
September 2017	Fractions, Lenses, Telescopes	3 days
October 2017	Structured Problem Solving (PBL)- Laser Safety, Stormwater	3 days
November 2017	Similar triangles- Light and Shadows, Pinhole Images	2 days
March 2018	Inverse Square Law and Spreading Light	1 days
April 2018	Interpolation and Light Spectra	2 days
May 2018	International Day of Light Photo Contest	

2.2 Fractions and lenses

To illustrate a practical use of fractions, students engaged in a three-day activity based on the Hands-On Optics Terrific Telescopes lessons. On the first day, students observed a demonstration of light refracting through an acrylic block and flat lens shapes. The acrylic shapes were from a kit supplied by Arbor Scientific (Item #P2-7680) that also included a "laser ray box" providing 1 to 5 separate beams for ray tracing through the various acrylic shapes. The concept of a focus was discussed and students identified the focal point and focal length for the lens shapes. They then spent a few minutes with two different focal length "education grade" converging lenses (from Surplus Shed) projecting images of distant objects onto a wall to determine the focal length of each lens.

On the following day, the students were introduced to the thin lens equation and, guided by the teacher, performed the calculation to determine lens focal length given object and image distances. Returning to the lab, they measured object and image distances using a meter stick optical bench (Carolina Biological Supply), the lenses from the previous day, the filament of a clear light bulb for the object and a cardboard screen. Before returning to the classroom for calculations students were shown how to place the two lenses on the bench, creating a telescope for viewing through the classroom windows. Calculations were far more time consuming than expected, especially in the sixth grade classrooms. Nonetheless, the calculated focal lengths matched the ones measured on the previous day fairly well.

The third day we planned to complete the Hands-On Optics resolution activity, having students read an eye chart through a telescope from several distances in a long hallway. They were instructed to note their distance from the chart and the height of the smallest letter they could see from that distance. To expedite matters, we constructed the cardboard tube telescopes from kits purchased on EBay that were the same as those in the Hands-On Optics kit. As it turned out, the youngest students were unable to even find the eye chart. Older students were able to take some data but not enough to make meaningful conclusions. Nonetheless everyone seemed to enjoy the activity, especially looking through the 4.5" Newtonian telescope set up to look out the window. Figure 1 shows several scenes of students engaged in telescope use.

2.3 Structured problem solving (PBL)

For this activity we chose web-based Challenges (scenarios) developed by the PBL (Problem Based Learning) Projects of the New England Board of Higher Education.[5] The three PBL projects, supported by the Advanced Technological Education program of the National Science Foundation, present students with "real world" problems in Photonics, Sustainable Technologies and Advanced Manufacturing. The goal of the Challenges is to teach content while at the same time allowing students to practice structured problem solving, written and oral communication and teamwork. At the heart of the method is a tool called the "Whiteboards", four pages that walk students through the details of structured problem solving beginning with problem analysis and continuing with self directed learning (independent research), team brainstorming, and solution testing. The Challenges are presented in a series of short videos that show a problem to students in the context of the company or research university that solved the problem originally. After sharing and critiquing student solutions, comparison can be made to the organization's solution.

Figure 1 - (top) Students experiment with different methods of supporting the cardboard telescopes while viewing an eye chart at the end of the hallway. (bottom) Looking through the small Newtonian telescope.

Sixth and seventh graders engaged in the most straightforward of the Challenges, the Tookany-Takony Frankford Watershed Partnership problem to develop neighborhood-based solutions to the issue of storm water management. The math involved is area and volume, converting rainfall (in inches) on an area to cubic feet or gallons of water stored. For many 6th and some 7th graders this was the first real world application of mathematics Their expectation was that math should involve no more than memory and drill work.

The 7th grade classes did better working in groups than most of the 6th graders. They were able to self designate tasks for each person in the group and then put the work together as a group and present their information in front of the class using a poster. Sixth grade students had difficulty with assigning tasks so that the project work load was equally divided. In addition to the poster and presentation, students assessed their teammates and themselves on teamwork. Based on the responses, some sixth graders felt that they did more than their fair share of the work and some felt that others took over too much and their own ideas were neglected. Overall the projects went well, however, with students especially in the 6th grade taking the time to learn and understand math calculations that they may not yet have seen in math class.

Because of their more advanced level of math knowledge and general maturity, 8th and 9th graders were presented with the Laser Safety Challenge, developed with the assistance of the International Laser Display Association (ILDA). The problem involves a legal case concerning the targeting of an aircraft with a laser pointer and students need to decide the innocence or guilt of the perpetrator. Students had no previous knowledge of laser safety and most groups enthusiastically engaged in research on both aircraft and laser specifications. When issues such as units of light measurement arose the instructor provided focused instruction on an as-needed basis. On the second day, students were given laser pointers and allowed to measure beam spreading in a long corridor. They then used ratios to determine beam area at the distance of the airplane. On the third and final day, students informally presented their solutions to the class. All teams agreed on the solution even though they had been arrived at independently.

2.4 Light, Shadows and similar triangles

All classes did the same activity for this lesson, which was developed as part of SPIE's Dumpster Optics program. The lesson is based on a tutorial developed at the University of WA.[6] On the first day, students used LED finger lights to trace and observe the path of light from the bulb through a 1 cm triangular hole to a screen. At each step, they first predicted what they expected to see and then made the observation. If prediction and observation did not agree they needed to figure out why before proceeding. In the final step, separate LED lights were replaced by a continuous light source, a clear globe linear filament bulb. Students observed a low resolution pinhole image of the filament on the screen. The large triangle was replaced by a smaller one to produce a clearer image of the filament. Most students found the production of an image by a small hole to be interesting.

On the second day, students were introduced to the pinhole camera and pinhole images formed, for example, under leafy trees. We had intended to allow each student to make their own camera but a shortage of materials prevented that. Instead, students made pinholes out of pieces of soft drink cans and inspected and measured them with a USB microscope. We provided home made oatmeal box pinhole cameras loaded with black and white film paper and took a 30 minute photo of each classroom while students were working. (See Figure 2.)

Figure 2 - Roughly 30 minute oatmeal box pinhole camera exposure of classroom (left), inverted version (center) and oatmeal box camera (right).

The final day we had planned to set up a long filament bulb, pinhole and screen and ask students to predict and then measure image size using object and screen distance and similar triangles. However it was an exceptionally warm November day and we decided instead to take the classes outside and use the same mathematics to measure the height of a tree. Most, if not all, students were happy with this decision.

2.5 Spreading light

This simple experiment was easily accomplished by students in all grades. Given a small, bare light bulb, a square centimeter hole and a printed centimeter grid they were asked to determine how the illuminated area on the grid depended on distance from the bulb. (See Figure 3.) After some issues with keeping bulb, mask and screen aligned and figuring out how to handle illumination of partial squares, students in all grades quickly noticed the quadratic relationship.

On the second day, students were asked to graph their data and observe and discuss the shape of the graph. Younger students needed quite a bit of assistance in setting up the graph and may not have grasped the full significance of it not being a straight line. Nonetheless, they were able to predict how many squares would have been illuminated at distances they did not measure. For the 8th and 9th graders this was a good introduction to the graphs of functions. Graphical Analysis software (www.vernier.com) was used to do curve fitting on student data and some time was spent exploring graphs of other functions.

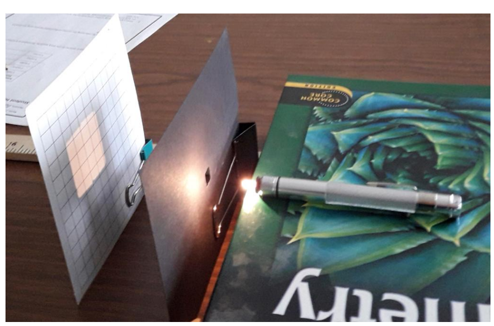

Figure 3 - Observing how light spreads from a "point" source. The light source was a MagLite® flashlight in candle mode. Binder clips were used to hold the mask and screen vertical.

2.6 Interpolation and light spectra

This final activity was undertaken in April with the class of 8th and 9th grade students only. We began by showing students videos of high speed optical food sorting machines[7] and asking how they thought they might work. Next we gave each student a diffraction grating slide and showed them several different light sources- incandescent, fluorescent, gas tubes, lasers and LEDs. A discussion followed on using light spectra to identify materials and on the importance of the hydrogen spectrum to astronomy. Students were then challenged to determine the wavelength of the H-alpha line by comparing the hydrogen emission spectrum to the full visible spectrum and dividing the full spectrum in successive halves until they could estimate the value of H-alpha. This was done as a class with the spectra projected on the whiteboard. (See Figure 4.) Despite the approximate nature of the spectra provided, students were within a few nm of the correct value.

Figure 4 - Graphic used to find the wavelength of the H-alpha line through interpolation.

The second day was spent looking at sources of light around the classroom using the RGB function on a Vernier Go Direct® Light and Color Sensor (Item #GDX-LC). Examination of the RGB output of smartphones and laptops led to a discussion of the possible health issues related to blue light exposure at night. Students were interested to see the difference in RGB output of a phone screen with and without night blue light filtering applied.

2.7 IDL Photo contest

We decided to end the program with a photo contest to celebrate the International Day of Light (May 16). The theme of the contest was "Light in out Life" and in addition to a photo with light as the central subject students were required to submit a short statement on how their submission related to the theme of the contest. This was a voluntary activity and open to the entire student body. Approximately 20 entries were received in two divisions, middle school and high school. Entries were judged by members of the SBS staff based on artistic impression, originality and how well the photo expressed the theme Light in our Life. Three winners were awarded in each division. Prizes consisting of IDL coffee mugs and gift certificates were awarded at the annual MathCon, an annual one-day event in May when members of the Mu Alpha Theta mathematics honor society present projects on math and its applications. The authors also attended the event with optics demonstrations and the winning photographs on display. (See Figure 5.)

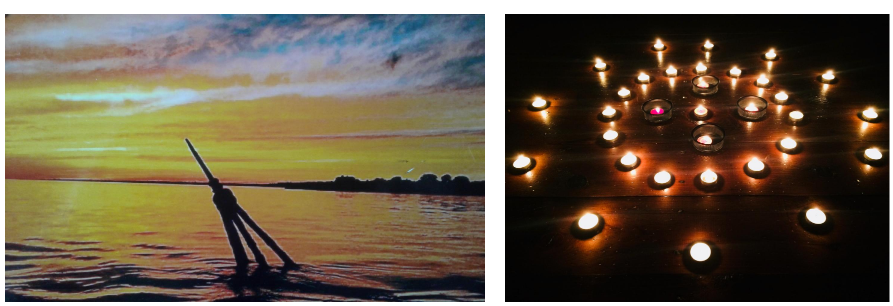

Figure 5 - Two of the winning "Light in our Life" photo contest entries.

3. PRE AND POST SURVEY RESULTS

In order to gauge the effectiveness of our program we asked students to fill out brief surveys before the first activity in September and after the final activity in April. Students responded to 14 statements on a 1 to 5 scale where 1 was completely disagree and 5 was completely agree. The survey questions and summarized results are presented in Table 2. Of the total 77 students, 68 completed both the pre and post surveys.

In previous projects we did not see many pre-post differences meeting the level of significance ($p<0.05$) as we did here. Whether this is due to the optics and math program we presented, a general maturing of students of this age or some other factor is unclear. We were pleased to see that in all grades the average response to "I think memorizing formulas is the best way to learn math" dropped by a significant amount. Also, all three grades saw significant increases in math interest and perseverance in problem solving. In general, students were more understanding of the role of mathematics in other academic subjects as well as in life and career and they felt less math anxiety during testing.

One anomaly was the response to teamwork. Evidently, middle school students do not enjoy working in teams, at least if they are not teams of their own choosing. While we hoped to see more students enjoying working in teams as the school year progressed, quite the opposite was true. Sixth and seventh graders response to the teamwork question was essentially unchanged while the 8th/9th grade class showed a significant drop in their response to " I enjoy working in teams to solve problems." (average dropped from 3.8 to 3.2, $p = 0.03$).

Table 2. Pre/post survey questions and summarized results. "x" indicates question for which $p<0.05$ for averages between pre and post testing.

Statement	**direction of response**	**p < 0.05**		
		6th	**7th**	**8th-9th**
I think memorizing formulas is the best way to learn math	↓	x	x	x
I find myself very nervous during math tests.	↓	x	x	
When I learn math, I wonder how the things I have learned can be applied to real life.	↑	x	x	
I think solving complex problems will be an important part of my life and career.	↑		x	x
When I learn new things, I think about what I have already learned and try to get a new understanding of what I know.	↑	x	x	
I am always curious to learn new things in math and I enjoy learning math.	↑		x	x
I expect math will be important in my life and career.	↑		x	x
I have good problem solving skills.	↑	x		
I think math is an interesting subject.	↑	x	x	x
Though learning math can be difficult, I feel happy when I can solve math problems.	↑	x	x	
I try to connect what I learn in math with what I encounger in real life or in other subjects.	↑		x	x
I enjoy working in teams to solve problems.	↓			x
I really make an effort to do my best in math class.	↑		x	x
If I cannot solve a problem right away, I persist in trying different methods until I get the solution.	↑	x	x	x

The post survey also asked students to reflect on the year's activities by responding to four questions. While not a single student had heard of photonics in September, by April most knew it had to do with light and about half the students gave reasonably good explanations, for example,

Studying lasers and light beams.
Photonics is the science of light and fiber optic technology.
It's the science of how light works

In response to "What is one thing you learned from the Light and Optics program?" responses included,

I learned that it is easier to learn math when you are doing a project than sitting in class
That you can use math in art.
I learned how math and science are related.
I learned how lasers work and that light is really interesting.

Students were asked which activities they liked best and least. Among the favorites were:

I liked going outside to measure the trees because we got to learn outside of the classroom.

I liked the different action gradings [sic] and seeing the rainbow colors from regular lightbulbs.

Shining the lasers through the lenses

And at least one student cited irritation with teammates as a factor in the least favorite activity,

Measuring the trees because my group didn't do the work

4. CONCLUSION

We noticed that student response to activities varied greatly by grade level. Older students can successfully engage in more content oriented activities, emphasizing functions and graphing. Younger students were suspicious of activities that took them out of the math classroom and their expectation of memorization followed by practice drills. In fact, many questioned why they were being taken out of "math class" to work on projects, prompting the teachers to explain (over and over) that math is useful because it allows one to solve problems and answer questions. Older students were much more receptive to inquiry based science and seemed to enjoy learning about light.

A future program for 6th and 7th grades should be geared toward clearing up the misconception that mathematics is arithmetic drills and rote learning by incorporating activities relevant to their own experiences as well as practice in structured problem solving with "real world" problems. For all grades, it would be helpful to schedule the activities so that the math topics are closer to the order in which math is usually taught. In that case, each grade would do different activities at different points in the school year. We plan to continue our collaboration and apply what we have learned to future projects.

5. ACKNOWLEDGEMENTS

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