Turning Eyes to the Big Sky project: Learning optics in middle school

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ABSTRACT

The Turning Eyes to the Big Sky project offered schools in southwestern Montana a unique opportunity to strengthen science instruction. The project implemented, in a formal setting, a nationally established informal science curriculum on light and optics, the Hands-on Optics *Terrific Telescopes* curriculum. *Terrific Telescopes* was implemented in 8 middle-school classrooms, reaching 166 students during the 2010-11 school year. As part of the project, we conducted a teacher workshop and assessed student learning outcomes and teachers' experiences with the curriculum. The goals of our assessments were to improve our understanding of how students learn key optics-related principles, provide evidence of the learning outcomes of *Terrific Telescopes*, and find out how teachers adapt it for use in formal settings. Our research established that students in every classroom learned optics concepts and identified ways to support and supplement the curriculum for use in classrooms.

Keywords: optics education, telescope, middle school, student conceptions

1. INTRODUCTION

At the end of the 20th century, the National Research Council (NRC)[1] highlighted the prevalence of optics in our everyday lives and predicted them becoming even more critical in the next century. Optics is a rapidly developing industry with a growing need for qualified workers. To influence students' career choices in this direction, their awareness of and interest in optics must be sparked well before they graduate from high school. SPIE—The International Society for Optical Engineering has long recognized this need and invested in pre-college education in light and optics. In 2001, SPIE and the Optical Society of America (OSA) held a series of workshops that culminated in a vision for optics education in the 21st century[2]. Among the high-priority topics they identified for problem-solving were reaching a diverse group of learners, preparing grade K-12 educators to teach optics, and activating SPIE volunteers to help accomplish these goals. Turning Eyes to the Big Sky (TEBS) merged these key tasks in a project led by a SPIE undergraduate member (author RH) that provided training to six middle-school teachers and assisted them in implementing the *Hands-on Optics* (HOO) *Terrific Telescopes* curriculum[3] in their classrooms. While other projects have reported on similar teacher preparation or curriculum implementation projects related to HOO[4,5], TEBS took the further step of measuring student outcomes and collecting teacher feedback after the curriculum was taught. The results of TEBS add to our understanding of how to effectively teach optics, specifically basic geometric optics, to pre-college students.

2. LEARNING OPTICS

Understanding the behavior of light is foundational to learning optics but challenging for students. Previous research shows that students do not readily understand that light travels through space[6], and variously describe it as filling space and remaining stationary, remaining as a glow around a source, comprising rays that fill space, or as rays spreading and illuminating space or surfaces[7]. Students also express misunderstandings about the conditions that cause light to "bend" when passing through objects[7,8,9]. And students tend to interpret light rays concretely, as physical entities emitted by a source, rather than as abstract, geometric representations used by scientists[7,10,11].

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Optics Education and Outreach II, edited by G. Groot Gregory, Proc. of SPIE Vol. 8481
84810G · © 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.928895

Prior studies also have shown that understanding how images are formed with lenses is difficult for students. When asked to reason about a converging lens task, where a light bulb shines through a convex lens and appears as an image on a screen, many students did not employ light rays in a way that could accurately explain how the lens formed the image[12]. Students expressed difficulty understanding the relationship of the components in the task (bulb, lens, and screen)[10]. When asked what would happen if the lens was removed, students often incorrectly predicted that removing the lens would sharpen the image[13] or that an image would still form on the screen[14]. Many made erroneous predictions about what would happen if the screen were moved away from or toward the lens: that the image would change size but remain sharp[7,10] or that the image would become fuzzy but remain visible[10].

The research has focused on students in eighth-grade through university, when geometric optics is usually taught, but similar challenges and ideas are found among individuals from elementary school through adulthood[9,15]. At any grade level, instructional approaches that allow students to reason about phenomena they experience firsthand can help them develop deep understanding of difficult concepts[16,17]. The telescope provides an experiential way for students to learn key concepts in optics[18] and may remove yet another conceptual difficulty that students encounter. Instruction on light often couples it with instruction on how the eye receives light from objects, a concept difficult for students to understand[6,11]. Students are better able to interpret the propagation of light when they consider it independently of sight[19]. While extending one's vision is the purpose of using a telescope, it is possible to investigate the telescope's interaction with light without tackling how the eye sees.

3. TURNING EYES TO THE BIG SKY PROJECT

The motivation for the TEBS project was to strengthen science instruction on light and optics in late elementary and middle-school grades. Specifically, its goals were to train teachers to teach light and optics, involve students in light and optics instruction, integrate science-related technology into classrooms, place telescopes in the hands of hundreds of students, and inspire students to pursue science-related careers. TEBS pursued these goals by implementing a nationally-established informal science curriculum, HOO's *Terrific Telescopes*, in formal classrooms during the 2010-11 school year. The project collected data to measure teacher and student responses to and learning from the project.

3.1. Instruction and materials

The *Terrific Telescopes* curriculum comprised the core of TEBS instruction. An educational collaborative of SPIE, OSA, and NOAO[3] developed *Terrific Telescopes* to teach the optics of telescopes[5]. It was originally designed for use in science centers around the world. It has been used in a range of informal and formal education settings, training 178 teachers and reaching upward of 30,000 people[20]. TEBS moved *Terrific Telescopes* into the classroom and provided resources for teachers to implement it.

Terrific Telescopes taught the basic properties of positive lenses, used to focus rays of light to create images. The curriculum engaged students in approximately two-to-three weeks (in the classroom) of activities that included investigating the behavior of light shone through an acrylic block and convex lenses, finding the focal length of lenses, and exploring the magnifying properties of lenses and other objects. It culminated in building simple refractive telescopes, a project that enabled students to apply and extend their knowledge of lenses[5].

Funding from a number of organizations allowed TEBS to provide each participating classroom the full set of materials necessary to teach *Terrific Telescopes* and more. A SPIE Education Outreach grant provided each classroom a *Terrific Telescopes* toolkit that included several positive lenses, five simple refracting telescope kits, an acrylic block, a laser, and other materials. SPIE provided 300 additional simple refracting telescope kits for the project, resulting in approximately one telescope kit per student in each classroom, and provided funding that allowed TEBS to double the other materials for each classroom. Edelman Financial Services provided 75 Galileoscopes, 50-mm-diameter objective refracting telescope kits[18], which were distributed five per classroom. A number of organizations donated astronomy and science handouts and posters to classrooms.

TEBS supplemented the *Terrific Telescopes* implementation with two additional events. First, author RH, a NASA Science Public Outreach Team (SPOT) member, gave SPOT's *Eye on the Big Sky* presentation to each classroom prior to the pretest and implementation of *Terrific Telescopes*. The presentation covered basic astronomy and current NASA missions in our Solar System. The goal of the presentation was to introduce students to telescopes and excite them about science. Second, all participating students, teachers, and their families were invited to a free end-of-year Star

Party during the university's annual Astronomy Day (held after the posttest for all classrooms except one). The Southwest Montana Astronomical Society set up telescopes for night viewing but that was unfortunately cancelled due to overcast skies.

3.2. Participants

The overall TEBS project involved 15 teachers and approximately 409 students in fourth through ninth grade classrooms in southwestern Montana. Because the *Terrific Telescopes* curriculum has been found most appropriate for middle-school students[21], a finding corroborated by our own experience, we focused our analysis on the sixth through eighth grade classrooms participating in TEBS (8 teachers and 166 students in 7 public schools). Table 1 describes the student populations of the participating middle schools and the communities in which they were located. Schools in our analysis varied in size from 38 to 639 students in grades seven through eight, and included two schools serving Kindergarten through sixth grades. Student populations were predominately White (91%-100%) and a large percentage of students at every school qualified for free or reduced lunch (22%-45%). Schools ranged from rural (town population 1,396) to urban by Montana standards (town population 37,280). One of HOO's goals was to reach underserved students; while the majority of students in TEBS were not ethnic or racial minorities, many were underserved in terms of their rural locations and the lower household incomes that qualified them for free or reduced school lunches.

Table 1: Demographics of Participating Schools

School	A	B	C	D	E	F	G
Grades	7-8	K-6	6-8	7-8	K-6	7-8	7-8
Student Enrollment	639	256	319	38	162	94	52
Free or reduced lunch (%)	45	30	41	43	N/A	34	22
American Indian or Alaskan Native (%)	5	<1	2	0	0	1	0
Asian American (%)	1	<1	<1	0	1	0	0
African American (%)	<1	0	0	6	1	0	0
Hispanic or Latino (%)	2	<1	3	0	0	2	0
Native Hawaiian or Pacific Islander (%)	<1	<1	<1	0	0	2	0
White, Non-Hispanic (%)	91	97	95	94	98	95	100
Town Population	34,200	1,650	7,380	37,280	37,280	1,396	37,280

We recruited teachers within a two-hour drive of the university (to make SPOT visits feasible) by sending invitations through university and state contact lists for teachers of science, and by contacting schools and teachers directly and via a press release. Table 2 describes the eight middle-school teachers who took part in TEBS (names are pseudonyms). Teachers ranged in teaching experience from 1 to 35 years, and in education from a bachelor's degree in elementary education (grades K-8) to a doctorate in science education. They taught sixth through eighth grade classrooms with enrollments of 13 to 29 students per classroom. The number of middle-school students participating in the *Terrific Telescopes* instruction totaled 166; our analysis included the 156 students (94 female, 62 male) who returned consent forms and for whom we had both pre- and posttests (94%).

Table 2: Demographics of Participating Teachers

Teacher Name	Thomas	Vaughn	Sanders	Rogers	White	Larson	Becker	Oliver
School	A	A	B	C	D	E	F	G
Grade Taught	8	8	6	8	8	6	7	7
Students Participating	29	25	17	21	13	21	18	22
Highest Degree	BS	MS*	MS	MS*	BS*	BS	EdD*	MS*
Years Teaching	1	25	19	2	4	30	35	8
Sex	M	M	F	F	F	F	M	F

* Highest degree in science education, technology education, or a field of science.

3.3. Teacher workshop

At the beginning of the 2010-11 school year and before implementing the curriculum in their classrooms, participating teachers met at the university for a one-day workshop. RH led the workshop with the support of author ML, a professor of science education, and JS, a professor of electrical engineering and physics and director of the Optical Technology Center. JS gave teachers an overview of the science of light and optics. The team facilitated the teachers, working in small groups, in completing the *Terrific Telescope* activities. ML led the teachers in discussion about using the activities in inquiry-based instruction. At the workshop, teachers received the *Terrific Telescopes* curriculum guide, all the materials, state teaching license renewal credits, and a project t-shirt.

3.4. Data collection

Teachers. We collected multiple sets of data from teachers. First, we gathered teacher feedback on the workshop itself, which included self-assessments of their knowledge of light and optics, and their readiness to teach *Terrific Telescopes*. Second, we administered the draft student test on light and optics to teachers before and after the workshop. We compared teachers' pre- and posttest scores to measure their learning from the workshop, scoring their tests using a similar approach to that described for students in the next section. We also gathered teachers' feedback on the test itself, using it to revise the test (clarifying, adding, and re-ordering questions) before they administered it to their students. Finally, teachers answered a survey after concluding the TEBS project, providing feedback on the *Terrific Telescopes* curriculum and their experience teaching it, and giving recommendations for how to improve the experience for teachers and students.

Students. We assessed student attitudinal and learning outcomes by having teachers administer a test to students before and after they engaged in the instruction. We used the same test for pre- and posttests, allowing us to compare student scores before and after TEBS. The test asked two attitudinal questions: the first was "Do you like science?" which students answered on a five-point scale (1 = I do not like science at all, 2 = I kind of don't like science, 3 = I don't know whether I like science or not, 4 = I kind of like science, 5 = I like science very much). The second was "Have you ever thought about becoming a scientist?" to which students were asked to answer yes or no. The next set of questions investigated what students knew about light rays, asking them to identify what the lines coming off a drawing of the sun represented, and to illustrate how light from a flashlight would get to an apple. The following set queried their knowledge about telescopes: focus, focal length, and image detail; these three questions are included in Appendix A. The final question asked students to identify parts of a telescope in a drawing, prompted with the terms: tube, simple magnifier, and objective lens.

Table 3: Sample Coding Scheme for Pre/Posttest Question 10: "Which telescope will give a more detailed image of the bird? Please explain your answer."

Points	Description of Understanding	Example Explanation
0	*None*: Circled either telescope but gave no explanation	"It just works this way"
1	*More Naïve*: Circled either telescope; did not discuss focal length; may have included inaccurate ideas about length of tube, distance from object, or image detail	Explained choosing Telescope B because: "It's bigger/longer"
2	*Intermediate*: Circled telescope B; incorporated one aspect of expert understanding but included inaccurate ideas; or had a correct but partial explanation	"The longer the telescope, the less focused it will be but more detailed"
3	*More Informed*: Circled telescope B; reflected expert understanding, that a longer focal length telescope yields a larger or more detailed image; included no inaccurate ideas	"Telescope B is longer so it has a greater focal length so you can see farther and more detail."

We scored students' pre- and posttests using a coding scheme (Table 3). Two researchers developed specific criteria for each question based on the levels of understanding expressed in the answers, resulting in a score of 0-3 points for each question. They developed the coding scheme in an iterative manner: applying it independently, checking agreement, and revising the scheme to reflect negotiations about codes. After multiple iterations, the two researchers independently coded, then compared their codes for approximately 14% of the tests, including both pre- and posttests randomly selected from each classroom. The inter-rater reliability level for each question was 0.90 or above (proportion agreement) (range = 0.90 to 1.00). Test status as a pre- or posttest and students' identifying information were masked during scoring.

4. RESULTS

4.1. Teacher outcomes

Workshop feedback. We surveyed teachers at the end of the one-day workshop to find out how effective it was. They indicated their level of agreement on a 6-point scale (1 = strongly disagree, 2 = disagree, 3 = slightly disagree, 4 = slightly agree, 5 = agree, 6 = strongly agree) to five statements about the workshop. The statements and means of teacher responses to them are presented in Table 4. Overall, teachers were very satisfied with the workshop, agreeing that it improved their understanding of light and optics and prepared them to teach these topics in their classrooms.

Table 4: Post-Workshop Feedback from Middle-School Teachers; N = 8

Statement	*M*	*SD*
As a result of this workshop, I feel prepared to teach the *Terrific Telescopes* curriculum in my classroom.	5.25	0.71
The instruction in the workshop was appropriate for the audience (teachers).	5.63	0.52
The instruction in the workshop was appropriate for the topic of light & optics.	5.50	0.76
This workshop improved my basic knowledge about light & optics.	5.62	0.52
Overall, I was satisfied with this workshop.	5.75	0.46

Learning from the workshop. We gave teachers the draft student test before and after the workshop to measure how their understanding of light and optics changed as a result of the workshop. A paired-samples t test showed that teachers' post-workshop scores (M = 8.88, SD = 1.36) were significantly higher than their pre-workshop scores (M = 6.50, SD = 1.69); $t(7) = 5.16$, $p = 0.001$ (all tests had an alpha = 0.05 unless otherwise indicated). The effect size was very large[22] (Cohen's d = 1.82). Teachers left the workshop knowing much more about light and optics than when they arrived. However, the average post-workshop score was only 68% of the total 13 points possible, with teachers' scores ranging from 7 to 11 points.

Feedback on curriculum after implementation. After they completed the TEBS project, we asked teachers whether they would consider teaching the *Terrific Telescopes* curriculum again in their classroom. They responded on a scale of 1 to 10, where 1 = "strongly no" and 10 = "strongly yes." Seven of the teachers indicated they would teach it again, but one indicated s/he would not, explaining that the curriculum guide was not clear (for all teachers, M = 8.63, SD = 1.93). We also asked teachers to indicate on the scale of 1 to 10 how satisfied they were with the TEBS project. Teachers were very satisfied (M = 9.00, SD = 1.41), but the same teacher was the least satisfied, explaining s/he had hoped to gain a deeper understanding of optics in the project.

We asked teachers how they modified the *Terrific Telescopes* curriculum in their classrooms. Some teachers described implementing the curriculum as it was, others described modifying the materials. Two teachers used clay to affix lenses to a meter stick to help their determine focal length; two substituted candles in activities involving light because it improved the visibility of the images; and instead of using an eye chart to measure resolution of the telescope, which the class found difficult to use, one teacher used a chart with a single letter on it and compared the distance at which it came into focus with the naked eye versus the telescope.

We also asked teachers how they would recommend changing the *Terrific Telescopes* curriculum. While many teachers were pleased to have teacher background information, they identified the need for resource materials for students, too, to aid them in making sense of light and optics concepts. They recommended including explanations and background information for students in multiple modes (e.g., powerpoints, videos, diagrams, demonstrations, readings, and vocabulary). Several teachers named concepts that needed more development in the curriculum: optics, the nature of light, and specifically, refraction. One teacher suggested combining the activities involving building a telescope to reduce repetition, and two seventh grade teachers advised dropping the resolution activity as it was too advanced. One classroom's teacher and students all requested more clear directions and explanations for the activities, especially for building the refracting telescope. One teacher raised concerns about the suitability of the questions on the pre/posttest.

Teachers made comments that provided insight into issues of incorporating the *Terrific Telescopes* curriculum into a formal science classroom setting. Implementing *Terrific Telescopes* seemed unproblematic for the majority of teachers, but several identified issues they needed to accommodate. One teacher added frequent formative assessments to check on student learning through the unit. Another had students use science notebooks, sketching and writing about concepts they were learning, and referring back to them as the unit progressed. One teacher attempted to connect the material to other topics students were learning, especially the electromagnetic spectrum. In one school, astronomy was taught in eighth grade, light and optics in seventh, and the time available for teaching a given topic was limited, which together made the curriculum challenging to implement. The limited time for teaching science in one sixth grade classroom resulted in several days elapsing between activities, requiring a lot of review for students to be able to make connections between activities. Most teachers, however, said they and their students found this a great unit of study.

Teachers had recommendations about the TEBS project as well. Several teachers encouraged keeping or expanding the teacher workshop to prepare them to teach the curriculum. Two advocated for continuing to provide teachers the necessary materials to teach the curriculum (e.g., lenses, lasers, acrylic blocks). All teachers affirmed they would welcome a SPOT presenter into their classroom again, saying that students love having guest speakers and learning applications of what they are studying.

4.2. Student outcomes

Attitudes about science. One of TEB's goals was to positively affect students' attitudes about science. The attitudinal questions revealed mixed results for this goal. Students indicated a statistically significant, lower "liking" of science at the time of the posttest (M = 3.94, SD = 0.99) than during the pretest (M = 4.13, SD = 0.81); $t(155) = -3.09$, p = 0.002. The effect size was medium, Cohen's d = 0.25. On average, students moved slightly toward not knowing whether or not they liked science after TEBS, from "kind of liking" science before. However, students indicated a statistically significant, higher occurrence of thinking about becoming a scientist at the time of the posttest (M = 0.46, SD = 0.50) compared to the pretest (M = 0.39, SD = 0.49); $t(153) = 3.14$, p = 0.002. This effect size was also medium, Cohen's d = 0.25. More students considered becoming a scientist after participating in TEBS. Post-hoc, one-way ANCOVA tests (alpha = 0.01) identified no statistical differences in the changes in students' attitudes between classrooms (liking science: $F_{(7,147)} = 1.34, p = 0.234$; becoming a scientist: $F_{(7.145)} = 1.79, p = 0.094$); or in males compared to females (liking science: $F_{(1,153)} = 0.23, p = 0.632$; becoming a scientist: $F_{(1,151)} = 1.22$, $p = 0.272$).

Learning about light and optics. We were interested in how much students learned about light and optics in the project. A one-way ANCOVA revealed that students' posttest scores did not differ significantly between classrooms when pretest scores were taken into account ($F_{(7,147)} = 1.94, p = 0.067$). Student learning outcomes were similar in all classrooms. Therefore, we pooled students and tested their learning outcomes using a paired samples t test. There was a significant difference between pretest (M = 9.61, SD = 2.72) and posttest (M = 11.49, SD = 2.83) total scores; $t(155)$ = 7.63, p = 0.000. Students experienced large overall learning gains as a result of participating in TEBS (Cohen's d = 0.61). Yet mean posttest scores were just 64% of the total 18 points possible. Students' scores on the sets of questions for focus and image and for parts of a telescope improved significantly, yielding moderate effect sizes across classrooms (Table 5). The mean posttest score for the set of questions on focus and image (see Appendix A) was low, however, and equaled 43% of the total possible for this set. Understanding of light rays did not improve significantly.

Table 5: Student Learning Outcomes by Concept and Between Classrooms

Concept (total possible score)	Pretest		Posttest		Paired-samples t test		Effect size	One-way ANCOVA between classrooms	
	M	SD	M	SD	t (df)	p	d	F (df)	p
Light rays (6)	3.61	1.31	3.71	1.40	0.82 (155)	0.412	0.07	2.69 (7,147)	0.012
Focus and image (9)	3.31	1.47	3.87	1.34	4.30 (155)	0.000	0.34	1.28 (7,147)	0.265
Parts of telescope (3)	1.69	1.15	2.17	1.06	3.95 (155)	0.000	0.32	0.93 (7,147)	0.483

Note: alpha = 0.01 for these post-hoc tests

5. DISCUSSION

The TEBS project met its goals. We prepared eight middle-school teachers to teach *Terrific Telescopes*, increasing their knowledge of light and optics as a result, and providing them materials that will allow them to teach the curriculum in subsequent years, something they said they planned to do. We involved more than 150 middle-school students in light and optics instruction and improved their understanding of these topics. The project successfully integrated science-related technology into eight middle-school classrooms, and placed telescopes in the hands of more than 150 students, including underrepresented students. More middle-school students thought about becoming a scientist as a result of their experience in TEBS.

Students improved their understanding of light and optics concepts in all classrooms. There were no differences in student learning between classrooms, indicating the *Terrific Telescopes* curriculum works in different school contexts, at all middle-school grade levels, and when taught by different teachers.

The relatively low mean posttest scores for both teachers and students raise issues concerning the test questions themselves. First, some test questions did not align completely with the curriculum. Specifically, our test included questions on light rays, which are instrumental in understanding formation of images by lenses, but light rays were not part of *Terrific Telescopes* instruction. Not surprisingly, students did not demonstrate an increased understanding of this topic after participating in the curriculum. While one course of action would be to drop questions on light rays from the test, we suggest a different course. Student learning could be better supported by including explicit instruction on light and optics (including light rays) as part of, or in concert with, the *Terrific Telescopes* curriculum. That notwithstanding, our light ray questions were not adequate to assess whether students understood rays as representations, rather than as physical entities, and could be revised to distinguish that understanding.

A second issue is that the not-to-scale drawings in the questions about telescope focus and image formation (Appendix A) elicited unexpected ideas in student explanations. For example, some students explained that the distance between the bird and telescope would affect the sharpness of the image that formed. A potential argument is that the test questions set up the situation for such an idea to arise, thus they were flawed and students' unexpected ideas should be disregarded, but we assert these ideas should be taken into account. They appear to be intuitive or experiential ideas that instruction can build upon. They also signal areas in which teachers (and the curriculum) should help students develop a deeper and more flexible understanding, for example, by allowing them to make predictions and investigate the effect of distance on an image. At the same time, the emergence of ideas such as this led to us revise our test questions to separately assess different concepts, for example, how to modify telescope components to make a blurry image sharper, and the effects of varying the distance between a given telescope and an object.

We gained insight into issues of implementing *Terrific Telescopes* in the formal classroom setting. Classroom teachers are accountable for student learning, and moreover, of learning specific science concepts identified in K-12 standards. HOO curricula were developed to align with these standards, which may have allowed teachers to more readily incorporate *Terrific Telescopes*. While each teacher made changes to respond to her/his own students or context, curriculum developers could include elements that would benefit all teachers, specifically, identifying connections to other topics, and infusing formative assessments that would allow teachers to monitor student understanding and adjust instruction accordingly. Given teachers' need for evidence of student learning, and the iterations it is taking our team to develop a valid pre/posttest, it would be valuable if curriculum developers provided a test for teachers to measure student learning outcomes of *Terrific Telescopes.*

Terrific Telescopes provided an experiential way for middle-school students to learn concepts of light and optics in the classroom. It did not erase difficulties students have in understanding how lenses form images, but it did lead to improved understanding. The TEBS project results underlined the importance of assessing student understanding to determine whether instructional goals are being met, and of supporting teachers in learning the science themselves and providing the resources they need to implement the curriculum.

ACKNOWLEDGEMENTS

We gratefully acknowledge Joe Shaw for assisting with the teacher workshop and reviewing this manuscript, and Kristi Knaub for her assistance in coding tests. The TEBS project was made possible by donations of more than $20,000 in funds and materials from the following organizations: SPIE, Montana State University (Undergraduate Scholars Program, Optical Technology Center, Department of Education, and Extended University), NASA (Montana Space Grant Consortium, Space Science Student Ambassador Program, Atmospheric and Imaging Assembly, Solar Dynamics Observatory, Astrobiology Institute), Edelman Financial Services, John and Jane Mather Foundation for Science and the Arts, and a private donor.

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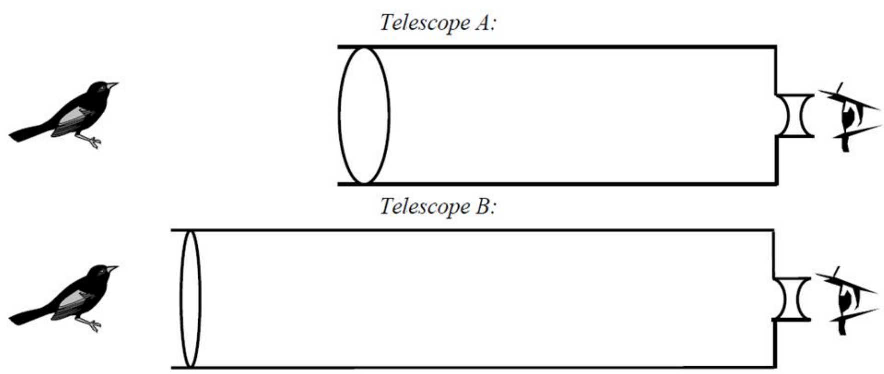
APPENDIX A

Student pre/posttest questions for telescope focus, focal length, and image formation.

8. Two telescopes are shown below. Please **draw** where the image of the bird would come into focus inside each telescope.



9. Which of the telescopes shown above has the longer focal length? Please **circle** your answer and explain why you think that is.

Telescope A / Telescope B

Please **explain** your answer here.

10. Which telescope shown above would give a more detailed image of the bird? Please **circle** your selection and explain why you think so.

Telescope A / Telescope B

Please **explain** your answer here.