Lighting Up Science:
Novel Education Kits for Grades 5-8

Steven J. Davis* and Amy J. R. Bauer
Physical Sciences Inc. 20 New England Business Center, Andover, MA USA 01810-1077

ABSTRACT

In this paper we discuss several science education modules that we developed and pilot tested in grades 3-7. The modules are optically-based and consist of physical kits and associated curriculum materials. The modules emphasize real-world applications such as color displays, environmental monitoring, telecommunications via a light beam, CD-players, and bar code readers. Small groups of 4-5 students have used the kits and provided valuable feedback. We have pilot tested these modules with over 500 students and will highlight several of the modules including pre- and post-class questionnaires completed by the students. The kits use modern photonic materials including light emitting diodes and simple solid state optical detectors. We also discuss how these modules are consistent with National Science Content Standards and cover both science and technology applications.

Keywords: Science education, light and color, applications of optics and light

1. INTRODUCTION

In this paper we describe a series of science education modules that we developed and pilot tested for science education at the elementary and middle school levels. We used light as the centerpiece of our kits and developed five separate modules, each consisting of a physical kit and associated curriculum material. The modules were pilot tested in four schools within New Hampshire, and the results were very encouraging. We worked with a team of 12 teachers and 2 curriculum development experts. The results reported here were obtained in during the school year 1999-2000. We have continued this work through outreach activities.

One of the goals of our work was to integrate modern, yet inexpensive technology into the classrooms of younger students. We selected light as the central theme of our kits for several reasons.

- Light is ubiquitous and even the youngest students are familiar with light
- Light is an important component of science curricula and national science standards
- Numerous modern, important, real world technologies are based upon light

The National Academy of Science and the National Research Council recently published the results of a seminal study: "Harnessing Light, Optical Science and Engineering for the 21st Century." They emphasize the importance of light today and discuss how important light will become in the 21st century. Systematic case studies of learning, e.g., Shapiro's "What Children Bring to Light," have also used light as a model with elementary school students. Light is an excellent topic since it can be made very visual for qualitative studies with younger students while offering many opportunities for more quantitative studies with older students.

Our modules were based on some of the latest developments in the photonics industry: bright, light-emitting diodes (LEDs) and miniature light detectors. These miniature, inexpensive ($1 to $3) devices are ideal for a variety of exciting experiments. Bright, blue LEDs have become commercially available and when combined with previously available red and green LEDs, form the three primary colors. Thus, a small package containing these three diodes can be used for a variety of explorations including: colorimetry, fluorescence, communication by light, as well as more traditional studies of the properties of light. These LEDs have been developed in conjunction with diode lasers that are used extensively in modem society, e.g., bar code readers, CD players, DVDs and Blu-Ray™ devices. LEDs are also finding wide spread use in traffic lights, as automotive tail brake lights, and as displays in numerous electronic devices. The LEDs are close relatives of diode lasers (such as those in laser pointers), but offer several distinct advantages as educational tools for younger students: they cover a larger wavelength range (blue to deep red), are eye safe, and are much less expensive.

Optics Education and Outreach, edited by G. Groot Gregory, Proc. of SPIE Vol. 7783,
77830B · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.862691

AAAS's Project 2061 has defined the important science concepts that students should learn by the end of the 12th grade in their Science for All Americans.[3] These topics are then broken down into Benchmarks for Science Literacy[4] which are appropriate for grade levels K through 2, 3 through 5, 6 through 8, and 9 through 12. These benchmarks take into account students' cognitive abilities and build on topics successively from the earliest grades on up. They strive to teach students scientific facts, as well as the ability to think scientifically, and stress the interrelatedness of the sciences. The NRC has further advanced the efforts of AAAS and their Benchmarks for Science Literacy by developing the National Science Education Standards.[5] Their goal is to *"create a vision for the scientifically literate person [and] to guide the science education system toward its goal of a scientifically literate citizenry." The principles behind these standards strive to teach all students all the sciences and stresses that 'learning science* is *an active process.'* This hands-on and minds-on learning approach is gaining popularity. These interactive lessons rely on student experiments to discover new scientific principles for themselves.

Peter Garik, an NSF educational consultant notes that *"in classroom demonstrations it* is *not clear that students grasp the concepts. However, when students become involved in hands on experiments, the project becomes their activity, and not the teacher's. They begin to explore and produce ideas that would otherwise have to be force fed."*[6] The National Science Education Standards (NSES) also emphasize inquiry based science education. In their NSES, the NRC also states *"Learning science is something students do, not something that is done to them."* Our modules facilitate this type of learning. In addition our kits are consistent with the needs and programs described in a recent NSF publication: "Education for the Future."

Our kits were developed to allow students to explore and construct their knowledge. The constructivist approach to learning has regained popularity, and numerous studies have described the educational benefits of this type of learning. Two recent books, "Elementary School Science in the '90's" by Loucks-Horsley et al.[8] and Shapiro's "What Children Bring to Light" both present numerous examples of constructivist approaches to science education in the Elementary and Middle School Grades. Shapiro' even uses light as the subject of her case study of six, fifth grade students. In her study she carefully reviews the literature beginning with Piaget in 1929.[9] The change that is now occurring in science education is the realization that children do not learn science by simply accepting the views of scientists. They enter school with notions about how the world operates, and often hold onto these views even after "crystal clear" lectures. Construction and validation of knowledge through experience are extremely important components of learning science. Our modules are designed to facilitate this.

We coordinated our Phase I effort with the Elementary Science Curriculum recently adopted by the Londonderry NH School District. The foci of this curriculum are the New Hampshire State Frameworks in Science and the National Science Curriculum documents. This curriculum is called Science Curriculum Improvement Study (SCIS 3). The preamble to these NH standards is: *"The development of strong scientific abilities in conjunction with an understanding of basic scientific concepts is a major component of a student's elementary education program and overall development as a learner. Recent national documents such as Project 2061. Benchmarks for Science Literacy. and the National Science Education Standards have called for renewed efforts in the reform of science education. These documents call for an inquiry based model that encourages students to investigate, discover, and reason. By using this model. students. acting as scientists. can explore and enjoy ideas and concepts that are stimulating to inquisitive learners. Being actively engaged in science enables students to formulate questions and develop strategies to find answers to those questions, solve problems, think creatively and critically, communicate, and make scientific connections. And this model allows students to understand the natural connections between science, technology, and our society.*[10] As we show below, our modules were consistent with this philosophy, and we successfully integrated our materials into the classrooms.

2. DESCRIPTIONS OF MODULES

We developed five modules including associated curriculum materials and pilot tested the materials at four schools within New Hampshire: The Matthew Thornton School, North School, and Middle School, all in Londonderry, NH, and The Swazey Central School, Brentwood, NH. The pilot testing involved approximately 500 students, 26 hours of class time, and training for 12 teachers.

The five modules are described below:

Module 1. Paths of Light

Using small beakers filled with a scattering material, students make their own miniature light box and visually observe reflection and refraction using small mirrors and lenses. They also use a concave mirror to observe how we can concentrate light. One experiment uses the beaker as a model for the eye and students can explore how their eyes focus light onto the retina and visualize the function of eyeglasses.

Module 2. The Color Maker

This kit contains a small, hand held box that we named the Color Maker. It contains four LEDs: white, red, green, and blue. Red, green, and blue (ROB) are the three primary colors of light and can be combined on a screen to make any color including white. The small groups explore the many colors that can be made and devise their own color recipes. Students prepare their own codes for colors and see if other groups can produce the color. Curriculum material relates these concepts to color TV and computer display screens.

Module 3. CD Player

The students construct and experiment with a simple but operational CD player. They use light sources similar to those in a CD player to produce sounds. They also make their own CD and play it. We challenge them to design and play CDs that make certain tones.

Module 4. Bar Code Reader

Students construct a simple bar code reader and learn several codes. Once they have learned the codes, they become the processor and directly experience how the reader processes the code to produce the price and the identity of the item being purchased. This module includes a game as an assessment activity.

Module 5. Communication by Light

This module facilitates studies of modern telecommunications including cable TV, the telephone, and the Internet. Students construct an operational photonics-based telecommunication unit consisting of a light source, detector, and speaker. They progress from making simple sounds with the light source to broadcasting radio stations and CDs. Challenges include the incorporation of fiber optics into the transmission system.

3. INTRODUCTION INTO THE CLASSROOM

Prior to the development of the kits, we presented a description of our concept to the Londonderry School Board at a formal public meeting, and the board voted their approval for us to present the materials in the classrooms. We also began our interactions with two curriculum development coordinators to aid in our initial curriculum development. Once we had developed the physical kits and tested them at Physical Sciences Inc. (PSI), we arranged meetings with the principals of two elementary schools and one middle school where we presented an overview of the materials. The principals then contacted several of their science teachers and we had separate coordination meetings with the teachers at the various schools. At these meetings we discussed the general nature of our project, and demonstrated the particular modules that would be used. We also handed out associated curriculum materials to the teachers. On most occasions we left a complete kit and curriculum with the teachers for several days so that they could work with the materials prior to the classroom introduction.

In order to demonstrate that the modules had educational value, we developed a series of pre and post-lab quizzes that were administered to each student. Due to the relatively brief time that we were with the students, usually an hour to an hour and a half with each class, we selected this method as a learning assessment tool. These quizzes were not labeled as such to minimize student anxiety. We developed these quizzes in conjunction with our two curriculum coordinators. The teachers typically administered the pre-lab quiz a day or two prior to the lab. Occasionally, we administered them early in the lab period.

The quizzes were designed to assess the students' general level of knowledge of the subject prior to it being presented in the activity. Students were told that these were not tests and that if they did not know an answer just state that they did not know. One quiz was developed for each module. Typically a series of three to five questions was asked. Some questions were in the form of diagrams. For example, the module titled "Paths of Light" presented to grade three asked about reflection from both a flat and a concave mirror.

3.1 Classroom Activities

We began the activities with a short discussion of the particular subject being presented. We would often ask questions similar to the pre-lab quiz. For example, with the Communication by Light module, students would often suggest that flashing a light similar to Morse Code would be an effective method. We would ask, "Why not simply leave a light on as the message?" The students recognized that some sort of a flashing pattern or an intensity change was required to send a message. These discussions then led into the laboratory activities. Teachers often assisted with these discussions.

The kits and written materials were distributed to each group, typically three to five students. In all classes, students were accustomed to working in small groups either in clusters of desks or at small benches. Our pre-class coordination with the teachers facilitated this format. Typically, the groups were of mixed gender, but there were also groups of just boys or girls. In general, the groups worked well together. Each student was able to work directly with the materials, and this enhanced the student interest. We also prepared a series of three to four presentation slides to help guide the discussion and to assist the students in the orientation of the modules on their desks or benches.

The written materials included some background information and simplified instructions, diagrams, and tables for data collection. Often, two students would be recorders of data for part of the lab, then the roles were switched with other members of the group. The students recorded their observations in tables and answered some questions that were included in the curriculum materials. Some questions encouraged students to express their ideas and concepts about what they were observing.

Each lab also included at least one practical assessment exercise that the students completed. These were designed to let students extend and apply what they had learned. Assessment activities included a team game (Bar Code Reader), sending codes to another group (The Color Maker), and a challenge posing a new problem such as how to get light around an obstacle (Paths of Light). Examples of assessment activities are described below. We collected all the materials at the end of the lab to use as part of our assessment.

Teachers actively participated, and we and they circulated to all groups of students to pose and answer questions. The students in each group were very engaged in the activities and there was much discussion among them. We observed numerous very inventive solutions to the problems especially in the assessment activities. Some are presented below in our discussion of the individual exercises. We had over 25 hours of classroom contact with students, and this was an essential component in development and iterations of our kits. In some classes, a teacher presented the entire class and worked our modules into his or her lesson plans. We always left time at the end of each lab for discussion about what had been done.

Often we related the activity to real world technologies such as color TV, telecommunications, and supermarket checkout counters. Some presentation slides were developed for this discussion as well. We also left a post-lab quiz with the teachers who would administer it some time later. This time period varied from two to five days depending on the teacher. One teacher waited over 2 weeks prior to giving the quiz in order to evaluate longer term retention. Our post-lab questions included open ended questions to allow students to express what they had seen and learned and to pose questions for further investigation.

Module 1. Paths of Light

The Paths of Light module was designed to allow younger students to explore in a very visual manner how light beams propagate. Often, students have difficulty with the concept of a light propagation because we only see light by reflection or by scattering. Thus, we wanted to make our light beams visible. The Paths of Light Module contained a three color light source (red, orange, and green), a beaker, and a series of flat and concave mirrors, and lenses. The kits also contained a small amount of non-dairy coffee creamer that was added to water to produce a slightly cloudy liquid that efficiently scattered the LED beams when the beams passed through the beakers. In effect, each group had their own miniature light box. Often teachers use much larger devices as classroom demonstrations to show light beams. With our modules the students became deeply involved, and completed many manipulations of the light beams. The intense LEDs are quite collimated and many students called them “lasers”; this of course heightened the interest level.

This lab contained several explorations for the students all based upon visualization of the LED light beams in the beaker. The natural divergence of the beam was easily seen in the beaker and was correlated with the observation that the spot projected on a small screen became larger the farther the LED light source was placed from the screen.

Next, students were provided a small flat mirror that they hung inside the beaker. Then they used the light source to study angular reflection from the mirror. The angle was easily changed by rotating the beaker. It was very easy to see even in a qualitative sense that the angle of reflection increased as the angle of incidence was increased. This provided an excellent example of the law of reflection. We confined the explorations to conceptual or qualitative investigations, but they can become more quantitative for older students. For example, if a protractor were placed under the beaker, it would be very easy for students to explore the law of reflection quantitatively similar to the Hands On Optics kits recently developed by SPIE and OSA.

The written materials had outlines of the beaker and the mirror and students were asked to illustrate what they saw. These experiments were repeated with the concave mirror in place of the flat mirror. This mirror produced a short focus (- 1 in.) and graphically demonstrated how light can be concentrated. This elicited numerous discussions and questions about telescopes, radar antennae, and satellite dishes. Typical observations recorded by some third grade students are shown in Figure 1.

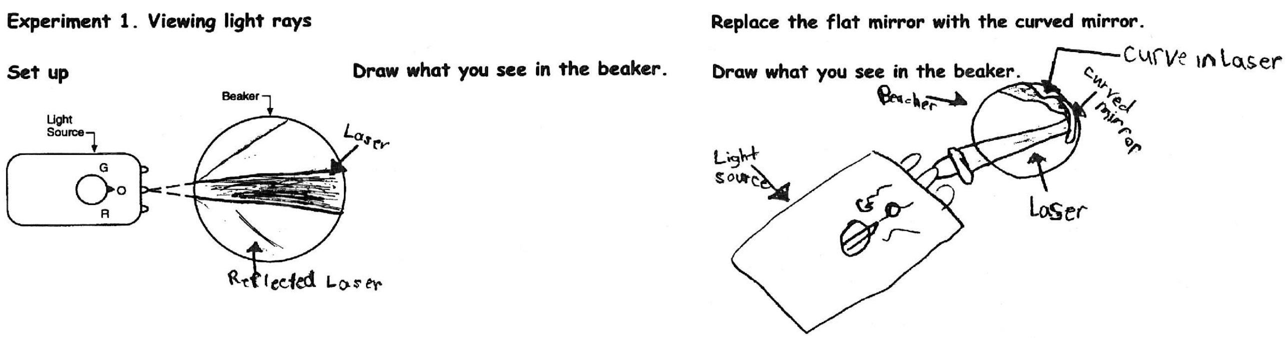

Figure 1. Observations made by third grade students using the Paths of Light modules.

Model of the Eye

Students also explored the effects that a simple lens has on the light beam. By changing the distance from the lens to the beaker, they were able to visualize the convergence of the beam to a focus and the subsequent divergence beyond the focal point. As part of this experiment, we had the students place the lens at a distance that produced a focus at the back of the beaker. This occurred with the lens about 1/2 in. in front of the beaker. This represents a simple but effective model of the eye. Next we had the students move the lens slightly so that the focus was just behind or in front of the back edge of the beaker. We then provided a pair of eyeglasses or students used their own. When the glasses were placed between the LED source and the lens, changes in the cone of light and focal point in the beaker were easy to observe. Students were very intrigued by these observations. One third grade girl had put her glasses in the beam and saw the light cone become sharper and the focus move closer to the front of the beaker. She said that she was farsighted. Dr. Steven Davis, the PI, told her that he was nearsighted. She thought for a moment and then responded by saying that his glasses would probably have the opposite effect on the focus. He handed her his glasses, and she confirmed her prediction. She and her group were very excited by this successful prediction. This is an example of the types of minds on interactions that we observed.

Assessment Activity

Finally, we also presented an assessment activity in the form of a challenge problem. We removed the beaker and placed a small screen in its place so that the LED beam made a spot on the screen, we placed an obstacle such as a shoe box between the light source and the screen so that the beam was blocked. Then we challenged each group to design a way to get the beam past the obstacle and make a spot on the screen.

A short time later, we handed each group several small mirrors, each affixed to a base. The mirrors were only 1 inch in diameter, and the alignment of the mirrors had to be fairly precise. We purposely did not use larger diameter mirrors in order to pose a significant challenge. Students then attempted to devise and demonstrate a solution. Some groups developed successful solutions within a few minutes, and other groups had more difficulty. Most students seemed to enjoy this challenge, but a few became somewhat frustrated. We circulated to the groups and, for those having difficulty and asked them to think of what the light beam did in the beaker when it hit the mirror. This often led to solutions; some students immediately made the connection, while others looked at their lab notes. This provided an important lesson about the value of recording observations. When they finally saw the red, green, or orange spot on the screen students were very excited and appeared to have a sense of accomplishment. They often then developed alternate solutions with two, three, or even four mirrors.

This activity pointed out quite dramatically the difficulty that young students have with the concept of light propagation since they cannot see the beam. With the beakers, the beams were visible due to the scattering medium and it was easy to follow the beam. When we removed the beaker, some students encountered difficulty because they could not see the beam. Some students found that they could track the beam with a small piece of white paper; the LED beam would show up as a spot on the paper. We told these students that this is how professional laser scientists track laser beams in the laboratory. They were quite excited to hear that their solution was also used by scientists.

Students devised several interesting variations of a standard periscope as shown in Figure 2, which shows some of the student drawings.

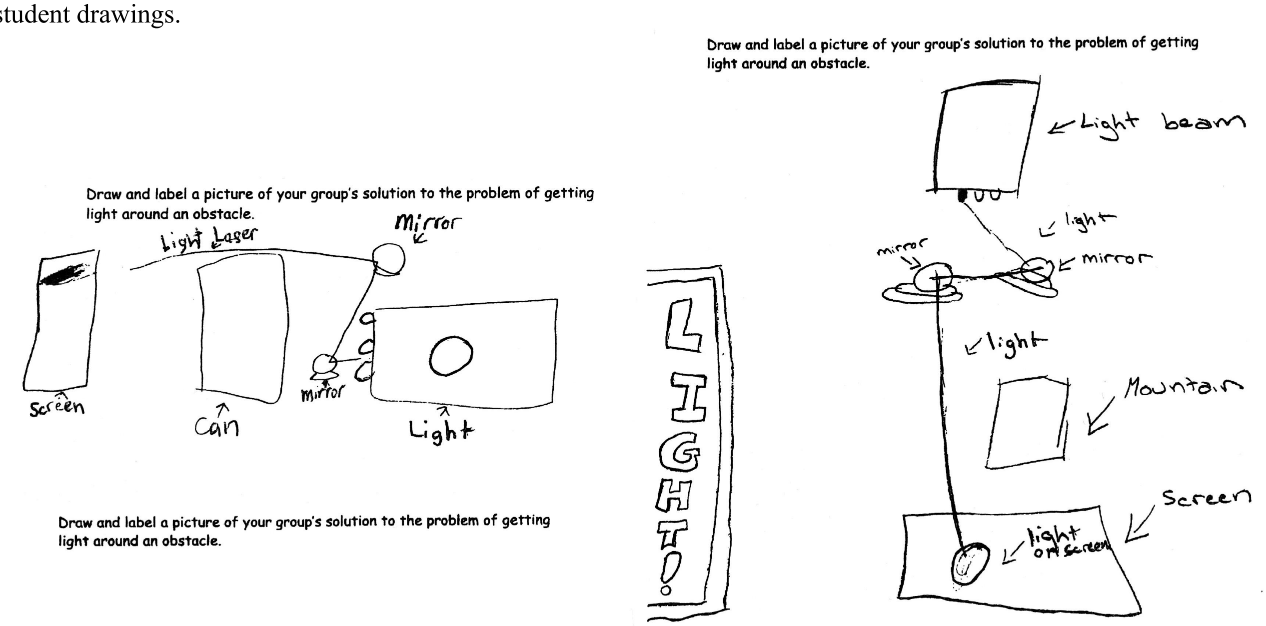

Figure 2. One group of third grade students' solutions to the Paths of Light assessment activity.

Module 2. The Color Maker

One of our modules captured the visual attention of students at all grade levels tested (3,5, and 6). We introduced The Color Maker into three grade levels (3, 5, and 6). We developed this module because of the very recent dramatic advances in LEDs. In our Phase I proposal we had proposed to use intense blue, green, and red LEDs in order to produce the primary colors. This allowed us to use state-of-the-art, solid state light sources that produce essentially no heat. Recall that one of the attractive features of our modules is that students explore science and technology using the very latest light sources available. This is a significant attention grabber. Indeed, until recently it would have been impossible to build such a versatile, compact, and student-friendly device.

A photo and a diagram of the Color Maker are shown in Figure 3. The small project box (2 x 3 x 6 in.) contains four intense LEDs (red, green, blue, and white). The intensity of each LED is controlled by a knob attached to a small potentiometer. Each knob was independently adjustable with a dial reading of 0 to 10. This allowed the students to vary the intensity of each LED from no light to maximum emission intensity. Each knob was colored to signify which LED it activated.

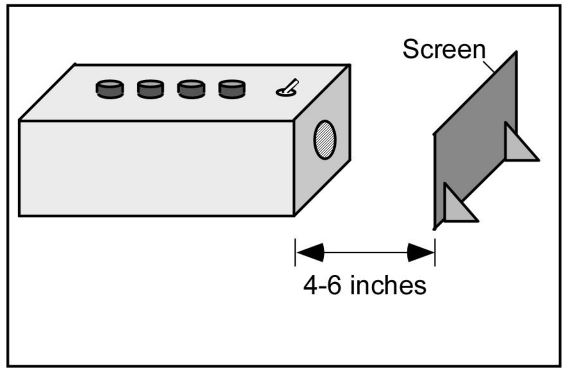

Figure 3. Color Maker and one configuration.

The three primary color LEDs (red, green, and blue) and the white LCD were clustered to form the projection source. The beams from the three primary color LEDs were well mixed a few inches from the exit port. To enhance mixing we also installed a holographic diffuser plate at the exit port of the Color Maker. When the Color Maker was positioned about 4 to 6 in. from a small white screen, the beams from all three primary color LEDs were nearly entirely overlapped and a 3 to 4 in. spot of light was visible. The new, intense LEDs provide sufficient light output that the spots were visible in a fully lighted room, but the effects were much more dramatic in subdued lighting, available in any classroom. Completely darkened rooms are not required. Next we discuss some of the experiments that students completed with The Color Maker.

Experiment 1. Exploring White Light

Most students, even third graders, have been exposed to prisms and can draw a crude spectrum or a rainbow. However, they are much less confident in discussing white light or the addition of different color light beams. We found that our Color Makers provided an excellent tool for better understanding white light. We first handed out small transmission gratings mounted in 35 mm slides. With only the white LED on students could see a complete visible spectrum through the grating. With the white LED off, they consecutively turned on the red, green, and blue LEDs while keeping the white LED on. Through the grating, they saw that the red, green, and blue LEDs each produced their own color, but the colors covered some spectral range since LEDs are not monochromatic. Then with all LEDs on including the white the students observed that the three LEDs produced a spectrum that nearly covered the entire spectrum of the white LEDs. Since we had positioned the white LED to be above the other three, the white light spectrum appeared above the individual colored LED spectra. This provided a very convenient and graphical spectrum that resembles white light. It provided an excellent introduction to the remainder of the Color Maker module.

Experiment 2. Adding Primary Colors of Light

The curriculum materials contained information encouraging students to think of colors as recipes much like cooking a cake; i.e., three parts red, seven parts green, and one part blue gives a color. In the first exercise the students set up the experiment with a small white screen as described above. Then they completed recipes for five colors provided in the written materials. After all groups had completed the five colors, we compared colors and found that most groups agreed. There was some discussion on shades that were close to each other. Entries from two groups of fifth grade students are shown in Figures 4a and b. We discussed that color is a perception and there is often disagreement on colors that are close to each other. Once they had grasped how to use the Color Maker, students used the curriculum materials to make up their own recipes and record the colors that they made. Students really enjoyed this activity and spent considerable time exploring. All students in the group used the Color Maker and designed their own favorite color. Since the LED output powers were continuously adjustable, a nearly infinite set of colors is possible. A sample is shown in Figure 4c.

Color Recipes to Try

(a)

Number of Red	Number of Green	Number of Blue	Final Color
7	5	0	orange
8	4	0	peach
7	0	6	Purple Ret
0	8	6	aqua
9	4	6	florecent pink

(b)

Number of Red	Number of Green	Number of Blue	Final Color
7	5	0	Yellow, orange
8	4	0	Oraage
7	0	6	Purple
0	8	6	turquise
9	4	6	light Pink

(c)

Number of Red	Number of Green	Number of Blue	Color You See
3	2	5	Turquoise
8	10	2	Neon
10	1	8	Pale green
5	1	7	Violet
6	4	10	Blue-violet

Figure 4. Color recipes and student observations from two groups of fifth grade students.

Assessment Activity

The written materials asked the students to record their recipes carefully. Each group then wrote the numerical codes of their two favorite colors but did not write down the color. Then groups exchanged these codes and each group used three digit codes (e.g., red = 2, green ~ 5, and blue = 7) to produce and record the two colors. Then the groups compared how well they did. Students found that they could send a color code message using only three numbers that identified the intensities of the three LEDs. We found that the agreement was better than 90%. In other words, students had progressed from little knowledge of color mixing to a rudimentary understanding of how we can encode and produce colors with only three numbers. We discussed with the students that this encoding is very similar to digital color coding and is often used in full color displays. For example, false color encoding is often used in medical imaging scans to increase contrast and help physicians locate diseased tissue. This method uses various intensities of red, green, and blue to produce these images. We also discussed how color monitors, LED displays, and color TVs including flat screen devices produce colored images using red, green, and blue.

Experiment 2. Colors of Objects

The addition of colored lights described above is an important element in the understanding of light and color and reinforces how we can make many colors including white with our three primary colors. However, we also wanted to extend the utility of the Color Maker to experiments that focused on why objects appear to be colored when we view them. For this exercise, we prepared three foam board squares (4 x 4 in.) and painted them either red, green, or blue. Groups of three boards were then glued together to produce a single board of three strips: red, green, and blue.
With the boards placed about 12 in. from the Color Maker, students began investigations of color. In subdued lighting, the effects were very dramatic. With only the red LED on the red stripe was very bright red. Some students said that it looked like there was a light inside the red stripe. In contrast, the blue and green stripes appeared very dark or black if the room lighting were dim. Analogous observations were made with just the blue or green LEDs illuminating the

stripes. Students tried all sorts of color combinations. With all three LEDs on the strips appeared normal as if in sunlight. When one color LED was removed, that color also disappeared from the stripes. They also used the white LED to illuminate the stripes. We let the students explore for about 15 min and then posed a series of questions. Discussions of reflection and color selective reflection and absorption followed. We also discussed photosynthesis. Photosynthesis is activated by the absorption of blue and red light. Thus in a leaf, green is the predominant color that is reflected.

On a subsequent day, the classroom teachers gave the post-lab quiz. We were not present for these quizzes. The completed quizzes were sent to us for analysis. We discuss the results of the pre and post-lab quizzes later.

3.2 Applications of Photonics and Light to Modem Technology

One of the goals of the pilot testing effort was to demonstrate that our kits could be used to let young students explore not only important aspects of the science of light but also modem technology applications of light. These applications are already an important part of students' lives. We chose three real-world applications with which students are familiar:

- CD player
- Bar code reader
- Communication by light (telecommunication technology).

Students have seen a barcode reader in action, most know that a CD makes music or can be used in a computer, and students have talked on the telephone. Our kits are also relevant to DVDs including Blu-Ray™ discs. We found that we had immediate attention when we would begin a lesson with for example: "Today you all are going to make your own CD player, construct your own CDs and play them." Students were very eager to learn about technologies that play roles in their lives.

Module 3. CD Player

Our goal with all the modules was to develop simple, yet operational devices that embodied the salient components of an actual system. The CD player provides a good example of our approach. We designed and built eight small "CD drivers." A small DC electric motor was used to rotate the disks. The motor was driven by a pair of size C batteries and the speed of the motor was controllable with a knob (potentiometer). A small on/off switch and indicator LED lamp completed the CD drive system. We attached a small hardwood biscuit to the shaft of the motor and glued three small velcro patches to the biscuit. Two sets of CDs were used. The first was a surrogate CD and was actually a 4 in. diameter plastic knitting form available in craft stores. We sprayed the disk with silver paint to make the disk more reflective. These knitting disks contain a series of spokes and numerous concentric circles. When it rotates it interrupts a beam of light as the spokes pass through the beam. The second set of CDs were actual blank CDs. They were used in a reflective mode as described below and brought a sense of the real world to the CD Player activity. Students attached the CDs to the motor shaft via three velcro patches that had been glued to the disk. Students used an LED light source and light detector that we had developed previously. The light detector output was connected to a miniature speaker/amplifier (Radio Shack).

The CD player lab began with students becoming familiar with the light detector and speaker combination. The light detector box contained a CdS photoresistor that was in series with a 9 V battery. A small milliamp meter displayed the current that was directly proportional to the intensity of the light hitting the detector. A mini phone jack was used to connect the photocurrent to the speaker/amplifier. Upon turning on the detector and speaker, students noticed that the light detector meter needle reading increased as the detector was directed towards the room lights. An audible buzz was also apparent from the speaker. The teachers encouraged the students to point the detectors at other light sources such as aquarium lights, computer monitors, and the sun. The computer monitor gave a lower tone, and the sun produced a steady hiss.

These explorations allowed the students to become familiar with the detectors. Teachers emphasized to us that it is important that young students be able to play with new equipment. This play time is an important element of the learning process. These activities about the sounds of light provided such an opportunity and also allowed them to investigate a new phenomenon: the sounds created by man made and natural light sources. This led to a series of discussions involving students, teachers, and us. We asked why the fluorescent lights and TV monitors produced a buzz but the sun did not. Numerous inventive theories were postulated by the students such as: "The sun goes through a screen and a window," and "The sun is brighter." Further questioning about possible differences between the light sources led some students to state that the artificial lights are electric and "have electrons and volts." Finally, we had discussions on alternating current and the fact that this leads to alternating light intensity that we cannot perceive hut the light detector can see with ease. Most students realized that the sun does not blink regularly and seemed to appreciate that a steady intensity (hiss) was reasonable. The TV monitor produced a much lower tone since the screen refresh rate is only 30 Hz.

Next, the students reconfigured the setup with an LED beam passing through the surrogate CD and input into the light detector. Written lab materials asked students to slowly turn the disk by hand. When they did this, they heard a series of clicks. Then students, using the lab guides, turned on the CD driver motor and began to produce a series of interesting sounds that ranged from a reasonable imitation of a motor cycle to a loud siren. The lab guide suggested that they investigate the relationship between the speed and the tone produced. Some students noticed that they could imitate the sounds produced by the TV and fluorescent lights if the speed of the disk was correct. This demonstrated a CD that operates by transmission, but this is not the way a real CD operates.

We introduced the next concept by holding up an actual CD. These devices are of course opaque and highly reflecting. The curriculum materials challenged the students to construct a reflection CD. This caused some considerable discussion within the lab groups. After several attempts the student groups broke out of the mind set of a transmission CD and moved the light source and light detector onto the same side of the surrogate CD. The silver paint that we had put on the surrogate CD produced enough reflection that the detector produced output sufficient to produce a sound. For this exercise the students had to put the light source and detector at an angle with respect to the plane of the rotating disk. There were several successful versions of this invented by the students.

Assessment Activity

Students worked with their new CDs for a while until we presented them with the challenge (assessment) problem. Teachers handed out a blank CD provided in the kits to each group. They also handed out an erasable overhead transparency pen. Students were then given a worksheet. This activity asked the groups to design and playa CD that would play a low tone and a second one that would produce a higher tone. These were completed by writing a design on the shiny side of the disk. The pen lines would interrupt the reflected light beam and cause a sound. Many novel designs with the concomitant sounds were produced. At the end of this activity we had time for discussion about real CDs. In an actual CD the information is stored in a long track (5 km) that contains as series of miniature (micron size) pits and plateaus. A focused diode laser beam is incident on the rotating disk and different levels of constructive and destructive interference in the pits and plateaus produces changes in the light that reaches a detector. Although our CDs do not rely upon interference of a coherent laser beam, they do produce variations in the reflected light intensity that reaches the detector. Thus, students had in fact built and operated at least two versions of a CD player. They gained an appreciation of how information is stored on a CD and can be read by a beam of light. These are the essential elements of CD and DVD players.

Module 4. Barcode Reader

The barcode reader was a simplified version of an actual system. For this unit we used the same LED light source, light detector, and speaker as previously discussed. Our barcodes were made from distinctive patterns of stripes on small acetate strips that were then taped to small pieces of Plexiglas. We used Plexiglas so that the barcodes would be easy for the students to manipulate. A sample barcode kit is shown in Figure 5.

We began the barcode lab similarly to the CD player lab. Students familiarized themselves with the light source, detector and speaker. They hooked the components together and began to discover how they could turn visible pulses of light into audible pulses of sound. Once they were comfortable with the units, teachers distributed three distinct surrogate barcodes to each group of four students. We pilot tested these units with third grade classes.

The students were then guided by the written material through a brief investigation of the barcodes. When the students "swiped" the barcodes between the light source and the light detector, they heard series of clicks. They often had interesting descriptions of these sounds. The written material asked them to change the swipe speed and describe how sound differed.

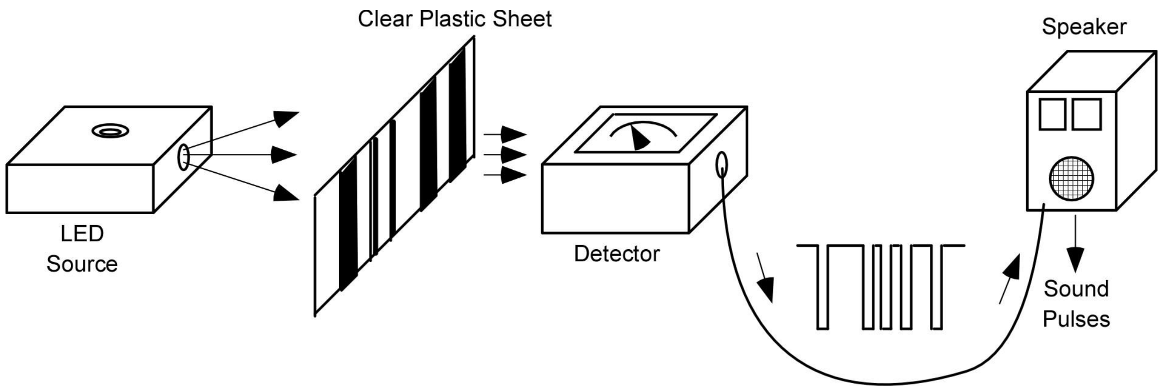

Figure 5. Barcode reader kit configuration.

Assessment Activity

After the students were quite familiar with all the aspects of their equipment, we introduced them to a game that also served as an assessment activity. This game involved all students within a group and illustrated the functions of the equipment and the roles of people at a typical check-out counter. These players and the functions that they served are listed below:

- **Salesclerk**: teaches processor which barcode goes with particular item
- **Customer**: chooses items to buy and takes them to salesclerk
- **Processor**: decodes barcode after hearing sound made by swiping through barcode reader
- **Cash register**: receives the identity of the purchased items from the processor and looks up the prices of the items. Adds up the order and presents the total to the customer.

Each of the three barcodes was labeled, e.g., hot dogs, cereal, pickles, and we supplied a price for each on a separate sheet of paper. The processor had to learn the audible pattern made when the salesclerk swiped the barcodes. Most groups had their processor turn his or her back to the group so that he or she could not see the barcode. After a few minutes the processor was ready for customers. The customer handed the Plexiglas pieces to the cashier, who swiped each one. The processor listened and stated what the item was. The cash register then found the price and added up all the items before telling the sales clerk the total.

We decided that three codes were sufficient for the processor to learn, i.e., we were concerned that four or five sound patterns might require more time than we had available in the average class. We were concerned that this would be a bit boring for students, but they soon demonstrated a new twist. One young girl (customer) brought her three items (barcodes) to the salesclerk and announced: "I want three of these, one of these, and two of these. This provided a new challenge for the processor. We observed that once the processor had learned the three codes, he or she was very accurate.

This activity was continued until every student within a group had an opportunity to play each role. At the end of the game, time was reserved for discussion. We pointed out that real barcode readers work by reflection of light and not by transmission. The principles of reading and processing the data are identical. We did develop a reflection barcode reader, but did not introduce it to the class because the sounds produced were softer due to insufficient reflection. In addition, alignment of the light source and detector for reflection is more tedious than for a transmission device. We wanted the students to concentrate on how barcode readers use light to read information, not spend time aligning the equipment. Through the discussions students expressed great interest that in real barcode readers the processor must be taught the codes just as they had to learn a code and equate it with an item.

Module 5. Communication by Light

As a final module concerning modem technology applications of light, we introduced students to telecommunications. In fact, students used the materials in this module to construct and operate a modem telecommunication network consisting of:

- LED light source
- Miniature radio to modulate the light source
- Light detector
- Amplifier/speaker to hear the signals broadcast.

A Communication by Light module is shown in Figure 6.

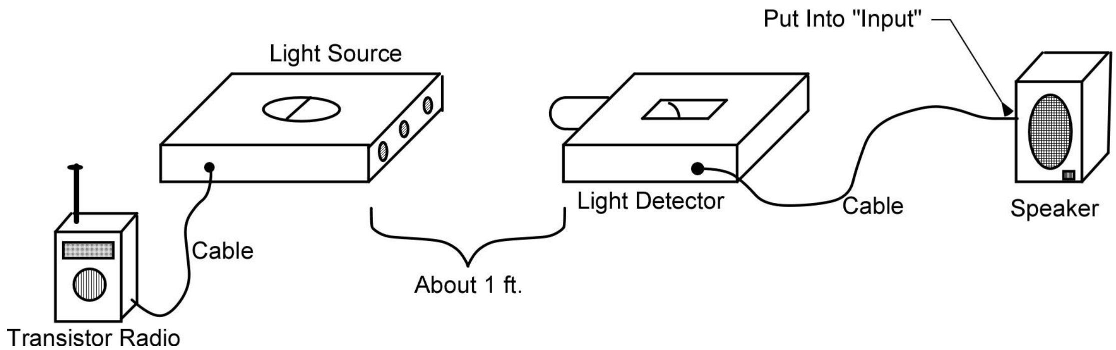

Figure 6. Communication by Light kit setup.

This module let students explore how we can electrically modulate a light source with a radio, microphone, or CD and subsequently detect the modulated signal at a different location. Students were very excited to be working with materials that are really quite similar to actual modern telecom systems (miniature LEDs, solid state light detectors, and fiber optics)

Teachers and students were provided with curriculum materials that discussed the basics of communication including sound vibrations. This module provided interesting examples of energy conversion, an important element of grades 5 and 6 in the school system where we piloted these kits. We also provided a few slides as discussion guides. For example, in the pre-lab quiz, we posed the question of how one might communicate with light. Most students realized the one needs some sort of code, e.g., blinking the light such as in the Morse Code. They appreciated that very little information can be relayed with the light simply turned on. However, less than 1 % of the students realized that they send "real" messages by light when they use a telephone.

Using additional written guides with diagrams, each group assembled their own telecom system using the light source, detector, radio, and speaker. We allowed the students to explore the possible solutions as much as possible given our limited class time. We suggested that they first learn how the light detector and light source worked. Then they added the speaker and radio. Some classes had already used the light detector, light source, and amplifier/speaker in the CD lab. These students were very comfortable with the material and more rapidly converged on a working telecom system. Students tuned to their favorite stations and also transmitted using all three LED colors.

Most students had preconceived notions about how things should work and often tried these approaches. For example, on numerous occasions we saw groups initially direct the light beam into the detector but then hook the radio output directly to the amplifier speaker. This provided music, but when asked what happens when they blocked the light beam, they were surprised to observe that the music continued. Usually a few iterations led to a working system. Some students noticed that if the light source and detector were placed very close to each other and they put a finger over the LED, that they could still detect the radio signal if it was the red LED. This led to discussions about how well red light travels through tissue and is used by doctors in modern medical practice.

Assessment Activity

The free space propagation of the voice or music modulated light beams described above is a relevant and interesting introduction to modern telecommunications, but requires that the light source and the detector be in fairly close proximity (1 to 2 ft). We posed the question to the students of how they might communicate with a modulated light source if there were a larger distance between the source and receiver or an obstacle such as a tree or hill in the way. In other words how could this technology be used in real world applications. We asked the groups to come up with some ideas of how this might work. Numerous concepts evolved including mirrors on hills and poles.

Teachers then placed an obstacle such as a can or shoe box between the light source and the light detector so that no light could pass. We told the students to think of this as a mountain. We then handed out small mirrors on stands and the groups began to try their solutions. Some very clever designs using only two or sometimes three mirrors began to unfold. Some groups discovered that a small piece of white paper could be used to track the beam as they adjusted the mirrors. The results were similar to the grade 3 exercises in the Paths of Light module. At the end of this exercise we discussed how this approach is actually used in the real world, e.g., microwave relay towers that can often be seen on hillsides. Some groups had worked quite hard to align the mirrors and were very pleased when the light beam finally reached the receiver. This emphasized how crucial the alignments must be in real devices.

Finally, we handed out a 7 ft length of plastic fiber optic to each group without a description. The fiber was covered by a black sheath of plastic and looked like a wire. Students in each group would invariably look at the sides and ends of the fiber. Only rarely did we encounter a student that knew immediately what the "wire" was or what it could do. As they continued to inspect the fiber, occasionally a student would be looking in the end of the fiber while the other end was pointed toward a window or room light and he or she would see a bright spot in the end of the fiber. Having made this connection, the group would place the fiber next to the LED and direct the other end into the light detector, and their radio transmissions were operational again. A solution to communication around a mountain developed by a group of 5th grade students is shown in Figure 7.

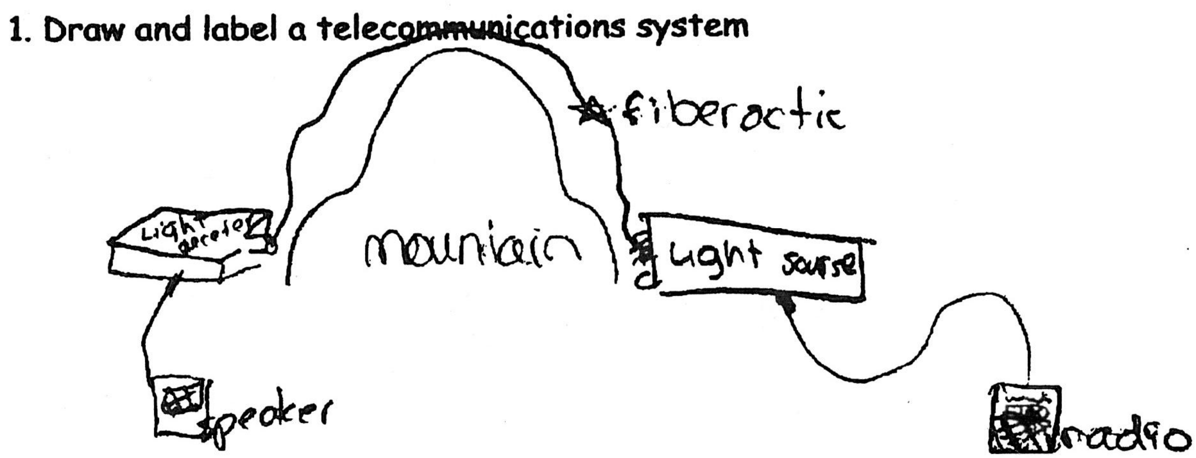

Figure 7. Communication over a light beam using a fiber optic to go around an obstacle. (5th grade students' solution.)

These explorations caused great interest and we soon found one group communicating with another by sharing fibers. One group even broadcasted to two other groups using two fibers pointing at one LED. Thus, true telecommunication networking had begun.

3.3 Assessment of Modules

Module I. Paths of Light

These modules were completed by several third grade classes. Over 70 third graders completed this module. Reflection was the major concept that we stressed in this module. Although students also completed some exercises on refraction and scattering, time limitations forced us to spend most of the class time on reflection. The quiz questions asked students to complete ray diagrams of how light interacts with both flat and concave mirrors.

Analysis of the third grade student pre-lab and post-lab quizzes showed that 68% of the students could draw a good description of a light wave hitting a flat mirror at an angle prior to the lab. After the lab over 80% of the students were able to provide a correct response. With the curved (concave mirror) only 24 % of the students responded with a correct drawing prior to the lab; after the lab over 57% responded correctly. The concave mirror was new concept to most students, and the visualization in the beakers seems to be an effective learning tool.

Module 2. The Color Maker

The experiments developed for these modules are very visual and captured the attention of all ages. The pre-Lab quiz asked whether we can make white light with other colors of light. We also asked why apples appear red. The post-Lab quizzes asked how we can make white light and what happens when green light hits a green surface. For third and fifth graders, less than 20% of students knew that white light can be made from other colors of light and less than 10% knew why an apple appears red. In the post quiz, greater than 50% knew that white light can he produced from red, green, and blue light, 50% could describe what happens when red light hits a blue surface, and 90% accurately described what color we would see when white light hits a green surface (a question similar to: Why does an apple appear red?).

Module 3. CD Player

We asked several questions on the pre-lab quiz concerning CDs and how they operate. Different questions that addressed the same material were asked on the post-Lab quiz. For example, prior to the lab, greater than 95% of students knew what a CD was, hut less than 20% knew how they store data or are read. After the lab, more than 70% of the students knew that a laser reads the CD and that CDs spin so that all the information can he read.

Module 4. Barcode Reader

We asked several questions about barcodes both pre-Lab and post-Lab. While 95 % of the third grade students knew that they had seen a barcode reader prior to the lab, only 24% of the students knew what the “red light” is used for in a barcode reader. After the lab, in which they had experienced reading barcodes with light, greater than 64% of the students responded by stating that the red light is used to scan or read the information on the barcode. The post-Lab quizzes typically did not ask the same questions hut sought to illucidate whether students had learned during the particular activities.

Module 5. Communication by Light

It was clear from the actual laboratory activities and assessment activity that the students were learning and applying their knowledge. The pre- and post-Lab quizzes also demonstrated that the students were grasping the concepts. For example, the pre-Lab quizzes indicated that most students recognized that one could communicate with light via a flashlight and some sort of code. Some students also drew diagrams showing how they might communicate with sunlight and a mirror. However, no students suggested using modem telecommunications that are all around them such as cable TV or fiber optic telephones. On the post-lab quiz many students suggested using fiber optics and telecommunication networks. In addition, nearly 70% of all students were able to draw and label the major components of a modem photonics based telecommunications system including a modulated light source, fiber optic delivery cable, light detector, and speaker.

Teacher Evaluation of Modules

In addition to the assessment activities, we also discussed the laboratory exercises with the teachers after the students had left. Teachers provided suggestions and critiques. Indeed, we were able to incorporate many of their suggestions into subsequent classes. We also had each teacher fill out a questionnaire on the particular module that had been introduced. These were very helpful and were another way that we actively involved the teachers. While space limitations prevent a detailed presentation of these surveys, all 12 teachers were very pleased with the results. All stated that they would feel comfortable using the materials without our being present. However, some indicated that they would want more training.

4. SUMMARY

We have presented the results of our initial introduction of optics-based educational modules for grade levels 3-7. The pilot testing was successful, and students seemed to enjoy the activities. Our pre-and post-activity quizzes indicated that the students had learned key points about optics and some applications to real world devices familiar to students. We have now worked with ~1500 students. We plan to extend these results and develop new modules. We will continue to emphasize visualization of light beams. In addition our intense LED sources will facilitate experiments that illustrate other important phenomena such as light induced fluorescence.

5. ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under a Small Business Innovation Research Grant, and we are grateful for this support. We also thank the many teachers and students who participated.

REFERENCES

[1] "Harnessing Light, Optical Science and Engineering for the 21st Century," National Research Council Report, National Academy of Sciences Press, Washington, DC (1998).
[2] Shapiro, Bonnie, [What Children Bring to Light], Ways of Knowing Science Series, Teachers College Press, NY, NY (1994)
[3] "Project 2061: Science for all Americans," American Association for the Advancement of Science, Washington, DC (1989).
[4] "Benchmarks for Science Literacy," American Association for the Advancement of Science, Washington, DC (1993).
[5] "National Science Education Standards," National Academy Press, Wash. DC (1996).
[6] Garik, Peter, "Fractals in the Classroom," MRS Bulletin, January, 1994, 44.
[7] "Education for the Future," National Science Foundation Directorate for Education and Human Resources," NSF 94-65 (1994).
[8] "Elementary School Science for the 90s," The National Center for Improving Science Education and Association for Supervision and Curriculum Development, Alexandria, VA (1990)
[9] Piaget, J., [The Child's Conception of the World], Routledge and Keegan Paul, London, 1929.
[10] "SCIS3 Science Curriculum," Londonderry NH School District (1996).