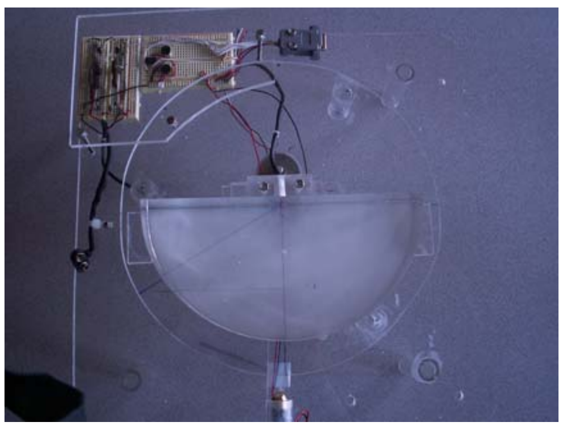
Polytechnic University
Professor Vikram Kapila
SMART Program
Summer 2005

FINDING THE CRITICAL ANGLE OF A PRISM



Team 5 Report:

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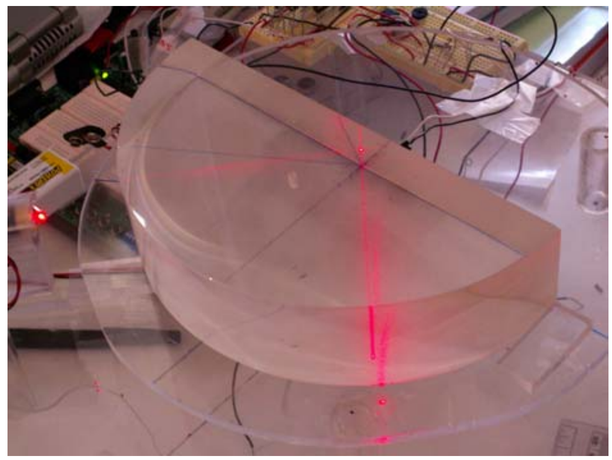
1. INTRODUCTION

What would life be like for us without the Internet, modern telephone communications and minimally invasive medical imaging equipment? All of these technologies depend greatly on the use of fiber optic cables. Fiber optic lines are strands of optically pure glass as thin as a human hair that can carry digital information over long distances. These cables are able to contain a beam of light just as a pipe contains a flow of water. Light, which travels in a straight line, is made to bend around corners as it travels through these strands of glass.

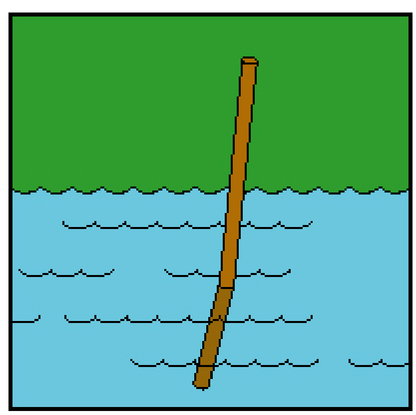


In our SMART project, we have chosen to demonstrate the basic physics principles that underlie the operation of a fiber optic cable – critical angle and total internal reflection. Our constructed device uses a laser and an acrylic lens to measure the angle of incidence at which the light traveling through the lens ceases to leave the lens but rather reflects back into it.

In this report, we discuss the principles behind total internal reflection, the experimental procedure we designed to measure the critical angle of the acrylic lens, and the progress of our efforts to construct a mechatronics device to accomplish that goal.

2. BACKGROUND

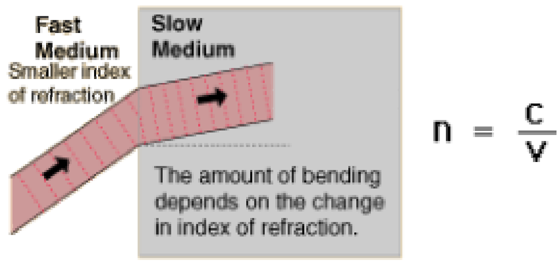
A. Refraction of Light



If you have ever half submerged a stick or pencil into water, you have probably noticed that the object appears bent at the point it enters the water . This optical effect is due to **refraction**. As light passes from one transparent medium to another, it changes speed, and bends. How much this happens depends on the **refractive index** of the mediums and the angle between the light ray and the line perpendicular (**normal**) to the surface separating the two mediums (**medium/medium interface**). Each medium has a different refractive index. The angle between the light ray and the normal as it leaves a medium is called the

angle of incidence. The angle between the light ray and the normal as it enters a medium is called the **angle of refraction**.

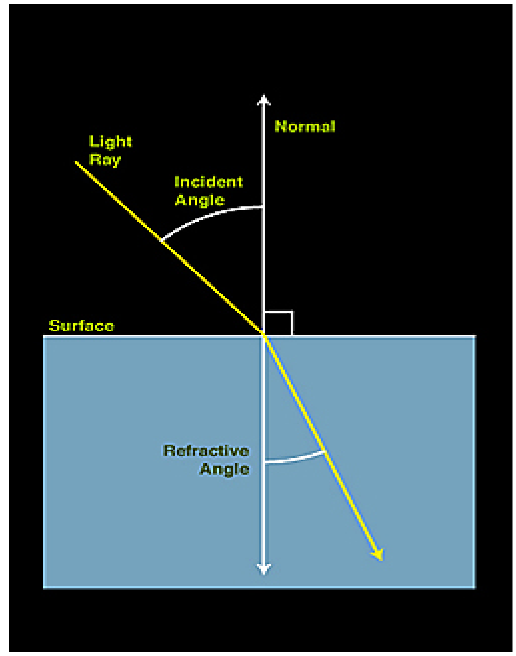
The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium: n = c/v.



The indices of refraction of some common substances are given below. The values given are approximate and do not account for the small variation of index with light wavelength which is called dispersion.

Material	Index of Refraction	
Vacuum	1.0000	<--lowest optical density
Air	1.0003	
Ice	1.31	
Water	1.333	
Ethyl Alcohol	1.36	
Acrylic	1.49	
Crown Glass	1.52	
Light Flint Glass	1.58	
Dense Flint Glass	1.66	
Zircon	1.923	
Diamond	2.417	
Rutile	2.907	
Gallium phosphide	3.50	<--highest optical density

In 1621, a Dutch physicist named Willebrord Snell (1591-1626), derived the relationship between the different angles of light as it passes from one transparent medium to another. When light passes from one transparent medium to another, it bends according to Snell's law which states:



$n_1 * \sin(\theta_1) = n_2 * \sin(\theta_2)$

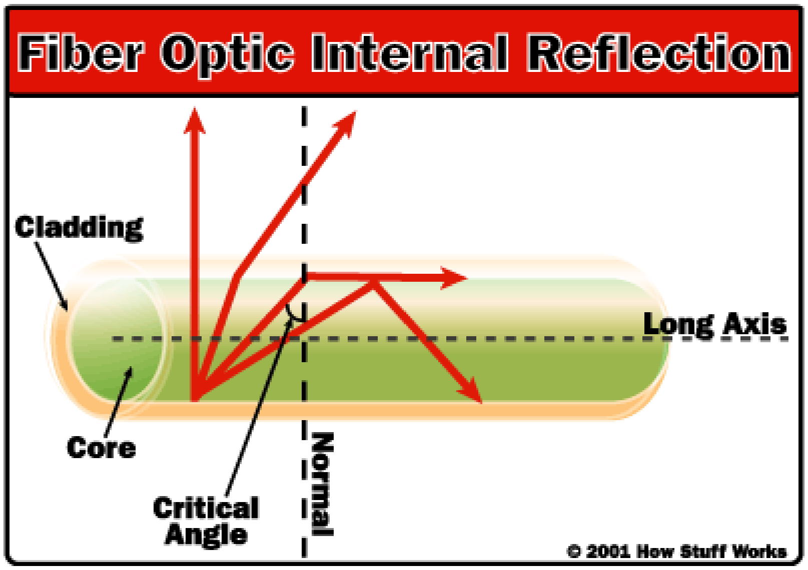
where:
n_1 is the refractive index of the medium the light is leaving,
θ_1 is the incident angle between the light ray and the normal to the medium to medium interface,
n_2 is the refractive index of the medium the light is entering,
θ_2 is the refractive angle between the light ray and the normal to the medium interface.

B. Critical Angle and Total Internal Reflection

When light passes from a medium with one index of refraction (m1) to another medium with a lower index of refraction (m2), it bends or refracts away from an imaginary line perpendicular to the surface (**normal line**). As the angle of the beam through m1 becomes greater with respect to the normal line, the refracted light through m2 bends further away from the line.

At one particular angle (**critical angle**), the refracted light will not go into m2, but instead will travel along the surface between the two media (**sine [critical angle] = n2/n1** where n1 and n2 are the indices of refraction [n1 is greater than n2]). If the beam through m1 is greater than the critical angle, then the refracted beam will be reflected entirely back into m1 (total internal reflection), even though m2 may be transparent!

In physics, the critical angle is described with respect to the normal line. In fiber optics, the critical angle is described with respect to the parallel axis running down the middle of the fiber. Therefore, the fiber-optic critical angle = (90 degrees - physics critical angle).



Total internal reflection in an optical fiber

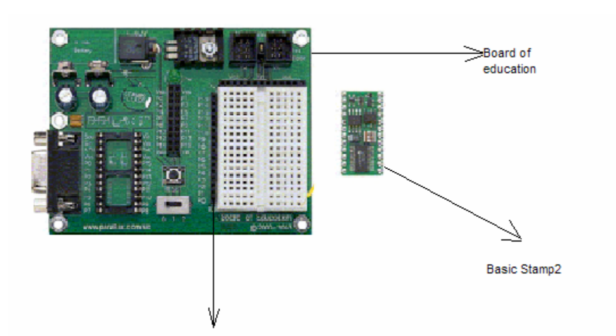
In an optical fiber, the light travels through the core (m1, high index of refraction) by constantly reflecting from the cladding (m2, lower index of refraction) because the angle of the light is always greater than the critical angle. Light reflects from the cladding no matter what angle the fiber itself gets bent at, even if it's a full circle!

Because the cladding does not absorb any light from the core, the light wave can travel great distances. However, some of the light signal degrades within the fiber, mostly due to impurities in the glass. The extent that the signal degrades depends upon the purity of the glass and the wavelength of the transmitted light (for example, 850 nm = 60 to 75 percent/km; 1,300 nm = 50 to 60 percent/km; 1,550 nm is greater than 50 percent/km). Some premium optical fibers show much less signal degradation -- less than 10 percent/km at 1,550 nm.

3. <u>COMPONENTS OF THE PROJECT</u>

A. *Base Component: Board of Education*:

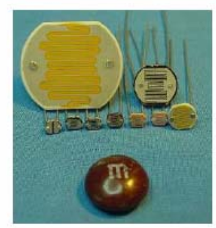
The "Board of Education" (BOE) is a term that refers to the circuit board used in these projects. The BOE (shown at right) is the main component of our mechatronics project. It connects the microcontroller (the Base Stamp2) to the sensors, actuators and other components that make up the device.



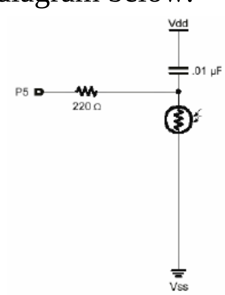
The Base Stamp2 (BS2) has 16 pins that can communicate with the components attached to the BOE.

The BS2 executes a computer program that is written in the PBASIC language. This program controls the sequence of steps that the device performs. Any pin on the BS2 can be defined in the PBASIC program to be an input or an output pin. If a pin acts as an input pin, it detects whether the circuit attached to the pin contains a high voltage (between 1.3 volts and 5 volts) or a low voltage (less than 1.3 volts). If the pin is made to be an output pin in the program, it supplies the attached circuit with either a high or a low voltage. There are some restrictions regarding the amount of electric current that must be adhered to in order to avoid damaging the BS2, which is quite costly. Each pin can supply up to 20 mA and can sink up to 25 mA. The BS2 has a limit of 5 V that it can handle. (All current in these circuits is direct current (DC)). Attachment 1 to this report is a copy of the program for this device.

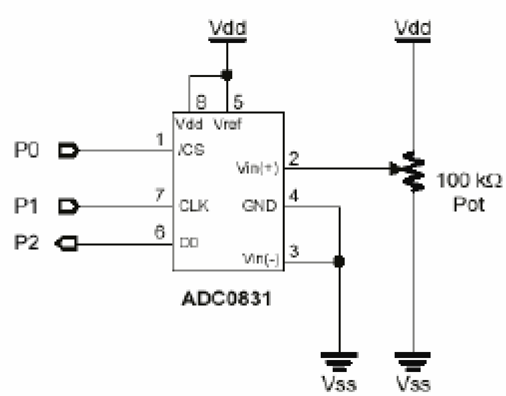
B.: Photoresistor



Photoresistors are variable resistance devices whose resistance decreases as the intensity of light increases. This sensor is often used with a capacitor to detect the amount of light that is present. The circuit that we used for the photoresistor is shown in the diagram below. Using a special command in the PBASIC language (RCTime), one is able to measure the time it takes to charge up the capacitor, which is a function of the resistance of the photoresistor.

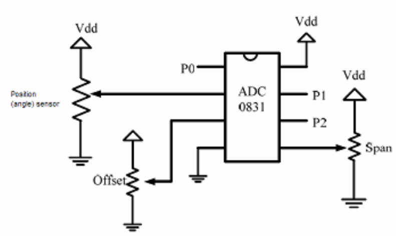


C. ADC 0813 Chip (Analogue-Digital Converter)



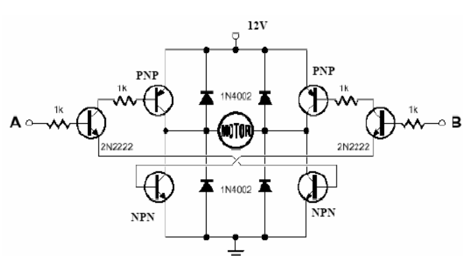
The ADC chip converts analogue data to digital signals. In our project, the ADC chip functioned as an angle measurement device. The potentiometer changes the resistance of the circuit as the motor rotates. The change in resistance causes a change in the voltage at that point in the circuit. There was a linear relationship between the change in voltage, as measured by the ADC chip, and the angle through which the motor turned. Using the functions of the PBASIC language, we were able to read on our computer how many degrees from the starting position (the normal to the prism) that the light source had moved.

We modified the circuit shown above so that we could attain a full range of 5 volts within the limited range we expected our light source to move. This was necessary due to the precision concerns. The problem is that the ADC can only handle 8-bits, which means a range of 0 to 255. In our project, we were only concerned with the measurement of an angle of less than 60 degrees, much less than the potentiometer's full range of approximately 270 degrees. By using two additional potentiometers, we would have the ability of defining 0 degrees as our starting position, and 60 degrees as our maximum position. We dealt with this experimentally; when the laser was positioned at the starting point (0 degrees), we set the zero potentiometer to 0 volts. We then repositioned the laser 60 degrees from that starting point and set the span potentiometer to 5 volts. Writing the necessary program converted the voltage to a degree measurement. The diagram below shows the additional two potentiometers that are connected to pin3 and pin5 of the ADC0831 chip:



D. H-Bridge Circuit

The H-bridge enables a device to reverse the direction of a DC motor. The H-Bridge circuit is shown below:

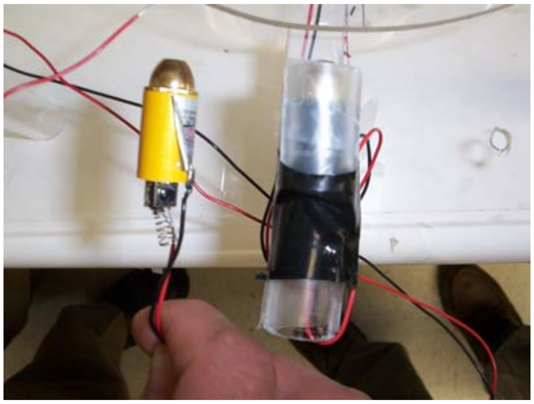


Giving the two pins that the H-bridge is connected to different bit-values determines the direction.
0-0: Stop
0-1: Forward
1-0: Backward
1-1: The bridge fell down...

E. Laser

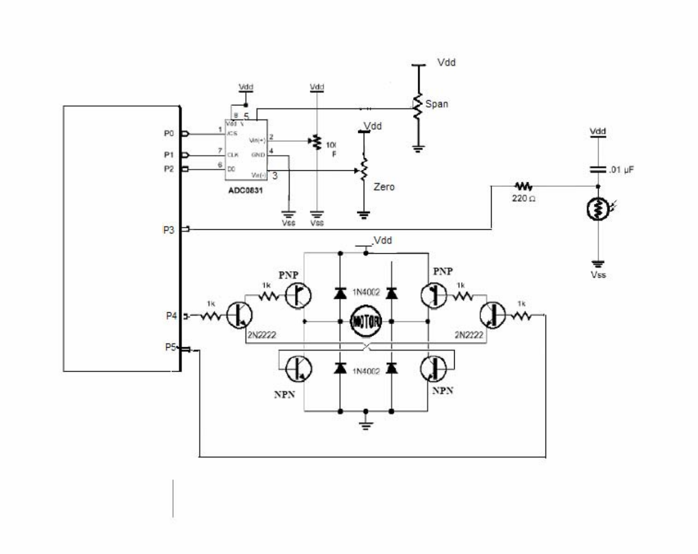
We initially purchased as our source of light a button-activated Class IIA laser that ran on three 1.5-volt batteries. We decided to reconfigure the laser so that it was powered by our 5 volt circuit rather than by the batteries. In this way, the light did not have to be turned on independently of our circuit. We cut the frame of the laser to expose the wiring and we bypassed the button by soldering a wire to a direct connection to the light source. The ground wire was attached to the frame of the laser.

When this laser was hooked up to the 5-volt circuit, the intensity of the laser beam was greatly diminished, compared to the original intensity with the batteries. We reconnected the laser to the batteries and found that the original intensity of the beam was lost. After the project was sufficiently completed to begin testing, we found that the lower intensity prevented consistent results from our device. We concluded that our inelegant soldering technique was the probable cause of the loss of light intensity.



We decided to purchase a new laser. This second laser was a Class IIIA device. We again carefully cut the frame to expose the wiring, but now enlisted the aid of Nathan to solder our wire connection. The new laser initially displayed a lower intensity when wired in our circuit. When the batteries were reconnected, however, the original high intensity returned. We determined that we needed to reduce the resistance of the circuit in which we had placed the laser. When we cut the resistance in half (from 200 Ω to 100 Ω), the laser's intensity returned to its original level. We were now ready to perform our final testing and finalize the program for the device.

F. Completed Project Circuit Diagram



4. <u>EXPERIMENTAL PROCEDURE</u>

Critical Angle Experiment:

Connected to the motor is an arm that has an ability to rotate clockwise or counter-clockwise. The semi-circular lens's center is positioned exactly at the axis of rotation. The light source makes a 0 degree with the normal at rest. When the experiment is initialized, the arm starts rotating counter-clockwise moving away from the normal. Remember that since the light is perpendicular to the tangent at any point, it penetrates right into the prism and refracts and finally leave the medium. There is a certain point, though, after which no light get out. As seen on the picture above, the light sensor pinned at the center stops receiving light. When there is no light that goes out, which is the total reflection, the sensor sends a signal to the basic stamp and BS2 stops the motor by sending the proper signals to the H-bridge. The program that we coded enables us to see the real angle values. That final value on the screen is the critical angle of the medium. After 10 seconds, the arm starts moving, this time in the opposite direction, and stops at the 0 degree with the angle.

Goal:
To find out the critical angle of certain media using an automated design.

Experiment Procedure:
1. Connect the BS2 to the DB-9 adapter located on the test-bed and to a computer with another serial cable.
2. Connect the BS2 to a 9V power source
3. Download the criticalanglefinder.bs2 file to the BS2.
4. The arm will start moving. Do never interfere with the motion. Wait until it stops.
5. Note down the final value on the screen. That is the critical angle.

6. The arm will resume its motion in the opposite direction back to the original position.

5. ACKNOWLEDGEMENTS

We are most grateful to Professor Vikram Kapila of the Mechanical Engineering Department of Polytechnic University. We have found the SMART Program to be an extremely valuable program for our own professional development. We are confident that our students will be the ultimate beneficiaries of the experience we received this summer at Poly.

Nathan (Sang-Hoon) Lee was an inspiration to us. He presented the lecture topics clearly and consistently provided common applications of the concepts to make the lectures relevant to us. During the design and construction phase of the workshop, his keen ability to help us overcome the obstacles we encountered, always provided with his wonderful sense of humor, kept us free of frustration and motivated us to emulate his example as a teacher.

Ashuman Pranda and the entire staff of student fellows also provided us the technical expertise needed to meet the very short deadlines necessitated by a four-week program. We are grateful to each of them.

Finally, we thank Polytechnic University, which was a most gracious host to us this summer, and the National Science Foundation which provided the very generous funding for this desperately needed, but expensive, program. We commit to meeting our obligations to bring the acquired skills back to our students and school community.