Telescopes for the Body
– An introduction to Arthroscopic Surgery
Motivation and Outline

• Surgery usually involves a major incision into the body in order for the surgeon to fix whatever is wrong.

• Major incisions are accompanied by long recovery times, risk of infection, bleeding and pain to the patient.

• Doctors do not want to have to open up the body unnecessarily.

• Of course if you have to be opened up, the incision has to be large enough to get the surgeon’s hands and tools inside.

• To minimize these effects doctors employ fiber optic scopes to see inside of the body and to perform surgery through several small incisions.

• To understand how this is done we need to understand some of the physics behind light and how light propagates.

• Then we’ll “build” a telescope (called an endoscope) to view the body’s inner secrets and use this to look at an arthroscopic surgery.
The Physics of Light and Optical Fibers

• Light has a dual nature. It can act as a particle or a wave. We’ll look at its wave nature first.

• Light is an electromagnetic wave – needs no medium to propagate

• Light is composed of oscillating crossed electric and magnetic fields

• The speed of light is a constant.
  In vacuum light travels at $c = 3 \times 10^8 \text{ m/s}$

In a material light travels at a speed $v = \frac{c}{n}$, where $n = \text{index of refraction}$.

• A spectrum of light can be generated by changing the frequency ($f \lambda = c$) of oscillation of the $E$ and $B$ fields
In order to eventually make a telescope for the body we need to make light travel through transparent materials, illuminate the object of interest, and then image the image the object.

When light encounters an obstacle it can be absorbed, transmitted, or reflected.

We’ll ignore any absorption effects for now.

At a transparent interface (such as say air and a glass window) between two transparent materials with indices of refraction $n_1$ and $n_2$, the light will be
- reflected according to the law of reflection $\theta_1 = \theta_r$
- transmitted according to the law of refraction (Snell’s Law) $n_1 \sin \theta_1 = n_2 \sin \theta_2$

Suppose that light with an intensity of $S_o$ is incident on a transparent substance then the percentage of light that is reflected from the interface is given by $S_r = \frac{(n_2 - n_1)}{(n_2 + n_1)^2}$.

The percentage of the light intensity that is transmitted through the interface is $S_T = 1 - \frac{S_r}{S_o}$.

Since energy is conserved $S_o = S_r + S_T$. 

http://physics.ucsd.edu/students/courses/fall2002/physics2cl/Manual/2CLmanual_revised-2_files/image544.jpg
Total Internal Reflection of Light

- When light is transmitted from a material with a higher index of refraction to a material with a lower index of refraction the light will enter the second material and also be reflected off of the interface between the two materials back into the first material.

- The frequency of the light remains constant across the interface between the two materials while the wavelength of light changes (which is associated with the change in speed of light).

- This means that the light ray changes speed when passing between the two materials of different optical characteristics.

- This speeding up or slowing down of the light is called *refraction* (or the bending of the light ray.)

- The angle of refraction is calculated using Snell’s law as light travels from one material to the next given the angle of incidence in the first material.

- Two results from Snell’s law
  - The angle of refraction is less than the angle of incidence when light travels from a lower to a higher refractive index material
  - The angle of refraction is greater than the angle of incidence when light travels from a higher to a lower refractive index material
Total Internal Reflection of Light

• Suppose that we take a piece of material which we’ll call the core and surround it with another material, called the cladding.

• We’ll take the core to be a material with a higher refractive index than the cladding.

• If conditions are right the light may not actually enter the second, lower refractive index material but rather stay contained with in the higher refractive index material.

• Instead the refracted ray of light will not propagate in the lower refractive material and only the reflected ray will remain and will propagate totally in the higher refractive index material.

• This is called total internal reflection (TIR) and is governed by $\sin \theta_c = \frac{n_2}{n_1}$. For light incident at angles of incidence greater than the critical angle all the light will be TIR.

\[ \sin \theta_c = \frac{n_2}{n_1} \]
Optical Fibers and Total Internal Reflection

Small core – very few modes of light propagation. This is called a single mode fiber.

Larger core – more modes of light can be propagated. This is called a multimode fiber.

For any core, the light needs to strike at angles larger than the critical angle for total internal reflection.

Total internal reflection demonstration using a He-Ne laser. The laser has a wavelength of 632.8 nm and the optical fiber is constructed out of glass ($n_{\text{glass}} \sim 1.5$) and is surrounded by air ($n_{\text{air}} = 1.00$).
Optical Fiber Bundles

• Bundles of fibers are generally needed to reconstruct an image. The bundle of fibers acts just like a lens and can be used to magnify the images.

• Typical single fiber sizes are 10 – 100-microns in diameter and the bundles are about 1-cm in diameter.

• For large core fibers, those greater than about 10-microns, geometric optics and ray tracings can be applied to construct the image and determine its properties.

• For small core fibers, electromagnetic theory, using Maxwell’s equations and solving a wave equation for the propagation modes of the light along the fiber.

• Two types of fiber bundles
  - Coherent bundles – all fiber strands are in the same orientation. There is no “twisting” to the fibers and these are used to form high quality images of an object.

  - Incoherent bundles – all fibers have different orientations so that the image gets “jumbled”. These are generally used to transmit light to illuminate an object.
Making an Endoscope

The optical fiber bundles are built into the hand control wand.

The hand control unit contains all of the various tools like water, air, suction, forceps, incoherent bundles for light to illuminate the target and coherent bundles for images.

http://www.endoscoperepair.com/generaltools.htm

http://www.daviddarling.info/images/endoscope_diagram_1.jpg
A problem solving example using the physics of light

• Suppose that the red laser light ($\lambda = 632.8 \text{ nm}$) from the demonstration is incident on the front surface of a plastic pipe used as an optical fiber with an index of refraction of $n = 1.30$. If the pipe has a diameter of $1 \text{ cm}$ and the light is incident at an angle of $30^\circ$ with respect to the normal to the surface, what is the angle of refraction?

• What is the critical angle for the light in this pipe?

• Will the light be totally internally reflected?

• If at the front surface of the pipe, the light has an intensity of $1 \text{ W/m}^2$, what percentage of the light is transmitted into the pipe and what percentage is reflected from the front surface?
Medicinal Fiber Optic Scopes

• Optical fiber scopes that are used for different procedures have different names but the scopes themselves are all essentially the same.

• Some typical medical fiber scopes include:

  *Endoscopes* – used to investigate organs like the stomach or intestines (colonoscope)
  *Laparoscope* – surgeries involving the abdomen (gallbladder removal & appendectomies) & gynecological surgeries
  *Bronchoscope* – lungs
  *Cystoscope* – urinary tract
  *Angioscope* – blood vessels
  *Arthroscope* – joints like the knees or shoulders

An excellent view of the peritoneal cavity obtained by transluminal (across the peritoneal cavity) endoscopy showing the stomach, liver and greater omentum.
Arthroscopic Surgery

Arthro = joint
Scope = optical viewing device

• Arthroscope = optical device used to view and repair the interior of joints like the knee, ankle, elbow or shoulder.

• The figure on the right shows several arthroscopic views of a tear and repair on the body.

• Any ideas what the surgery could be?
Arthroscopic Surgery – Rotator Cuff Repair

Background – Suppose that you’ve fallen and landed outstretched arm and have managed to get up, but you’ve unfortunately torn your rotator cuff.

The rotator cuff is a group of 4 muscles that originate on the shoulder blade and become thick tendons as they attach to the lateral aspect of the humeral head. The muscles are important in raising the arm above the shoulder, but their true function is to pull the humeral head into the socket and keep it there. This action stabilizes the shoulder and allows the other large muscles about the shoulder to act on the arm to raise it.

The least invasive procedure is to have arthroscopic surgery to reattach the rotator cuff to the humeral head.

http://www.kingsorthopedics.com/articles/shoulder_anatomy/
Arthroscopic Surgery – Rotator Cuff Repair

Shoulder & Rotator Cuff
Major surgical incision vs. arthroscopic

http://www.healio.com/orthopedics/journals/ortho/2012-6-35-6/%7Bb5b405e2-52c9-4d32-ac34-5d9a8261f929%7D/biologically-enhanced-healing-of-the-rotator-cuff

http://consultqld.clevelandclinic.org/2015/01/going-all-arthroscopic-for-augmentation-of-rotator-cuff-repairs/
Arthroscopic Surgery – Rotator Cuff Repair

The procedure – Form a surface on the humeral head (by scraping the bone) to anchor the muscle (usually the deltoid muscle) and tendons (the major tendon that connects the deltoid to the humerus is the supraspinatus) of the damaged rotator cuff. Drill holes in the humeral head to receive the suture that will anchor the muscles to the humeral head. Suture the rotator cuff to the humeral head.

http://www.kingorthopedics.com/articles/category/double_row_arthroscopic_rotator_cuff_repair/
Arthroscopic Surgery – Rotator Cuff Repair
Arthroscopic Surgery – Rotator Cuff Repair

Below is a video showing the actual repair of the rotator cuff.

You, the doctor, are looking at an image projected on a TV monitor from the arthroscope. There are actually two scopes: one is a lamp and the other takes the reflected light from the structures and the signal is transmitted fiber optically (by total internal reflection) to a digital-to-analog converter which sends the converted signal to the TV which gives you the picture.

The arthroscope is inserted through a small incision in your shoulder and two other small incisions are made to insert the tools.

Surgeons perspective: Brigham and Women's Hospital orthopedic surgeon Scott D. Martin, MD, said, "Arthroscopic rotator cuff repair is minimally invasive and decreases operation time compared to other rotator cuff procedures. There's also less pain after the surgery, more rapid restoration of motion, and easier rehabilitation. Pain relief and functional results of arthroscopic rotator cuff repair are equivalent to open repair with an important difference - there's no risk of the serious complication of deltoid muscle detachment." - This Brigham and Women's Hospital banner above is a link to a movie of a full arthroscopic rotator cuff repair surgery.
Summary

• Application of some simple physics on the reflection and refraction of light form the backbone of the optical fiber.

• Optical fibers have a minimal loss of light intensity meaning that most of the light that is contained in the fiber is conveyed from one end to the other without losses to the surrounding coating.

• Optical fibers can be bundled together to form a telescope that can be used to view images of the interior of the body.

• Optical fiber scope surgeries are generally minimally invasive and offer patients a quicker and sometimes painless recovery.

Homework for Friday, January 6, 2017

Kane Chapter 2
Read 2.3 – 2.4 and do
Question Q2.1
Problems P2.1, P2.4, P2.6, & P2.8

Kane Chapter 3
Read 3.1 – 3.4