LASIK EYE SURGERY:
The Underlying Physics and the Future
Glasses and contacts have become a nuisance of the past due to the immediate successes of LASIK eye surgery. LASIK, or *laser-assisted in situ keratomileusis*, was largely made possible due to Columbia-based Spanish ophthalmologist Jose Barraquer in 1950. Barraquer developed the keratome knife for the purpose of what he called keratomileusis, cutting a flap of the cornea and altering the shape to improve vision. The next major step came when researcher R. Srinivasan, working at IBM, concluded that an ultraviolet excimer laser could be used on living tissue with precision and without thermal damaging in 1980. The years since then, the LASIK eye surgery has transformed into what it is today, a trend for the age. The basic principles of physics called upon by LASIK include optics and quantum physics. These basic principles work together to improve the everyday lives of millions of people each year.

In order to understand LASIK surgery, one must understand the basic anatomy and physiology of the eye. Light enters through the cornea, the outer lining of the eye, into the aqueous humor fluid. Light next travels through the pupil, the opening of the colored iris, to the crystalline lens. Unlike a camera lens, this lens has ciliary muscles which contract and relax in order for light to be correctly oriented to focus onto an image on the retina. The retina of the eye has rods and cones which determine intensity and frequency of light and transfer the information to the optic nerve to the brain. Essentially we see (perceive vision) with our brain, not our eyes.

The eye is heavily reliant on the major topics of the subject of optics. The first would be the ray model of light and how the model relates to lenses. The light entering the eye should be focused in order to create a picture. The cornea and the crystalline lens act as lenses that focus
incoming light on the surface of the retina. The crystalline lens essentially acts as a convergent lens with a focal length where the retina is. Therefore, light focuses on the retina. We can see the ray model of light at work in the picture of the flower.

The second major optical topic that the eye is concerned with is refraction. Refraction is the change in direction of a wave due to a change in speed, or it is the bending of light as it travels through different materials. This behavior is quantified by Snell’s Law. Snell’s law states the product of the sine of the angle at which a wave travels and the materials index of refraction stays constant at all points. In the diagram, the ray of light propagates from underwater to the air. The index of refraction of water or $n_1$ is greater than the index of refraction for air, $n_2$, which we take to be about one. Therefore the angle at which the wave propagates through water will be smaller in magnitude to the normal than the angle at which the wave would propagate through air. The index of refraction, $n$, is calculated by determining the quotient of the speed of light and by the speed of the wave in a particular material.

Now we can apply Snell’s law to the eye. The cornea has an index of refraction of about 1.376 so the $v$ of light through the cornea should be $2.18 \times 10^8 \text{ m/s}$. Light entering at an angle of 45 degrees will leave at an angle of about 31 degrees. This will be the most dramatic refraction as the index of air is about 1; therefore, this is where most refractive errors can be corrected. Then the light travels through the aqueous humor (index of 1.336) through the pupil into the crystalline
lens. The crystalline lens has a variable index on its surface between 1.386 and 1.406. The ciliary muscles shape the lens accordingly and wave focuses at the focal point on the retina to be interpreted. The darkening of this lens is referred to as a cataract.

After we see observe how refraction works throughout the eye, we should introduce why LASIK eye surgery is needed. LASIK is used to treat three types of refractive errors: myopia, hyperopia, and astigmatism. Myopia is also known as nearsightedness and occurs when the light focuses an image in the vitreous humor rather than the retina. They can see near objects well but cannot see far objects. Hyperopia, or farsightedness, occurs when the light hits the retina but does not focus. This is the opposite of myopia. Astigmatism is when the cornea is not curved perfectly like a basketball but more like an egg. People with astigmatism generally experience blurred vision and possibly distortion of images. There is an unequal bending of the rays of light so it causes both myopia and hyperopia.

LASIK eye surgery would not be possible without the scientific marvel that is the laser. The laser is a star product of the field of quantum mechanics. The word laser is an acronym for Light Amplification by the Stimulated Emission of Radiation and was first proposed by Einstein. Lasers allow for the production of coherent light where all of the light is of the same wavelength and are in phase with each other. All photons travel essentially in the same direction and can be easily focused onto a smaller area in order to increase power density. How exactly does a laser work?
The first thing we need is a way to amplify light. To do this, we need what is called a laser medium, some type of substance than is composed of excitable atoms. Generally the process will involve four different states, the ground state level one, the lower laser state level two, the upper laser state level three, and the excited state level four. To the left, we can see the mechanism by which a laser medium works for a typical four level laser. First, we need to excite the atoms to level four. In order to do so, we must add energy to the system in some way such as applying a voltage. This will cause the ground state atoms to become excited and then rapidly decay to level three, the upper laser state. As more atoms are excited to this level, we can see there are more atoms in the upper laser state than the lower laser state and the ground state. This population inversion is crucial for lasers because atoms in the upper level state can emit photons identical to incident photons (building light intensity) while the atoms in the other two states would try to absorb the photon.

This whole process needs to be very exact as the properties of the photon must coincide with the capabilities of the medium used. This is why most lasers give off a single color. When a suitable photon passes through the atom, the atom in the upper laser state drops to the lower laser state, an identical photon to the incident photon is emitted. This photon is also in phase with the incident photon, amplifying the light as desired. The \( E \) in the energy equation shown should be the energy of the upper level state subtracted by the energy of the lower level state.
Now, we need to find a way to increase the power of the laser and maintain efficiency. For this, we can turn to a setup called the laser oscillator. A laser oscillator is a device that uses the laser medium itself to provide the incident photon. Essentially, we take the medium system we discussed and place that medium between two mirrors, one that is a total reflector and another which is a partial reflector. The energy for the pumping of atoms from ground state to excited states is applied for an outside source. When the photon is produced and amplified out one ends of the medium, it reflects off the mirror again through the medium. The whole process repeats many times in order to have millions of photons of the same wavelength in phase with each other. The light builds intensity in the laser cavity. The reason that one mirror is a partial reflector is so some of the beam can escape, called our output beam. This whole process is also very intricate as the mirrors have to be essentially perfectly placed and intricately curved to coincide with the wavelength and polarization of the incident light.

Now that we understand how the laser beam is produced, we should bring in the special types of lasers used during eye surgery. These lasers are called excimer lasers. Excimer is short for “excited dimer.” The first excimer laser was built by N. Basov, V.A. Danilychev, and Yu.M. Popov at the Lebedev Physical Institute in Moscow in 1970. The excimer laser almost exclusively operates in the ultraviolet spectrum. They used a Xenon dimer to produce a beam of 172 nanometers, hence the excimer laser.
Excimer lasers perform laser action due to their laser medium possessing a bound excited state and a repulsive ground state. The laser medium is formed by the combination of inert noble gases Argon, Krypton, and Xenon and a reactive gas such as Fluorine or Chlorine. At the ground state, an outside source applies energy to the atoms at ground state. Normally repulsive, these atoms begin to form temporary bonds with each other leading to either dimers of noble gases (Xe₂ etc) or halogen complexes (XeCl) with noble gases and halogens. Because these excited atoms are generally complexes, the correct term for an excimer laser is an exciplex laser (excited complex.) These complexes exist in the upper laser state. When a photon passes through the medium, the complexes give off an identical photon each and then return to their ground state where they instantly break down to their original separate atoms.

Now that we understand excimer lasers, we should touch upon what they are commonly used for. Excimer lasers are common in three particular areas: production of nanochips, micromachining, and laser eye surgery. The reason these excimer lasers are so important for laser eye surgery is because they are in the ultraviolet. Rather than burn the eye, the laser disrupts the bonds between atoms that compose the surface tissue. The bonds break, and the layer soon disintegrates without changing the surrounding material at all. This process is called photoablation or ablation, NOT BURNING! All excimer lasers must be approved by the FDA before they can be used.

There are two basic types of excimer lasers used for LASIK surgery. The first is the broad beam laser which has a beam of a large diameter ~7.0 mm. This laser has the shortest time for ablation (not burning) of the eye. The speed reduces the probability of any complications
cause by the movement of the pupil. The only negative side effect would be a slightly increased possibility of complications related to ablation. These possibilities can be reduced by using shorter pulses to ablate the cornea.

The other major type, scanning lasers, are broken down into two sections, the slit scanning laser and the spot scanning lasers. The slit scanning lasers use smaller beams with a rotational mechanism with slit holes that enlarge. The laser beam scans across these holes during surgery, leading to a smooth uniform beam which leaves broad beam lasers obsolete. The possibility of complications due to the movement of the pupil increases unless a special tracker is attached. Spot scanning lasers use radar technology to track the eye’s movement. These lasers can treat astigmatism with the potential for the smoothest ablations due to the extremely small diameter. These must be fitted with the special tracker optional for slit scanning.

Now that we have covered how the eye works and the quantum mechanics of the excimer laser, we can begin discussing the procedure of LASIK eye surgery and its underlying physics principles. As we have touched upon before, LASIK is used to treat a few major refractive errors causes by irregularities in the curving of the cornea. Corneas that are steeper than they should be often lead to nearsightedness, myopia. Myopia is usually 3.0 or more diopters with a diopter = 1/focal length. This causes the image to focus in front of the retina. Corneas that are too flat would cause hyperopia or farsightedness which is in the negative diopter range. The picture
to the right shows how contact lenses help myopia and hyperopia. Essentially, LASIK avoids contact lenses by actually changing the shape of the cornea to focus on the retina. Astigmatism, the third major refractive error that can be fixed by LASIK, is caused by an irregularly shaped cornea. An astigmatism is less than 3 diopters, positive or negative.

LASIK or laser-assisted in situ keratomileusis begins with a thorough eye exam to determine whether one is a good candidate for LASIK surgery. After being cleared and assessing the risks of the surgery, a candidate must stop wearing any corrective lenses for a few weeks before the surgery as the eye should be in as natural state a state as possible. Contact lenses can strain the eye leading the eye to not be positioned as it normally would be. Also a candidate must also not use any topical creams, perfume, lotions, and makeup the days before the exam as they could interfere with the sterility of the operation. These cosmetic items could also interfere with the functioning of the excimer laser. The perfume results in a large “deterioration of beam power over time.”

After entering the office, the patient will have his or her cornea examined by the surgeon. The examination will take first place by means of corneal pachymetry. A corneal pachymeter will determine the thickness of the cornea, using ultrasound technology and providing results into the micrometers. Surgeons will often use the pachymeter after the procedure to check for bubbles in the cornea. The thickness of the cornea is essential to determining the correct radius of curvature, according to the more general lens equation to the left. The next step after determining thickness is to create a topographical map of the surface. The surgeon can use this map to determine the level of astigmatism; this knowledge leads the surgeon to determine where

\[
\frac{1}{f} = (n-1) \left( \frac{1}{R_1} - \frac{1}{R_2} + \frac{t(n-1)}{nR_1R_2} \right)
\]

where,
- \( f \) is lens focal length
- \( n \) is material's index of refraction
- \( t \) is center thickness
- \( R \) is radius of curvature
  - \( R_1 \): convex is positive, concave is negative
  - \( R_2 \): concave is positive, convex is negative
to operate and how much tissue must be removed. Often before the surgery begins, patients are prescribed antibiotics in order to reduce the chance of infection.

The actual operation is generally occurring with the patient wide awake and functioning. Many choose to be under an anesthetic (Valium) to ensure a quasi-painless procedure. The patient’s face shall be cleaned to further increase safety and then there will probably antibiotic drops and anti-inflammatory drops administered. The surgeon will often tape your eyelashes out of the way. An eyelid holder will hold your eye lids open and prevent blinking. You will then be taken to the laser suite, positioned under the excimer laser, and given numbing drops. Your eyelashes will be taped out of the way, and an eyelid holder will be placed between your eyelids to keep you from blinking.

Now, the surgeon uses a suction ring in order to position the patient’s eye. The patient’s ever should not move during the procedure in order to avoid any harmful effects. However, the large amount of pressure often causes the small blood vessels in your eyes to burst into the sclera (white part.) This subconjunctival hemorrhage is harmless and should disappear after a few weeks. Increased suction can also cause a dimming of the eye.

The method of the actual cutting of the flap is variable for different professionals. However the classic way to cut the flap is using a mechanical microkeratome with an oscillating metal blade. A microkeratome is a surgical instrument designed to cut the flap needed for LASIK. The surgeon cuts the flap and
leaves a hinge at one side. The stroma (inside of the cornea) is now exposed. The flap usually is a length of somewhere between 100 and 200 microns thick depending on what the surgeon feels is most appropriate for you. The cornea itself is about 550 microns thick, or comparatively half a millimeter. The flap making process generally takes no more than 30 seconds to a minute.

After the flap is lifted back, it is normal to feel a pressure sensation. Lighting will disappear at this time and the room will be very blurry. The surgeon will ask the patient to fix your vision on a target light. During this time, the excimer laser begins to work. The laser remodels the cornea by vaporizing parts of the stroma without heating or changing the surrounding stroma. The excimer laser is a "cold" laser meaning it does not remove tissue to heat, therefore not burning. However, the concentrated light disrupts molecular bonds that hold corneal cells together in a process referred to as photoablation. After these bonds are disrupted, the cells will often disintegrate and the patient will perceive a faint odor. However, as the corneal cells try to move away, the cells strike each other which in turn cause a buildup of friction. This can raise the temperature of the cornea to 110 degrees F which is much higher than normal body temperature. Some surgeons use a vacuum device to suck up the corneal cells to avoid the odor and discomfort of the patient. Also, current excimer lasers with the tracking system often track the eye 4000 times a second and often have pulses of about 1 millijoule for 15 nanoseconds.

After the cornea has been reshaped, the flap of corneal tissue is unhinged and set back into place. The eye itself is a physical phenomenon. The eye will try to create a natural vacuum
and seal itself back to place as it no flap was made. The physician will check for any debris or air bubbles when the flap is repositioned. There are four forces which will lead to the corneal flap being held down. First, hydrostatic forces between the flap and the corneal stroma will create a seal between the two tissues. Next, the endothelial (inner lining) cells constantly pump fluid out of the cornea to maintain its clarity. This will create the natural vacuum. Following this, epithelial cells will grow over the end of the flap and then finally, there will internal healing occurring over several months.

Eye shields and anti-inflammatory drops are prescribed for protection and comfort. Painkillers are often used for mild discomfort situations. A follow up with the surgeon is necessary to ensure everything went well. There are other versions of LASIK to be discussed shortly but the classic LASIK surgery can be summarized in a few basic steps: "ICAR"

1. Immobilization of eye
2. Cutting of corneal flap
3. Ablation
4. Repositioning of flap

There are multiple different types of laser eye surgeries that are related to LASIK. LASIK itself as was brought up in the discussion is actually an improvement from Photo Refractive Keratectomy. LASEK, or Laser Assisted Sub-Epithelial Keratomileusis, is an advanced form of Photo Refractive Keratectomy that involves the cutting of the epithelium followed by an excimer laser treatment to reshape the cornea. Following the treatment, the epithelium is replaced. This is common when patients have a cornea too thin for LASIK.
The next major version of LASIK is Epi-LASIK which is essentially a combination of the procedures of LASIK and LASEK. In Epi-LASIK, an oscillating plastic blade is used to create the flap in the cornea. This type of surgery is often preferred by people with low myopia. This modified version uses a separator to preserve the living layer of epithelium. Epi-LASIK seeks to reduce discomfort and lower the healing time of LASEK. Another less common version of LASIK is the CK LASIK. CK is the abbreviation for “conductive keratoplasty.” This is the type of LASIK used for people that suffer from hyperopia and presbyopia. Presbyopia is defined as the condition of the eye where one tends to lose focus for near objects with age. Conductive keratoplasty makes use of radio waves to heat and reshape the cornea versus ablation methods used by classic LASIK techniques.

The last two most common types of LASIK surgeries are Wavefront-Guided LASIK and IntraLASIK. Wavefront-Guided LASIK (WGL) makes use of a wavefront analyzer that creates an almost exact three dimensional image of the eye. Classically, the surgeon does not have exact knowledge of a patient’s eye and can only predict what the effects will be. However, wavefront technology takes into account many more factors of the eye and how it bends light. Some machines can use over 2000 data points in a single eye. It sends a signal in through the eye and traces through the points where the light travels, increasing accuracy while creating a personalized surgery. This has severely revolutionized the LASIK field as surgeries become even safer and more effective. WGL is the most effective surgery for people with refractive errors much more complicated that the problems caused by a regular astigmatism.

IntraLASIK is more commonly called bladeless LASIK. It makes use of a femtosecond laser rather than a mechanical keratome blade which greatly reduces the chance of complications such as corneal surface abnormalities and irregular astigmatism. The corneal flap is cut out by a
laser and surgeon errors can be avoided. The most reliable and coincidently most expensive LASIK surgery available is the combination of WGL and IntraLASIK to create Wavefront-Guided IntraLASIK. In this version of Lasik, the WGL sensor system makes a map of your individual eye and the corneal flap is made by the femtosecond laser keratome rather than a blade.

The future of LASIK eye surgery is not exactly clear. There seems to be however a simple list of goals. First, we would like the ability to create postoperative 20/20 vision of higher quality. There are many side effects and adverse effects that come about due to LASIK eye surgery. One can be described as the halo effect, the appearance of a fuzzy “halo” around all light sources. At first, this type of effect seems to not be serious but when driving at night, the halo effect can be extremely dangerous as headlights appear as huge balls of light. The physics behind halo effects is not completely understood but seems to be related to the size of the ablation zone and how much tissue is removed. Many believe that increasing the ablation zone will lead to a lessening of the halo effect. The Munnerlyn formula states that we must also lose more tissue with an increased ablation zone. This could come to a large percentage of the cornea (possibly 80 to 100 microns) which is quick dangerous for the patient.
The second major goal of LASIK Eye surgery is to allow the possibility of super vision. This would be vision better than 20/20 and is an interesting concept with large amounts of philosophical controversy and scientific inquiry. The dangers of LASIK are quite high and most believe such an operation would drastically decrease safety as long term effects would not be fully understand. The long term effects of LASIK currently are not understood.

The third apparent major goal of LASIK is to correct more refractive errors. Procedures such as CK LASIK are opening the floodgates to other possibilities. Most believe the reduction of corneal aberrations and irregularities could in turn decrease adverse side effects. Researchers have concluded that IntraLASIK using Wavefront-guided technology is definitely the best way to go about LASIK surgery. This would lead to a thin precise corneal flap, which in turn allows for the cutting required by the larger ablation zone to be tolerable and effect. At least half of corneal tissue should be remained untouched.

Although LASIK has had large amounts of success in our consumer market, many experts believe that LASIK will soon be replaced with Implantable Collamer Lenses. ICL and LASIK are similar except in some situations of myopia, ICL is much more effective and has a greater 20/20 vision retention rate. Also ICL is a reversible surgery so the dangers are severely lower than those of the permanent LASIK. Other scientists speculate that intrasomal ablation, a unique procedure using the femtosecond laser, may replace LASIK due to its correcting the eye without incision. The cornea would not be weakened and side effects would be much lower. There would be less overall energy applied to the cornea. Although the future of LASIK is not fully known, currently millions of people are receiving the operation every year. The success rates are in the ninety percent range. One could even say it’s become a common trend for people
to turn to LASIK to rid themselves of glasses and contacts. The basics of optics and quantum mechanics marvel, the laser, have come together to improve the lives of millions of people.

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<th>ADVANTAGES OF LASIK OVER THE ICR</th>
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<tr>
<td>• No material permanently implanted in the cornea</td>
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<td>• The laser is able to treat astigmatism</td>
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<td>• The results are more accurately adjustable with additional “enhancement” laser surgery</td>
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<tr>
<th>ADVANTAGES OF THE ICR OVER LASIK OR PRK</th>
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<tr>
<td>• No surgery is performed in the central visual axis, thereby eliminating the possibility of central visual distortion by scarring from PRK or flap wrinkles from LASIK</td>
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<td>• Unlike laser procedures, the ICR procedure is reversible</td>
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<tr>
<td>• Surgical results as good or better than LASIK and PRK in that there is a higher percentage of patients achieving better than 20/20 vision</td>
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<tr>
<td>• Adjustable in the future to account for changes in eye focus for near associated with aging</td>
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Statistically, almost 20% of patients had enhanced visual performance (although we cannot predict which patients will achieve this result, and cannot warrant that any given patient will have this result)
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Very nice few
Good discussion of refraction
Super auto-transforming in presentation
Overall good job!

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