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Senior Project
Laser Cutting

Question: How are lasers able to cut through things without mass, and what are practical uses of laser cutting?
Thesis: Lasers don't actually "cut" things but vaporize them, and they are used in many different ways, from delicate eye surgery to making precise and fast cuts in factory metals.

Lasers are focused, high energy forms of electromagnetic radiation. They can have wavelengths in any part of the electromagnetic spectrum, including all colors of visual light, and are the result of a very high quantity of light particles called photons being focused into a very small point. However, lasers are much more complicated than simply shining a light through a focusing lens, as will be explained shortly.

My original topic of interest for this research project was looking into how lasers can cut through things despite not having mass, and what the modern applications for that technology are. As I did my research however, I discovered that lasers don't technically "cut" anything, and that what they do instead can be used as a substitute for a great deal more than just cutting. Despite their many uses and benefits, lasers still have limitations and drawbacks which are responsible for the fact that we aren't in a Star Wars-esque laser age.

Despite the fact that lasers have only become commonly used in recent decades, their history goes back to the early 1900s. The first step towards modern lasers was Albert Einstein's discovery of the photoelectric effect and stimulated emission, which was the subject of a paper he published in 1916. When shining a light at an excited electron, he observed that the electron then emitted a photon of its own and returned to its lower energy ground state. Upon this discovery, he then tried changing both the brightness and color of the light. When he changed the brightness, the resulting photon had the exact same speed as before, but when he changed the color, shorter wavelength blue lights resulted in a photon that moved faster and longer wavelength red lights resulted in a photon that moved slower. The photon that was emitted when the electron was stimulated by the light was identical to the incident light, and as such moved in the same way as it. Furthermore, it was also in phase with the incident photon which meant that the peaks and valleys of their waves coincided with one another.

The first significant application of Einstein's discovery came in 1951 from a researcher named Charles Townes who was working with microwaves. He tried to amplify the strength of the microwaves through stimulated emission, which he was successful in doing. This worked because, like the visual light that we use to see, microwaves are part of the electromagnetic spectrum and as such are made up of photons, just ones whose wavelength is much shorter than that of any color of visual light. Using stimulated emission Townes was able to design a high concentration of microwaves that were focused in a single direction. He called this technology the MASER, which stands for "Microwave Amplification by Stimulated Emission of Radiation", and his first working model was built in 1964. While the maser was initially given its distinct name, now it would simply be called a microwave laser, due to the fact that it works in exactly the same way as any other type of laser (e.g. visible light, x-ray, infrared, etc.) except through focusing waves in the microwave spectrum.

The first working LASER (which stands for "Light Amplification by Stimulated Emission of Radiation") was fired by Theodore Maiman in 1960. This laser used stimulated emission to cause the emission of photons by the electrons in atoms of chromium to create a focused beam of electromagnetic waves in the red spectrum of visible light. Maiman, along with two other physicists who worked with him on the laser named Nikolay Bosov and Alexander Prokhorov won the Nobel Prize in physics for their work on the laser. Despite this, another scientist named Gordon Gould actually holds the patent for the laser, as he had begun his research into lasers in 1957, before Maiman and his colleagues. Regardless of who can claim credit for inventing the laser, it is an extremely useful and interesting piece of modern technology.

A fundamental concept to understanding lasers is to understand the electromagnetic spectrum. I've mentioned it several times already, as it is something all lasers are a part of. The electromagnetic spectrum is a range of different types of "light", including the visible light we use to see things. All members of the electromagnetic spectrum are waves, specifically transverse waves, which do not have mass and move at the speed of light, which is 299,792,458 meters per second. Transverse waves resemble sinusoidal graphs in a cartesian plane; the wave oscillates between specific peaks, or high points, and valleys, or low points. As transverse waves, electromagnetic radiation does not travel through matter. This is why light can travel through space, which is a vacuum containing little to no matter in most places, from the sun to Earth, but sound can't. Sound, on the other hand, is a longitudinal wave, and is transmitted through the vibration of particles. Since there are no particles near enough to each other to transfer vibrations in space sound waves cannot travel. Conversely, sound has a much easier time travelling through solids than light, since there are more particles to vibrate and transmit sound through, while electromagnetic waves are often reflected or absorbed by solids. There are some electromagnetic waves that can travel through different types of solids and there are some solids that allow certain types of electromagnetic waves to travel through them, but that will be discussed later.

The reason the electromagnetic spectrum is called a spectrum, is because there are several different types of electromagnetic waves. Two of the most important characteristics of waves are their wavelength and their frequency, and changing these values changes what type of electromagnetic wave you are working with. Wavelength is the amount of distance the wave travels before it completes a full cycle (i.e. from one peak to the next peak, or one valley to the next valley) and is measured meters, centimeters, nanometers, etc.. Frequency is how many cycles a wave can complete in one second, and is measured in hertz, kilohertz, etc.. You may notice that these two descriptions are fairly similar, and that is because they are inversely proportional to each other; as wavelength increases frequency decreases, and vice versa. As a result, changing one automatically changes the other proportionally, and it is equally correct to describe an electromagnetic wave in terms of its frequency or its wavelength. However, it is most common to use wavelength when referring to the specific type of wave, and frequency is more often used when discussing the energy of a wave in particular, so that is how these values will be used throughout this paper.

In order of longest wavelength to shortest, the electromagnetic spectrum contains radio waves, microwaves, infrared waves, visible light waves, ultraviolet waves, x-ray waves, and gamma waves. Visible light is used to refer to all electromagnetic radiation that the human eye can perceive, and it too has a wavelength spectrum that is simply a rainbow: red is the longest wavelength color and violet is the shortest wavelength color.

Laser, as previously stated, is an acronym for Light Amplification by Stimulated Emission of Radiation. A laser is essentially combining an extremely high number of identical photons together in a small area to form a wave with a very high amplitude, leading to a very high energy output capable of many complicated and useful applications to fields like engineering and medicine.

When an atom, after being excited to a higher energy state, decays back to its ground state it releases the extra energy from the excited state in the form of a photon of a certain wavelength depending on the atom. This is called spontaneous emission, as it happens naturally in excited atoms' electrons without a specific cause or trigger. The other process by which electrons emit light is known as stimulated emission. An electromagnetic wave of a specific frequency passes through an atom in an excited state, directly causing the electron to decay back to its ground state and release the energy in the form of a photon identical to the incident wave that caused its emission. However, the incident wave isn't absorbed by the electron; both it and the new wave are moving in the medium, doubling the amount of waves there were originally. This is one of the primary reasons why it is stimulated emission that is necessary to create a laser and spontaneous emission can't. Stimulated emission is the result of adding energy into the laser medium's system with the result of amplifying the light in the system (as the name laser implies), while spontaneous emission is a natural conservation of energy within the system.

This amplifying characteristic of stimulated emission combines with an important characteristic of all waves, which is that they have no mass. Because of this, more than one wave can occupy a point in space at one time, and when they do, they combine to form a composite wave based on the source waves' amplitudes, wavelengths, frequency, and phase. Phase, a term not previously discussed, refers to where a wave is in its wavelength at a given point in time, such as being at a peak, at a valley, or at any other point in between. To add two or more waves together, you combine their waveforms which can be represented on a graph where the horizontal axis is time and the vertical axis is amplitude. You overlay the waves in question on the graph, and at each time value you add up all values for amplitude in the waves that you've plotted. When peaks are added to peaks or valleys with valleys, this leads to significant increases in the amplitude of the wave, at least at particular points along the waveform, and thus a higher energy output as well, since that corresponds with amplitude. However, when a peak combines with a valley, that leads to a reduction in amplitude since you would end up adding a positive and a negative together, which would bring the resulting amplitude closer to zero. When waves with different characteristics combine the resulting composite is often messy in appearance as opposed to the standard sinusoidal form of a wave, and are inconsistent with their output of energy due to fluctuating frequencies resulting from the combination of waves that don't match up.

However, a second important aspect of stimulated emission solves this issue. The photons that are released during stimulated emission are identical to the incident photon that caused the decay of the electron, having the same wavelength and amplitude. Additionally, they are "in phase" with the incident photon, meaning that they start at the same point in their wavelength from an arbitrary "time-zero" and travel together from there. When combining this with the fact that they have the same wavelengths and amplitude, that means that every peak of the incident wave corresponds with every peak of the wave emitted by the stimulated electron, and the same goes for every valley and all points in between, effectively doubling the amplitude, and thus energy output, of the laser wave when the base waves combine to form it.

To actually produce a laser, there are several important applications of the concepts previously discussed that must be incorporated. First is stimulated emission. Stimulated emission can occur whenever a photon of a particular frequency interacts with an atom. However, in order to have enough photons to maintain a laser, there needs to be a high number of atoms in a particular regulated area. This area is called the laser medium, because it is where the photons that produce the laser are created through stimulated emission. This is still not enough to form a laser. To do so, there needs to be a "population inversion." This is when more atoms in the laser medium are in a higher energy excited state than the stable ground state. When an atom absorbs a photon, it gains energy and enters a high energy excited state. This state is unstable, which is why it decays quickly back to the base state, emitting a photon containing the excess energy. However, there is an intermediate state called the metastable state. The metastable state is lower energy than the excited state and can be maintained millions of times longer despite also decaying after a certain point. The population inversion occurs when more atoms are in the metastable state than the ground state. When a metastable atom decays and emits a photon, it can react with any other metastable atom it comes into contact with, causing stimulated emission and resulting in a doubling of the photons contained in the laser, leading to a maintainable laser as long as new photons are pumped in via an external light source.

Lasers are the result of the many in-phase-photons created through stimulated emission being focused together into a single point, creating a small number of waves with a high amplitude and energy output aimed in one direction at a single point. This is what is called a laser beam, and it is a very important characteristic of any laser.

The typical sinusoidal representation of electromagnetic waves, while useful for demonstrating all the characteristics of waves (e.g. amplitude, wavelength, etc.), isn't entirely accurate to how waves behave. That representation depicts them as one line going in one direction, while waves act more like what happens when a rock is thrown into a body of water; the ripples originate at the center and radiate outwards, decreasing in height as they get further from the source of the wave. This is also true of lights. Lamps contain spherical bulbs that radiate light out in every direction that is transparent to it. Lasers the result focusing that light into a single point and directing it in a single direction, creating a laser beam that can be pointed in whatever direction is necessary for the desired function. This also focuses all the energy of the electromagnetic radiation contained in the beam into a very small area, leading to a high energy output wherever the beam shines.

In order to create a laser beam, the laser medium needs to be in a space with a mirror on each end of it, which causes the photons inside to reflect back and forth between the two ends of the laser, causing them to be travelling in the same direction. However, with two perfectly reflective mirrors, the light has no way of leaving, so one of the mirrors will be very slightly transparent, allowing some of the light in the laser to escape and be focused into a beam by lenses placed beyond the mirror, while keeping the rest of the light in the laser to continue the process of stimulated emission. Most lasers are cylindrical because that shape lends itself to the required mirror setup, and even more so to how focusing lenses work, a subject which will be discussed shortly.

When building a laser, one very important factor to consider is energy efficiency. Lasers require outside power in order to function, effectively converting electrical energy into light in the laser beam. Any energy that goes into the laser and doesn’t come out in the form of light is wasted energy, and efficiency is measured as the percentage of energy that goes in and comes out in the laser beam. There are three points in the creation of a laser where energy can be wasted. First, when powering the light that’s used to cause stimulated emission, a large amount of the electricity that goes into it is converted into heat energy as opposed to light that can be used in stimulated emission. Second, the light produced by the light source will be made up of many different wavelengths of light. The laser beam that results from this process, however, will only be made up of one wavelength. This is because the atoms used in stimulated emission only emit one wavelength of electromagnetic radiation depending on the type of atom, meaning that any wavelengths of light other than the one the atom in question reacts with will not be utilized in stimulated emission, and thus will be wasted. Finally, even after the correct wavelengths of light stimulate emission from the atoms in the laser medium, some of that light will escape through the sides of the laser that aren’t the mirrored ends, not forming the final beam and thus turning into wasted energy. Most of the energy that goes into producing a laser doesn’t come out in the form of the beam, and many lasers have an efficiency of less than 1%.

The final factor to consider when constructing a laser is the wavelength of the waves in the laser beam. As previously discussed, the wavelength of an electromagnetic wave changes the type of wave that it is in the electromagnetic spectrum. A very common practical application of lasers is for cutting, a subject that will make up most of the remainder of this paper, and lasers with different wavelengths do this differently. The energy output of a laser is inversely proportional to its wavelength. A laser with a higher wavelength outputs less energy, and usually cuts by vaporizing the material it is shone at, while a laser with a shorter wavelength has a much higher energy output, and cuts by destroying the covalent bonds that bind atoms together. The wavelength of the laser depends on the atoms used in stimulated emission contained within the laser medium, so it is important to be deliberate with what atoms are used.

With the necessary background history and physics of lasers in general explained, now I'll move into the main part of my paper: laser cutting. Because lasers output a lot of energy very quickly into a very precise area they are highly useful for achieving a cutting effect. The reason I say it like that is because cutting lasers don't actually cut their targets like scissors or a saw. As you shine a laser's beam at a target, the laser rapidly transfers energy to that target, causing a phase change. However, it does it so quickly that the solid you are shining it at actually vaporizes rather than melts, and changes phases directly from solid to gas, skipping liquid. The rate of energy transfer also contributes to a laser's accuracy. Lasers are very precise tools, and as such directly heat up only a small area. However, atoms that are heated vibrate rapidly and transfer heat to other atoms through conduction, leading to a much larger area gaining energy. However, lasers transfer energy to the target material so quickly that they vaporize the atoms before they can conduct heat to other atoms, ensuring that only the desired area is affected by the laser.

There are three different types of cutting lasers I learned about during my research. They all cut materials through vaporization, but the differences between them is how the laser beam is produced. The first cutting laser I learned about was also the first laser ever constructed. The ruby laser was made by Theodore Maiman in 1960. It consisted of a synthetic cylindrical ruby with chromium atoms suspended inside of it that was placed inside of a helical lamp, with mirrored surfaces on the ends of the ruby to keep the photons emitted during stimulated emission reflecting back and forth. As previously discussed, one of the mirrors was slightly transparent to allow some of the photons to escape and be focused into the laser beam by a lens. The chromium atoms in the ruby were actually laser medium as opposed to the ruby, making the ruby laser much more about the chromium than the ruby itself. The reason Maiman chose to suspend the chromium atoms in the ruby was because if he'd had a solid block of chromium, the light from the lamp would stimulate the outer atoms but then be reflected away from the block. This means that most of the chromium atoms in the block would not be stimulated to the metastable state and thus there would be no population inversion, preventing the creation of a laser beam. To get around this, Maiman commissioned the creation of the synthetic ruby he ended up using with chromium atoms suspended inside in a lattice pattern. By spreading them out he prevented any of them from being concealed beneath layers of other chromium atoms. This allowed for all of the atoms inside the ruby to be stimulated, creating the circumstances necessary for a population inversion. The lamp used in the ruby laser had a light wavelength of 550 nanometers, because that was the wavelength necessary to excite the chromium atoms to the excited state. After the atoms decayed into the metastable state, when they decayed further into the ground state they released a photon in the red spectrum of visible light. These photons were the ones that then caused stimulated emission in the rest of the metastable chromium atoms leading to the production of the laser beam, which had a wavelength of 694.3 nanometers. The lamp was also very bright. This didn't change the energy in each of the photons, rather made it so there were many more photons travelling from the lamp to the chromium atoms in a given time frame. Since one photon can only excite one chromium atom, having more photons led to the excitation of more chromium atoms and resulted in a population inversion happening faster. However, it is important to note that making the lamp brighter does require more energy, making the ruby laser less efficient. Ruby lasers suffer greatly from the previously mentioned sources of inefficiency. They are at most around 3-4% efficient, and often operate at less than 1% efficiency.

Among the most common lasers used today is the carbon dioxide (CO2) laser. The laser consists of a cylindrical tube filled with gas, around 75% helium and around 12.5% of each nitrogen and carbon dioxide making up the remaining 25% of the gas, that can have an electrical current passed through it. The gas is the laser medium like the chromium in the ruby laser, and the electrical current serves the same purpose as the ruby laser's lamp. The ends of the tube are mirrored just like in the ruby laser, with one of the mirrors being slightly transparent to allow the photons emitted in the laser to pass through and be focused by a lens. The laser beam in the CO2 laser is produced in a different way than in the ruby laser, but the basic idea is still the same. In the CO2 laser, an electric current is passed through the gas inside the tube, exciting the nitrogen molecules to a higher state. The nitrogen molecules then transfer their energy to the CO2 molecules, which become excited to a higher energy state as a result. The CO2 molecules decay into a metastable state and then further back to their ground state, at which point they emit photons that can react with any metastable CO2 molecules they encounter to cause stimulated emission. The excited nitrogen molecules cause a population inversion in the CO2 molecules, which then emit enough photons through stimulated emission to form a laser beam as the photons pass through the partially transparent end of the tube. However, there is an important difference between the light produced by the ruby and CO2 lasers. The ruby laser's beam is red visible light, while the CO2 laser's beam is infrared light which has a longer wavelength. There are four different ways an electromagnetic wave can interact with something: it can be absorbed by the target, it can be transmitted (or pass through) the object, it can be scattered by the object (meaning the constituent waves are separated), or it can be reflected. Red light is reflected by glass, while the infrared light of the CO2 laser is absorbed. This means that if the mirrors in the

CO2 laser are made of glass, the light will be absorbed by it rather than be reflected back and forth. To get around this, the mirrors in CO2 lasers are made differently. The fully reflective end is usually glass that is coated with copper or molybdenum, and the slightly transparent end is most commonly made of zinc. A very important advantage of CO2 lasers over other types of lasers is their efficiency. CO2 lasers usually convert around 20% of the energy used to power them into the light in the laser beam with the remaining 80% being wasted, mostly through conversion to heat energy. While this may seem low, 20% efficiency is actually extremely high for lasers, with most operating at similar efficiency levels to the ruby laser.

The third and final type of laser that will be discussed in this paper is the neodymium aluminum yttrium garnet crystal laser, or Nd:YAG for short. The Nd:YAG laser works very similarly to the ruby laser. The cylindrical garnet crystal has neodymium atoms diffused throughout it in the same way that the ruby in the ruby laser has chromium atoms diffused in it. A light is shone into the garnet, exciting the neodymium atoms, causing a population inversion in the same way as the ruby laser. The beam that is produced by the Nd:YAG laser has a wavelength only slightly longer than red visible light. As a result, the mirrors on the ends of the garnet in th Nd:YAG laser can be made of glass like in the ruby laser because visible light can be reflected and transmitted by glass as opposed to the infrared light produced by the CO2 laser. Another result of the Nd:YAG laser’s similarity to the ruby laser is its efficiency. Like the ruby laser, it operates most commonly at less than 1% efficiency, so on paper the CO2 laser is a much better tool for the energy put into it relative to the energy pumped out in the laser beam.

These different types of lasers each have their own advantages and drawbacks, however because the Nd:YAG and ruby lasers work in very similar ways and thus have similar properties, I will be comparing the CO2 and Nd:YAG lasers directly. Assume that what is said about the Nd:YAG laser is true for the ruby laser.

The CO2 has several advantages over the Nd:YAG laser. First is its efficiency. CO2 lasers are around 20 times more efficient than Nd:YAG or other crystal medium lasers, which obviously means that much more of the energy that goes into powering the laser is returned in the form of the laser beam. Second is the durability. The CO2 laser, being mainly a glass tube and a gas mixture, is hard to break. The most common way for a laser to be damaged is to overheat the medium. However, because the medium is gas, it can't be damaged or warped like the garnet in an Nd:YAG laser or the ruby in a ruby laser. A CO2 laser's efficiency means that less of the energy is converted to heat than in other lasers, so it doesn't heat up as quickly either. By comparison, an Nd:YAG garnet is highly vulnerable to overheating and can be rendered useless if it is warped or damaged from excessive heat. Additionally, the CO2 laser is much cheaper to repair if damaged, replacing the relatively durable glass tube, versus the much more expensive and fragile garnet in the Nd:YAG laser. Third is the operating capabilities. Lasers can either operate by firing extremely short pulses or by firing continuous beams over periods of time. I will go into more depth on this later on, but in short because the CO2 laser doesn't overheat as quickly it can operate in either pulsed or continuous mode, while the Nd:YAG overheats too quickly to fire continuously, making the CO2 a more versatile laser in this respect.

The Nd:YAG laser also has some advantages over the CO2 laser, however. First how it interacts with glass. As I mentioned earlier, the CO2 laser emits a beam in the infrared spectrum, meaning it is absorbed by glass, while the Nd:YAG laser cannot. This means that an Nd:YAG laser beam can be transported via optical fiber from the laser to the target, while a CO2 laser must be used directly through air, or be transmitted through the use of mirrors. Second is the wavelength of the lasers. Many metals, such as aluminum, reflect more radiation from the spectrum of light that is emitted by CO2 lasers than that of Nd:YAG lasers. This means a CO2 laser would need to shine more light on the target than an Nd:YAG laser to cut through it, meaning a CO2 laser would take more energy to perform a certain task than an Nd:YAG laser.

Now, onto applications of these cutting lasers. The most important thing about applying lasers to a certain task is the amount of energy they output to the target. The energy of a single photon is equal to Planck's constant (6.63 • 10^-34 Joule seconds) multiplied by the frequency of the light in hertz. As previously mentioned, wavelength and frequency are inversely proportional to each other, meaning that waves with a longer wavelength have lower frequencies and thus less energy per photon, and waves with shorter wavelengths have higher frequencies and thus more energy per photon.

To find the energy of an electromagnetic wave as a whole rather than just a single photon, is a bit tricky. The usual calculation for energy is mass times the speed of light squared (E = mc^2), but light doesn't have mass. The first thing to do is to square this equation, resulting in the equation E^2 = p^2 • c^2 + m^2 • c^4, where E is energy, p is momentum, c is the speed of light, and m is mass. Then, because light has no mass, we can plug in 0 for mass, setting the entire second term equal to zero leaving us with E^2 = p^2 • c^2. From there we can find the square root of the whole equation, giving us E = pc, the equation for the energy of a massless particle like a photon. A problem you may notice with this is that momentum is dependent on mass since it is equal to mass times velocity, and if mass is 0 then momentum is 0, and so energy is 0. This is not the case, however, because waves don't get their momentum from their mass, rather purely from their motion in a medium. Imagine you and a friend are holding both ends of a rope. Your friend snaps their end up, sending a wave through it to your end. When it reaches you, it jerks your arm. The momentum that was imparted on your arm was not from the rope, since it did not move; it was the movement of the wave itself that caused the change in your arm's momentum. To calculate a wave's momentum, you divide Planck's constant by the wavelength of the wavelength of the wave. Once you have the momentum of the wave, you can plug it into the massless energy equation we found earlier and find the energy of any wave.

However, there is one more factor that must be accounted for before we can find the energy imparted by our laser, which is that there are two different ways a laser can operate: pulsed mode or continuous wave mode. Some lasers can do either, but most are one or the other. Pulsed mode is when a laser only fires in extremely short bursts, often in the nanosecond scale. Lasers that operate in pulsed mode usually do so because they have a very high energy output, but it is so high that it very rapidly overheats the laser medium potentially damaging it. The short pulses give it time to cool between firings. Continuous wave lasers can fire continuously for much longer periods of time. They have a lower energy output than pulsed lasers, but also heat much less quickly, allowing for continuous use without the risk of damaging the laser. Each laser operating mode has a different energy output calculation. For pulsed lasers, the energy is equal to the average external power going into the laser divided by the frequency of the pulses ($E = P/f$). An important note is that in this case, frequency means the number of pulses per second that the laser fires, not the frequency of the light in the laser beam. For continuous wave lasers, the energy is equal to the average power sent from the power source to the laser multiplied by the time over which it operates ($E = Pt$). A final note on these equations before moving into the practical applications of lasers is that from what I found in my research, these calculations are both for an ideal laser with 100% efficiency, where all power going in comes out in the form of the beam. I would suggest that you multiply the result of these equations by the percentage efficiency of your laser in decimal form.

One field where lasers are extremely useful tools is in industry. Utility lasers used for drilling, cutting, or otherwise performing normally mechanical tasks have several properties that make them advantageous. First, the accuracy of laser beams is many times greater than traditional tools, allowing for more precise operations. Second, lasers are waves of light and therefore work at the speed of light, drastically increasing production and manufacturing efficiency when lasers are involved. Third, lasers are non-contact tools. When cutting thousands of things with scissors, a saw, or other mechanical tool, the tool will eventually dull after continued use. Because lasers are non-contact, they cannot dull and no matter how fragile the laser medium is, if it is operated correctly the laser can remain in use far longer than any mechanical tool.

The first specific use I will discuss is cutting metal and other materials with lasers. Cutting lasers have several advantages over mechanical cutting instruments. First, because lasers are non contact tools, they have benefits over mechanical tools for both fragile and very hard materials: because they don’t come into contact with the fragile material they won’t damage or break any part of it that isn’t meant to be cut, and hard materials that would dull a saw or like cutting instrument can’t dull the laser due to the lack of contact. Second, due to their aforementioned accuracy, lasers can cut much more intricate patterns than mechanical tools. Third, it is relatively easy to increase the cutting power of a laser by placing a focusing lens in the path of the beam that causes the waves that compose the beam to angle to a single point that varies depending on the lens. When the beams converge on that single point, the accuracy of the laser is increased even further by decreasing the area where the laser is cutting the target material, and the energy output is greatly increased at the focal point because all of the waves are converging their energy at that one point.

While there are many benefits to cutting with lasers, there are also obstacles. One is that when using a lens to focus the laser beam, beyond the focal point the lasers continue to travel at their angled trajectories, resulting in the waves spreading away from each other. This makes it so that cutting with a focused beam after its focal point is next to useless, so the laser has to be moved to make sure the distance from the laser to the target and the distance to the focal point match. However, most of the other problems result from how lasers actually cut, through vaporizing the target. This leads to a few obstacles. First, because some of the material is turned into vapor there is actually a loss of material that doesn’t occur with mechanical tools. While this can simply be accounted for in measurements, it is necessary to do so nonetheless. Second, the vapor that results from laser cutting can condense on the sides of the cut, causing it to end up being rough. Third and most importantly, the vapor can remain airborne between the laser and the cut. This airborne vapor can either absorb light from the laser or reflect it away from the target, resulting in a decrease in the laser's efficiency since less energy is reaching its target, decreasing a laser’s already low energy efficiency. There is a way to deal with this, which is by blowing the vapor away from the cutting area to exhaust fans that can remove it. Beyond that, it can be done in a way that provides a side benefit: it’s been found that using oxygen to blow the vapor away increases cutting efficiency by causing the metal at the contact point of the laser to combust in a controlled way, removing additional material from the target.

The second specific use of lasers is as drills. Laser drills work in exactly the same way as laser cutters, vaporizing the target material, and as such have many of the same benefits (not dulling) and drawbacks (vapor condensation). However, they have obstacles of their own to consider. First, if drilling with a laser focused by a lens, the beam will be angled and the walls of the resulting hole will be angled as well. If the lens has a longer focal length the effect can be mitigated, but regardless it will still be there. Second, laser drills are very impractical for drilling large holes, since the beams only cover a very small area, and cutting larger areas would require massive amounts of energy. Despite these issues, lasers excel at drilling small holes. Small drill bits are prone to dulling and breaking, but because lasers are non contact tools they can do neither, making them perfect for the task. Furthermore, their extremely high accuracy that makes them a bad choice for large holes is ideal for making small holes in a given material. However, it is important to note that if the target material is thick and the laser is being focused with a lens, the problem of conical holes arises once again.

The final industrial use for lasers I will discuss is as welders. Welding lasers work differently from cutting and drilling lasers. When welding with a laser, the process involves melting the target material rather than vaporizing it. The laser heats up the target metals until they melt, and then they can cool down and solidify together creating the desired weld. Because of this, welding with lasers is a much more delicate process than cutting or drilling. If too much energy is supplied to the laser, the output will be too high and it will vaporize the target instead of melting it. If there is too little energy, the laser doesn’t heat the target fast enough and the energy is transferred away from the target area by conduction and no melting occurs. If the energy output is only slightly too little, the energy is conducted away from the target area, but the laser is still outputting much faster than the conduction and causes melting, but due to the conduction it is a larger area than desired. One significant issue with laser welding is that most metals reflect some amount of electromagnetic radiation. Any waves that are reflected are wasted energy, but more importantly if they are reflected back into the laser they may damage it, so the angle at which the laser comes into contact with the target metal is important to keep in mind. One benefit that lasers have over other welding methods when used successfully is the issue of conductivity of the two materials being welded together. If they are the same material, this is generally not an issue since they'll have the same properties. However, if, for example, one is trying to weld a piece of steel with a piece of copper, copper has 10 times the heat conductivity of steel, and as such it will melt much faster. Laser welding provides an escape from this problem, in that the energy transfer from a laser to the metal is such that any metal's heat conductivity is effectively very slow. As a result, it is very easy to weld with a laser because the entire welding process is finished before the metal can conduct the energy very far from the target area.

The other field I will discuss where lasers are useful is in medicine. The first experiment on the medical applications of lasers was conducted in 1960 by Gerard Grosof, Gordon Gould, and other researchers. They directed a ruby laser into the eye of a rabbit, and found that the laser had burned a hole in the rabbit’s retina, but didn’t affect any parts of the eye in front of it. This discovery provided a way for doctors to operate directly on a patient’s retina without damaging or disturbing the other components of the eye that were in front of it. This was an example of the different ways a laser can interact with targets I mentioned earlier: reflection, absorption, scattering, and transmitting. The ruby laser's beam was transmitted by the rabbit's cornea, lens, and vitreous humor, but was absorbed by its retina. The first step in choosing a laser for medical purposes is to know how the tissue that will be irradiated will react to the wavelength of a given laser. For example, the wavelengths emitted by CO2 lasers are in the infrared spectrum. These wavelengths are absorbed by water molecules. This makes CO2 lasers a good choice for cutting tissue with a high water content, such as muscle tissue.

Like in the industry lasers just described, medical lasers cut through heating the target molecules and/or atoms. When a laser heats a target material, that causes the molecules to vibrate. They then cause molecules near them to vibrate and so on and so on. This can lead to the laser causing a general burn rather than a precise cut due to the conduction of heat to all molecules in a region as opposed to just those originally targeted. This effect is more intense the longer the tissue is exposed to the radiation. As such, engineers typically prefer higher frequency lasers since they have a higher energy output and thus are able to cut through the tissue more quickly, giving less time for conduction of heat between molecules to take place. There have been lasers produced in the violet and ultraviolet spectrums that transfer energy to the tissue so fast that they actually cause shockwaves that tear the tissue apart. The cuts can be made so fast that there is virtually no time for a temperature change to occur in surrounding tissue, leading to these types of lasers being called "cold lasers."

Lasers have several advantages over mechanical tools when used in surgery. First is the factor that is almost always an advantage, which is the accuracy; laser beams can be thinner than a hair, meaning they can make much more precise cuts in tissue than any other cutting instrument. Second, laser beams can be made up to a few millimeters wide allowing them to damage larger areas of tissue in sweeping motions if the situation calls for it. Third is something unique to surgical lasers. When cutting a small blood vessel with a laser, something called “photocoagulation” occurs, which is that the laser seals the blood vessel almost instantly, minimizing any bleeding that would result from the cut. This happens due to the laser’s high energy output. This is by no means the only way to do this; many other methods of sealing blood vessels, such as heater probes, are much less expensive than a laser. Despite this, when one is cutting tissue with a laser it is a valuable side benefit, and there are scenarios where photocoagulation is the best tool for the job, such as if a doctor needs to stop bleeding in the retina. As previously mentioned, lasers can operate on the retina without disturbing the other parts of the eye which other medical instruments cannot do.

While lasers offer some benefits over traditional cutting instruments, there are also new hazards that result from their use. First, lasers that go into someone’s eye damage the retina severely, resulting in significant and potentially permanent vision loss. While medical professionals obviously know not to look into a laser, there is still the risk of the laser reflecting off of something in its path, for example a scalpel the surgeon is using, and being redirected into someone’s eye. Second, lasers used to cut tissue through vaporizing it are supposed to output sufficient heat energy to vaporize the tissue almost instantly. However, it has been observed that hazardous viruses and spores in the affected tissue can survive the vaporization of the tissue and become airborne as a result, presenting a significant hazard to anyone nearby. This is a problem that does not occur when cutting with mechanical tools, which is one of the primary reasons why lasers are not as common in the medical world as in the industrial.

Despite the dangers and impracticalities, lasers have several tasks for which they are used in the medical world. First is the removal of kidney stones. The doctor fires a pulsed laser with a wavelength of 504 nanometers, which is in the green spectrum of light, through a fiber optic cable at the kidney stone. The laser vaporizes part of the stone, but the temperature change that causes the phase change is so fast and violent, it sends shockwaves into the rest of the kidney stone that cause it to vibrate extremely rapidly, fragmenting into small pieces that can be much more easily passed later. In this respect it is different from other laser applications, since the vaporization is only a means to an end as opposed to outright being the solution to the problem. One reason a green laser is ideal is that wavelengths in that spectrum aren’t easily absorbed by hemoglobin, which is an important component of blood. Since lasers have to be absorbed by the target to have any phase change or destruction effect on it, the interaction green light has with hemoglobin means that if the laser misses the kidney stone and hits neighboring tissue the damage will be minimal.

The second medical application vision correction. The most common reason for blurry vision is that the cornea, which is the part of the eye most responsible for focusing light, doesn't do it correctly. The way to fix this is to reshape the cornea so that it can better do its job. The procedure starts with a small incision in the cornea being made with a blade called a microkeratome, opening a flap in the cornea. Then a high energy ultraviolet laser begins firing nanosecond pulses at the patient's cornea, reshaping it by vaporizing specific tissue. The pulses are brief enough so that the surrounding tissue is not damaged by thermal conduction. The laser is computer operated and the desired shape of the cornea is preprogrammed to minimize inaccuracy and risk of harm to the patient.

The third and final application is tattoo removal. Tattoos naturally fade over time as the granules of dye used in them are gradually broken down by the immune system. In laser tattoo removal, a ruby laser with a wavelength of 694.3 nanometer wavelength is fired in 30 nanosecond pulses at the patient's skin. This wavelength is more readily absorbed by most tattoo dyes than the skin, allowing the granules under the skin to be broken down without significant damage to the skin. The speed at which the laser heats the granules of dye causes shockwaves to occur in them, just like with the kidney stones, causing them to break up into much smaller chunks. This makes it much easier for the immune system to break down the dye, and the tattoo should be fully gone within a few weeks of treatment, although sometimes the patient may need more than one session for successful results.

Lasers are a very interesting and valuable technology. Their ability to transfer energy from one point to another at literally the speed of light makes them excellent for the jobs they are used for, particularly cutting. Their base cutting efficiency eclipses mechanical tools that are more commonly used, and when lasers are used by factories, hospitals, or any other facility that needs to cut or shape things they often greatly increase the speed, accuracy, and quality of those cuts. This begs the question: where can lasers go from here? One interesting possibility could be sculpting. An artist could connect a laser to a computer and program it to carve a block of material into a specific shape and do so faster and with more accuracy than they might be able to mechanically. A very useful medical application could be to treat cancer tumors. You could use a highly accurate pulsed laser to vaporize the cancerous tissue until it's gone. The laser's accuracy would ensure that it only heats the cancerous tissue, and using it in a pulsed mode could prevent damage to surrounding tissue via heat conduction, similarly to the way lasers are used to correct vision through reshaping one’s cornea. In fact, I wouldn’t be surprised if this is already being done in the medical world. My final thought for future possibilities of lasers is more related to lasers in general as opposed to cutting lasers, and is pure speculation. Because of how quickly lasers transmit energy, could it be possible to create wireless power through their use? It would obviously require lasers with much higher efficiencies than we have now, since the majority of the energy put into a laser is lost before it can be turned into the laser’s beam, but if we had lasers with higher efficiency we could create potentially wireless energy transfer that moves energy from the laser’s power input to the beam’s target at the speed of light, where it would be absorbed and sent through wires to its final destination. It’s probably pure fantasy, but maybe the technology to accomplish this will be available one day.

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