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Physics, 3D printing, and the World Around US

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Introduction

It is argued that the printing press is one of the most revolutionizing inventions that humanity has ever developed (Kreis). It spread information both quickly and accurately, and connected people across hundreds of miles to the same, standardized information. Scientists could compare experiments, validate results, and publish nationally all because of one machine. It raised the literacy standards immensely and encouraged reading, writing, and learning to all people (Kreis). Look forward 500 years and technology has pushed civilization forward to the point where paper printing is generally accepted as a commodity. Even further, printing itself has become an entire new industry due to the invention of the three dimensional (3D) printer. Printing has both literally and figuratively taken on a new dimension. It's no longer just about getting words on paper, but getting a design in the computer. Just like the original printing press, it is possible that the ramifications from this rising science and art have not even been fully discovered. With all that said, what are the limits, possibilities, and future of 3D printing? Will there be another revolution that we can't see coming? The following paper will explore these areas and take a deep dive into what 3D printing is, its properties, and future as an industry.

What is 3D Printing?

3D printing, also known as Additive Manufacturing, is a method of construction by which the device adds successive layers of material(s) together to form a figure/solid. Often printers are used for rapid prototyping, keeping costs low while generating an initial product. Or sometimes they are used to make an intricate piece to machinery that would be difficult to design with standard cast molding. All in all, 3D printers are used to keep costs low where they can and improve the quality and speed of manufacturing. There are many different printers for different applications, and more will be covered on this is the "types of 3d printers" section. With all these different types of printers come different types of materials. The materials range from plastics and metals to ceramics and biomedical tissues. Most printers follow the same general process for executing a print: receive the imported 3D file, interpret the data using their respective viewing programs, and run an algorithm to execute the print. The most common 3D file would be the stereolithography (STL) file. This is a typical exporting method for 3D computer-aided design (CAD) models. Nearly all 3D printers accept STL files, however the interpretation of this code by each printer can vary from printer to printer, so more will be covered in the "types of 3D printers section.'' Once the STL file has been imported into the 3D printer's pre-printing program, the object is modeled layer by layer, and can be checked for errors before finally printing.

Types of 3D printers

Stereolithography (SLA): As stated earlier, SLA printing was the first method invented and relied on UV light, or a laser striking a material to set it into a permanent, harder state. The plastic material, or polymer, is held in a box underneath the laser where it is in a liquid state. The laser moves across the top layer of the polymer and creates a very accurate, hard resin. Once the layer is complete, it is lowered a minuscule amount by a movable platform and the next layer is etched on above it. SLA printing is regarded as one of the most accurate and best finishing 3D printing techniques that there are, but it still has its problems (Chen). While printing, any overhangs in the design will need to be supported by layering in support structures. These structures are then removed manually after the finished print and this can leave imperfections. Once all supports are removed, the material must be cured with the UV light. One issue with the UV light is that it can dry out the resin to the point where it becomes dry and brittle. If it is cured too long it can crack, and ruin the print. Even though the post print process is involved, SLA printing is still used today for its high accuracy and high reliability.

Fused deposition modeling (FDM): Also known as Freeform Fabrication (FFF), FDM is the most popular and well known printing technique today (Chen). A nozzle, called an extruder, heats up plastic and deposits it onto the previous layer, where it hardens and bonds together. The first layer is strewn out onto a platform known as the bed. FDM is still subject to support materials for overhangs, and it can have layering issues where one doesn't bond to the previous. Depending on the use of the object, this may not be an issue, but if the object needs to be air or watertight, this is problematic. One solution to this is to use acetone to lightly break down the plastic and melt them together, closing the gaps. These prints do not require any curing, but acetone and light sanding is used to clean up certain discontinuities. A recent important evolution in FFF technology is the use of polyvinyl alcohol (PVA) plastic. PVA plastic dissolves in water. When printing with a dual extruder (two nozzles), one can be used to deposit standard polylactic acid (PLA) plastic, and the other can use PVA for the supports. The supports, rather than manually tearing, cutting, or breaking off, can just be dissolved in water.

Selective Laser Sintering (SLS) & Selective Laser Melting (SLM): Sintering means taking a material just up to its boiling point, whereas melting means bringing that material above its boiling point. SLS and SLM use a laser that strikes a powdered plastic, usually nylon, to form together a solid (Palermo). The platform exposes a thin area of plastic for each layer and then drops slightly for each subsequent layer. SLS/SLM is very accurate and because of the laser, it doesn't require any curing. It also doesn't require any supports because any overhangs rest on the powdered nylon underneath them. In addition to plastics, ceramics, glass, and even metal can be printed using this technique.

It should be noted that there are many other types of 3D printers used commercially and residentially, but they will not be covered in this paper.

Physics, Engineering, and Applications

Computer science might be the language of all additive manufacturing, but there are many areas within 3D printing that rely on physics, engineering, and mathematics. Within physics and engineering, topics such as support minimization, infill design, and material strength (all three of which are covered in a later section) all play directly into the end result of a print. These areas within additive manufacturing play a large role in the development, approach, and applications to 3D printing. By examining them, one can get a clearer picture of where 3D printing is as an industry and its possibilities moving forward.

<u>Physical Properties</u>

All materials have their breaking point. This goes the same for the wide array of materials used for 3D printing. There are hundreds of subsections that fall under those main categories of materials (metal, plastic, ceramics, class, and medical tissue) (Jackson). This paper will be exploring the most popular type of 3D printing that's growing in accessibility for non-commercial use: FFF/FDM thermoplastics. In thermoplastics, there are hundreds of materials that can be swapped in for most FDM printers, but there are a heavily weighted top three most used: Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and Polyninyl Alcohol (PVA) (Jackson). There have been many tests that look at the intrinsic properties of these materials and the results are valuable. Compression, tension, and impact tests compare the mecahnical properties between ABS and PLA clearly. Infill and support designs have been analyzed for material conservation and thermodynamic spread. The next sections explore the physics behind these properties.

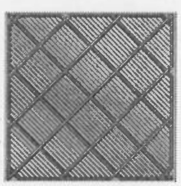
Strength

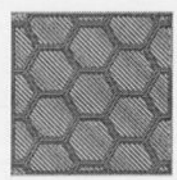
Typically, there are 4 standard integrity tests that engineers preform on a material in order to test its strength. They are compression, tension, flexure, and impact. Many different companies have performed these 4 tests on ABS and PLA, with different controls, to yield interesting results. Un-notched IZOD impact tests (standardized, repeatable material tests) reveal that ABS handles impulse about three times better than PLA (Letcher). This is the only agreed upon parameter where ABS is stronger. PLA is a stronger material if looking at its compression and tension values compared to ABS (Letcher). 3D printing company MakerBot and 3D printing material company Optimatter both reported PLA as having a compression value of 2600 psi and ABS as 1100 psi (Makerbot, 3D Matter). For tension, PLA is higher again at 6800 psi and ABS at 4900 psi (Makerbot, 3D Matter). The flexural strength, or its breaking point due to bending, is slightly more obscure. The flexure strength of ABS cannot seem to be agreed upon. This could be in part due to the variety of ABS strands, or major differences in testing apparatuses, but where MakerBot gives PLA a significantly higher flexure strength over ABS (9000 psi vs. 5300 psi), Optimatter shows ABS and PLA having equal flexure strength (around 10,000 psi) (Makerbot, 3D Matter). One final test to consider is elongation, which measures how ductile a material is. PLA is brittle, when it yields to the given stress applied, it snaps, shatters, or otherwise cracks apart. ABS on the other hand has been observed elongating up to 50% of its original length (Makerbot, 3D Matter), bending slowly and stretching. This could be in part where the ambiguity lies within the flexure strength testing. If different companies/labs measure yielding at different positions, there is no set standard.

Infill

One variable that can change with each print is the way that the object is filled with material on the inside. It is typical that not all of the object will be filled with material and for example, a 25% percent infill pattern leaves the object 75% hollow. Typically in FDM/FFF printing, infill percentages are around 20%-40% (3D Matter). While it seems odd that the object is mostly hollow, most objects do not need the added strength that the additional weight and cost of the material brings. The way in which this added material contributes to the strength of the objects cannot be agreed upon by material engineers (Bodaghi). Some conclude that the material is logarithmically proportional to the strength (3D Matter), while others argue it is, quite oppositely, exponentially proportional (Bodaghi). This could be in part due to experiment variations, testing procedures, and material specifications (more on this can be found in the limitations section). Both agree though that for most applications, the strength needed in a print is well under 15 MPa, which is under 30% infill.

One example of experiment variations is the pattern at which the infill is layered. The most common types of infill patterns are rectilinear, triangular, and hexagon.

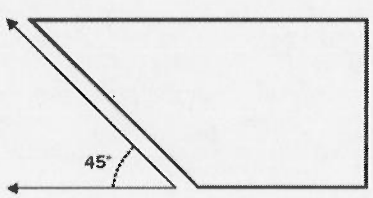


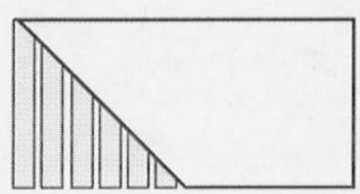


Most printers come standard with a rectilinear, or grid default, but triangular infills can be set for more strength (Letcher). Hexagonal designs are used for efficiency due to the most area for a given amount of filament used. This can be verified by looking at the area formulas of the grid (square), equilateral triangle, and hexagon. For a side length of 1, the areas are 1, 0.43, and 2.6 respectively. By covering the most area, the honeycomb reduces the filament used per print. It has over a 2.6 times area covered vs. the square, and only uses 1.5 more filament. This results in (2.6/1.5 = 1.73) a 1.73x the area covered per filament used. This change would be irrelevant if the square was 1.73x stronger than the honeycomb, but this is not the case. MatterHackers tested these patterns at a 10% infill and found that PLA hexagons yielded to tension at 7.7 MPa, where the grid did at 8.4 MPa (3D Matter). This 1.09x difference in strength is sacrificed for the 1.73 times less material used and for most prints, is worth it. Not only is money less of a factor with less filament, but so is print speed (Brubaker). These lower print times are partially due to the shallow 120 degree angles at the corners of the hexagons, making it easer for the printer to change directions and as mentioned above, partly due to the less material used (Brubaker). These changes in speed are proportional to filament used, so with the 1.73x more area covered per filament used, this also translates into a sizable speed gain for that infill percentage (Brubaker). Where these changes in printing speed and object strength are really seen is on the larger print scale, especially commercially.

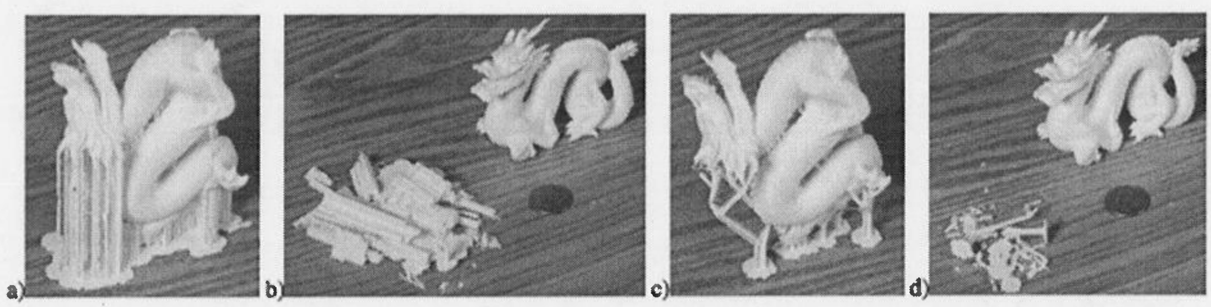
Supports

There are many instances within 3D printing that require the use of support materials in order to complete the prints. In FDM/FFF printing, this is usually when the overhang is more than 45 degrees (Ezair).





The supports are designed to be removed from the main structure after the print is finished by snapping, peeling, or dissolving off. Even with the use of supports, large overhangs can prove to be troubling for some software to process. Sometimes, it is even better to slice a design in half (a sphere for instance), print both halves separately, and then adhere them together after. Seeing how this slicing process can change characteristics of the print such as strength and accuracy, sometimes supports are mandatory. Since that is the case, minimizing the volume of supports is the next best option. Some work has been done on ways to minimize support structures on an object with an algorithm created by researchers at Perdue University. The researchers were able to compute the support volumes beneath the 3D printed object and the code would then change the orientation angle of the object in order to choose the smallest amount of support structures (Vanek). They redesigned conventional supports to utilize the printer's ability to print out less than 45 degree overhangs and implement that into support structure, rather than conventional, purely vertical supports (Vanek). This is illustrated in the four images below:

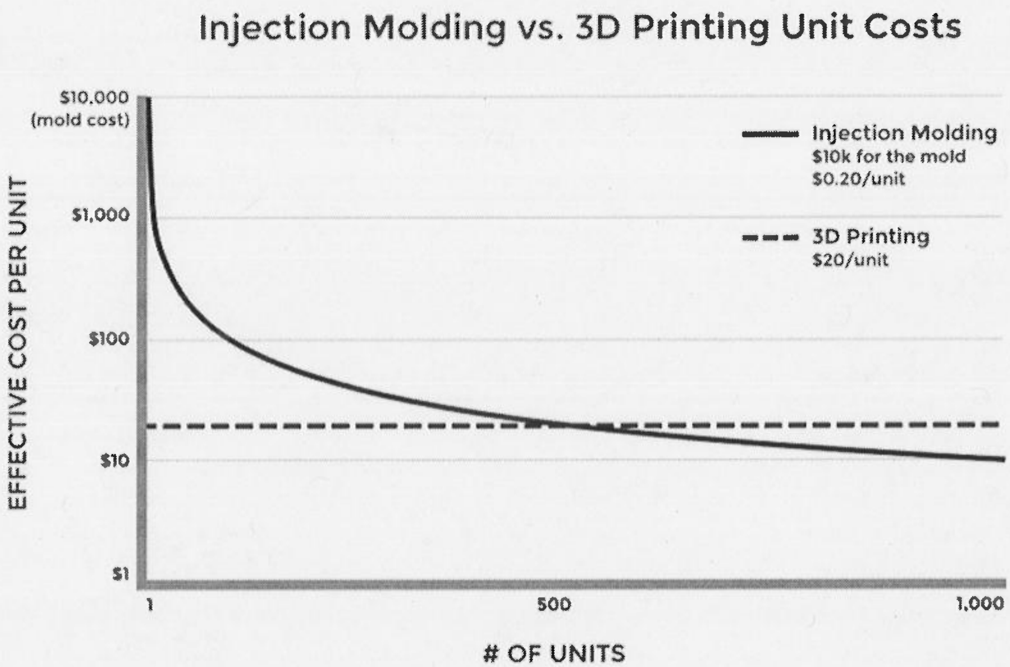


The standard supports are pictures a) & b) and the optimized supports are pictures c) & d). As illustrated in the images, this resulted in less material used and an easier post processing. There is a balance between where to place the supports how big to make them. If the supports are not placed correctly, or too thin, the print will fail. While these types of supports are relatively new and still not a staple on most printers, it is expected that they become the standard feature once more research and programming is done (Vanek).

Cost Analysis

One of the biggest advantages of additive manufacturing is the cost reduction that can be seen versus conventional injection molding for plastic (Chen, and Zhen). A review from the U.S.

Department of Congress shows a typical example of the benefits of 3D printing vs. Injection molding (Thomas) illustrated in the graph below:



For an initial mold costing of $10,000, after 500 units the price per product is equal. But when will the total amount of money invested in products be the same? Integrating each curve and setting the results equal to each other shows that the amount of money invested does not actually equal each other until about 4700 units. So at the 4701st unit, a company would have spent more money 3D printing the products rather than injection molding them. This is why 3D printing is becoming such a viable option for companies. It takes thousands of units to save money with injection molding, not to mention the time to actually create the mold. Acquiring a printer is fast and usually at a fraction of the cost. The graph assumes that neither method encounters any failures and according to the study, printing fails more often than injection molding (Thomas). Each printer has different failure rates and failure expenses, so it can be difficult to estimate the total amount incurred (Thomas). But the study does broadly illustrate this problem with the following graphic:

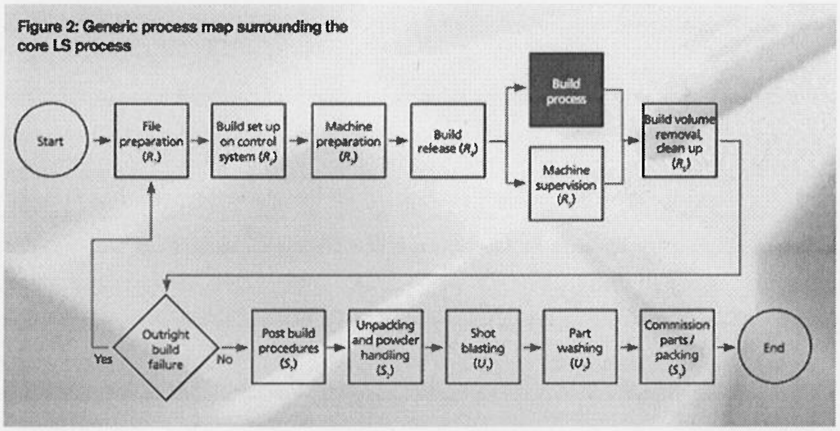


Figure 2: Generic process map surrounding the core LS process

When the print fails it has to reprocess back to step one and incurs expenses at each step along the way. With that said, residential printers fail much more often than commercial printers. These failures are partially due to the actual mechanics of the printer (materials used, printing style, curing process) and partially due to the higher quality of commercial printers. There is no golden equation that solves which manufacturing type a company should pursue, but rather each company should be looking at 3D printing as an option for many of their products and calculate costs for themselves.

Not all companies will need to produce hundreds, or thousands of parts though and that is where 3D printing can really be useful. Many companies in the auto and aviation industries use 3D printed metal pieces to replace and fix old, outdated parts no longer made. It would be more expensive and time consuming to try to make them another way (Thomas). Rachel Boagey, a writer for the journal Professional Engineering, takes it even further by estimating that 3D printing for prototyping cars "will see a threefold increase in revenue by 2025," making it a viable option for full prototyping. Local Motors has even developed the plans for a car that would be 90% made from 3D printing (Boagey).

Limitations

While 3D printing is an extremely innovative, useful, and practical method for manufacturing, it still has much ground to cover before it becomes a market standard. Printers pose different issues of entry for different fields. For example, in education, it might not be affordable. For the medical community, it might not have the essential accuracy and precision. In the assembly line, it might be too slow. While these problems are valid right now, as 3D printing technology continues to grow, some of these drawbacks could become more manageable. Going back to educations, specifically grades 9-12. As STEM classes innovate with growing technology, 3D printing could become a valid option in meeting those needs. With newer printers emerging, schools can buy older, but still competent printers, at a much reduced price in order to meet budgets. Price is probably the biggest roadblock for 3D printing as a whole right now on the consumer level. It is difficult for a hobbyist to justify spending upwards of $1,000 on a printer when they can outsource it for $5.00. In addition, not all printer software is user friendly, and the learning curve can be steep for someone who knows nothing about 3D printing. Combine this with printers that need manual bed leveling, small margins of errors, and failed prints and most consumers outsource (D'Aveni).

Conclusions

3D printing is changing the way that companies and consumers consider manufacturing products. There is much promise in 3D printing, but it is clear that there are some major roadblocks ahead if it is to have strong influence in the manufacturing field. If 3D printing does end up revolutionizing manufacturing, it very well could be a repeat of the previous printing revolution back in the 1600's. Time can only tell what will be built from here.

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I took my knowledge of 3D printing and decided to make an orrery, primarily out of 3D printed parts. An orrery is a mechanical model of the solar system, driven by gears. The following explains that in more depth.

Designing an Orrery

There are many ways to design and craft an orrery. It can be made of wood, metals, plastics, or other materials. They can include just the earth and moon, or include all the planets in the solar system. For simplicity I have chosen to make an orrery with the sun, earth, and moon. I have also strategically designed the moon gear train to also be a part of the earth gear train (rather than two separate apparatuses), which helps keep the numbers of gears low.

This orrery is built with 9 working gears pictured below (Figure 1), and 4 driving gears for the crank that are not pictured below. There are 3 systems that make up the orrery: the moon (green & yellow), the earth rotation (all except maroon), and the earth seasons (maroon).

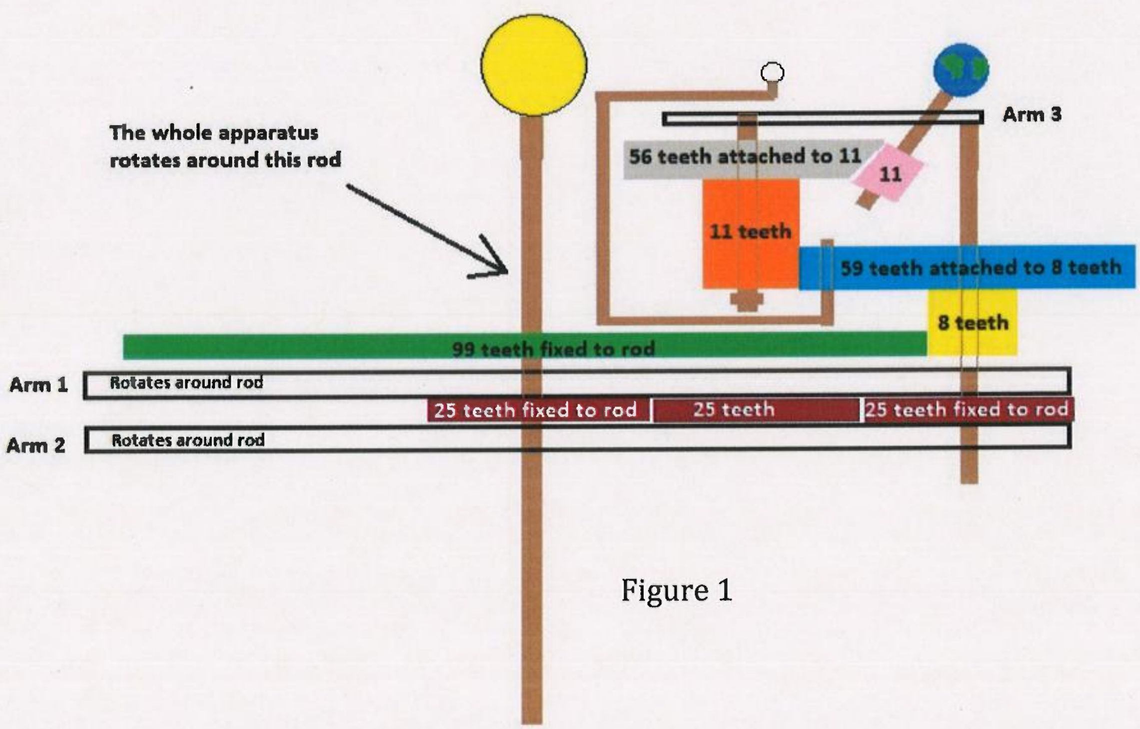
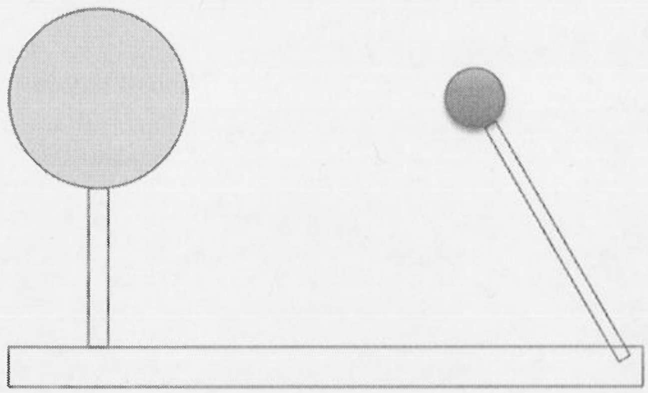


Figure 1

It is important to establish why we need the maroon gears. Imagine the picture below. As the earth revolves around the sun, the north pole will always point toward the sun and even though there is a 23.5 degree tilt, it will not experience a change in seasons.



How to fix that problem: because the earth revolves counterclockwise (CCW) as viewed from above, the rod it is attached to needs to rotate clockwise (CW) relative to the arm that it is on. The rotation rate is 1:1, but it is easier to visualize by thinking about how much the earth rod needs to rotate for ¼ a revolution around the sun. When it revolves ¼ the way around the sun, it will have needed to rotate ¼ turn CW relative to the arm that it is attached to in order to have a change in seasons. This is why the maroon gears are needed. They all have the same number of teeth, and they ensure that the rod rotates 1:1 with the arm that it is attached to.

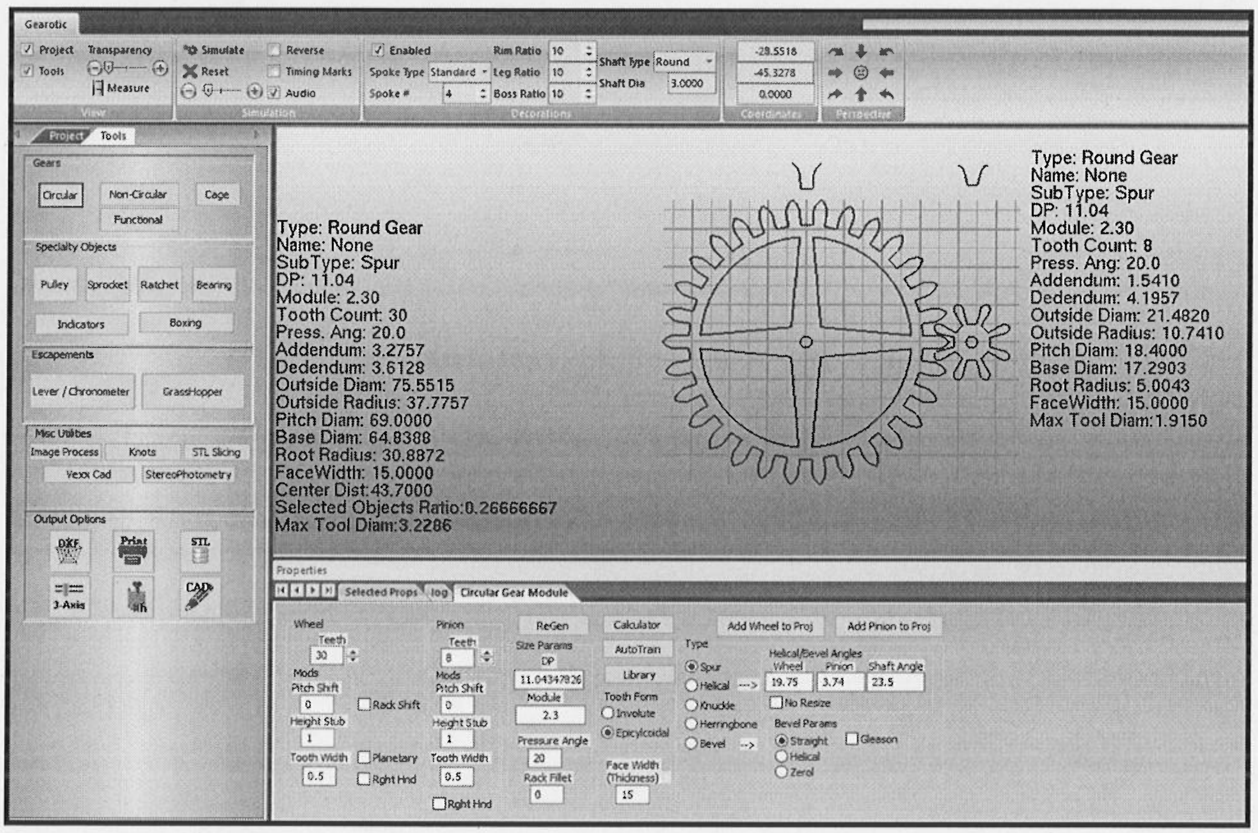
The moon system is driven by the 8 tooth running around the 99 tooth. This gives a ratio of $\frac{99}{8} = 12.375$, or $\frac{365.2422}{12.375} = 29.51$ earth days per lunar cycle. Compare this to the 29.53 day actual value, and this only has a 0.07% error.

The earth rotation is determined by all gears on the picture. First let's just look at all the gears at face value. That is: $\frac{99}{8} \times \frac{59}{11} \times \frac{56}{11} = 337.91$. This would be correct if "arm 3" wasn't directly fixed to the rod that runs through the 59, 8, and 25 tooth gears. But it is indeed directly connected to that rod. And because of the seasons, that rod rotates 1 time per revolution of the earth around the sun. In this situation, the 11 orange is spun around the blue 59 1 extra time per year. It would be tempting to just add $\frac{59}{11} = 5.36$ to 337.91, but this would be incorrect. The order operations matter because the extra revolution will also be affected by the $\frac{56}{11}$ ratio after the fact, amplifying that too. So the correct ratio calculation looks as follows:

$$\left[\left(\frac{99\ teeth}{8\ teeth} \text{ x } \frac{59\ teeth}{11\ teeth}\right) + \frac{59\ teeth}{11\ teeth}\right] \text{ x } \frac{56\ teeth}{11\ teeth} = 365.215$$

and results in the earth revolving CCW around the sun with a percent error of 0.008%.

The gears were designed in an application called Gearotic Motion. It allowed for design and simulation of the orrery. The image below shows the design tab of GM and how valuable it can be in designing accurate and properly meshing gears:



Gearotic motion had many different types of gears to choose from: spur, epicycloid, bevel, knuckle, and all were customizable in size, teeth, as well as various other parameters. Even with all the options, nearly all gears were created using the epicycloidal function, which is standard for orreries. This is because of the different properties that associate with spur/epicycloidal gears. The most important thing to notice about the spur gears in figure 3 is the whole depth, or addendum and dedendum added together.

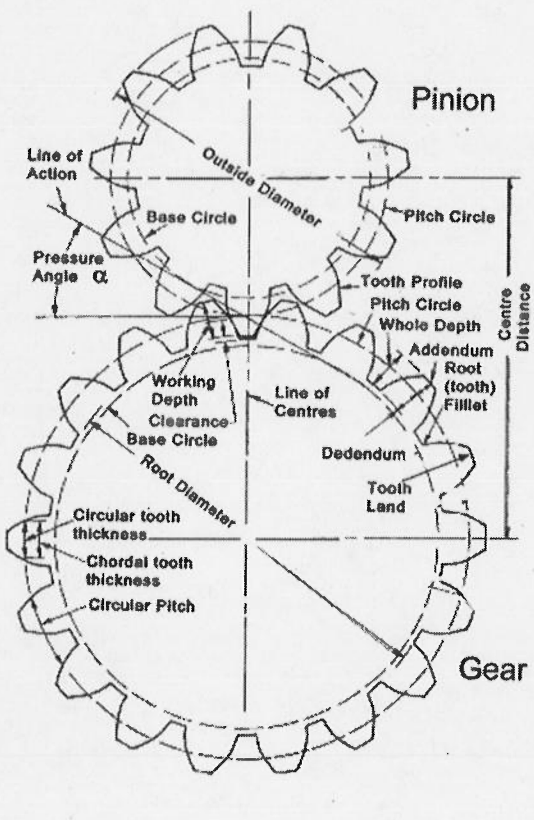


Figure 3

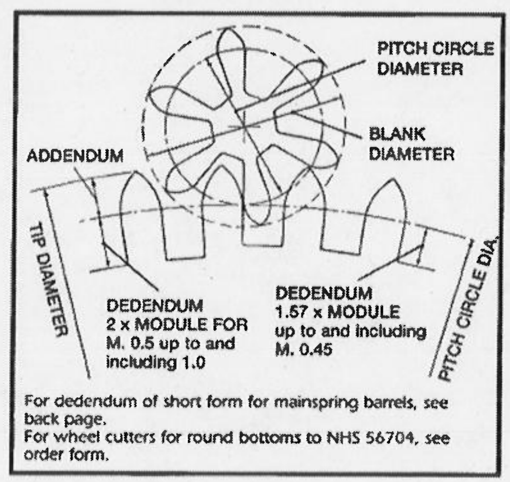


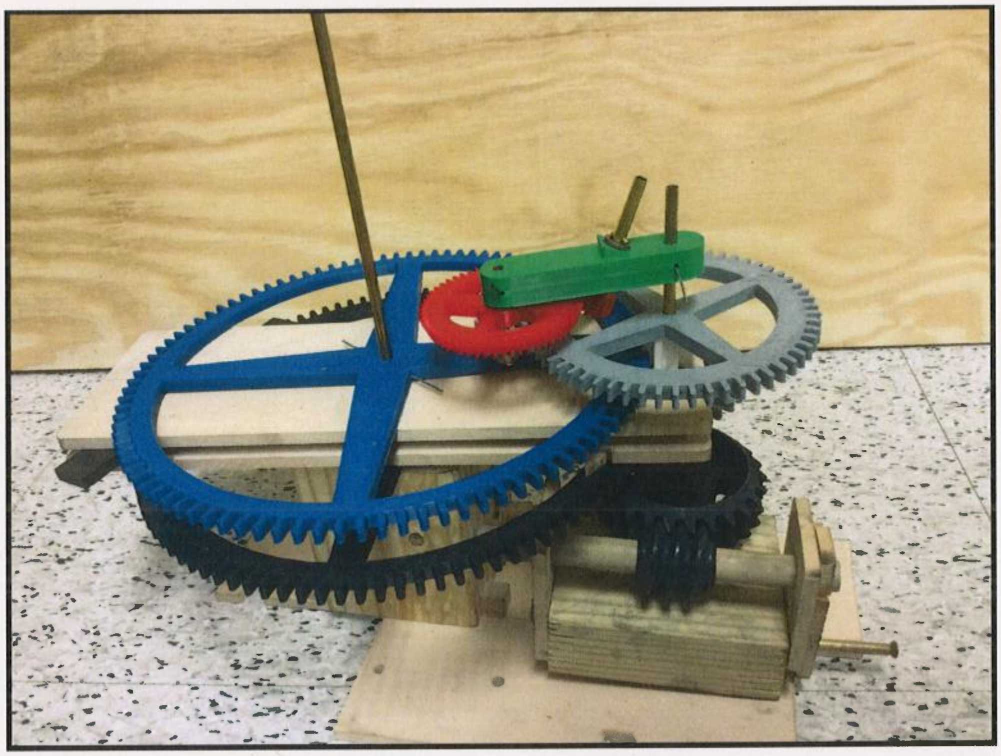
Figure 4

These gears have short, strong whole depths, with much friction. Epicycloid gears on the other hand (Figure 4) have long whole depths, low friction, and are weak. This is why clocks, orreries, and other low impact machinery utilize them.

I designed the gears in geartotic motion based off of the constraints of the 3D printers I was using, a Lulzbot Taz 5/6 and a MakerGear M2. The build area on the Taz 6 is about 11 inches by 11 inches and much bigger than the MakerGear, so I set the biggest 99 tooth gear to that size. I did this to try to make the teeth as big as possible and consequently increase the accuracy of each tooth. I used a layer height of 0.15 mm for maximum accuracy and no gears needed supports except for the worm gear used in the crank. That also determined the diameter of the 25 tooth maroon gears since 3 of those have to equal the same distance of the 99 and 8. The Taz 5 and 6 have a 0.5 mm nozzle and were sufficiently accurate for all the gears except for the beveled 56 and 11. These needed more precision because the tooth size was under 3 mm at its base. The MakerBot M2 has a 0.35 mm nozzle and performed much better at the smaller scale. Because the 99 tooth gear was so big, it tended to warp at the edges and bend upward as it cooled. In order to work around this problem a thin layer of glue was placed around the rim of the gear that held it down as it dried on the printer bed. A 15-20% honeycomb infill was used for the gears, which proved to be plenty strong for this low force application. The worm gear used standard supports between the spirals, but other than that no supports were used.

In addition to Gearotic Motion, Tinkercad was used to create a few of the assemblies on the orrery. The main being “arm 3” that holds the earth 23 degree axis. Because Tinkercad is free, basic, and is accessible anywhere with internet, it made for a great modeling software for simple designs and minor edits. It could be exported to the 3D printer as a STL file and then printed via gcode on the MakerBot or Cura for the Taz.

The biggest problem I encountered was the actual assembly and weight distribution. The disproportionate weight and inconsistencies in the gear teeth led to jerky and inconsistent motion. Once proper weight was established by placing extra mass on the backside of the apparatus, the orrery operated more smoothly. The printers worked precisely and there were few issues with accuracy/extruding. Even so, a reprint only took a couple hours to complete.



Finished prototype

In conclusion, designing this was much more challenging than I had imagined, but it was very cool to put my engineering knowledge and 3D printing research to use. Although it is not perfectly finished, I did learn a lot through the process of this project and hope to continue it in the future with more knowledge and better results.