Novel Mechanical Mechanisms for the Development of Undergraduate Knowledge

by

Michael L. Stern

Submitted to the Department of Mechanical
Engineering in Partial Fulfillment of the
Requirements for the degree of

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May 19, 2009

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Abstract:

Although MIT Students have been taught an enormous amount of theory and design, they are not exposed to simple machine elements and designs from the past. As a result, students often spend time reinventing things when the answers have been already developed. This project focuses on presenting students with designs from the past that are useful, novel and make the student think. This agenda is one that is being approached by a number of others. In particular, there are the Clark Collection at the Museum of Science and KMODDL (Kinematic Models for Design Digital Library), an online resource containing both photographs and video of models and 3D printing templates, all aiming to make this knowledge more accessible to a wider group of people. The goal of the present work is to create a more easily understood set of models that can be made inexpensively and can be produced around the world. The models included in this collection focus on four main themes: pulleys, gears, ratchets and mechanisms that convert rotary to linear motion. By using consistent coloring to act as a legend, educational descriptions that accompany the models to provide context, and a simple design to allow for fabrication using a laser cutter, the educational goals of the project were executed and met. The models are more easily understood and cost a fraction of the amount to fabricate as those made with a 3D printer while being more robust and visually pleasing.

Thesis Supervisor: Barbara Hughey, PhD

Title: Instructor

Introduction:

Although engineers at MIT go through an exhaustive course of study and learn immense amounts about analysis, design and manufacture, they often are not exposed to many valuable mechanisms that are not in common use today. As a result, many mechanical engineers reinvent ways to do things that were solved in the last couple of centuries. This project will focus on historic mechanisms that will make students think both about how these mechanisms work and about where they can be employed in design. The educational goal is to help students expand their knowledge and think outside the box.

Cornell University has begun a project with a similar agenda called KMODDL (Kinematic Models for Design Digital Library). Their project focuses on the establishment of an online resource containing digital representations of many Kinematic Models. The models are displayed through photographs, selected video and in certain instances CAD (Computer Aided Design) models and templates for 3D (three dimensional) printing. These digital representations continue to expand the number of people who can access these models. Additionally, the work on 3D printing mechanical models is very exciting because it allows for the dissemination of physical models as an educational aid around the world via the internet.

While the portion of the KMODDL project focusing on the dissemination of models is very logical, certain aspects of the fabrication method present some difficulty. The technique of using 3D printing assembled models has certain inherent compromises in it. The material used is required to be layered plastic, and as such is inherently weaker than solid material and acts as a less efficient bearing surface. We propose an alternative fabrication method suitable to 2D (two dimensional). This enables manufacture with a laser cutter or waterjet and provides a cheaper fabrication method with a wider selection of usable materials. The models could be more robust and like the 3D models could be shared around the world via the web. A potential downside to this manufacturing choice is the increased complexity of manufacturing and assembly. However, the educational goals of this project make the somewhat more complex manufacturing and assembly a key component to the advancement of student knowledge.

Mechanisms from several different categories have been selected for study, including ratcheting mechanisms, partial gears, and rotary-to-linear mechanisms. Many of the selected mechanisms have been modeled using SolidWorks and the CAD models have been animated. Mechanical analysis of torque and force capacities as well as kinematic analysis of each mechanism have been performed and presented in an easy to understand format. Finally, the mechanisms have been manufactured using readily available materials and techniques and displayed in the Pappalardo Laboratory where students can interact with them.

Mechanism Selection Process:

Selecting the mechanisms to be studied in this project grew out of a visit to the Boston Museum of Science. During this visit, all of the models in the Clark Collection were both photographed and videotaped in motion. The magnitude of the challenge for choosing the mechanisms became clear after discovering that there were more than one hundred different objects in the collection. It had been decided that the focus should be on general mechanisms, and therefore, the engine and water pumping sections were dismissed. Given that the mechanisms were selected based on their educational value, it seemed wise to establish a concrete set of criteria with which to evaluate them. This task seemed well suited to the use of a Pugh Chart where a table is created with different models on one axis and attributes on the other. The attributes chosen to measure the mechanisms were whether they seemed: novel, useful, "make you think" and are manufacturable. The first three criteria focused on the educational goal of the project and the fourth was a nod to feasibility, particularly given the goal of the project to fabricate the models in 2D. Each model was rated from zero to three in each category. A selected section of the Pugh chart is shown as an illustration below and the entire Pugh chart is included appendix A.

Name	Novel (0-3)	Useful (0-3)	Makes You Think (0-3)	Manufacturability (-1, 0, 1)	Total
Inclined Plane	0	3	0	1	4
The Lever	0	3	0	1	4
The Screw	0	3	1	-1	3
Belt Drives	2	2	1	1	6
Chain Drives	0	2	1	0	3
Slotted Connecting Rod & Treadle Drive	2	1	2	0	5
Slotted Bell Crank Drive	2	1	2	0	5
Slotted Yoke Drive	3	2	2	0	7
Universal Joints	1	3	1	-1	4
Out Of Line Drive	1	2	1	-1	3

Figure 1: Section of Pugh Chart Used For Model Selection, Highlighted Models Were Selected

In this subsection two items score six or higher. The belt drives and slotted yoke mechanisms that scored higher were given more consideration during the selection process. Examination of the mechanisms that scored highest on the criteria led to the development of themes that encompassed similar mechanisms. As themes came together during later research, certain other mechanisms from 507 Mechanical Mechanisms by Henry Brown that had not been fabricated for the Clark Collection were also selected as they fit in very well with the established themes.

History of Significant Mechanisms:

The focus of this project is to uncover educationally relevant and practically useful mechanisms from the past that are still significant and useful today. Given the extreme age of most of the mechanisms covered in this project, there is a large amount of uncertainty about exactly when or how many of these mechanisms were first invented. Following are the best estimates of the historical appearance of the four types of mechanisms examined in detail in this project: pulley, gear, ratchet, and slotted yoke.

The Pulley:

The simplest of the mechanisms, the pulley, is also the earliest mechanism to have been used. Although there is a strong similarity between the wheel and the pulley, the wheel has been used for transportation since before 3000 BC while the development of the pulley remained unseen for still quite some time (Lilly 6). It is known that pulleys were not used on ships by the Egyptians or for major construction projects such as the pyramids where they would have been useful for hoisting. Instead during the construction of the pyramids, rollers were used as small wheels for pushing the blocks up ramps. The first documented use of a pulley is in an Assyrian relief in the eighth century BC, raising the question of exactly why the seemingly simple transition from wheel to pulley took so long to achieve (Lilly 27). It appears that the development of the pulley from the wheel was not as simple as one might guess.

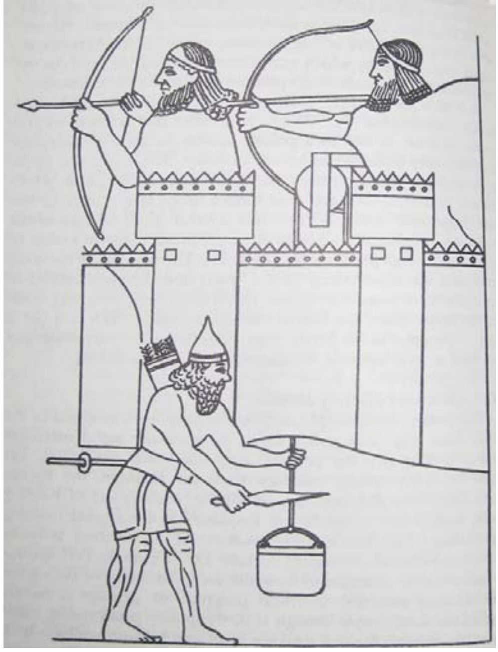


Figure 2: Assyrian Relief Showing a Pulley (Lilly 28)

While one explanation for the delay has involved the transition from the Bronze Age to the Iron Age and the improved material properties of iron versus bronze in the development of the pulley, this does not seem like a satisfactory answer since wooden pulleys are valuable and must have been used prior to metal pulleys. Furthermore, it seems that using wooden pulleys would be an essential step before making the jump to metal pulleys that are much harder to fabricate.

Be it as it may, the pulley has been a mainstay of mechanical mechanisms and has been around for almost three millennia, having been used continuously during this time for all sorts of machines and making an enormous impact on construction machinery. As shown in Figure 3, a major advantage of using pulleys is that they can be arranged with differing diameters to create mechanical advantage.

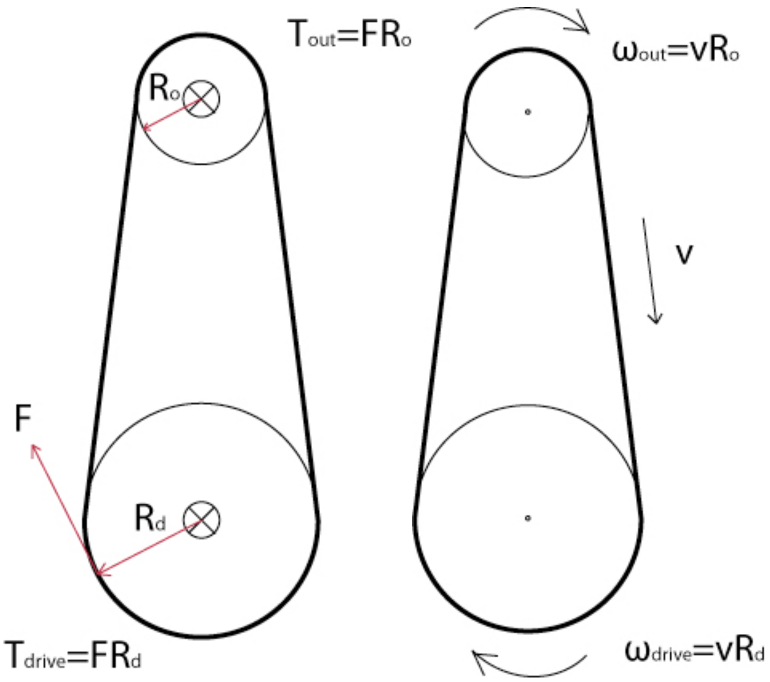


Figure 3: Torques and Velocities of two pulleys of differing sizes

Since the force exerted by the cable between the top and bottom pulley must be the same mathematically, the inputted torque and angular velocity can be related to the output torque and angular velocity as seen in equation 1 and 2.

$$\tau_{out} = \tau_{drive} \cdot \frac{R_d}{R_o} \tag{1}$$

$$\omega_{out} = \omega_{in} \cdot \frac{R_o}{R_d} \tag{2}$$

This ability to vary the output torque and angular velocity creates mechanical advantage and is one of the reasons that pulleys are such an important technology.

Gears:

Historically, the second mechanism of interest to this project to be developed appears to be the gear. Again, this invention is a development of the wheel but for a slightly different purpose with a new unique feature. Similar to pulleys, gears allow for power transmission between axles, but have the additional capacity to create well-defined speed and torque ratios between different axles. Although this coordination can be achieved with pulleys, the addition of gears insures extremely tight tolerance. The teeth on a gear, unlike the flat surface of a pulley, geometrically constrain the rotation, enabling exact ratios of rotation, a fact that made gears indispensable in the invention of highly precise timepieces. In addition, the teeth on the gears allow for greater torque transfer without slipping, another advantage over pulleys.

Gears are thought to have come into use sometime before 87 BC. This date comes from the significant archeological find of an old ship located off the coast of Anti-Kythera, a small island lying between Crete and mainland Greece in the 1900's. Found aboard were the remains of an intricate "calendrical computer with remarkably complex trains of bronze gear wheels" (Cardwell 22). It is pictured below.

Figure 4: Ancient Bronze Gear Salvaged Off the Coast Greece (Williams 67)

Although it was very corroded by the millennia under the sea, it was concluded after study that "Whatever its purpose there can be no question of the immense practical skill and clear understanding of the kinematics of gearing that it reveals" (Cardwell 23).

The intricate and sometimes bizarre methods of gearing employed in the partial gears that are explored in this project may not have been invented quite as early as described in the previous paragraph. Nevertheless, it is likely that they followed relatively quickly, because partial gears allow for additional control and flexibility over conventional gear systems.

Gears are probably the most widely used of any of the mechanisms covered in this project. They are ubiquitous and integral to everything from cars to timepieces and power tools.

The Ratchet:

The ratchet follows the progression from gears and appears when the profile of a gear is altered to allow for driving in only one of the two rotary directions. The ratchet is usually used with a pawl, a finger-like device that prevents turning in one of the two directions. Although documentation of the development of the ratchet has not received the same scrutiny as the gear and the pulley, a ratchet falls into the same category as a gear. For example, in a find dating from between 400 - 700 AD of parts of a Byzantine sundial calendar, a ratchet is pictured along with other bronze gears although it receives no mention in the text.

Figure 5: Byzantine sundial calendar with Ratchet from 400 – 700 AD (Williams 68)

Although this find is not conclusive, it likely provides an indicator of the ratchet’s development demonstrating that the ratchet seems to have been in use by the time of the Byzantine sundial calendar.

Ratchets are used in a wide array of devices and systems. They appear in the ratcheting socket driver, many screw drivers, winches and other devices. They provide one of the most effective ways to limit rotary motion to a single direction and as such are quite indispensable.

Slotted Yoke or Scotch Yoke:

The most mysterious in origin of the mechanisms studied here is the slotted yoke, one of many mechanisms used to convert rotary motion into oscillating linear motion. The slotted yoke has very little written about it and as such the inventor or inventors as well as date of first introduction appear to have been lost in history. One of its first appearances is in 507 Mechanical Movements by Henry Brown published first in 1868 where it and other variations are illustrated.

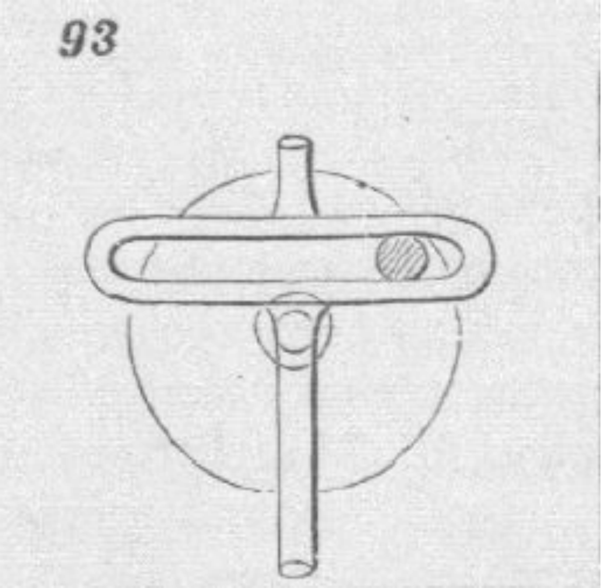


Figure 6: Slotted Yoke Schematic as Illustrated in 507 Mechanical Mechanism from 1868 (Brown 28)

Given the fact that the slotted yoke is one of a large number of mechanisms that convert rotary to oscillating linear motion, it is not as indispensible and therefore not used as widely as the other mechanisms that are part of this project. However, the slotted yoke is used in various pumps and also has been used as part of certain shear cutting machinery and certain engines, most notably the automobile engine the SyTech developed by CMC research in Australia. The SyTech engine boasts smaller dimensions, lower weight and reduced Noise Vibration Harshness (NVH). Additionally, if offers the possibility of better emissions and fuel economy although those claims have yet to be proven (Edgar).

Collections of Mechanisms

Clark Collection of Mechanical Movements:

Figure 7: Picture of Clark Collection in the Museum of Science

The main collection that influenced this project is the Clark Collection of Mechanical Movements located in the Museum of Science in Boston. The museum has on display over one hundred functioning models built by William Clark in the 1900's based primarily on the book by Henry T. Brown, 507 Mechanical Movements (KMODDL, Clark Collection).

Reuleaux Collection of Mechanisms and Machines at Cornell University

Named after the mathematician and mechanical engineer Franz Reuleaux, the Reuleaux Collection at Cornell consists of 219 models, most of which were acquired by Cornell's first president, Andrew White. Pictured below is an illustration of the Reuleaux collection on display at Cornell (Moon).

Figure 8: Illustration of Cornell's Reuleaux Collection, Cornell University Sibley School of Mechanical Engineering from Scientific American, 1885 cover (Taimina)

At one time there were over 800 models designed and made by Franz Reuleaux. However, many of the original models were destroyed in Germany during World War II. The main fabricator of the Reuleaux models was the German company Gustav Voight Mechanische Werkstatt in Berlin (KMODDL, Reuleaux Collection).

Kinematic Models for Design Digital Library (KMODDL) – Cornell University:

Cornell University has worked to digitize some of the collections of mechanical models both in its possession and from elsewhere creating an online archive and resource for Cornell students as well as students and other visitors from around the world. This collection includes works both from the Clark Collection and the Reuleaux Collection of models. It has 3D CAD models for 3D printing of selected models. Below is an example of the still imagery that can be accessed.

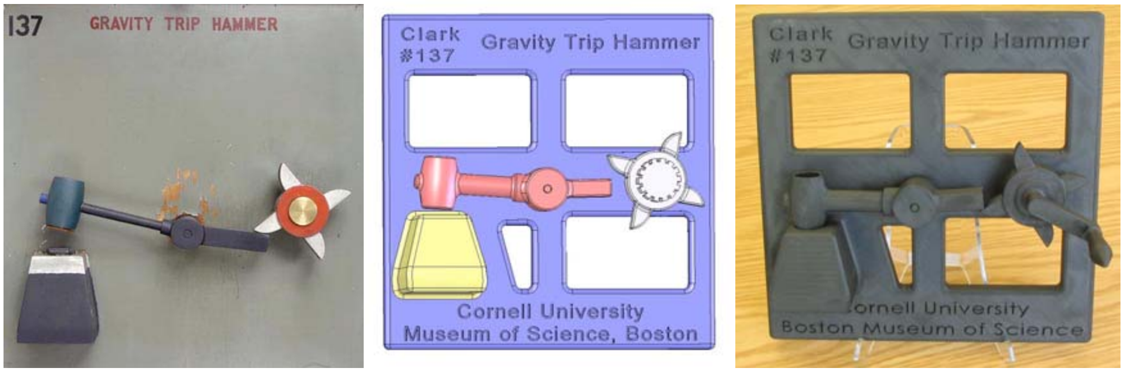


Figure 9: From left to right photograph of model, CAD model, and 3D printed model (KMODDL Gravity Trip Hammer)

Additionally, there are also videos and photographs for almost every model. As part of the project, many of the original literary works on which the models were based have been digitized and posted for free on the website as well (KMODDL).

Design and Manufacturing Terminology and Methodology:

A goal of this project was to facilitate the ability to share and learn from significant mechanisms from the past with models available through online designs. This was made possible through CAD (computer aided design) and CAM (computer assisted manufacturing) described below. Two important fabrication technologies, laser cutting and 3D printing, are also described below.

CAD (computer aided design) is the method of drafting that has become ubiquitous in an era of computers. It allows the user to create 2D and 3D models for engineering and design purposes. Digital assemblies of parts can be very useful in design and engineering for visualization and simulation. The value is enhanced by a large range of analytical tools that allow the user to model stresses, deformations or motions of a part or an assembly when subjected to a force. The widespread use of CAM (computer assisted manufacturing) has greatly increased the value of creating CAD models. Not only does a CAD model often greatly help with the engineering and design, but it can now also be invaluable in creating a prototype.

CAM (computer assisted manufacturing) refers to manufacturing work pieces by using computer designs and then using a wholly or partially computer operated tool to bring that design into the form of a physical object.

The 3D-printer is a relatively new technology that allows for the computer-aided manufacturing of full 3D objects. There are virtually no limits on the form that can be made using a 3D printer. Instead, it is the material that is limited. Unlike a milling machine or lathe which can be used with many materials, a 3D printer usually can only use one type of material. 3D printers are exceptionally good at making mockups for presentations or displays.

A laser cutter is a 2D cutting machine. The raw material is placed on a flat bed and a moving laser print head focuses a CO_2 laser on a specific section of the material. Movement of the laser head allows almost any shape to be cut. Laser cutters can also used for etching by decreasing the depth of cut. They can cut or etch wood, cardboard, acrylic, and certain other non-toxic plastics as well as etch glass and a large variety of metals.

Project Development, Design and Fabrication:

Design Process & Goals:

The design process began as the selection process came to completion. The four major themes had been chosen and specific mechanisms had to be designed and created that would contribute to the new models' educational value and ease of dissemination. From these two goals, four main criteria arose: first, the models should be above all else simple; second, that there should be a meaningful color legend; third, that all designs be compatible with fabrication in two dimensions; and finally, that every model be accompanied by documentation for the viewer. These goals were designed to address perceived shortcomings in the work being done in the Clark Collection and KMODDL, the online design library.

Although the Clark Collection is a wonderful resource and truly captivating for people of all ages, it requires that the viewer of the exhibit figure out exactly how the mechanisms work with very little guidance from the exhibit itself. Many people stand and look in awe at the mechanisms with no idea what is happening. Even with my education and engineering knowledge, I found myself working hard at understanding, staring and then carefully trying to evaluate what was going on with the particular object exhibited. The questions that would arise over and over again were: what element in the model is being driven? Why are certain things certain colors and other things different colors? As a result, I designed the mechanisms with the following key criteria.

The first criterion was to eliminate complexity in design that did not directly contribute to the theme of the individual mechanism. The mentality of simple design affected my selection process in that models that incorporated many different themes were dismissed in favor of those that showed only one concept at a time.

A second design goal was to ensure that color was incorporated strategically. Color would be used to help the viewer to understand what parts were being driven by a motor or hand crank and what parts instead were moving as result a of power transmitted between parts.

In an effort to address the shortage of information about each model, short descriptions were written about each mechanism briefly mentioning its history, use and importance, as well as explaining its mechanical operation. Finally, all designs were created for fabrication with 2D CAM tools, in particular, a laser cutter. Each design was set up in discrete layers, such that it can be manufactured from stacked layers of acrylic, a robust and easily available plastic. The layered acrylic design serves three main purposes: it keeps costs low, it is quite strong, and finally, it can be easily fabricated around the world using any laser cutter and computer connected to the internet, providing access as an educational tool.

The design process began by reviewing the selected models through photographs, videos and in person and by sketching out potential configurations that remained true to the motion and constraints of the mechanism but only required 2D cuts. The next step was to begin the process of digitization where the hand drawn designs were built up in 3D using SolidWorks.

Fabrication and Analysis

3D Modeling Using Solid Works

Solid models were built keeping the general scale similar between models. The models were built completely except for those that required gears. SolidWorks, unfortunately, does not support simple fabrication of gear teeth as a function within it. As a result, the models' design in SolidWorks for those models with teeth kept the fundamental geometry but without the individual gear teeth which were added later.

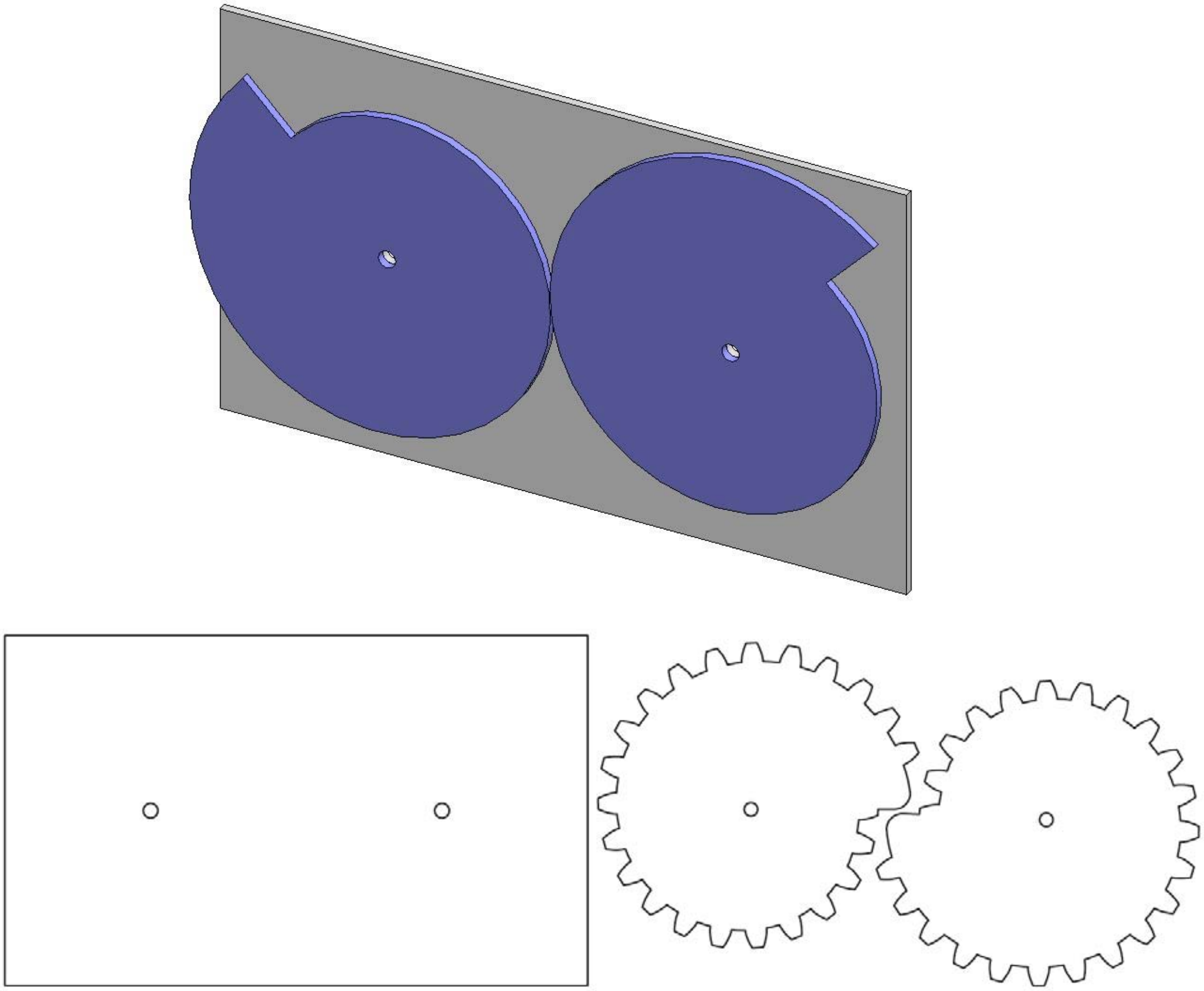


Figure 10: SolildWorks model of spiral gear compared with final drawing

After creating the SolidWorks models, two different operations were conducted in parallel: analysis of the mechanism in an appropriate manner for that mechanism and the creation of cut files for fabrication.

Readying CAD Models For Laser Cutting

Each CAD model created in SolidWorks required additional formatting to prepare it to be cut out of an acrylic sheet. The process began by creating an assembly drawing within SolidWorks that included each unique part used in that particular model. The drawing was cleared of all center marks for holes, dimensions, and sheet formatting and then exported as a DXF file. The DXF files were then opened up in Adobe Illustrator where their parts were organized in a space efficient manner for cutting and any elements of the assembly that were used in a quantity greater than one were duplicated.

At this phase of the process the teeth for the gears were added to the cut files. This was accomplished in two parts. First, a simple free online gear generation tool, part of a woodworking website created by Mathias Wandel, was used (Wandel). These files were only available as a PLT file which became an unfortunate intermediate step requiring an additional conversion to generate DXF files out of them. This conversion was accomplished with Total CAD Converter 1.01 and from there the DXF files were incorporated with the Adobe Illustrator cut layout files. Then, the gears were fitted to the geometry required for the model. For certain models it was as simple as cutting away unwanted sections of teeth, but for the spiral gear, individual placements of sections of teeth to fit the curve of the spiral were required.

Laser Cutting

With the files formatted correctly and the requisite parts for each model in place the files are ready for cutting. The laser cutter used for this project was a Universal V460 60W laser Although the final material used was acrylic models were prototyped first in sheet cardboard. Laser cutter power and speed settings for the cardboard were 100% and 12% respectively. When cutting acrylic the speed was reduced to1.5% of its maximum. A cardboard prototype of the Three Diameter Gear is shown below.

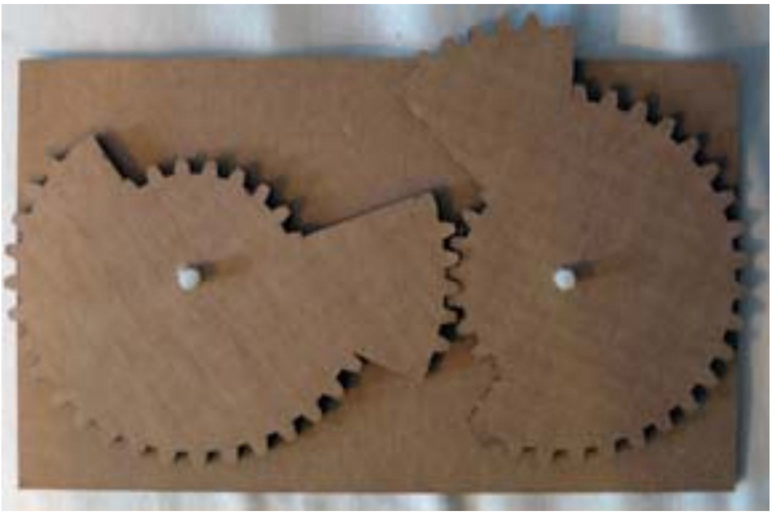


Figure 11: Cardboard prototype of Three Diameter Gears

With a working cardboard model to demonstrate the feasibility of the design, the model was next made out of acrylic. Figure 12 shows an acrylic model midway through laser cutting.

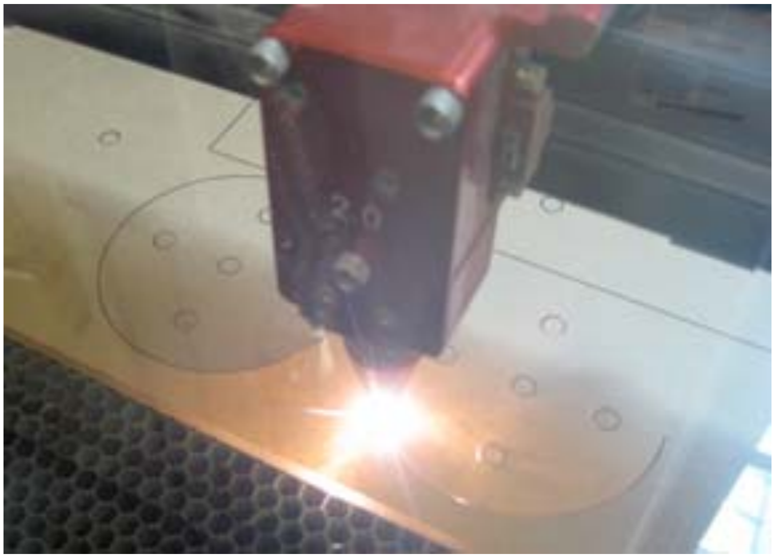


Figure 12: Cutting of Acrylic in the Laser Cutters

The protective coating on the acrylic was removed after laser cutting and the models were assembled.

Assembly:

The models were specifically designed for relatively simple assembly. Delrin rod (0.25" diameter) was fit for the axles and pins that hold each layer of the model together. Depending upon the element of the design, either the through holes were made to be slightly tight for press fit or slightly loose to allow for free rotation. After testing different press and loose fits, it was found that pressing into a hole of 0.244" diameter worked well while a 0.26" diameter hole made an effective bearing diameter. At every rotary interface a small Delrin washer was inserted to create a lower friction bearing surface. Additionally, where needed to prevent the Delrin rod from moving axially, E-clips were fitted to the ends of the rod.

CAD Analysis

For the Slotted Yoke model, dynamic analysis using CosmosMotion, a feature of SolidWorks, was performed. The analysis focused on the motion of the slotted yoke, and the relationship between the angular position of the driving wheel and the horizontal displacement of the yoke. Within CosmosMotion it is possible to track relative displacements with respect to time by creating an animation of the motion using a constant speed motor within SolidWorks and then recording the relative displacement.

Hand Calculation

For the majority of the models the complexity of mating geometry caused analysis in SolidWorks to be of greater complexity and difficulty compared to working out the results by hand. Therefore, for all but the slotted yoke, the fundamental kinematics and structural aspects were examined and solved analytically without SolidWorks.

Results

Full Collection

The full collection created for this project is displayed below. Each individual mechanism will be further discussed in detail.

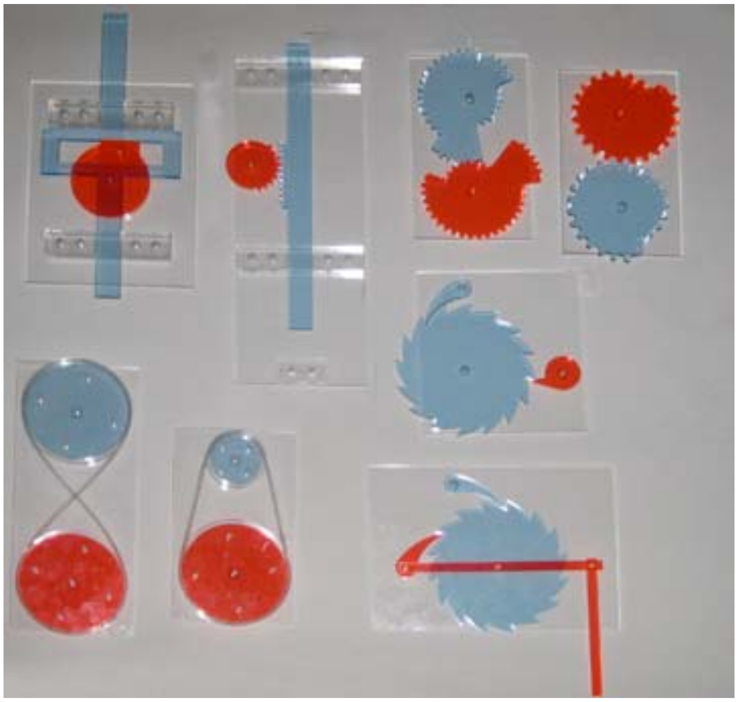
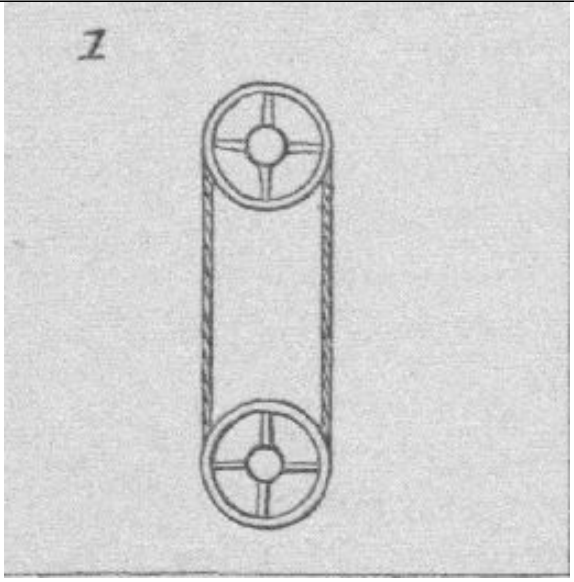
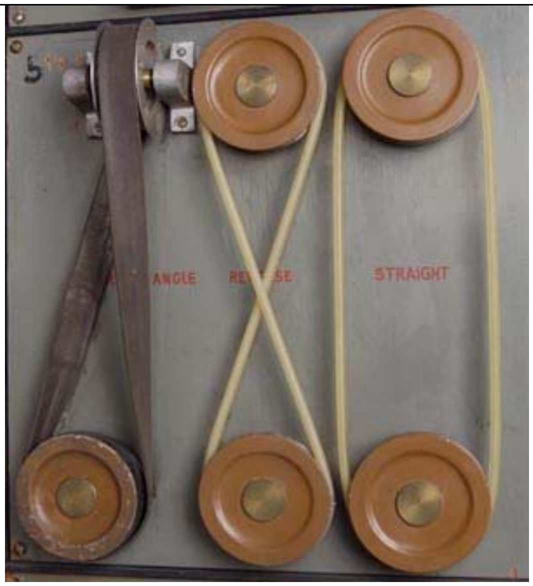


Figure 13: Displayed In This Image Is the Full Color Laser Cut Collection

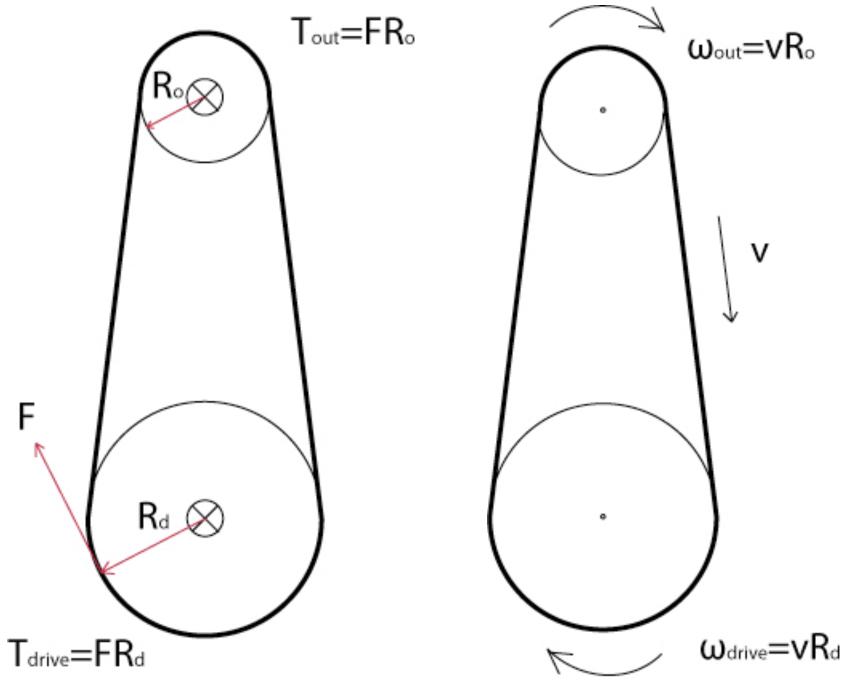
Mechanisms on Display

Each of the mechanisms and its summary as displayed for examination by students is presented below. It will be noted that each model has a blue and red section which allows the viewer to follow what is happening between the driving and driven elements of the mechanism when it is motorized in a display.

Straight Pulley

507 Mechanical Movements	**Clark Collection**
	
KMODDL Printed	**MY MODEL**
NA	

The pulley is a technology that has been around since at least the 8th century BC and came into existence as a development from the wheel. Most importantly, it is used for the transmission of power between two axles. Pulleys are a mainstay of machines and are used in every sort of device. In this model the larger pulley is twice the diameter as the smaller pulley.



Torques and Velocities of two pulleys of differing sizes

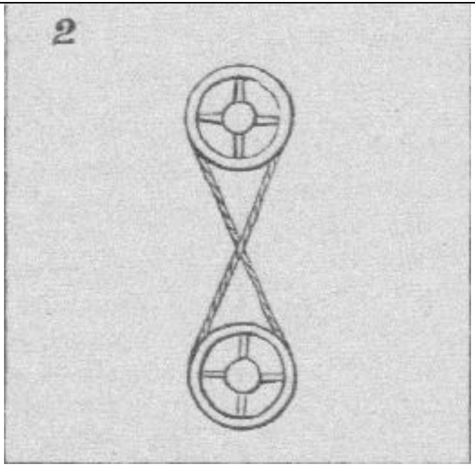
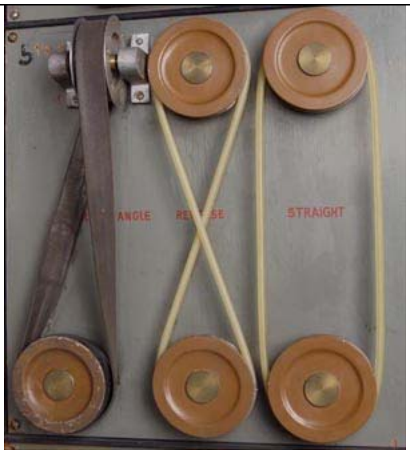
Since the force exerted by the belt between the top and bottom pulley must be the same mathematically, the inputted torque and angular velocity can be related to the output torque and angular velocity as seen in the following equations.

$$\tau_{out} = \tau_{drive} \cdot \frac{R_d}{R_o}$$

$$\omega_{out} = \omega_{in} \cdot \frac{R_o}{R_d}$$

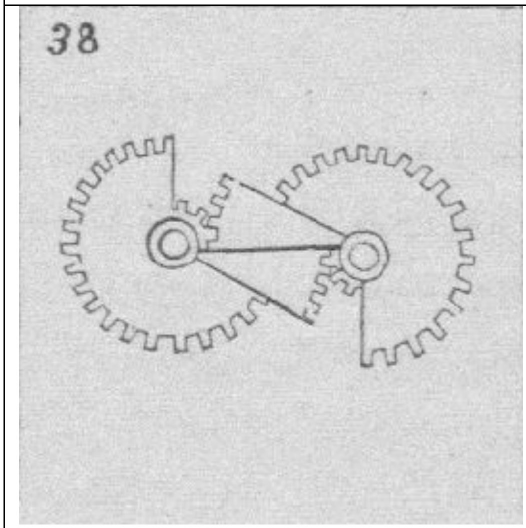
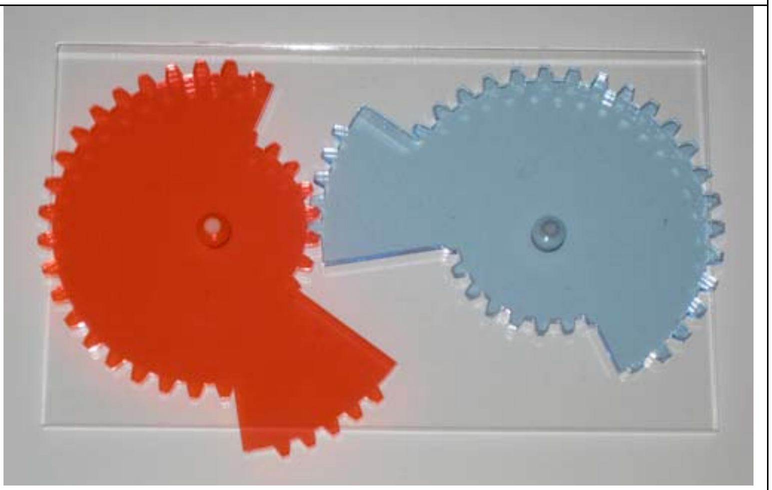
This ability to vary the output torque and angular velocity creates mechanical advantage and is one of the reasons that pulleys are such an important technology. For this example the torque felt on the small upper pulley is half of that produced at the larger one with a corresponding increase in angular velocity of a factor of two at the driven (blue) pulley

Crossed Pulley (See Straight Pulley for more information)

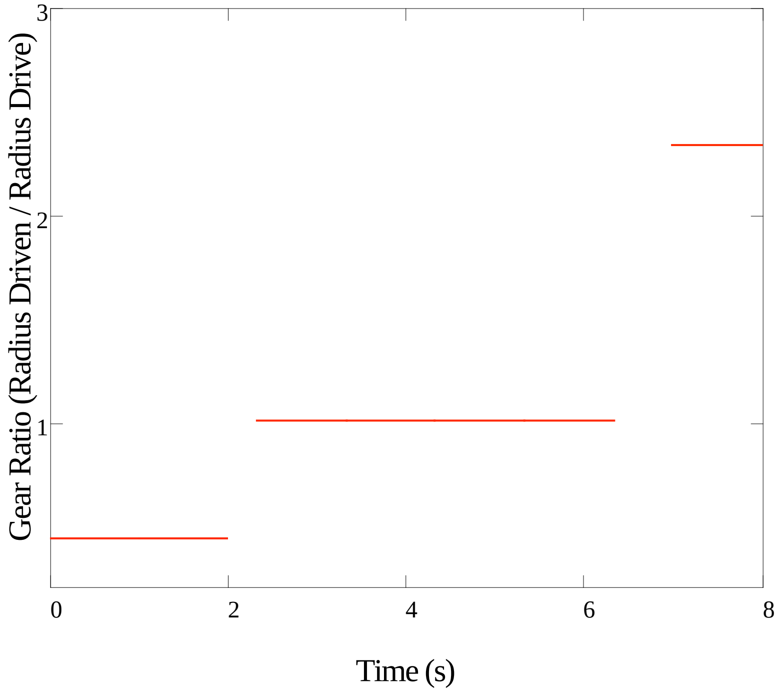
507 Mechanical Movements	**Clark Collection**
	
KMODDL Printed	**MY MODEL**
NA	

The crossed pulley is a particular way of connecting two axles creating two different directions of angular motion between them. Tracing out a figure eight with the line that connects the two different pulleys causes the output pulley to rotate in the opposite direction from the driven pulley. The threading of the line does not exclude the ability to create a mechanical advantage between the two axles as is present in the straight pulley.

Three Diameter Gear

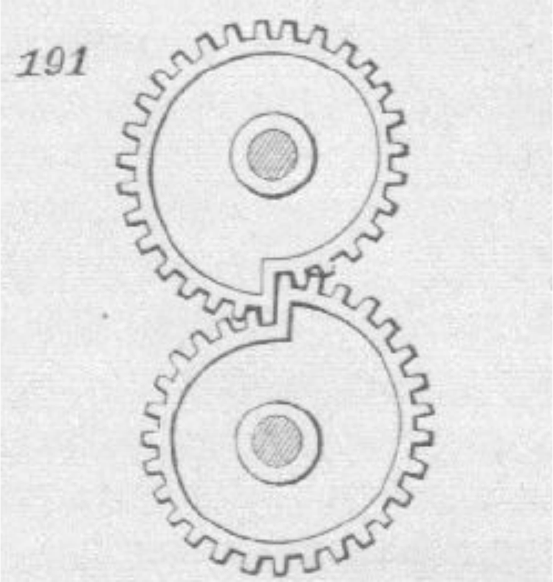
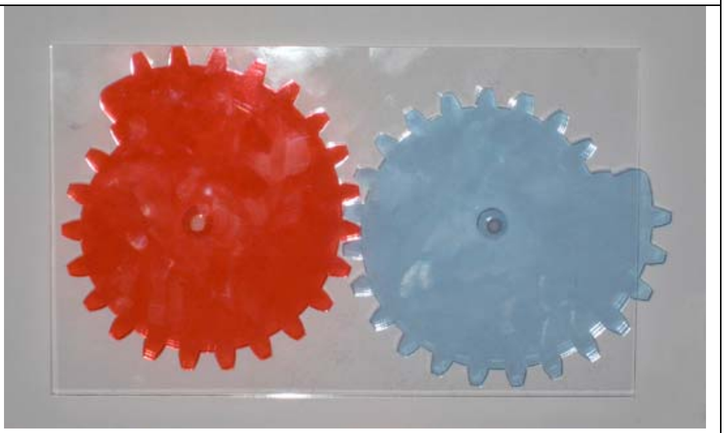
507 Mechanical Movements	**Clark Collection**
	**NA**
KMODDL Printed	**MY MODEL**
NA	

The gear is known to have been in existence in 87 BC based on evidence from an archeological find off the coast of Greece. The gear enables power transmission between different axles with selectable gear ratios. Although most people are familiar with simple circular gears, there are many additional geometric configurations that create interesting different types of motion. In the Three Diameter Gear the distinct three separate gear ratios cause the driven gear to rotate with three different relative angular velocities and relative torques. This is illustrated in the graphically below in a figure showing relative gear ratios during each cycle of the Three Diameter Gear.



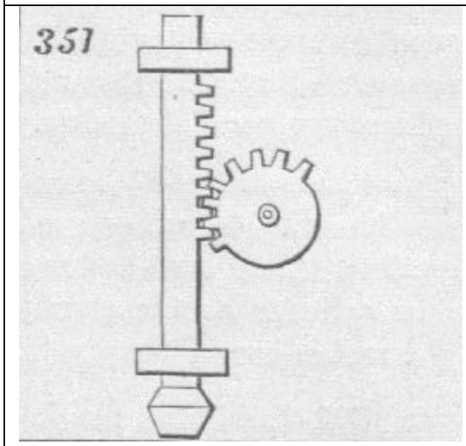
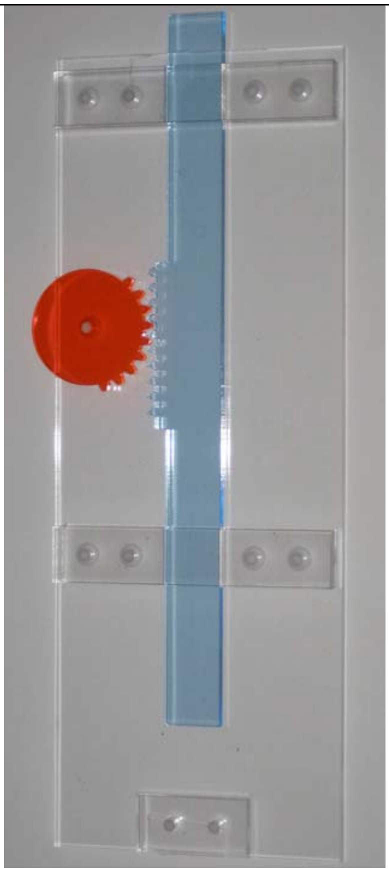
Gear ratio for Three Diameter Gear Over an 8 Second Cycle

Spiral Gear (See Three Diameter Gear for background)

507 Mechanical Movements	**Clark Collection**
	**NA**
KMODDL Printed	**MY MODEL**
NA	

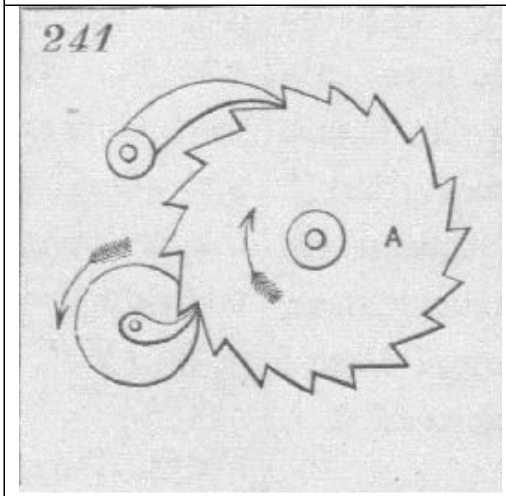
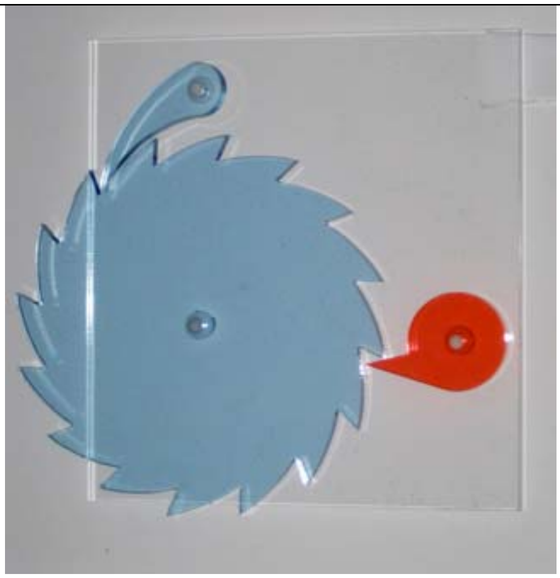
The spiral gear, is similar to the three diameter gear, in that it creates a variable gear ratio that depends on the position of the two gears. Unlike the Three Diameter gear, the gear ratio shifts slowly from one extreme to the other with a single sharp discontinuity once per rotation. Spiral gears are unidirectional since at the discontinuity of diameters they can disengage if driven clockwise. The spiral gear produces motion that most contemporary engineers would design using a computer or microprocessor yet can also be generated mechanically through geometry. Even in the age of computers and microprocessors, mechanical systems are preferable for some applications in order to remove complexity and increase robustness. Techniques like this can be used for a range of designs. For instance, a spiral gear could be very useful for a lifting arm where the greatest torque is needed when the arm is horizontal and the torque requirements decrease as the arm rises.

Gravity Stamp (See Three Diameter Gear for background)

507 Mechanical Movements	**Clark Collection**
	
KMODDL Printed	**MY MODEL**
	

The gravity stamp uses two interesting gearing techniques. First, it uses a rack and pinion where a circular gear drives a mating linear gear converting rotary motion to linear. The second involves the use of a partial gear, in which the gear is in contact only for a portion of each revolution. This approach can be used as it is here to define different regions which then have different actions or in the case where full rotation is not needed, to reduce size or cost.

Rotary Ratchet

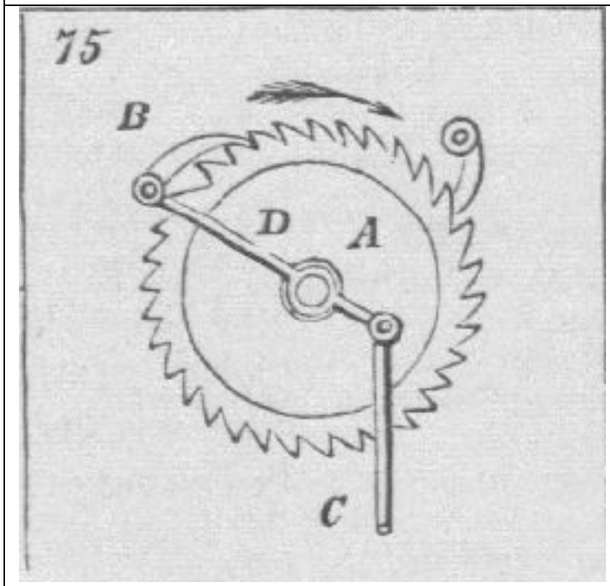
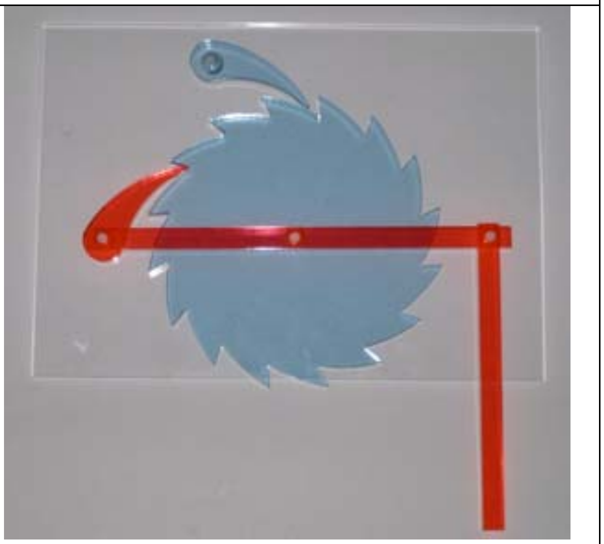
507 Mechanical Movements	**Clark Collection**
	
KMODDL Printed	**MY MODEL**
	

Ratchets, developed as a subset of both gears and the wheel, are known to have been in existence since at least 700 AD. They use an asymmetrical gear design and a pawl (a specialized cam) that restricts motion to only one direction making them an indispensible mechanism for design. The ratchet is driven by a small single toothed asymmetric gear and its back rotation is prevented by the pawl at the top, which is kept in position by gravity. An important consideration when using or designing ratchets is backlash, the fact that the ratchet will be able to be back driven a small amount before the pawl is stopped by one of the teeth. The maximum backlash will be a fraction of 360 degrees based on the number of teeth.

$$\theta_{backlash} = \frac{360}{n}$$

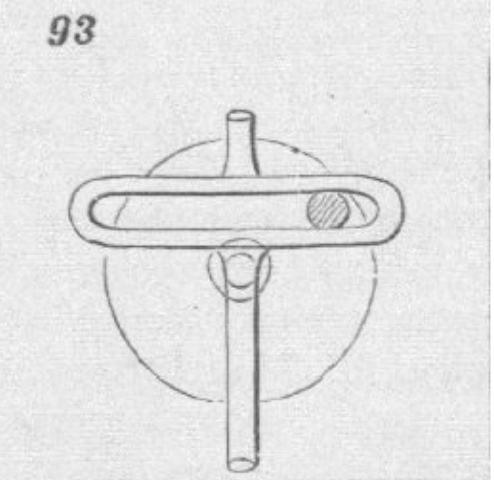
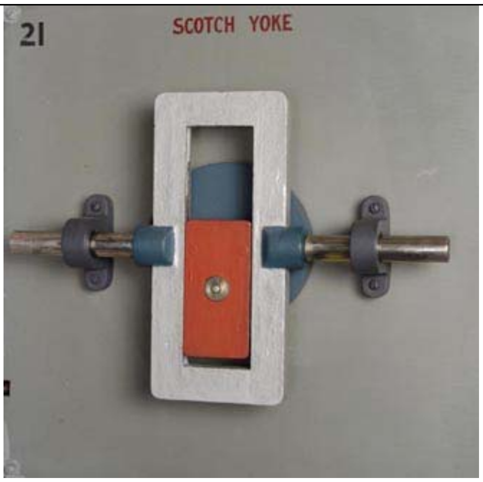
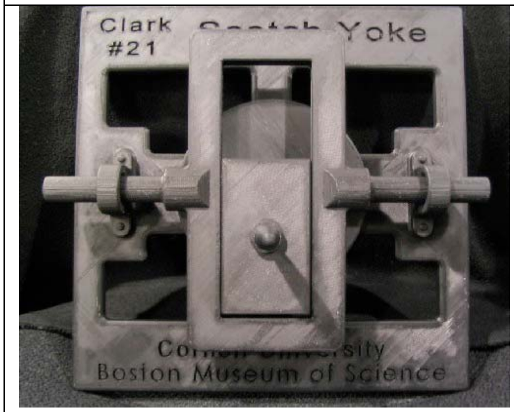
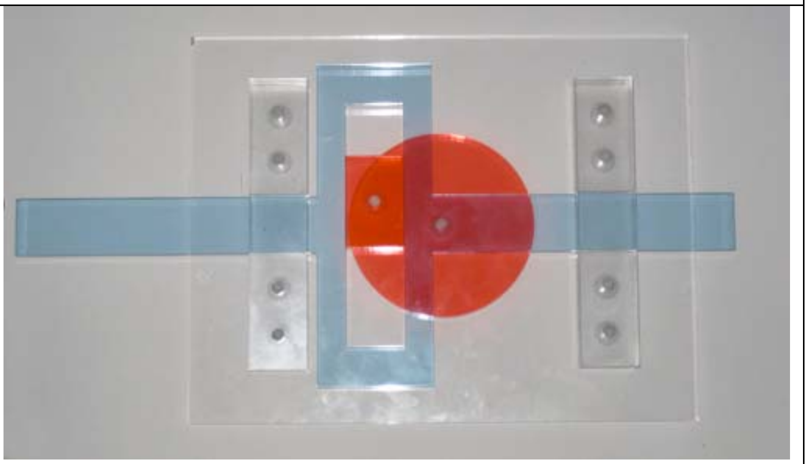
For the sixteen toothed ratchet in this model the backlash will at most be 22.5 degrees.

Oscillatory Ratchet (Rotary Ratchet for Background)

507 Mechanical Movements	**Clark Collection**
	
KMODDL Printed	**MY MODEL**
	

The oscillating ratchet uses an oscillating linear input to create an intermittent rotary motion. Unlike the rotary ratchet the oscillatory ratchet uses a pawl as the driving mechanism. As the linkage is moved down and the driving pawl moves up, it rotates the ratchet gear. When the linkage then is moved up causing the pawl to move down, it slides over the teeth of the ratchet gear which in turn is prevented from rotating backwards by the second pawl at the top. The oscillatory ratchet also uses gravity to keep the pawls in contact with the ratchet itself.

Slotted Yoke

507 Mechanical Movements	Clark Collection
	
KMODDL Printed	**MY MODEL**
	

The Slotted Yoke or Scotch Yoke is a type of mechanism from the family of mechanisms that convert rotary motion into oscillating linear motion. For the Slotted Yoke the driven circle moves a cam that drives the yoke to slide back and forth. Varying the relative size of the drive and mount location of the cam allow the motion of the yoke to be adjusted.

Analysis for different components

The analysis conducted on the models for this study focused on two major areas: kinematics of the design and failure modes. For each of the different themes of the study; namely pulleys, gears, ratchets and the slotted yoke, this type of analysis was conducted.

Pulleys:

For pulleys the kinematics of the design are quite simple, as laid out in the History of Significant Mechanisms section. Simple mechanical advantage can be established by using pulleys of differing diameters. The crossed pulley creates the very useful kinematic result of creating a different direction of rotation of the driven wheel with respect to the drive wheel.

Pulleys typically fail in one of three simple ways. The first is most easily understood qualitatively. It is the disengagement of the pulley belt with the wheel. This situation can most easily occur when there is a time of varying tension on the belt causing the belt to potentially slacken and skip out of the groove of the pulley. The second failure mechanism of the pulley is a loss of static friction between the pulley wheel and the belt and occurs when the frictional force is smaller than the force generated at the pulley by the torque it is transmitting.

$$F_{\max} = \mu \cdot 2T \tag{3}$$

In equation (3) μ is the coefficient of static friction between the belt and the pulley surface. From the max force we can easily calculate the maximum torque.

$$\tau_{\max} = F_{\max} \cdot R_{pulley} \tag{4}$$

If we take for example a tension of 20 N and a coefficient of friction between the pulley wheel and belt of 0.3, then we conclude that the max force possible to transmit is 12 N, and the maximum torque for the small pulley is 0.914 Nm and for the large pulley is 1.829 Nm.

For this reason it is necessary when designing pulleys to be aware of the maximum force capabilities. In order to circumvent the problem, it is possible to create a hybrid between a gear and pulley. A technique that is frequently used is to employ a belt that has notches and pulley wheels that have mating teeth to constrain motion further.

The final failure mechanism of the pulley is one that is applicable to every model used in this project, the possibility of shearing off the drive axle. This will occur if the force exerted on the pulley exceeds the maximum shear strength of the axle holding it in place.

$$F_{shear\_fail} = \sigma_{shear\_strength} \cdot area \tag{5}$$

For the models built with 1/4” Delrin axles the failure in shear should occur at around 2000 N.

Ratchets

Ratchets allow for unidirectional movement. Driven in one direction they rotate freely except for the small force taken to pass under the pawl. When driven in the other direction, they lock up, intertwined with the pawl. Although ratchets are able to create unidirectional movement, they do so in a discrete rather than continuous manner that is defined by the number of teeth that the ratchet has. It is only as each tooth passes the pawl that a portion of the rotational motion becomes fixed. As a result, there is always an opportunity for backlash in which a small amount of backward slippage occurs as a torque opposite to the drive motion is applied. The maximum magnitude of this backlash is given in equations (6) and (7) where θ is the angle of backlash, n is the number of teeth, L is the linear distance of backlash, and r is the radius of the ratchet.

$$\theta_{backlash} = \frac{2\pi}{n} \tag{6}$$

$$L_{arclength\_backlash} = \frac{2\pi \cdot r}{n} \tag{7}$$

For the ratchets of this model, which have 16 teeth, the maximum backlash is 22.5 degrees or an arc length of 3.0 cm. Therefore, it is very important to consider the effects of the maximum potential backlash when incorporating the use of ratchets in a design. Although conventional ratchets inherently have backlash, it is possible to create a ratchet without backlash. This is achieved by using a pawl and a toothless ratchet with extremely high friction coefficient between the outer surface and the tip of the pawl. As the ratchet is back driven, the friction prevents sliding and the geometry constrains the system. The disadvantage with this design is that the holding force against back rotation is typically much less than with the toothed ratchet.

The mechanisms for failure of a ratchet involve the mechanical failure of either the teeth of the ratchet or the axle of the ratchet depending upon their relative sizes and materials. The calculation for the maximum force before shear occurs in the axle was calculated above for the pulley and can be applied to the ratchet as well. An alternative possibility for failure is that a tooth of a ratchet is ripped off when it becomes locked during loading. For this calculation the shear at the base of the tooth can be calculated using equation 5 just as for the shear on the axle. For the modeled ratchet made of acrylic, the teeth are much stronger than the axle. Thus, we find that it would take over 10 kN of force to shear off a tooth while it would only take about 2 kN to shear off the axle. Another potential failure point of the ratchet is the buckling or bending of the pawl. While this can be calculated, the complex and changing geometry requires this to be calculated on an individual ratchet basis and can be calculated with a FEA (finite element analysis) software package.

Gears

Gears constrain two rotating axles to interact with a fixed mechanical advantage. This mechanical advantage gives rise to a multiplicative factor relating the relative angular velocity and torques of the two axles, which are inversely proportional. Hence, as the torque is increased through the gearing, the velocity must decrease. The mechanical advantage or gear ratio is defined in the same manner as that for the pulleys, mentioned earlier in equations 1 & 2. The gears used in this project are not the norm, and hence, it is worth examining the unique motion that they produce. The three diameter gear is special because it has three different gear ratios depending on the position of the gear during its rotation. This theoretically creates a piece wise defined function for the gear ratio between the two different gears. Given gears with radius 1.5”, 2” and 3.5” with sections of 105 degrees, 210 degrees and 45 degrees, we find a gear ratio which varies with time across one 8 second period.

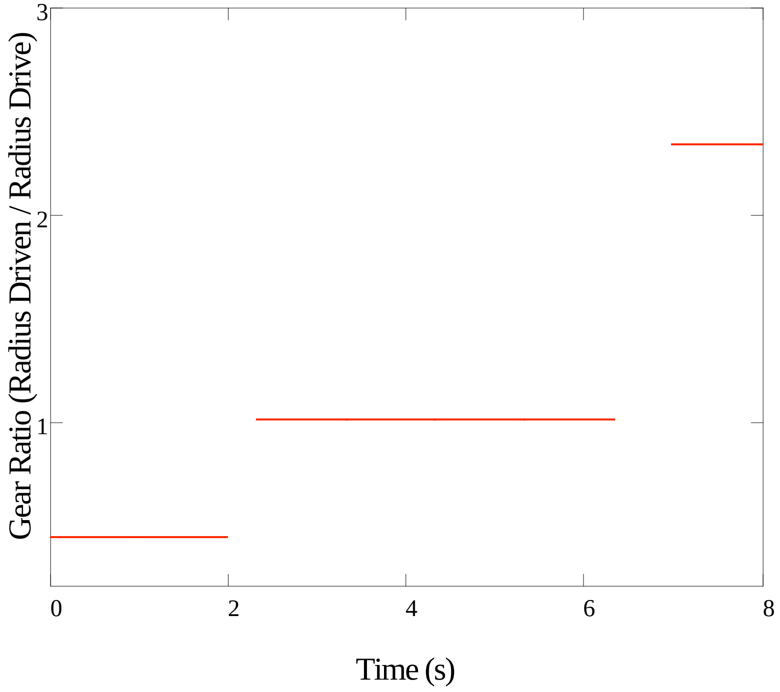


Figure: 14: Gear ratio for Three Diameter Gear Over an 8 Second Cycle

It is also possible to calculate the relative angular velocity of the driven gear from the driving gear and that allows the angular velocity to be plotted. This figure shows the driving gear powered at an angular velocity of one revolution, 2π radians, per 8 seconds (0.78 rad/s).

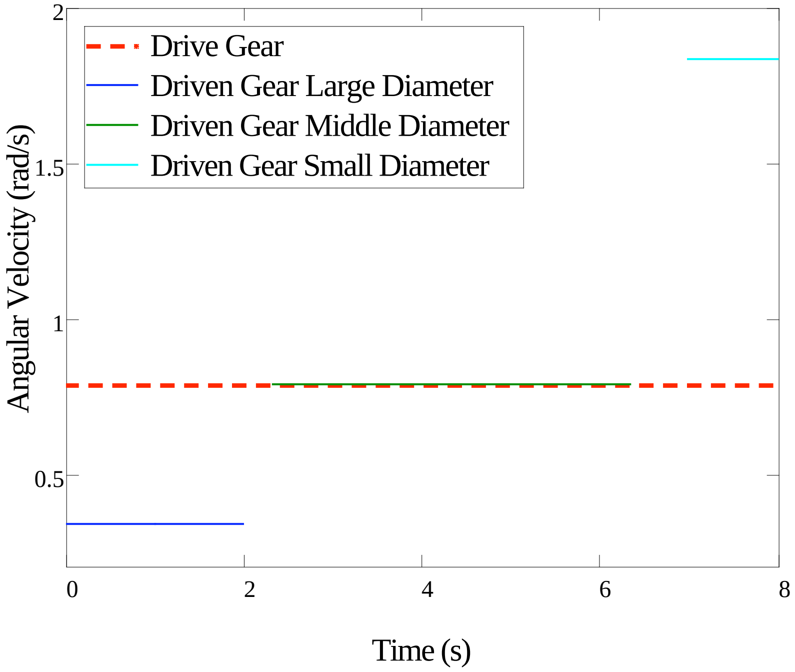


Figure: 15 Angular velocity for Three Diameter Gear Over an 8 Second Cycle

The torque can be related from the drive gear to the driven gear in a similar fashion, as displayed in figure 16. For this analysis we assume a torque imparted to the drive gear of 10 Nm. For the torque output it is obvious that there is an inverse relationship between the torque and the angular velocity.

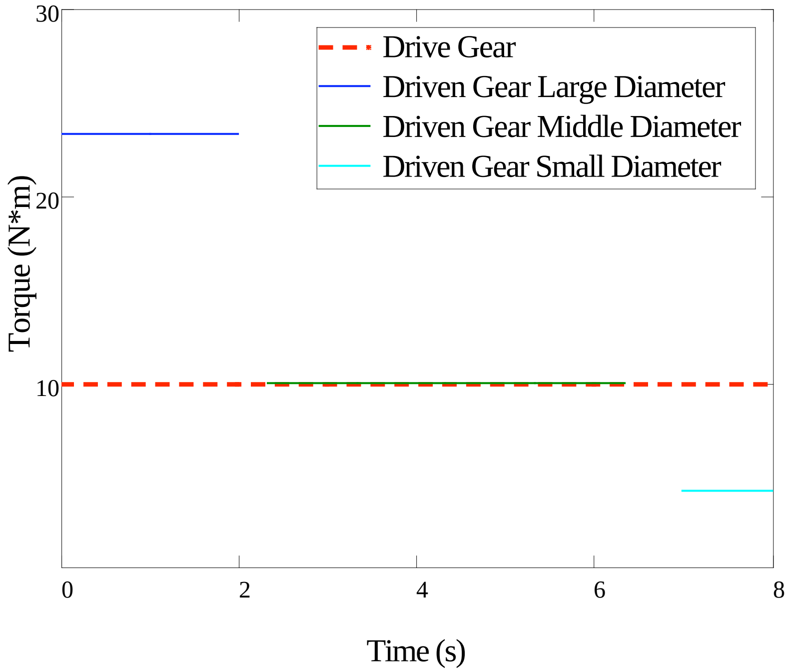


Figure: 16: Torque for Three Diameter Gear Over an 8 Second Cycle

In the same way that the gear ratio, relative angular velocity and torque were calculated for the Three Diameter Gear, similar calculations can be made for the spiral gears. Here we see that unlike the three diameter gear which is piecewise defined, we generate instead a smooth curve with only a discontinuity at the end of the spiral once each revolution.

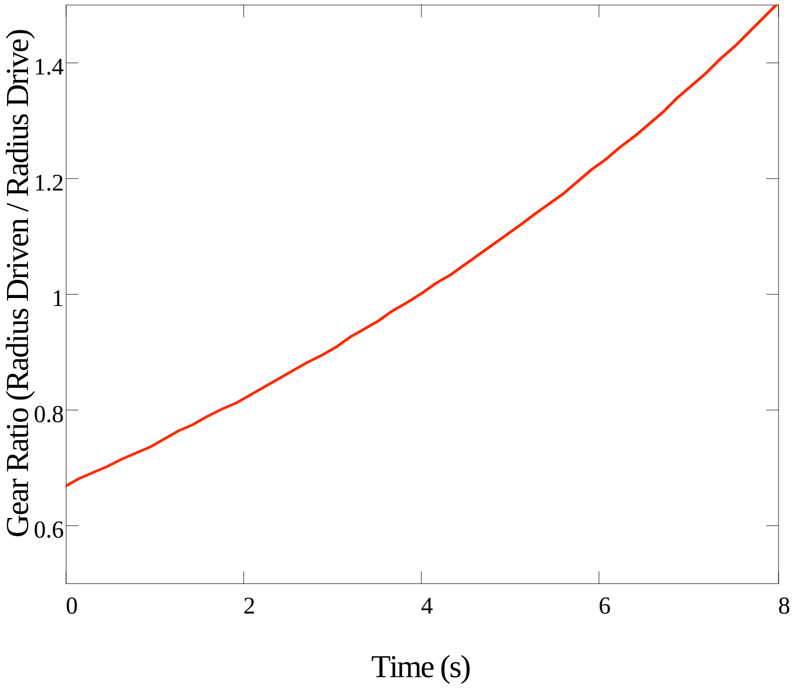


Figure: 17: Gear ratio for Spiral Gear Over an 8 Second Cycle

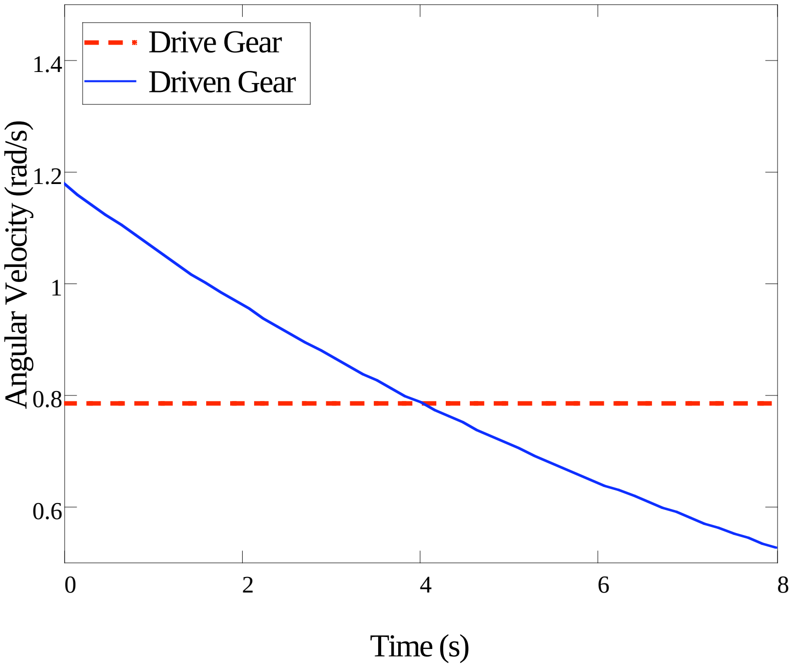


Figure 18: Angular velocity for Three Diameter Gear Over an 8 Second Cycle

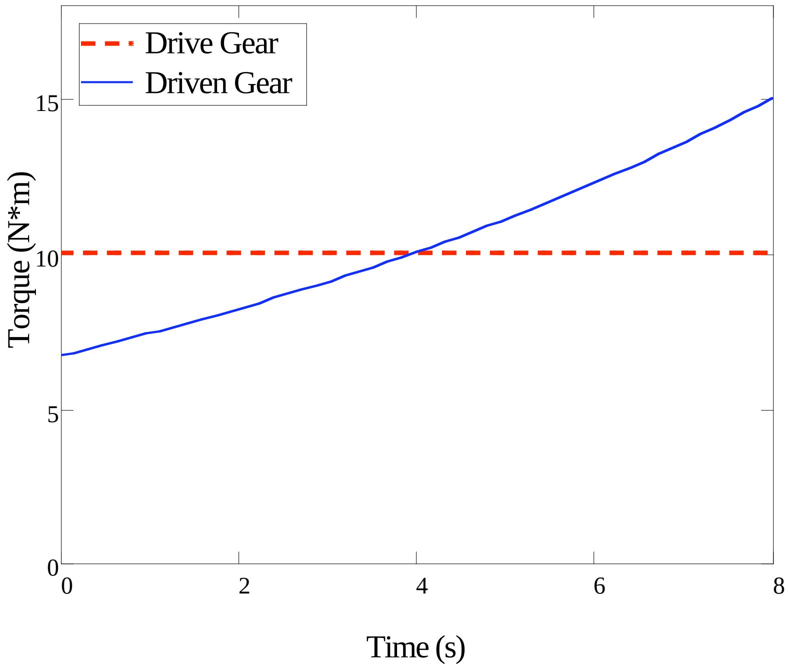


Figure: 19: Torque for Three Diameter Gear Over an 8 Second Cycle

An important design consideration of the gears used is potential backlash built into the gear system. This will determine amount of backlash that occurs when the direction of rotation is changed. The calculation for backlash of a gear, unlike that of the ratchet, is dependant not entirely on geometry but also on the manufacturing tolerances. As such, it is a more complicated process to calculate it. Given that low tolerance is correlated strongly to high manufacturing cost, it is useful to determine what level of backlash is acceptable since the more relaxed this constraint, the cheaper the design will become.

Gears can fail similarly to ratchets. They can have a tooth ripped off but unlike the ratchet where the geometry is relatively simple, most gears have more complicated geometries that require analysis done with FEA. Finally, since the gears are attached via axle, just as the pulley and the ratchet could fail if the shear becomes too great, so can the pulley.

Slotted Yoke

The slotted yoke’s function is to convert rotary motion to oscillating linear motion and as such the relationship between angular position and displacement of the yoke is of great importance. As cam of the slotted yoke is driven around by the wheel it is mounted on, the yoke is pushed back and forth. Plotted below is the horizontal displacement of the yoke versus the angular displacement.

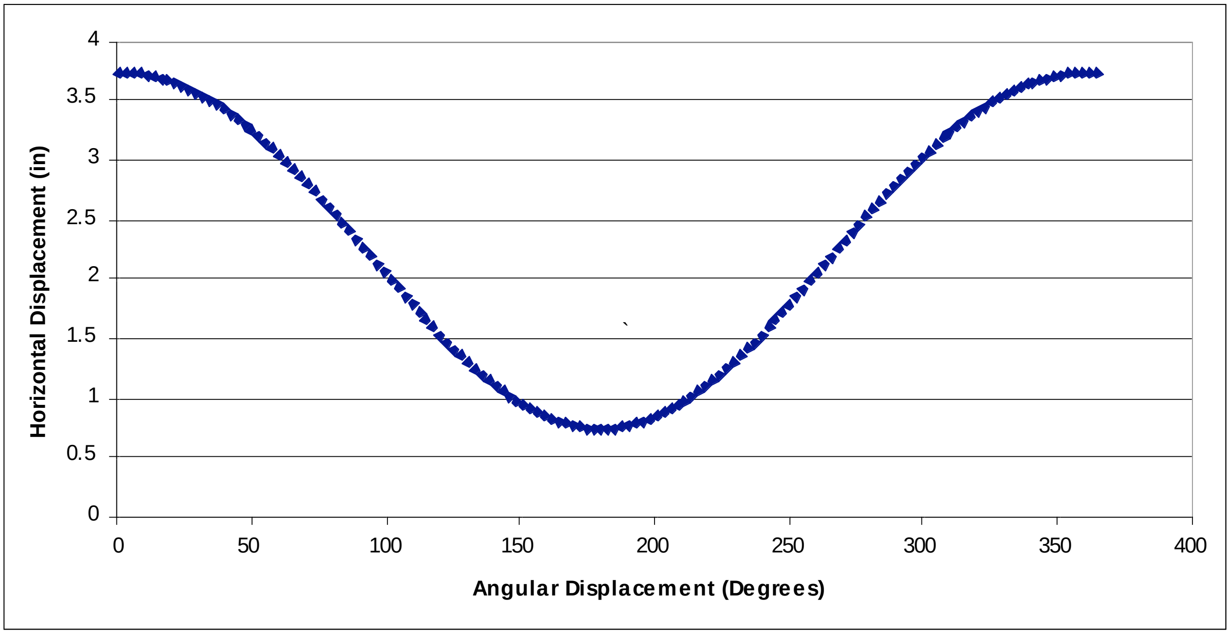


Figure 20: Relationship Between Angular Displacement and Horizontal Displacement of Slotted Yoke

It is interesting that this can also be viewed in a completely different manner by processing the data in a parametric manner relating angle to displacement. A defined closed form is produced which can be read to show all the possible states of the slotted yoke.

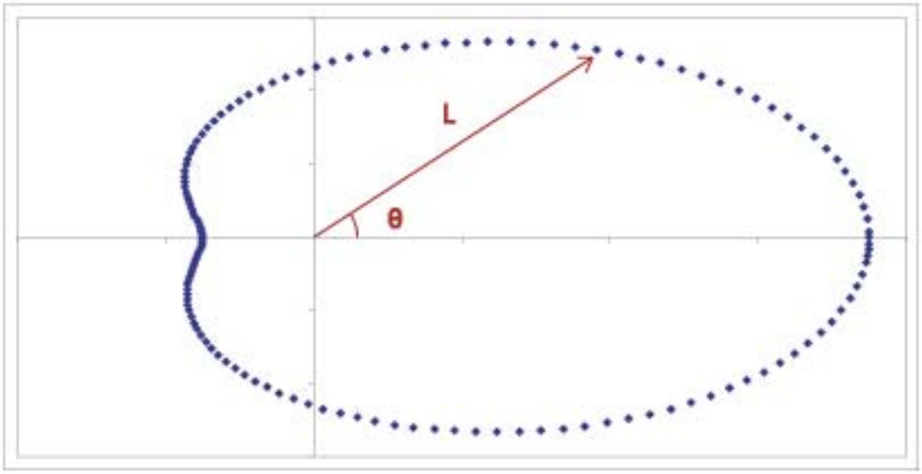


Figure 21: Possible Physical States of Slotted Yoke

For a given angle, θ, the corresponding displacement, L, is read out by measuring the length from the origin to the same point. It can also be read in opposite direction by creating a circle of a given radius and then determining which possible angles are feasible.

The failure mechanisms of the slotted yoke were not examined as closely as with the other mechanisms. It is clear that the cam axle can shear off in the same manner as the pulley or gear.

Conclusion

The most important goal of this project was to increase the dissemination of these useful teaching models from the Clark Collection in the Boston Museum of Science, and with the inexpensive fabrication method of laser cutting, this was proven feasible. The models now are inexpensive enough to be made in large quantities so that many students can have the opportunity to examine them without a trip to the Boston Museum of Science. The two secondary goals of this project were to enhance the educational value of the models and to facilitate simple and cheap fabrication. First, let us evaluate the fabrication. An initial fear involved in fabricating with a 2D limited CAM device was that the final models would be lacking. Fortunately, although the designs required alterations to be fabricated in 2D, that factor did not restrict the choice of many of the possible designs from the Clark Collection and the 507 Mechanical Movements nor did it disrupt any of the main themes of each model. The ability to stack 2D cut parts and assemble them into working useful models proved to be a great success for the project. The advantages of using the laser cutter were as positive as expected. Additionally, as expected, fabrication out of acrylic proved to be robust as well.

It was possible to make the models extremely inexpensively at around three hundred dollars for all eight models including cost of materials and laser cutter time. Assembly took approximately four hours and was not included in the cost estimate since time for assembly is considered an educational advantage of this approach. The total cut time for all eight models encompassed by this project was about one hour, and. materials cost (McMaster-Carr, Inc) was approximately one hundred twenty five dollars.

The cost advantage of the 2D laser-cut approach becomes more impressive when we compare the cost of laser cutting to that of 3D printing. Both are quite expensive to use, but the significantly shorter time requirements (1 hour for all 8 models) result in a total cost of fabrication of about forty dollars per model (Pololu) in this project. In contrast, the print time for many of the 3D models manufactured for KMODDL was more than forty hours (Lipson). As a specific example, the 3D printing cost for the Stamp was found from two different quotes to be at least eight hundred dollars (APP and Shapeways), which makes the cost of fabricating eight models as done in the present work prohibitively expensive. Therefore, we succeeded in greatly reducing the cost to manufacture simple educational mechanical models so that wide dissemination to undergraduate institutions and perhaps even secondary schools is feasible.

The second goal of this project was to enhance the educational value of the models. This challenge was approached from three different directions: a consistent use of color to denote how the model was driven, the addition of educational text summary to accompany the model and cheap manufacturing costs to promote dissemination. The addition of color was very successful. It is simple now to distinguish where the power enters the models and which parts are being driven as a result. The context of the textual summary helps to give the necessary theory and history to engage with the models for a wide range of audiences. Finally, the dissemination of this project is now substantially easier given its low cost and limited requirement for materials and tools.

There is still more work to be done to fully complete this project. First, given time constraints only a select number of models were made. There are hundreds more that would be interesting to fabricate. Second, transforming the individual models into a more complete museum like exhibit within MIT is an important part of making this project more widely accessible to students. Our intention is to make a display case in the near future to show the models in the Pappalardo Laboratory. Third, it would be interesting to do a research study comparing the educational effectiveness of the three different collections of mechanical mechanisms studied in this project: the Clark Collection, KMODDL and the 2D laser cut collection design for this project.

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Appendix

Appendix A

Name	Novel (0-3)	Useful (0-3)	Makes You Think (0-3)	Manufacturability (-1, 0, 1)	Total
Inclined Plane	0	3	0	1	4
The Lever	0	3	0	1	4
The Screw	0	3	1	-1	3
Belt Drives	2	2	1	1	6
Chain Drives	0	2	1	0	3
Slotted Connecting Rod & Treadle Drive	2	1	2	0	5
Slotted Bell Crank Drive	2	1	2	0	5
Slotted Yoke Drive	3	2	2	0	7
Universal Joints	1	3	1	-1	4
Out Of Line Drive	1	2	1	-1	3
Out Of Line Drive	1	2	1	-1	3
Scotch Yoke	2	2	2	0	6
Eccentric Drive	2	1	1	1	5
Eccentric Drive	1	1	1	1	4
Eccentric Drive	2	2	2	1	7
Pulley Lifts	0	3	1	0	4
Cone Pulleys	2	2	1	0	5
Straight Line Drive	3	2	1	0	6
Multiple Straight Line Drive	3	2	1	0	6
Straight Line Motions	1	2	1	0	4
Rotary Into Rectilinear Motion	2	2	2	1	7

Variable Speed and Reverse Drive	3	1	2	-1	5
Ratchet Lift					0
Reciprocating Rectilinear Motion	2	2	1	0	5
Ratchet Wheels	1	3	1	1	6
Ratchet Wheels and Drivers	2	2	2	0	6
Geneva Movement	2	2	1	0	5
Continuous Rotary Into Intermittent Motion	3	1	1	0	5
Wave Wheel	2	2	2	-1	5
Oscillating Into Intermittent Circular Motion	?	?	?	?	0
Square Gears	2	1	1	1	5
Elliptical Gears	2	1	1	1	5
Reverse From Rotary Motion	3	2	2	0	7
Crown Wheel and Pinion	1	1	0	-1	1
Worm and Gear	0	3	1	0	4
Miter and Bevel Gears	2	2	1	-1	4
Worms and Gears	1	2	1	-1	3
Swash Plate Gears	3	1	2	-1	5
Variable Reciprocating Movement	2	1	1	0	4
Reverse Motion	3	1	2	-1	5

Sewing Machine	1	1	1	-1	2
Automobile Engine Starter					0
Universal Joint					0
Auto Timer and Distributor					0
Multiple Disk Clutch					0
Multiple Gear Drive	3	1	3	0	7
Lazy Tongs Motion	1	3	1	0	5
Old Oaken Bucket					0
Bailing or Lifting Scoop					0
Balance Pump					0
Force Pump	1	3	1	-1	4
Overshot Water Wheel					0
Vertical Paddle Propeller Wheel					0
Bailing Press	1	3	0	0	4
Gravity Trip Hammer	2	2	1	0	5
Gravity Drop Ore Stamp	2	2	2	0	6
Gravity Drop Hammer	2	2	1	0	5
Pile Driver					0
Rotary Conveyor					0
Trunk Type Engine					0
Oscillating Cylinder Engine					0
Oscillating Piston Engine					0
Double Quadrant Steam Engine					0
Elliptical Gear Engine or Pump					0
Horizontal Slide valve Engine					0

Figure A1: Pugh Chart of Mechanisms from Clark Collection Certain Mechanisms Unrated If Off Theme

Appendix B -Sheet Layouts for Cutting

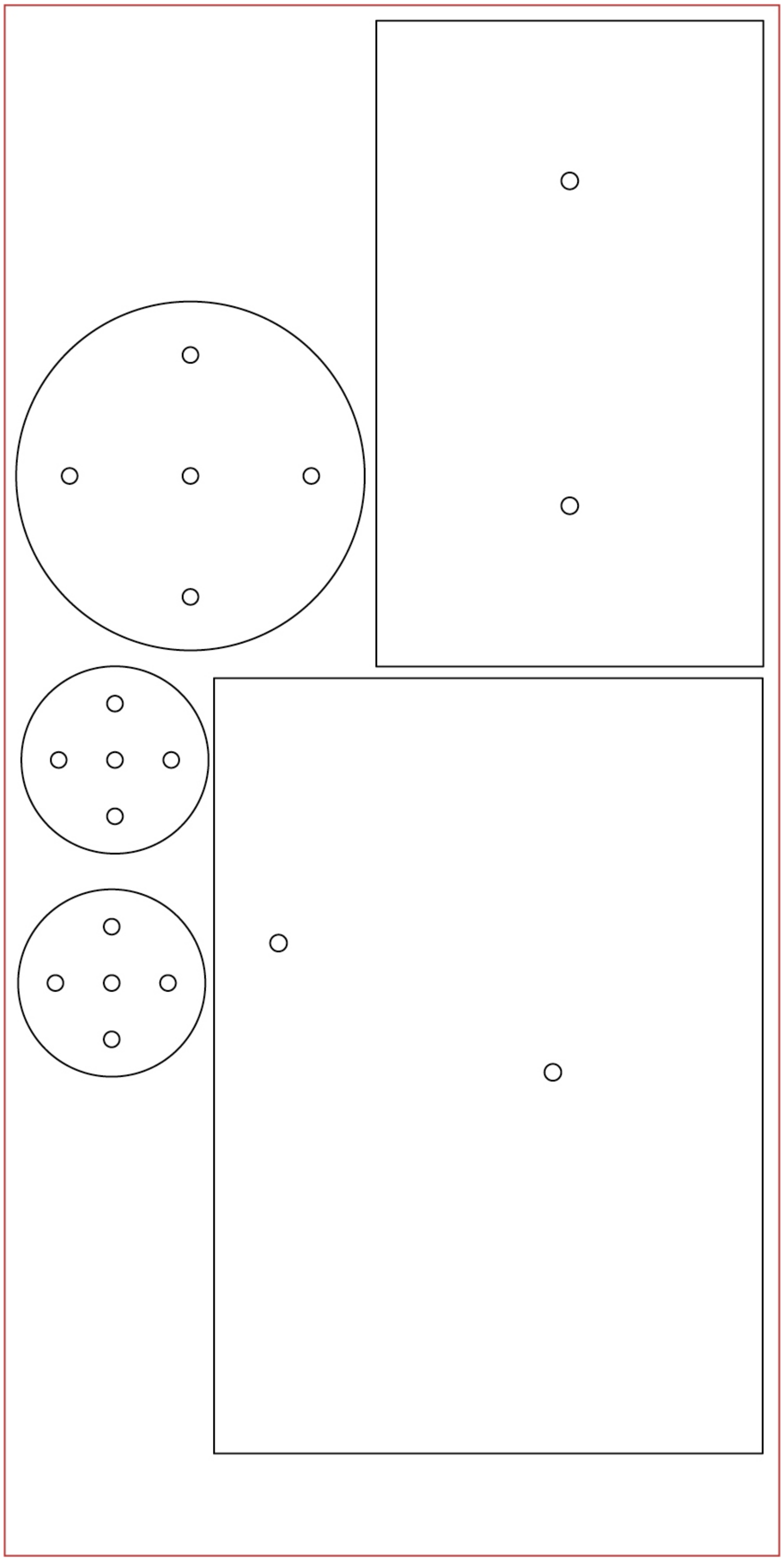

Figure B1: Clear Sheet 1

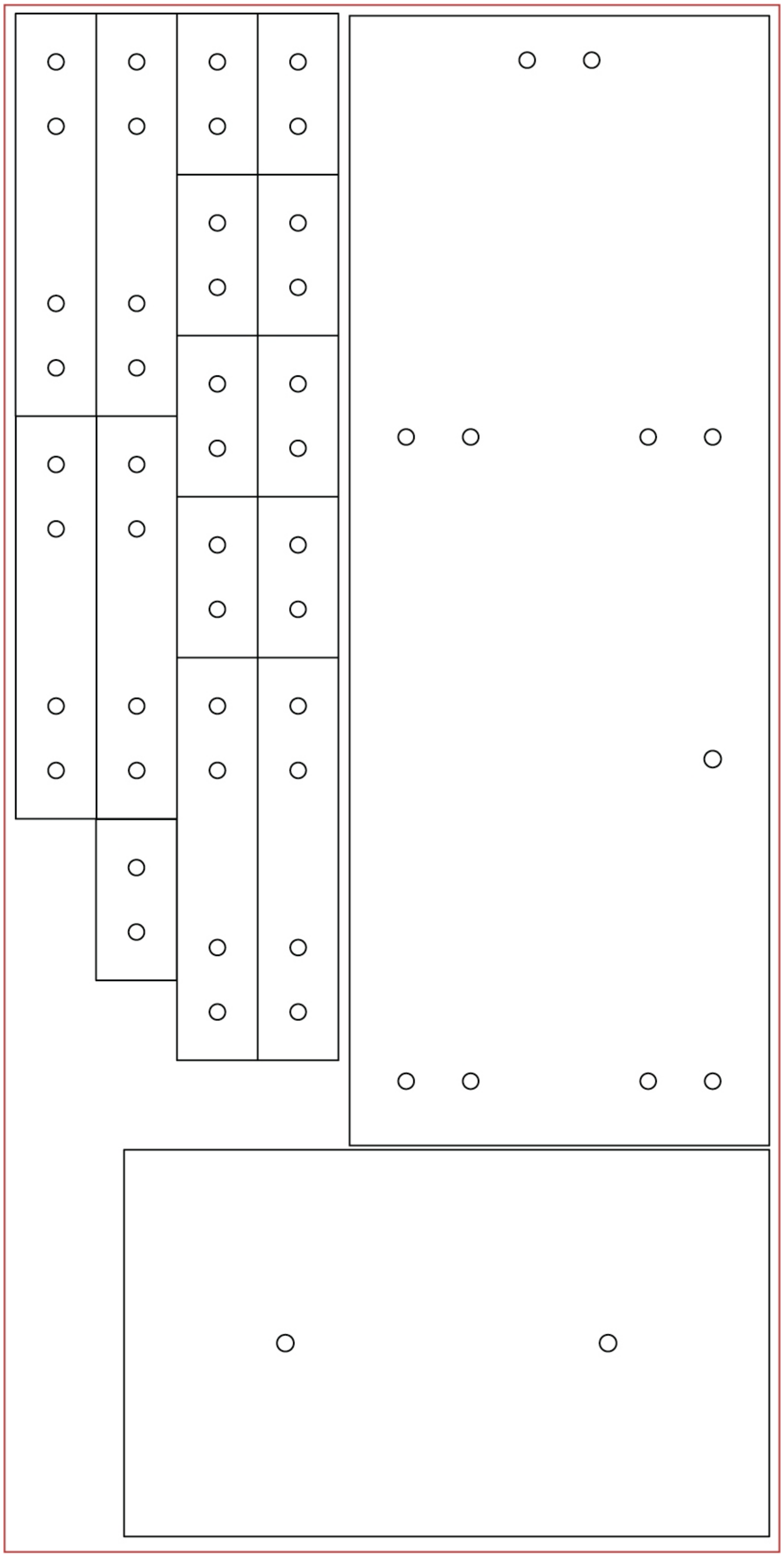

Figure B2: Clear Sheet 2

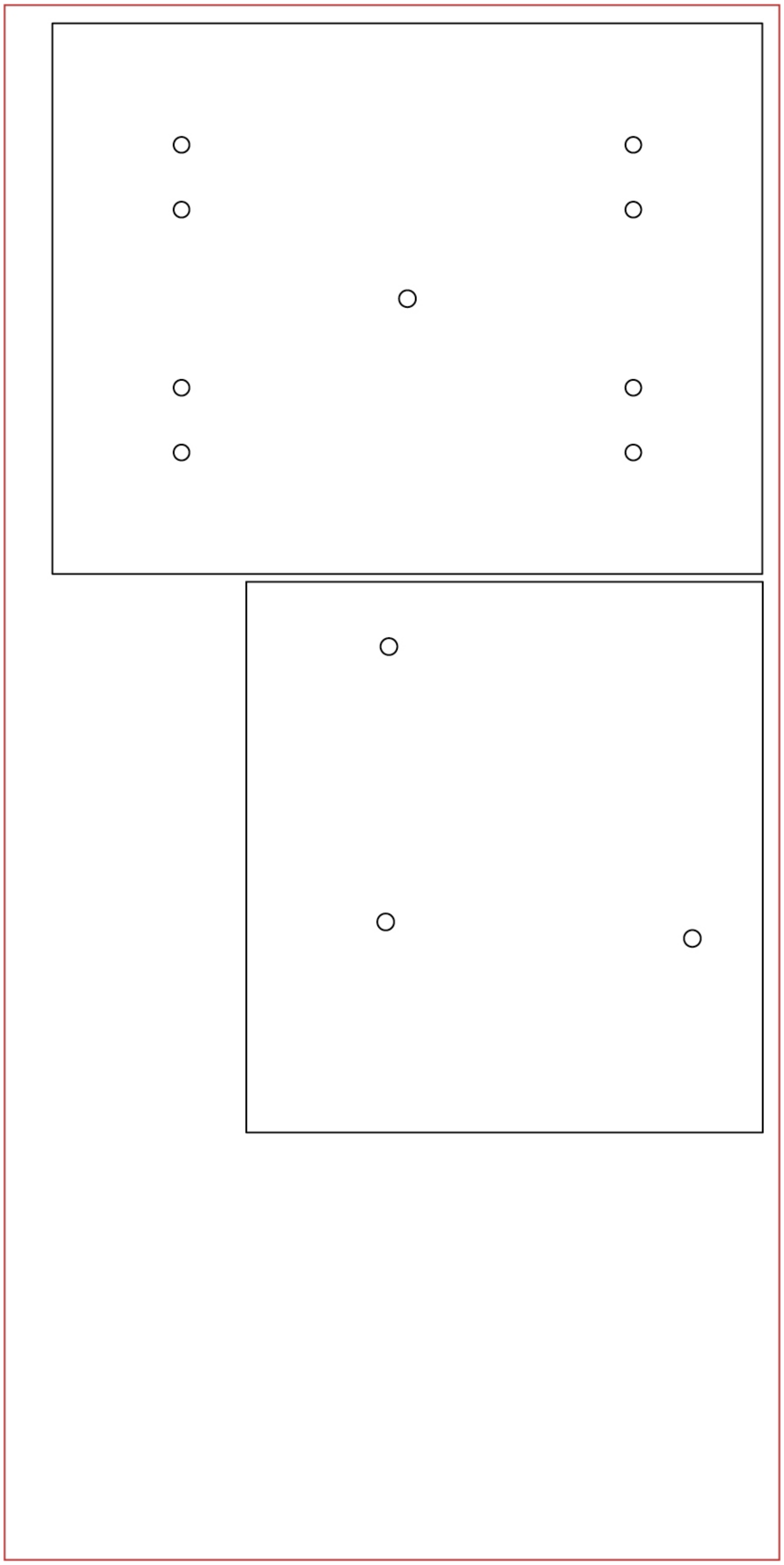

Figure B3: Clear Sheet 3

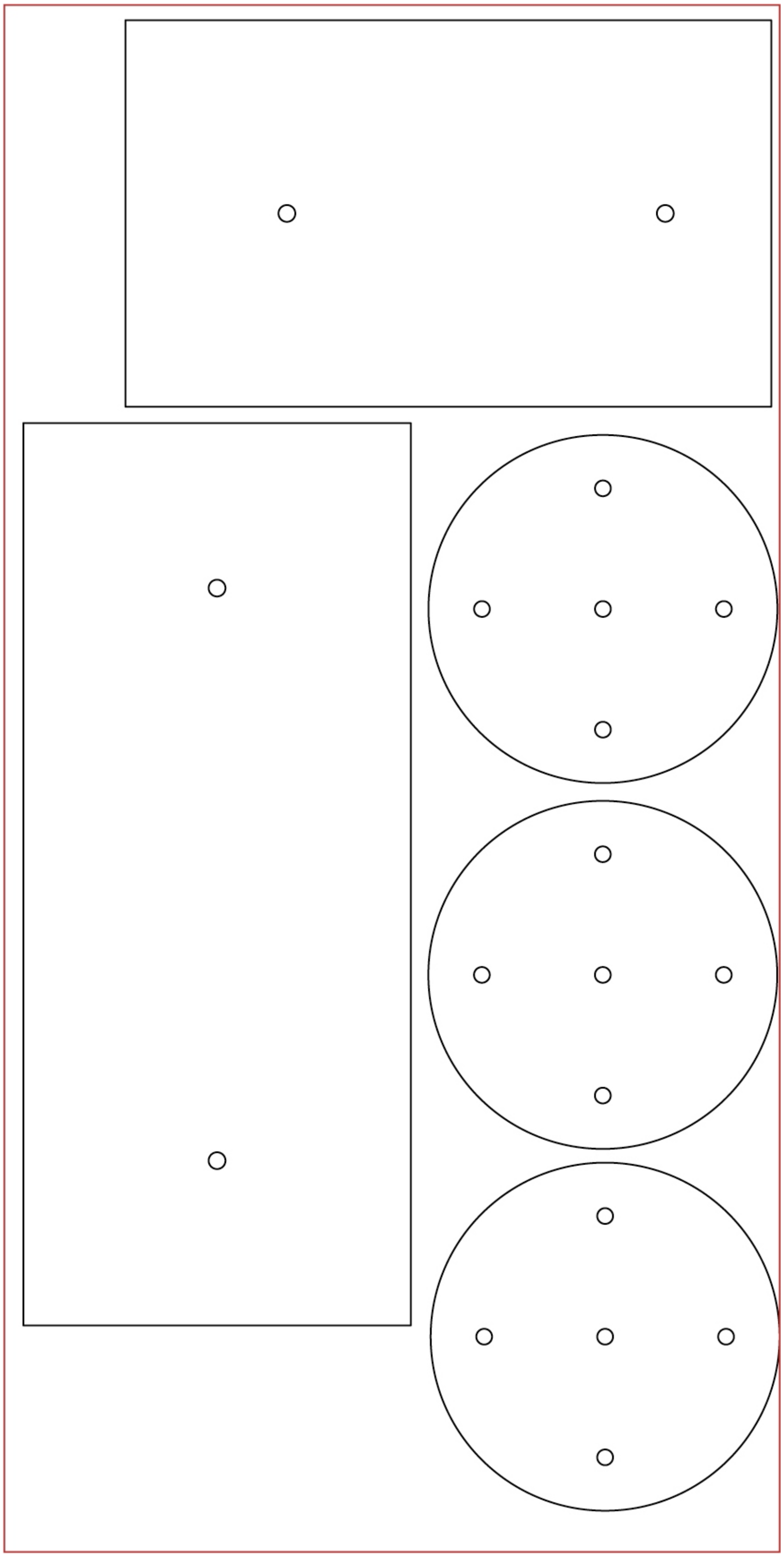

Figure B4: Clear Sheet 4

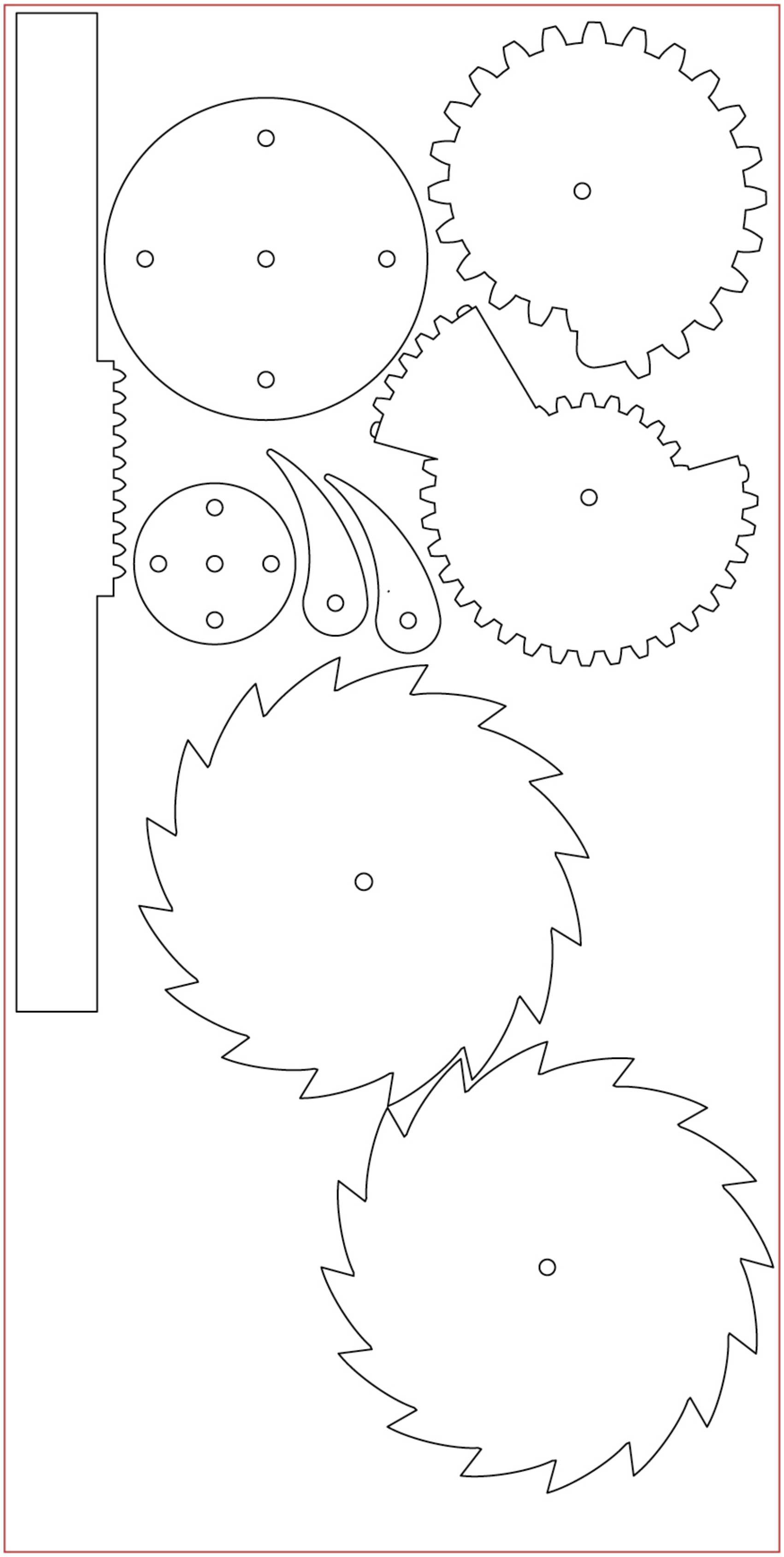

Figure B5: Blue Sheet 1

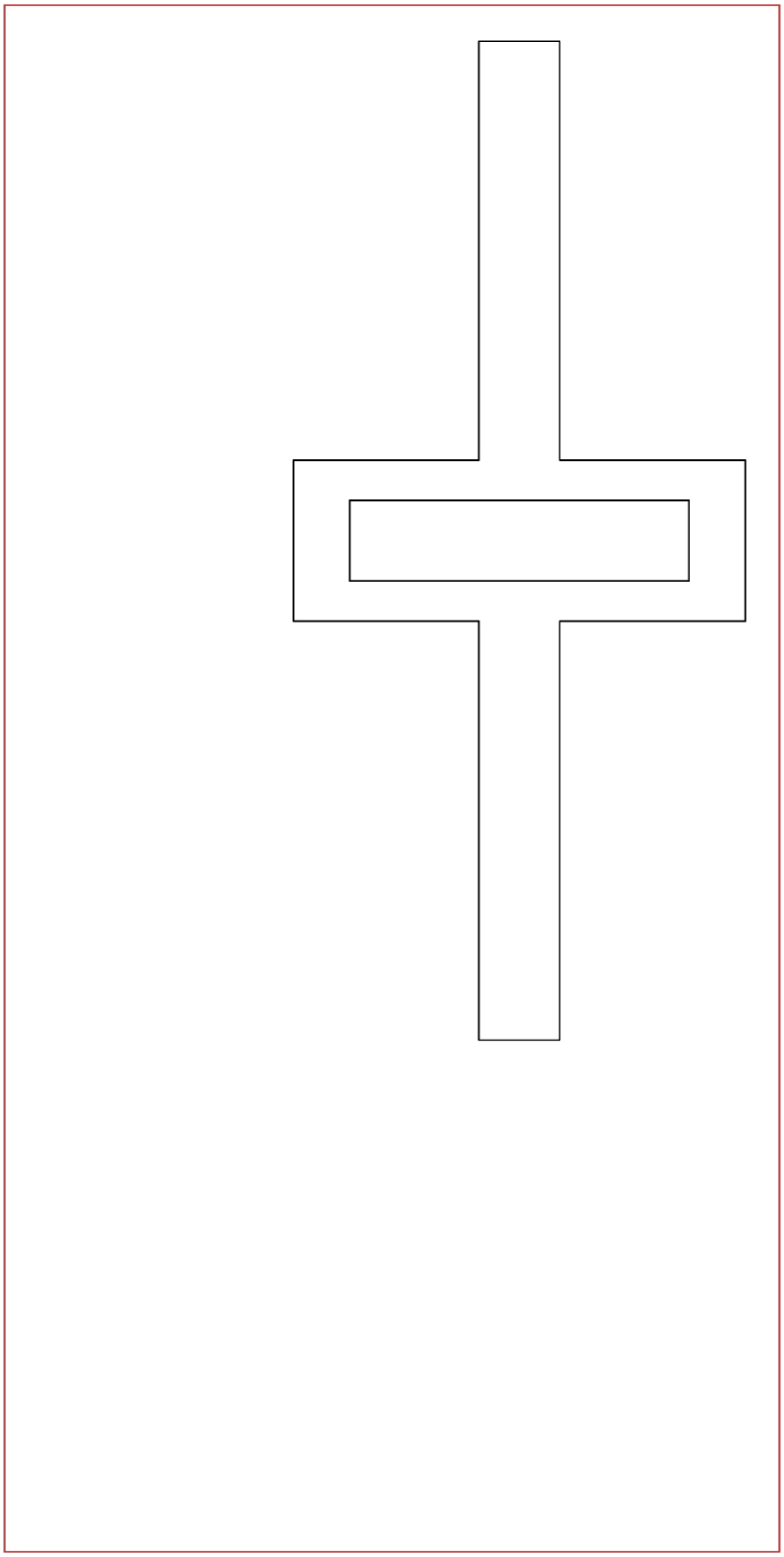

Figure B6: Blue Sheet 2

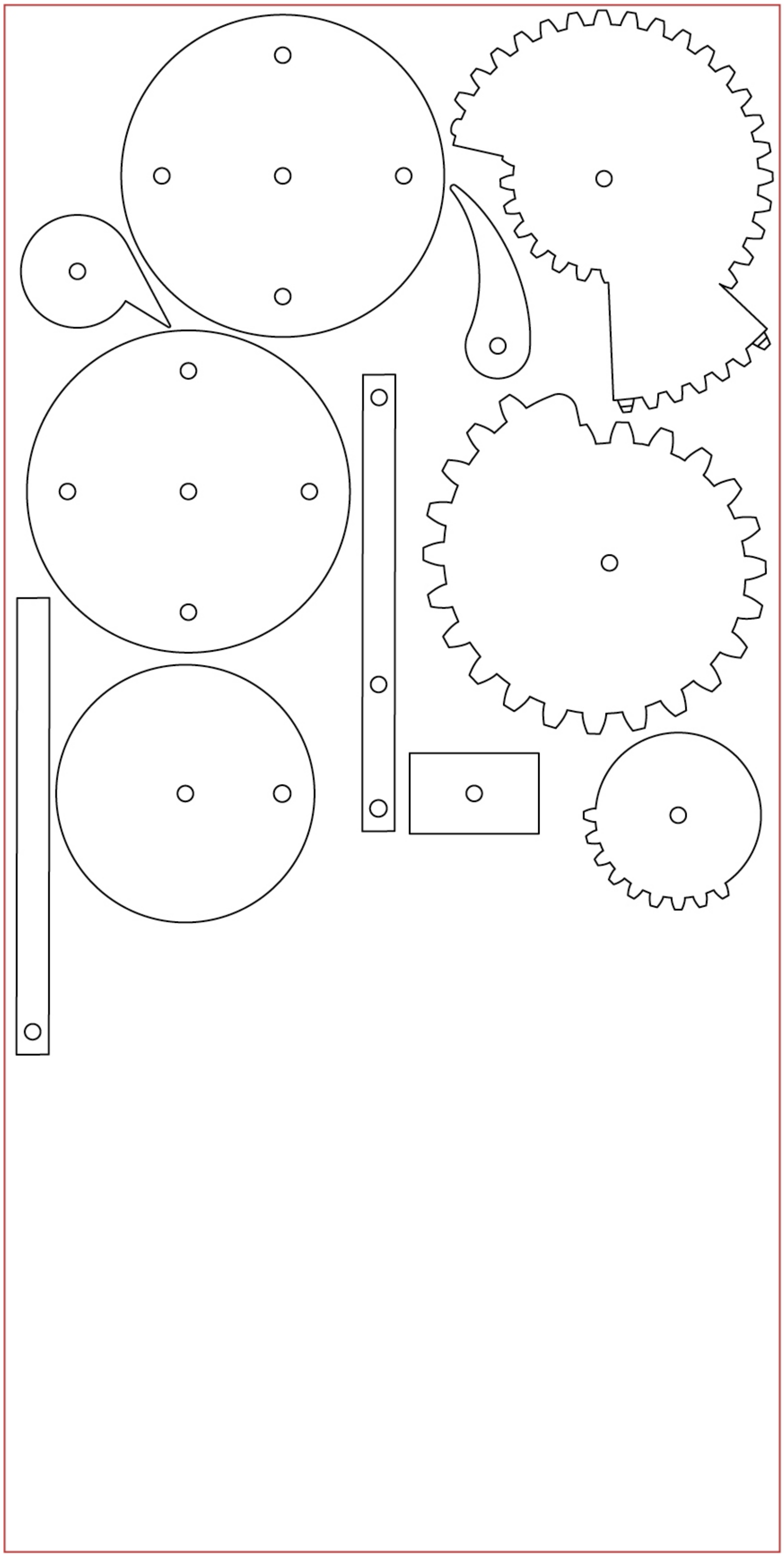

Figure B7: Red Sheet