Marine Chronometer Project

Group 75: Confidently Exhilarated

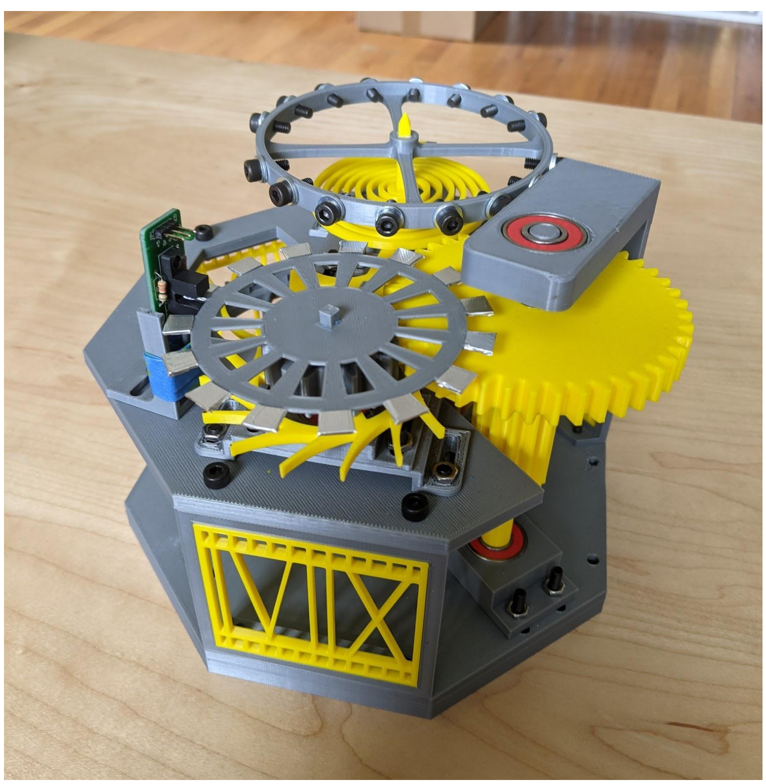
ENGS-146
Spring 2021

Mason Brady, Andrew Moura,
Schae Nelson, Soon Young Shimizu

Abstract

For the last 6 weeks of ENGS146, we were tasked with creating a marine chronometer clock that was not only accurate within 10% of one second, but also precise and ticked for as long as possible. Our goal was to create a clock that resembled a traditional watch or clock by having a circular design. The clock consisted of four distinct subsystems (the mainspring, gear train, escapement, and balance wheel and hairspring) that were carefully designed using Onshape, printed and tested using the supplied Ender 3 3D printer, and assembled through numerous iterations. Scoring was based on precision of ticks as well as time ticked. Our group had the lowest cumulative sum score and won the Timex award, given to the team with the best (lowest overall rank sum) score. In addition, with our novel and elegantly designed two level clock, we won the Patek Philippe award, given to the team with the most beautiful and aesthetically pleasing design. This was a great culminating experience in engineering, and we had the opportunity to go more in depth in CAD software, work with 3D printers and understand their tolerances, as well as work collaboratively with a team remotely. Below is a table of our final run times and precision numbers during the competition day as well as a picture of our final clock.

Pulses	PulseLength	AvgPulseLen	N	P	Score
206	991	964	198.71	0.96	191.24
99	950	1025	101.5	0.92	92.98
71	3455	1118	79.44	0.89	70.56
64	1088	968	61.97	0.82	50.98



I. Introduction

For the Marine Chronometer project, we were asked to create a mechanical clock with dimensions bound by the size of our 3D print beds. Additionally, the clock needed to be mounted onto a foam suspended platform so that when the competition g-code was run, the clock experienced a mechanical disturbance. After mounting the clock onto the foam platform, a height variance of less than 2mm at each corner was expected to ensure proper motion and to make sure the clocks did not touch the print bed. So, our clocks were expected to be within a certain weight range that would not overpower the bed stepper motors or the foam absorbers. Every component of our clock aside from the fasteners and bearings had to be uniquely designed 3D printed parts. The power mechanism for our clock design was up to our team's discretion to decide between a spring or pendulum, and we also had to consider a mounting mechanism for the encoder that would determine the accuracy and precision of our clocks. Every clock had to meet a performance regiment of 60 pulses per minute with a 10% variance for a duration of at least 10 seconds on competition day.

Our team's utmost priority was to create a ticking clock, so we decided to keep each subassembly simple so that iterations were quick and efficient. Our clock was divided into four main subassemblies: the mainspring, gear train, escapement, and balance wheel and hairspring. Each group member was responsible for a subassembly, and once designed, testing was split into two further groups: the mainspring and gear train in one and the escapement and balance wheel and hairspring in the other. By working closely with adjacent subassemblies, we were able to identify meshing and mounting issues early on in the design process. Once this testing phase was complete, the majority of our hard work was finished because we only had to connect the two major assemblies together through proper gear meshing. Our success is largely due to this highly efficient design strategy. For the remainder of this report, we will dive deeper into the design process for each of the subassemblies. More specifically, we will discuss the problems that were encountered and how we overcame them with analysis and testing methods to create new design iterations. Following this is a discussion of our final design and its overall performance on competition day, and lastly, our appendix provides a bill of materials for every component used within our clock design and a few diagrams of essential subassemblies: the gear train, mainspring, and balance wheel and hairspring.

II. Discussion

A. Overall Design & Theory

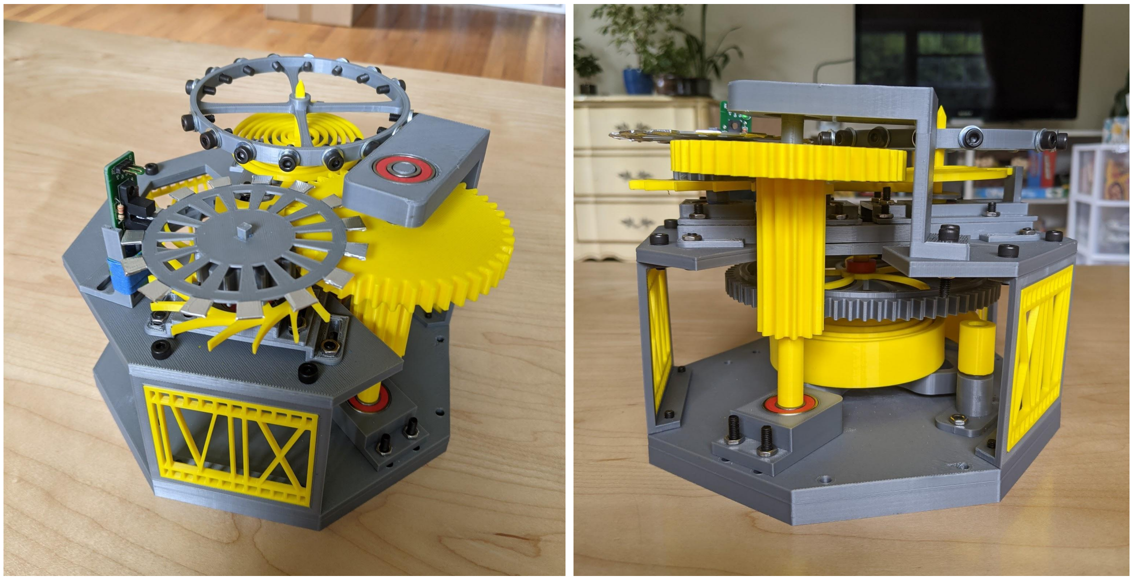


Figure 1: Final Clock Design

Our team set out to build a clock that was more “clock-like” compared to previous designs in Spring 2020. While we initially designed our components around a circular plate to mimic a wall clock, we finalized on an octagon shape to simplify prints and assembly. Our clock is separated into two areas with the mainspring assembly on the bottom, the escapement and balance wheel assemblies on top, and the gear train connecting the two planes. By keeping the escapement and balance wheel and hairspring isolated on the top plate, this allowed for simple integration. If issues were to arise on the bottom half of the clock, then the top plate could easily be unscrewed and placed to the side without affecting its alignment. For mitigating problems, this design helps contain the issues in one area and negates the probability of translating problems to other subassemblies when attempting to problem solve.

Next, we will go through the individual systems in more detail.

i. Mainspring

The mainspring subassembly was placed on the bottom of our clock design to allow for the largest possible spring. The more power we provided to our clock, the longer it would tick for, so it was a design priority to allocate proper space. Additionally, the main gear has a large diameter to allow for proper power dissipation throughout the gear train. We would have greater mechanical advantage if we slowly dispensed power from the mainspring rather than with a smaller gear because our clock would translate power more efficiently. The knob was also strategically placed at the base of the clock so that when force was applied to crank the spring, the other components would remain untouched. If the knob was placed at the top of the subassembly, then we would have to consider additional mounting schemes to ensure each component would not shift. The mounting scheme for this subassembly was also meant to say completely isolated from the escapement and balance wheel and hairspring subassemblies, and the best way to achieve this was to provide a bearing attachment at the bottom of the top plate. This design left an untouched top plate for the two more complex subassemblies of our clock. By segmenting our clock in this manner, this limited unnecessary interactions that could propose additional issues.

ii. Gear Train

The purpose of the gear train is to distribute the power held in the mainspring to the escapement mechanism and also create a mechanical advantage by gearing down. The clock consisted of three gears. The first was a gear connected to the mainspring mechanism that would turn as the spring was unwound. Second was an intermediate gear which connected the mainspring gear to the escapement. Last was a gear that was attached to the escapement that allowed it to turn. Each gear in the gear train had the same module (the ratio of teeth to pitch diameter) to ensure proper and efficient meshing.

iii. Lever Escapement

In a clock mechanism, the escapement is designed to transfer power from the gear train to the balance wheel. This transfer of power is also responsible for making the clock tick through a combination of an escapement wheel and pallet fork. The escapement wheel receives power from the gear train, and a single tooth makes contact with the first leg of the pallet fork to distribute power through the fork to the balance wheel. The fork is then moved by the balance wheel, which allows the escapement wheel to move before being caught by the second leg of the pallet fork. This process is repeated until the mainspring cannot provide enough power to properly activate the balance wheel. When the escapement hits the two legs of the pallet fork it causes the familiar "tick-tock" of a clock.

iv. Balance Wheel & Hairspring

The function of the balance wheel and hairspring is to regulate the release of energy delivered by the mainspring in tandem with the lever escapement system. The pallet fork transfers energy to the balance wheel by hitting the impulse pin, which is fixed to the axis of the balance wheel. As the balance wheel rotates, a spiral spring, or the hairspring, is compressed concentrically and returns the balance wheel to its neutral position. This swing allows the impulse pin to hit and release the pallet fork. This process transfers energy back to the balance wheel and sets the balance wheel into an oscillating motion. Each swing or beat locks and unlocks the pallet fork and produces the iconic ticking sound. The period of oscillation is determined by both the hairspring spring constant and the moment of inertia of the balance wheel.

B. Design Iterations & Analysis

I. *Chassis & Mounts*

The first iteration of the chassis was a cylindrical design with two levels. The difficulty/time required to print a circular design was noted early in the design process and quickly modified. We decided to modularize our chassis into an octagonal prism using multiple pieces with flat faces fastened with M4 nuts and screws. Holes and/or slots for various subassemblies were added onto the top and bottom plate as necessary. We only supported the top plate with three walls as this was the minimum number necessary for support and allowed enough access to the mainspring knob for winding.

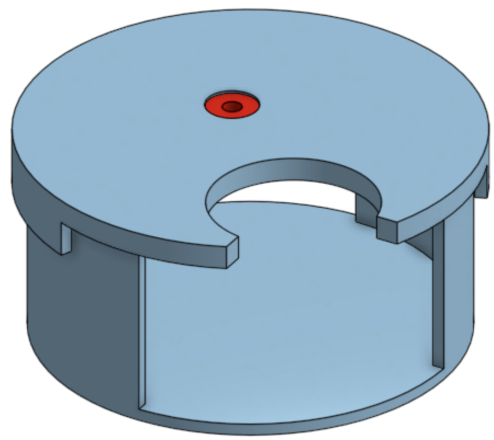


Figure 2: First chassis design

The mainspring axis was initially mounted only at the bottom. However, due to stability concerns, we added an additional mount to secure the top of the mainspring axis. This top mount was made to be adjustable in the second iteration of the chassis. But we realized that the adjustability was not necessary for the mainspring, and introduced too many unnecessary degrees of freedom. For the final iteration of the chassis, the mounts were integrated directly into the top and bottom plates. We also added openings on the top plate to provide a top view of the mainspring (and reduce print time).

As the escapement and balance wheel assemblies needed the most precise adjustments, we decided early on that they should be set on slider mounts with slots on the top plate. However, sliders directly on the top plate introduced interference issues with screws and alignment issues with the vertical gear. To address this, we assembled components on a separate mount, which would then be screwed on the top plate. This mount would also have adjustability to line up the escapement gear with the vertical gear while maintaining the precise distances of the escapement/balance wheel assembly.

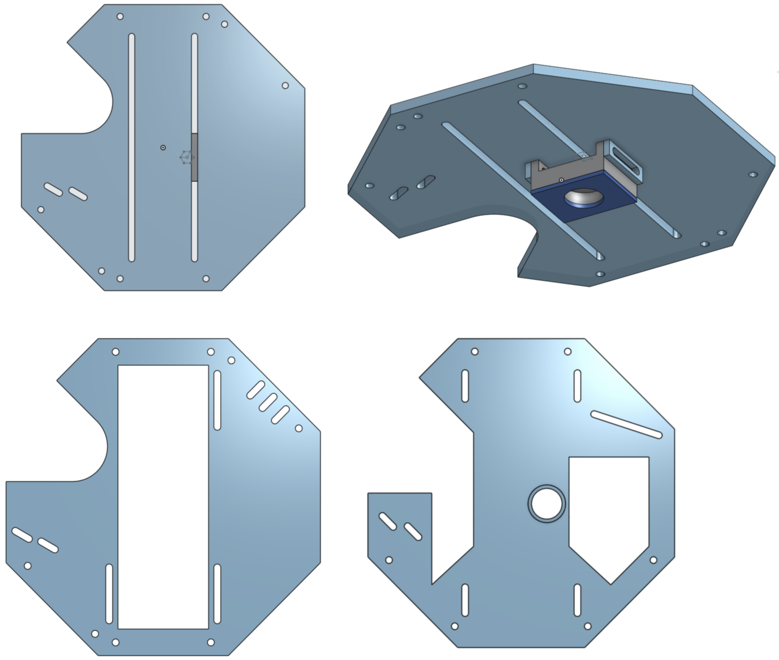


Figure 3: Top plate design iterations

II. *Mainspring*

For the first few iterations of the mainspring itself, they were far too small for the allocated space. The extrusion height was also far too small and had too many turns, so minimal power was being supplied. Many iterations were needed in order to find the right extrusion height, thickness, and number of turns. Figure 4 shows a few examples of the initial spring iteration process.

Figure 4: Spring iteration process

Figure 4 also provides the first iteration for the main gear, ratchet, axis, and knob. This first iteration provided immediate feedback on what needed to change. The ratchet was far too thick and the grooves in the main gear were also too rigid to allow for any movement. This led to the next iteration that had more exaggerated grooves and a thinner ratchet. It was quickly established that the ratchet has to be flexible enough to navigate about the grooves but rigid enough to keep the spring taught in tension. By rotating the ratchet about the main gear, the functionality of the ratchet and groove design was quickly established. If the ratchet was allowed to rotate in one direction and remain in place when force was applied in the opposing direction, then this was validation that the spring would remain taught when cranked. This iteration process was relatively quick, and once the design and functionality was established on a smaller scale, it was enlarged for one of the latest iterations. For the last iteration, the overall design remained the same, but a lip was provided to keep the ratchet flush to the gear as it was cranked. Previous iterations did not have this feature, so some of the ratchet branches would uplift as it rotated about the axis. As an additional precautionary measure, the ratchet was printed with a 40% infill to prevent snapping.

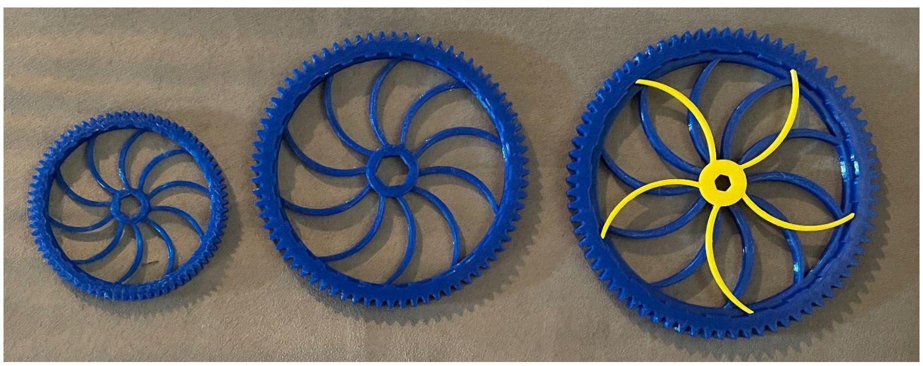


Figure 5: Main gear and Ratchet iterations

The first knob and axis was based upon a completely different clock design, and when the final design layout was established, only one additional iteration was needed. The knob shape itself had more defined corners added and was enlarged to allow for easier cranking from the base. The axis goes through the knob so that it can be press fit into both the top and bottom plates. Lastly, the printing method for the knob was crucial. A 20% infill for the axis was not able to provide the mechanical integrity needed to crank the spring at a higher tension. Therefore, the axis needed to be printed at 70% to prevent it from snapping.

After we were confident in a mainspring design, we tested its power production on a test rig with both the mainspring and gear train subassemblies. Through this testing, we were able to establish that this spring provided ample power. Once our clock was fully assembled, we decided to test multiple spring iterations to see if we could further optimize our clock's performance. We tested four additional designs: a 3 turn - 2 mm thick, 3 turn - 3 mm thick, 4 turn -2.5 mm thick, and a 5 turn - 2 mm thick spring against the initial design. The extrusion height was kept constant at 20mm.

Figure 6: Mainspring iterations

When winding each spring the same amount, the initial spring design proved to withstand the longest. So, our final spring design was a 4 turn - 2 mm thick spring.

III. *Gear Train*

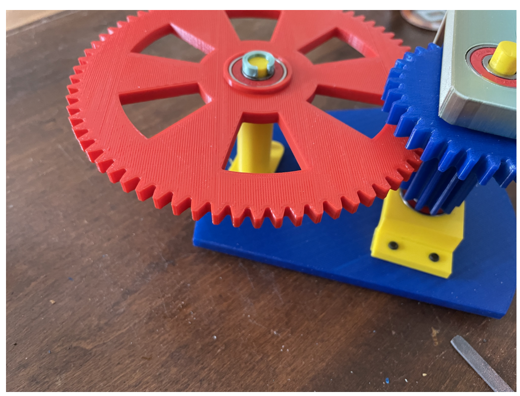


Figure 7: First gear train iteration

The first aspect of the gear train design was determining how to mount the gears as well as how to support them. Given that we had a mainspring that took up most of the footprint of the bottom of the clock, we had to incorporate a second level. For this reason, we had to create a tall vertical gear to transfer the power from the mainspring on the bottom of the clock to the escapement on the top. Figure 7 shows the first interaction of part of the gear train to ensure the proper meshing of the gears as well as to determine if having a support on the top and bottom of the vertical gear would provide enough support. Both were successful in this test and we moved on to test the gear train with the mainspring assembly.

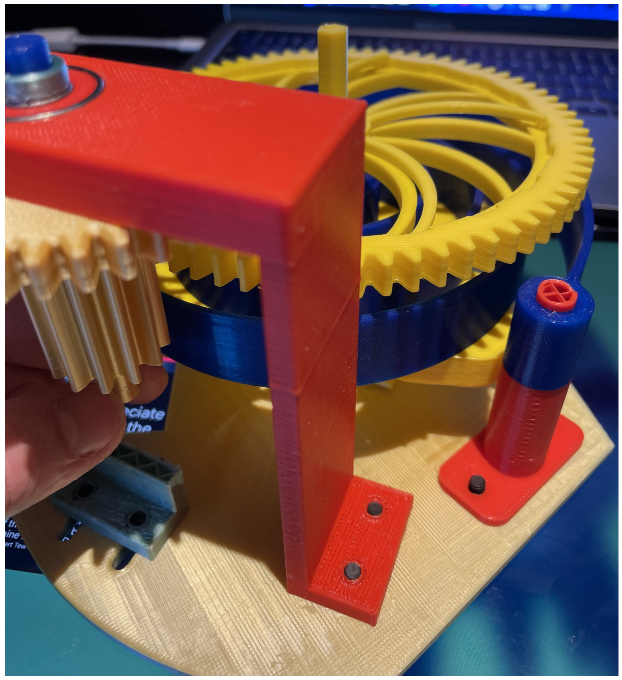


Figure 8: Gear train and mainspring assembly

Figure 8 shows the first mainspring and gear train assembly. We were able to validate the subsystems together so that we could wind the mainspring and have the vertical gear turn as a result. In this test, we realized how much torque the mainspring provided. This forced us to increase the infill of the mounts as well as the vertical gear to handle the forces.

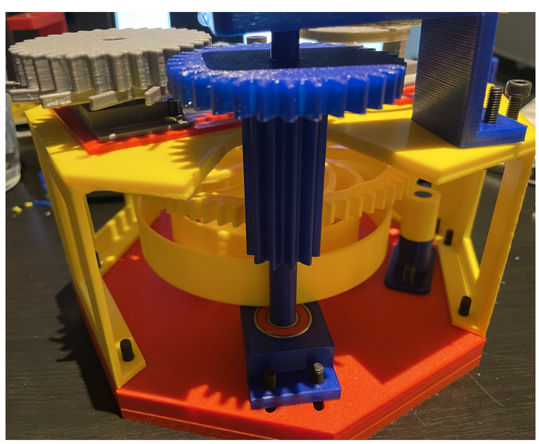


Figure 9: Gear train with mainspring and escapement assemblies

Our next iteration was combining all of the subsystems into a working clock. As can be seen in Figure 9, a gear is attached to the escapement which allows it to spin. The clock worked well at this point, but even with the mainspring fully wound, was only providing about 25 seconds of runtime. To try and maximize the runtime, we capitalized on the mechanical advantage of the gears. We increased the gear size of the top of the blue vertical gear and decreased the size of the escapement gear to get a longer runtime.

IV. *Lever Escapement*

Our escapement is based on the commonly used swiss-lever design. In the first iteration, we designed a simple mount with an initial concept design of the fork and wheel. This design allowed us to gain more insight into the mechanics of the system. However, this design was far from functional and required reducing the sizing of the components and a more sophisticated testing apparatus.

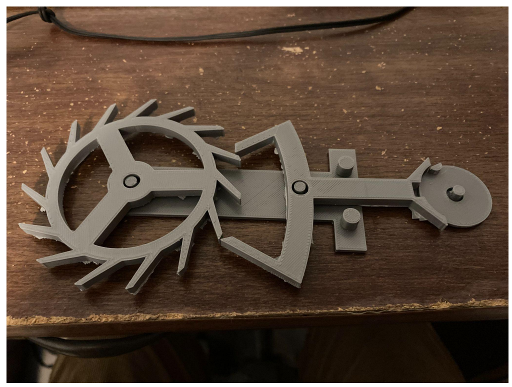


Figure 10: First escapement design

In the second iteration of the escapement, we were able to reduce the sizing of the fork and wheel with Onshape's transformation tool. Through our design reviews it was evident that providing adaptability in the design was vital. It was determined that a sliding assembly would allow for adaptability and ease of construction for the escapement. For this set-up we created sliders for each part of the escapement, fork, brakes, wheel, and one for the balance wheel assembly. Each slider supported a bearing that held each component's axle. In conjunction with the sliders, we created a mount where the sliders can sit for testing purposes.

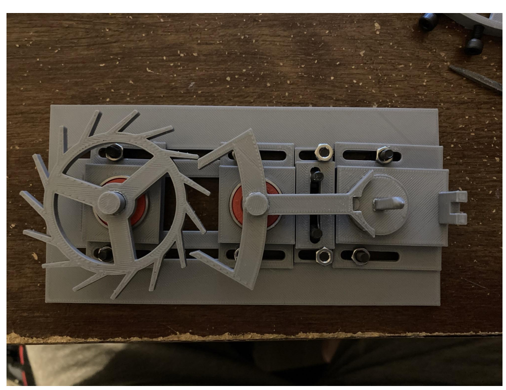


Figure 11: Second escapement design iteration

After testing the second iteration we appreciated the adaptability, since having proper spacing of the escapement proved to be highly influential on the performance of the clock. This iteration proved to work very well, however, the parts were very thin and would not interact with one another at times. Also, the disc part of the impulse pin would interfere with the pallet fork. Mounting the escapement to the clock was initially planned to be done where the top plate of the clock had slots for each slider to go on.

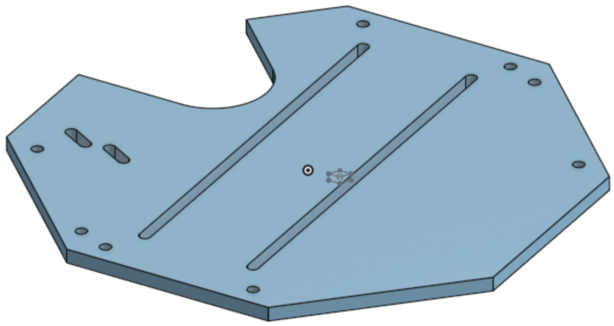


Figure 12: Sliders for escapement mount on top plate

However, when assembling the clock it was very difficult to alter the positioning of the escapement features underneath the top plate. Issues in this design lead to changes in the mounting of the escapement, size of components, and heights of the impulse pin, fork and wheel.

After changing the thickness of the wheel and fork they never missed interactions. Lowering the height of the impulse pin disc and raising the actual pin part also fixed the friction problem. Our third iteration of the escapement also included a slider mount that was secured to the top plate that had slots to correspond with the four corners of the mount. However in this design we had to create a hole in the top plate to make room for the nuts and screws.

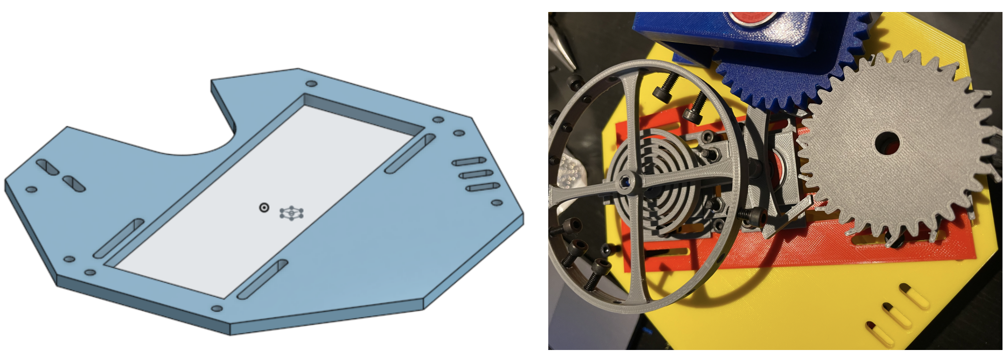


Figure 13: Sliders and opening for escapement mount on top plate

This hole removed our ability to support the top of the mainspring axles. Therefore, we decided to have a raised slider mount that created space for the screws without compromising support of the main axle. The raised slider support, thicker escapement pieces, and lower impulse pin created our final design.

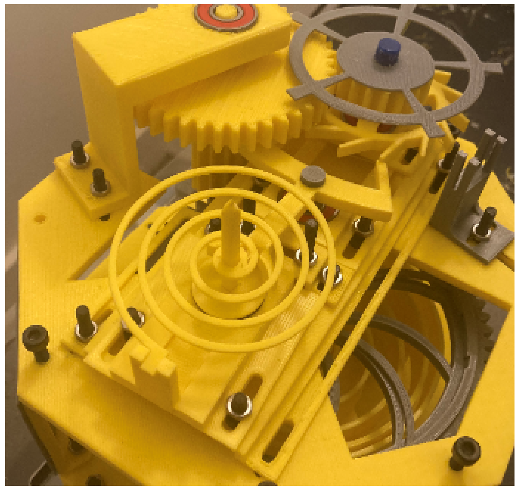


Figure 14: Final escapement mount design

Another design that was explored was the escapement design provided by Abbey Clock[1] (Figure 15). Designed with its carefully laid out geometry, the escapement wheel and pallet fork was described to maximize efficiency/transfer of energy from the mainspring to the balance wheel. The clock with this escapement ran more than twice as long as the previous escapement design (93s vs 191s)! It also produced a very precise clock (P = 0.96) without needed asymmetrical adjustments to the balance wheel masses to accommodate for energy losses down the system.

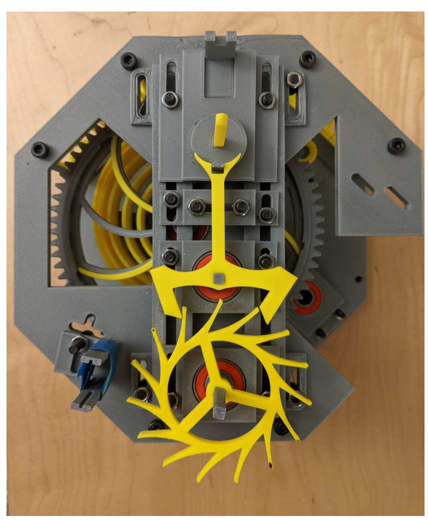


Figure 15: Abbey Clock Escapement Design

[1] http://www.abbeyclock.com/escpdf.html

V. *Balance Wheel & Hairspring*

The balance wheel underwent minimal iterations, mainly adjusting its diameter from 5cm to 10cm and adding holes for screws. The increase in diameter and accomodation for screws allow the balance wheel to hold more mass and inertia than the 5cm. This enables us to adjust the wheel for our individual clocks uniquely to produce an oscillation closer to 1 sec per beat.

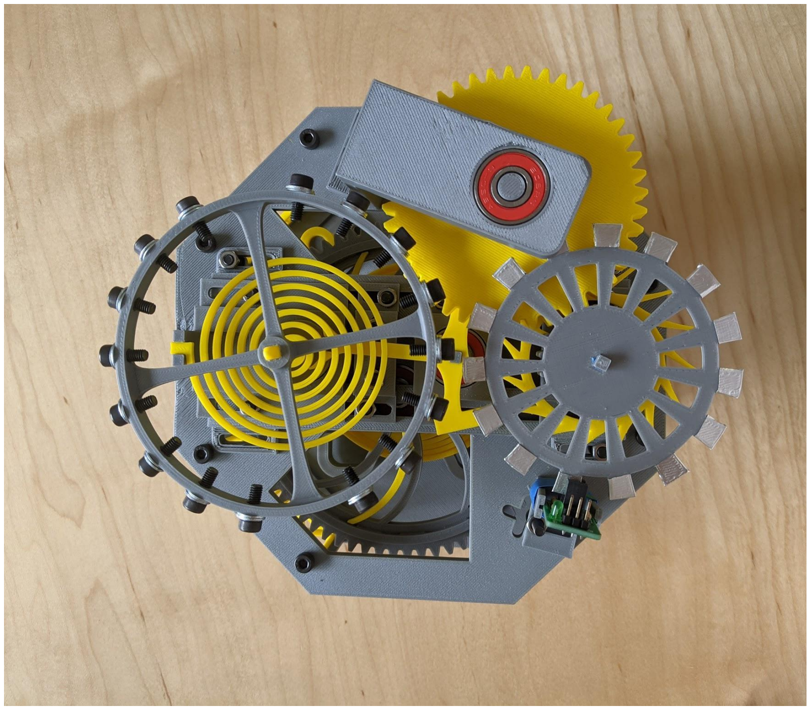


Figure 16: Final balance wheel and Hairspring assembly

The hairspring underwent several iterations with different diameters, thicknesses, turns, and depths which affected its spring constant,

$$k = Ebt^3/12L,$$

where E is the elastic modulus, b is the width, t is the thickness, and L is the total length of the spring. This affected the period of oscillation of the system:

$$T = \sqrt{I/k}.$$

To facilitate testing of the hairspring, the mount was designed to accommodate hairsprings of different diameters by utilizing an adjustable slider.

Springs with low spring constants (1mm thick or 1mm deep springs) were not capable of producing a force to return the balance wheel in a swing, while springs high spring constants (thicker springs or springs with fewer turns) produced a force capable of producing a faster oscillation. A spring that had 7cm in diameter with 7 turns, 2mm thick and 3mm deep produced an oscillation around 800-1200ms. We decided to use this hairspring and adjust the oscillation with mass adjustments on the balance wheel.

One other aspect that was tested was the inclusion of a terminal end. A terminal end is intended to facilitate a concentric compression of the hairspring, which would theoretically contribute to the precision of the clock. However, it did not produce a significant difference in precision compared to the 7cm hairspring, therefore, we did not continue testing this design.

Figure 17: Hairspring iterations

VI. Final Designs

Here we present each team member's final clock!

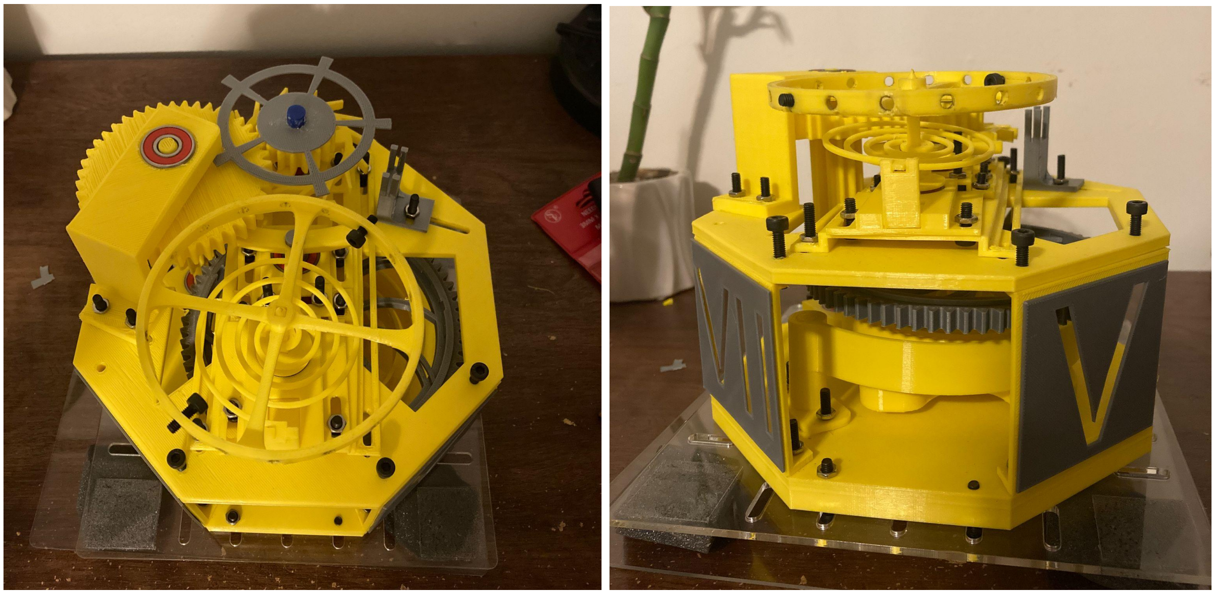


Figure 18: Andrew's Clock. Used yellow as the main color of the clock to have it pop. Silver was chosen for various components such as the wall panels to match the Bruins hockey team. Wall panels numbered to mimic the location of a clock (XII at 12, V at 5, and VII at 7).

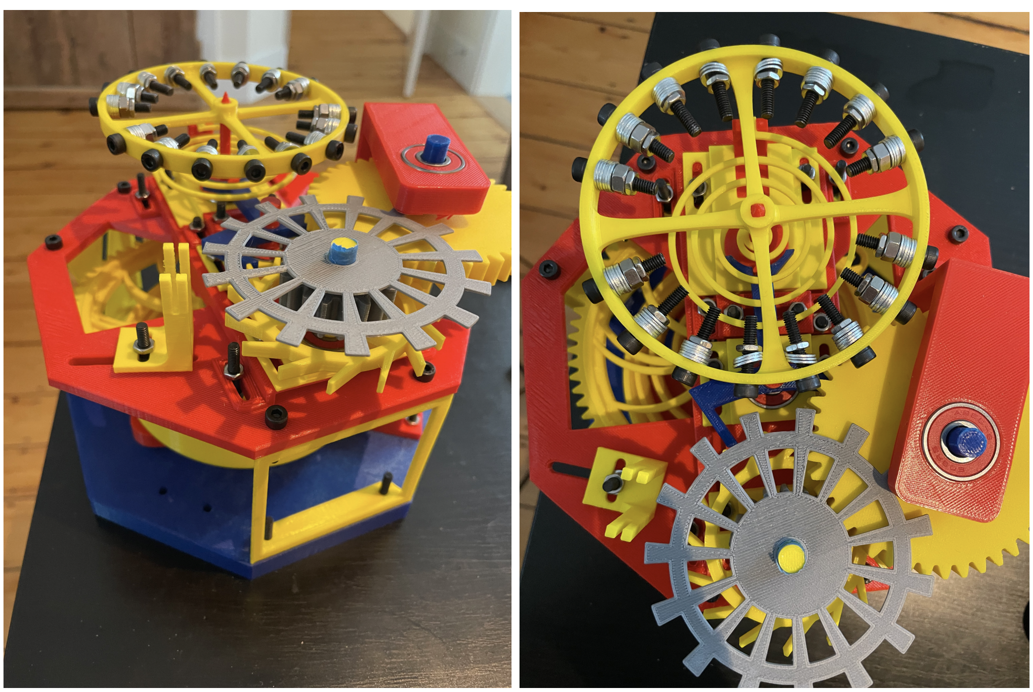


Figure 19: Mason's Clock. This clock was meant to be as colorful as possible. The spring was yellow because it had the best properties, but other than that, the colors were meant to be distributed through the clock assembly.

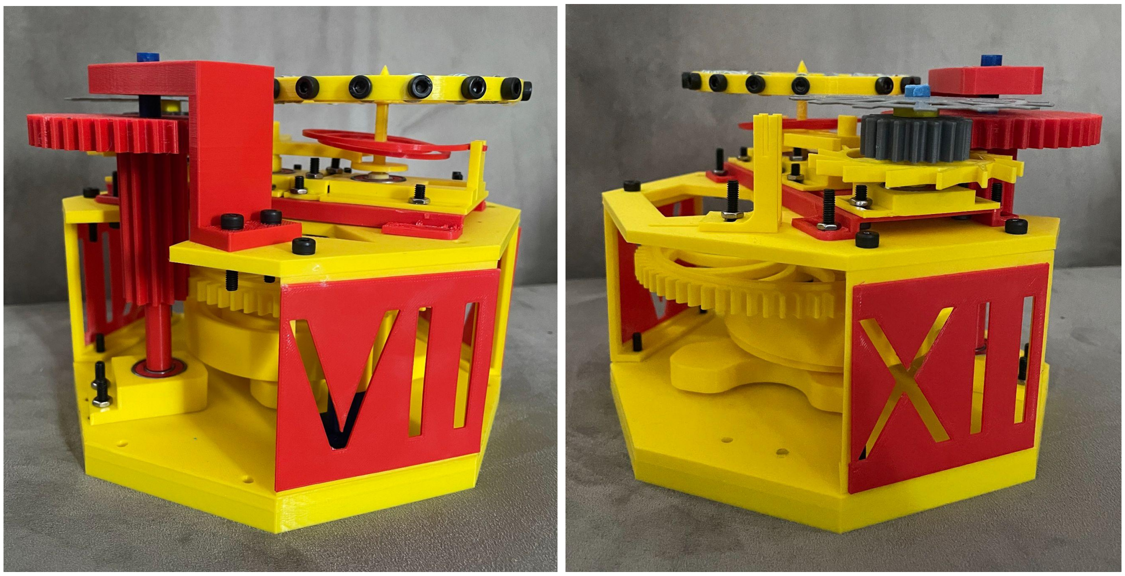


Figure 20: Schae's Clock. Used primarily red and yellow. There are some hints of blue and grey to change things up. Yellow had superior mechanical properties, so this color dominated the clock design.

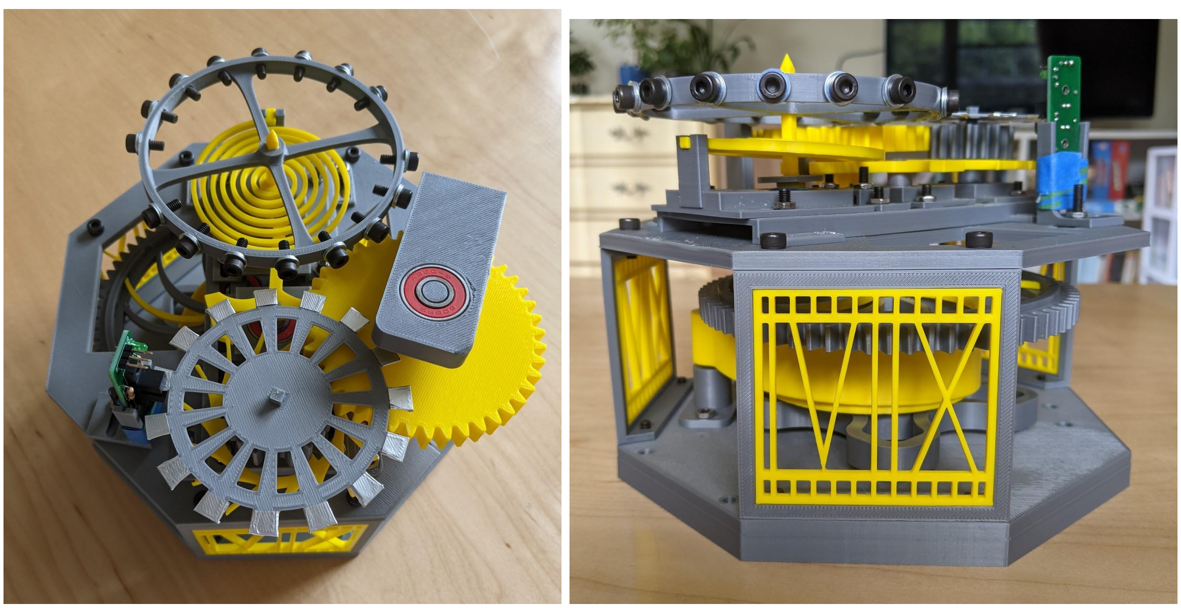


Figure 21: Soon Young's Clock. Utilized the abbey clock escapement mechanism and opted for more minimalist wall panels. Main color used was silver, using yellow as accents. Also features an escapement wheel with aluminum foil covered teeth for extra pizzazz (and to trigger the encoder properly).

III. Conclusion

At the start of this project our group decided on major design and scheduling goals. It was made clear in the beginning of the term that front loading much of the work was key to past year success. Therefore, we planned to have our clock working a week ahead of schedule and have multiple iterations completed for each design review. These two goals were met, and we believe meeting these goals were the reason our clock was successful in achieving the best overall award. Our design goals were to have an aesthetically pleasing clock that took the shape of a classic wall mounted clock, and have a long running clock that could run for 1-2 minutes.

We split up roles based on subassembly, mainspring, gear train, escapement, and balance wheel. The main spring was designed to be as large as possible to maximize the duration of the clock. To achieve our final mainspring, various gear designs were tested in coordination with the gear train. With the clock built, multiple springs were printed to test different dimensions, turns, and color. The gear train underwent alterations on gear dimensions to find the best gear ratios and height relations with the mainspring and escapement. Most escapement changes were based around the mounting of the clock. Different slider mounts were created and tested by manufacturing the clock. The thickness and height relationships of the components were changed to improve functionality. We were also able to have one clock utilize a design from Abbey clocks. Lastly, to fine tune the precision of our clocks the balance wheel and hairspring were tested at length. Different size balance wheels with higher and lower quantities of mass were experimented with. Many hairsprings underwent testing, varying size, thickness, and amount of turns all lead to differing results.

Once our clock was completed, we designed walls that depicted roman numerals which correspond to the location of the clock. After adding this feature we were very happy to have met our goal of maintaining the appearance of a clock. Due to having met this goal our group received the most aesthetic clock award. Our other goal was to have a long running clock, we met the desired time, however, we were unable to achieve the longest run time. Although we didn’t have the longest run, our clocks maintained high precision to achieve the best overall clock. Some issues were present in our clock design. A major problem was the security of the encoder. With the rocking of the clock there were times that the encoder became dislodged from its mount reducing our precision. Our clock also would stop ticking before the main spring was completely unwound, we believe this was due to friction throughout the system. Overall, we believe our clock was a great success despite experiencing some minor problems.

An elegant designed clock assembly that can be 3D printed does have commercial potential. Our clock has large pieces that can be observed and played with easily. We believe that because of this it would be a great teaching tool to demonstrate the workings of a clock. Teachers could purchase our clock to utilize in class and teach about mechanical design. There is also potential for our clock to be a wall mounted art piece, or a desk toy. Individuals interested in engineering would enjoy showing colleagues and friends the inner workings of the piece.

IV. Appendix

A. Bill of Materials

Part ID	Name	Contributing Member	Quantity		Part Number	Sub assembly
00-01	M4 10mm Screws	-	26		00-	Hardware
00-02	M4 20mm Screws	-	25		01-	Chassis
00-03	M4 Nuts	-	21		02-	Mainspring
00-04	Washers	-	36		03-	Gear train
00-05	22mm Bearing	-	7		04-	Escapement
01-01	Bottom Plate	Group	1		05-	Balance Wheel
01-02	Top Plate	Group	1		06-	Encoder
01-03	Wall	Group	3			
01-04	Wall Design XII	Group	1			
01-05	Wall Design V	Group	1			
01-06	Wall Design VII	Group	1			
02-01	Mainspring	Schae	1			
02-02	Knob + Axis	Schae	1			
02-03	Ratchet	Schae	1			
02-04	Main Gear	Schae	1			
02-05	Spacer	Schae	3			
02-06	Mainspring Mount	Mason	1			
03-01	Vertical Gear	Mason	1			
03-02	Escapement Gear	Mason	1			
03-03	Bottom Gear Support	Mason	1			
03-04	Top Gear Support	Mason	1			
04-01	Pallet Fork	Andrew	1			
04-02	Escapement Wheel	Andrew	1			
04-03	Impulse Pin	Andrew	1			
04-04	Pallet Fork slider	Andrew	1			
04-05	Pallet Fork axle	Andrew	1			
04-06	Slider	Andrew	2			

04-07	Brake Slider	Andrew	1			
04-08	Slider Mount	Andrew	1			
05-01	10cm Balance Wheel	Soon Young	1			
05-02	7723 Hairspring	Soon-Young	1			
05-03	Balance Wheel Axis	Soon-Young	1			
05-04	Balance Wheel Slider Mount	Soon-Young	1			
05-05	Hairspring Mount	Soon-Young	1			
06-01	Encoder Wheel	Group	1			
06-02	Encoder Mount	Group	1			

B. Gear Train

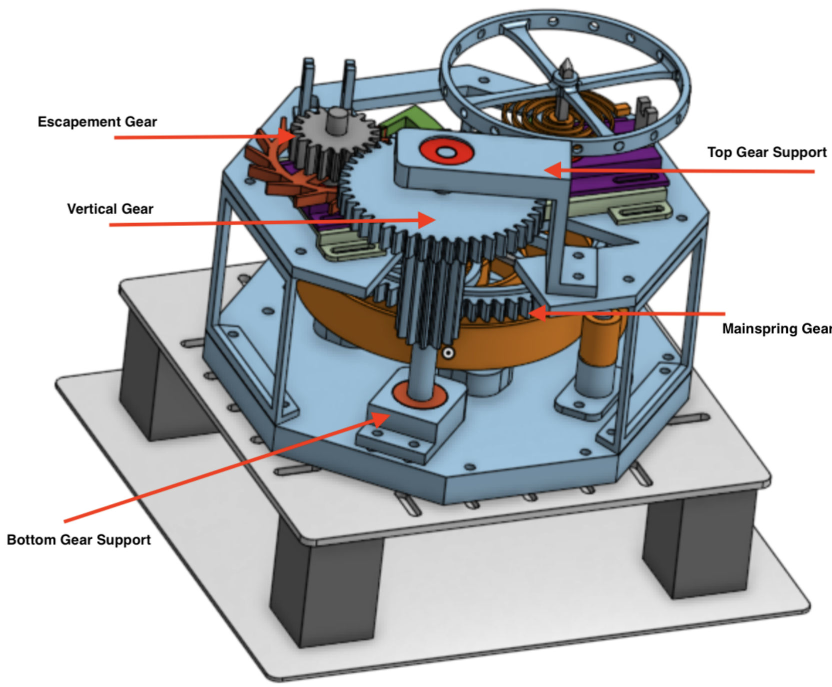


Figure 22: Onshape Final clock assembly

Figure 22 shows the final assembly with the change in gear sizes. The final gear specs were:

Mainspring Gear: 72 teeth
Vertical Gear: 12 teeth on bottom and 44 teeth on the top at 70% infill
Escapement Gear: 12 teeth

These gear ratios allowed our clock to tick for roughly 100 to 200 seconds, and even longer while stationary.

C. Mainspring

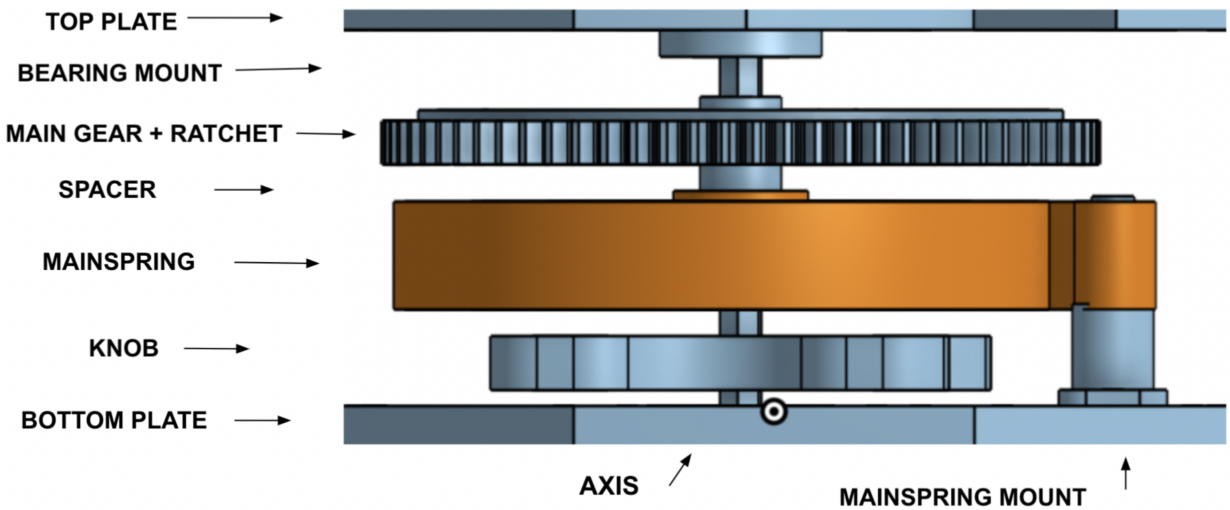


Figure 23. Mainspring Subassembly

The structure of the mainspring subassembly begins with the knob and axis piece. The knob and axis are one piece that are press fit into bearings in the top and bottom plates. The 8.3mm axis is a hexagonal shape, and the main gear, ratchet, spacers, and mainspring are all press fit onto this central axis. There are three spacers that are used to adequately arrange the components on top of one another and allow for proper movement. Two spacers are placed above the mainspring, and one is placed above the ratchet to keep the main gear secured in place when winding the mainspring. The main gear has an extruded lip that keeps the ratchet flush to the main gear as it is wound in tension. This gear is the first component in the gear train that translates the power from the mainspring to the rest of the clock subassemblies. The spring has 4 turns that are 2 mm thick with a height of 20 mm. It is secured into place by both the ratchet and the mainspring mount, so that when the user turns the knob, the spring slowly tightens. These two components work in unison, and without both, cranking the mainspring would be much more difficult.

D. Balance Wheel & Hairspring

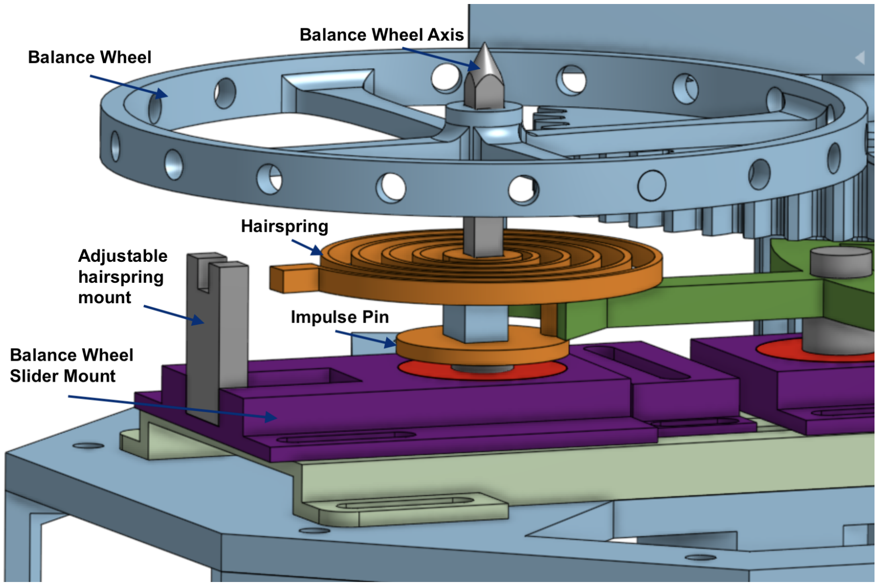


Figure 24 : Balance Wheel & Hairspring Subassembly.

The balance wheel, hairspring, and impulse pin are press fit through a 4mm x 4mm square axis. A square rather than cylindrical axis allowed the components to rotate together without gluing them directly onto the axis. The point on the axis is an artifact from an earlier design to accomodate a jewel bearing if it proved necessary. A 2mm thick, 10mm diameter ridge was added towards the bottom of the axis to create a space and prevent the impulse pin from rubbing on the mount and fix the axis vertically in the bearing. The axis transitions into a 8mm diameter rod that press fit into the bearing. The bearing is press fit into the BW slider mount. The slider mount includes a cavity for the hairspring mount to sit and slide in to adjust its distance from the hairspring.