



MEDIUM MOON PHASE CLOCK

SP15 Build Notes

Assembly notes for a medium size 3D printed clock with a moon phase dial

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Revision History

10-Apr-2025 Original version

Description

This is a medium size version of my favorite 3D printed clock. It is designed for people that want a smaller clock, or maybe they only have a Prusa Mini or BambuLab A1 Mini. It shares all the features of the larger moon phase clock. The gears are highly visible. The dial is as large as a “mini” printer can produce. The slightly smaller size makes it more reliable using less drive weight.

Mechanical clocks have always fascinated me. Building a traditional brass clock requires specialized equipment, but 3D printers have made it possible for anyone to build their own clock. I try to simplify the process while still maintaining a classic look. Construction only needs a few metal arbors cut to length and screws in addition to the 3D printed parts. This clock is accurate to a minute or two per week and the moon phase is accurate to one day every 2.6 years. Runtime is 7.8 days per winding.

Traditional grandfather clocks often incorporate a moon phase dial above the primary dial. This location would block the view of the large prominent escapement near the top of the clock. So, the moon phase dial was placed inside the main dial and made as large as possible. I have never seen it done this way, but it feels like it belongs there. It seems unlikely that this is the first clock built this way, but it is the first that I am aware of.

This guide shows the assembly process. Simple construction techniques require only a 3D printer and a few hand tools.

The design requirements for this clock are:

- 1) The clock must be accurate. This clock typically maintains an accuracy of 1-2 minutes per week.
- 2) The clock must be reliable. The deadbeat escapement used in this design has proven itself to be very robust. The clock often starts ticking as soon as the weight is applied.
- 3) The clock must have a long runtime. Eight days is a reasonable length allowing for winding once per week. It could have been made longer, but this would come at the expense of reliability.
- 4) The clock must look good. I think the prominent moon dial looks great on this clock. Hopefully, you like it as well.
- 5) The clock should be easy to assemble. This clock can be built using a few common hand tools to cut the arbors to length. Most parts fit together using one standard screw size.

The clock can be printed on any machine with a 170x170mm build plate. This includes the Prusa Mini, BambuLab A1 Mini, and many other printers. The 6.5" (165.1mm) dial is the largest component that determines the minimum printer size.

Quick Start

This clock is designed to be easy to print and assemble. This manual will walk you through the process. Here are the most important steps if you want to get started right away.

- 1) Order the non-printed components listed on page 21 and follow the metal cut list on page 22.
- 2) Print the test cookies shown on page 14-15 to determine layer heights for a few components.
- 3) Print the frame components listed on page 16 using 0.2mm layer heights and 4 perimeters.
- 4) Print the gears listed on page 18 using 0.15mm layer heights and 4 perimeters.
- 5) Print the miscellaneous components listed on page 17 using 0.2mm layers and 4 perimeters
- 6) Refer to the gear and spacer cross reference charts on pages 19 and 20.
- 7) Follow the pre-assembly cleanup steps shown on pages 23-26.
- 8) Component pre-assembly construction steps are on pages 28-39.
- 9) The step-by-step process of adding the gears is on pages 40-47.
- 10) Weight shell information is on pages 48-50 after determining how much your clock needs.
- 11) Additional debug steps are on pages 52-54.

Details

Moon Phase

The moon phase dial is the most distinctive feature of this clock. It shows the transition from a new moon to a full moon and back to a new moon over a 29.5 day cycle. Many grandfather clocks place the moon dial above the main dial, but this would block the view of the escapement which is another prominent feature in my clocks. Inside the main dial seemed like a natural place for the moon dial.

I looked through several clock books looking for examples of moon phase dials. About 1/3 of the old grandfather clocks have a moon dial above the main dial. Only a few have a tiny moon dial inside the main dial. I decided to make the moon phase be the primary focus of this clock by making it as large as possible in the center of the main dial. I really like the look and wonder why this is not more common.

New gears were needed for the moon dial. The moon follows a 29.530588853 day cycle around the earth. This is rounded down to 29.5 days allowing 0.030588853 days of error every 29.5 days. This adds up to just one day of error every 964 days which is quite reasonable.

The moon dial has two moons, one visible and one hidden. This allows a visual image to transition from a small sliver near the new moon to a fully visible full moon and back to a small sliver. Images of globes are used to block the view during each new moon. A moon dial with two moons will make one half of a rotation every 29.5 days or one full rotation every 59 days. The gearing starts at the hour hand which rotates once every 12 hours, so the moon dial needs to be geared down by a factor of 118:1 relative to the hour hand. The simplest gear ratio uses a 59:6 and a 60:5 set of gears. The 5 and 6 tooth pinions are unusual, but they work when the small pinion is driving a larger gear.

The biggest challenge in this design was making the new gears fit into a clock. The traditional method in grandfather clocks appears to add them above a fully functional clock module. An intermediate plate could be used to isolate the new gears, but this adds extra complexity to a 3D printed clock. I wanted the new gears to be integrated within the main set of gears. The hour hand gears already integrate without using an intermediate plate. I used a similar method to integrate the new moon phase gears.

The 59:6 and 60:5 gear sets have nearly the same tooth size as the existing 54:12 gears in the clock. They integrate nicely using the same arbor spacing. The 59 and 60 tooth gears are larger than the existing 54 tooth gears. This is offset by the smaller 6 and 5 tooth pinions. The challenge was preventing the largest 60 tooth gear from interfering with the nearby arbors.

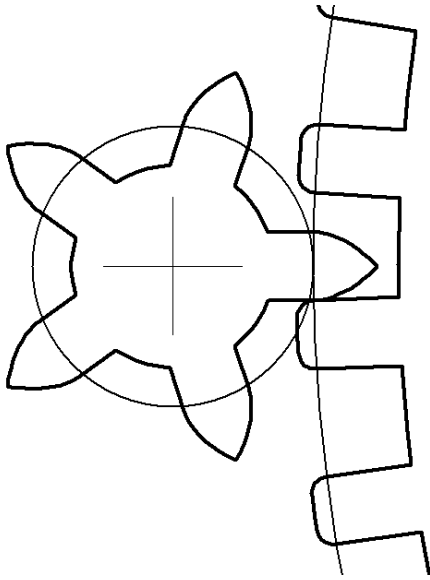


Figure 1: 60:5 gear tooth profile

The solution was to use a modified cycloidal gear shape. The 5 tooth gear drives the 60 tooth gear. In this case, the 5 tooth gear has the active surfaces outside the pitch circle and the 60 tooth gear acts like a large pinion. The active surface on the 60 tooth “pinion” is inside the pitch circle and the tip addendum was reduced as much as possible. This keeps the overall size of the large gear to be as small as possible. The tooth shape was optimized for 3D printing while still maintaining uniform velocity for smooth operation.

A similar gear profile was made for the 59:6 ratio gears. The sizes of these gears work great and integrate perfectly with the other 54:12 gears in the clock.

Perfect Print Gears

The large version of this clock used a modified “fancy gear” profile that was first described on a web site called “Gary’s Wooden Clocks”. The web site is now gone, but the basic concept is that clock gears only rotate in one direction and the back side of each gear tooth can have any shape as long as it doesn’t interfere with any other gear teeth. I have been optimizing the concept to make 3D printed gears that allow fast printing with minimal retractions. Reducing retractions helps minimize stringing on the gear teeth so the important surfaces are as smooth as possible.

This design changed the gears to “Perfect Print Gears”. They use a modified cycloidal profile with enhancements for 3D printing.

The oldest known clocks used hand cut variations of cycloid gears. This style works great with traditional gears and lantern style pinions. The traditional gear tooth profile has been optimized over many centuries for use in clocks. Some of these clocks are still in operation today, so obviously the gears are efficient. The typical usage in a clock has a large brass gear with a small steel pinion. The pinion teeth appear to be small and delicate, but they are made from hard steel that wears well against the large softer brass gear teeth. Brass against steel is somewhat self-lubricating so these gears can last for centuries when used in a clock.

Below is a closeup of a traditional 40 tooth brass epicycloidal gear meshing with an 8 tooth steel pinion. It works great in brass and steel.

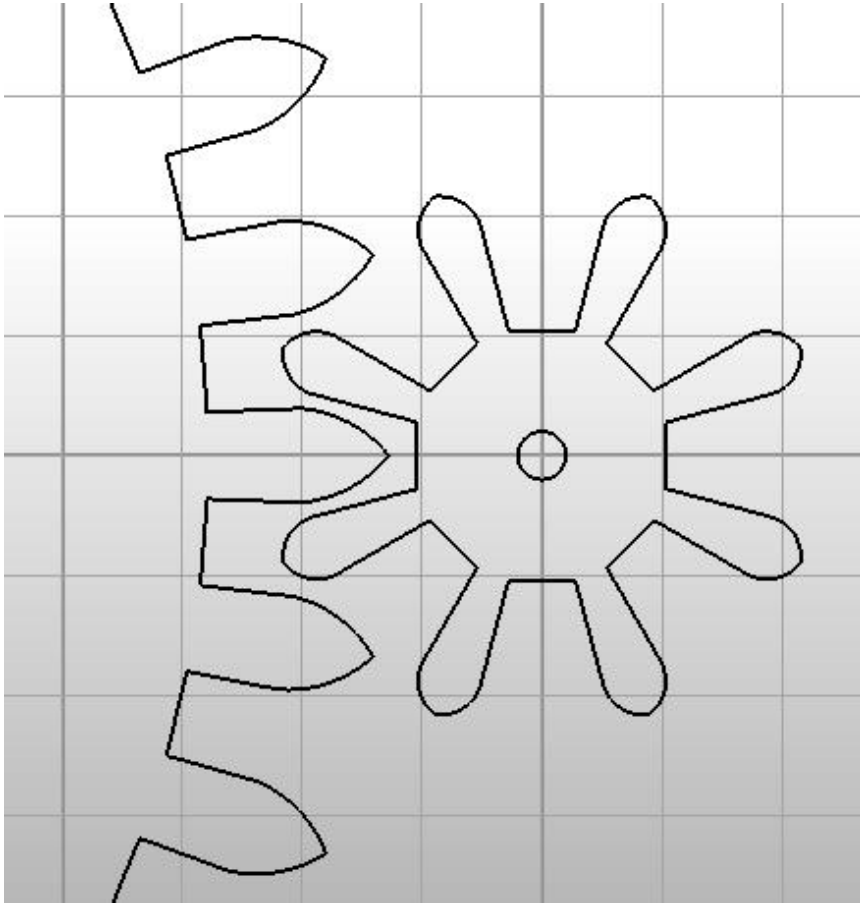


Figure 2: Traditional cycloid gear

Unfortunately, the results are not so great when 3D printed. The slicer output is shown below. The large gear is acceptable, but the pinion is a mess. The pinion teeth are way too delicate and would certainly wear out quickly if they are made from the same material as the larger gears.

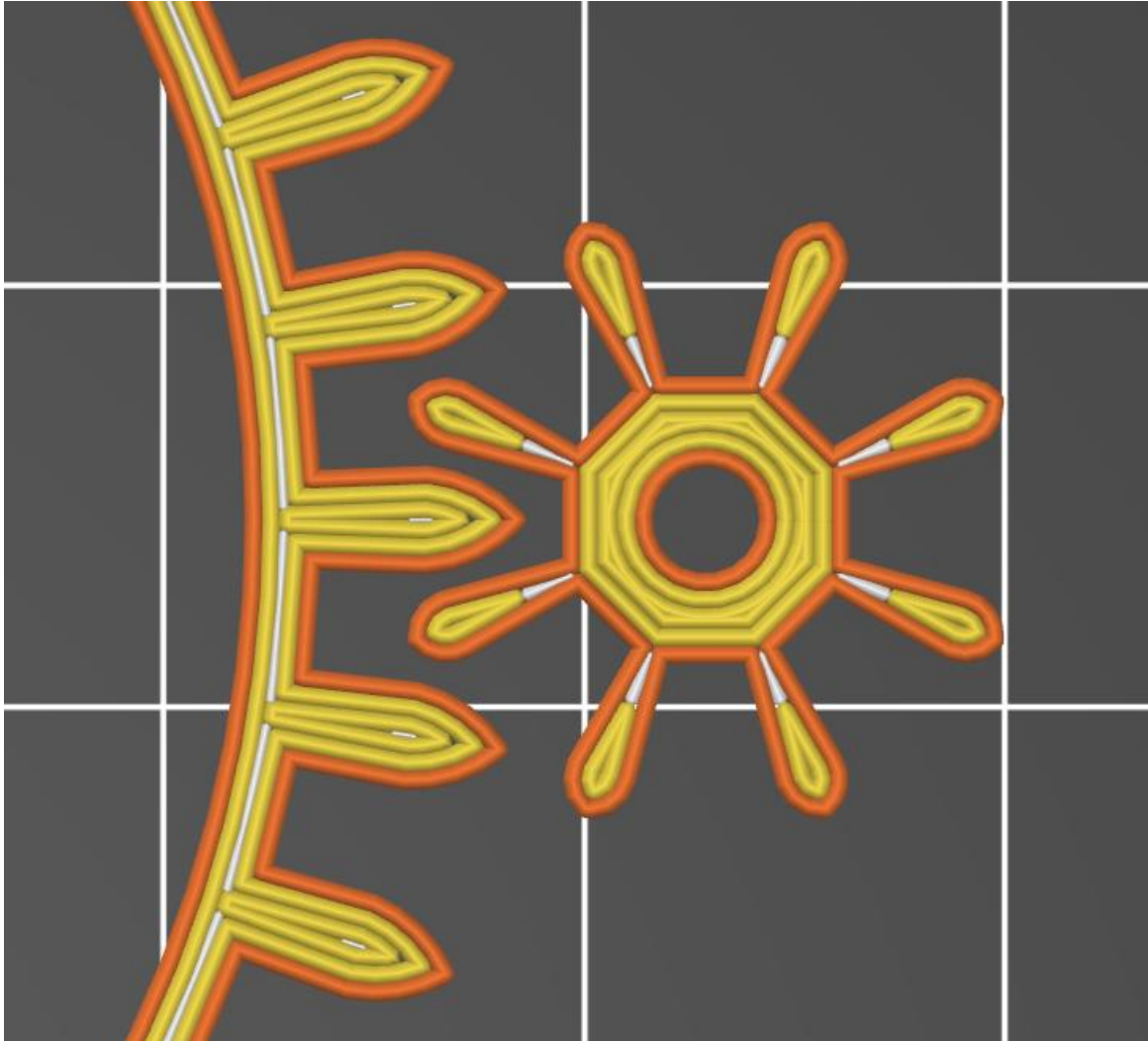


Figure 3: Traditional cycloid gear slicer output

Several changes are required to make these gears work in a 3D printer. The pinion needs to be made much thicker to give it some strength. The main gear was made slightly narrower to give some extra space. Backlash was also reduced. The result is better, but not perfect. The pinion leaves are a bit weak at the base and each tooth requires several retractions while printing. The pinion would likely have extra stringing or blobs as it prints. Even the large gear has a few retractions to print the wide portion of each tooth.

The modifications for 3D printing were based on two primary criteria. The gears must have constant velocity and low friction. Constant velocity implies that if the input gear rotates smoothly, then the output gear must also rotate smoothly. Low friction is an obvious requirement for efficient power transfer. These two criteria work together. Gears designed with constant velocity will typically have low friction. A secondary design criteria is ease of printing. This is a desirable characteristic, but not necessarily required.

The gear tooth profile used in these clocks was designed with uniform width side walls that print cleanly and a tooth tip that provides constant velocity. The result is shown below. Notice the clean the filament paths. All the pinions in these clocks have at least 12 teeth so they do not need to extend into the primary gear. Most of the tooth engagement takes place with the primary tooth touching the pinion side walls after the line of centers, so friction is minimized. I call them “Perfect Print Gears”.

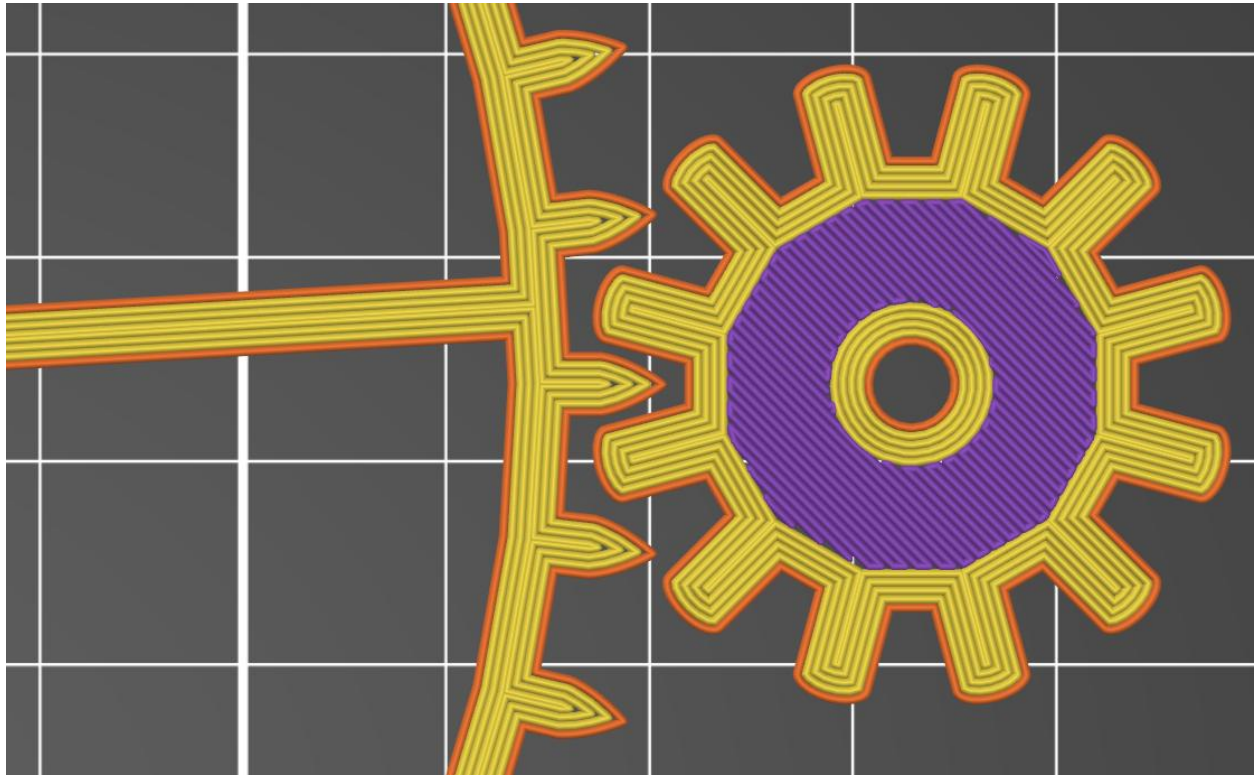


Figure 4: Perfect Print Gear slicer output

Many of my older clocks use involute derived “fancy gears”. They were optimized to print cleanly, but still suffered from what I call “sticky gears”. Everything would work for a while, then the escapement would slow down. I believe that this was caused by the additional friction when the involute gears engage before the line of centers. The clock would likely keep working if the gears were made using brass and steel pinions, but 3D printed gears could be sticky. A quick fix is to grease the pinions, so the teeth slide past each other when engaging. The release of this clock has been waiting for a cycloidal derived “perfect print gear”.

The perfect print gears appear to be much more reliable when used in a 3D printed clock. I have already updated several of my oldest clocks to use perfect print gears. The result is a huge increase in reliability. The clocks run better using a slightly smaller drive weight. And more importantly, they are significantly less likely to randomly stop running. This is all due to the switch to cycloidal “perfect print gears”. Over time, I will convert more of my clocks to use this gear tooth profile.

Clock Overview

A pendulum clock is conceptually very simple. A spring or falling weight provides energy to a pendulum swinging at a constant rate, dependent only on length. A series of gears convert the periodic pendulum motion into a display for the hours and minutes. The challenge is to make everything work elegantly and accurately. I start with a basic sketch of the clock, then fit gears to be as symmetrical as possible.

The total print time is around 70 hours on a Prusa MK4 style printer with input shaping. Around 1.3kg of PLA filament is needed. The non-printed parts are hidden as much as possible. Some basic tools are required, such as screwdrivers, drill bits, files, etc. The skill level required is intermediate to advanced.

The large version of this clock started with involute gear profiles generated using Gearotic and imported into TurboCAD for final adjustments. This clock uses cycloidal style gears optimized for 3D printing. Experiments determined a good size. Involute gear profiles were designed using Gearotic and imported into TurboCAD for final adjustments. One early experiment determined a good gear size. They needed to be large enough to print accurately, but not so large to exceed the capabilities of my printer. I printed various gear sizes ranging from 10 diametrical pitch (mod 2.54) down to 40 DP (mod 0.635). A 60 tooth gear would be 6" in diameter at 10 DP, 3" at 20 DP, and 1.5" at 40 DP. The 40 DP gears were printable with some distortion. Gear tooth pitches between 10 DP and 20 DP seem to work well for 3D printing. This clock uses an intermediate 14.29 DP (mod 1.778) gear size.

The next step is to design the overall gear train. Most pendulum clocks share the same basic structure with differences in the gear ratios. The primary requirement is that the minute hand should rotate once per hour and the hour hand should rotate once per 12 hours. The rest of the design uses simple math to calculate the gear ratios. There is a bit of trial and error to find good gear ratios. Eventually, everything starts looking like a clock. The figure on the next page shows a simplified model of the gear train.

Many clock designs have just one gear between the escapement and the minute hand. This often uses gear ratios of 8:1 and 7.5:1. I chose an alternate design using an additional gear with 5:1 ratios between stages. This has several advantages, primarily the ability to allow 12 tooth pinions with reasonably small tooth counts on the larger gears. This helps reduce friction to enable long runtimes.

The gear ratios selected have the escapement rotating once every 28.8 seconds. A 20-tooth escapement and a 20.32" pendulum length beats exactly 5000 times per hour. These gear ratios were selected to keep the pendulum length proportional to the rest of the clock.

The hour hand gears are separated from the primary gear train using a friction clutch to allow setting the time without affecting the pendulum. Two sets of gears with 54:12 and 48:18 ratios provide the 12:1 reduction between the minute hand and the hour hand. The spring shown on the following diagram indicates the friction clutch used to isolate gear 4b from gear 4a when setting the time.

The moon phase dial starts with a 6 pin gear on the hour hand driving a 59 tooth gear. A second friction clutch drives 5 tooth gear providing power to the 60 tooth moon dial with a 59 day cycle. The extra friction clutch allows the moon phase to be adjusted without affecting the hour hand. It was tricky to integrate without increasing the overall thickness of the clock. The solution was to move the friction clutch below gear 5 even though gear 9 sits above gear 5.

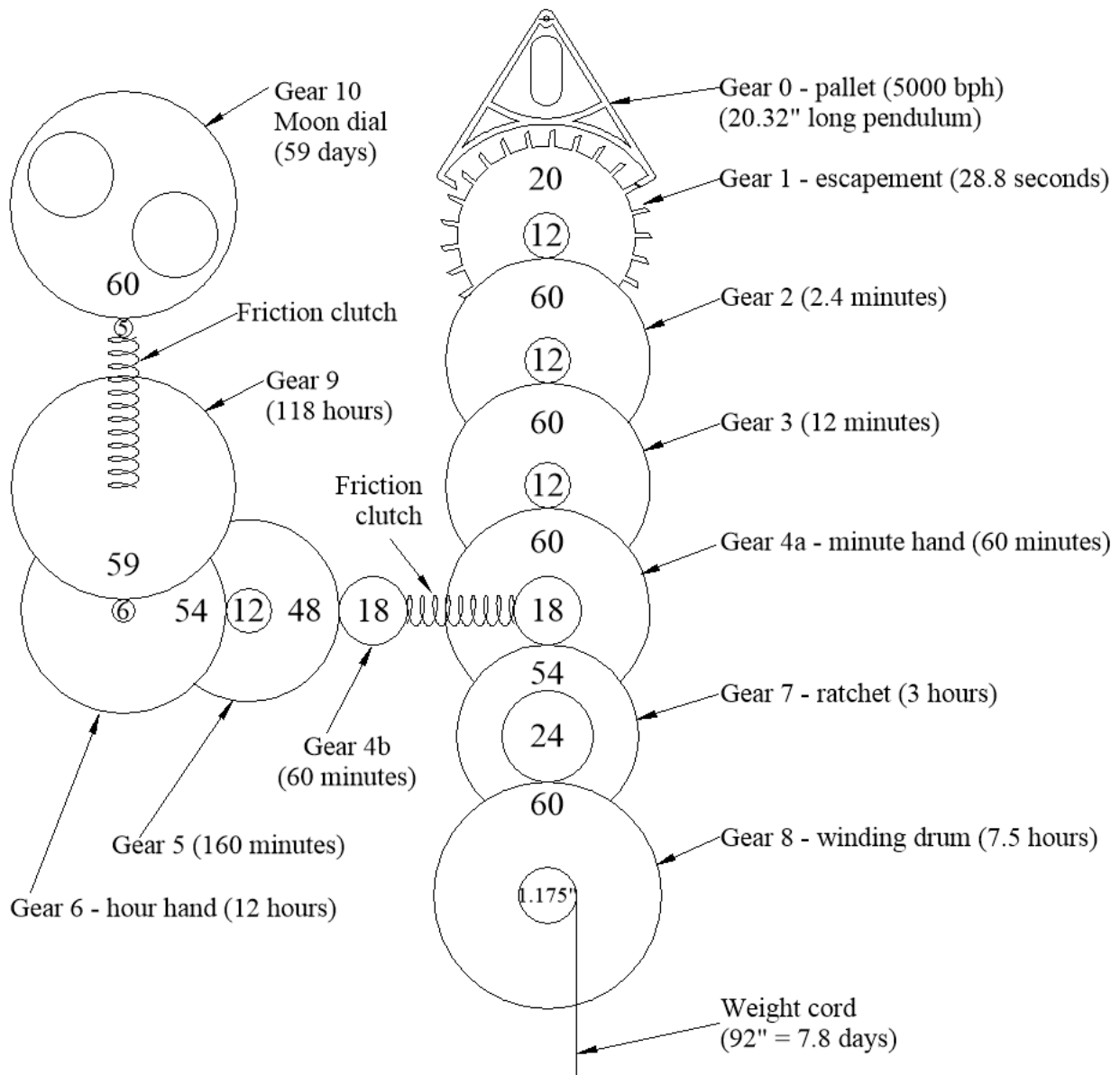


Figure 5: Clock gear train

The next design step is the power train below the minute hand. The target for this design is to wind the clock once per week. Two sets of gears reduce the speed so the winding drum rotates once every 7.5 hours. A 1.175" drum releases 3.69" of cord per revolution or 11.81" per day. The clock hanging at a reasonable height allows 46" of drop before the weight hits the floor. Doubling the effective height using a pulley in the weight shell allows 92" of cord to be released every 7.8 days.

The weight shell pulley provides several benefits in addition to doubling the runtime. It shifts the center of gravity back to the center line so the clock hangs vertically. It also helps guide the cord closer to the middle of the drum when winding.

This clock seems to run great using under a pound of drive weight per day of runtime. My clock uses a 6.5 pound (2.9kg) weight for a 7.8 runtime. Your clock may need more or less weight depending on the gear train friction.

It would be possible to increase the runtime of this clock by reducing the winding barrel diameter. The drive weight would need to be increased proportionately, which would increase the stress on the frame. I decided to keep everything simple and release the clock with the most reliable runtime option of 7.8 days. Winding once a week is very easy to live with.

The clock frame is a two piece shell with front and back segments. The overall frame size requires each frame piece to be split into multiple smaller pieces that join together using a common screw size used throughout the clock. A great thing about 3D printers is the ability to integrate many details into each piece. The arbor locations and support columns are fully integrated with the large flat portions of the frame. A printed keyhole hanger hangs the clock on the wall. The top of the frame has a robust support bar to prevent frame sag from the heavy weight shell. There is even a convenient built-in winding key storage location.

The front frame integrates the dial, numbers, and globes into a single 3D print. This is the largest component at 6.5" diameter that sets the minimum print bed requirement at 166x166mm. Layer based color changes are needed to highlight the globes and the numbers. The remaining frame pieces are smaller than the dial, although some may need to be placed diagonally on some printers.

The pendulum bob is a two-piece clamshell with a few pennies added for weights. The pendulum rod uses simple printed parts that drop into position to create a long pendulum without using glue. It pivots on two small ball bearings with the grease removed to lower the friction. Adjustable nuts below the pendulum bob are used to set the period. One full turn adds or subtracts about 3 minutes per day. It is easy to fine tune the accuracy to within 1-2 minutes per week.

The complete set of gears shown in figure 3 were first arranged for a symmetrical front profile with enough clearances around the dial for the support posts. The oversized 59 tooth gear 9 adds some asymmetry that was balanced by stacking it with gear 5 to match the thickness of the gear 7 ratchet. The clock side profile was used to finalize the gear thicknesses and positions. Some parts were nested together to minimize the overall thickness. For example, gear 10 sits inside some of the frame segments, and the hour hand sits below the surface of the dial.

One challenge in this design was the integration of the moon dial friction clutch without increasing the thickness of the frame. The hour hand gears are naturally close to the main dial and the moon phase gears need to be in front of them. The friction clutch needs to either be on the central arbor or the gear 5 arbor. The central arbor already has a friction and no room for another. Adding the moon phase friction clutch between gear 5 and gear 9 would have added a lot of extra thickness. Instead, the gear 9 shaft was passed through gear 5 where there is plenty of room for the friction clutch. These gears rotate slowly, so extra friction of PLA turning inside PLA is not a concern.

Printing the Parts

Most of the parts in this clock are easy to print. Just pick a color and print them. The main dial and moon gear require some color changes to look their best. This was made as simple as possible using layer based color changes. Many recent 3D printers can automatically print using multiple colors, but this clock can easily be printed using a single color printer. In fact, I only own single color printers.

The gear 10 moon dial needs a color change to highlight the moon and stars. There are three options for a flat (2D) moon, a 3D moon, or a screen capture from Georges Melies 1902 film "A Trip to the Moon". Each option looks different depending on your filament and where the layer change occurs. Experiment with `test_cookie_moon_flat`, `test_cookie_moon_3d`, and `test_cookie_man` to find the one that works best. They are designed to print with 0.15mm layers (and a 0.20mm bottom layer). The color change should occur at either 1.70mm or 1.85mm. The same layer heights for color changes should be used for gear 10. The test cookies are in the misc subdirectory of the zip file.

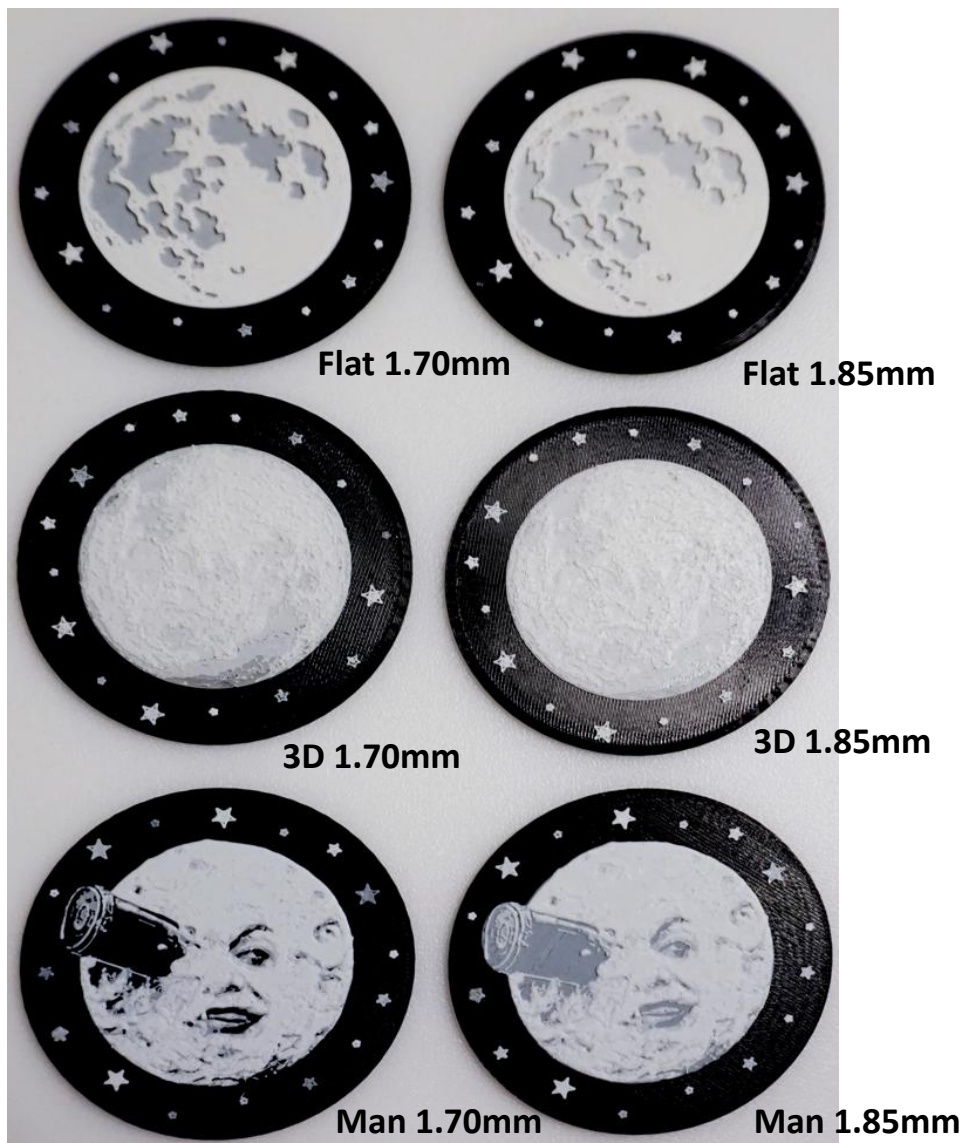


Figure 6: Moon gear test cookies

The dial can also receive color changes to highlight the globe and numbers. The dial can be printed using 0.20mm layer heights similar to the rest of the frame. Test_cookie_globe1 and test_cookie_globe2 can be used to find good colors and layer heights for the globes. The complete set of color changes for the globes is shown below. Use the same layer heights for frame_dial_roman, plus additional changes back to white at 4.20mm and finally black at 12.80mm for the main dial numbers



Dial layer changes:

0.00mm White

2.80mm Blue

3.20mm Brown

3.80mm Black

Not shown:

4.20mm White

12.80mm Black

Figure 7: Dial globe test cookies

The components to print for this clock have been divided into subdirectories in the zip file to help keep parts organized. The frame, gears, and weight shell each have their own subdirectory. Everything else is in the misc subdirectory.

I use two printer presets for all of my clocks. Most parts use a preset with 0.20mm layer heights, except for the gears that should work better with 0.15mm layers.

Printer characteristics:

Material	PLA
Nozzle Size	0.4mm
Starting Preset	0.20mm STRUCTURAL in PrusaSlicer
Layer Height	0.2mm for most parts (gears should use 0.15mm)
Perimeters	4 for most parts
Top Layers	7
Bottom Layers	6
Seam Position	Random
Scarf Joints	Enable this feature if it is available in your slicer
Perimeter Generator	Arachne for most parts (gears should use Classic)
Fill Density	25%
Fill Pattern	Cubic or other strong infill pattern
Elephant Foot	0.25mm (look at the slicer to determine what works best)
Supports	Never needed for any parts in any of my clocks
Orientation	Usually already optimal. Some parts may need to rotate to fit your bed.

Some of these settings may be overkill, but you only need to print the parts once and you will be able to enjoy the clock for many years. There is a preset for SPEED that is about 20% faster than STRUCTURAL, but I recommend STRUCTURAL for higher accuracy.

I print all my clocks on Prusa machines. Any modern printer can print these clocks as long as the bed is large enough. The 6.5" (165.1mm) dial needs a bed size that is at least 166x166mm. I use two printers working together to make everything go faster. One printer makes the frame and the other printer makes the gears. The first printer to finish starts printing the miscellaneous parts. The weight shell can be saved until after you test how much weight your clock needs.

Below is the lists of parts to print. The colors listed are what was used to print most of my clocks. You are free to go wild with any other colors you like.

Frame Parts

The frame is often printed in a neutral color so the primary focus can be on the gears and moon dial. The frame dial needs a few color changes for highlights. The frame can be printed using 0.2mm layer heights with 4 perimeters and 25% infill for strength.

Part Name	Color	Print	Notes
frame_back_center	tan	1	
frame_back_lower	tan	1	
frame_back_standoffs	tan	1	
frame_back_upper_a	tan	1	
frame_back_upper_b	tan	1	
frame_dial_roman	many	1	Needs several layer changes to highlight the globes and numbers. Use the test cookies to determine colors and layer heights that look good plus an additional change near the top for the numbers.
frame_front_lower_a	tan	1	
frame_front_lower_b	tan	1	
frame_front_upper_a	tan	1	
frame_front_upper_b	tan	1	

Table 1: Frame components to print

Gears

The gears will work better using finer 0.15mm layer heights. The thinner layers take slightly longer to print, but friction should be reduced because the layer line ridges should be smaller. Everything else in the clock works fine using 0.20mm layers.

IMPORTANT DETAIL: The gear in this clock are designed to use the classic slicer. Some of my other clocks are optimized for Arachne, but the algorithm kept changing and adding in extra retractions. It became impossible to keep up with so many Arachne algorithm changes, so I switched the gears back to the classic slicer. Everything except the gears can use Arachne if you want.

The gears print best using 4 perimeters.

Most gears can be any color you like. Dual color silk PLA looks great. The cover photo uses red/blue silk PLA that changes color as the gears rotate. I used to use MatterHackers Blue Raspberry Quantum PLA, but recently switched to Eryone red/blue dual color silk PLA for less than half the price. There are many other color combinations that should look just as nice.

Most gears are simple prints. Gear 10 with the moon dial needs a color change to switch from a dark background to a lighter color for the moon and stars.

Part Name	Color	Print	Notes
gear_spacers	red/blue	1	All spacers in one file
gear0_pallet	red/blue	1	
gear1_20_12_esc	red/blue	1	
gear2_60_12	red/blue	1	
gear3_60_12	red/blue	1	
gear4a_60_18	red/blue	1	
gear4b_18	red/blue	1	
gear5_48_12	red/blue	1	
gear6_54_6	red/blue	1	
gear7a_54_ratchet	red/blue	1	
gear7b_24	red/blue	1	
gear7c_clicks	red/blue	1	
gear8_60_8days	red/blue	1	
gear9a_59	red/blue	1	
gear9b_5	red/blue	1	
gear10_60_moon_3d	black, white	1	Select one of these with color changes at 1.70mm or 1.85mm. Use the test cookies to determine which one you like best.
gear10_60_moon_flat	black, white		
gear10_60_moon_man	black, white		

Table 2: Gears to print

Miscellaneous Parts

All the random parts used in the clock are included in the misc directory. The optional test cookies have already been described. All of the other parts are required to build the clock.

Part Name	Color	Print	Notes
hand_gothic_hour_loose	copper	1	Start with the normal hour hand and select a different fit if needed
hand_gothic_hour_normal	copper		
hand_gothic_hour_tight	copper		
hand_gothic_minute_loose	copper	1	Start with the normal minute hand and select a different fit if needed
hand_gothic_minute_normal	copper		
hand_gothic_minute_tight	copper		
pendulum_arm_lower	tan	1	
pendulum_arm_mid_a	tan	1	See notes
pendulum_arm_mid_b	tan	1	See notes
pendulum_arm_upper	tan	1	
pendulum_bob_back	copper	1	
pendulum_bob_front	copper	1	
pendulum_nuts	tan	1	
swing_gauge	black, white	1	Needs a layer change at 2.2mm
test_cookie_*	multiple	???	Sample parts used to determine moon and globe colors
winding_key_arm	tan	1	
winding_key_knob	copper	1	

Table 3: Miscellaneous part to print

Notes:

The pendulum arm is composed of four segments. The upper and lower pieces are a fixed size. The two middle segments help determine the overall length. The theoretical length for a 5000 bph pendulum is 20.32". The actual length will be longer because of the mass of the arm. Different arm densities could need longer or shorter middle arm segments. My clock operates at the correct rate using one copy of pendulum_arm_mid_a and one copy of pendulum_arm_mid_b. They are different lengths, so you can use two copies of mid_a to slow the clock down or two copies of mid_b to speed up the clock if needed.

Weight Shell

The weight shell is the last component to be printed. It can wait until the rest of the clock is completed and you have tested how much weight is actually required. More details are later in this manual.

File Name	Color	Print	Time	Filament	Notes
weight_shell_bottom_2p4	Gold	0	0h 47m	10.88g	2.4" diameter weight shell
weight_shell_top_2p4	Gold	0	9h 57m	96.05g	
weight_shell_short_2p4	Gold	0	8h 29m	81.17g	
weight_shell_quarter_2p4	Gold	0	5h 20m	47.32g	
weight_shell_bottom_2p6	Gold	0	1h 0m	14.05g	2.6" diameter weight shell
weight_shell_top_2p6	Gold	0	11h 0m	107.32g	
weight_shell_short_2p6	Gold	0	9h 19m	90.12g	
weight_shell_quarter_2p6	Gold	0	5h 47m	51.98g	
weight_shell_bottom_2p8	Gold	1	1h 12m	17.49g	2.8" diameter weight shell
weight_shell_top_2p8	Gold	1	12h 5m	119.19g	
weight_shell_short_2p8	Gold	0	10h 10m	99.56g	
weight_shell_quarter_2p8	Gold	1	6h 14m	56.81g	
weight_shell_bottom_3p0	Gold	0	1h 26m	21.34g	3.0" diameter weight shell
weight_shell_top_3p0	Gold	0	13h 13m	132.04g	
weight_shell_short_3p0	Gold	0	11h 3m	109.72g	
weight_shell_quarter_3p0	Gold	0	6h 40m	61.62g	
weight_shell_bottom_3p2	Gold	0	1h 41m	25.62g	3.2" diameter weight shell
weight_shell_top_3p2	Gold	0	14h 28m	145.49g	
weight_shell_short_3p2	Gold	0	12h 5m	120.36g	
weight_shell_quarter_3p2	Gold	0	7h 10m	66.52g	
weight_shell_pulley	Gold	1	0h 29m	4.76g	Pulley used for all sizes
Total		4	20h 0m	198.25g	

Table 4: Weight shell parts to print

Here is an image of the spacers used in the clock. They print as a single file, gear_spacers.stl. They will be referenced in this document as spacer_{arbor_number}. The numbers in the diagram below indicate the gear each spacer is associated with. For example, spacer_0 goes on the same arbor as gear0_pallet.

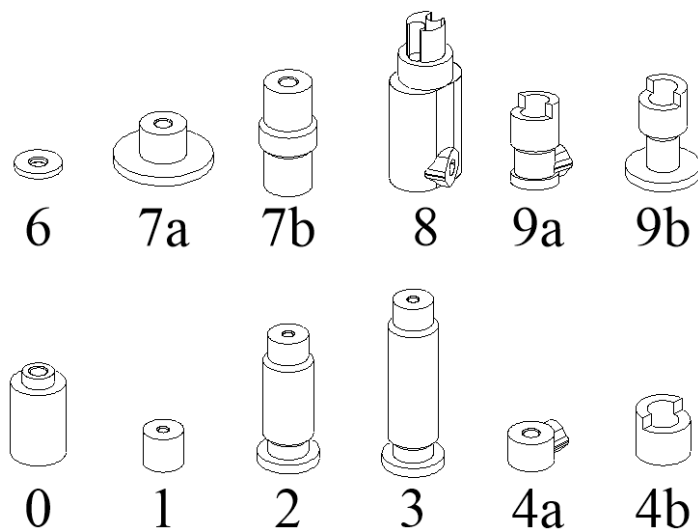


Figure 8: Spacer reference chart

Here is a summary of the gears used in the clock. The names include the arbor number and gear tooth counts to help identify them. This diagram shows the “fancy gears” from an early design. The updated “perfect print gears” look nearly identical except for the shape of the gear teeth.

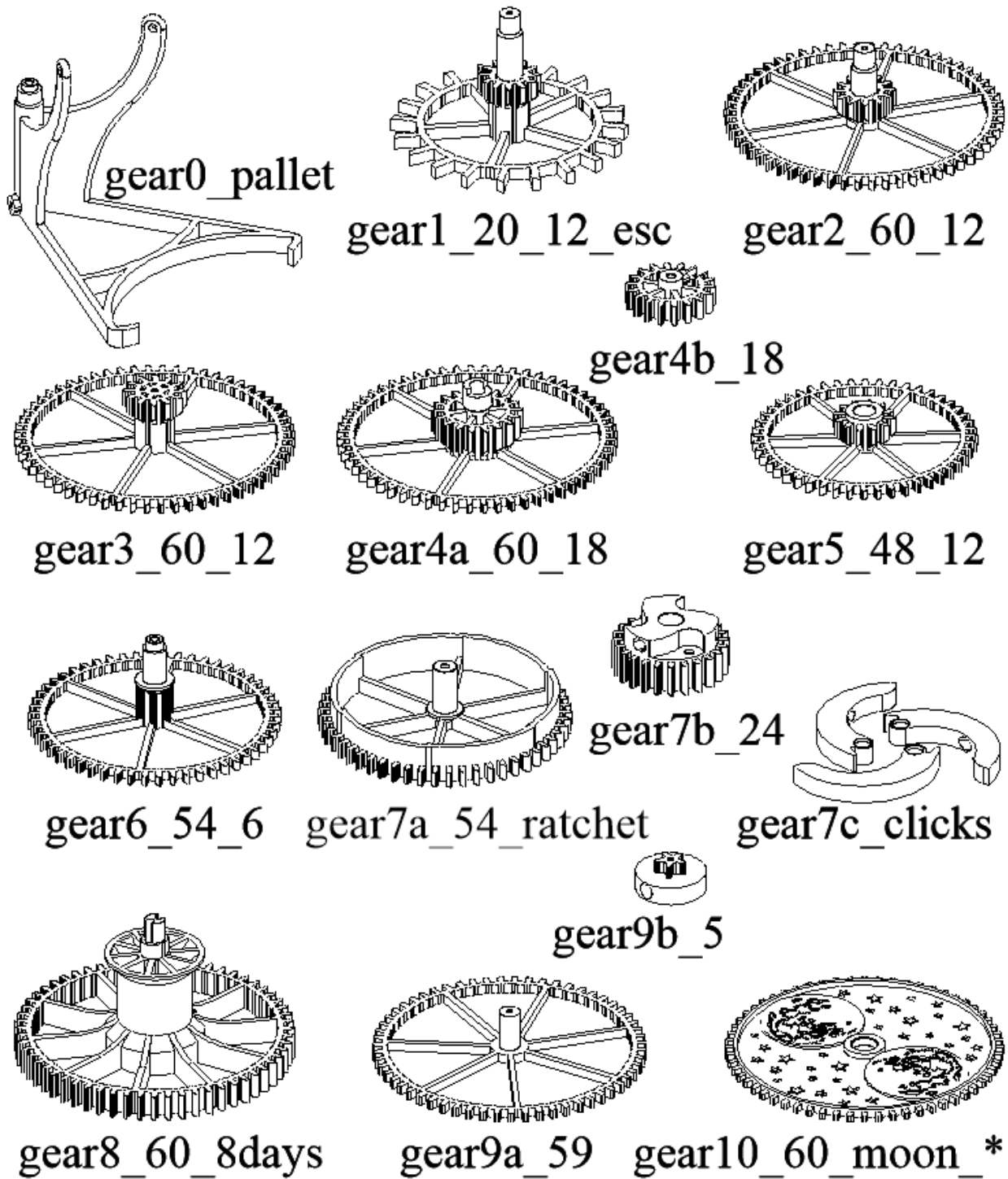


Figure 9: Gear reference chart

Additional Components

This clock consists mainly of 3D printed parts, but a few metal components are required to minimize friction so the clock can have a long runtime. The bill of materials has been reduced as much as possible. Several hard to find parts have been eliminated and the screws have been consolidated to a small number of sizes.

Small ball bearings and metal arbors have been used to reduce friction in a few critical locations. A clock built completely from 3D printed parts would have higher friction and shorter run times. 1/16" music wire is much stronger and significantly lower friction than a printed PLA arbor. Steel screws are much stronger than printed screws. I tried to keep most non-printed parts hidden as much as possible.

The following non-3D printed components are required. Part numbers from McMasterCarr are provided for some parts although many can be found cheaper at your local hardware store, Amazon, or eBay. Many parts can be substituted with the closest metric or imperial size. For example, the arbors can use either 1.5mm (0.059") or 1/16" (0.0625") music wire. I prefer 1.5mm because a 1/16" (1.6mm) drill bit can be used to clean up the holes leaving the perfect amount of clearance.

Parts kits for all the non-printed parts except the weights are available on Etsy if you want to avoid finding all the parts. Check the main description where the model was purchased for a link.

Qty	Component	McMC Part No.	Notes
37	#6x3/4" flat head wood screw	90031A151	Metric equivalent is M3.5x20mm
1	#8x1-1/2" or #8x1-1/4" pan head wood screw	90190A203 90190A201	For mounting clock on wall, metric equivalent is M4.2x32-38mm
10	M3x8mm socket head screws	91292A112	M3x10mm may also work
24" (60cm)	3mm stainless rod	1272T33	Brass or plain steel rod should be OK. See cut list
14" (36cm)	1/16" or 1.5mm music wire	89085K85	Either 1/16" or 1.5mm diameters can be used. See cut list
12' (3.6m)	microfilament fishing line		I use PowerPro Spectra Fiber braided fishing line 65 lb. test. Other brands of braided line are OK
~8 lb.	lead shot or BBs		BBs are safer than lead shot and only need a slightly larger weight shell
2	608 bearing		Generic skateboard bearings
3	623RS bearing (3x10x4mm)		Used to support the pendulum.
5	click pen springs		Used for ratchet and friction clutches

Table 5: Non-printed parts

Low friction bearings used to support the pendulum are critical to reduce friction on the fastest moving part. I find that cheap 623RS bearings available for around US\$8 for 10 work great. The rubber seal is easy to remove for cleaning out the thick factory grease. The larger 608 bearings used in the winding barrel are commonly called skateboard bearings. Any quality is acceptable since they rotate very slowly.

Metal Cut List

The following diagram can be used to cut the metal parts. The gears near the escapement use small diameter 1.5mm or 1/16" music wire to reduce friction. Either size is acceptable. Music wire needs to be cut with a hardened cutter. An abrasive Dremel cut-off disk also works.

All other metal rods are 3mm in diameter. Stainless steel works best, but brass or plain steel should also work. The minute hand arbor needs a flat notch filed at one end to fit into the minute hand.

Cut all metal pieces and clean up the ends by rotating them while gently touching them to a bench grinder or sanding disk.

Cut Metal Parts

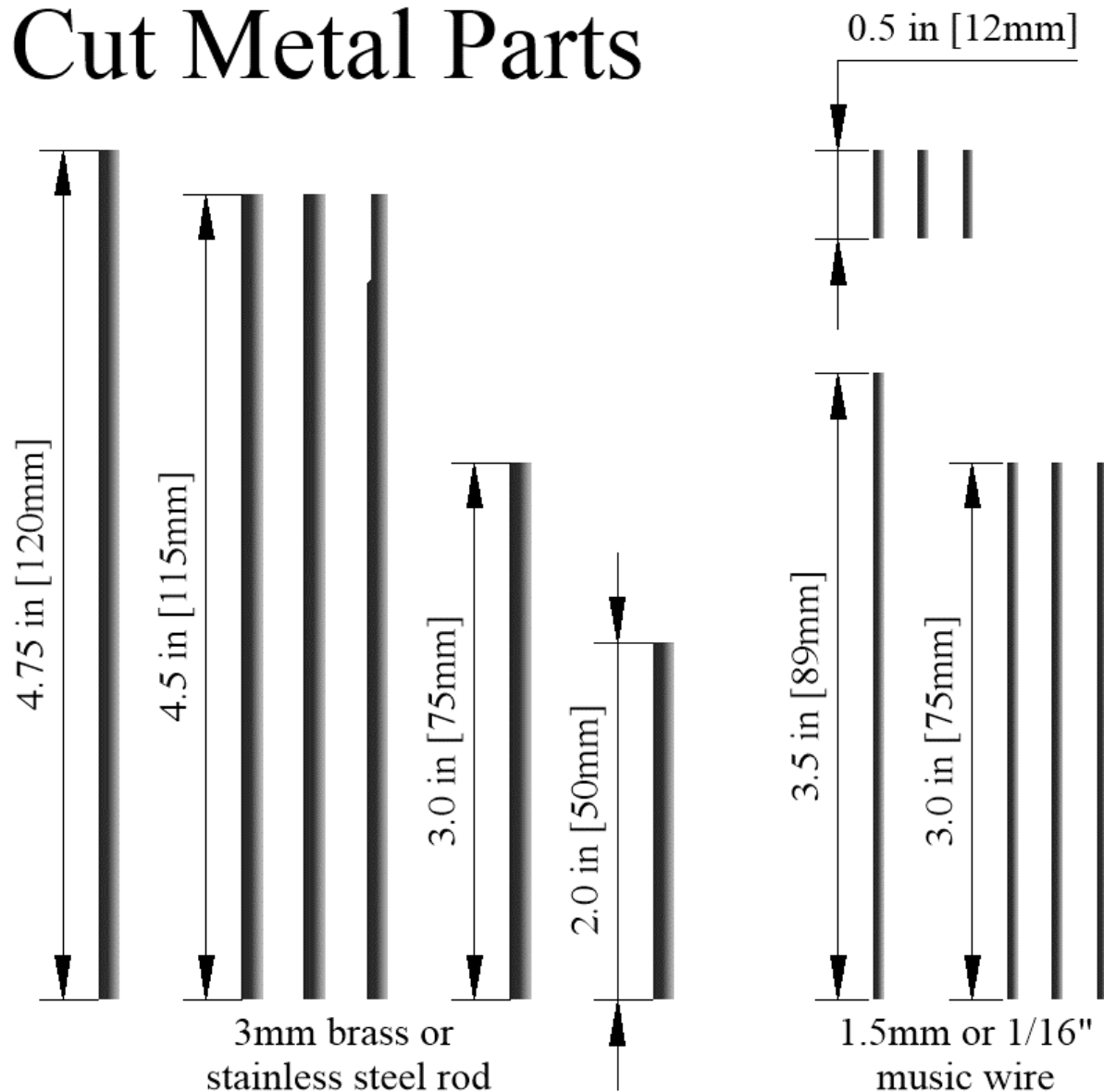


Figure 10: Cut metal parts list

Component Pre-Assembly

IMPORTANT: This section will guide you through the process of getting the components ready to build the clock. You may be eager to rush in and start putting the clock together, but more effort spent in this section of the assembly process will reduce debug time later.

You will need:

- 3D printed frame parts
- 3D printed gears
- 3D printed pendulum arm and bob
- Pennies or small weights for the pendulum bob
- Screws and bearings from the “additional components” list
- Phillips head screwdriver and hex key to match M3x8mm screws
- Cut metal arbors with the ends de-burred
- 1.6mm (1/16”) drill bit
- 3.2mm (1/8”) drill bit
- Pin vise or slow speed hand drill

Optional tools:

- Sandpaper or small hand files

Most of the 3D printed parts will be assembled in this section, with the exception of the weight shell. It can be printed later after the clock is hanging and you can determine how much weight your clock needs to run reliably.

Component Pre-fit

The most important step in reducing friction is to dry-fit the components and make adjustments as needed. The first step is to drill the arbor holes to the proper sizes. 3D printers often make holes smaller than expected. The easiest solution is to drill them to the proper fit. I use small pin vises to manually drill through the center of each gear. A power drill will also work, but go slowly to avoid melting the part.



Figure 11: Pin vise

Drill the ends of every gear to the proper size. The gears are designed so only a short portion from each end needs to be drilled out. The middle portion opens up to provide extra clearance around the arbor. Use a 1/16" or 1.6mm drill bit for the 1.5mm arbors and a 1/8" or 3.2mm drill bit for the 3mm arbors. This provides the proper amount of clearance without being too loose.

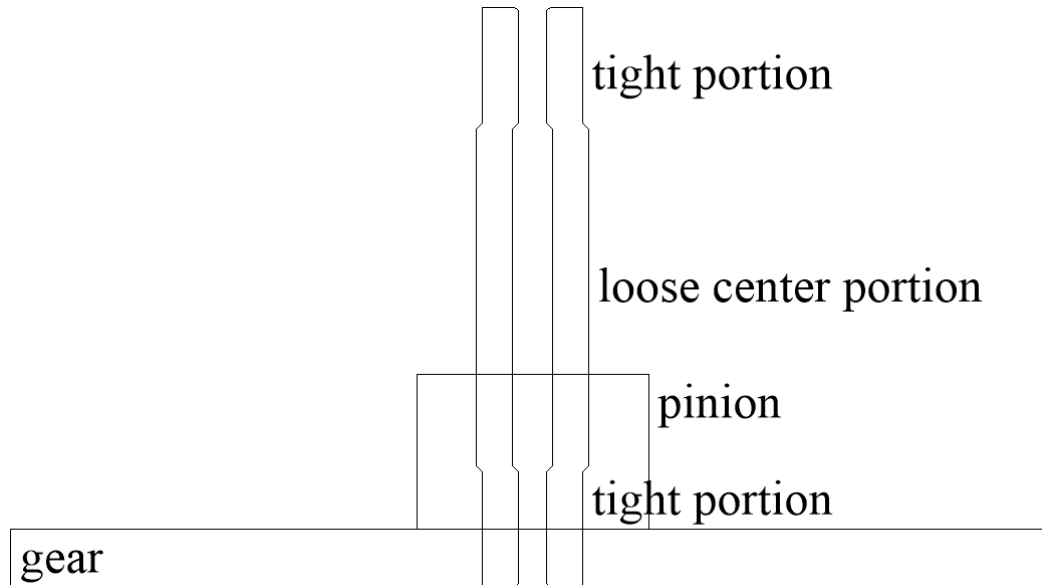


Figure 12: Gear side profile

Drill both ends and blow through the hole to clean out the swarf. Test each gear by spinning it on an arbor. Gears with properly sized holes should spin for 10-20 seconds. If it slows quickly, then drill it again. It will be obvious when the hole has enough clearance.

There are a few 3D printed parts that need to move inside other printed parts when the clock is running. They need to be checked for the proper fit and adjusted if needed. Use hand files or sandpaper to adjust the sizes of either component until the parts rotate smoothly. These parts involve PLA rubbing against PLA, so feel free to add a light coat of lithium grease to the sliding parts.

Note: Many of the diagrams in this manual were copied from the SP14 large moon phase clock assembly guide. The parts are similar, but not exactly identical. Diagrams were updated where it was needed for clarity. For example, the lower back frame has two pieces in SP14, but only a single piece in SP15. The diagram showing the back frame assembly was updated for SP15, but many of the diagrams using the back frame still show SP14. It should be easy enough to follow along.

Check the following 3D printed parts for proper fit. Sand or file the gear shafts until they fit easily. A light coat of grease is acceptable.

Gear 6 (hour hand gear) needs to rotate where it passes through the dial. Gear 6 is highlighted in red. It rotates slowly, but excess friction here may allow the pendulum to swing, but the time will not change.

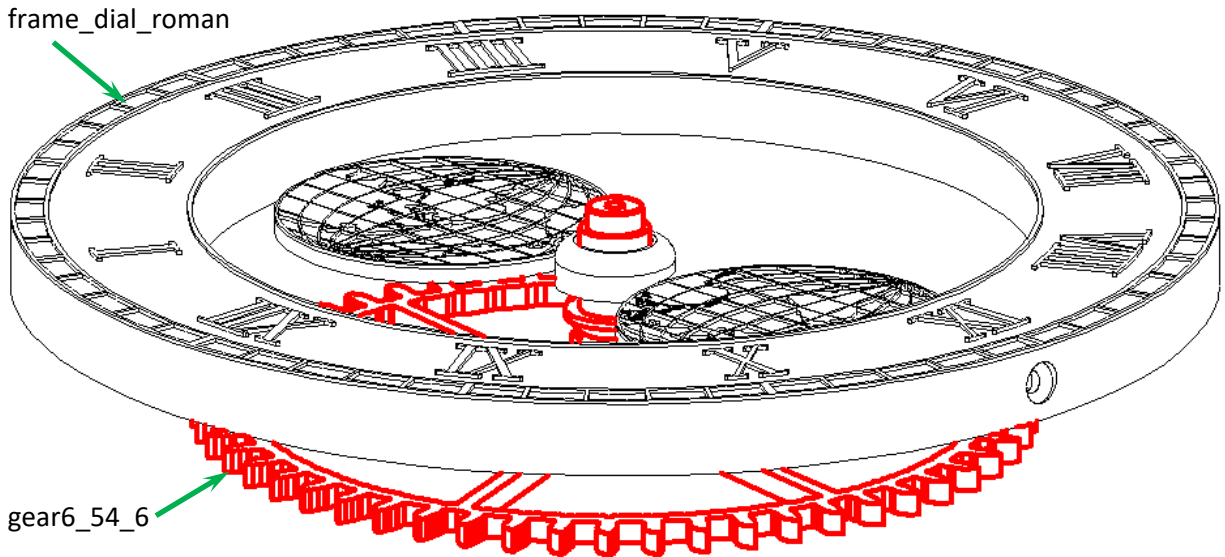


Figure 13: Gear 6 fit into main dial

The gear 10 moon dial also needs to fit over gear 6 and rotate.

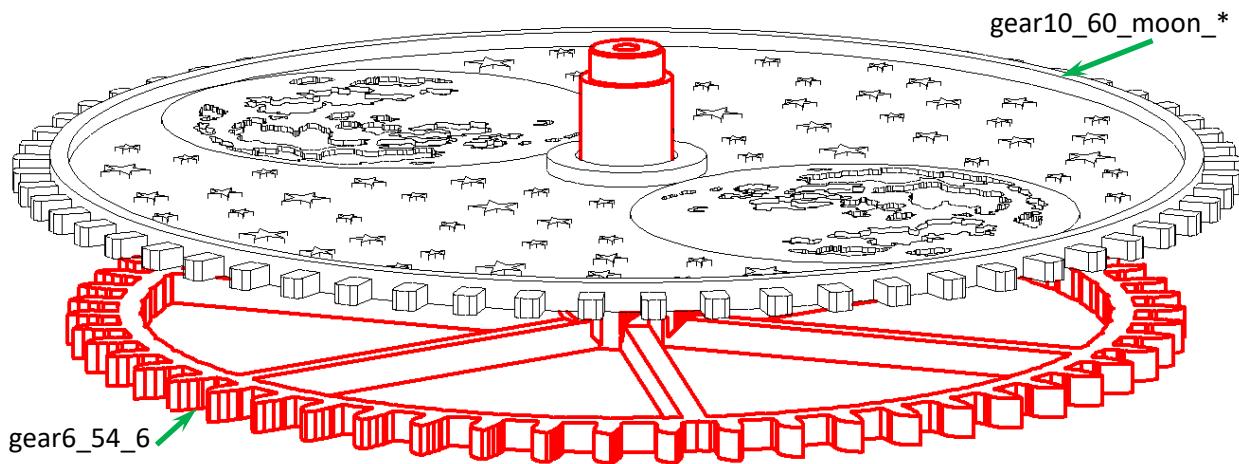


Figure 14: Gear 10 fit onto gear 6

The shaft on gear 9a needs to fit into the large hole in gear 5 (highlighted red).

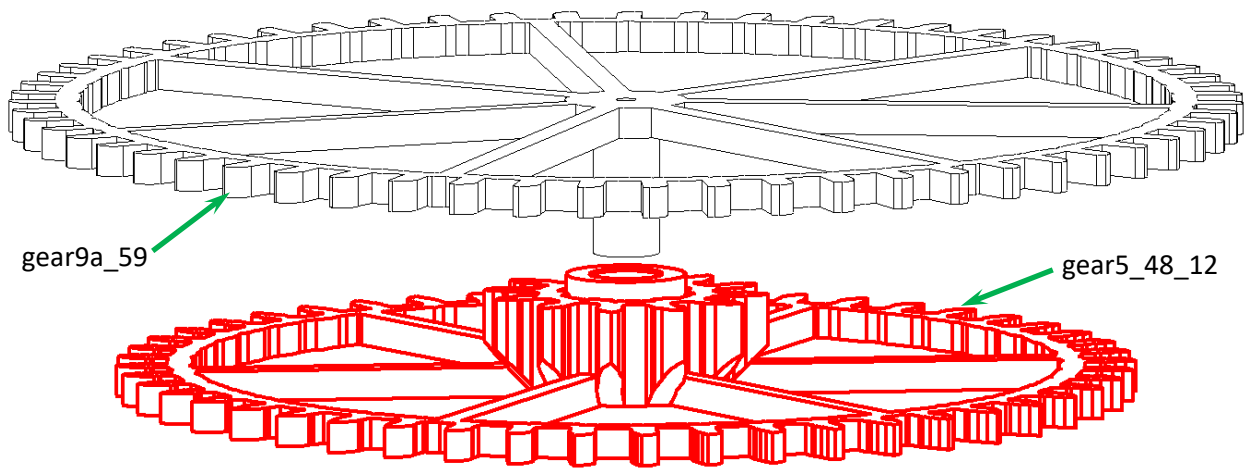


Figure 15: Gear 9 fit into gear 5

And gear 7b needs to fit over the center post of gear 7a (highlighted red). It must be able to rotate.

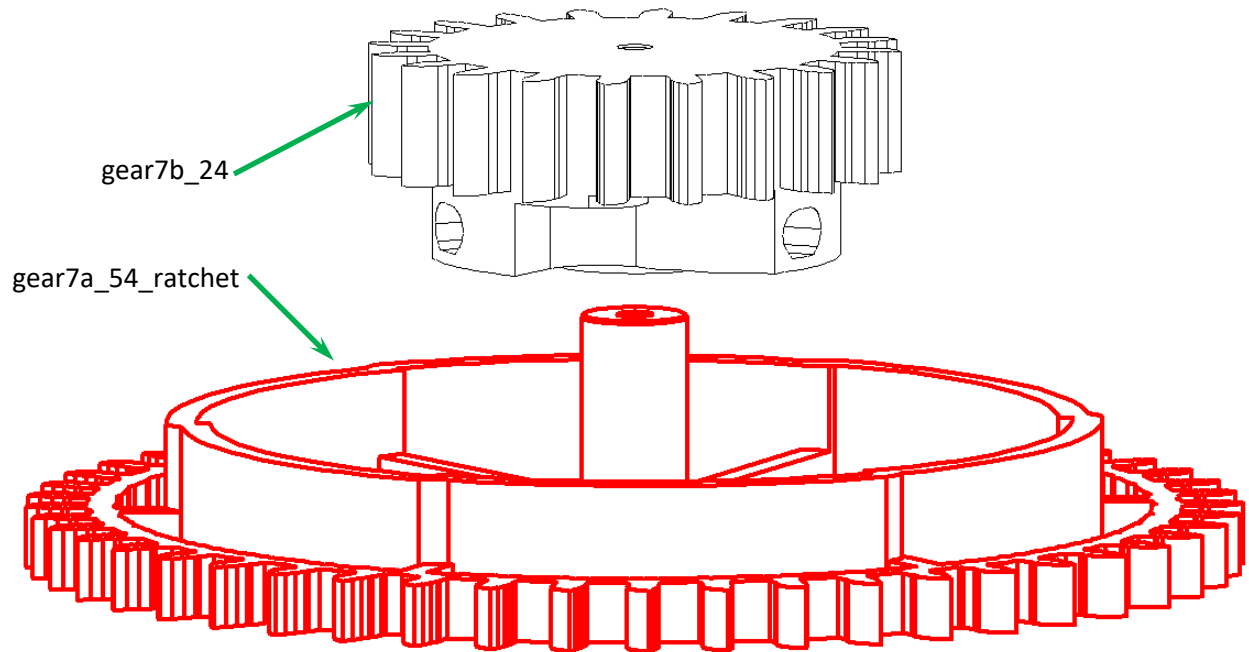


Figure 16: Gear 7b fit onto gear 7a

Notes on Friction

It is worth stating how important it is to reduce friction in a mechanical clock. My clock uses 7.5 pounds of weight falling 46" every 7.8 days. The pendulum will tick 936,000 times in 7.8 days, so the energy of the weight shell dropping one inch (2.54cm) needs to provide enough energy to keep the pendulum swinging 20,348 times. This gives us an idea about how little energy is available to keep the clock ticking. There is not much room for wasted friction.

This clock laughs at YouTube videos showing a standalone clock escapement with a wrench hanging on a string and you can visibly see the weight dropping with each tick. It makes a good display and the pendulum amplitude is usually quite strong. However, a complete clock would need a huge drive weight or a really short runtime if the escapement used that much energy. Everything needs to be much more efficient to build a clock that will run for 7.8 days.

Another way of looking at the energy in the clock is to calculate the forces at various places. The 7.5 pound weight uses a pulley, so there is only 3.75 pounds of force at the winding drum with a distance of 0.5875" from the pivot point. The outer rim of gear 8 is 2.1" away from the pivot point, so it only has 1.05 pounds of force at the teeth. Gear 7 has a 54:18 ratio, so it has even less force at the gear teeth. Each gear in the drive train has less force than the previous gear, although the energy is the same because they rotate at higher speeds. The escapement only has 0.013 ounces of force remaining, which is less than the weight of a common house fly. Theoretically, the clock would be stopped by a house fly landing on the escapement wheel. This gives us an indication of the tiny amount of energy available for each tick of a weight driven clock. Btw: a fly landing on the escapement could stop the clock, but it should start up again if he flies away before the pendulum loses its swing.

Make sure to complete the component pre-checks to minimize friction before moving on to building the clock. Another equally important friction test on the pendulum support bearings will be done later.

My clock has been running great using around 6.5lbs of drive weight. Your clock may require slightly more or less weight depending on overall friction in your clock. Hold off on printing the weight shell until you clock is closer to completion.

I sometimes add dry Teflon lubrication to all of the moving parts of the clock, but the clock also seems to run just fine without any lubrication. I have also used lithium grease on the pinions and pallet arms on some of my clocks. Just a tiny bit is needed. Apply it with a toothpick and wipe away most of it. It is generally considered a bad idea to oil or grease the clock gears because oil holds dust that can scrape the surfaces. I have not noticed any bad effects from greasing PLA clock gears, even after running for several years. PLA even seems to be safe with the solvent in dry Teflon lubrication, but try a small component before adding lubricants to the entire clock.

The small 623 bearings used to support the pendulum work best with the thick factory grease removed to minimize friction. Remove the rubber seals using a needle and wash the grease using solvent (paint thinner, mineral spirits, acetone, 90%+ alcohol, etc.). 91% isopropyl alcohol used for cleaning the print bed works great for removing the factory grease from the bearings. Let them soak overnight and brush out the grease or use a blast of compressed air, then let them soak again in fresh alcohol. Add a drop of dry Teflon lubrication or lightweight oil to minimize rust if desired.

Frame Assembly

The frame on this clock is designed to fit together easily using tapered alignment pegs and screws to hold things together. The alignment pegs do most of the work so the screws only need to hold the parts together. Sand the pegs if they don't fit completely with your printer tolerances. Assemble the components shown below using #6x3/4" or M3.5x20mm flat headed wood screws. M3x20mm wood screws may also work. A 608 bearing sits in a pocket in frame_back_lower.

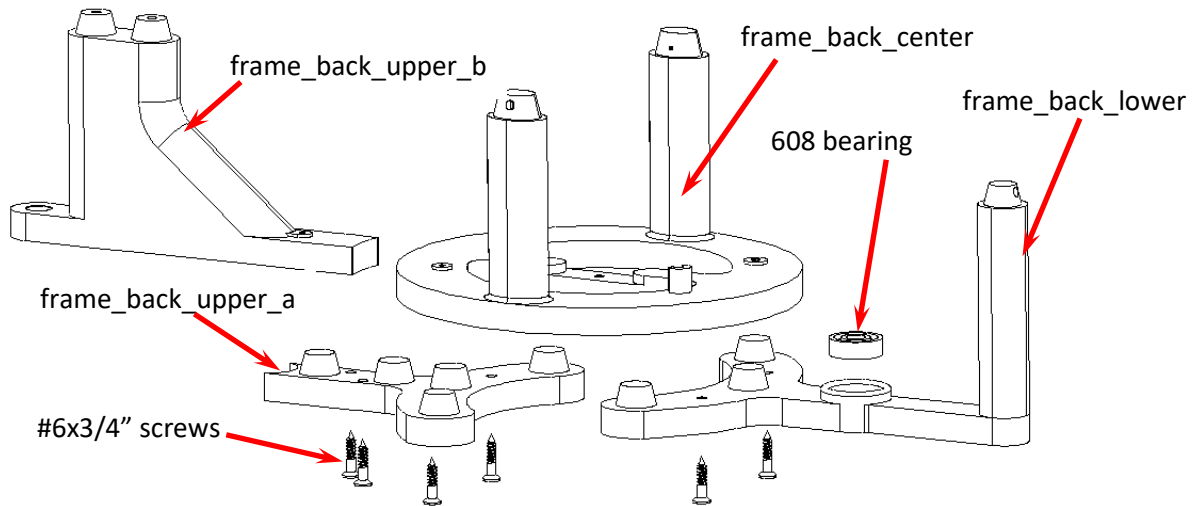


Figure 17: Back frame assembly

The standoffs are all in one file, frame_back_standoffs. Attach them according to the diagram below. The large upper standoff needs to be oriented so the narrow portion of the built-in keyhole hanger is near the top. The lower standoffs use a short pin to keep from spinning when tightening the nuts. The smaller standoff goes near the top.

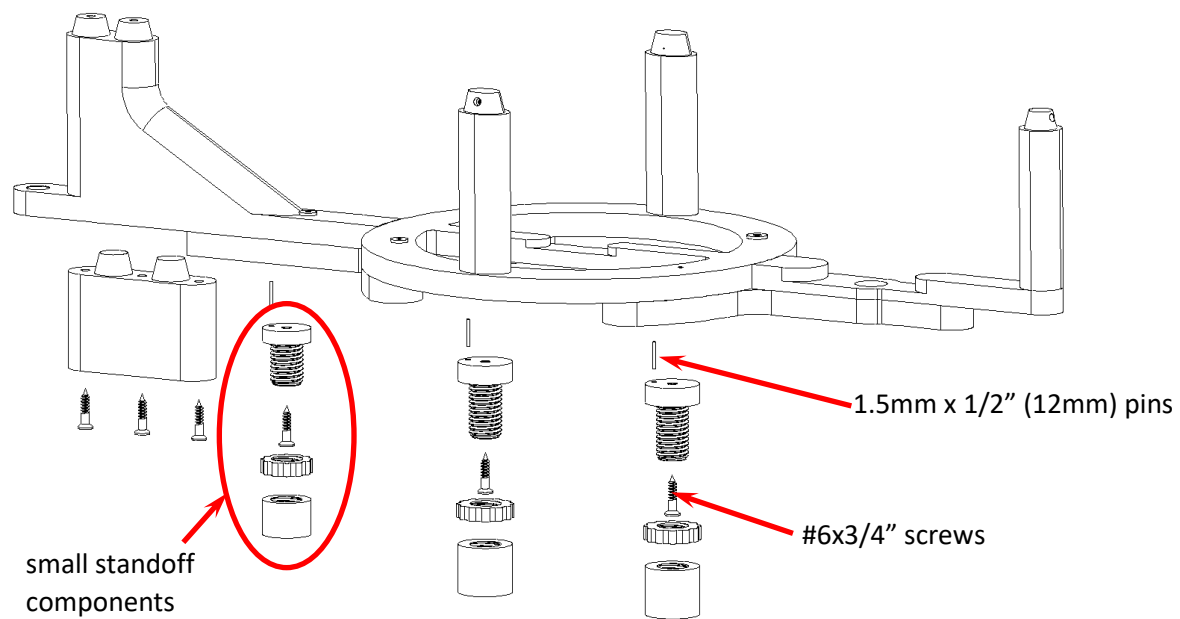


Figure 18: Back frame standoffs

The front frame assembles using 5 pieces, one 608 bearing, and eight #6x3/4" wood screws to match the diagram below.

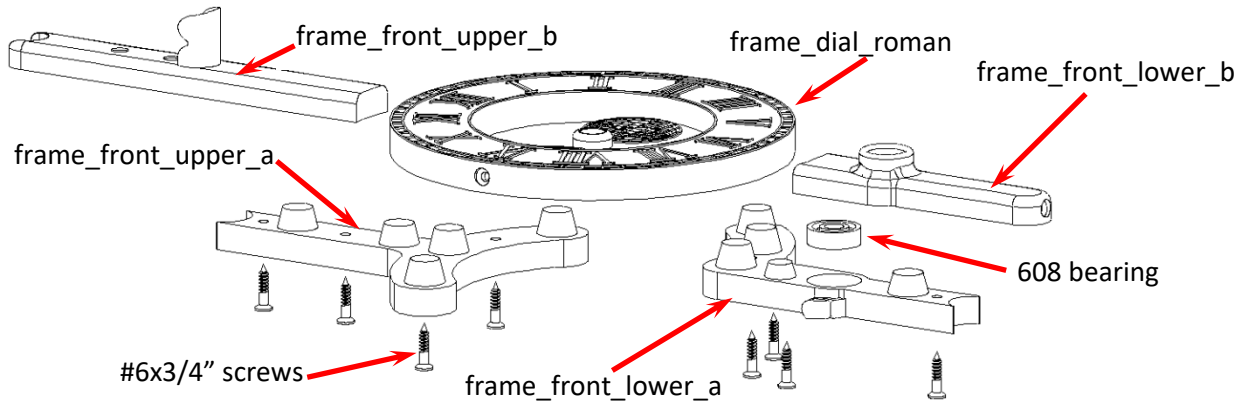


Figure 19: Front frame assembly

The completed front and back assemblies join together using five #6x3/4" wood screws (highlighted red). The lower three screws go in at an angle to spread out the forces on the small tapered pegs to help prevent splitting. These screws do not need to be very tight, just enough to keep the dial from falling off. Check that the frame halves go together. The front frame will need to be removed to add the gears.

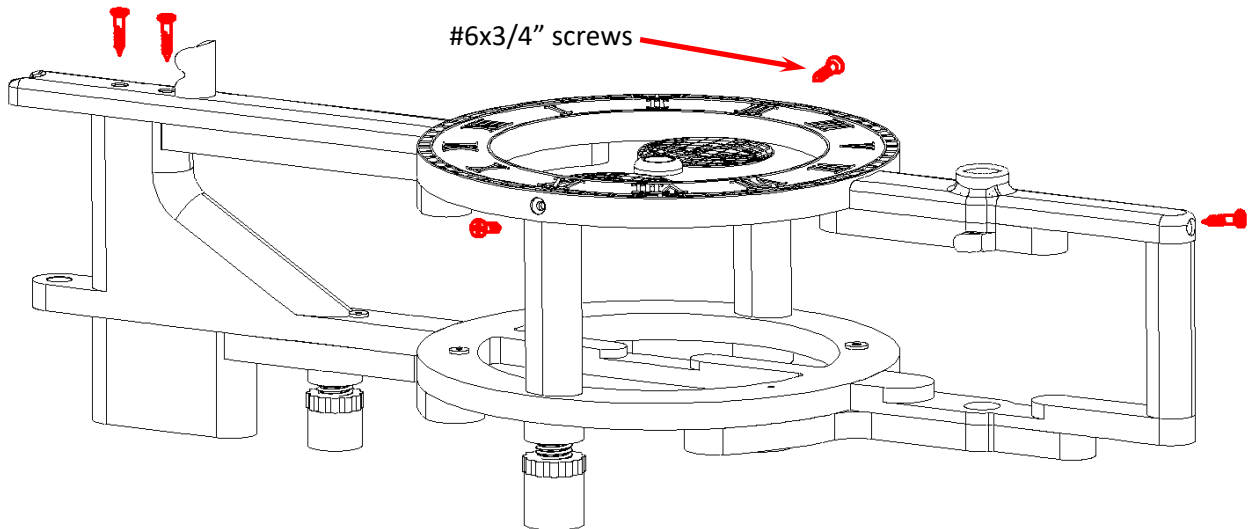


Figure 20: Complete frame assembly

Hanging the Clock

IMPORTANT: The clock frame is designed to support a heavy weight shell without sagging. The weight distribution has about 40% of the weight hanging on the back frame and 60% hanging on the front frame. There is a strong horizontal support beam holding up the front of the clock and it is critical to set it up properly so the beam can function as intended.

The steps to hang the clock are:

- 1) The most important step is to adjust the mounting screw depth so the upper standoff is held tight against the wall. This will allow the support beam to stay horizontal as it is intended. The screw should go into a wall stud so the screw does not pull away from the wall.
- 2) Move the adjustable lower standoffs to their shortest position close to the back frame.
- 3) Hang the clock on the mounting screw.
- 4) Adjust the mounting screw depth until the upper standoff is tight against the wall. You should be able to gently pull down on the front frame without creating a gap between the upper standoff and the wall.
- 5) Adjust the lower standoffs so they touch the wall. They should not push the frame away from the wall.
- 6) Pull down the front frame to make sure there is minimal frame sag.

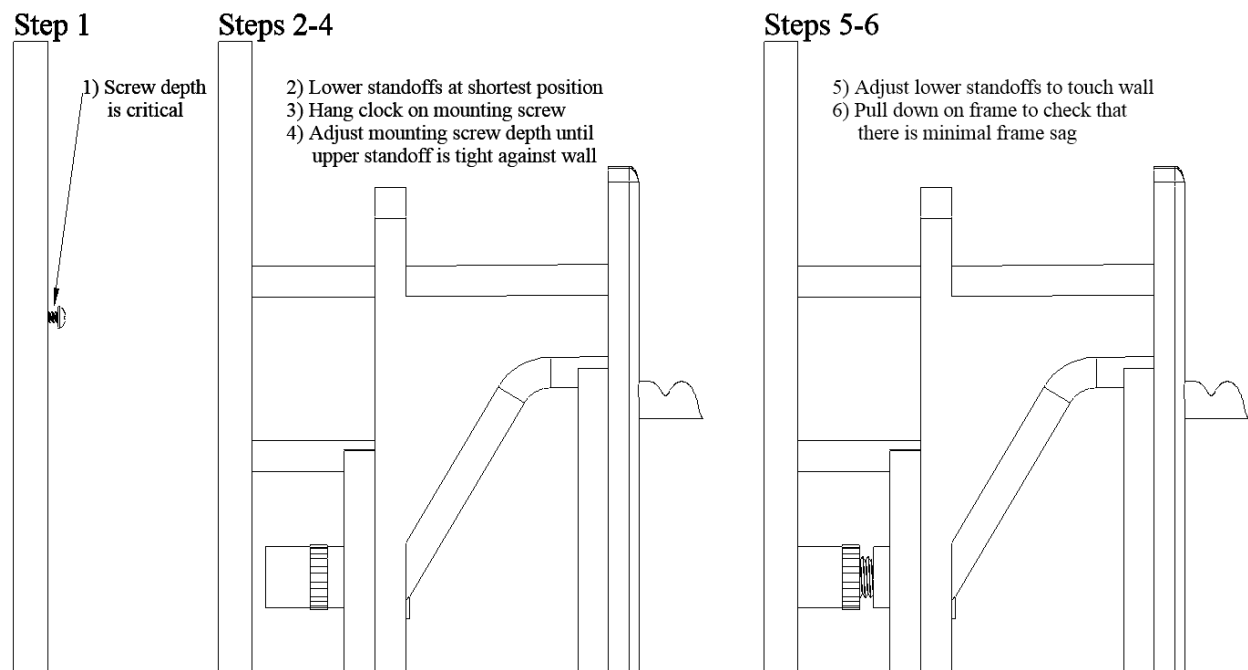


Figure 21: Hanging the clock

Gear Pre-Assembly

A few gears should be assembled into larger modules before adding them into the clock.

Add the pallet components in the order shown with a tiny amount of the rod extending through the top bearing. Secure the arbor position using a M3x8mm set screw. Make sure the 623 bearings can slide over the rod. Some 3mm rod is oversized so it will not fit into the 623 bearings and you will need to reduce the diameter. The easiest solution is to spin the rod in a hand drill and hold some sandpaper around the shaft. You only need to reduce the ends enough for the bearings to fit.

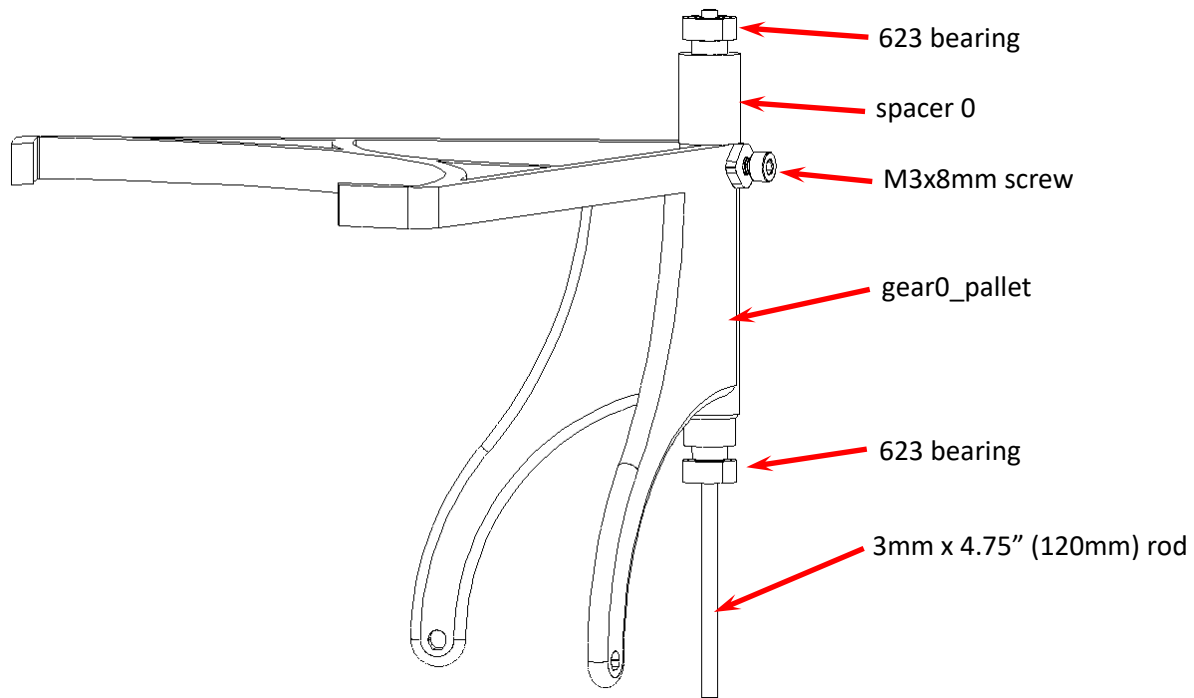


Figure 22: Pallet arm pre-assembly

The gear 4 assembly includes the friction clutch used to change the time while the clock is running. Insert the components in the order shown and secure the positions using two M3x8mm set screws. The arbor should extend through the bottom by about 0.25" (6mm). Spacer4b should completely interlock with the notch in gear4a_60_18. You should be able to hold gear4b_18 and rotate gear4a_60_18 with a small amount of resistance.

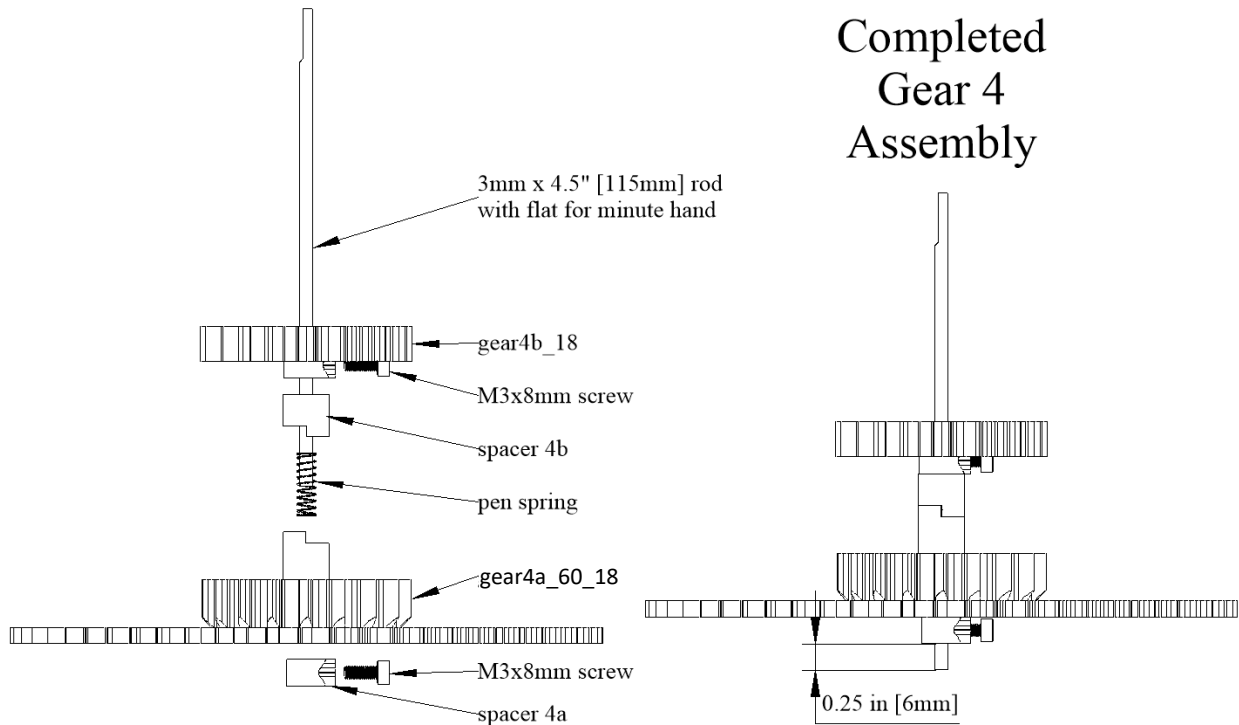


Figure 23: Gear 4 pre-assembly

The ratchet assembly starts by adding the three clicks onto gear 7b. The clicks need to spin freely on the screws. Drill the holes to fit the screws if needed.

Add the clicks to gear 7b using three #6x3/4" wood screws. Tighten the screws then back them off so the clicks swing freely. Add three pen springs into the holes. Turn everything over and place gear 7b onto the ratchet. It should rotate easily in one direction and hold in the other direction. Add a small amount of lithium grease to the tips of the clicks if they feel sticky.

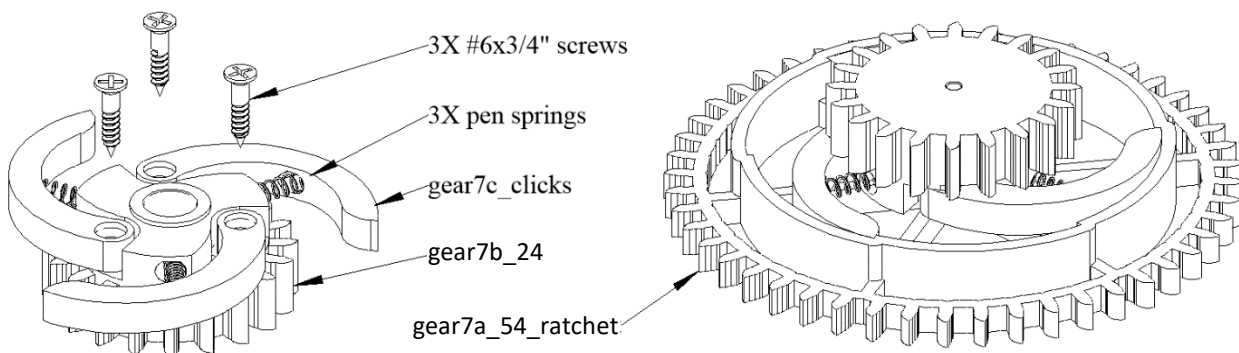


Figure 24: Gear 7 pre-assembly

The gear 8 assembly includes the winding drum and two arbors for the winding key. Insert the rods through the spacer and gear 8 so the rods reach the tip of gear 8. Secure the rods using two M3x8mm set screws. Check that a large 608 bearings will slide completely over the rods and onto the small extensions on the spacer and gear 8. If needed, the rods can be filed down so the bearings will fit.

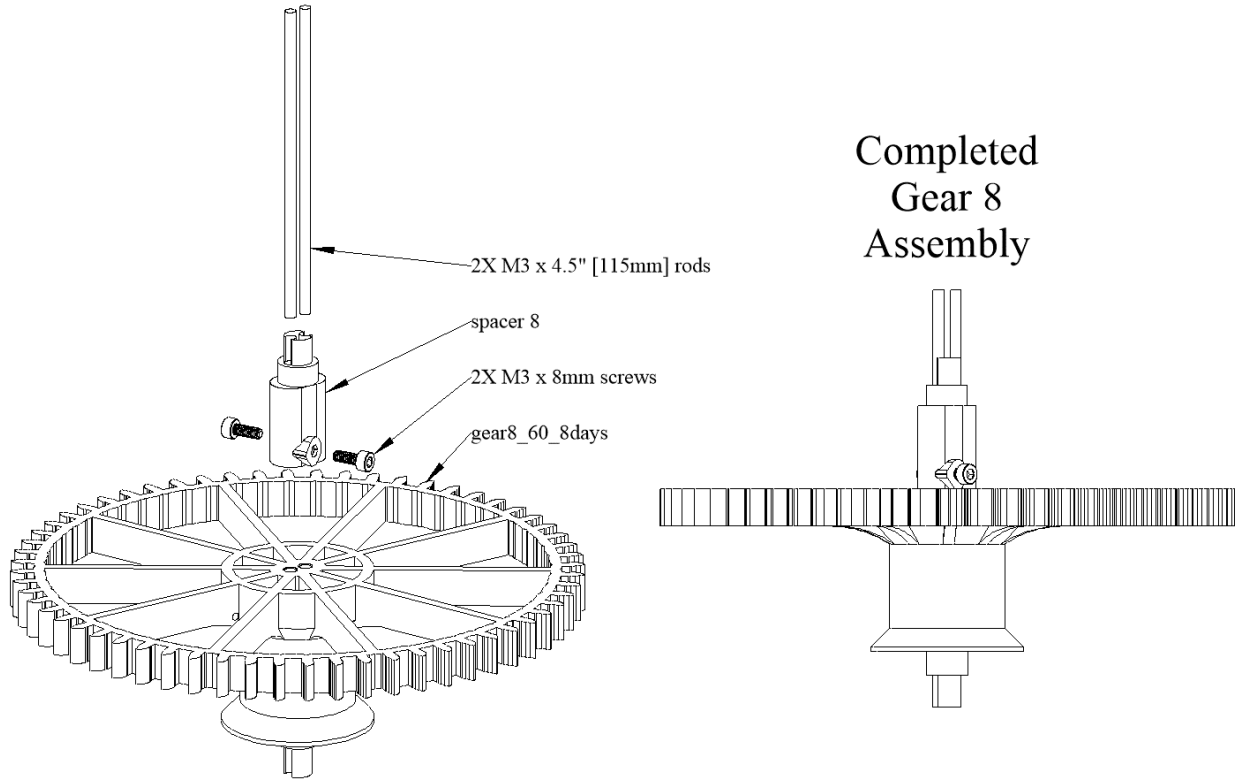


Figure 25: Gear 8 pre-assembly

Tie one end of the fishing line around the hole in gear 8. Wrap the line around the drum in the direction shown.

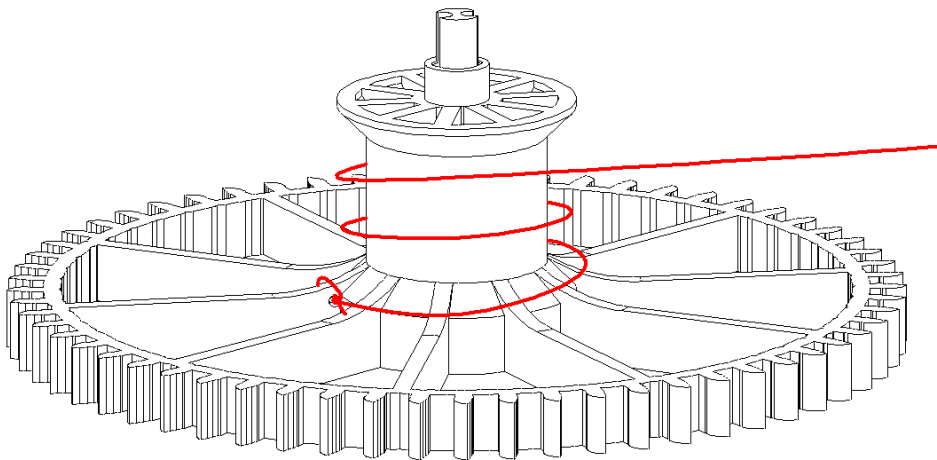


Figure 26: Winding drum cord

The gear 9 assembly adds a second friction clutch for changing the moon dial time without affecting the hour and minute hands. The spring was moved below gear 5 to minimize the clock size. Gear 9a extends through gear 5 to contact the spring.

Insert all the components in the order shown and compress the spring between spacer 9a and spacer 9b. This assembly uses the longer 3.5" (89mm) music wire arbor. Tighten the set screws with 0.275" extending through the top and 0.675" extending through the bottom. Gear 9b should rotate relative to gear 9a with a small amount of resistance. Gear 5 should spin freely around the gear 9a shaft.

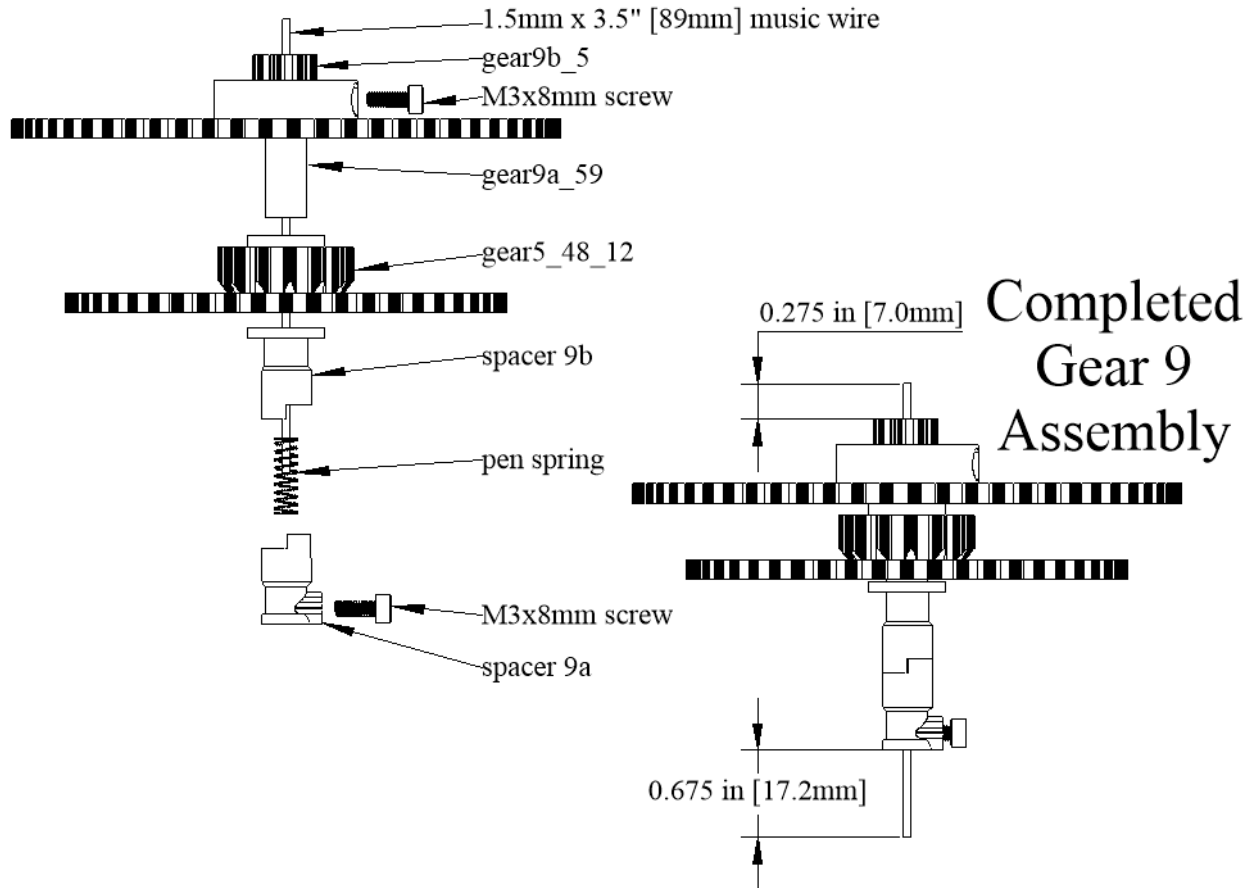


Figure 27: Gear 9 pre-assembly

The pendulum bob is a two-piece shell filled with pennies or washers for weights. The actual weight is not a significant factor in regulating the time. A heavy bob and a light weight bob will both swing at approximately the same rate. It only needs enough momentum to continue swinging during minor disturbances and not be so heavy that it creates excess friction at the pivot point. The bob could be filled with washers, small rocks, or anything that fits. Pennies are cheaper than washers and they fit nicely. Secure the back of the pendulum bob with two #6x3/4" wood screws. The assembled pendulum bob on my clock weighs just over 6 ounces (170g). The bob slides over the lower portion of the pendulum shaft when assembled. Two printed nuts are used to adjust the length of the pendulum to set the rate. Start with the nuts positioned near the center of the available threads.

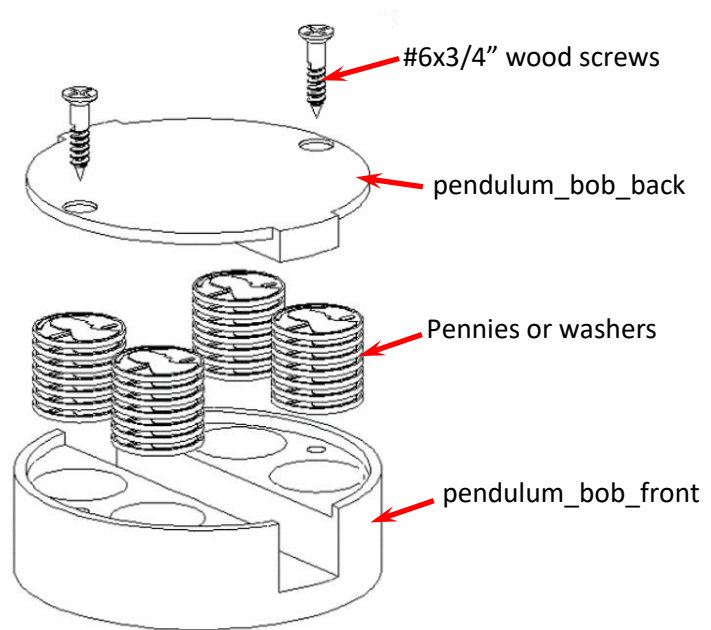


Figure 28: Pendulum bob

The updated pendulum bob includes additional pockets between the pennies that can be used if you want to fill the bob with something like steel BBs. Any weight that comes close to 5-6 ounces (140-170g) is acceptable.

The winding key is a simple part that should have obvious assembly. Attach the winding_knob to the winding_arm using a #6x3/4" wood screw. Tighten the screw until it is secure, but still loose enough to spin easily. A small drop of oil could be added.

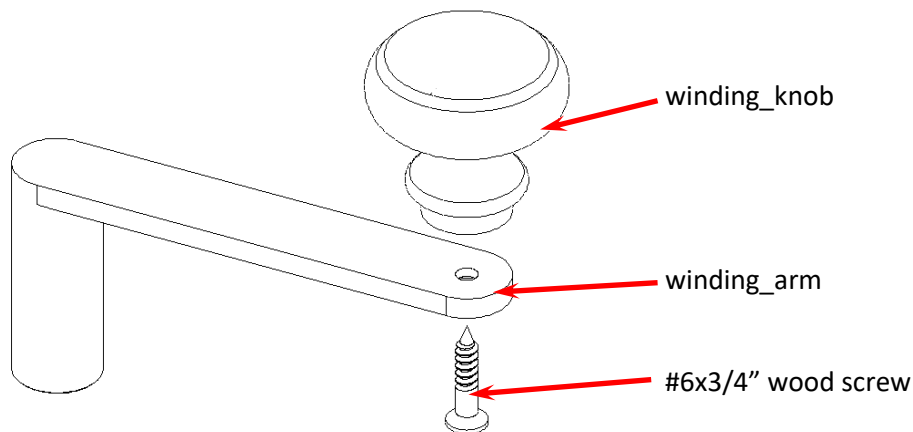


Figure 29: Winding key

Pre-Assembly Checks

It is a good idea to test a few things before assembling the entire clock. We will be testing the pendulum free swing time and checking for proper clearances in the gear stacks with the most components. If these tests pass, then there is a greater chance of having a functional clock. Any adjustments that need to be made are easier to finish before the entire clock is assembled.

The pendulum support bearings are an important feature in all of my clocks. I believe that if small ball bearings with modern quality were available 500 years ago, we would see a lot of them supporting pendulums. They are extremely durable when operating well below their maximum load capacity. My oldest clock is nearly 5 years old using a ball bearing pendulum support with no signs of wear. The pendulum amplitude is still as strong as it was 5 years ago.

The first step is to remove the thick factory grease to minimize friction. Use a pin to remove the rubber seal from the 623RS bearings and soak them in alcohol or mineral spirits to remove the grease. A coat of Teflon dry lube or very light weight oil can be added to minimize rust.

Add a 623 bearing into the back frame and insert the previously assembled pallet module. Add spacer_0 and another 623 bearing. Add the front frame and secure it with the upper screw. The other frame screws are not important at this point.

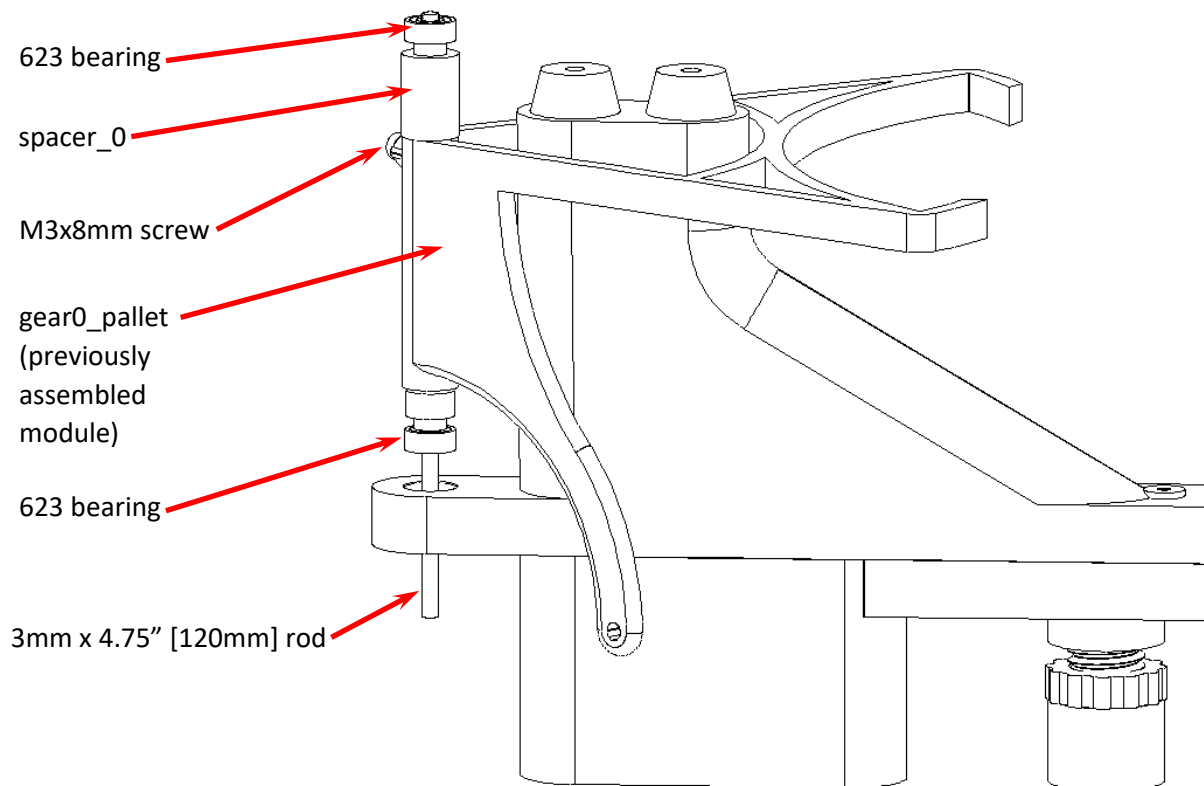


Figure 30: Pallet assembly for bearing free swing test

The pendulum arm consists of four segments. Pendulum_arm_upper goes onto the pallet arbor using three M3x8mm screws. Hang the clock on the wall using a #8x1-1/2" or M4.2x38mm pan head wood screw. Other screw sizes will work as long as they fit into the upper standoff and are long enough to go into a wall stud. This single screw will eventually need to support 8-10lb (4-5kg) without pulling away from the wall. It needs to be fairly strong.

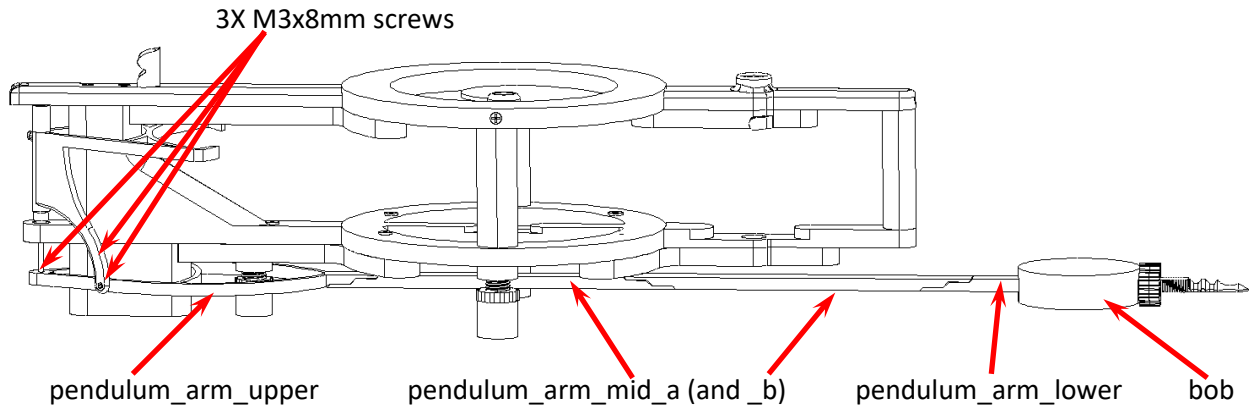


Figure 31: Pendulum assembly

Hang the clock frame on the wall and add the pendulum arm and pendulum bob. Each pendulum arm segment hangs on the segment above it. This makes it easy to remove the pendulum when moving the clock. Swing the pendulum to one side and measure how long it takes for the amplitude to degrade to a negligible amplitude. It should swing for at least 5 minutes, preferably 10 or up to 20 minutes. Bearings that degrade in amplitude in less than 5 minutes will not make a reliable clock without an extremely large drive weight. Swap the bearings or clean them again before proceeding.

I have purchased many 323 bearings from multiple vendors and have never seen a batch of 10 bearings without at least 9 perfect bearings that swing for over 10 minutes. Most swing for around 18-20 minutes. I have not found a better method of supporting the pendulum that is easily available without going to a specialty clock shop. This assumes that the rubber seals have been removed and the thick factory grease has been removed. The free swing test does require a properly weighted pendulum bob and bearings that fit properly in the frame so the rod is not binding. I usually purchase the cheapest bearings from Amazon, eBay, and AliExpress. They all have good enough quality to work as a pendulum support bearing. The few rare bad bearings will feel gritty, as if they were dropped in sand. I suspect that even they would start to work if they were cleaned again, but bearings are cheap enough that I throw them out and use the remaining good ones.

The minute hand arbor has the most components stacked in one place. If each component prints slightly taller than expected, the stack can be pinched when the front frame is attached. Add the gears shown in the picture below, starting with the previously constructed gear 4 assembly, spacer_6, gear6_54_6, and gear10_60_moon_3d (or _flat). Don't forget about spacer_6 between gear4b_18 and gear6_54_6. Place the front frame on top and make sure it is fully seated. Check that there is clearance between gear10_60_moon and the front frame. This is called end shake. The target is more than 0, but less than 1mm of end shake. If the frame pinches the gears, trim a tiny bit from the tips of gear4a_54_18 and spacer_4b, or make spacer_6 thinner. Test that the top two gears spin freely and independently from the gear 4 assembly.

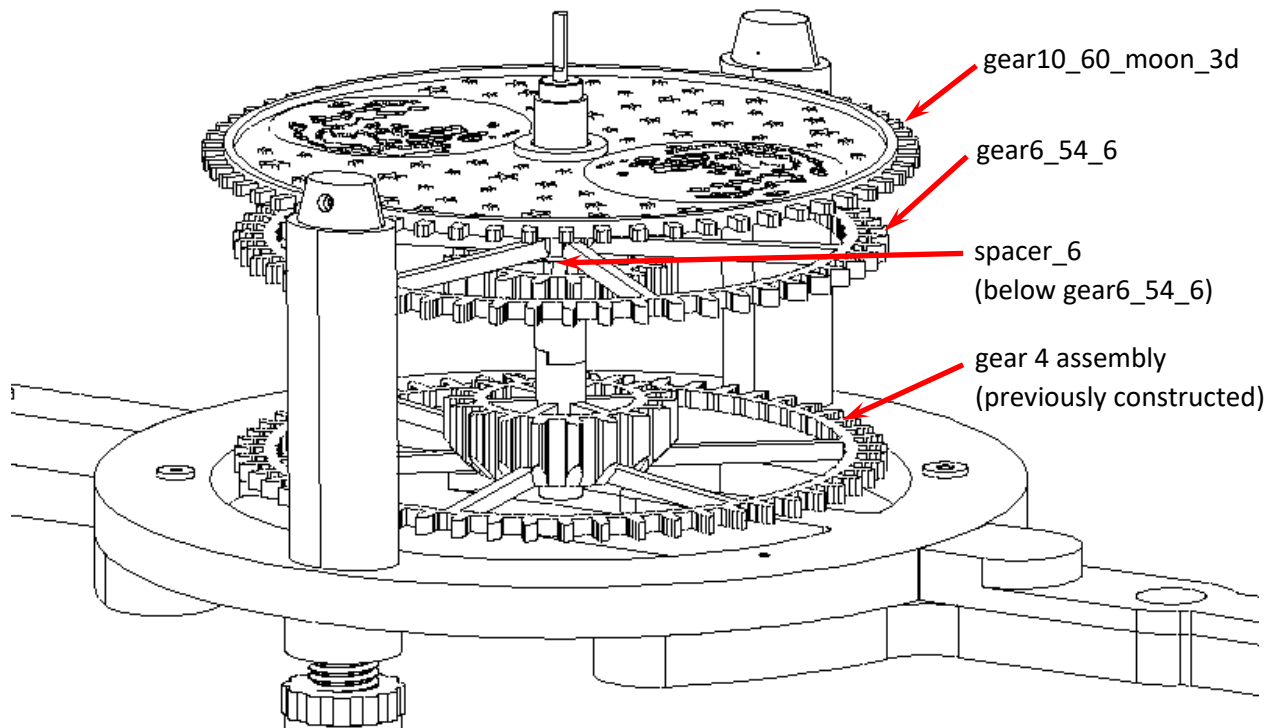


Figure 32: Central arbor end shake test

Add the previously completed gear 9 assembly to the lower left position and add the front frame. Check for a small amount of end shake. Trim spacer9a and spacer9b if needed.

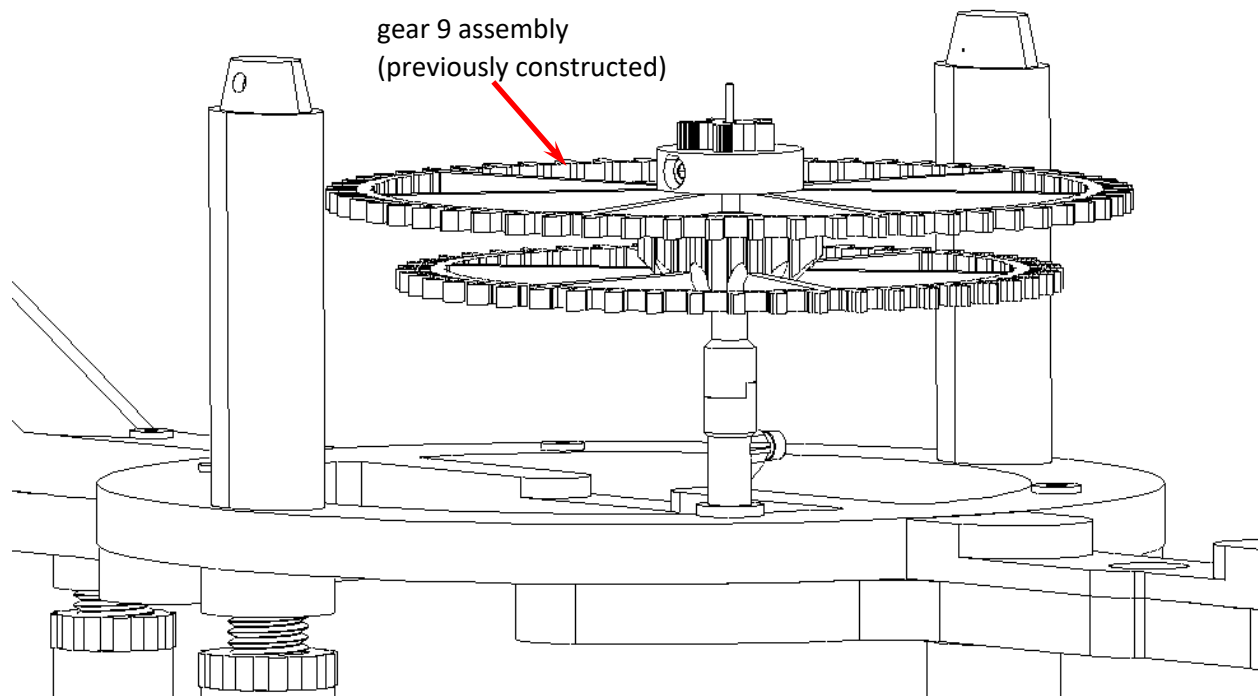


Figure 33: Gear 9 end shake test

Don't start assembling the clock until all of the previously listed pre-checks have been completed.

Pre-check summary:

- 1) Visually inspect the gears for defects like elephant foot or excess stringing
- 2) All gears spin on their arbors
- 3) All arbors spin in the frame arbor holes
- 4) Gear 6 fits through the front dial and spins easily
- 5) Gear 10 fits over gear 6 and spins easily
- 6) Gear 5 spins easily on the gear 9a shaft
- 7) Gear 7b spins on gear 7a and the ratchet is working
- 8) Pendulum bearing free swing test runs for at least 5 minutes, preferably 10-20 minutes
- 9) The gear 4 assembly, spacer_6, gear 6, and gear 10 have some end shake inside the frame
- 10) The gear 9 assembly has some end shake inside the frame

If all of these pre-checks are good, then it should be OK to start the final clock assembly. The most common issues that might cause the clock to be non-functional are the bearing free-swing test, excess friction on arbors, or lack of end shake.

Building the Clock

The gears are easiest to add from the bottom layer and working towards the top. Start with the back frame sitting on a workbench. Place the pre-assembled minute hand arbor into the 3mm hole in the center of the clock.

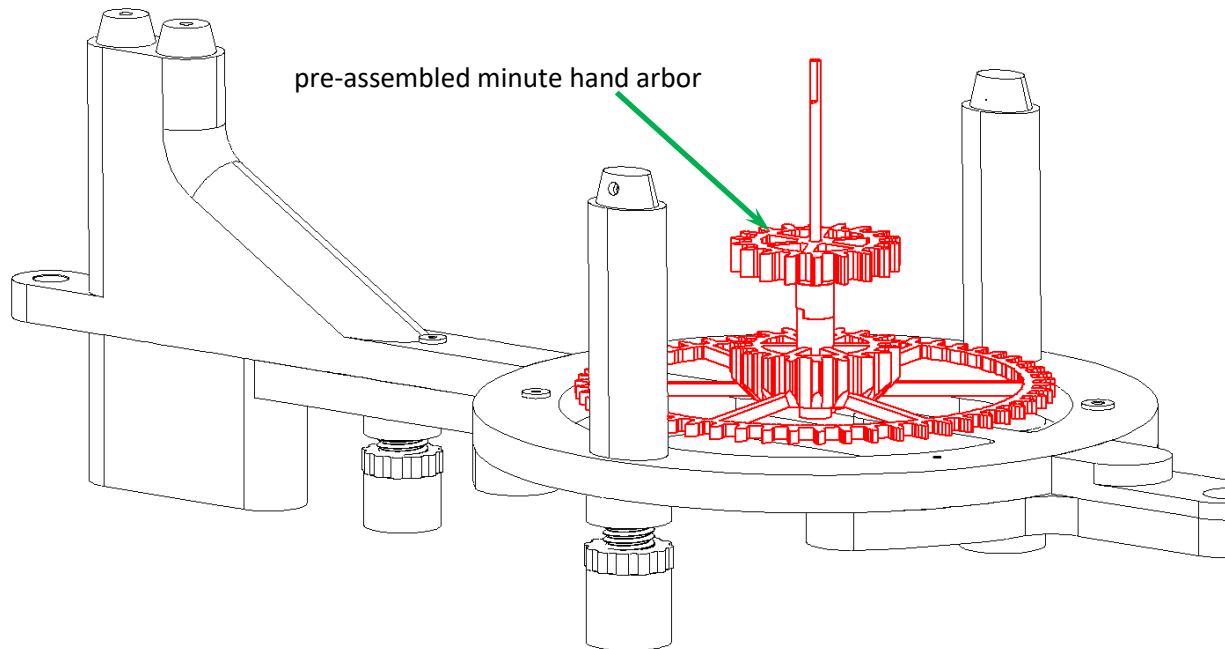


Figure 34: Minute hand gear

Add a 1.5mm x 3" (75mm) arbor, gear3_60_12, and spacer_3 into the upper left position. Both gears should spin easily.

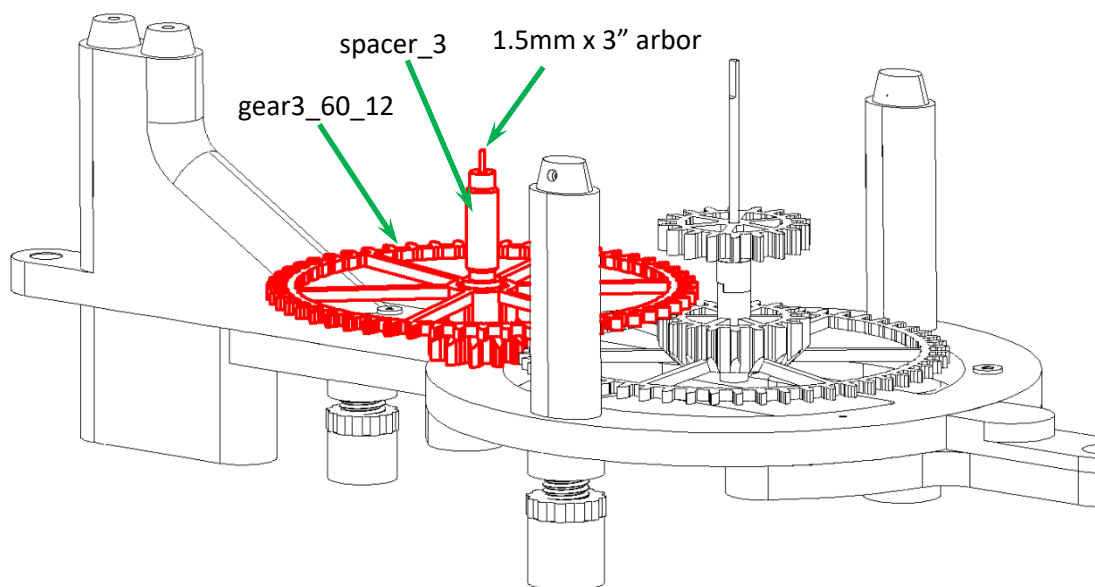


Figure 35: Add gear 3

Add a 1.5mm x 3" (75mm) arbor, gear2_60_12, and spacer_2 into the upper right position.

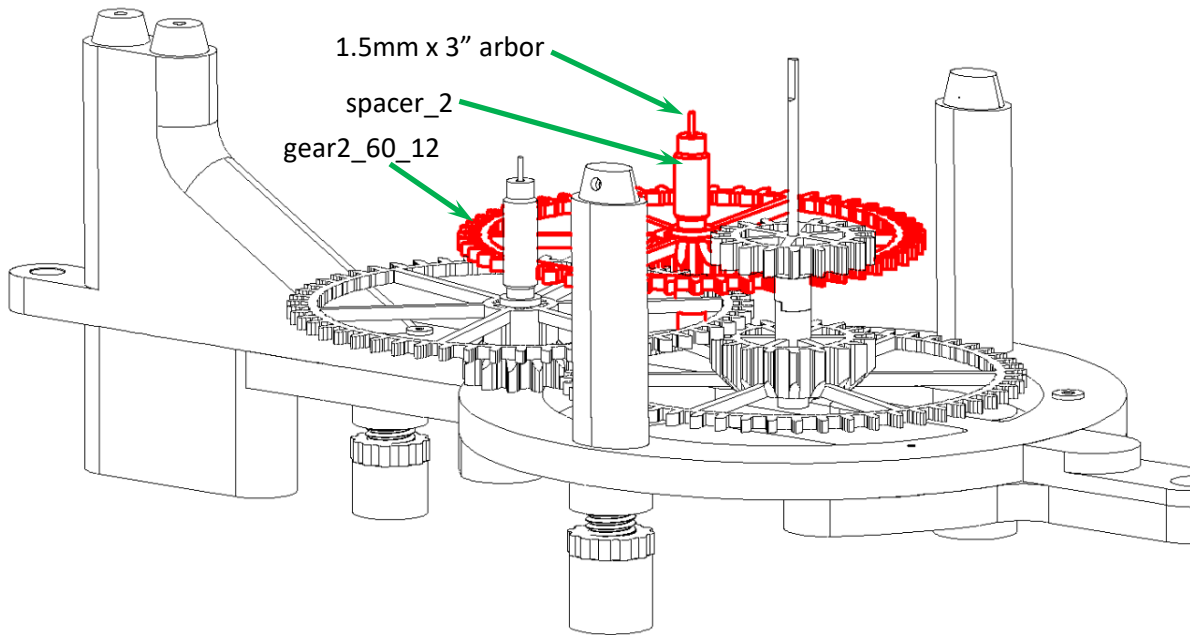


Figure 36: Add gear 2

Add a 1.5mm x 3" (75mm) arbor, gear1_20_12_esc, and spacer_1 above gears 2 and 3.

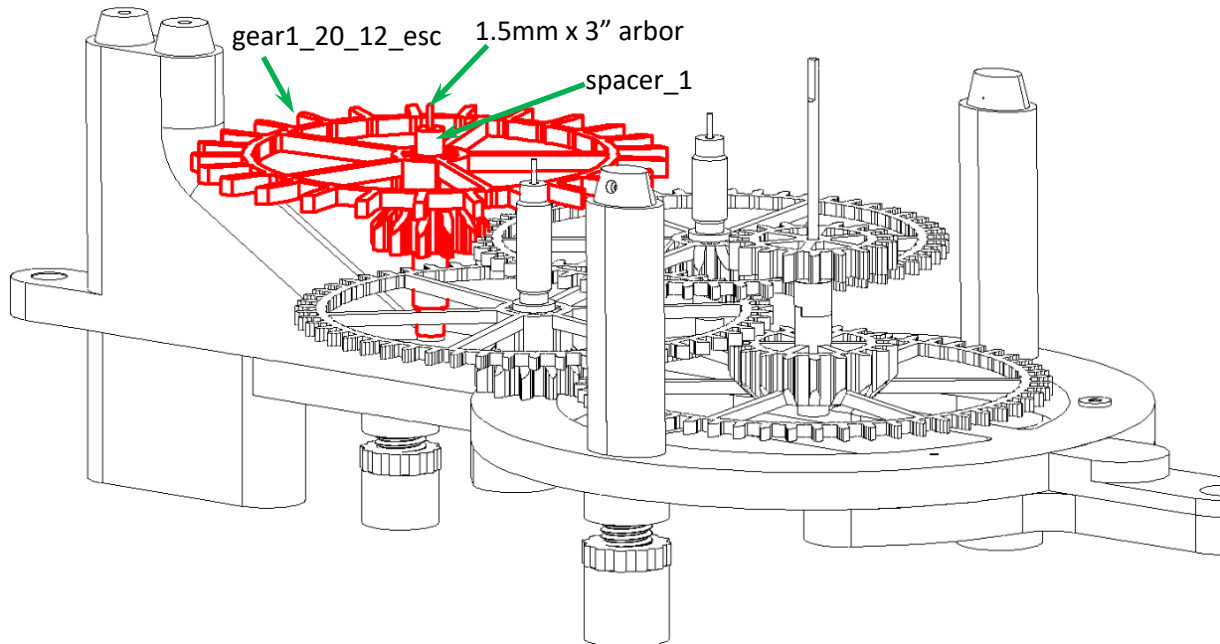


Figure 37: Add the escapement

The pallet assembly has several components. Put them back in the same order that were used in the pendulum free swing test. A 623 bearing should be in the hole in the back frame. Spacer_0 and a 623 bearing should sit on top of the pallet arbor with a tiny bit of arbor extending through the top bearing.

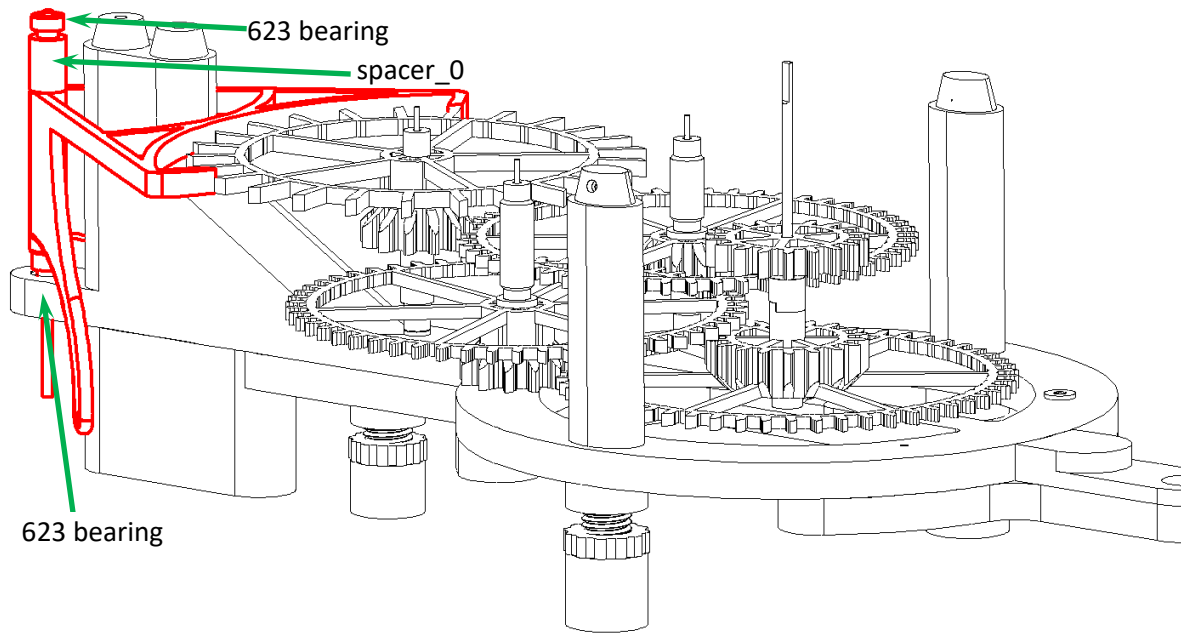


Figure 38: Add the pallet

Here is another view of the pallet arbor with pendulum_arm_upper attached using three M3x8mm screws (one hidden from view).

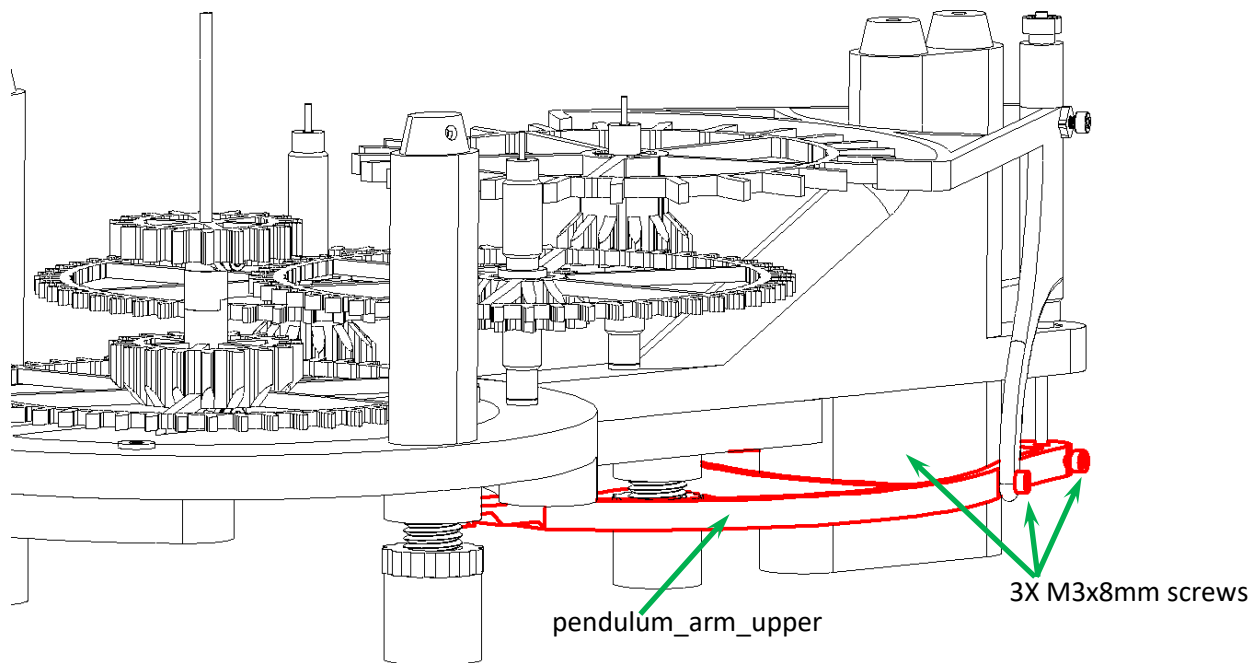


Figure 39: Pallet and top of pendulum

Here are all of the added components from the previous diagram shown at a different angle and without the frame cluttering the image. Of course, the arbor will pass through the back frame before the pendulum arm can be added.

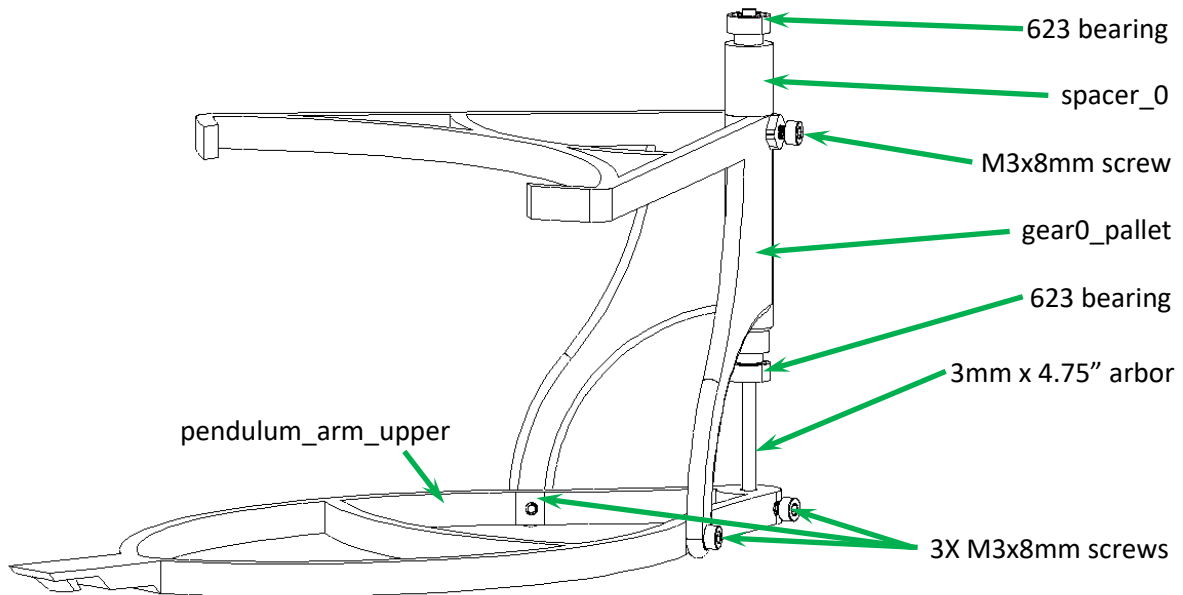


Figure 40: Pallet and pendulum arm detail

The previously assembled ratchet assembly is added to the lower right position. Spacer_7a is placed under the pre-assembled ratchet.

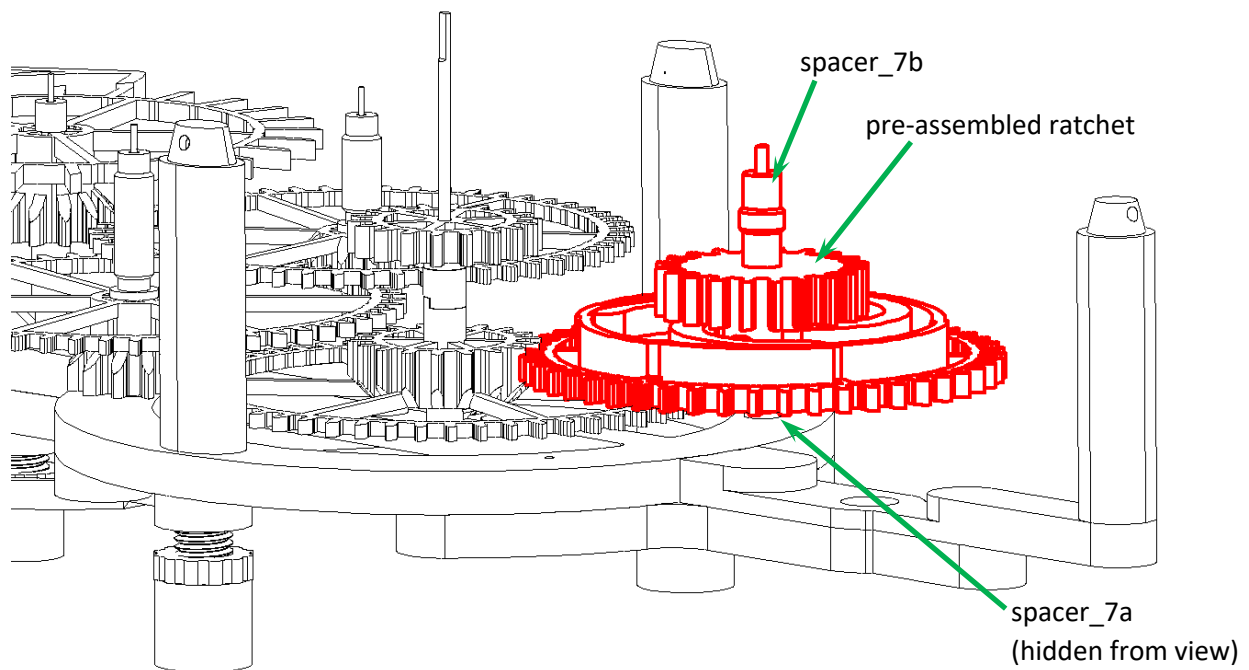


Figure 41: Add ratchet

Add the pre-assembled winding barrel into the lower frame position. The two lengths of 3mm rod should fit into the 608 bearing.

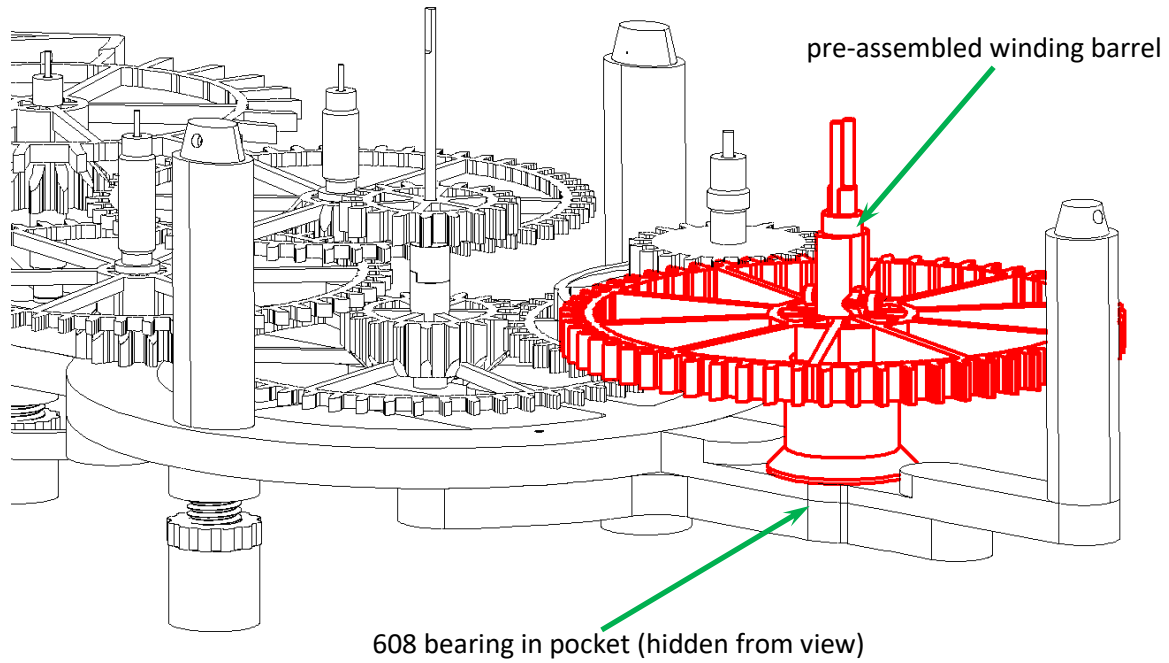


Figure 42: Add winding barrel

Add spacer_6 and gear6_54_6 onto the gear 4 minute hand arbor.

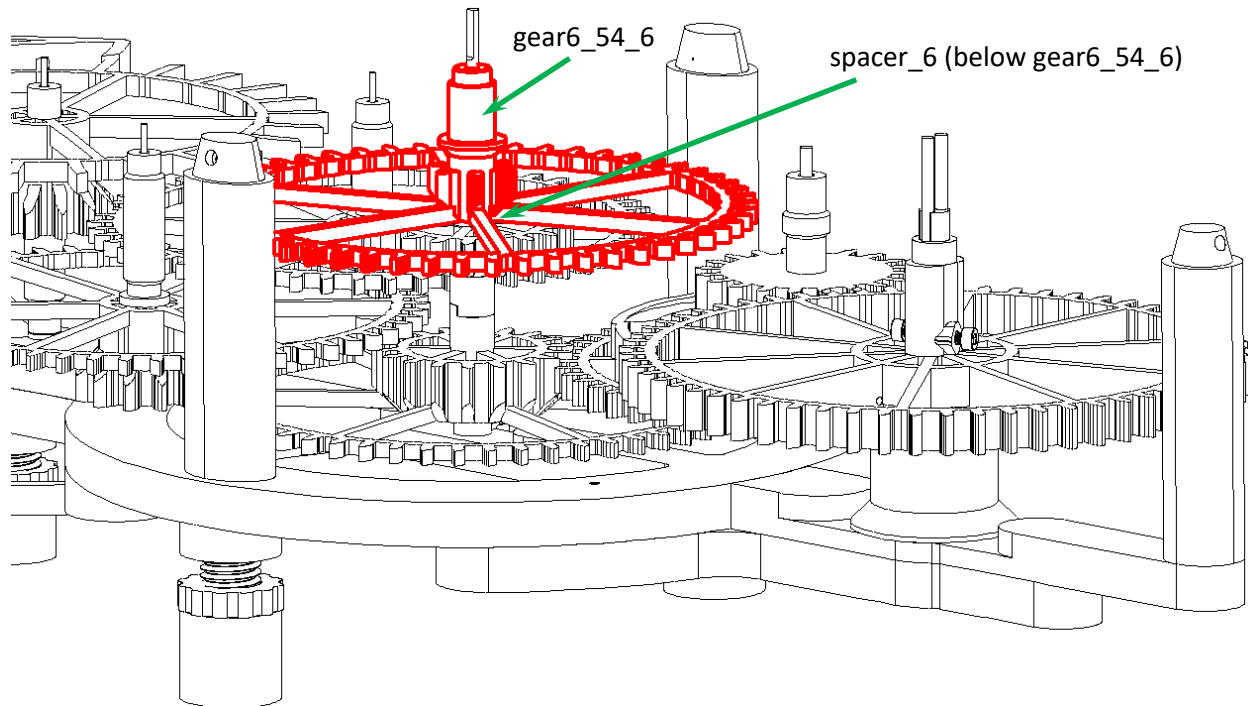


Figure 43: Add gear 6

Add the previously constructed gear 9 assembly to the lower left position. Gear 6 needs to fit between the two gears in the gear 9 assembly. The easiest way to assemble it is to lift gear 6 slightly and slide the gear 9 assembly into position until the gear 9 arbor drops into the frame.

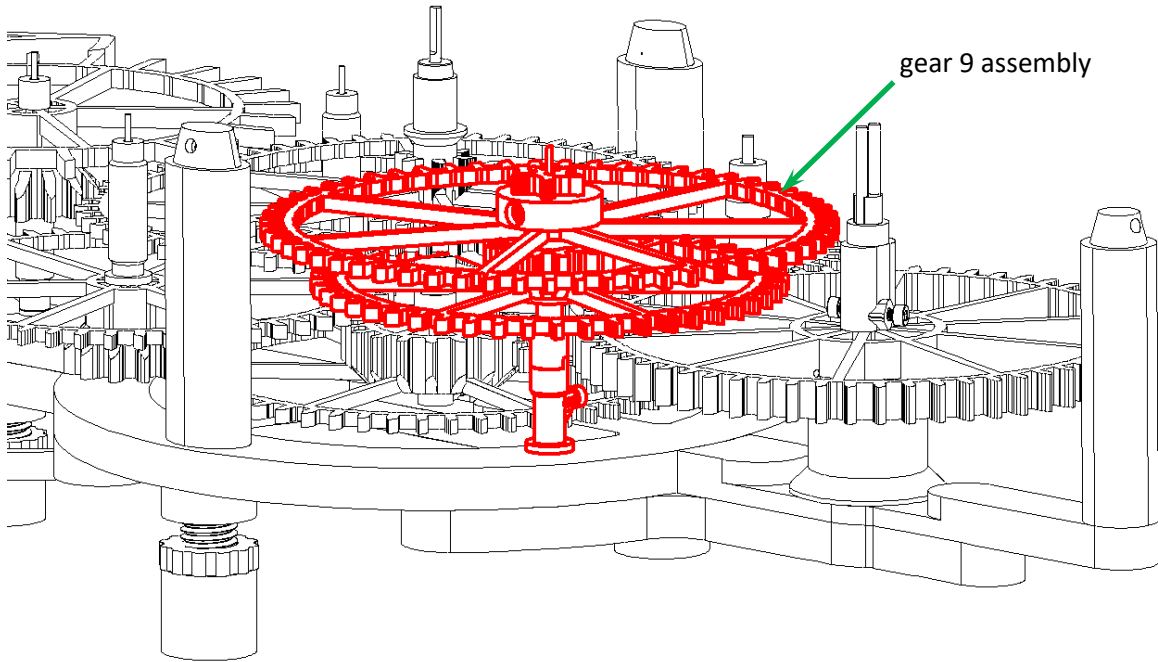


Figure 44: Add gear 9 assembly

Here is a side profile showing the positions of gear 6, gear 5, and gear 9.

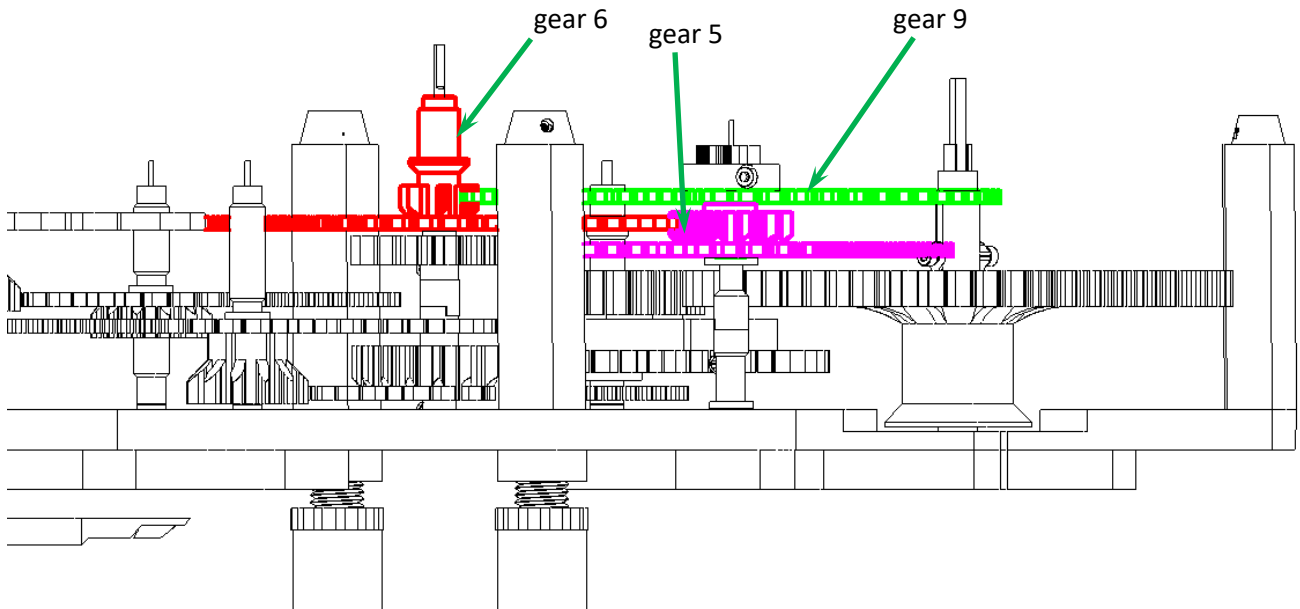


Figure 45: Gears 5, 6, and 9 detail

The final gear is the moon dial that fits over gear 6 on the central arbor.

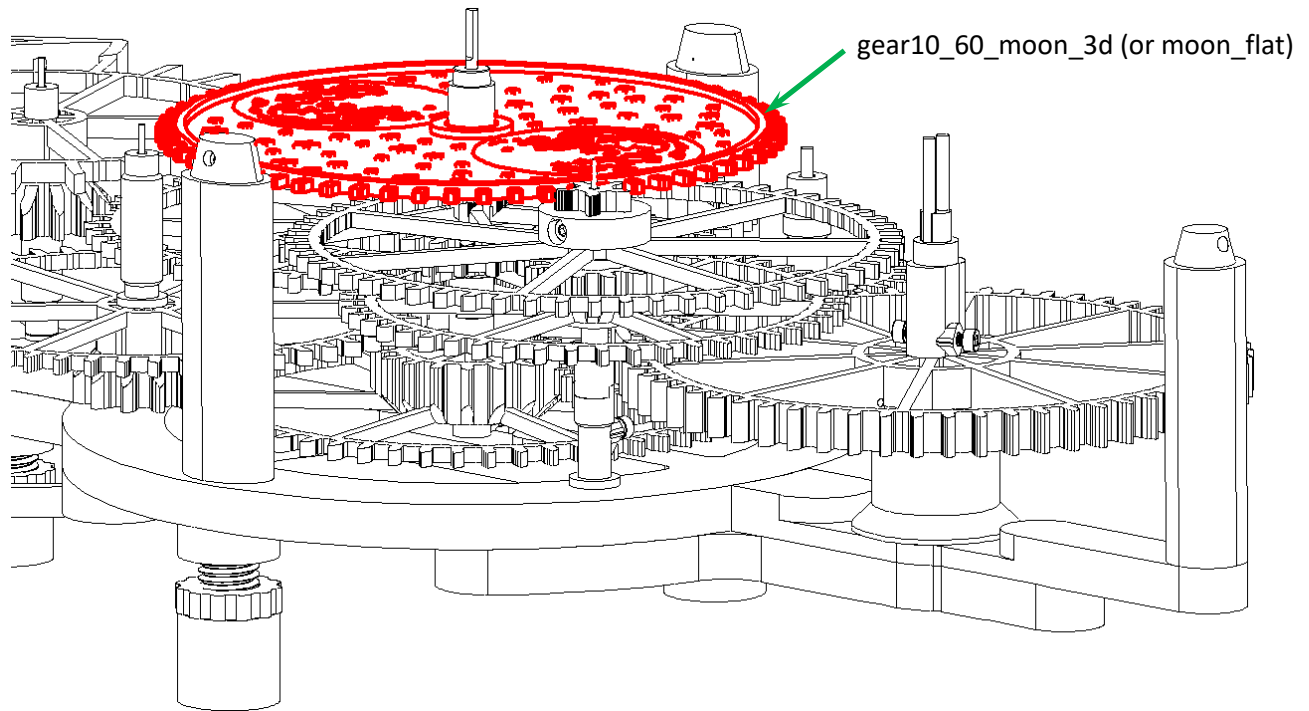


Figure 46: Add gear 10

The front frame can finally be added. Start by placing the dial over the minute hand arbor and wiggle each arbor into position one by one. Eventually, the frame should drop into position when all the arbors are lined up. Secure the frame using five #6x3/4" wood screws.

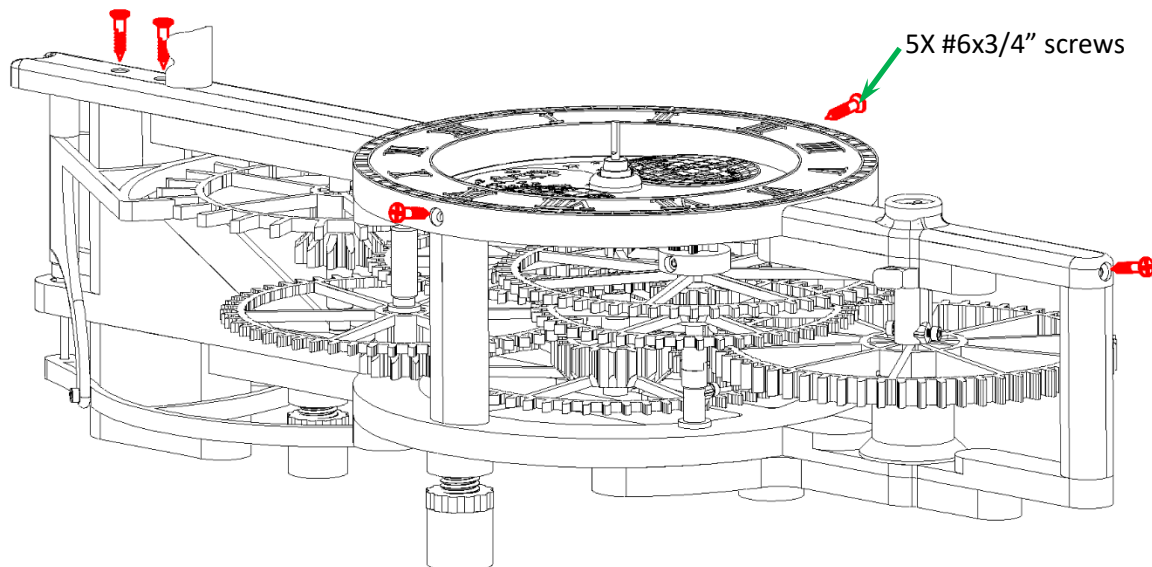


Figure 47: Add front frame

Everything is starting to look like a clock now. Add the hands and test the friction clutch to see that the time can be changed by rotating the minute hand. There are options for hands that fit tighter on the shafts if needed. The hour hand can be placed in any orientation and can be rotated to match the minute hand position. You can also test the moon dial friction clutch by rotating the moon dial from behind the front frame.

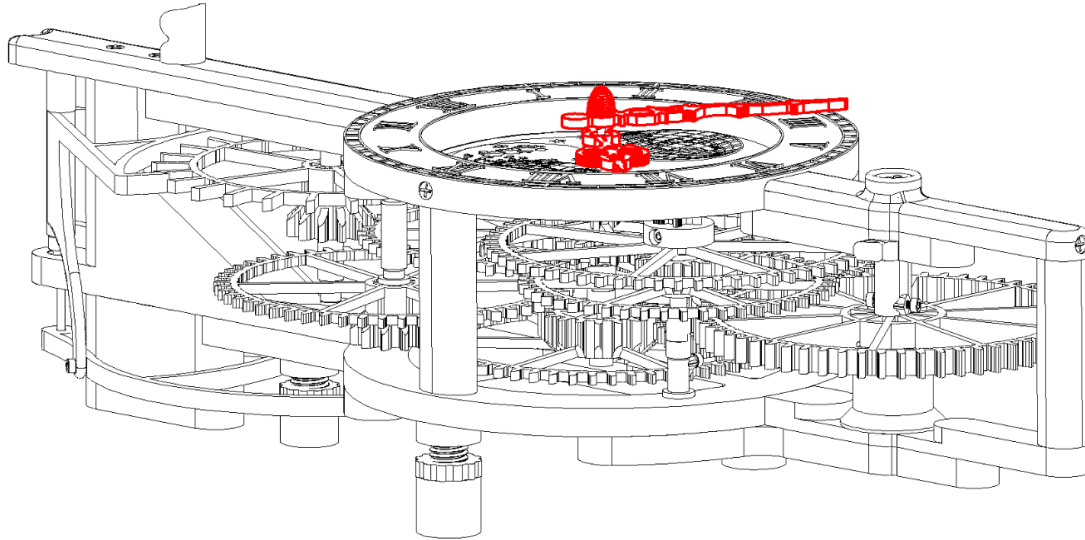


Figure 48: Add hands and test friction clutch

Testing the Clock

The clock mounts on the wall using a single screw driven into a wall stud. I use an #8x1-1/2" or #8x1-1/4" pan head wood screw, but anything that fits securely in the keyhole hanger should work. Placing the screw 74" (1.88m) from the floor will give around 46" (1.17m) of drop for the weights to fall during 7.8 days of run time.

It is very important for the hanging screw depth to be set properly for the clock frame to be supported without sagging. Follow the procedure on page 30. The horizontal support beam at the top of the clock frame is very robust, but needs the upper standoff to be tight against the wall for it to work properly. Start with the adjustable standoffs adjusted to a short position so they are not touching the wall. Hang the clock on the mounting screw and keep adjusting the screw depth until the upper standoff is tight against the wall. Then adjust the lower standoffs so they are flush against the wall. You should be able to pull down on the front of the clock without seeing any sagging. If there is any sag, the clock hanging screw depth probably needs to be tightened further.

The pendulum on this clock uses simple drop-in components. Hang the pendulum on the clock according to a previous diagram. The pendulum_arm_mid_a and pendulum_arm_mid_b segments have different lengths that can be changed if needed for further range of adjusting the time. Two copies of mid_a creates a longer pendulum to slow the clock down. Two copies of mid_b can be used to speed up the clock. The two pendulum_nuts should start just below the center of the threaded portion on pendulum_arm_lower.

Hanging the Weight

Printing the weight shell has been delayed until now so you can determine the exact size needed for your clock to operate properly. My clock will run with a very shallow pendulum amplitude using a 4.5lb (2.05kg) weight. It is very robust using a 6.5lb (3.0kg) weight. Your clock may need more or less depending on the overall gear train friction.

Tie a loop at the end of the line for the weight. It needs to be able to slip over the small hook on the side of the clock. It is easier to thread the line through the weight shell pulley if the loop is a few inches long. Using a pulley on the weight shell keeps the weight balanced near the center of the clock.

Hang various size weights on the line to see how much your clock needs to stay running. An easy method is to use a water jug where you can easily add or take away weight while testing. Start with around 3lb (1.4kg) directly on the line. This amount will later be doubled when the pulley is used. Make sure the frame stays vertical during this test so the clock stays in beat.

Move the pendulum to the side and release it. The escapement should turn one tick with each beat of the pendulum. Watch how the escapement moves. It should start to rotate as soon as the pallet tips move past the escapement teeth.

If the escapement is sluggish, it will not add any energy into the pendulum and the clock will quickly stop. Try adding more weight or reduce friction in the gear train until the escapement responds quickly with each tick.

Once everything is working reliably, start reducing the weight to see the minimum amount needed to keep the clock running. We can use this value to determine what size weight shell to print. Take the minimum working amount and double this value to account for the pulley, then add a 50% safety margin, for a total increase of 3X. My clock will run for hours with 2.2lb (1.0kg) directly on the line. Tripling this to 6.6lb (3.0kg) makes the clock extremely reliable.

Weight Shell

The weight shell assembly portion of the manual has been moved to the end with the expectation that you should build the entire clock before you can determine the required drive weight for your clock. The classic clock design books with hundreds of years of experience say there is no way of knowing the exact amount of weight needed. They can give a target range, but there are too many variables and the best way to determine the value is to test it in the completed clock.

The weight is a hollow shell filled with BBs or lead shot to provide energy to run the clock. There are multiple options to create different size weight shells using different densities of fill material.

Copper plated steel BBs have around 80% of the density of lead shot, so a weight shell filled with BBs would only need to be 25% larger than one filled with lead shot to achieve with the same weight. BBs are less toxic and easier to find than lead shot, so it makes sense to use BBs to fill the weight shells. Another option is steel shot ballast used for adding weight to boats. Scuba diving shops may also have ballast material that you can pick up cheaply. Make sure it has the density of steel or copper. Bags of sand will not be dense enough.

This is my new favorite weight shell material from Amazon. The cheapest option is the 50lb bag with enough to build about six clocks. It consists of small BB sized steel balls, essentially BBs without the copper plated shell. They have a slight oil coating, but they are perfectly fine inside the weight shell.



Click image to open expanded view



Roto Metals Ballast (50 Lb. Weight Filled) Steel Shot for Wakesurf Boats, 50 pounds Weight Bag, Yacht and Airplane Ballast. Made in USA

Brand: Roto Metals
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 #1 Best Seller in Wakeboarding Equipment Bags

\$64⁹⁹

Or \$10.83 /mo (6 mo). Select from 3 plans

Or \$10.83/month for 6 months with 0% interest financing on your Prime Store Card

Size	50 pounds
Color	silver
Material	Metal
Sport	wakesurfing
Brand	Roto Metals

Figure 49: Steel shot option for weight shell

BBs can be a cheap option if you only want to build one clock. 6000 BBs weighs around 4.5 pounds (2.0kg), so two containers should be plenty. The price moves around a lot and some brands are 10X more expensive, so shop around. Also make sure to get copper plated steel, not plastic airsoft BBs.



Roll over image to zoom in



Crosman Copperhead 4.5mm Copper Coated BBs In EZ-Pour Bottle For BB Air Pistols And BB Air Guns

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 #1 Best Seller in Airsoft BBs

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-44% \$9⁹⁹

List Price: \$17.91

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FREE Returns

Style: 6000 Count

1500 Count \$6.99 prime	2500 Count \$7.49 prime	6000 Count \$9.99 prime
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- 4.5mm COPPER-COATED BBs - Compatible with 4.5mm-caliber BB air rifles and BB air pistols
- 6000-COUNT EZ-POUR BOTTLE - Ideal for the BB air gun enthusiast or backyard plinking fun
- MADE WITH QUALITY MATERIALS - For consistent and reliable performance
- RECOMMENDED FOR USE WITH CROSMAN BB AIR GUNS AND BB AIR PISTOLS - (Not compatible for airsoft)
- AIRPOWER ADVENTURES - Start with CROSMAN

Figure 50: BB option for weight shell

Below is a table showing the approximate weights of various size weight shells. I have built a few of the sizes and extrapolated the rest. The normal height column uses weight_shell_top by itself. The weight increase from a single extension is also listed. You can add multiple extensions if needed.

Weight Shell Diameter	Lead Shot Normal Height	Lead Shot with One Extension	Normal Height Filled with BBs	One Extension Filled with BBs
2.4"	5.3lb (2.4kg)	6.4lb (2.9kg)	4.3lb (2.0kg)	5.2lb (2.4kg)
2.6"	6.5lb (3.0kg)	8.0lb (3.6kg)	5.3lb (2.4kg)	6.4lb (2.9kg)
2.8"	7.9lb (3.6kg)	9.7lb (4.4kg)	6.3lb (2.9kg)	7.8lb (3.6kg)
3.0"	9.4lb (4.3kg)	11.7lb (5.3kg)	7.6lb (3.5kg)	9.4lb (4.3kg)
3.2"	10.9lb (5.0kg)	13.5lb (6.1kg)	8.8lb (4.0kg)	10.9lb (5.0kg)

Table 6: Approximate weight shell capacities

My clock runs very reliably with the 2.8" shell filled with the steel shot (BBs) shown above.

The weight shell is constructed using a pulley with a small bearing at the top end. The two halves of the pulley enclose the bearing and a pin is pushed in from the side. A tapered tip on the pin helps when lining up with the bearing center hole. The pin is a snug fit. It is OK to drill the hole 90% of the way through so only a small portion is tight. It is also OK to have a loose fit and add a small drop of glue to hold the pin. The pulley should spin freely when assembled.

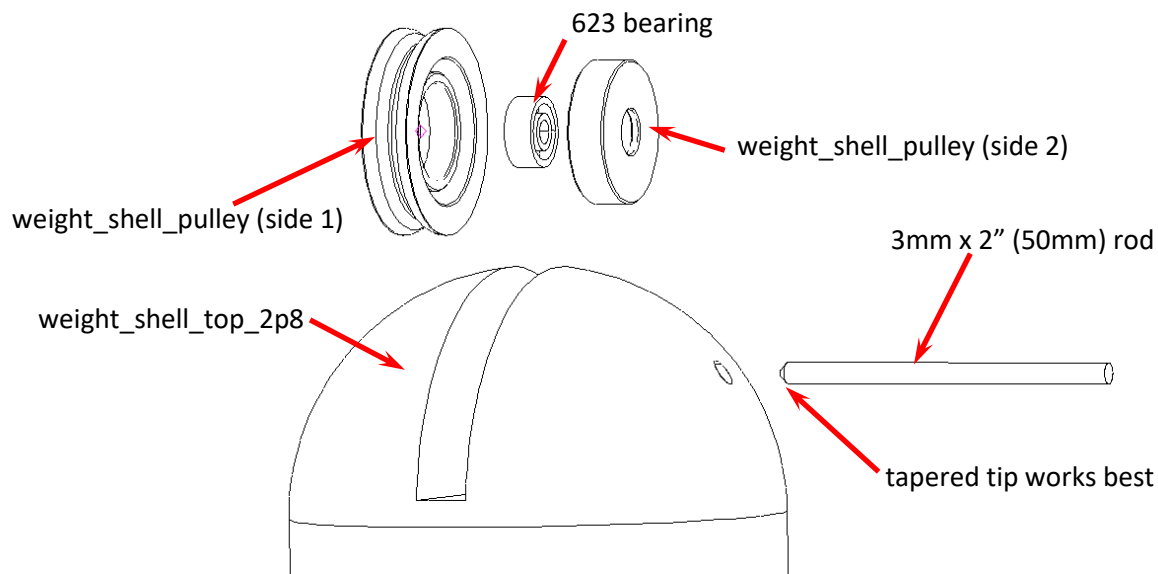


Figure 51: Top portion of weight shell

Turn over the weight shell and fill it with BBs (or lead shot). Take appropriate safety precautions if using lead shot. Assembly should be obvious when you see the parts. The bottom weight shell cover attaches using four #6x3/4" wood screws. Each weight shell extension uses an additional four #6x3/4" wood screws. Multiple extensions can be used if needed.

Setting the Beat

Move the pendulum slowly to the left and right until it ticks. The clock needs to be adjusted until the left and right sides are balanced. This is called setting the beat. You want the clock to make the sound of “tick.....tock.....tick.....tock.....” instead of “tick.tock.....tick.tock.....”. Tilt the frame to either side to set the beat. The tall layout of this clock should be close to the proper beat when the frame is vertical.

The clock should tick with a minimum pendulum amplitude of about 1 degrees to either side, however the clock becomes much more reliable with larger amplitudes. The deadbeat escapement allows the pendulum to swing several degrees above the required minimum. My clock has a swing of about 2 degrees on each side for a total amplitude of about 4 degrees. Use the swing gauge to measure the pendulum amplitude.

Push the pendulum all the way to one side and release. The clock should continue ticking and the amplitude will reduce to its natural state depending on the drive weight. Additional weight would increase the swing and the clock would be more reliable, although it does get louder.

Set the time by rotating the minute hand. Set the moon phase by rotating gear 10 from behind the dial.

Congratulations, you have completed your clock!!!

Adjusting the Rate

The clock should be reasonably accurate with the pendulum nuts near the middle of the adjustment range. Lowering the pendulum bob will make the clock run slower and raising it will make the clock run faster. Every 0.027” in change in pendulum length should change the rate of the clock by about a minute per day.

The threads below the bob have around 12.3 threads per inch. One full rotation changes the length by 0.081”. This would change the time by about 3 minutes per day. It is relatively easy to make small adjustments to get the time accurate to a minute or two per week.

The clock may change its rate during the first week or two as the components settle in to position and everything stabilizes to a consistent rate. Get past this break-in period before attempting the final timing adjustment. My clock is accurate to about a minute per week. I consider this to be pretty amazing.

Winding

Wind the clock by placing the key in the winding hole and rotate counter-clockwise. The ratchet should click as the cord is wound. Watch the cord to keep it spread across the winding drum instead of piling up in one spot. Sometimes, I guide the line while winding to help distribute the cord evenly.

The clock mounts to the wall on a single screw, so the clock may shift when winding and change the beat. I usually hold the frame steady with one hand while winding to keep it from tilting. You may need to reset the beat after winding if the position shifted.

Debugging

This clock was designed with the intention of being easy to assemble. Parts are designed to simply fit together and the clock will start working. However, there are hundreds of different printer designs with different tolerances that make each part slightly different. Some adjustment to get the parts to fit properly is expected.

This section of the manual will help guide you through some additional debug steps if your clock does not start working right away.

The pre-check summary is repeated to emphasize the importance of these steps. They are all related to reducing friction. Going through this list again will give your clock a good head start.

- 1) Visually inspect the gears for defects like elephant foot or excess stringing
- 2) All gears spin on their arbors
- 3) All arbors spin in the frame arbor holes
- 4) Gear 6 fits through the front dial and spins easily
- 5) Gear 10 fits over gear 6 and spins easily
- 6) Gear 5 spins easily on the gear 9a shaft
- 7) Gear 7b spins on gear 7a and the ratchet is working
- 8) Pendulum bearing free swing test runs for at least 5 minutes, preferably 10-20 minutes
- 9) The gear 4 assembly, spacer_6, gear 6, and gear 10 have some end shake inside the frame
- 10) The gear 9 assembly has some end shake inside the frame

A few additional checks can be added after the clock is assembled. It is important to notice how the clock is stopping to decide where to focus your debug efforts.

- 11) Is the clock hanging properly to minimize frame sag?

The first thing to check is if the clock is hanging properly. If the clock is simply hung on a nail, the main support beam will tilt downwards from the weight on the front of the clock. This will cause the thin sections of the frame to bend so the entire frame becomes a parallelogram and the gears can go out of alignment. They could become pinched by the frame. Or the gears could tilt so the sidewalls interfere. The hanging screw depth needs to be properly adjusted and it needs to be strong enough so it will not pull away from the wall.

- 12) Is the clock in beat? Move the pendulum slowly from side to side to observe.

A clock that is in beat will have a balanced tick tock sound as the pendulum moves back and forth. This clock should be close to being in beat with the frame vertical. The only adjustment is to tilt the frame left or right. Only a small amount of adjustment should be necessary. It is a good idea to check the beat after each winding since the frame might have shifted. A clock that was previously working great but stops running within 30 minutes of winding is often an indication that the beat was changed while winding.

- 13) Does the escapement rotate quickly when the pallet arms clear the escapement teeth?

This clock has a Graham deadbeat escapement that allows the pendulum to swing freely to its natural amplitude without pushing the escapement backwards. The escapement needs to rotate quickly when it changes from the “dead” portion to the active portion where the angled teeth

engage and the escapement pushes on the pendulum. If the escapement is really sluggish, it will not impart any energy into the pendulum and the clock will quickly stop.

If the escapement starts spinning slowly, it might barely touch the pallet arms before the pallet moves past. Some energy is transferred, but not the full amount. The clock may run, but the pendulum amplitude will be weak. The problem could be friction in the gear train or too small of a drive weight. The friction pre-checks may help. You could also try a small bit of grease on the pinion teeth. PLA seems perfectly tolerant of most lubricants. Adding extra drive weight may also help.

14) Does the pendulum slowly lose amplitude and eventually stop?

This could either be too much pendulum support bearing friction or not enough drive weight. Some builders mention that they get less than a minute on the pendulum free-swing test. I have not found a 623 bearing that runs for less than 5 minutes unless the bearing felt like it was dropped in sand. I have ordered hundreds of bearings and never see more than 1-2% that are bad. And I buy the cheapest bearings I can find. The bearings usually come in sets of 5 or 10. Try different bearings.

Another thing to check is if the bearings are really tight in the frame, they might be skewed and adding a side load which will cause extra friction. Enlarge the hole slightly so the bearings are loose but not sloppy in the frame.

If all the pre-check friction tests are working, then try adding a weight shell extension.

15) Does the clock stop in less than a minute?

If the pendulum free-swing test runs for 10 minutes, then the clock should run for several minutes unless the escapement is getting in the way of the pallet. You may see the escapement jump from the pallet arms hitting it. This may be caused by friction in the gear train not allowing the escapement to rotate quickly. Repeat the pre-check tests looking for where the excess friction is coming from.

16) What is the pendulum amplitude?

The minimum pendulum amplitude for the clock to run is one degree in each direction, however a clock with only one degree of swing will stop from the slightest disturbance. Two degrees in each direction will be much more stable. Try reducing friction or adding more weight to get closer to the two degree target.

17) Does the clock appear to run, but the time does not change?

This is usually a simple fix to reduce friction in the hour hand gears or increase pressure on the friction clutch spring. If gear 6 is binding where it passes through the frame, then the friction clutch will slip and the time will not change. Sand the gear 6 shaft or the frame opening where gear 6 passes through. Or it could be caused by a lack of end shake on the central arbor. Reduce the height of one of the gears in the stack or the spacers making up the friction clutch. Another option is to stretch the spring so it applies more pressure. The good news is that the primary gear train is working so the clock is almost completely functional.

18) Look at the clock from the side. Are any gear side walls touching?

The clock is designed with a reasonable amount of clearance between gears that are not supposed to touch. It is a balance between just enough clearance to make a compact clock or a lot of clearance making a really large clock. Possible causes include frame sag, warped gears, or too much end shake allowing extra sideways movement. Frame sag is usually fixed by following the clock hanging procedure. Warped gears may need to be re-printed. Excess end shake can be solved by adding spacers to limit the sideways movement.

19) If all else fails, test gear pairs looking for excess friction.

Most of the pre-check tests focus on individual components or small modules. Sometimes, the extra friction occurs when gears don't mesh properly. Try testing gear pairs and spin them by hand. For example, put just gears 3 and 4 into the clock. Do they spin easily? You may need the spacers or other gears above gears 3 and 4 so you can add the front frame to hold the arbors straight. Try again with gears 2 and 3. Keep going through the gear train testing pairs.

20) Test the entire gear train without the pallet.

After testing all the gear pairs, try the entire set of gears without the pallet. Hang the clock on the wall. Add the weight shell. All the gears and the escapement should spin. It may take an hour for the weight to reach the floor. This is also a great way to break in the clock.

If the gears stop, look for friction where they stop. Touch each gear. If it starts spinning, see if you can find anything near that gear causing friction. Start and stop the escapement. It should start spinning quickly each time.

These are the most common reasons why your clock might not be working right away. A mechanical clock is a complex piece of engineering, so there may be other reasons. There are a lot of moving parts. I try to design using loose tolerances, but there can still be things that need adjustment for your clock to function properly.

Once the clock is working properly, it should continue to work for many years. I have been running mine for a few months so far and it has been working flawlessly. My other clocks with similar construction techniques have been running for years.

I am available to answer questions and help you complete the last few debug steps to get your clock working. You can ask questions on MyMiniFactory or the forum at <https://www.stevesclocks.com/forum>. Try to provide as much information as possible. If there are different runtime options, mention which option you are using and how much weight you are using. The pendulum free-swing time for your clock may also be useful information.

You can post pictures of your clock on any of the web sites. The forum allows any type of clock related questions and comments, even related to clock designs from other designers.

Final Comments

Clock design has been a hobby of mine for many years. It really expanded about five years ago when I got my first 3D printer. The ability to quickly go from prototype to working clock is so easy with a 3D printer. I usually have several works in progress at any time. Some are grand plans that may take years to complete. Others are minor revisions.

The large version of this clock is one of the first designs where I can identify a start and end date to build the complete clock. A builder, Nick, posted a suggestion on my forum on 01-Jan-2024 asking about a moon phase dial. The fully functional prototype was posted on 28-Jan-2024. A few minor enhancements were made while writing the assembly guide in February. I started working on the “perfect print gear” enhancement through the remainder of 2024, before this smaller version of the clock could be completed. It is now one of my most reliable clocks.

The moon phase clocks have become my new favorite clocks. The 8 day runtime with just under a pound per day of drive weight appears to be extremely reliable. Adding the moon phase dial without making the clock too large was an interesting challenge. One day of moon phase error every 2.6 years is pretty incredible.

This clock has been released on MyMiniFactory. Feel free to check out my other clocks. They are easy to find by searching for “Steve Peterson clocks”. You can find additional information on my web site at <https://www.stevesclocks.com>

Parts kits for all the non-printed parts except the weights are available on my Etsy store. Check the main description on MyMiniFactory for a link. Both sizes of the moon phase clock plus SP2 and SP3 all use the same parts kit.

I have been experimenting with wooden gears in an attempt to make a wooden gear clock, but have not yet completed a fully functional weight driven pendulum clock. One of my goals is to shift my clock design efforts into wooden clocks. I actually started trying to build a wooden clock, but switched to printed clocks as soon as I received my MK3 printer. The 3D printer makes it so easy to build prototypes and I have released over a dozen designs so far. I may have a few more printed designs in progress, but I hope to get back into the workshop to start making a wooden gear clock soon. Stay tuned for more information.

Good luck with your clock build.

Steve

I recently had all of my clocks on display at the 2023 Bay Area Maker Faire. It was a great experience. Most of the people attending seemed to be interested in the large robots, but I still had a nearly constant stream of visitors for six days. It was refreshing to see so many young people asking how to design a clock. Here are all of the wall mounted clocks.



Figure 52: Maker Faire wall clocks

Sorry about the bad quality images. The lighting was horrible and there was only a few minutes between setup and a line of people in the booth. Here are the desktop clocks.



Figure 53: Maker Faire desk clocks