



3D PRINTED PENDULUM CLOCK

SP1 Build Notes

Build Notes for a 3D printed pendulum clock with an 8-day run time

Steve Peterson
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Description

I have always had a fascination with mechanical clocks so I designed one to be printed on my Prusa MK3. There are a few other 3D printed clock designs on the web, but most seem to have runtimes of around 12 hours. I wanted to see if it was possible to extend the runtime to several days with the ultimate goal of 8 days per wind. This design evolved over a six-month period to achieve that goal.

Details

A pendulum clock is conceptually very simple. A spring or falling weight provides energy to a swinging pendulum that swings at a constant rate. 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. Designing this clock has been a hobby of mine for many months. I started with a basic sketch of the clock, then fit gears to be as symmetrical as possible.

The total print time is around 89 hours plus a few hours to assemble everything. The few non-printed parts are hidden as much as possible. Some basic tools will be required, such as screwdrivers, hacksaw, files, etc. The skill level required is intermediate to advanced.

Involute gear profiles were designed using Gearotic and imported into TurboCAD for final adjustments. One early experiment was to determine the gear tooth 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 dot pitch down to 40 DP. A 60 tooth gear would be 6" in diameter at 10 DP, 3" at 20 DP, and 1.5" at 40 DP. The fine pitch gears were printable with some distortion. 10 DP gears are great for building a wooden gear clock, but would likely be too large for 3D printing. I selected 20 DP as my favorite gear size and printed them in gold colored filament to get them to look like brass.

The next step was to design the overall gear train. Most pendulum clocks share the same basic structure with slight 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 rotational speed of the different gears. There is a bit of trial and error to find good gear ratios. Eventually, everything starts looking like a clock. Figure 1 shows the model of the final gear train.

Most 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 4.5:1 ratios between stages. This has several advantages, primarily the ability to use 12 tooth pinions with reasonably small tooth counts on the larger gears.

The gear sizes selected have the escapement rotating once every 39.5 seconds. This could have been built using a 20-tooth escapement and a pendulum length of around 39 inches. Instead, I chose a 30-tooth escapement with a period of 0.658 seconds per swing in each direction. A pendulum with a length of just under 17 inches will satisfy the requirement. This length pendulum seems proportional to the size of the clock body. The pendulum beats at a rate of 5467.5 beats per hour.

The next step in the gear train design is a 12:1 ratio between the minute hand and the hour hand. There are many different tooth counts that would satisfy this ratio. The typical gears are 32:8 and 30:10 to

provide 4:1 and 3:1 ratio for a 12:1 overall ratio. One slight problem with this tooth count is that the pivot distance would interfere with the minute hand. This clock design uses a 48:18 and 54:12 gear design with 2.67:1 and 4.5:1 ratios. This places the pivot point just outside the footprint of the minute hand so there is no interference. The hour hand still rotates at 1/12th the rate of the minute hand.

Clock Gear Ratios

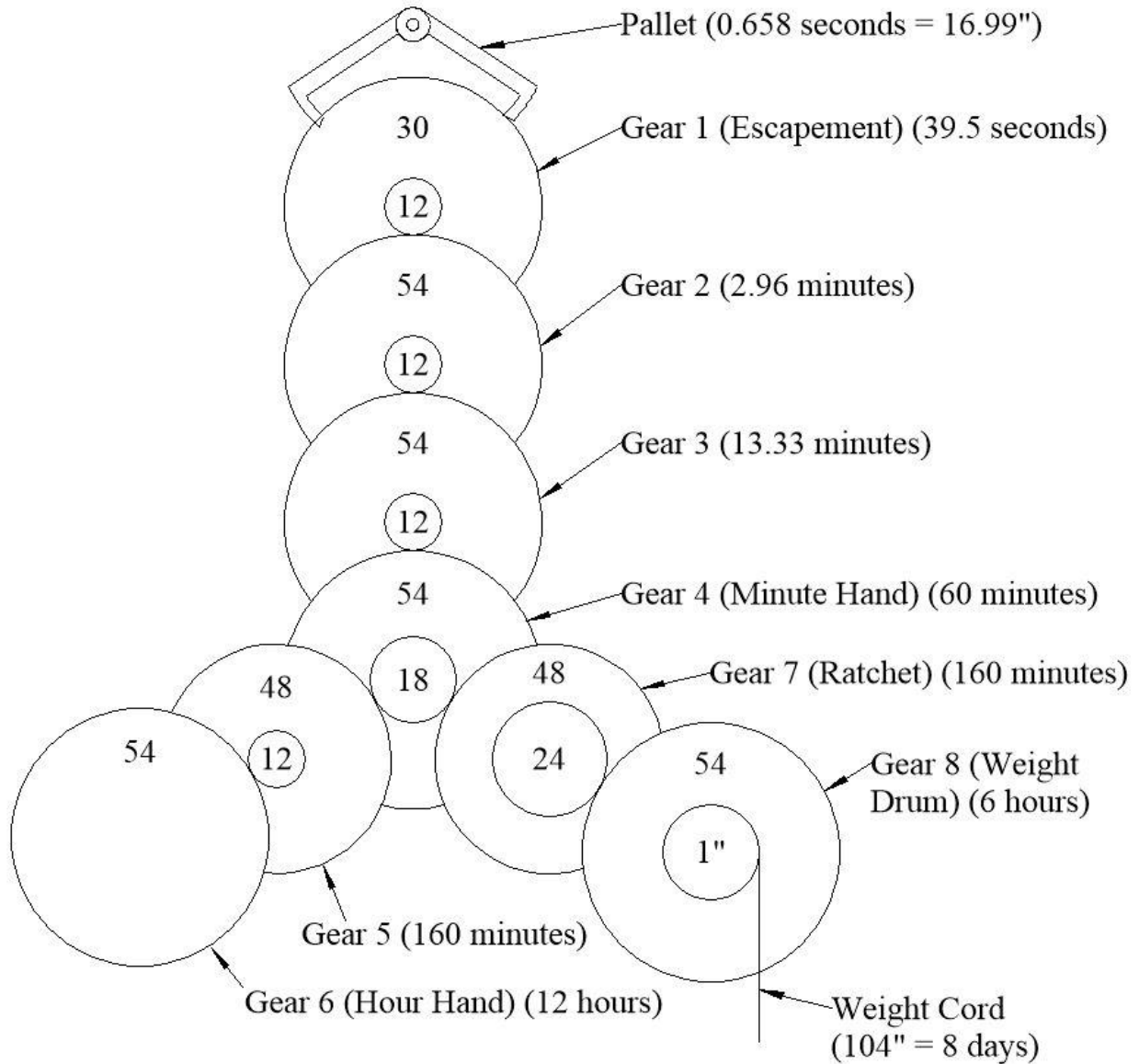


Figure 1: Clock gear train

The final component is the weight train to provide a power source. The target for this design is to have an 8-day runtime. The weight drum is placed along the center of the clock which puts the cord slightly to one side. Adding a pulley to the weight shell allows the weight to stay symmetrical with the center line of the clock. Gear ratios and weight drum diameter were chosen to allow an 8-day run time.

An 8-day run time with 52" of drop means that the weight can drop 6.5" per day. A pulley doubles the length to unwind 13" of cord per day. The 1" weight drum rotates once every 6 hours. Two gear sets divide this down to one rotation per hour of the minute hand. A 4.6 pound weight shell has just enough power to keep the clock running for 8 days, but I increased it to 6.4 pounds to make the clock run more reliably. Some of my initial experiments used a larger weight shell and a 3:1 divide ratio with only a 4-day run time. I added steel bushings at several critical locations to reduce friction enough to use the 8-day gear set.

The clock frame is a two piece shell with front and back segments. One great thing about 3D printers is that they can integrate a lot of details into each piece. All of the axle locations and support columns are fully integrated. The back frame uses a metal keyhole hanger to hang the clock on the wall. Standoffs push the clock away from the wall for pendulum clearance. The top of the frame has a robust support bar to prevent frame sag from the heavy weight shell. This design could easily handle double the weight with no visible sagging. The support bar also includes a convenient location to store the winding key.

The front frame integrates the dial and numbers into a single 3D print. The first few layers are printed tan colored with pauses for the ivory colored dial and black numbers. The same multi-layer technique is used to add gold highlights to the clock hands. The front and back frame sections just barely fit diagonally on the MK3 print bed. The pendulum bob is a two-piece clamshell with a few pennies added for weights. It pivots on two small ball bearings with the grease removed to lower the friction. The pendulum rod was printed in two sections and epoxied together with a threaded rod sticking out the bottom. The finial below the pendulum has an embedded 8-32 nylon friction nut for adjusting the pendulum length. One eighth of a turn adds or subtracts 10 seconds per day. It is easy to fine tune the accuracy to within 1-2 minutes per week.

The gear thicknesses and clearances were defined using the mockup in figure 2. Most gears are 0.2" thick. Gears 7 and 8 have the most weight on them, so they were made thicker with bearings supporting the weight on gear 8. The escapement and pallet were also made slightly thicker to provide a larger wear surface. The pallet has tiny ball bearings to support the weight of the pendulum. I experimented with several different sized bearings and picked a size that allowed a pendulum to "free swing" the longest. The load is significantly below their design limit so I am expecting them to last a long time.

The diagram below shows a mock-up of the gear locations relative to the frame. It was used as the starting point for determining gear thicknesses and clearances. Finally, the gears were built into a 3D CAD model to check again.

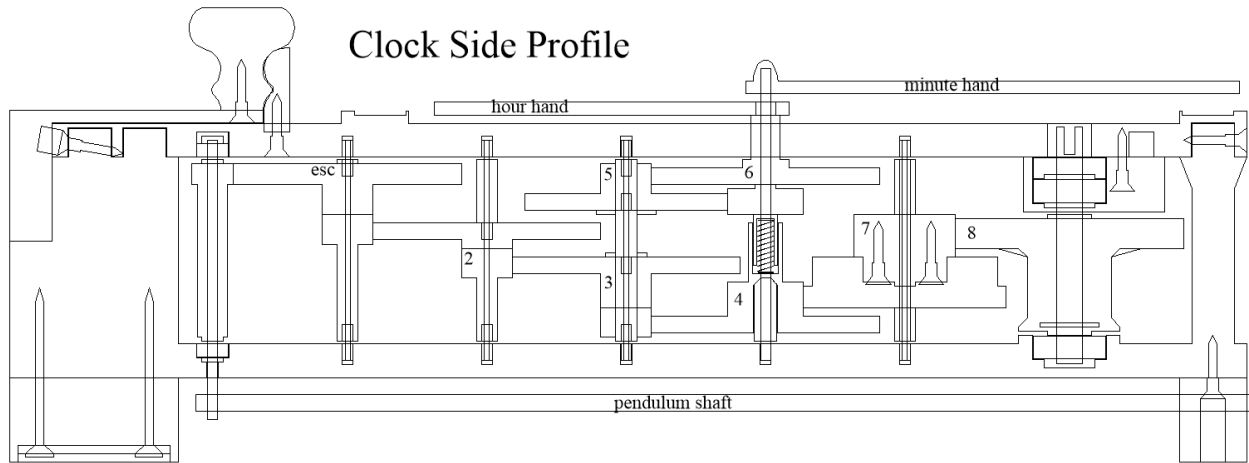


Figure 2: Clock side profile

The total print time for all of the components is almost 90 hours and about 3/4 of a spool of filament. The weight shell itself takes around 17 hours and each half of the frame is around 12 hours. Each gear takes around an hour. The total time from concept to ticking clock was around 6 months and a box full of experimental parts.

Printing the Parts

Most parts can be printed flat with the largest surface on the build tray. No supports were needed for any of the parts. I printed everything on a Prusa MK3 with a 250mm by 210mm build tray. The two largest components are the front and back frames. They just fit on a Prusa MK3 at a 35-degree angle.

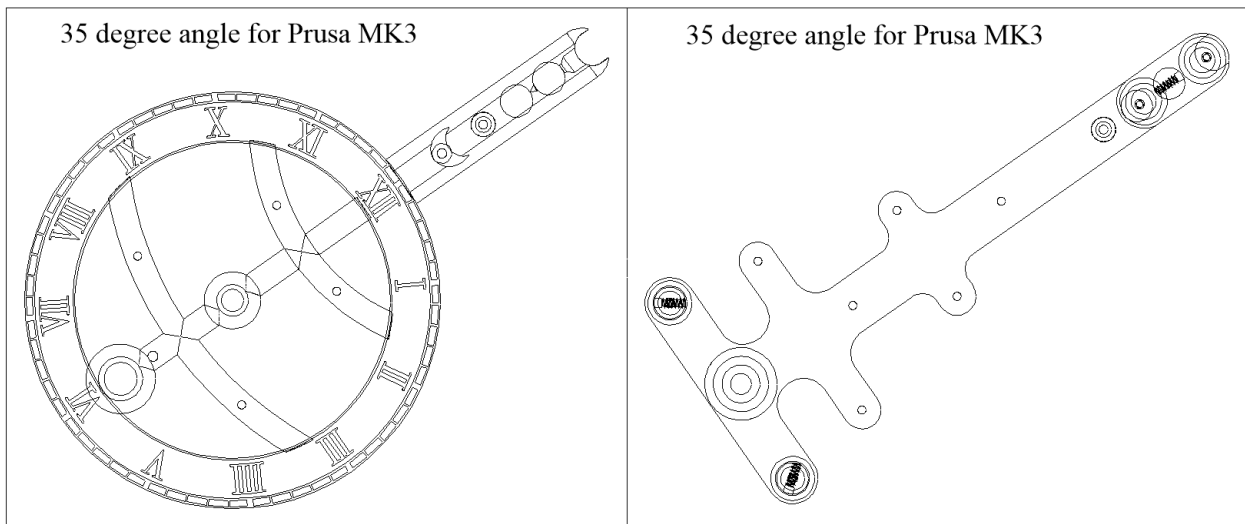


Figure 3: Prusa MK3 orientation

Another popular printer appears to be a Creality Ender 3 with a 220mm by 220mm tray. The frame should fit on this printer with a 45-degree rotation. The STL files are released with a 35 degree rotation, so they would need an additional 10 degrees of rotation to fit on a CR3.

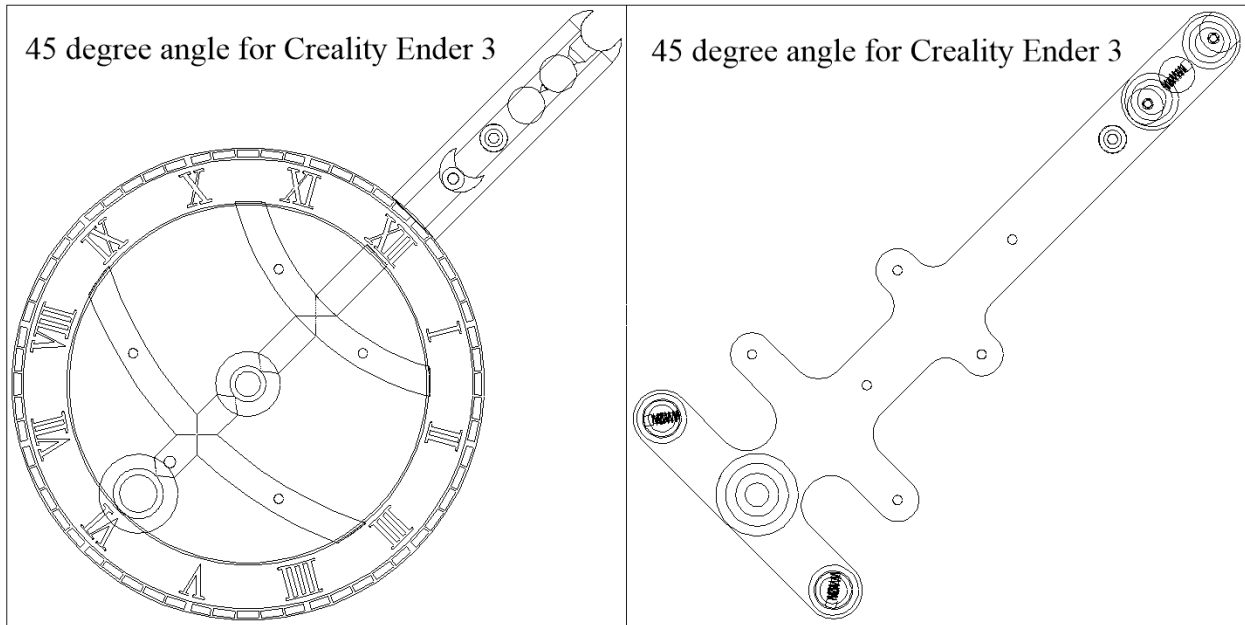


Figure 4: Creality Ender 3 orientation

The large frame components might print better with a brim. They are large and relatively thick so they have a slight tendency to curl up from the bed. And you won't see any problems until you are 10 hours into a 12 hour print. I had one failure printing the front frame where the left side started curling up just as the numbers were being added. This caused half of the numbers to be squished and really horrible looking. I added a 5mm brim and the next print was OK. It just barely fit on the print bed.

I have printed two working clock models (so far) using PLA as the only filament. Other filament types might work just as well or maybe even better. PLA works for me, so I will continue to use it.

All of the parts are designed to fit directly on the bed without any additional supports. I typically leave everything at 50% density. The frame might work just fine at 20% density, but I don't want to risk having it sag after hanging the weight. Most other parts are small or they have thin walls so there is almost no difference between 20% density and 50% density. The only settings changed from the defaults are seam position set to random and Cubic infill with 50% density. Random seam position is important on the weight shell to prevent it from having a long diagonal stripe where each layer starts.

The color choices listed in the table below are one example using "traditional" clock colors. They would create a clock like the one on the front cover. The gears are printed in gold color to make them look a bit like brass. The frame is a neutral tan color with ivory and black highlights for the dial. The print times were reported in Slic3r Prusa Edition 1.41.2 in normal mode. Stealth mode would be a bit higher. It is OK to combine parts into one long print job.

File Name	Color	Need	Hours	Minutes	Filament	Total Time	Total Filament
front_frame	Tan, ivory, black	1	11	55	46.52	11.92	46.52
back_frame	Tan	1	12	15	44.00	12.25	44.00
hanging_hook	Tan	1	2	5	6.16	2.08	6.16
back_standoff	Tan	2	1	10	2.08	2.33	4.44
pallet	Gold	1	0	48	1.35	0.80	1.35
escapement	Gold	1	2	30	4.80	2.50	4.80
gear2_54_12	Gold	1	2	5	3.85	2.08	3.85
gear3_54_12	Gold	1	2	14	4.19	2.23	4.19
gear4_54_18	Gold	1	2	19	4.70	2.32	4.70
gear4_lower	Gold	1	0	13	0.22	0.22	0.22
gear4_upper	Gold	1	0	9	0.15	0.15	0.15
gear4_18	Gold	1	0	29	1.02	0.48	1.02
gear5_48_12	Gold	1	1	37	3.03	1.62	3.03
gear6_54	Gold	1	1	44	3.30	1.73	3.30
gear7_48	Gold	1	2	49	5.97	2.82	5.97
gear7_clicks	Gold	3	0	19	0.47	0.95	1.41
gear7_24	Gold	1	1	34	3.46	1.57	3.46
gear8_54	Gold	1	3	57	10.01	3.95	10.01
bearing_holder	Tan	1	1	55	4.87	1.92	4.87
bearing_spacer	Tan	1	0	18	0.68	0.30	0.68
hour_hand	Black, gold	1	0	14	0.57	0.23	0.57
minute_hand	Black, gold	1	0	19	0.74	0.32	0.74
shaft_top	Black	1	1	16	4.45	1.27	4.45
shaft_bottom	Black	1	1	18	4.54	1.30	4.54
pendulum_front	Gold	1	5	4	17.09	5.07	17.09
pendulum_back	Gold	1	1	18	6.23	1.30	6.23
finial	Black	1	1	6	1.29	1.10	1.29
weight_shell	Gold	1	16	56	46.50	16.93	46.50
weight_bottom	Gold	1	0	56	3.85	0.93	3.85
weight_pulley	Gold	1	0	46	2.80	0.77	2.80
weight_pin	Gold	1	0	10	0.16	0.17	0.16
crank_handle	Tan	1	1	25	2.52	1.42	2.52
crank_knob	Gold	1	1	19	3.19	1.32	3.19
crank_shelf	Tan	1	0	44	0.82	0.73	0.82
cord_guide	Tan	1	0	32	1.09	0.53	1.09
swing_gauge	Ivory, black	1	0	20	1.29	0.33	1.29
misc_spacers	Gold	1	1	10	1.49	1.17	1.57
		40	72	978	249.49	89.10	252.65

Table 1: File names and estimated print times

Color Changes

The front frame has an integrated dial that needs a color change at 12.80mm to highlight the numbers. Another color change can be added at 10.25mm to add light color dial. My clock starts with a tan base layer, with a change to ivory at 10.25mm, and black at 12.80mm for the numbers. PrusaControl has a really easy method of adding layer changes.

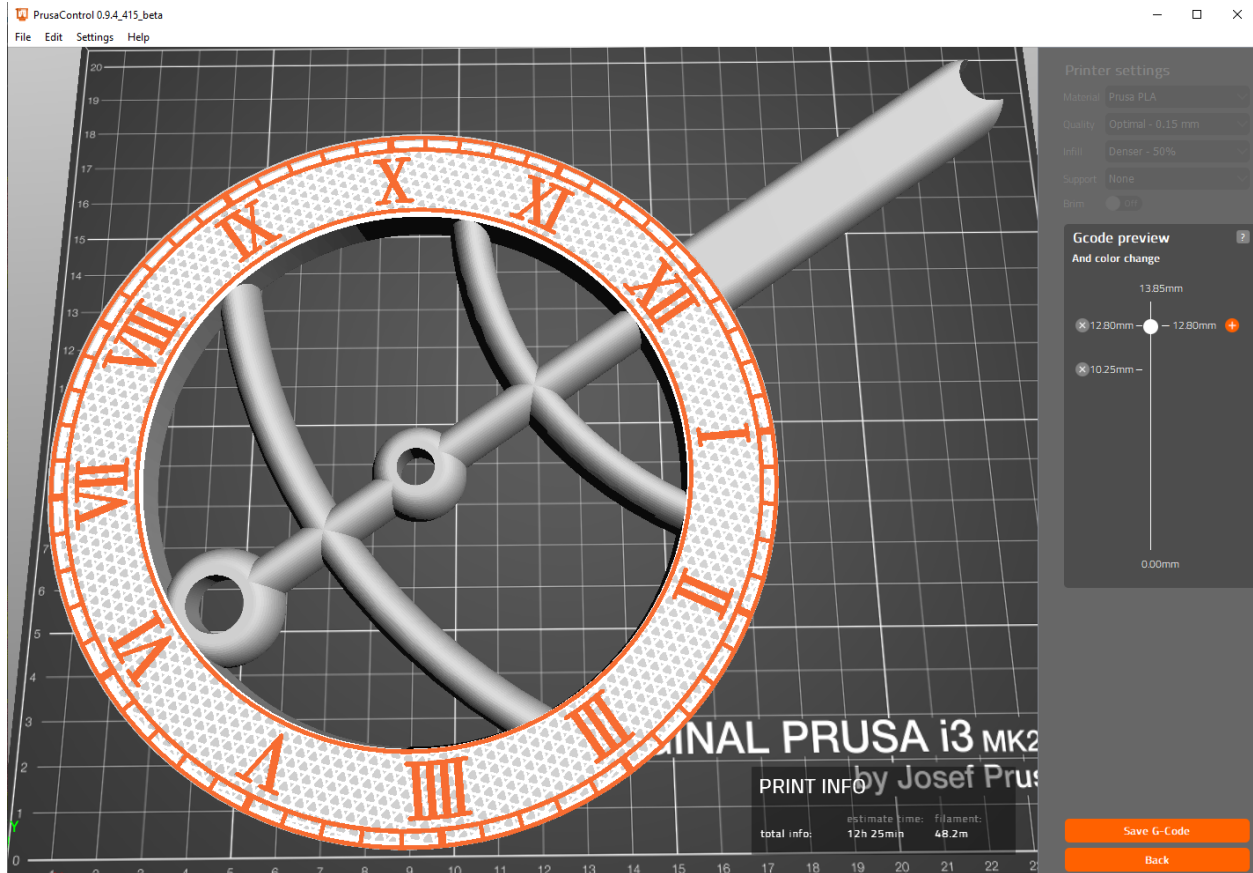


Figure 5: Layer changes for front frame

The hands can also get a color change at 2.75mm to highlight the borders. I used a black base color with gold highlights. My first design with single color hands looked a bit plain with either solid black or solid gold hands. The highlighted perimeter seems to make the hands a lot more visible.

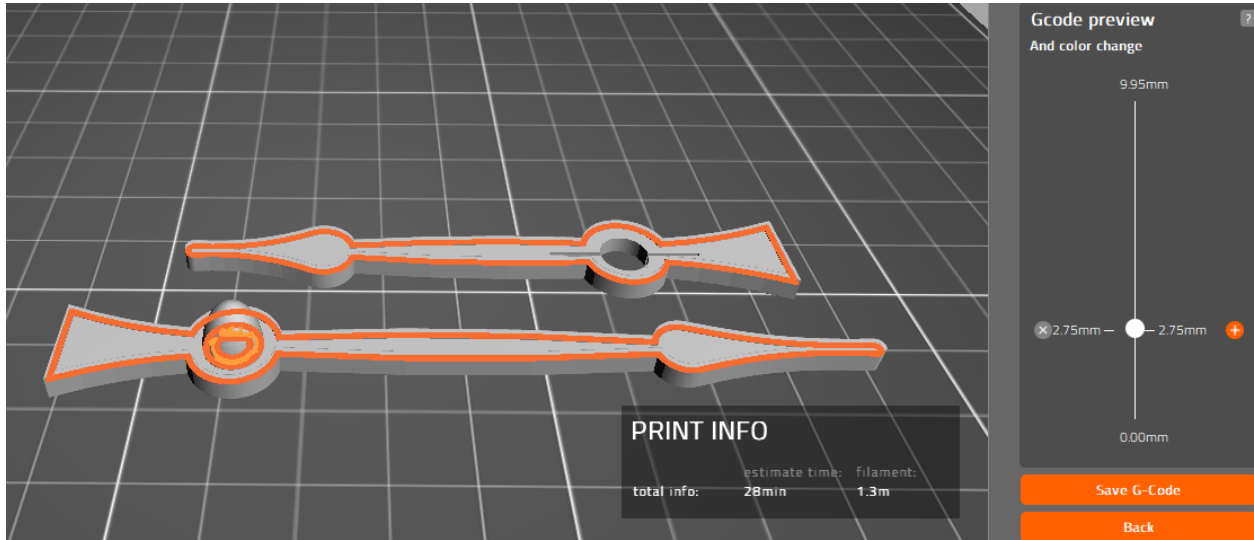


Figure 6: Clock hand color highlights

The swing gauge is useful for determining the swing amplitude and also for balancing the escapement trip positions. It needs a color change at 1.40mm.

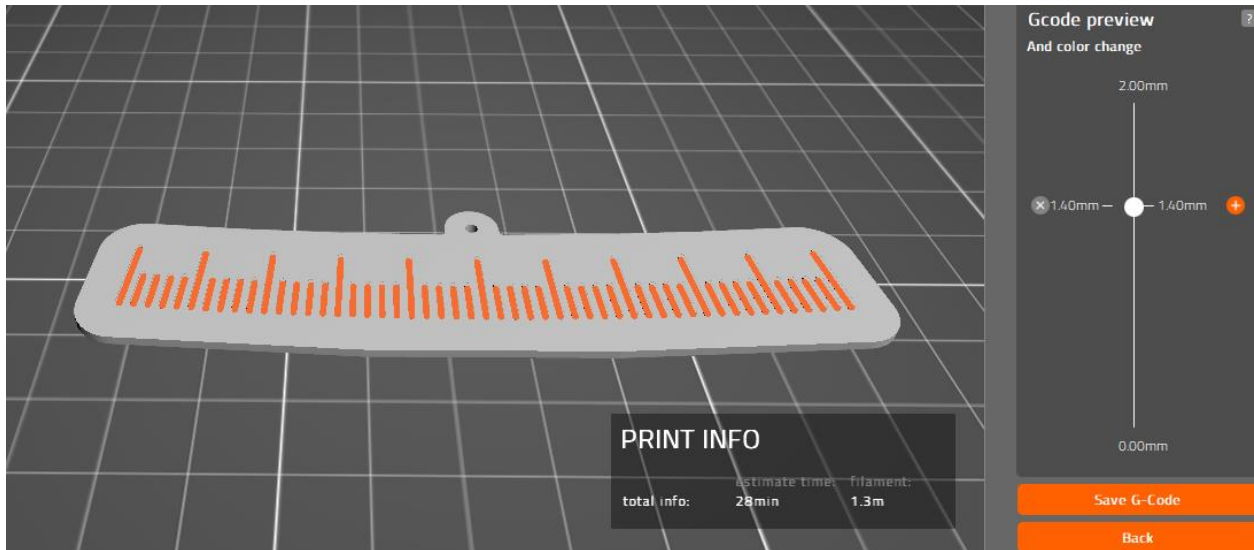


Figure 7: Swing gauge color highlights

Below is a CAD model of all the printed parts that needed color changes.

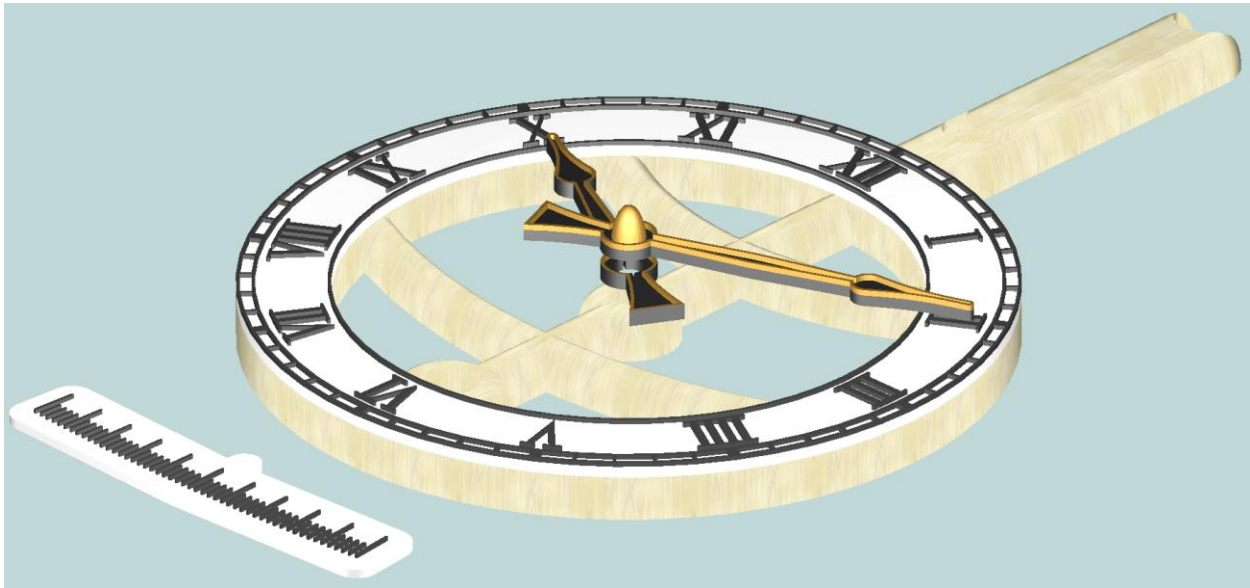


Figure 8: All parts with color highlights

The finial below the pendulum is used to adjust the speed of the clock by changing the length slightly. It is a single color, but needs to be paused at 6.95mm to drop in a 6-32 nylon insert locknut and continue printing. The position is at just after the hex shaped hole for the locknut closes. I treat this as a color change even though the color stays the same. The printer waits for you to remove the black filament, drop the locknut in the hole with the nylon portion up, then put the black filament back in. The finial is tall enough to benefit from a brim.

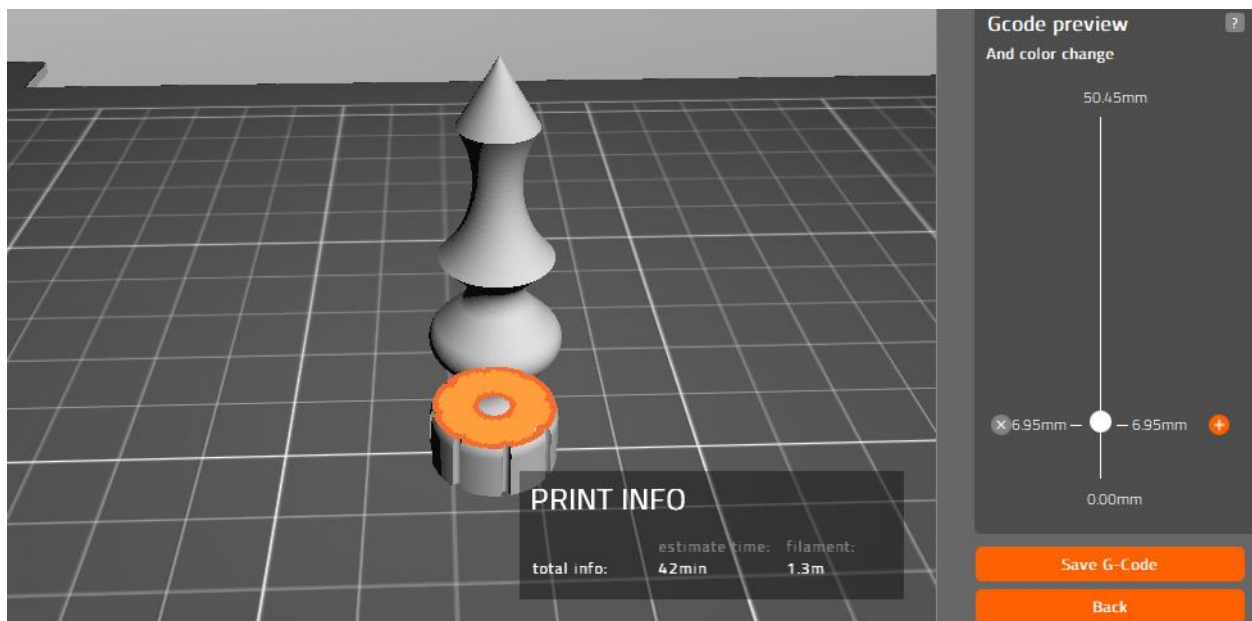


Figure 9: Pause finial at 6.95mm to insert nylon locknut

Additional Components

This clock consists mainly of 3D printed parts, but a few metal components are required. A clock could probably be built completely from 3D printed parts, but the friction would be much higher and the run times would be shorter. Printed gear axles would need to have a larger diameter than steel axles used in this clock. 1/16" steel rod is stronger and significantly lower friction than a PLA axle would be. Steel screws are so much stronger than printed screws. I tried to keep most of them hidden.

The following non-3D printed components are required. Part numbers from McMasterCarr are provided for most parts although many can be found cheaper at your local hardware store. The parts are a mixture of metric and imperial sizes. Some can be substituted with the closest size of either type. For example, the design uses a 5/16" (0.3125") brass axle to support the weight drum. This fits easily inside the 8mm (0.3150") hole of a 608 bearing. An 8mm brass axle would also work, but sometimes they come oversized and need to be sanded down to fit into the bearing. 5/16" brass always fits.

Qty	Component	McMC Part No.	Notes
12	6x3/4" flat head wood screw	90031A151	
1	6x1" flat head wood screw	90031A153	
10	4x1/2" flat head wood screw	90031A110	
5	6x1-5/8" drywall screw	99136A300	
2	6x2" drywall screw	99136A400	
1	6x1-1/4" pan head wood screw	90190A201	for mounting clock on wall
2.8"	5/16" brass rod	89535K138	for weight drum
12"	3mm stainless rod	1272T33	cut into 1x3.5", 1x3.3", and 4x0.7" pieces
15"	1/16" music wire	89085K85	cut into 5x2.60" and 1x0.75"
10"	1/8" stainless tube with 1/16" center hole		K&S part #87111, cut into 1x2.15" and 18x0.20"
8"	6-32 threaded rod	90034A049	cut into 2x1.9" and 1x3.0" pieces
1	nylon insert locknut	90631A007	
1	1/8" brass wheel collar		Great Planes GPMQ4305 or DuBro DUB139
1	4-40x3/8" machine screw	90279A108	for brass wheel collar
10'	microfilament fishing line		PowerPro Spectra Fiber braided fishing line 65 lb. test, Eq Dia 16
6 lb.	lead shot	9030K22	
3	608 bearing	6153K111	ceramic balls work best
2	R2 bearing (1/8x3/8x5/32)	57155K349	ABEC 3 or better, no rubber shields
1	keyhole hanger		Lowes 334849
4	click pen springs		

Component Pre-Assembly

Metal Parts

Most of the axles in the clock use pieces of music wire running inside small stainless steel bushings. This reduces the friction compared to metal axles in PLA. The first design of the clock used 1/8" metal rods running directly in holes in the PLA frame. The friction was high enough that the clock would often stop running every day or two. Doubling the weight helped somewhat, but was not enough to keep the clock running reliably even with a 4-day runtime. The local hobby shop has 1/8" stainless steel tubing with a center hole just over 1/16" that makes great bushings to reduce friction considerably. The raw material part number is K&S 87111 for a 12" tube.

The clock needs 18 short 0.2" bushings, and one 2.15" bushing. I cut them at the bench vice with a fine blade hacksaw. The length of the short bushing is not too critical. They will be pressed into 0.25" deep holes, so anywhere between 0.15" and 0.20" in length is good.

The ends need to be cleaned up to remove the burr. I use a bench grinder with a fine grit CBN wheel. A fine grit grinding wheel or disc sander should also work. A hand file could also be used. You need to have some way to hold the short bushing up to the grinding wheel. I use a short dowel with a piece of 1/16" music wire sticking out the end. It holds the bushing in place and allows it to spin while gently touching it to the grinder. A 1/8" pin vice would probably be safer. Rotate the pin vice to flatten the end and round off the outer corners. The inner corners can be cleaned up using a few twists with a countersink drill bit. I use one from a 5 piece set from Lowes item number 505624. The important characteristic is that the cutting surfaces need to extend all the way to the tip so it can be used to deburr a 1/16" hole.

The bushing ends are a lot easier to clean up when the tubing is long. I usually cut a short bushing from both ends, then clean up the ends of the long tube before cutting the next set of short bushings. Then half of the cleanup is done when the tube is easy to handle. The other end of each tiny bushing will need to be cleaned up using a pin vice.

The minute hand axle uses a 3.45" long section of 3mm stainless rod. It needs a flat filed at one end to prevent the minute hand from slipping on the axle. The pendulum uses a 3.3" length of 3mm rod. Make four 0.75" long pieces for hanging hook alignment pins.

Cut the 1/16" music wire into five 2.60" segments and one 0.75" segment. Clean up the ends by rotating them while gently touching them to a bench grinder or sanding disk.

The 5/16" brass rod needs a small amount of prep work before inserting into the weight drum. One end needs a 1/8" wide slot about 0.5" deep. It can be cut with two passes from a hacksaw and hand filed to final shape. The winding key needs to easily slide over the end. Keep filing until it fits. A 1/16" hole is drilled 0.500" from the other end for a 1/16" by 3/4" music wire pin.

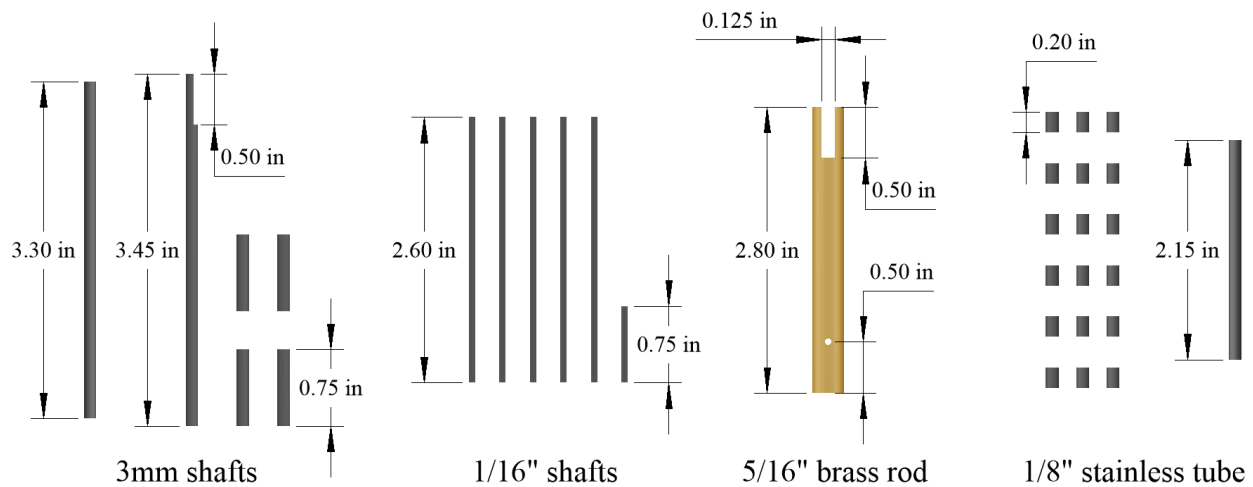


Figure 10: Metal parts

Back Frame

Gently tap a 0.2" bushing into the five holes in the back frame that are marked in figure 11. The minute hand uses a 3mm axle, so it does not get a bushing. The holes in the frame are sized for the bushings to be a tight fit. Depending on your printer settings, the holes might be a slightly different size than from my printer. It is OK to slightly increase the hole diameter with a 1/8" drill bit. Use a small drop of superglue if the hole is too small, but make sure to keep any glue out of the inside of the bushing. The bushing should remain flush with the surface of the frame.

The back frame uses standoffs to position the frame away from the wall for the pendulum. The hanging hook uses four 3mm by 0.75" stainless pins, the keyhole hanger, and two 2" drywall screws. The lower standoffs attach with 6x3/4" wood screws. All screw holes are printed with spiral tapped threads designed specifically for screws that are commonly available in the US. Drywall screws have 9 threads per inch and 6x3/4" wood screws have about 18 TPI. They should screw in relatively easily without fear of breaking.

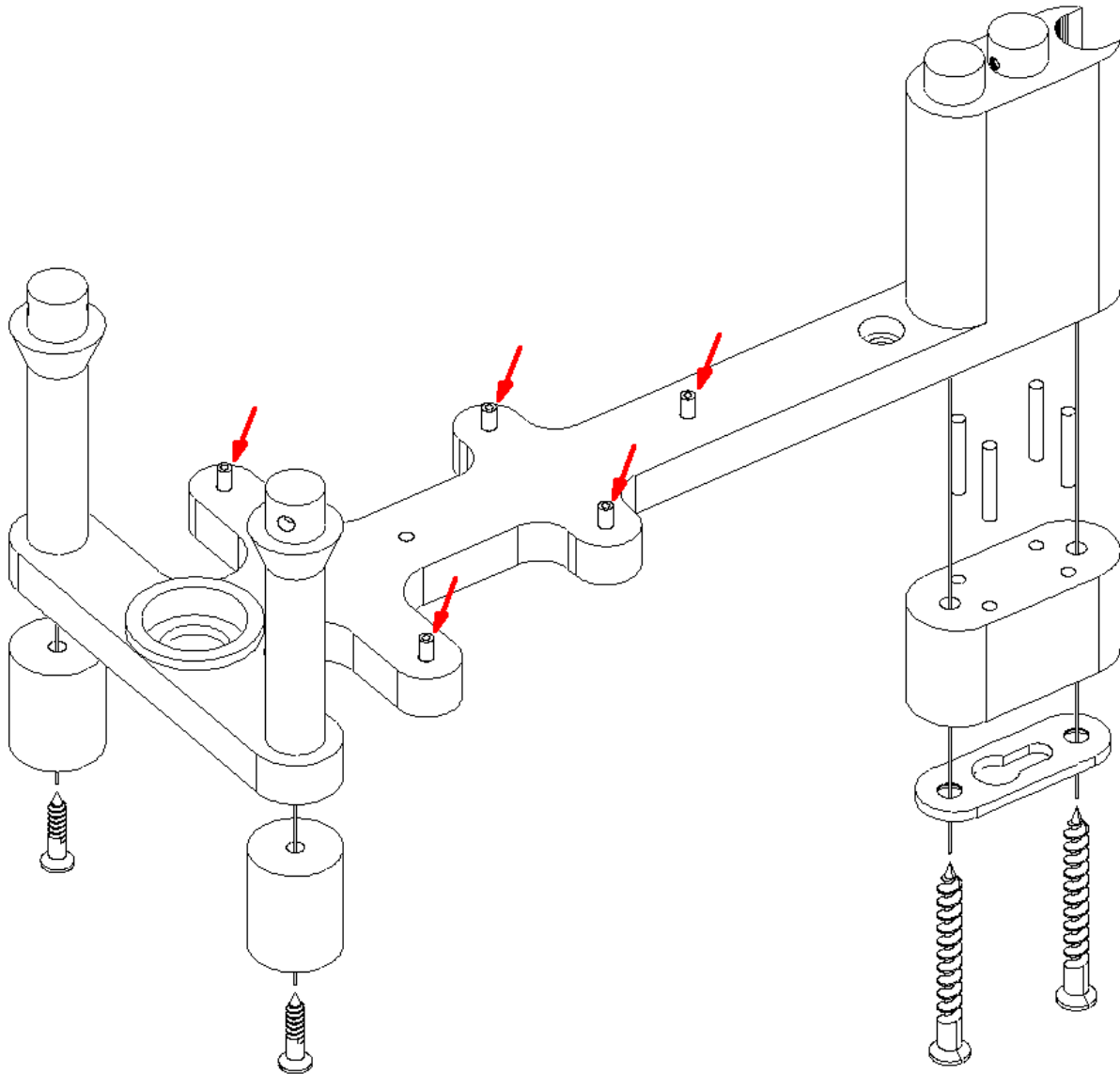


Figure 11: Back frame assembly

Front Frame

The front frame also gets five tiny bushings at the locations shown in figure 12. There are only five holes, so their locations should be obvious. The dial needs to be protected if you use a hammer to tap in the bushings.

Place one of the 608 bearings and the bearing spacer into the bearing holder. I purchase bearings from eBay and have had good luck with hybrid ceramic skateboard bearings. These have ceramic balls with metal races. Stainless steel races are best. I usually pay around US\$1.00-1.50 per bearing and stay away from the really cheap ones.

A clock should be expected to run for many years and any grease from the factory would harden in a few years. If you have bearings with seals and/or grease, then take out the seals and soak the bearings in solvent to remove any grease. I add a drop or two of dry Teflon bike chain lube to the bearing and wipe off any excess. The bearings should spin freely. They run at a low speed, so they might not need any dry lube, but seems like it should reduce friction slightly. Make sure any solvent in the Teflon lube is compatible with the 3D printed material.

The bearing holder attaches to the front frame with two 6x3/4" wood screws. Add a 6x3/4" screw to the side of the bearing holder for connecting the end of the weight cord in a later step.

Attach the winding key knob to its handle with a 6x3/4" wood screw. The hole is undersized so the screw bottoms out before the knob is tight. Back off the screw if needed so the knob spins freely. Add a small drop of Teflon lube to the winding key knob. The winding key sits on a tiny shelf that connects to the front frame with a 6x3/4" wood screw.

Test that the two halves of the frame go together easily and can be attached with three 6x3/4" wood screws. There is no need to over-tighten these three screws since they are only acting like pins to hold the frame in place. You may be taking the frame apart many times before the clock is finished and you don't want to strip the threads.

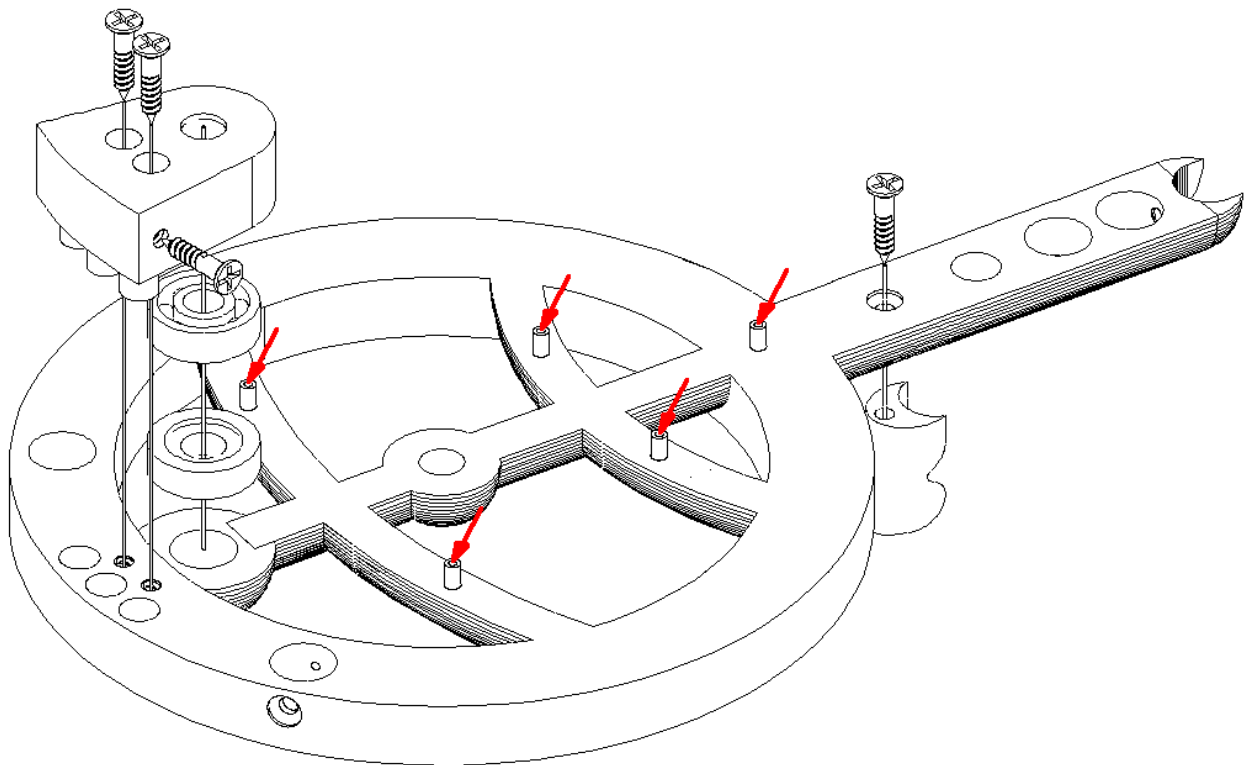


Figure 12: Front frame assembly

Gear Cleanup

Reducing friction is extremely important to get an 8-day runtime. The involute gear profile was designed to have very little friction as two gears rotate. The teeth actually roll past each other instead of sliding. Any imperfections in the gear tooth shapes should be cleaned up by filing or sanding.

The “elephant’s foot” on the bottom surface of the larger gears may need to be removed. The printer could be tuned to eliminate the elephant’s foot, but this would come at the expense of lower bed adhesion and possibly having a part break loose. I live with a small amount of squish out and clean up the gear teeth using hand files.

Start by running a fine-tooth needle file at a 45-degree angle between the teeth. One stroke with light pressure is all that is required to round over a small burr along the sides of two teeth. Follow up with a few strokes using a knife edge file to remove the burr. You need to use a sweeping motion along the curves profile of the gear teeth. Twist the file to get out to the tips of the gears. You should see the burr break loose. Only a small amount of material is actually removed. It should only take less than an hour to clean up all of the gears in the clock. Only the bottom side of the large gears that sit on the print bed need to be cleaned up.

Winding Drum and Ratchet

Slide the brass rod inside the winding drum and push it into position with the 1/16” by 0.75” pin to lock the parts in place. It is OK if it is a tight fit that needs to be tapped into position. This component never needs to be taken apart.

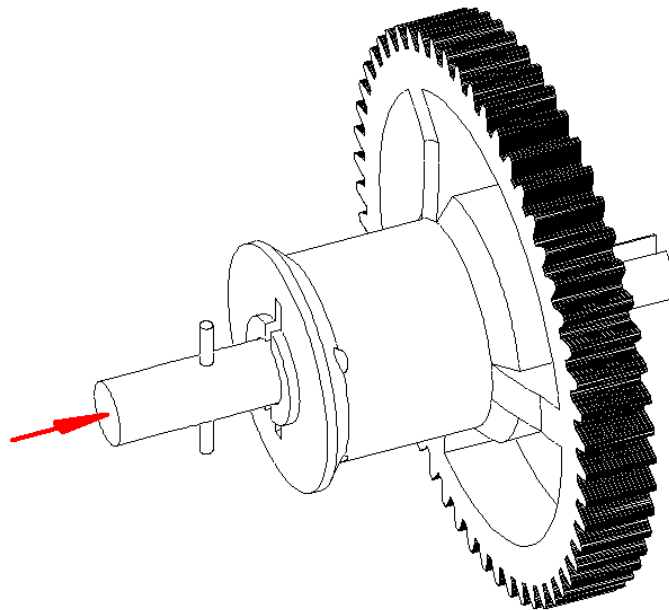


Figure 13: Winding drum

Insert one end of the microfilament fishing line through the side hole on the winding drum. Give the line one wrap around the drum and tie the end. Leave the line about 9 feet long. You can cut it to final length later. The brand I use is Power Pro Spectra Fiber Braided Fishing Line 65 lb. test with a diameter of 0.016". This brand appears to be more than strong enough. It has been running for a few months without showing any wear, but I keep inspecting it and will replace it if needed. I certainly don't want the weight shell crashing to the floor in the middle of the night. There may be better options to use cord specifically designed for clocks. I had fishing line already and it seems to be working OK.

The ratchet is the part you hear when winding the clock. Attach the three clicks (gear7_clicks) to the ratchet center hub (gear7_24) with 6x3/4" wood screws. Tighten them until they are snug, then back off the screws so the clicks swing freely. Cut down three springs from ball point pens so they are just under 0.7" long and insert them into the holes in the clicks. The springs should barely push the clicks away from the center hub with minimal force. The clock would work just fine with stronger springs, but it would be really noisy when winding. Shorter springs reduce the ratchet noise considerably.

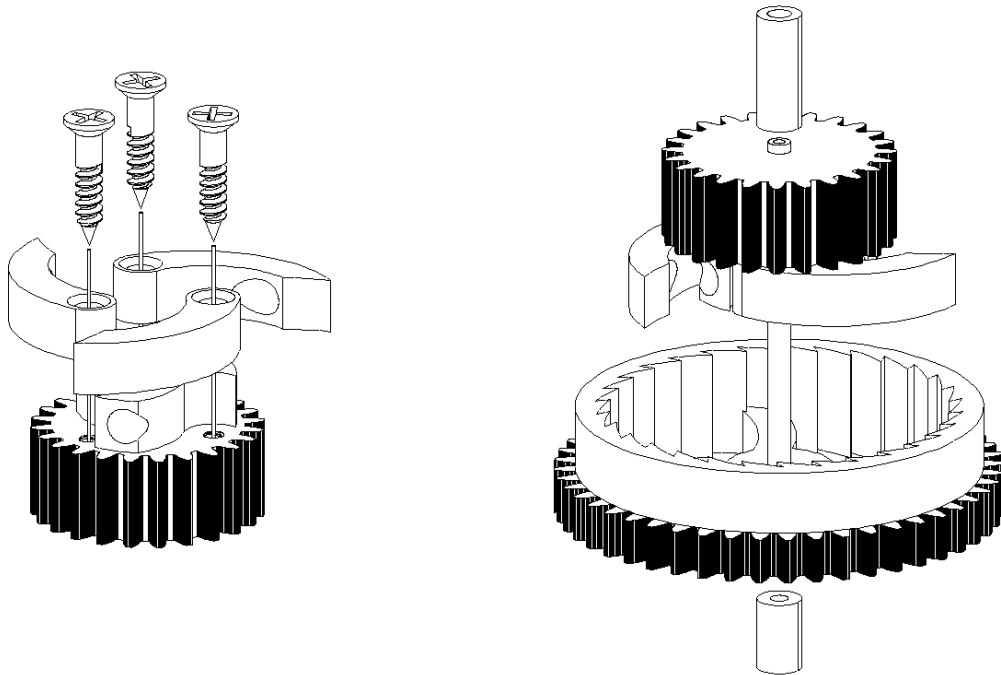


Figure 14: Ratchet

Place the assembled center hub inside the ratchet outer hub (gear7_48) onto the 2.15" stainless steel tube. The ratchet should turn easily in one direction. Check that the springs are just strong enough to push the clicks into the outer hub. Adjust their length if needed. Add a 0.40" spacer below and 0.65" spacer above the completed ratchet.

Minute Hand

The lower portion of the minute hand axle contains the mechanism that slips when setting the time. A spring holds the position during normal operation and allows it to slip when changing the time.

Position the bottom hub (gear4_lower) at the bottom end of the 3mm by 3.45" minute hand axle. It is designed to be a tight fit so it will need to be tapped into position with a hammer. The axle should stick out the bottom by 0.22".

Place gear4_54_18 over the bottom hub. It needs to be a loose fit so the gear can rotate on the hub. Cut a ball point pen spring to 0.75" in length and drop it onto the axle. Add gear4_upper and check that it can compress with a small amount of pressure.

Gently hammer gear4_18 onto the axle until it is 1.34" from the end. This should allow about 0.10" of compression in the spring. The bottom 54-tooth gear should rotate on the axle with a small amount of resistance. This part will allow changing the time without stopping the pendulum.

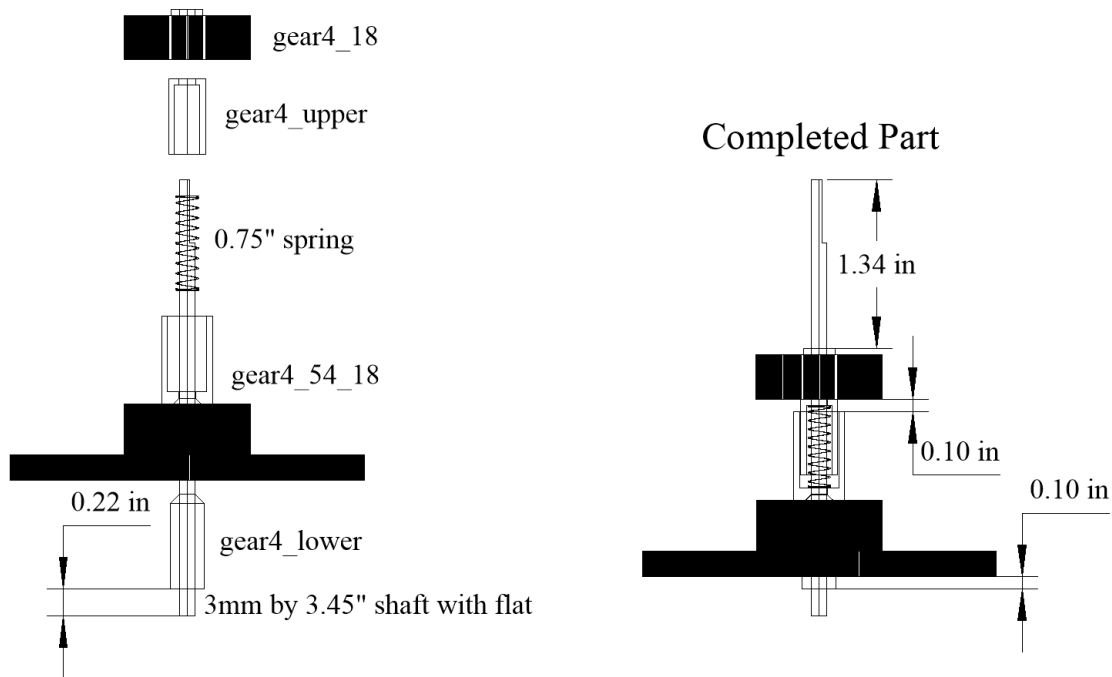


Figure 15: Minute hand assembly

Pendulum

The pendulum bob is a two-piece shell filled with pennies to add a small amount of weight. The actual weight is not a significant factor in regulating the time as long as it has enough momentum to continue swinging during minor disturbances. The holes could be filled with washers, small rocks, or just about anything that fits the holes. Pennies are cheaper than washers from the hardware store and they fit nicely. It might be a good idea to add a bit of glue if using anything that is smaller than the hole. Attach

the back of the bob using ten 4x1/2" wood screws. Ten screws are a bit of overkill, but they are hidden behind the pendulum so they are nearly invisible.

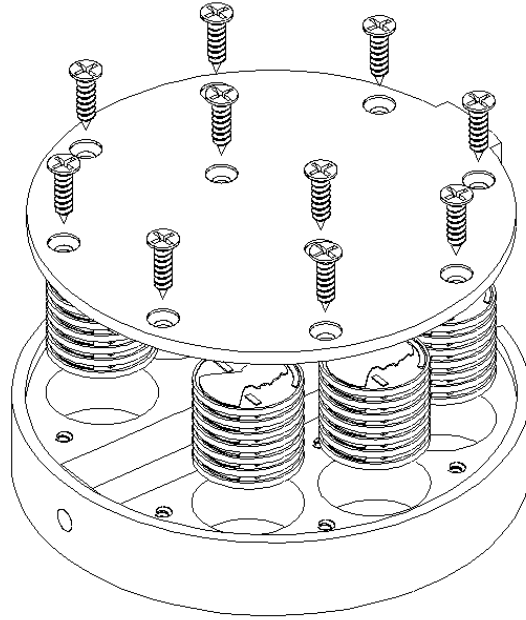


Figure 16: Pendulum bob

The pendulum shaft is printed in two segments to allow it to fit on the printer tray. Short lengths of threaded rod are glued with epoxy hold the shaft together. Clean any epoxy squeeze out from the seam before it sets. Use a straight edge and tape to hold the shaft straight. A 3" segment of threaded rod is glued into the lower end of the shaft with 2" sticking out for timing adjustment.

The top of the pendulum shaft has a brass wheel collar with a 1/8" hole to fit on the pallet shaft. I find these at the local hobby shop that sells RC planes. A few brands are Great Planes GPMQ4305 or DuBro DUB139. Remove the short set screw and press the collar into the pendulum shaft with the threads lined up with the side access hole. Add a 3/8" long 4-40 steel screw in place of the set screw. The picture below shows the steps in the three sections of the shaft. Obviously, the final result is a single component around 20" long.

The pendulum bob should slide easily on the shaft after the epoxy cures. Sand the corners of the shaft if needed to fit the bob. The finial with embedded 6-32 nylon locknut holds the bob onto the pendulum shaft.

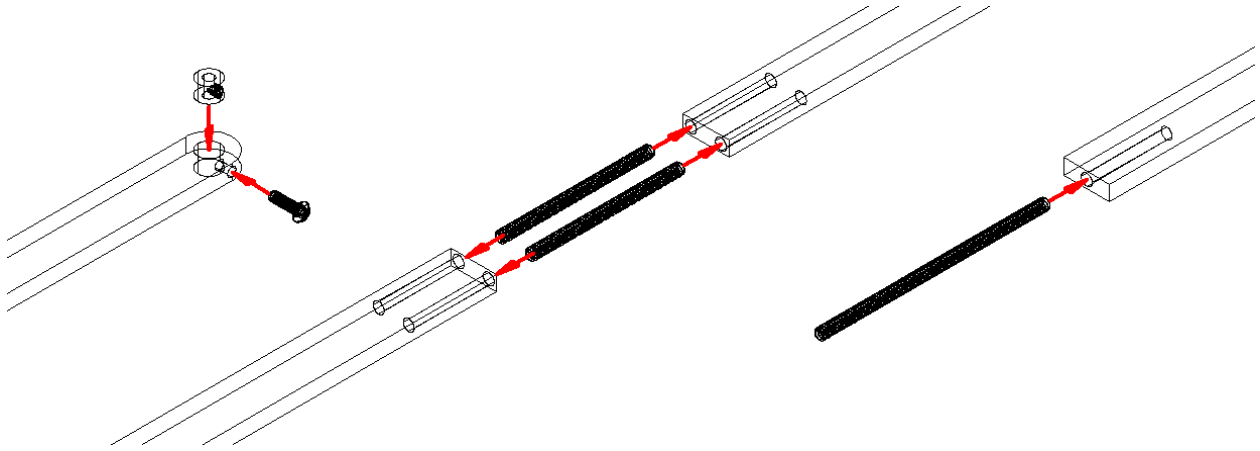


Figure 17: Pendulum shaft

Weight Shell

The weight shell is a hollow tube filled with lead shot that provides just enough energy for the pendulum to keep swinging. I designed multiple sizes of weight shells before settling on the 6.4 pound version that is 2.6" in diameter and 7.5" tall. I have had the clock running with a 4.6 pound weight shell that is 2.4" in diameter and 7.4" tall. The slightly larger one makes the clock more reliable.

The weight shell has the longest print time of the entire clock. It is fairly tall so a brim might be a good idea. Set the seam position to random to help hide the seam between layers. The walls are 0.060" thick to print with 4 passes using the standard 0.4mm nozzle. Internal supports are built in using 45-degree angles to print without any additional support.

Insert a 608 bearing into the weight pulley. It should be a tight fit to keep from slipping sideways and binding in the shell. Add a drop of Teflon lubricant to the bearing and wipe off any excess. The pulley is positioned into the top of the shell with the pulley pin and a 6x1" wood screw. The pulley pin has a flat that needs to line up with the flat in the top of the hole. Push the pin into position around the pulley and secure it with a 1" wood screw. The pulley should spin freely.

Turn over the weight shell and fill it with lead shot. It would be a good idea to wear disposable gloves for this step to minimize exposure to lead. Used lead shot appears to cost around \$2-3 per pound in 25-pound lots. Plug the four screw holes before filling the shell to prevent small pieces of lead from falling down the holes. Pack the weight shell with as much lead as it will hold. Secure the bottom cover to the weight shell using four 1-5/8" drywall screws. The weight shell should weigh a bit over 6 pounds.

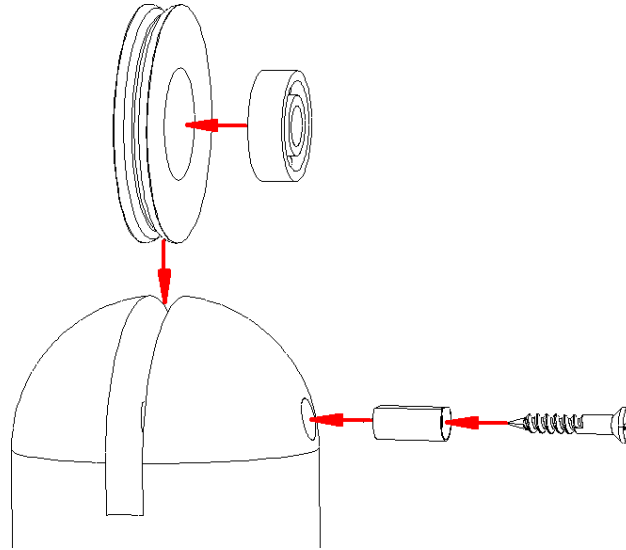


Figure 18: Top portion of weight shell

Building the Clock

Notes on Friction

It is worth stating again how important it is to reduce friction in a mechanical clock. This clock uses 6.4 pounds of weight falling 52" every 8 days. The pendulum will tick 1,049,760 times in 8 days, so each tick of the clock has the energy of the weight shell dropping 0.00005". After 78 ticks, the weight shell will drop the thickness of a sheet of printer paper. This gives us an idea about how little energy is available to keep the clock ticking. There is not much to give up as friction.

Another way of looking at the energy in the clock is to calculate the forces at various places. The 6.4 pound weight uses a pulley, so there is only 3.2 pounds of force at the winding drum with a distance of 0.5" from the pivot point. The outer rim of gear 8 is 1.3" away from the pivot point, so it only has 1.18 pounds of force. Gear 7 has a 2:1 ratio, so it only has 0.58 pounds of force. 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 0.035 ounces of force remaining, which coincidentally is the same as the weight of a house fly. Theoretically, the clock could 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 energy.

I think that any clock with similar parameters would be equally susceptible to stopping from the weight of a house fly. It is a physics problem of the forces involved in a small weight falling over an 8 day period of time. If the run time was cut in half or drive weight was doubled, then it would take two flies to stop the clock. I think it is more elegant to design a clock with the minimum amount of weight and reduce friction as much as possible. The amazing thing to me is that similar clocks were built over 300 years ago using simple hand tools.

I added dry Teflon lubrication to all of the moving parts of the clock. Just a tiny bit is needed. I use the tip of a toothpick and add a drop to each of the bushings. I also lubricated the escapement and pallet arms since they are continuously sliding past each other. It is generally considered a bad idea to oil the escapement because oil holds dust that can scrape the surfaces. Dry Teflon lubricant doesn't seem to leave behind a sticky surface to attract dust. And it appears to be safe for PLA. Make sure to test the lubricant before adding it all over your completed clock. It might dissolve other filament types.

Back Frame

At this point all of the components are ready to be assembled into a clock. I may try to create a video of the assembly process at some point in time. For now, this document is all I have.

The back frame is a large component that holds everything together. The image below shows what it should look like. The axes are shown for reference. They will be placed as the gears get positioned.

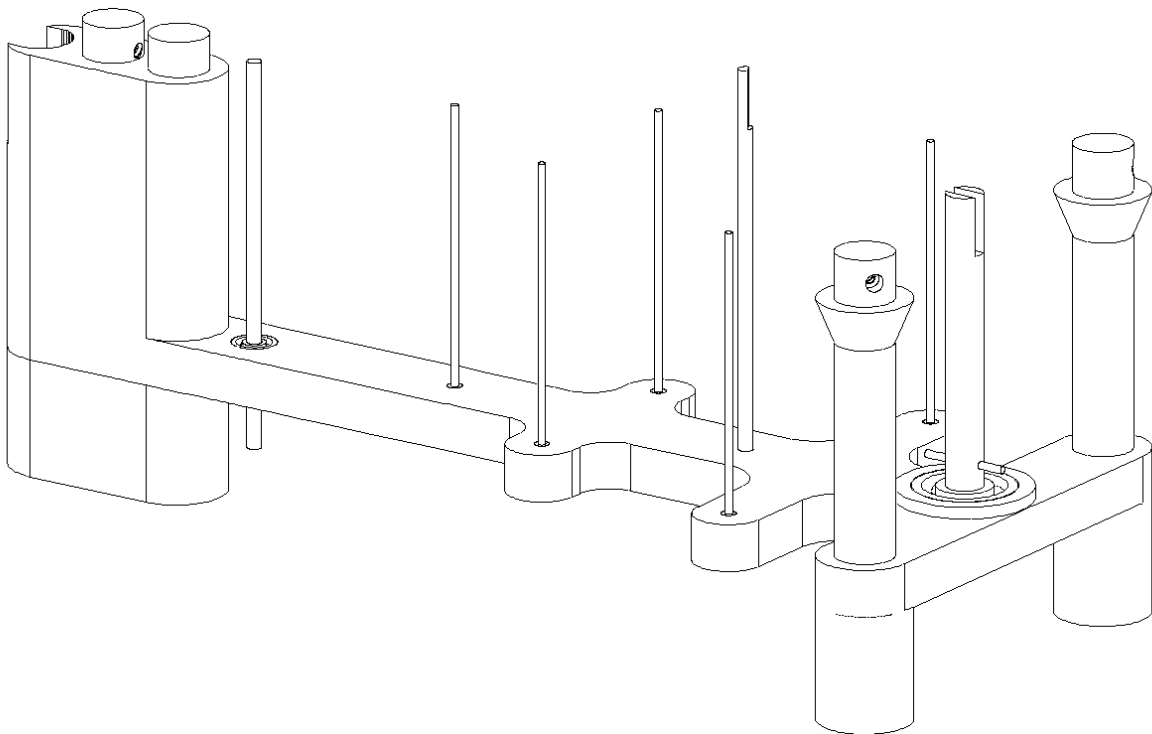


Figure 19: Back frame

Gears 4 and 7

The gears are easiest to place from bottom to top so they don't get in each other's way. Start with the minute hand assembly (gear 4) and ratchet assembly (gear 7). Gear 4 is a complete module. Gear 7 has loose spacers. Place a 2.6" by 1/16" axle in the pivot hole at the lower right of the frame. Add the 0.4" spacer, ratchet assembly, and the 0.65" spacer. The two gears should mesh without any interference.

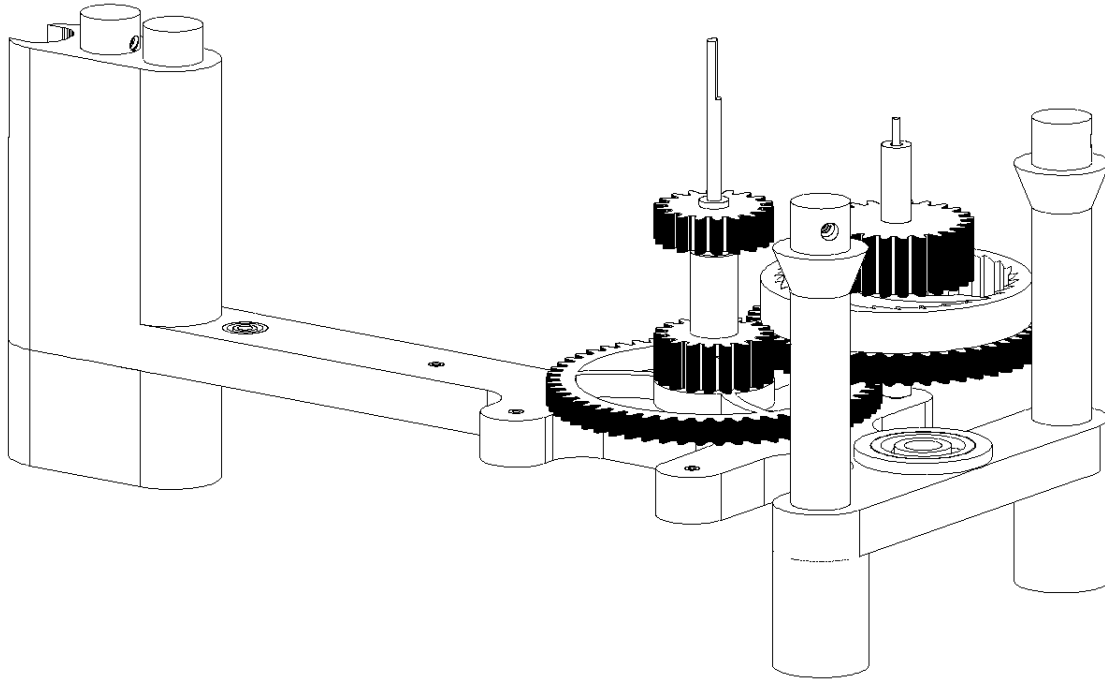


Figure 20: Gears 4 and 7

Gears 2, 3, and 8

Gears 2 and 3 need short bushings added. Gently tap two 0.2" stainless steel tubes into the top and bottom holes on each. These axles have pivot points in the frame and in the gear, so the friction is reduced as much as possible. The axle just floats inside four bushings.

Add a 2.6" by 1/16" axle into the upper pivot hole on the left. Drop gear 3 onto the axle so the 12 tooth pinion meshes with the bottom portion of gear 4. Add a 1.15" spacer with the hub closest to the gear.

Add gear 2 and the 0.75" spacer in the upper right pivot hole.

You can also drop a 608 bearing into the large bearing hole and add the winding drum assembly. It would be a good idea to add a drop of Teflon lubricant to the bearing and wipe off any excess. Gear 8 should already have about 9 feet of fishing line tied to it. Most of the line can be wrapped around the winding drum to keep it out of the way. Use the ratchet to determine which way to wind the line. Leave at least a foot unwound to be used for hanging the weight shell after the clock is mounted to the wall.

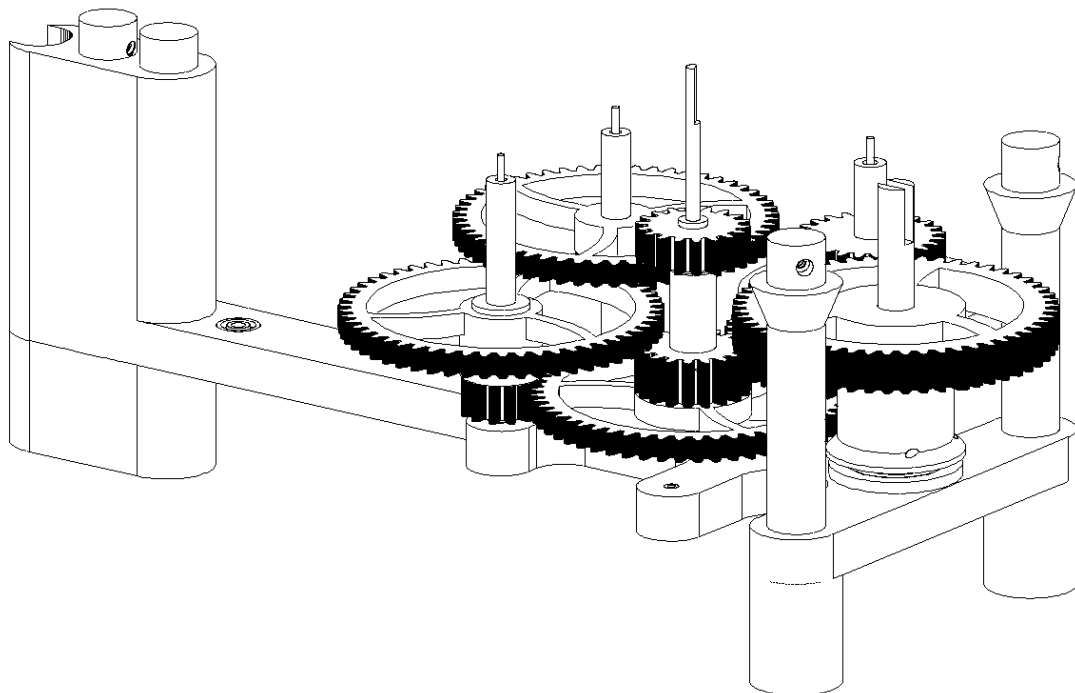


Figure 21: Gear 3, 2, and 8

Escapement and Pallet

The pallet and escapement can be added now. The escapement needs short bushings tapped in place. The pallet is a tight fit on the 3.3" by 3mm axle. The axle should be tapped into position so that it sticks out the top 0.275".

Add a 2.6" by 1/16" axle for the escapement. Add the escapement and a 0.05" spacer to the axle.

Add a small drop of Teflon lubricant to the 1/8"x3/8"x5/32" bearings and place one in the back frame bearing hole. The pallet and pallet axle are positioned into the bearing. Add a 0.05" spacer and the other small bearing to the pallet axle. The axle sticks out the back of the frame about 0.6" for attaching the pendulum.

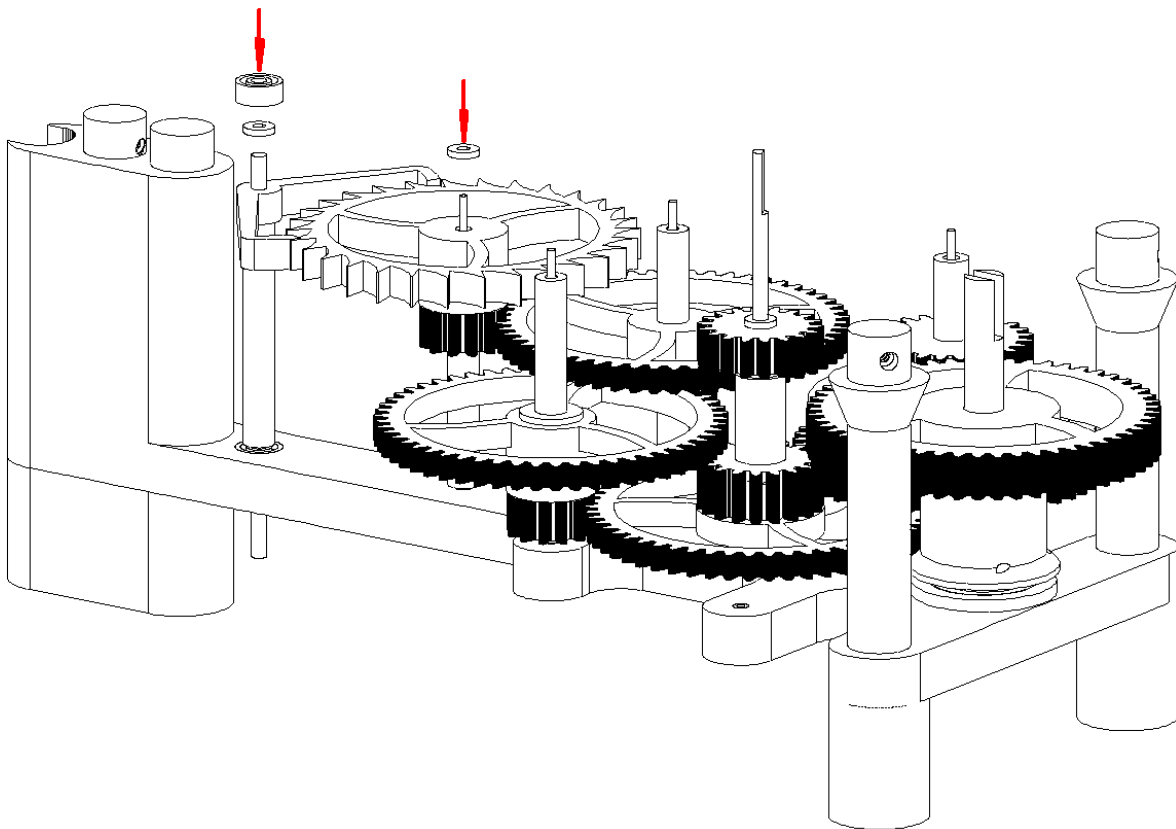


Figure 22: Pallet and escapement

Gears 5 and 6

Gear 5 needs two short bushings tapped into both sides. Place a 2.6" by 1/16" axle into the last remaining pivot hole. Add the 1.55" spacer with the hub up and place gear 5 on the axle. Gear 6 fits over the minute hand axle. Click the cord guide onto the lower support posts. Its purpose is to prevent the winding cord from slipping over the edge of the winding drum.

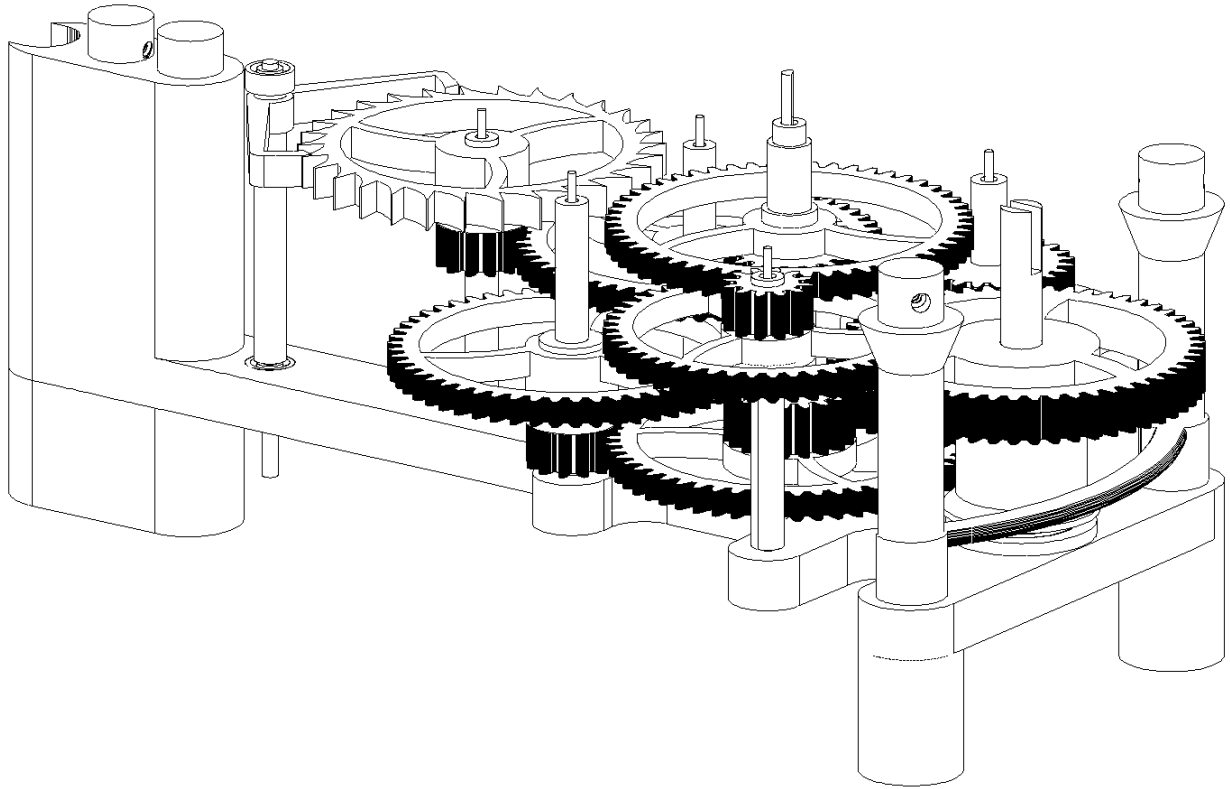


Figure 23: Gear 5 and 6

Front Frame

Now it is time to put the face onto the clock. This step is a little bit tedious because there are 8 axles and 4 support posts that all need to be positioned properly. I have probably assembled and disassembled my clock at least 50 times while fine tuning different parts. It is still tedious. My only advice is to be patient.

Start in a lower corner and work towards the top. The two halves will go together part way, then stop on a pinched axle. Move the pinched axle into its bushing and the frame should close a bit more until

the next axle is pinched. Hold the starting corner closed while working everything else into position until the frame comes together. The frame is held together by three 6x3/4" wood screws, two at the bottom and one at the top.

Add the hour hand onto the hub at the top of gear 6. It is a press fit and can be positioned in any direction. The minute hand has a flat and can only be positioned in one direction. Set the minute hand to the 12 position and move the hour hand to point to a full hour position. You should be able to change the time by rotating the minute hand and the hour hand should move with it.

Everything should be starting to look like a clock at this point.

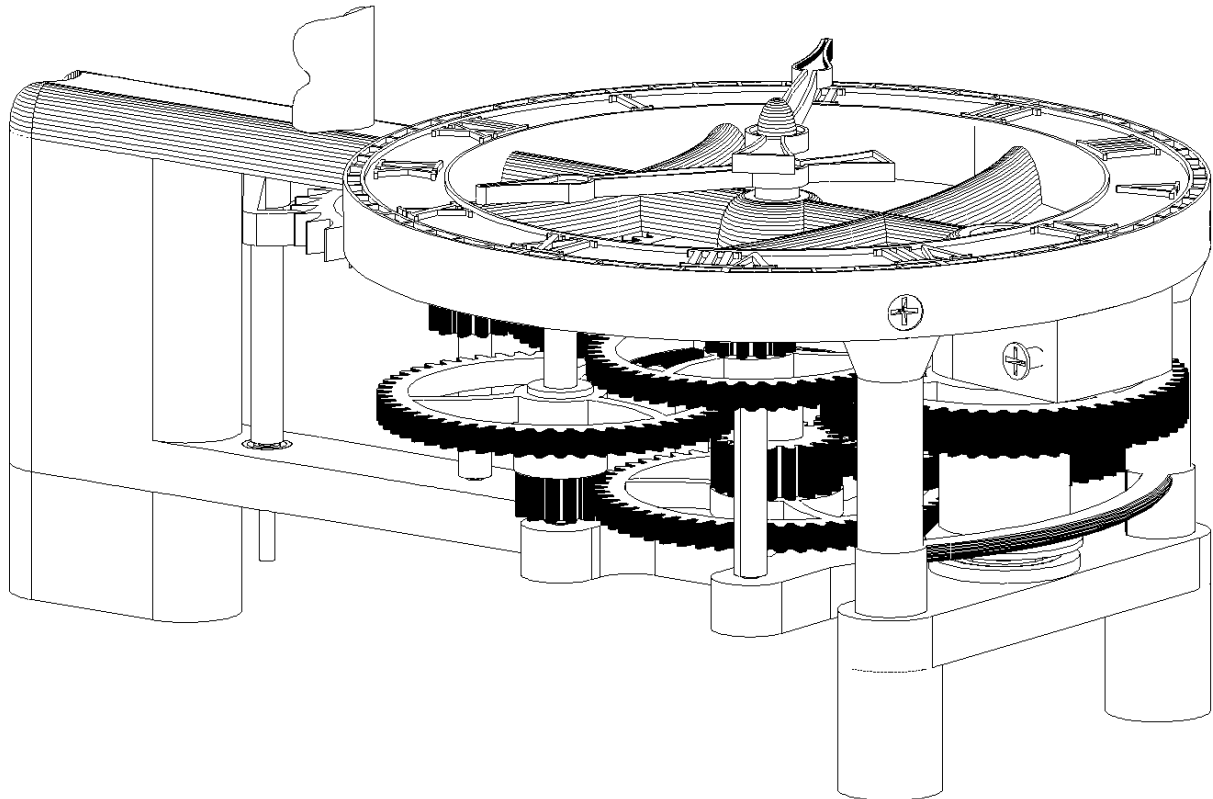


Figure 24: Assembled clock

Testing the Clock

Mounting the Clock

The clock mounts on the wall using a single screw driven into a wall stud. I use a 8x1-1/4" pan head wood screw, but anything that fits securely in the keyhole hanger should work. Placing the screw 69" from the floor will give 52" of drop for the weights to get a bit more than 8 days of run time. Leave the screw sticking out from the wall just enough for the clock to be snug. Place the clock on the wall and adjust it to be level.

Add the pendulum bob onto the shaft and secure it with the finial. The finial allows the pendulum length to be adjusted almost an inch in either direction from the center point. Screw the finial about an inch onto the threaded rod.

Add the pendulum shaft to the pallet axle and position it so the pendulum is close to the wall. Gently tighten the side screw at the top of the pendulum shaft. It should be just tight enough to hold the position and loose enough to allow it to slip when setting the beat. Make sure that the pendulum can swing freely. It should continue to swing on its own for at least 30 seconds or longer with no weights attached.

Attach the swing gauge to the wall so it is centered below the tip of the finial. It may be best to just tape it to the wall for now and adjust the height after the final pendulum length is determined.

Hanging the Weight

Tie an overhand loop at the end of the line on the winding drum. The loop should be about an inch long. It needs to be able to slip over the screw on the side of the bearing holder at about the 6:32 position. It also needs to be removable, so do not use a slip knot. See the picture below.



Figure 25: Overhand loop

Insert the end of the line through the weight shell pulley. Make sure that the line stays in the pulley groove and not along the side of the pulley. Hold the pulley in your right hand and loop the end of the line over the bearing holder screw. The screw is hidden so you may have to feel where to hook the line. I usually stick my left index finger into the loop, place my finger onto the end of the screw, and slide the loop over the screw.

You can lower the weight shell when the line is attached properly. The line should still be running down the center of the pulley. The clock might start ticking when you push the pendulum to one side.

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.....”. The swing gauge helps to determine if it is balanced. Each tall line on the swing gauge corresponds to 1 degree of pendulum motion. The short lines are 0.2 degrees.

The clock should tick at around 1 degree to the left and 1 degree to the right of the mid-point. If it is skewed to one side, then hold the pendulum steady and rotate the pallet arms. The screw at the top of the pendulum shaft should be loose enough to slip when adjusting the pallet position. Keep adjusting until the beat is centered. When it gets close, you can tilt the clock frame slightly to make the final adjustment.

Push the pendulum about 3 degrees to one side. The clock should continue ticking. The pendulum only needs about 1 degree of swing in each direction for the escapement to be functional. A bit of extra movement is desirable to keep the clock from stopping from a slight breeze. I like to see at least 3 degrees of swing in each direction. Adding additional weight would increase the swing and the clock should be a bit more reliable, although it does get louder.

Set the time by rotating the minute hand.

Congratulations, you have completed your clock!!!

Adjusting the Rate

The clock should be reasonably accurate with the pendulum length around 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 0.025” in change in pendulum length should change the rate of the clock by about a minute per day.

The threaded rod on the finial has 32 threads per inch, so one full rotation changes the length by 0.03125. This would change the time by about 70-80 seconds per day. Each tick mark on the finial will adjust the rate by about 10 seconds per day or a minute per week.

The clock may change its rate during the first week or two as the components settle in to position. Then it should stabilize to a consistent rate. Wait to 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 push the line to one side 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 moving. You may need to reset the beat after winding if the position shifted.

Debugging

Once the clock is working properly, it should continue to work for a long time. I have tested mine for a few months so far and expect it to last for many years. It took a few trials to get it to run reliably. I believe that I have added all the features into this design so your clock should be as reliable as mine.

If the clock has less than 2 degrees of swing, then there is probably friction or binding somewhere. You could take out all the gears and put back two at a time to see that they mesh properly. Test each pair of gears individually to see that they move smoothly with no noticeable friction. Then put in all of the gears and leave out the pallet. You should be able to apply pressure to the winding drum and have the entire gear train rotating.

In the past two months, my clock has only stopped once and it was just after winding. I assume that the winding cord got bunched up so it wouldn't unwind smoothly. This was with the smaller 4.6 pound weight shell. Increasing the weight to 6.4 pounds has made it very reliable, although I still keep an eye on the cord while winding.

Final Comments

Designing this clock has been a lot of fun and also a lot of challenges. I have built a few wooden gear clocks. None of them have been as satisfying as this clock. I received my Prusa MK3 3D printer about a year ago and rarely go out to the woodshop any more. I may try to port the design to wooden gears as a future project. A grasshopper escapement is also in the early design stages.

Good luck with your clock build.

Steve