Making a Wooden Clockworks

Part two: Getting things ticking

by Wayne Westphale

In part 1 we discussed the theory of how a clock works. Now is the time to make one. There are a variety of ways to cut gear teeth, methods that cover a broad range of accuracy, speed and expense. The method you choose will depend on your goal, your shop equipment, and your budget.

As an example of how low-tech clockmaking can be, for my first clock I turned the arbors on a lathe setup that consisted of an electric drill (as a headstock) clamped to a 2x4 (the lathe bed). A piece of angle iron, drilled and tapped to carry a pointed bolt, became a tailstock. A chisel served as a lathe tool and a piece of scrap as a tool rest. My first tooth cutters were reground spade bits, as shown in the bottom right photo on the facing page. Needless to say, this was doing it the hard way.

I've always tried to surpass each clock I've built with a better one, and along the way I've invested in some pretty sophisticated equipment—machines more often found in a metalworking shop. These are not essential to building a good clock, but they allow me, as a matter of routine, to achieve repeatable accuracy with little fuss. Expect this clock to tax your ingenuity in getting the necessary precision from your own machines and tools. There are ways around every problem as long as you understand the features in a clock that are critical to its operation.

Horologists don't speak of gears, but of wheels and pinions. Wheels, the large gears, have teeth; pinions, the small gears, have leaves. I cut teeth and leaves on two different machines, but the process is basically the same—I use a set of reground router bits to cut the gullets between the teeth.

The preparatory step, laminating plywood gear blanks, was described in part 1. The photos on the facing page show some of the actual cutting, including my jig for bandsawing circles. To cut the wheel teeth, I mount a stack of gear blanks on a mandrel and mount the mandrel on an old metal lathe, which I also use to turn clock arbors. The tool-bit holder on the lathe's cross-slide and compound has been adapted to carry a router, with the router bit perpendicular to the lathe centerline. By cranking one of the lathe's control wheels, the router bit can be positioned closer to or farther from the work, then locked in position to give a cut at a set depth. By means of another control wheel the router can be moved precisely along the length of the work.

The first step in cutting the teeth is to turn the lathe on at slow speed, then use an end mill or hinge-mortising bit in the router to trim the blanks to true round, sizing them to the correct diameter at the same time. This ensures that the arbor hole will be exactly centered.

The lathe is then turned off, and the blanks are indexed by a pin and a shopmade plate. The router roughs out the gullets one by one by traversing horizontally along the stack. I crank the router from the tailstock end up to the headstock end to cut a tooth gullet. Then I crank the router back to the tailstock end, turn the stack of wheel blanks to the next index location and repeat the process. (The escape wheel is a special case. It has three very critical surfaces on each tooth, and I make these as shown in figure 3, on p. 62.)

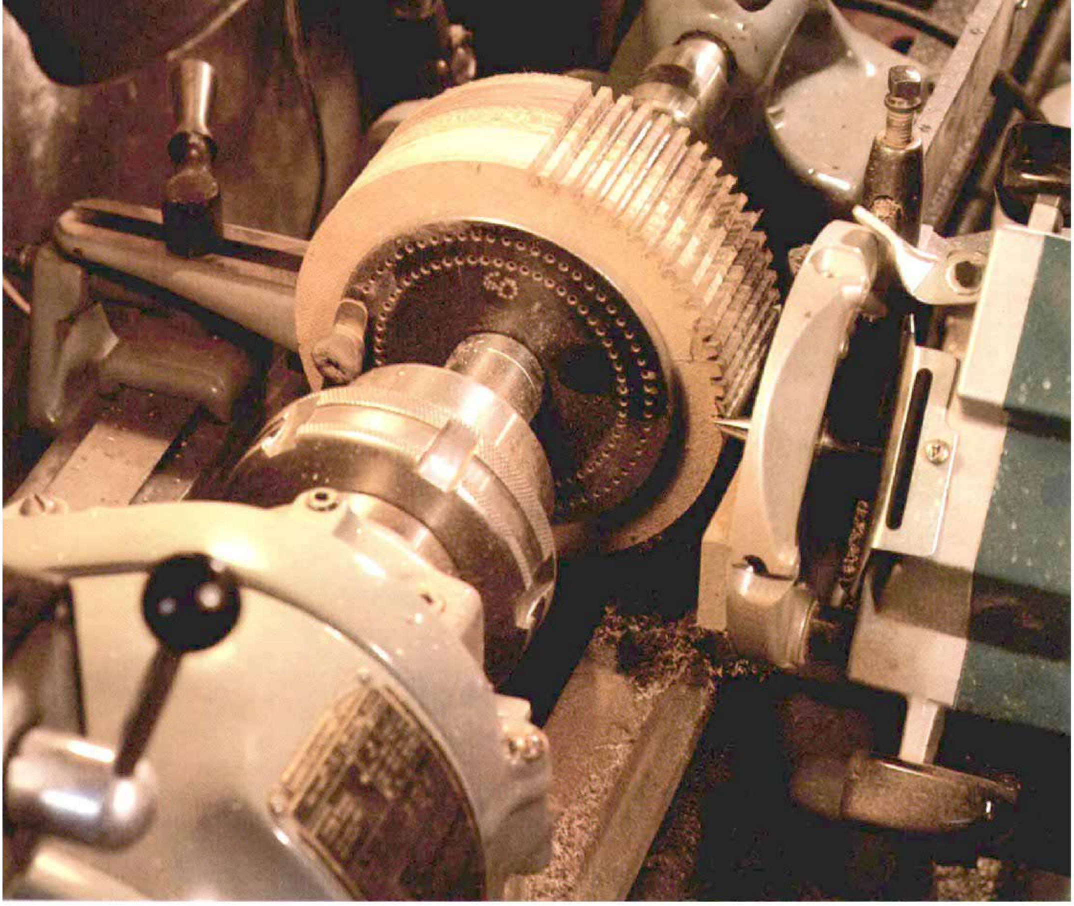
To minimize chipping—and maximize cutter life—I make several passes, each with a different cutter. The first cutter, as shown in figure 1, has straight faces, is easy to sharpen, and has an included angle of about 32°. It is a wasting cutter. I set it to about 80% of full depth. The next cutter profiles the tooth face and cuts to final depth. The last cutter eases over the tooth tip. The relief angle of this cutter is only 2° to 3°—the desired effect is to round over and burnish the tooth tip in one pass. Next, I lightly sand with 400 grit paper over a soft block to remove the burr left at the tips of the teeth.

This produces a stack of identical chip-free wheels. The method suits itself both to small scale production or, if you are making just one clock, to making any identical wheels that may be in it (there are two identical pairs in my grandfather clock). Pinions are cut in a similar way on a milling machine, as shown in center photo. The same operation could be accomplished with a drill press fitted with a compound table (available from Sears for under $80 and from time to time in various bulk-mail catalogs for even less) and a properly contoured cutter.

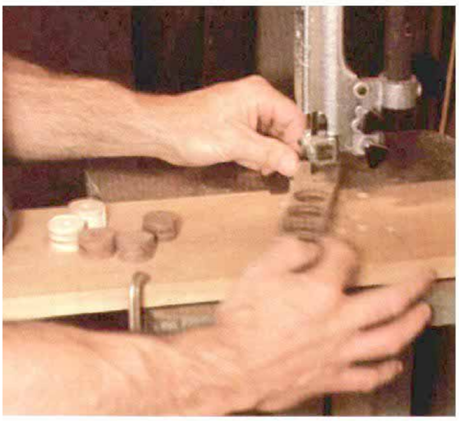
I profiled my cutters in a series of steps, as shown in figure 1. I began with a full-size drawing of each of the gear-tooth profiles. Figure 2, on p. 61, shows the exact profiles of the teeth and leaves in my grandfather clock. To achieve the necessary variety with the fewest number of cutters, I taper my cutters slightly at the tip, so that the tooth size, the width at the pitch circle, can be controlled by depthing the cutter as required. Pitch circle and other technical terms are explained in part 1.

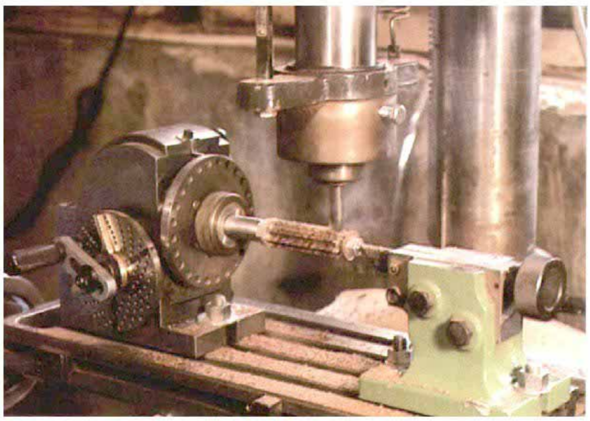
Arbors and bearings—I turn arbors in the metal lathe—it is fast and sure and will maintain 0.001-in. tolerances (exact sizes are shown in figure 2). I strive for a snug fit of wheel to arbor. A metal lathe is not absolutely necessary, though I would not recommend using dowels straight from the hardware store either. You'll find that commercial dowels are only approximately sized and only approximately round.

I recommend a piece of tool steel or 1/16-in. drill rod be pressed into the arbor to serve as a pivot. Wood-on-wood is too inefficient at this point from the standpoint of friction as well as durability. The pivot must be accurately centered. If your lathe has a



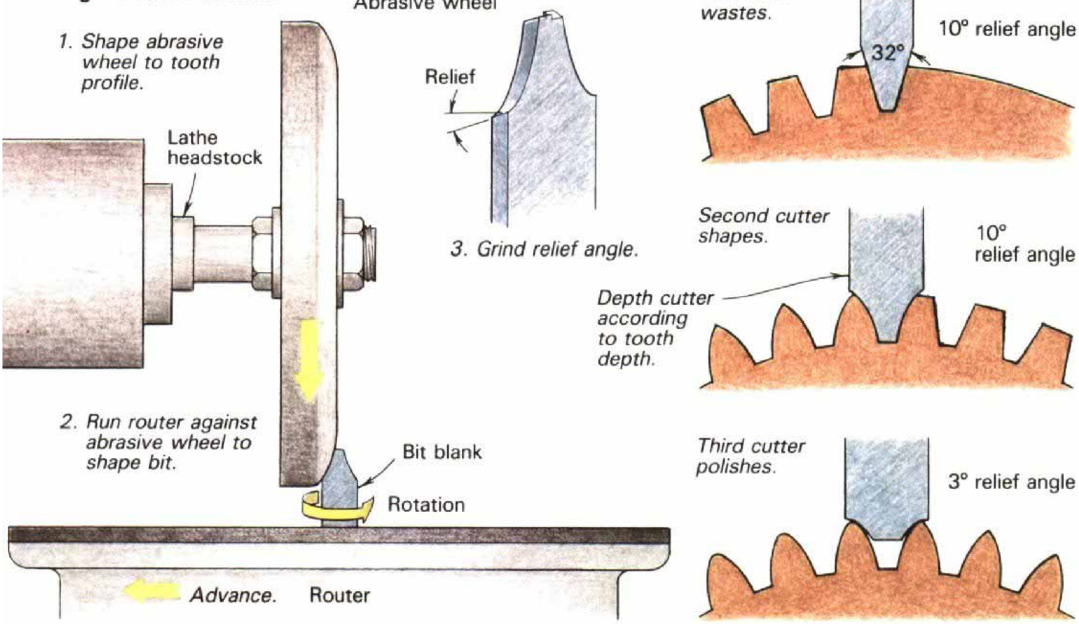
At left, large gears are cut by a router mounted on the cross-slide and compound of a South Bend metal lathe, which the author bought used for $4,000. The blanks are indexed by the pin opposite the router bit. Above, Westphale cranks the router along a stack of six wheel blanks, backed up at each end by a hardboard blank to prevent tearout.





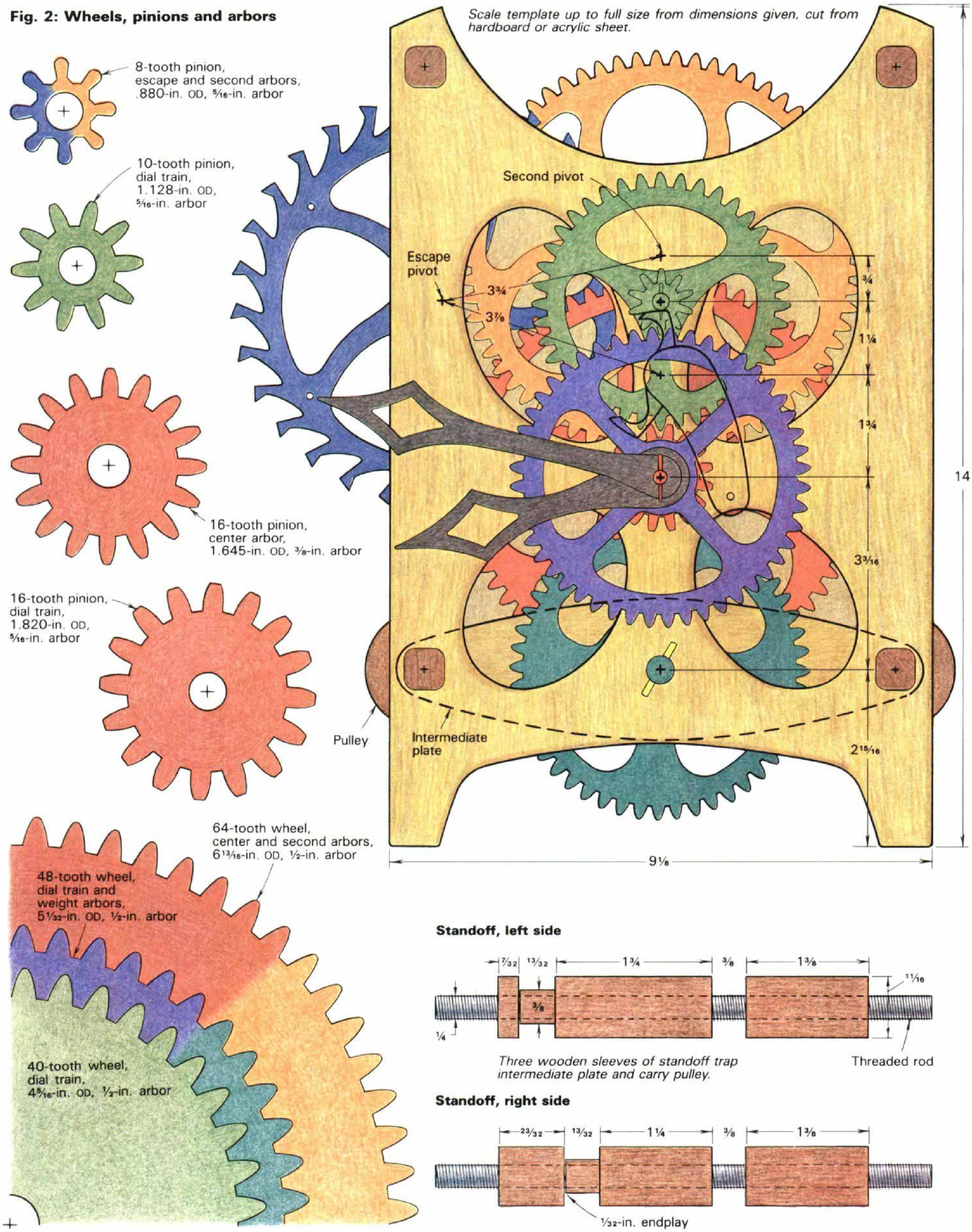
Left, a milling machine is the metalworker's precision version of a drill press, equipped with a table that can be moved horizontally on X and Y axes by hand cranks. The stack of pinion blanks is indexed by a dividing head, which calculates angles by means of perforated plates and a gearbox. It takes forty turns of the crank handle to rotate the output shaft one full turn. Far left, an efficient circle-cutting jig: The board has a runner on the bottom that rides in the bandsaw's miter-gauge slot, and a number of axle holes to suit the various gear sizes.

Fig. 1: Tooth cutters



Cutters are reshaped as shown in the drawing at left. Tooling need not be high-tech. Westphale shows two of his early gear cutters, reground spade bits, alongside the highly evolved ones he uses today.

Fig. 2: Wheels, pinions and arbors



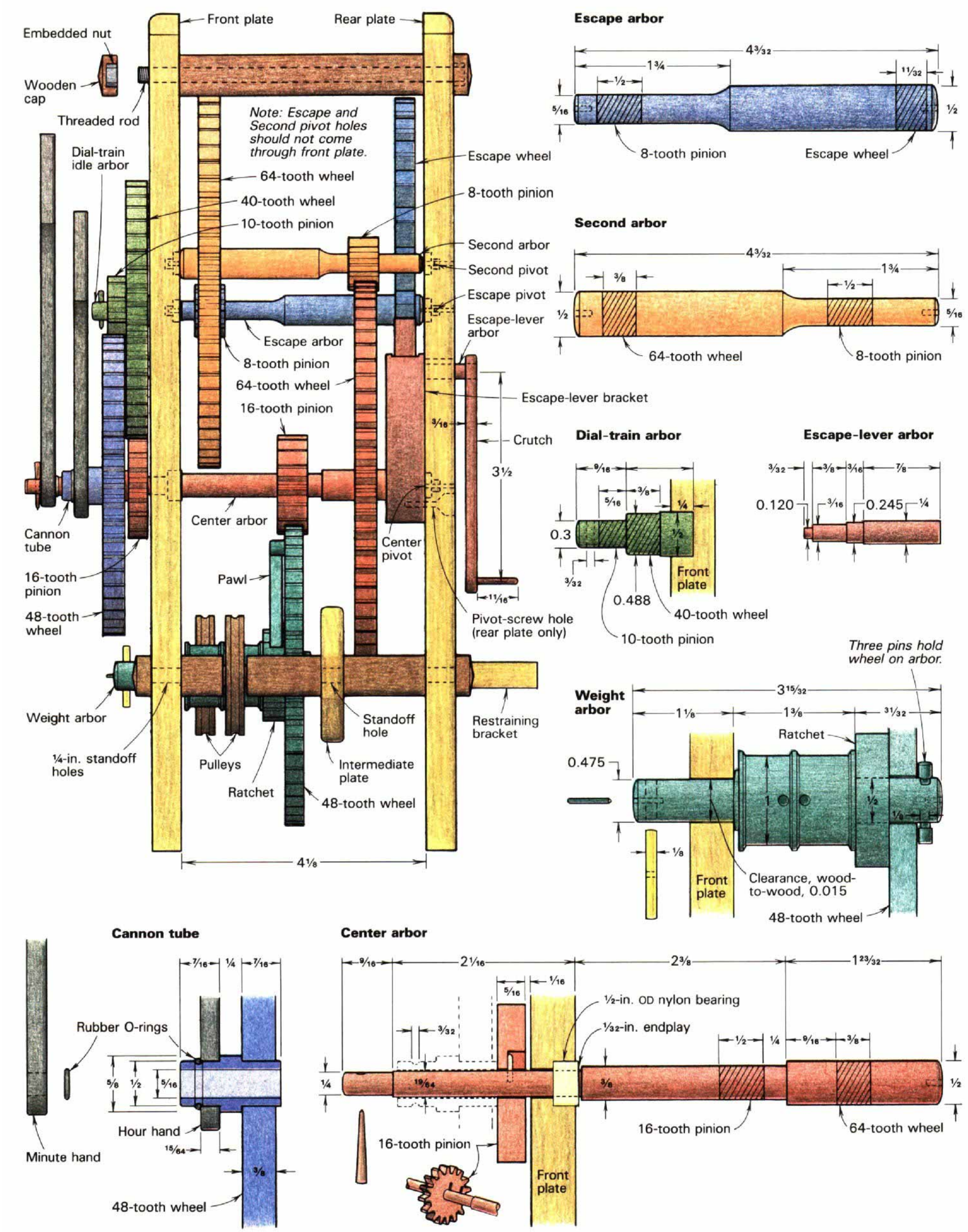
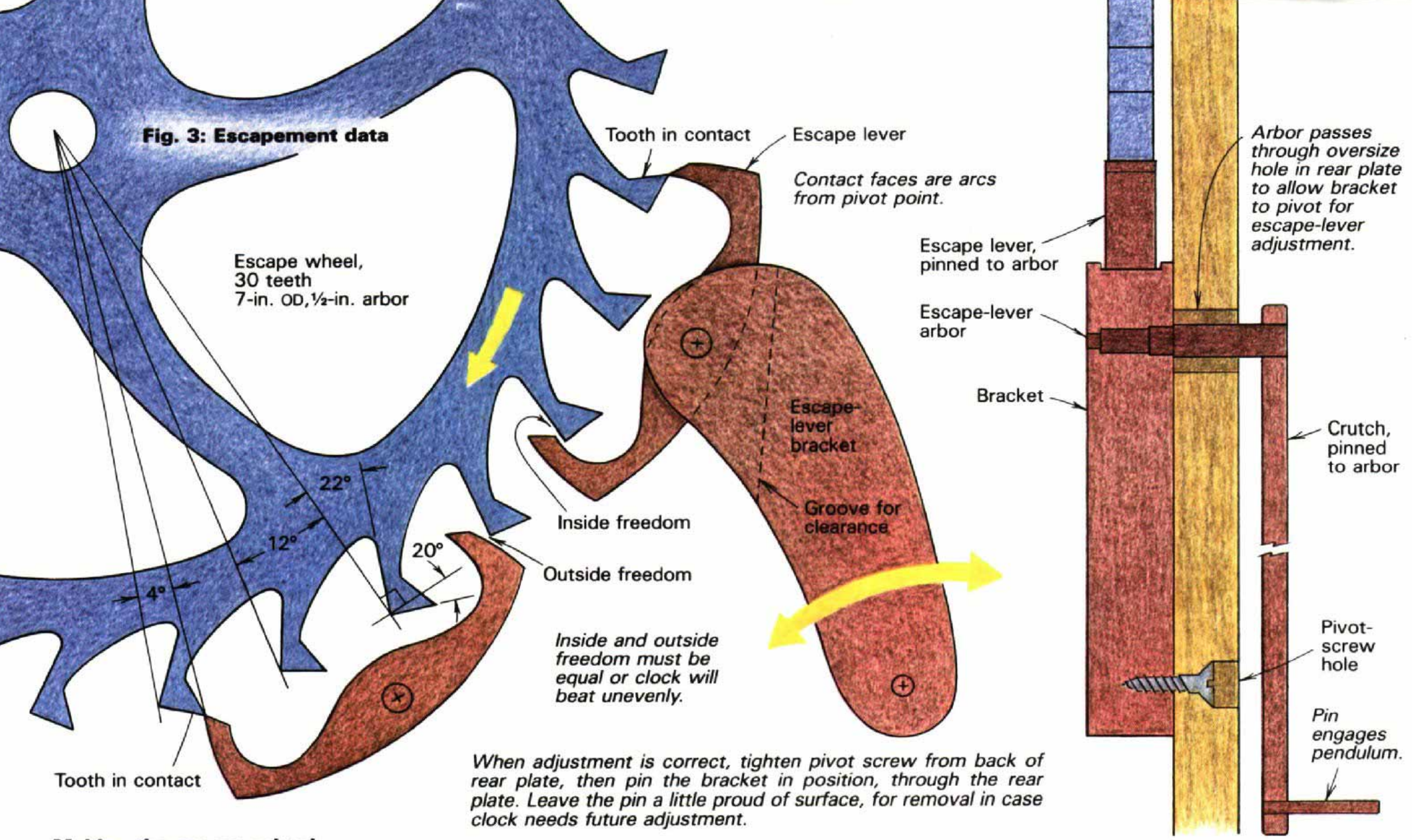
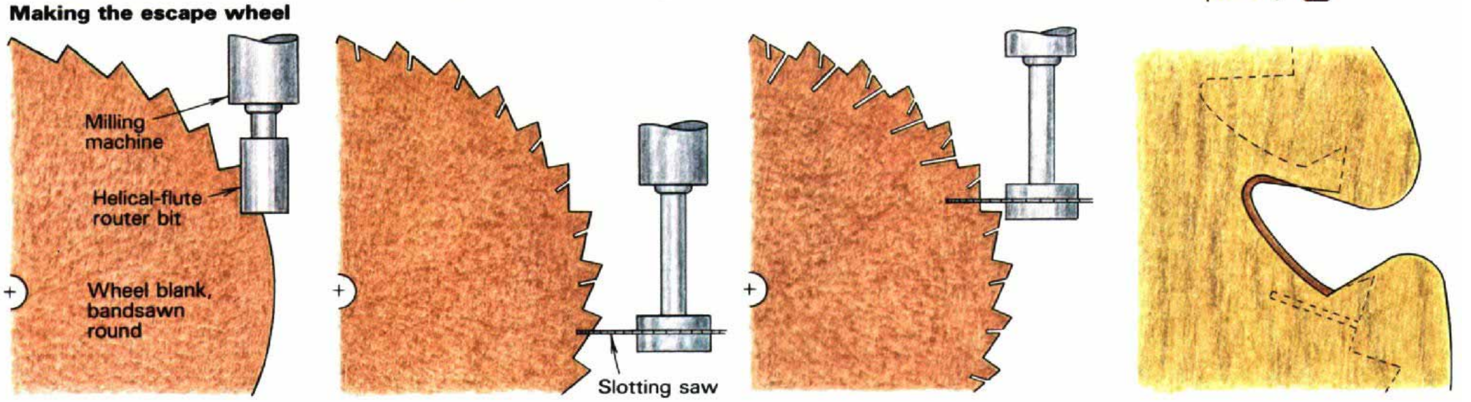

Embedded nut
Wooden cap
Threaded rod
Front plate
Rear plate
Note: Escape and Second pivot holes should not come through front plate.
Dial-train idle arbor
64-tooth wheel
40-tooth wheel
10-tooth pinion
Escape wheel
8-tooth pinion
Second arbor
Second pivot
Escape pivot
Escape-lever arbor
Escape arbor
8-tooth pinion
64-tooth wheel
16-tooth pinion
Escape-lever bracket
Crutch
3½
Center arbor
Center pivot
Cannon tube
16-tooth pinion
48-tooth wheel
Pawl
Pivot-screw hole (rear plate only)
Weight arbor
¼-in. standoff holes
Pulleys
Ratchet
48-tooth wheel
Standoff hole
Intermediate plate
Restraining bracket
4⅛
Escape arbor
4³⁄₃₂
1¾
½
¹¹⁄₃₂
⁵⁄₁₆
8-tooth pinion
Escape wheel
Second arbor
4³⁄₃₂
1¾
⅜
½
⁵⁄₁₆
64-tooth wheel
8-tooth pinion
Dial-train arbor
⁹⁄₁₆
⅜
⁵⁄₁₆
¼
0.3
³⁄₃₂
0.488
Front plate
40-tooth wheel
10-tooth pinion
Escape-lever arbor
³⁄₃₂
⅜
³⁄₁₆
⅞
0.120
0.245
¼
Three pins hold wheel on arbor.
Weight arbor
3¹⁵⁄₃₂
1⅛
1⅜
³¹⁄₃₂
Ratchet
0.475
1
⅛
Front plate
Clearance, wood-to-wood, 0.015
48-tooth wheel
Cannon tube
⁷⁄₁₆
¼
⁷⁄₁₆
Rubber O-rings
⅝
½
⁵⁄₁₆
Hour hand
¹⁵⁄₆₄
⅜
Minute hand
48-tooth wheel
Center arbor
⁹⁄₁₆
2¹⁄₁₆
2⅜
1²³⁄₃₂
⁵⁄₁₆
¹⁄₁₆
½-in. OD nylon bearing
¹⁄₃₂-in. endplay
³⁄₃₂
¼
¹⁵⁄₆₄
⅜
½
⁹⁄₁₆
16-tooth pinion
64-tooth wheel
Front plate

Fig. 3: Escapement data



When adjustment is correct, tighten pivot screw from back of rear plate, then pin the bracket in position, through the rear plate. Leave the pin a little proud of surface, for removal in case clock needs future adjustment.

Making the escape wheel



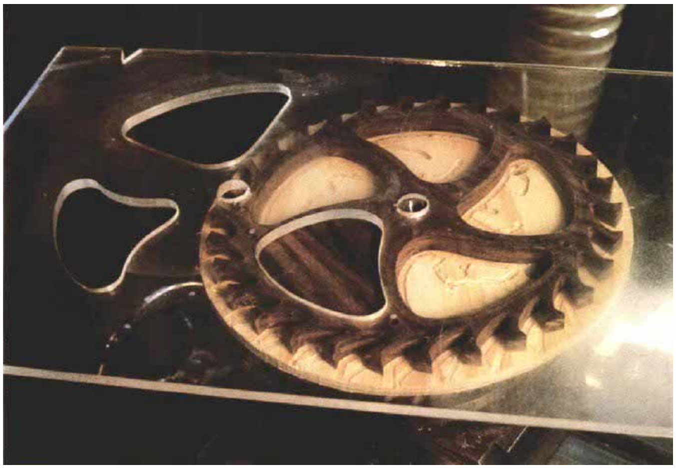
Westphale makes the teeth on his escape wheels with a series of straight cuts, as shown above, then routs out the curved shape of the gullets using a template and guide bushing (far right). The escape-wheel blank (or a stack of blanks) is mounted on a mandrel through the arbor hole, and the mandrel is fixed to a dividing head. The dividing head rotates and locks the wheel blank a fixed amount for each cut, ensuring even tooth spacing. Cutters are held in the chuck of a milling machine, the metalworking equivalent of a drill press. The milling machine adjusts precisely in three planes to locate the cutter relative to the work. The dividing head is attatched to a sliding table, worked by hand cranks, that moves the work horizontally past the cutter and back again for the next cut. When routing the gullets, the work is indexed under the template by the dividing head. Spokes are routed the same way (photo, facing page) then rounded over on a router table.

hollow headstock you can drill the pivot holes as I do, with a bit in the tailstock. If not, I'd suggest clamping a piece of scrap to your drill-press table and drilling a hole the diameter of your arbor through the scrap just off the edge of the table. Maintain the setup but change the drill to a size a few thousandths smaller than your pivot material; I find that a #53 drill bit works well. Insert the arbor from the bottom and drill carefully into the end. As the arbors are different diameters on each end, at least two different setups will be required.

Bearings, which I make from nylon rod, can be drilled with a similar setup. In this case, just drill part way through the scrap. For instance, if you use ⅝-in.-dia. bearing stock, drill a ⅝-in. hole ⅛ in. deep with a Forstner bit into the clamped scrap. Then drill a ¼-in. hole all the way through. Cut your bearing stock into ⅛-in.-thick wafers. Insert the wafer, drill the appropriate size pivot hole, then push out the completed bearing from below.

Engagement testing—Test wheel-and-pinion engagement patterns at various center distances. In a scrap of plywood, drill a hole for a pin that will represent the wheel arbor. Around it, draw a series of pinion-arbor holes, one at the nominal distance from center, the others at ⅓₂-in. increments from the ideal. Mount the pinion on a pin in various holes, revolve the gears, and note how the teeth mesh. Part 1 explains what to look for. Choose the distance that gives the smoothest action. There is some latitude, but many times, while working out the tooth profiles of the grandfather clock, I had to refine the contour of one cutter or the other, and sometimes both. You don't have to go with the exact tooth profiles and distances I've worked out, but they work well and I recommend that you try to match them.

Once the teeth have been cut, the wheels can be lightened with any number of spoke configurations. Spoke shapes are limited only by what is practical and aesthetically pleasing. My



The escape wheel nearing completion. The acrylic template remains stationary, with its far end clamped to a block on the workshop wall. To rout successive spoke holes, the work is turned by the dividing head, which has been set in position to hold the wheel horizontal. Spoke-hole patterns for some of the other wheels in the clock are also visible in the photo.

spoke template is shown in the photo above. I use a router and guide bushing with a ⅛-in. veining bit. Some of my spoke patterns are a series of round holes of various sizes, which can be cut with a drill or a circle cutter as size dictates.

Next the spokes can be rounded over on a router table, using a regular piloted roundover bit. After that, I seal the wood with a mixture of tung oil, polyurethane and mineral spirits, equal parts of each. I soak the wheel for a few minutes, then wipe off all the surplus. At the teeth surfaces, I use high-pressure air to blow away all external traces of the sealer—all I want left is what has soaked into the wood. After drying, I repeat the sealing step a couple of times until there is enough finish on the wheel to be buffed and polished. The final step is to wax the surface and buff it, but take care not to wax the tooth surfaces—they must run dry.

After finishing, the escape wheel gets a little extra treatment with 400 grit paper to polish the contact surfaces of the teeth.

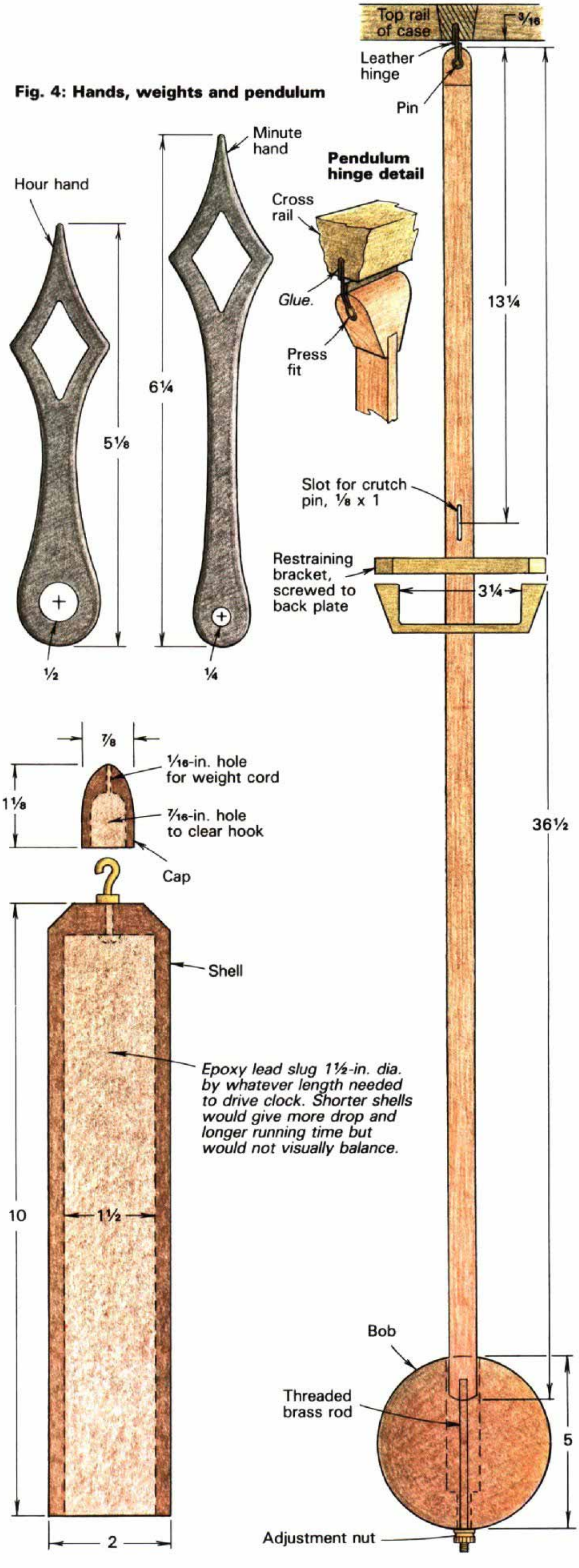
The wheels can now be balanced. Do this after the wheel and pinion are secured to the arbor (I use both glue and brass pins, driven at an angle). Wood density varies and sometimes wheels that you would reasonably expect to be balanced are not. To test them, I rest the pivots on the open jaws of a machinists' vise. The heavy side of the wheel will stop at the bottom. Rotate the wheel one-quarter turn and release. If the wheel stops in the same position, it needs balancing; if it doesn't turn, or the stopping position is random, it doesn't require balancing. Usually it will.

Mark the light side of the back of the wheel near the perimeter and drill a hole about halfway through the wheel. Insert a small lead plug or piece of lead shot and test again. Add more weight if required until the stopping pattern becomes random, then use a small nailset or punch to expand the lead in the hole. You can plug if you wish—I usually leave the hole open as evidence the wheel was balanced.

Setting up—The clockworks are supported by two outside plates. An intermediate plate carries the back end of the weight arbor. My template for the plates is shown in figure 2. Distances between pivots are critical, and should be adjusted in your clock according to how each wheel/pinion pair functions in the engagement testing described earlier.

My clock case is an open frame that is 76 in. high, 18 in. wide, and 11 in. deep. The clock plates are attached to the frame's crosspieces with screws from beneath. A photo of my finished clock was shown in part 1, and you are welcome to copy my case design as closely as you care to, but feel equally free to design

Fig. 4: Hands, weights and pendulum



Rout-a-clock

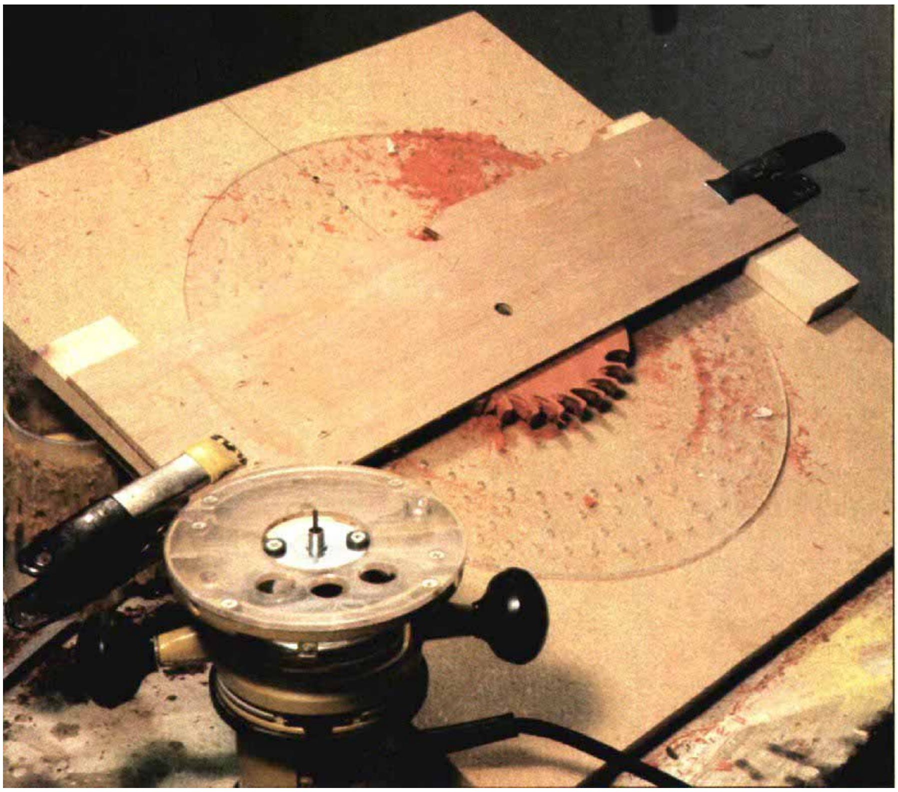
by Jim Cummins

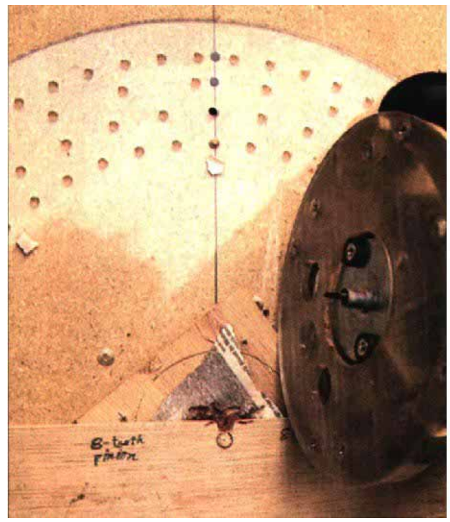
While editing Wayne Westphale's article, I had occasion to visit him in Colorado and watch him at work. He relies on precision metalworking equipment, which most woodworkers don't have, so I began trying to think of other ways to make a clockworks, using tools that might be found in any shop.

The various options seemed: to rig up a carriage on the drill press in imitation of Westphale's dividing head and milling machine, to rig up my lathe with a traveling router, or to focus on the indexing setup. I chose the last course and devised the router-template jig shown in the photos. Here are the basics:

The index wheel turns on a ½-in.-dia. pin that sticks up through a particleboard base. My index wheel is acrylic plastic (though it could be hardboard, etc.) with four concentric circles drilled for 64, 48, 40, and 30 holes (various increments of these give all the necessary divisions in Westphale's design).

Mark what will be the centerpoint on the wheel, then use a compass to lay out the four index circles. I worked out the spacing for the holes by using the circle division table that appears in *FWW on Proven Shop Tips* (or Methods of Work, *FWW* #38, p. 12). For those who don't have access to the table, here's how it works: Measure the exact diameter of the circle in inches, then multiply by one of the following factors: for 64 holes, 0.0491; for 48, 0.0654; for 40, 0.0785; and for 30, 0.1045. Work things out to as many decimal places as your calculator will allow. Set sharp dividers to the figure (you can measure with a machinists' rule in hundredths, or convert things to sixty-fourths as I did) and step off around





At left, routing an escape wheel on the indexing jig. The rough shape of the teeth can be cut using the template as shown. A second template is then needed to square off the tops of the teeth. Minor tearout can be patched with epoxy and sawdust. Pinion blanks (above) are too small to be screwed to the index wheel, but they can be glued to an oversize spacer for routing. The newspaper allows the finished pinion to be split free.

one of your own. Just be sure your design will accommodate the pendulum pivot as shown in figure 4.

Mount the plate assembly on the clock frame and hook up the pendulum and weights, shown in figure 4. My standard weights are three pounds each, but you may find that your clock will run on less (mine do, hut I allow a 50% safety margin for customers).

The clock should be set level, and the escape lever must be adjusted so that it performs as shown in the tick-tock sequence in part 1. Let the clock run for a while, as a test to see whether it is fast or slow, then adjust the pendulum bob a little to correct it. If the clock is running slow, shorten the pendulum, and vice versa. Keep a record of how often you make adjustments and of how many turns of the adjustment nut you make each time.

You will probably have to make many adjustments to get the clock just right. Clocks don't really run at a steady rate, but speed up and slow down minutely according to the weather and which particular teeth are engaged at any one time. But these slight irregularities average out. My grandfather clock is accurate to a few seconds per day. For the final bob adjustments you may have to let it run a week or more before you can tell whether it is gaining or losing time.

If your clock has problems, a careful rereading of part 1 should allow you to understand what they are. Clocks are fascinating and magical, but they follow physical rules. The important checkpoints are summed up here: The perimeter of wheels and pinions must be concentric with the arbor and the pivots must be the circumference to show the location of the holes. If it doesn't come out exactly right, adjust the dividers minutely and try again until it does.

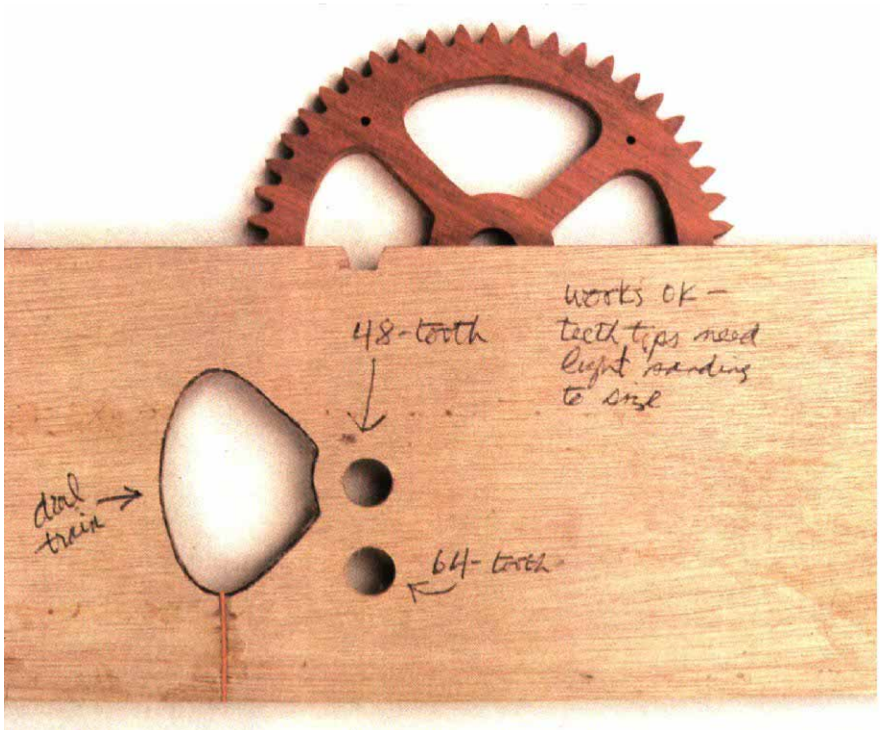
When the hole locations are scribed, drill the center hole. Next mount the wheel on its pin through the base, clamp the base to the drill-press table, and pivot the wheel around to drill the series of holes in each circle. I used a 3/16-in. twist drill (the plastic will ruin a brad-point).

Next, fit your router with a 5/16-in. guide bushing and a 1/8-in. straight bit with at least a 3/8-in.-long cutting flute. Shopping locally, I found that Black and Decker bits were longer than Master Mechanic bits, so I bought a half-dozen at $2.49 (I'm going to need at least that many more before I'm done). A router bit will give you a round bottom to the gullet, not as nice looking as Westphale's square corners, but perfectly functional.

Screw the wheel blank to the index wheel from beneath, with the screw holes where the spokes will eventually be. Use a spacer between (I used lauan plywood scraps) so the router bit doesn't chew up the index wheel. For the small gears, the pinions, I had to make two stepped-down center pins for the jig, one for a 3/8-in. arbor hole and another for a 5/16-in. arbor hole. The smallest pinions don't have enough wood in them for anchor screws, so I glued them to an oversize spacer with paper in the joint, as shown in the photo on the facing page.

Make templates that will rout the shapes of the gullets shown on p. 61. To use the jig, rout a gullet, turn the wheel a notch and rout the next, continuing until done. One critical point is to keep a sharp bit and to rout against the rotation, a technique called climb cutting. This helps prevent tear out.

My lauan plywood templates took me several tries each before I was satisfied, but each practice run of a few teeth will show you exactly what modifications are needed to come down to the correct shape. The template should be indexed by riding on the center pin—this ensures that the final wheels will be the same diameters as the practice pieces—and can be clamped as shown in the photo.



The teeth and spokes of this 48-tooth dial-train wheel were routed using the plywood template shown. To make the spoke template, the author bandsawed the spoke hole pattern, closed the entrance kerf by gluing a strip of veneer in it, then trued the shape with a rasp. Next step will be to round over the spokes with a piloted router bit.

Spokes are routed similarly. Make a template for one spoke hole, then use the index wheel to rotate the wheel the correct amount to space them equally. The spoke edges can be rounded over using a piloted bit in a router table, if you have one (I just clamped my router upside down in a vise).

All this has taken me about five weekends so far, with a good part of the time just spent musing about the myriad little decisions to be made at each step. I remember that it took me the best part of an evening to realize that I couldn't rout a tooth, but had to rout a gullet. Things like that.

In all, it's been as much of a challenge as Westphale promised and I've enjoyed the project thoroughly. My clock won't be ticking for at least a few more weekends, but the results so far are very promising, and I think I'm on the way. □

Jim Cummins, who putters weekends away at his frame shop in Woodstock, N. Y., is an associate editor at FWW.

at dead center of the arbor. Pivots must be straight, not bent (set the complete arbor, with wheel and pinion mounted, on the open jaws of a vise, then rotate the shaft briskly to check for wobble, warping, etc.) Allow 1/32in. endplay between the arbors and the clock plates (even so, if the plates warp the arbors may bind). Check for teeth jamming (bottoming or tips butting). Remove the escape lever assembly to check whether the rest of the gear train spins freely. Test pinion leaves for uniform spacing with a micrometer. Never use oil.

I've found that the most likely problem is eccentric wheels, pinions or arbors. One diagnostic trick, which I hope you will never need to use, may pinpoint an intermittent fault. If your clock regularly stops for no apparent reason, mark each pair of engaged teeth with small dots of masking tape. Then start the clock again. The next time it stops, look with suspicion at any taped pairs of teeth that are engaged as they were before. If it's not the teeth, the same test may pinpoint two gears that are slightly out-of-round, and that bind only when their long axes are aligned. A little work with a file may be all that's needed to put everything right. □

Wayne Westphale designs and builds clocks at his shop, Contemporary Time, in Steamboat Springs, Colo. His grandfather clock took two years to develop, and is copyrighted. Westphale extends to individuals the right to make a copy of his clock for their own use, but not for commercial purposes.