# A Wooden Escapement

## *Developing a Kit for Instructional Use*

Thomas Bensky

### *Introduction*

My university offers general education classes themed in how scientific, mathematical, and technological knowledge can be used to 'solve societal problems'. About ten years ago, I developed a course with this theme, based upon pre-1800 navigation, timekeeping and the 'longitude problem' of that era. I teach it both at my university and periodically, in London, England (due to the city's roots in the history of navigation and timekeeping). I wanted a final project for my students and since timekeeping is of critical importance, I decided to have them try to build a working mechanical clock escapement.

There would be many constraints, particularly for the navigation and clock making class that I teach in London. Resources here are more limited than in my 'normal' class in California. No workshop or power tools would be available, the cost would have to be low, and the entire activity portable. It would need to provide ten groups of two or three (largely uninitiated) students with a high likelihood of clock building success, after no more than a few hours of work. At least some flexibility in the design would be desirable. I decided that an escapement kit the students could assemble and 'fiddle with' was needed. But what would it be?

Work with scissors, cardboard and tape seemed messy and unpredictable, and kits[1], as well as Lego escapements on YouTube seemed too linear and simplistic. Most others, however spectacular, were too complicated to prepare or would require too much time to assemble.[2]

At about the same time, I was becoming interested in digital fabrication with CNC machines.[3] So, with an escapement kit as motivation, I purchased a Shapeoko CNC machine from Carbide3D, for use in my home workshop, and set forth to see what sort of escapement I could make with it.[4]

### *Wooden Escapement Kit*

A pendulum driving an anchor escapement made entirely from wood seemed most appropriate to ease students into this. The pendulum would be a yard (or metre) stick, as they are readily available (abroad), tend to stay straight, and would deliver a workable two-second period. After experimenting with the Shapeoko, $\frac{1}{4}$in thick cherry wood would serve as the stock for the escape wheel and anchor.

Many escapements were studied: in books, online and in London museums. I was drawn to a book by James Rudolph, on building a paper clock.[5] I wasn't going to use paper, but Rudolph's book had a tested escapement design that seemed to be based on straightforward geometry, so I began to work his patterns for an escape wheel and anchor into CNC ready form.

Preparing a shape to be cut by a CNC machine requires one to produce a 'tool path', that instructs the CNC where to move the spinning cutter relative to the stock in x,y,z planes. In this work, the tool path is always tied to lines of a 2D figure. The third dimension will come simply from the thickness of the stock. Typically, many passes are made along the lines by the CNC, until a desired cutting depth is reached. Although the Shapeoko comes with software called Carbide Create, it wasn't sophisticated enough to design an escape wheel, so AutoCAD was used instead.[6]

### *The Escape Wheel*

To start designing Rudolph's 24-tooth escape wheel, two circles of diameter 3.5 in and 2.5 in were drawn co-axial with each other and a $\frac{5}{16}$in center hole, **Figure 1**. A single tooth near the top is shown completed, as aided by using an adjacent pair of 24 total diameters shown for the larger circle. With all teeth completed, the diameter portions within the smaller circle were removed, as were the two original circles, **Figure 2**. This file is now imported into Carbide Create. This allows one to set up the tool paths, and eventually simulate the design, **Figure 3**. The software also generates G-code, which is what actually runs the CNC machine, resulting in the escape wheel in **Figure 4**, after about 20 minutes of cutting.

### *The Anchor – Part A*

Problems arose quickly with Rudolph's anchor. The escape wheel was fitted with an arbor (a $\frac{5}{16}$in dowel) and mounted in a roller bearing, with a drive weight tied around the arbor. The anchor, whose arbor was also mounted in a bearing and attached to the pendulum, was positioned so it could engage the teeth of the wheel. With this, the escapement simply would not run, no matter what was tried. Despite this discouragement, an escapement prototype was evolving that could be studied and iterated upon, owing to the power of the software and CNC combination. Many bleary-eyed hours were spent staring at the interaction between the anchor and escape wheel teeth, and quite a lot was being learned.

It became clear that the observations and adaptations needed to produce a working anchor/escape wheel combination would be the focus of this kit. Thus, students would need to be able to make adjustments to provide the desired flexibility. This would either have to be in the centre distance between escape wheel and pallet arbors, or in just the anchor itself. Since the former is rather uninteresting, it was set to 2.36 in (6 cm), and adjustments were built into the anchor itself. We now pause the discussion of the anchor, to look at the mounting hardware.

### *Mounting Hardware*

The $\frac{5}{16}$in dowels used for arbors fortuitously form a good friction fit into common skateboard or fidget spinner bearings.[7] With this in mind, front and back faces were designed from 0.8 in thick alder stock, with 0.440 in recessed (or 'pocket cut' holes) to a depth of 0.273 in to hold pairs of bearings for each

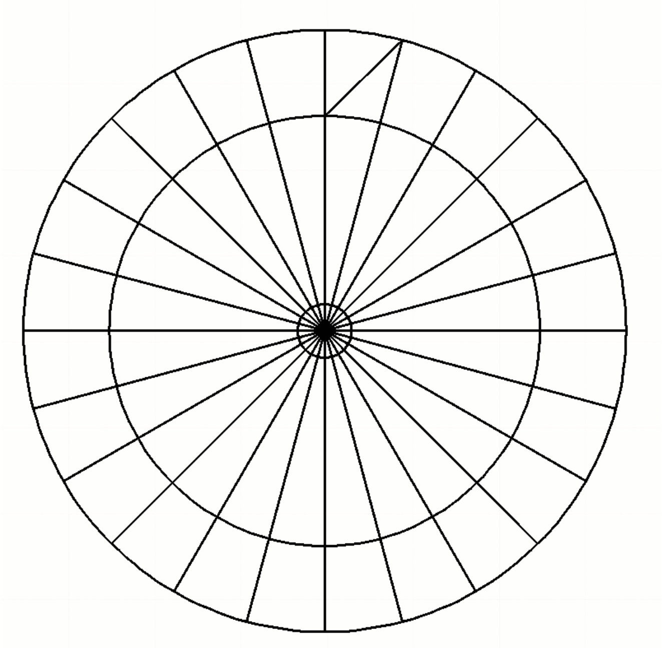

Figure 1. Beginning of an escape wheel: A 3.5 in and 2.5 in circles coaxial with a 5⁄16 in hole. Radii of the 3.5 in circle are added at 15 degree increments. Small diagonal line at top shows how teeth will be formed.

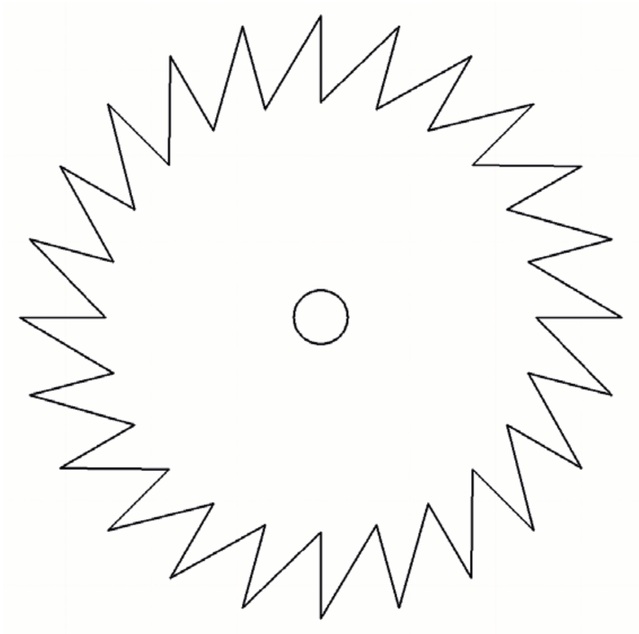

Figure 2. All teeth completed, with inner radial lines broken and guide circles and removed.

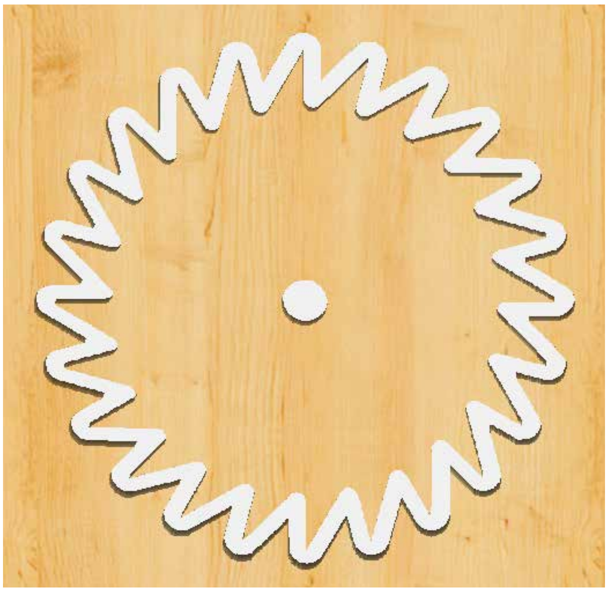

Figure 3. Simulated escape wheel, prior to cutting.

Figure 4. The completed escape wheel.

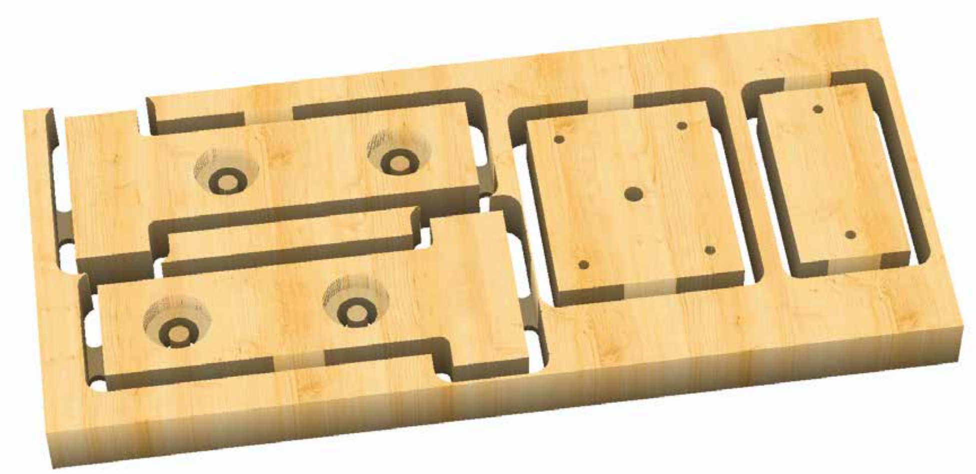

Figure 5. Simulated design of the front and back faces of the clock mount (left) and top and bottom mounting plates (right). Large recessed holes are to hold roller bearings.


Figure 6. Front and back mounting panels for the clock.

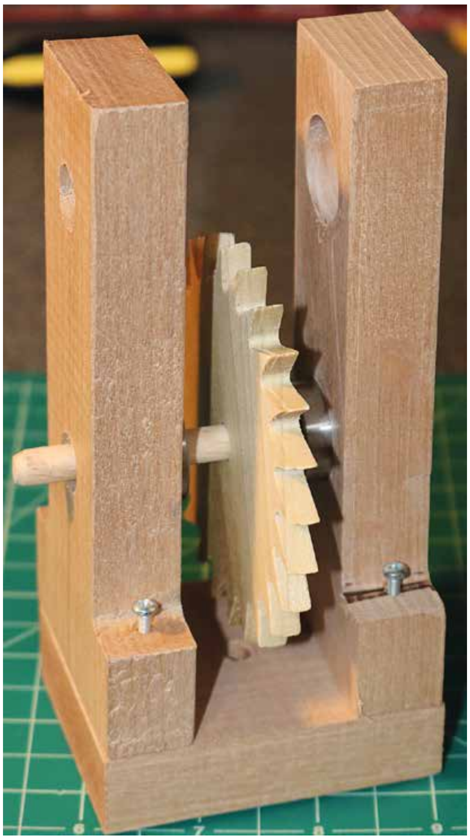

Figure 7. A loose fitting of escape wheel thus far.

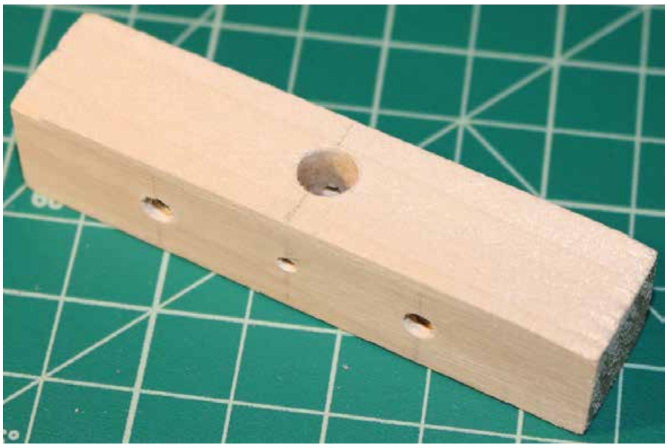

Figure 8. Base for tunable anchor no. 1.

Figure 10. Interaction of the tunable anchor with the escape wheel.

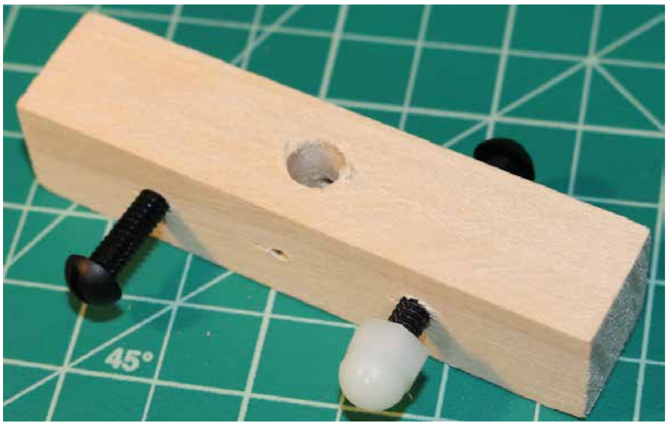


Figure 9. Plastic screws as the anchor pallets.

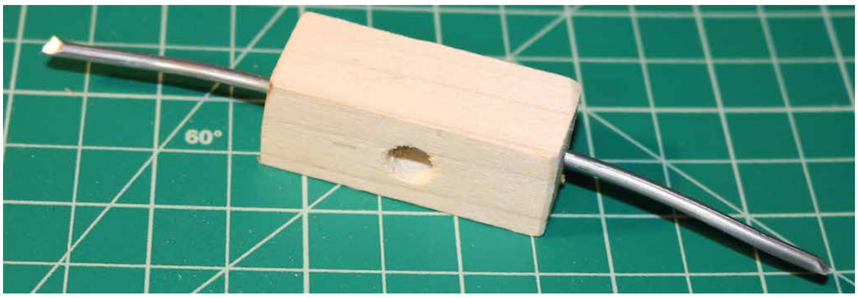


Figure 11. Another tunable anchor. Bendable aluminum wires will interact with the escape wheel.

Figure 12. Assembly of the wire-based anchor into the escapement.

Figure 13. Wooden pendulum clamp on back of the anchor's arbor. Yardstick pendulum is just visible extending downward.

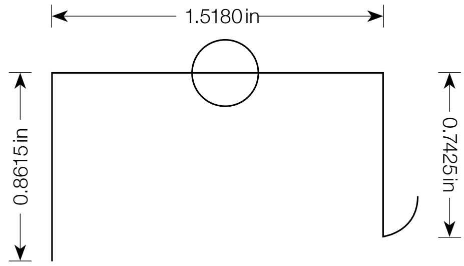


Figure 14. Minimal interacting surfaces of the screw-based anchor. All dimensions are in inches.

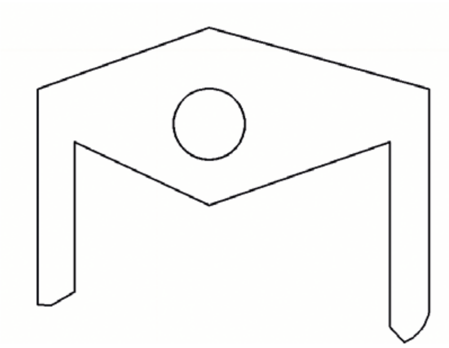

Figure 15. The fixed anchor design.

end of both the anchor and escape wheel arbors, as shown in **Figure 5**, by the pair on the left.

The rectangular pieces to the right in this figure are the top and bottom of the frame, with the small holes being no. 6 screw holes that will hold the frame together (no glue is needed).* As shown in **Figure 6**, bearings are pushed into the pocket holes. Bringing everything together in a loose fit is shown in **Figure 7**. The arbor and bearings for the anchor are mounted (not shown) in the upper pair of opposing pockets above the escape wheel.

### *The Anchor – Part B*

Lacking a working anchor, and bothered by little understanding between requirements for the escape wheel versus anchor geometries, a YouTube video by user Clickspring helped me to move this work forwards.[8] It indicated how often the escape wheel/anchor interaction step is a 'subjective process', requiring a bit of repeated cutting and trying until it finally works. With this idea in mind, two adjustable anchor mechanisms were developed.

### *Adjustable Anchor 1*

In the first anchor, ¾ in × ¾ in × 3.5 in stock was drilled with a 5⁄16 in centre hole to accommodate an arbor. On the perpendicular face, two tapped no.10–32 holes were made, separated by 1.6 in (4 cm), as shown in **Figure 8**. Plastic screws are shown installed in **Figure 9** and with its interaction with the escape wheel in **Figure 10**.

This escapement will work after many adjustments, and the plastic screws are ideal for small amounts of sanding and shaping by the students.[9] The orientation of the screws, including the optional use of smooth, rounded acorn nuts is an open decision. The penetration depth of the screws into the teeth is readily adjusted by turning the screws in their threads. The stop and release action can also be easily studied.

### *Adjustable Anchor 2*

In the second anchor, the same ¾ in x ¾ in stock, now 2 in long, was prepared as before, but now with two 3⁄16 in holes on its outer longitudinal faces, to hold no. 9 gauge aluminum wire, **Figure 11**. This is mounted on the movement as shown in **Figure 12**.

The figure shows a common starting configuration that often results in at least a few initial ticks and tocks. The malleable nature of aluminum means pliers can be used to shape the wire into many possibilities until the escapement runs. Optimising, the ends of the wire can be fashioned into small loops, or smoothed with sandpaper to minimise friction.

### *Final Construction*

Both adjustable anchors will result in a working escapement with a 50 gramme drive weight and a 100 gramme pendulum bob. The yardstick pendulum is mounted to the back of the anchor arbor using the clamping mechanism shown in **Figure 12**. The orientation of the pendulum, when vertical, with the angle of the anchor is a free parameter, adjusted by loosening the two top clamping screws. The yardstick itself is clamped between two wooden plates by the four screws (lower half of **Figure 13**). With the screws loose, the yardstick can be slid up and down, to adjust the timekeeping. A similar clamp is at the bottom of the yardstick to hold the bob.

### *A Fixed Anchor*

Continued puzzlement over the logic between the escape wheel teeth and anchor geometries was beginning to work itself out. The most careful work during development of this kit was done with the aforementioned anchor no. 1. The two screws were shaped and adjusted until the escapement had an

* In the USA, screws are often named by a gauge number. The number 6 screw cited here is similar in size to an M3.5 screw, although of course the thread and head specifications would be quite different. –Tech. Ed.

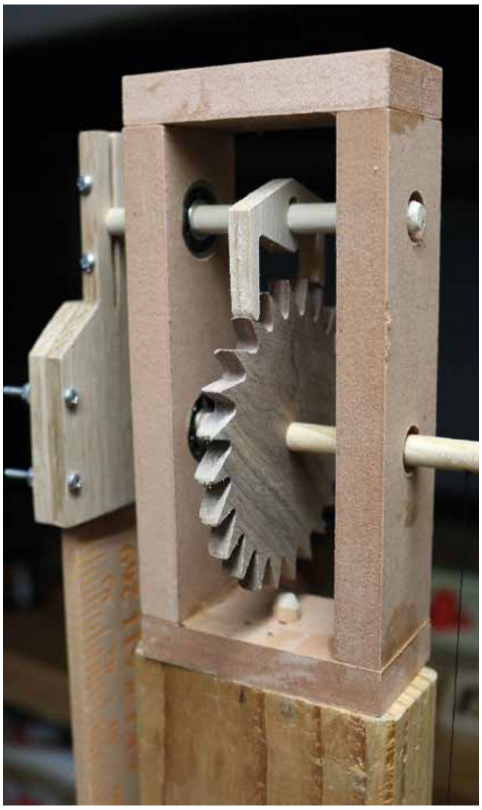

Figure 16. Final escapement assembly.

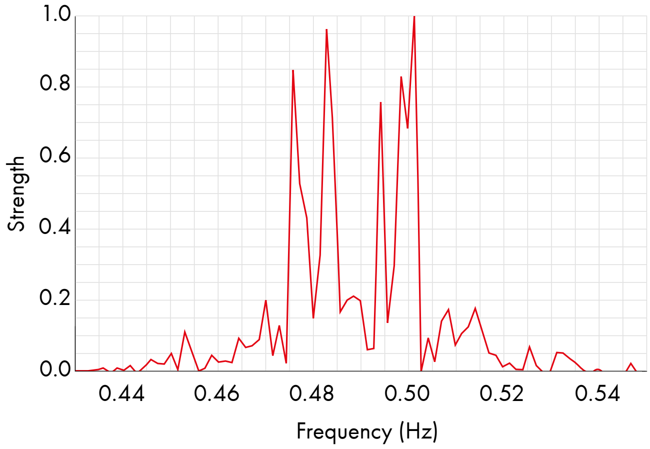


*Figure 17. Fourier transform of the angular speed vs. time of the escapement's pendulum.*

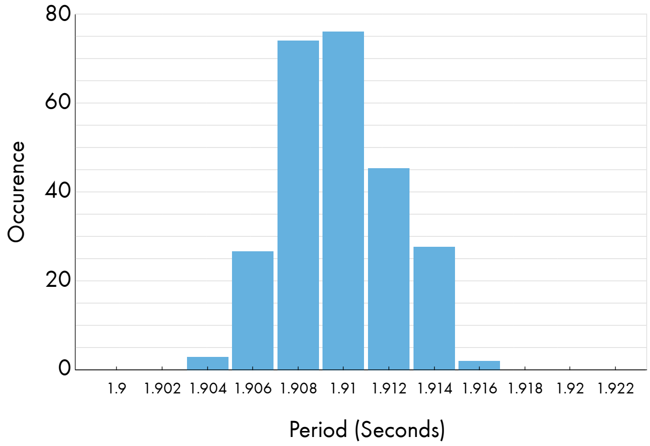


*Figure 18. Distribution of pendulum swing times, as measured by passing the pendulum through a photogate timer.*

even and consistent running with minimal drop on the entry and exit sides.

The working anchor was then removed and measured, realising that only the surfaces interacting with the escape wheel needed to be reproduced, in their positions relative to the arbor mount. This is shown in **Figure 14**, and was definitely an epiphany moment in the puzzling process of designing an anchor. All that was needed now was to connect the open ends to make a CNC ready object, **Figure 15**.

Indeed, the anchor worked almost immediately when inserted into the escapement. The only free parameter is its angle relative to the pendulum, which is adjusted as described above. This fixed anchor has since evolved through 15 small iterations, with continued careful study of its interaction with the escape wheel. In the iterations, the CNC design was altered down to one millimeter, which the Shapeoko happily accommodated. The final form of the escapement is shown in **Figure 16**; a slight push of the pendulum will start it running.

### *Escapement Performance*

Three measurements were carried out to assess the escapement. The first was performed by attaching a small wireless gyroscope to the pendulum bob.[10] This captured the angular speed of the pendulum versus time for approximately 1000 seconds (or 500 swings of the pendulum). The Fourier transform of this was taken and is shown in **Figure 17**. The escapement seems to be operating in five modes, near 0.5 Hertz (the frequency of a one metre pendulum). The Q of these modes ranges from 155 to 284.

In the second measurement, the pendulum was passed through a photogate timer for 500 cycles.[11] A histogram of the periods measured is shown in **Figure 18**, showing an average period of 1.911 seconds, with the width at half maximum 0.018 seconds.

Lastly, the photogate timer was positioned to capture the passage of a clock hand attached to the escape wheel arbor. If a time indicator were to be made, the best estimate of one cycle time of the hand would be (24 teeth)(1.911 seconds) = 45.86 seconds (i.e. imagine a clock face with '45.86 seconds' at the top, instead of a 12). Next, the drive weight was configured to run the escapement for 90 minutes, while the cycle time of the minute hand was tracked with the photogate (based on the internal clock of a MacBook Air laptop). The accruing sequence cycle times of the hand were linearly correlated with the sequence generated by 45.86 n, where n=0, 1, 2, 3, so a numerical regression was performed. This showed the escapement to gain about 4.5 milliseconds/second relative to the laptop clock, during the 90-minute run.

### *Conclusions*

The complete escapement kit is shown in **Figure 19**, consisting of 20 total parts. Not shown are the yardstick, string, and drive and bob weights. Over two dozen escapement kits have been used by approximately 200 students both in the local and abroad versions of the class mentioned. When running, the arbor on the escape wheel turns once every 45 seconds, and will run for about 15 minutes before the weight hits the ground.

Although not a simple or easy process, digital fabrication

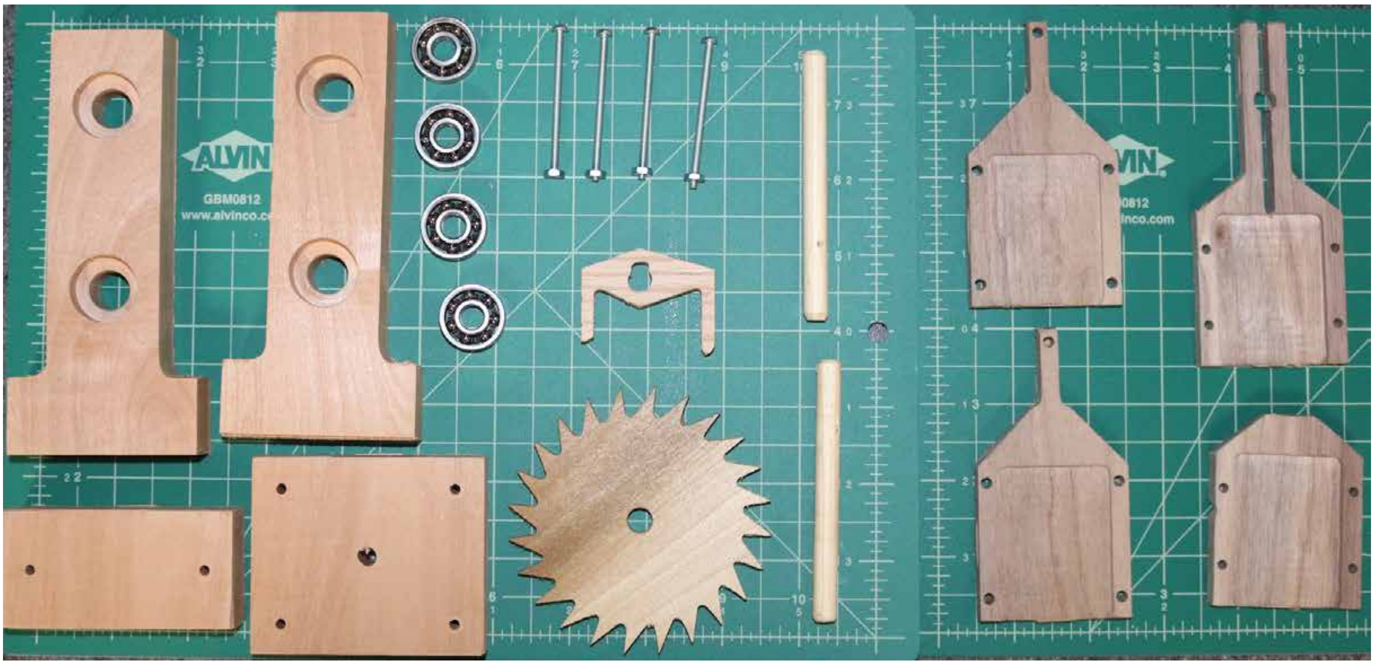


*Figure 19. The full escapement kit, minus the yardstick pendulum, the drive and bob weights, and number 4 screws and nuts for the pendulum clamps.*

has helped enormously, as it is possible to instruct the CNC machine to cut the parts, after loading stock into the machine and zeroing the cutting tool. After assembling the parts, small adjustments will lead to a running escapement. I was not able to achieve such consistency using a scroll saw.

Students seem to engage in this 'clock building' activity quite happily. They spend the allotted time interacting in small groups, adjusting either aforementioned anchors 1 or 2, winding the weight and nudging the pendulum until it runs. Most can assemble the kit and have it working in under two hours, and when it runs for the first time, a happy emotional response is often heard. The kit seems to be doing its job in making for a gentle introduction to clock building, and the analysis and development trials outlined above provide much to discuss, as well as fodder for additional student assignments.

The issue of a time indicator is still not obvious to some, in which case I ask them to think carefully about the motion of the escape wheel arbor. Our full activity involves them 'calibrating' the clock against their phones' stopwatches and making a dial, complete with a hand attached to said arbor.

Ongoing work includes developing a gear train that will drive a minute hand. Also, although somewhat difficult for the Shapeoko, a metal version of this escapement is planned.


### *Acknowledgements*

Thank you Dr. Tom Gutierrez for his help with the Fourier transform, and the California Polytechnic International Centre, in particular Cari Vanderkar and Nayree Barnett for supporting the London 'study abroad' programme. Thank you also to the London-based Foundation for International Education for their hospitality. Lastly, we wish to express a sincere appreciation for the vibrant culture surrounding the history of timekeeping and navigation in England.



### *About the Author*

Tom Bensky is a Professor of Physics at California Polytechnic State University, in San Luis Obispo, California, USA. There, he teaches a wide variety of courses, ranging from introductory physics and astronomy, on up to advanced physics labs. His interest in horology began in 2008, when he was accepted to teach a course about the 'longitude problem' at his university's summer London-study programme. He has since been back many times, taking students around the London area, showing them antiquarian clocks and navigation instruments.

Tom can be reached at tbensky@calpoly.edu


ENDNOTES


1. Justin Koullapis, 'Gifts for Budding Horologists', *Horological Journal*, vol. 157 (Dec 2015), p555.
2. Editors of Scroll Saw Woodworking & Crafts, *Making Wooden Gear Clocks: 6 Cool Contraptions That Really Keep Time* (Pennsylvania: Fox Chapel Publishing), 2016. This includes designs by Brian Law and Lisa Boyer.
3. Mike Flannery, 'Clock and Watchmaking: Endangered Crafts?', *Horological Journal*, vol. 160 (June 2018), pp262–263.
4. http://www.carbide3d.com/shapeoko
5. J. Rudolph, *Make Your Own Paper Clock*, 10th Anniversary Edition edn (William Morrow Paperbacks, 2001).
6. http://www.autodesk.com (accessed 18 April 2019)
7. http://www.amazon.com, search term ASIN #B06XTZJDCC (accessed 18 April 2019)
8. https://youtu.be/T28sGA597IE?t=4m30s, by user Clickspring (accessed 18 April 2019)
9. https://youtu.be/oZmjBCppGvk, by user phystv (accessed 18 April 2019)
10. W. Bensky, 'Wi-Fi based Wireless sensors for data acquisition', *The Physics Teacher*, vol.56 (Sep 2018), pp393–7. Available online at https://aapt.scitation.org/doi/10.1119/1.5051157
11. https://www.vernier.com/products/sensors/vpg-btd/ (accessed 18 April 2019)