HOW THINGS WORK

Section Editor: **H. Richard Crane**
Department of Physics, University of Michigan, Ann Arbor, MI 48109

The Quartz Analog Watch: A Wonder Machine

People live closer to quartz wristwatches than to any other kind of equipment, yet few (even among physicists) would be able to describe in more than general terms how they work. That's partly because the watches are so small and compact that even when the back is opened (Fig. 1), the works are no less a mystery. It took a number of inquiries to watch companies to get explanations that satisfied me and that I thought would satisfy other physicists.[1] Quartz watches come in two categories: analog, the ones with hands, and digital, the ones with the liquid crystal readout. One kind, the analog, will be enough for this time around. Digital may be left for later.

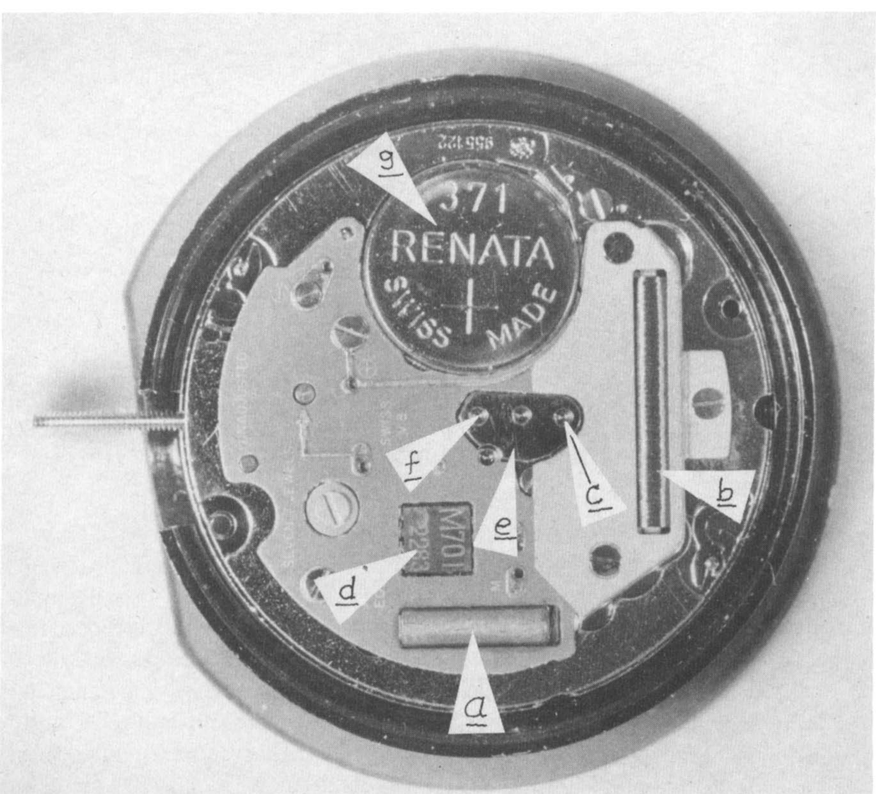

Fig. 1. Quartz analog watch with back cover removed. a, capsule that contains the quartz tuning fork; b, coil that momentarily magnetizes the stator of the motor; c, axle of the motor armature; d, integrated circuit (IC); e, gear box; f, concentric axles of the three hands; g, battery.

A word here about the term "quartz watch." The term is short for any watch whose time reading is derived from the vibration of a crystal through the *piezoelectric effect*,[2] the standard crystal for watches being quartz. An electronic circuit drives the crystal in vibration at its resonant frequency. The resonant frequency is extremely high. Stepping the high frequency down and using it to control the turning of the hands (of an analog watch) is the job of 90% of the parts found in the watch.

The description falls into three parts: (1) the quartz crystal, its form, and how its frequency is set to a standard; (2) the integrated circuit (IC) chip that drives the crystal in vibration, scales its frequency down, and forms pulses that turn the motor; and (3) the motor that drives the train of gears that turns the hands.

The description here will be of the watch of a particular company; other makes may differ in details, but not in basic principle.

When I learned that the resonant frequency of the quartz crystal in a watch is only a little over 30 *kilo*hertz, I was greatly puzzled. All the crystals I had worked with in my ham radio days were in the *mega*hertz range. And the smaller the crystal the higher was the frequency, so how could the frequency of the almost microscopic crystal in a watch be so low? The answer, I found, is that the crystal for the watch does not vibrate in the standard mode, that in which opposite faces move toward and away from each other. The crystal is cut in the form of a miniature tuning fork,[3] the two arms of which move toward and away from each other (Fig. 2A). The tuning fork is mounted in an evacuated metal capsule, a in Fig. 1, whose outside diameter is only 1 mm. I have not opened one of the capsules, but can imagine how small the tuning fork must be.

The second marvel about the tuning fork is how its frequency is adjusted *on a production line* with such accuracy that the watch will meet the company's claim of losing or gaining no more than a minute a year. That translates into two parts per million in frequency. Adjustment can only be done physically: by changing the shape or distribution of mass. Now enter the laser. The frequency of the tuning fork as cut from the crystal of quartz is, intentionally, a little too high. Then spots of gold are deposited (probably by evaporation) near the ends of the arms, to add enough mass to make the frequency a little too *low*. On the production line, while the frequency of the tuning fork is being compared (electronically) with the standard, a laser beam starts evaporating the gold of the spots, causing the frequency to increase. When the frequency matches that of the standard, the laser beam cuts off, and is ready for the next tuning fork.

To see what the IC chip has to do, we can start with the fact that the second hand of the watch (and the other two hands also) advance discontinuously once every second. The IC chip scales frequency down by successive divisions by 2. Therefore the turning fork frequency in Hz must be a power of 2; in fact it is the 15th power, 32,768 Hz. One minute per year for the watch translates into matching the tuning fork frequency to that of the standard to within 0.06 Hz. Evidently that is doable, in production-line fashion.[4]

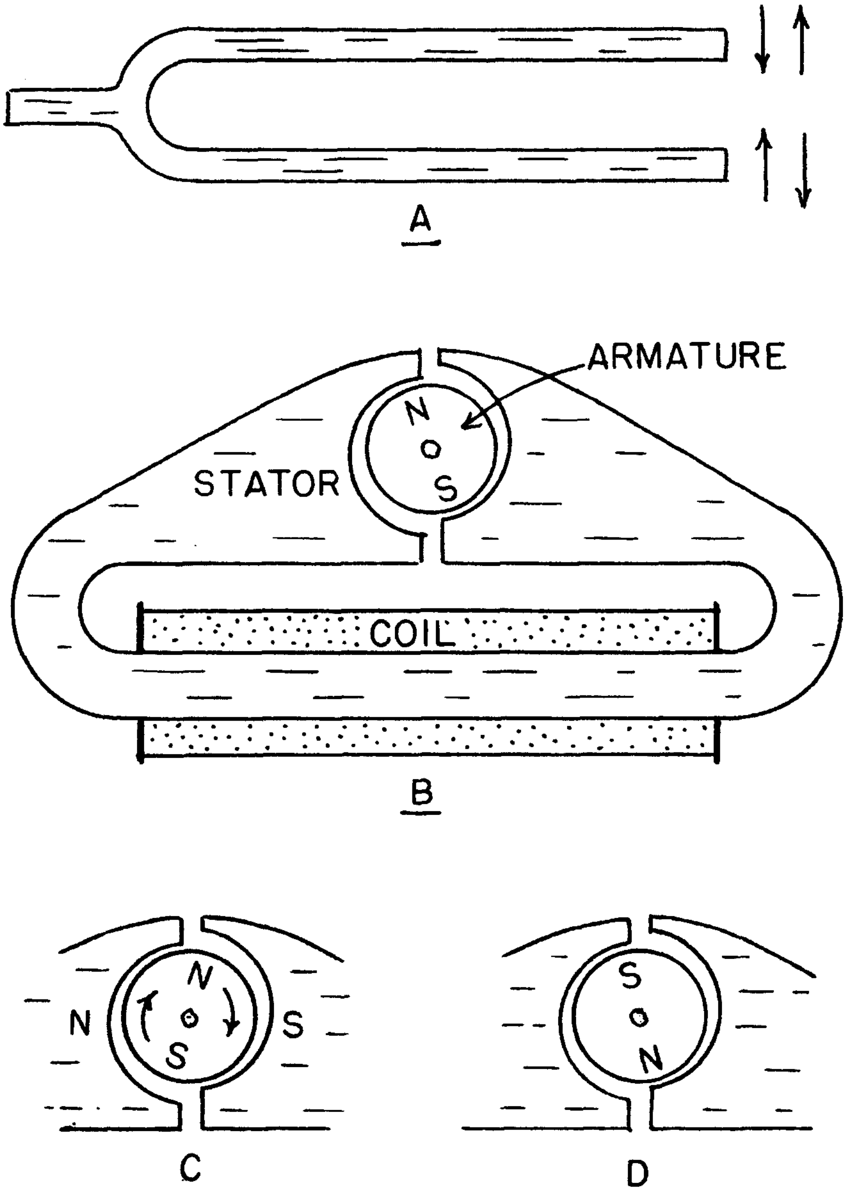

Fig. 2. A, a conventional tuning fork; vibrates the same way as the one in the watch. B, the motor, with the armature in the resting position when the stator is unmagnetized. C, current in the coil, stator magnetized in the sense shown, armature starting rotation, clockwise. D, stator again unmagnetized, armature comes to rest as shown, 180 degrees from starting position.

It's interesting to think of the overall reduction of the frequency of the tuning fork. To the rotation of the hour hand it is 2 to the 21st power, and if the watch has a calendar, it is 2 to the 26th!

We come to the last of the three ingenious parts of the watch: the motor. It is one of a class called a stepping motor. The name describes it: in response to an electric pulse, the rotating part (the armature) advances by a finite angle and stops, to await the next pulse. The stepping motor, diagrammed in Fig. 2B, can be identified in Fig. 1 by its coil, b. The soft iron stator is concealed by a plate that holds it in place. The axle of the armature is at c.

In Fig. 2, B, C, and D show the action. The soft iron stator, normally nonmagnetic, can be made magnetic momentarily by current in the coil. The armature is a permanent magnet. The key to the stepping action is that the armature is not in a cylindrical cavity in the stator. The halves of the cavity are offset, as shown. When there is no current in the coil, the armature seeks a position such that its poles are nearest to the soft iron, as in both B and D. While it is residing at rest in that position, the coil receives a pulse of current from the IC (d in Fig. 1), making the stator magnetic, with such polarity that the poles of the armature are repelled. That makes the armature start rotating in the sense that will get its poles farther from the stator, namely clockwise, as in Fig. 2C. The current in the coil lasts only long enough to start the armature rotating. Once started, it goes on to find the next position in which its poles are nearest the (nonmagnetic) soft iron, which will be 180 degrees from where it started. The next pulse of current in the coil (which must be in the opposite sense to that of the first one) will start the armature on the second 180 degrees of clockwise rotation. So that is the response to the current pulses from the IC, which are short, alternating in direction, and spaced one second apart.

The rest of the story, from the stepping motor to the turning of the hands, is old stuff: a train of gears (e in Fig. 1) that reduces the rotation of the motor to the appropriate rate for each of the three hands, whose concentric axles are at f. Not to forget the battery, g, the biggest component of all.

References

1. We are indebted to Dan Fenwick, Swiss Watch Technical Center, 1817 William Penn Way, Lancaster, PA 17601 for a very informative technical pamphlet.
2. A more complete discussion of piezoelectric oscillations will be found in a footnote in an earlier "How Things Work" column [*Phys. Teach.* **26**, 120 (1988)].
3. The use of a tuning fork is not new. The Accutron, which had its day before the advent of quartz watches, had a steel tuning fork, of frequency 300 Hz, driven by a battery and one transistor. The rest was mechanical: first a ratchet wheel, then a gear train leading to the hands. The watch, held to the ear, was used by doctors to check hearing.
4. Another case of precision in mass production, described in these columns is how steel balls, spherical and uniform to 0.0001 inch are made, cheaply, by the billions [*Phys. Teach.* **24**, 561 (1986)].

William F. and Edith R. Meggers—Project Award

Call for Proposals

The William F. and Edith R. Meggers Project Award of the American Institute of Physics is a biennial award designed to support projects for the improvement of high school physics teaching in the United States and/or projects for the advancement and diffusion of physics and its application to human welfare. The Meggers Project Award Committee invites proposals for the 1994 Award.

Criteria

a. Objectives

The 1994 objectives are to support projects at the high school level designed to increase interest in physics and enhance the quality of physics education.

b. Guidelines

1) Projects must be clearly directed toward accomplishing the 1994 objective; 2) Proposals are invited from individuals as well as groups; 3) Projects that can serve as models for others are encouraged; 4) Projects that propose the use of the entire budget for the purchase or rental of equipment will be disallowed; 5) A completed proposal will consist of: Title, Abstract, List of Personnel, Objectives, Description of Activities (five or fewer pages), and Budget; 6) For successful proposals, a required report on project activities is due August 31, 1995.

Nature of the Award

The Award consists of monetary support. A total of $25,000 is available to be awarded for one or more outstanding projects in the 1994 competition.The Meggers Project Award is made possible by an endowment created by the gift of a stamp and coin collection from William F. and Edith R. Meggers to the American Institute of Physics.

Procedures

The 1994 Meggers Project Award will be approved by the AIP Executive Committee in time for an announcement in June 1994. Selection will be recommended by the Meggers Project Award Committee, appointed by the AIP Director of Physics Programs.

Send proposals to: **John S. Rigden, American Institute of Physics, One Physics Ellipse, College Park, MD 20740-3843; 301-209-3100**

Deadline for receipt of proposals is April 15, 1994.