Inside a Quartz Watch

From a piezoelectric tuning fork to a stepping seconds hand

Companion to the interactive edition at `theisegoria.github.io/quartz-lab/`, and to the automatic-watch lab at `theisegoria.github.io/watch-lab/`. Component values, currents and ratios throughout are typical rather than specific to any one calibre.

The argument in one paragraph

A mechanical watch *measures.* Energy enters an escapement, a balance wheel answers with an interval, and every imperfection in that negotiation appears as rate. A quartz watch *counts.* A laser-trimmed sliver of silicon dioxide vibrates 32 768 Hz, fifteen toggle flip-flops halve that number down to exactly 1 Hz, and the single pulse left over is spent turning a magnet through half a revolution. Nothing downstream of the crystal is allowed to influence the rate. That structural fact, rather than the raw frequency, is what makes quartz timekeeping a different category rather than a better version of the same thing.

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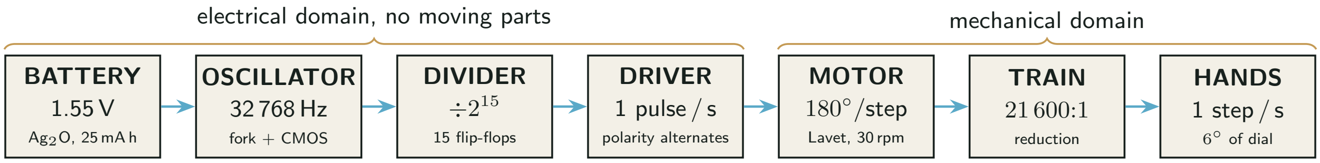

Figure 1: Seven stages. Everything left of the motor is electronics; everything right of it is a watch in the ordinary sense. Total draw is about 1.3 µA, of which the motor takes roughly 0.5 µA, about as much as all of the silicon put together.

1 The signal path

> **Power budget.** Oscillator 0.3 µA, divider and logic 0.5 µA, motor pulses 0.5 µA. From a 25 mA h silver-oxide cell that is roughly 19 000 h, or a little over two years. The cell's voltage stays nearly flat until it collapses, which is why a quartz watch keeps perfect time right up to the moment it stops.

2 The resonator

2.1 Why quartz is piezoelectric

α-quartz belongs to trigonal crystal class 32, which has no centre of symmetry. Strain displaces the Si^{4+} and O^{2-} sublattices by different amounts, so a deformed crystal carries a net dipole and therefore a surface charge. The converse effect is what drives the resonator: electrodes patterned along each tine apply a field that makes one face of the tine extend and the other contract, and a bar that lengthens on one face and shortens on the other bends. The same electrodes then read back the charge generated by that bending, which closes the feedback loop. The crystal is simultaneously the actuator and the sensor.

2.2 The flexural mode, and why antiphase matters

For a flexural tine the resonant frequency follows the cantilever result

$$f \approx \frac{\beta_1^2}{2\pi}\frac{t}{L^2}\sqrt{\frac{E}{12\rho}} \approx 0.162\,\frac{t}{L^2}\sqrt{\frac{E}{\rho}}, \qquad \beta_1 = 1.8751, \tag{1}$$

so frequency scales with tine thickness and with the *inverse square* of tine length. With $E \approx 78\,\mathrm{GPa}$ and $\rho = 2650\,\mathrm{kg/m^3}$, a tine roughly 2.4 mm long and 0.1 mm thick lands near 32 kHz. The forks are photolithographically etched to micron tolerances and then finished by laser: ablate gold from the tine tips and the frequency rises, deposit gold and it falls, a few parts per million per pass. The tips are chosen because the mode shape has maximum displacement there and therefore maximum mass sensitivity.

> **Why 32 768 and not 100 000.** It is 2^{15}, so fifteen halvings land exactly on 1 Hz using nothing but toggle flip-flops. It is also a sweet spot for power: CMOS dynamic power goes as CV^2f, so a higher-frequency crystal buys short-term stability at a linear cost in battery life.

3 The crystal as a circuit

To the electronics the fork looks like the Butterworth–Van Dyke network of Figure 3: a *motional* branch $L_1C_1R_1$ in parallel with C_0, the static capacitance of the electrodes and can.

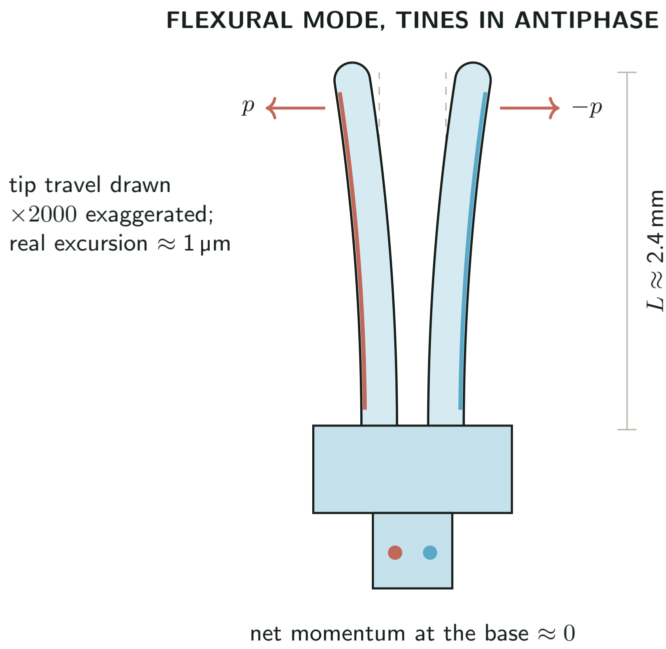

Figure 2: The two tines carry equal and opposite momentum, so the reaction forces cancel where the fork meets its mount. Almost nothing leaks out, which is why Q reaches 10^4 to 10^5. Drive the tines in phase instead and the base shakes, energy escapes, and the resonance collapses.

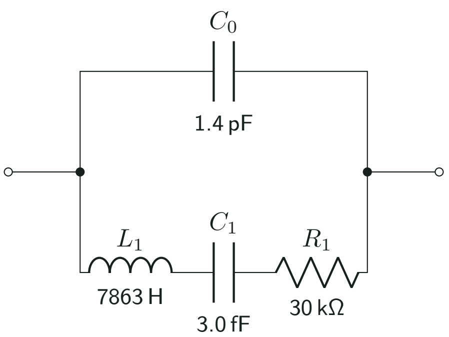

Figure 3: The Butterworth–Van Dyke equivalent circuit. L_1 is not an inductor: it is the *mass* of the vibrating tines expressed in electrical units, because a series LCR and a mass–spring–damper obey the same second-order equation. C_1 is the tine stiffness and R_1 is every loss mechanism added together. $Q = \omega L_1/R_1 \approx 54\,000$.

The network has two resonances, series and parallel,

$$f_s = \frac{1}{2\pi\sqrt{L_1C_1}}, \qquad f_p = f_s\sqrt{1+\frac{C_1}{C_0}} \approx f_s\left(1+\frac{C_1}{2C_0}\right), \tag{2}$$

and with a load capacitance C_L presented by the oscillator the operating point sits at

$$f_L = f_s\left(1+\frac{C_1}{2\left(C_0+C_L\right)}\right). \tag{3}$$

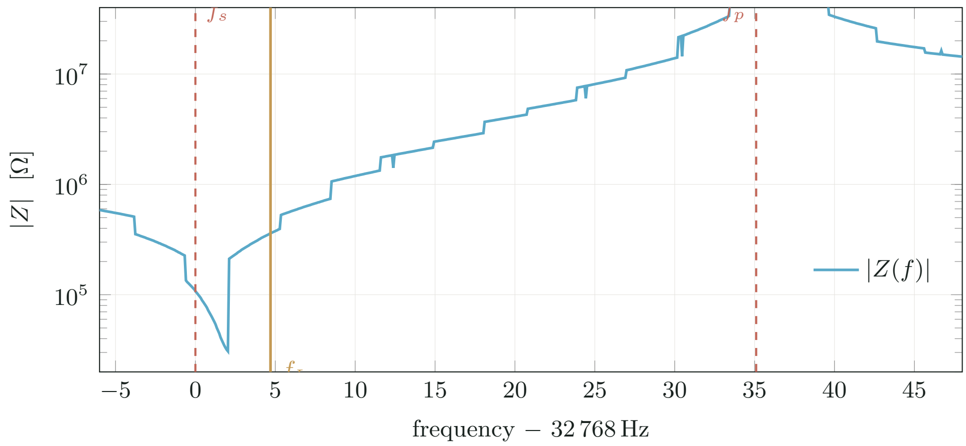

Figure 4: Impedance of the crystal against frequency. The deep minimum at f_s equals R_1; the sharp maximum at f_p sits about 35 Hz higher, roughly 1070 parts per million. The circuit can only pull the frequency inside that window, and in practice only across the small part of it selected by C_L.

The gap is the stability. Sliding C_L from 4 pF to 20 pF moves the operating point by roughly 200 ppm: about nine minutes a month of adjustment authority, and that is the *entire* regulation range of a quartz watch. Compare a balance wheel, whose rate moves with amplitude, position and mainspring torque. The crystal simply refuses to run anywhere else.

4 Sustaining the vibration

The tidiest way to see the circuit is that the inverter and its two capacitors present a *negative resistance* to the crystal,

$$R_{\text{neg}} = -\frac{g_m}{\omega^2 C_g C_d}, \tag{4}$$

and oscillation grows whenever $|R_{\text{neg}}| > R_1$. With $g_m = 1\,\mu\text{S}$ and $C_g = C_d = 12\,\text{pF}$ this is about $-164\,\text{k}\Omega$, a margin of roughly $5.5\times$ over R_1. Designers want three to five times and no more: excess margin wastes current and overdrives the fork.

Amplitude then grows from thermal noise as $e^{t/\tau}$ with

$$\tau = \frac{2L_1}{|R_{\text{neg}}| - R_1} \approx 0.12\,\text{s}, \tag{5}$$

so full amplitude arrives after roughly half a second. The same enormous L_1 that makes the fork stable makes it slow to wake: a high-Q resonator is a flywheel, hard to disturb and equally hard to spin up. Drive level matters at the other end of the scale, because overdrive causes non-linear bending, accelerated ageing and, in extreme cases, fracture at the tine roots. Watch crystals run at well under a microwatt.

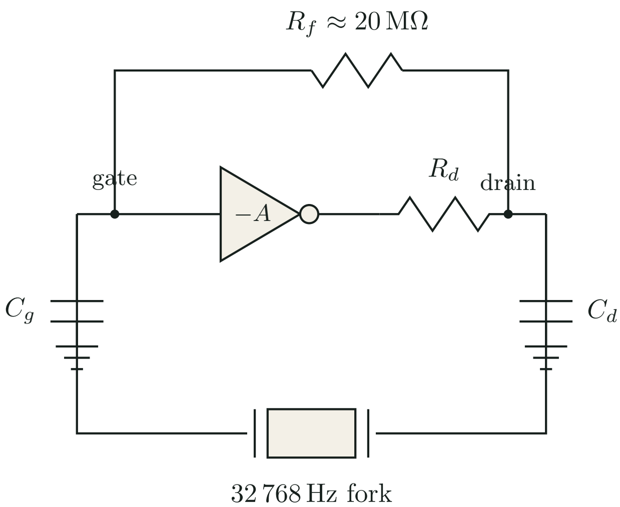

Figure 5: The CMOS Pierce oscillator. The inverter contributes 180° of phase shift and the π-network of C_g, the crystal and C_d contributes another 180°; with loop gain above unity the circuit has no choice but to oscillate. R_f biases the inverter into its own linear region, and R_d limits how hard the fork is driven.

5 Counting down

Fifteen toggle flip-flops, that is D flip-flops with the inverted output wired back to the input, each change state once per two input cycles:

$$32\,768\,\mathrm{Hz} \xrightarrow{\div 2} 16\,384 \xrightarrow{\div 2} 8192 \;\cdots\; \xrightarrow{\div 2} 2 \xrightarrow{\div 2} 1\,\mathrm{Hz}.$$

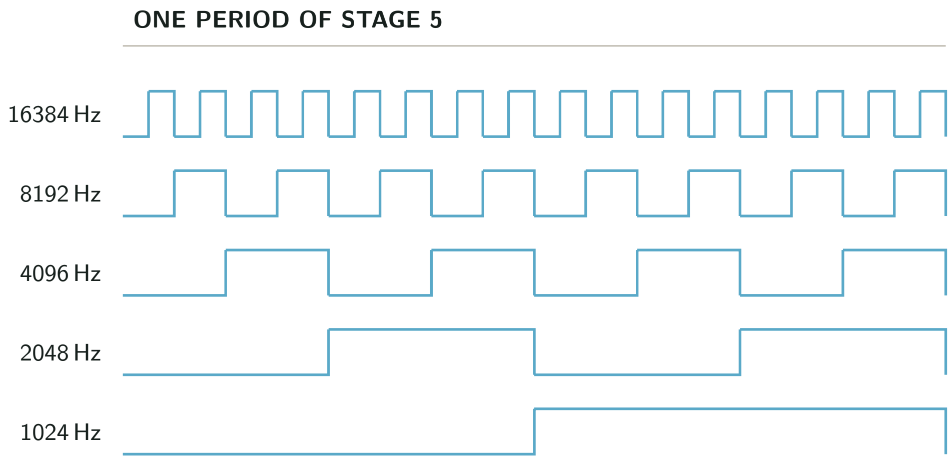

Figure 6: The first five stages of the divider over one period of the fifth. Every stage is a perfect 50 % square wave and the edges never drift relative to one another: division by two is exact in a way that no analogue process is, with no error term to accumulate.

Two practical notes. First, dynamic power is CV^2f per stage and f halves each time, so the whole chain costs about twice what stage one costs; designers shrink the first flip-flop and let the rest be lazy. Second, the motor does not want a 50 % duty cycle at 1 Hz. It wants a 4 ms to 8 ms kick, so the driver gates a fast stage (say 256 Hz) with the 1 Hz stage to cut a short pulse, then alternates its polarity every second.

6 The Lavet stepper motor

This is the most-manufactured electric motor in the world, and the only place in a quartz watch where anything is still allowed to be difficult. A bipolar permanent-magnet rotor about 1.4 mm across sits in a bore in a soft-iron stator; one coil of roughly 12 000 turns of 20 µm wire, about 2 kΩ, magnetises the stator.

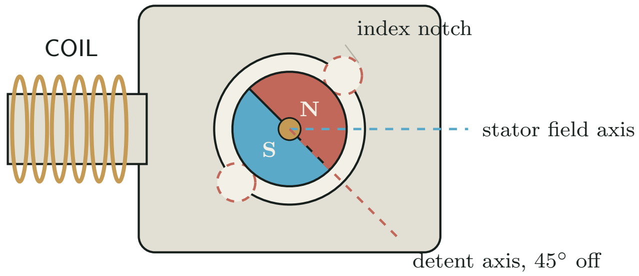

Figure 7: Cross-section. Two index notches in the bore saturate locally and rotate the rotor's rest orientation about 45° away from the stator field axis. Without them the rotor would rest exactly on the field axis, a pulse would produce zero starting torque, and the direction of rotation would be undefined: a dead centre.

6.1 Torque, and why the step succeeds

Take θ from the rest position, positive in the direction of travel. The detent (cogging) torque has period 180° because the rotor is bipolar; the coil torque pulls the rotor towards the field axis, which the notches have placed at $\theta = 135°$. Writing J for the rotor inertia and b for damping,

$$J\ddot{\theta} \;=\; \underbrace{-\,T_c \sin 2\theta}_{\text{detent}} \;+\; \underbrace{T_m \sin(135° - \theta)\, \Pi_{[0,t_p]}(t)}_{\text{coil pulse}} \;-\; b\dot{\theta}. \tag{6}$$

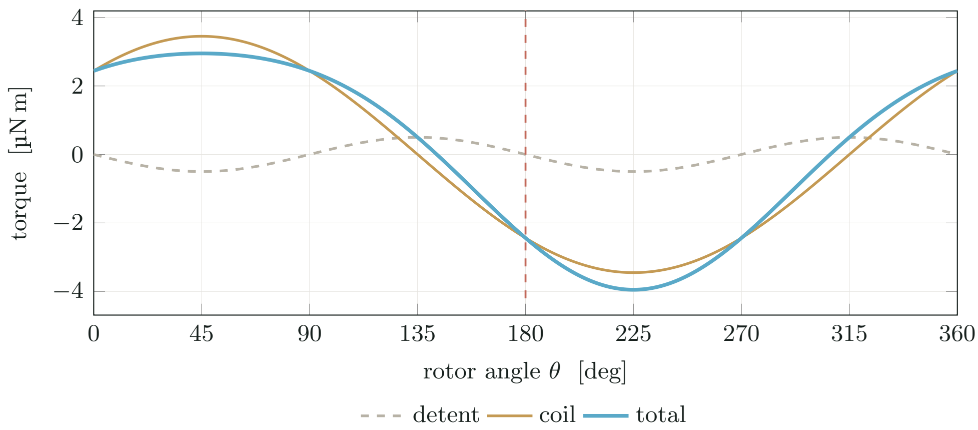

Figure 8: Torque against rotor angle during the pulse, with $T_c = 0.5\,\mu\mathrm{N\,m}$ and $T_m = 3.45\,\mu\mathrm{N\,m}$. The coil pushes the rotor the whole way past 90°; beyond that the detent torque itself changes sign and carries the rotor into the next stable position at 180°.

Integrating (6) with $J = 2 \times 10^{-12}\,\mathrm{kg\,m^2}$, $b = 2 \times 10^{-9}\,\mathrm{N\,m\,s}$, $t_p = 4.9\,\mathrm{ms}$ gives a step that completes in about 6 ms, overshoots slightly, and rings down into the detent well over the following 20 ms. The interesting behaviour is at the edges of the parameter space: shorten the pulse or weaken the drive and the rotor fails to clear the 90° barrier, falling back to where it started; overdrive it and the rotor overruns to 360° and the seconds hand jumps two.

Adaptive drive. Because the failure boundary is sharp, modern ICs cut the pulse short, then sense the rotor's own back-EMF to confirm it moved. If the step landed, the next pulse is trimmed shorter still; if it failed, a full-power correction pulse fires immediately. The motor therefore runs permanently a few percent above its own failure threshold, which is where the battery life comes from.

6.2 Why the polarity alternates

After one step the rotor has turned 180°, so the same field polarity would push it backwards. Reversing the pulse each second restores the geometry, and the bonus is zero net DC through the coil: no electrolytic corrosion and no progressive demagnetisation of the rotor.

Chopping the pulse gives the current budget. With the coil at $2\,\mathrm{k\Omega}$ across $1.55\,\mathrm{V}$ the peak is $775\,\mu\mathrm{A}$; at a $15\,\%$ chopper duty the mean during the pulse is $116\,\mu\mathrm{A}$, the energy per step is about $0.88\,\mu\mathrm{J}$, and the average contribution is $0.57\,\mu\mathrm{A}$.

7 The train, running backwards

A mechanical watch gears *up*, from a slow barrel to a fast escapement. A quartz watch gears *down*, from a fast rotor to slow hands. Same wheels, opposite errand.

Table 1: A representative reduction from rotor to hour hand. The overall ratio is $30 \times 60 \times 12 = 21\,600$ to one, and there is no escapement anywhere in the chain.

Wheel	Speed	Carries	Note
Rotor	30 rpm mean	—	half a turn per second
Intermediate	6 rpm	—	first reduction
Fourth wheel	1 rpm	seconds hand	6° per step
Third wheel	—	—	transmission
Centre / cannon	1 turn per hour	minute hand	
Hour wheel	1 turn per 12 hours	hour hand	motion work, 12:1

The visible signature is the tick. A quartz seconds hand advances 6° once a second because the rotor makes exactly half a turn per second and the train divides by sixty. The "sweep" of a mechanical watch is really 28 800 tiny steps an hour, also discrete, just below the threshold at which the eye separates them.

The structural point is deeper than the aesthetics. In a mechanical watch the train sits *inside* the timing loop: friction and torque variation reach the balance and change the rate. In a quartz watch the train is strictly downstream. Gum it up and the hands stop, but until they do they are never *late*. The loads involved are trivial, roughly a microjoule per second, so pivots need no jewelling for wear and wheels are often moulded polymer. The engineering difficulty moved upstream into the silicon.

8 What is left to go wrong

An XY-cut tuning fork has a parabolic frequency–temperature characteristic with its turnover near 25 °C:

$$\frac{\Delta f}{f} = -\beta\,(T - T_0)^2, \qquad \beta \approx 0.035\,\mathrm{ppm}/^\circ\mathrm{C}^2,\ T_0 \approx 25\,^\circ\mathrm{C}. \tag{7}$$

Note that the parabola opens *downward*, so every departure from the turnover makes the watch run slow. This is why ordinary quartz watches, as a class, lose rather than gain.

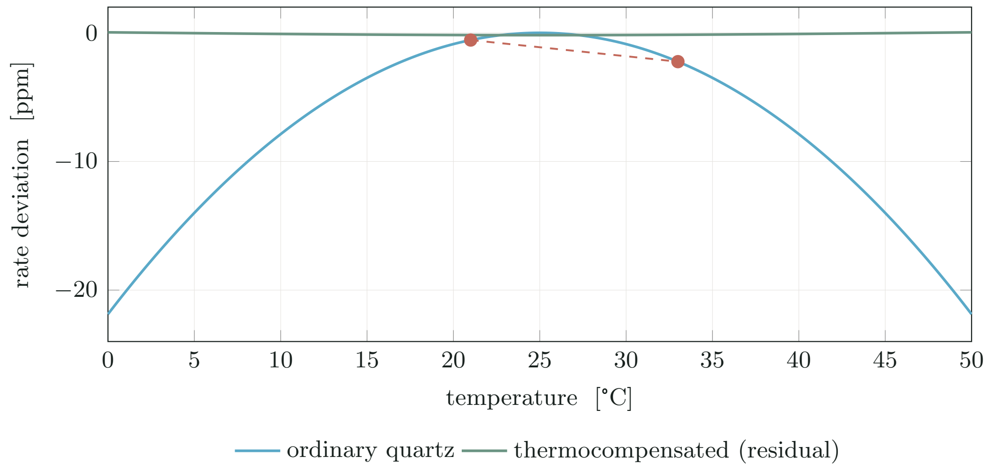

Figure 9: The whole error budget of an ordinary quartz watch, in one curve. The two marked points are a typical duty cycle, 14 h on a 33 °C wrist and 10 h on a 21 °C desk, which average to about −1.5 ppm, or −4 s a month.

8.1 Trimming by deletion

You cannot economically make a crystal that is exactly 32 768.000 Hz. Instead the crystal is deliberately left running slightly fast, and once a minute the IC *deletes* a small number of counted pulses. One pulse per minute out of 32768×60 is

$$\frac{1}{32768 \times 60} = 0.51\,\text{ppm} \approx 1.3\,\text{s/month}, \tag{8}$$

which is the adjustment resolution. Because the trim lives in the digital domain, the adjustment itself cannot drift.

Thermocompensated movements close the loop: a temperature sensor is sampled every ten to sixty seconds and the inhibition count is indexed to the measured temperature. The parabola is a known, stable, per-crystal curve, so it can be cancelled almost entirely. What remains is ageing, roughly 1 ppm to 2 ppm in the first year and less thereafter, caused by stress relaxation in the mount and mass transfer on the tines.

9 Two ways to divide a second

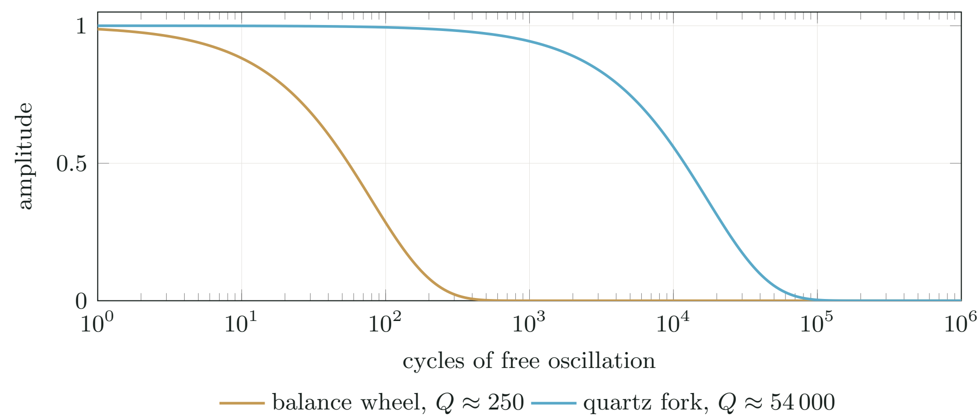

Figure 10: Free ring-down. Q counts the radians of oscillation a resonator keeps before losing $1/e$ of its energy, which is the same thing as how hard it is to talk out of its own frequency.

For a resonator perturbed by a phase error φ per cycle (friction, an off-centre impulse, a change in position) the fractional rate error scales as

$$\frac{\delta f}{f} \approx \frac{\varphi}{2Q}. \tag{9}$$

A quartz fork has roughly two hundred times the Q of a balance wheel, so it converts the same disturbance into two hundred times less error. Everything else in this document, the divider, the motor, the trim, is bookkeeping around that single fact.

Table 2: The comparison, end to end.

	Mechanical, chronometer	**Quartz, ordinary**	**Quartz, compensated**
Timebase	balance + hairspring	etched quartz fork	fork + temperature sensor
Frequency	4 Hz, 28 800 vph	32 768 Hz	32 768 Hz
Quality factor	200 to 300	5×10^4–10^5	5×10^4–10^5
Rate spec	$-4/+6$ s per day	±15 s per month	±10 s per year
Fractional	$\approx5\times10^{-5}$	$\approx6\times10^{-6}$	$\approx3\times10^{-7}$
Dominant error	position, amplitude, mainspring torque, temperature	the temperature parabola	crystal ageing
Regulation	hairspring length or balance inertia	trimmer capacitor or fixed inhibition	temperature-indexed inhibition
Energy	mainspring, ∼40 h, wrist-wound	25 mA h cell, 2–3 years	cell, 5–10 years
Train's role	inside the timing loop	downstream only	downstream only
Failure mode	drifts, then stops	keeps perfect time, then stops dead	keeps perfect time, then stops dead

Two hybrids

Seiko's Kinetic replaces the battery with a rotor-driven generator but keeps the quartz timebase. Spring Drive keeps the mainspring, barrel and gear train of a mechanical watch and deletes only the escapement, replacing it with an electromagnetically braked glide wheel that a quartz oscillator holds to exactly eight turns per second, which is why its seconds hand genuinely sweeps.

An escapement is an analogue negotiation: energy goes in, the balance answers with an interval, and every imperfection in the negotiation shows up as rate. A quartz watch removes the negotiation. The crystal decides the interval alone, in a domain where a divider can be exact and a trim can be an integer. What is left for the mechanism to do is to spend one pulse a second turning a magnet.