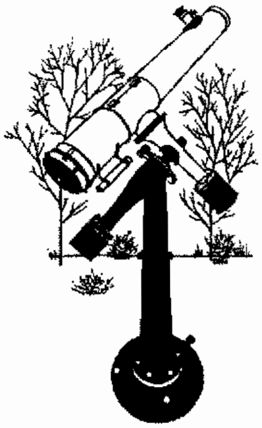


THE AMATEUR SCIENTIST

Scientific American. September 1974

A venerable clock is made highly accurate by equipping it with quartz-crystal works

Conducted by C. L. Stong

Technological advances have relegated pendulum clocks to the status of charming but unreliable antiques. One such instrument, however, has been modernized by its enthusiastic owner, Laurance M. Leeds (10232 El Dorado Drive, Sun City, Ariz. 85351). Leeds coupled his 80-year-old Seth Thomas wall clock to a quartz-crystal oscillator. The clock now ticks off the time to an accuracy of about one second per year.

"As a clock fancier," Leeds writes, "I have long enjoyed the operation of pendulum wall clocks. I have also often wished that I could somehow make one run with high accuracy. Eventually it occurred to me that perhaps I could synchronize the beat of the pendulum to a submultiple of the fixed frequency of a quartz-crystal oscillator. The experiment worked. Week after week the old pendulum now 'notches up' the 60th second of every minute in almost exact coincidence with the signals of radio station WWV, on which the National Bureau of Standards broadcasts accurate time and frequency data.

"For my Seth Thomas clock I designed the system of electronic synchronization to control the rate of the pendulum through any tendency it might develop to vary within a maximum range of about 30 seconds per day. In other words, the pendulum remains locked to a submultiple of the frequency of the crystal even though the clock experiences forces that would cause an uncontrolled pendulum to speed up or slow down by as much as 15 seconds per day. This hold-in-range capability is considerably more than adequate because without controls the clock kept time to within a few seconds per day for many years in spite of variations in temperature and barometric pressure and the degradation of the oil in the bearings of the clock.

"The heart of the timekeeping system is the quartz-crystal oscillator. The quality and the cost of this apparatus can vary widely. The devices are available commercially and can also be made at home.

"The best commercial oscillators have a short-term stability of better than .0001 second per day, or roughly one part in a billion. Their cost, however, may be beyond the reach of most amateurs. Moreover, to realize the full potential of the best oscillators the experimenter must have access to equally costly accessories for calibrating the crystal periodically. The performance of quartz crystals changes with age.

"Experimenters who are modestly well equipped to construct electronic devices can make relatively simple crystal oscillators by dispensing with precise temperature controls and the other refinements of the best oscillators. Although these simplifications reduce the timekeeping accuracy of the oscillator by several orders of magnitude, the resulting performance is still impressive. For example, a quartz crystal of the 'AT-Cut' family that has been ground to vibrate at a selected frequency of from one to five megahertz will, when it has been properly compensated by a tuning capacitor of negative temperature coefficient, maintain an accuracy of one part in 10 million through a temperature variation of 15 degrees Fahrenheit. (Incidentally, experimenters who rely on the transmissions of WWV as the calibration standard must bear in mind that a single calibration cannot be assumed to be better than one or two parts in 10 million. The station's signals reach most receivers after one or more reflections from the ionosphere, which is rarely at rest. The Doppler shift and vagaries in electromagnetic propagation therefore degrade the accuracy randomly.)

"I made my oscillator with a crystal bought from the International Crystal Manufacturing Company (10 North Lee, Oklahoma City, Okla. 73102). When I ordered the crystal, I specified the frequency and mode of its operation, the value of the tuning capacitance and the type of holder in which the crystal was to be mounted. I also informed the manufacturer that the crystal was for a horological application in which a minimum variation in frequency was essential; that the operation was to be at room temperature within the limits of 20 and 28.5 degrees Celsius; that within this range the frequency must not increase with temperature, and that the rate at which the frequency changed within the specified range of temperature must be within limits sufficiently narrow to be nullified by the use of a Type N750 capacitor for a portion of the tuning capacitance. The N750 is a special ceramic capacitor that has a negative coefficient of temperature of about 750 × 10^{-6} per degree Celsius [*see top illustration on page 194*].

"Before making an exact measurement of the temperature characteristic of the crystal I operated it continuously in an oscillator circuit for a period in excess of three months. I find that this 'aging' is necessary for the short-term stability of the crystal to settle down to a few parts in 100 million. After this procedure I put the crystal and its oscillator circuit in a housing fitted with controls for maintaining any desired temperature within the specified range of operation.

"The influence of temperature on the rate at which the crystal vibrated was then measured and tabulated as I altered the proportion of Type N750 capacitance in the tuning capacitor. Proper temperature compensation requires the accuracy of these measurements to be one or two parts per 100 million. The measurements are made by beating the unknown frequency against a secondary-standard crystal oscillator of known stability. Piano tuners employ the same principle when they beat the sound emitted by a string against that of a tuning fork.

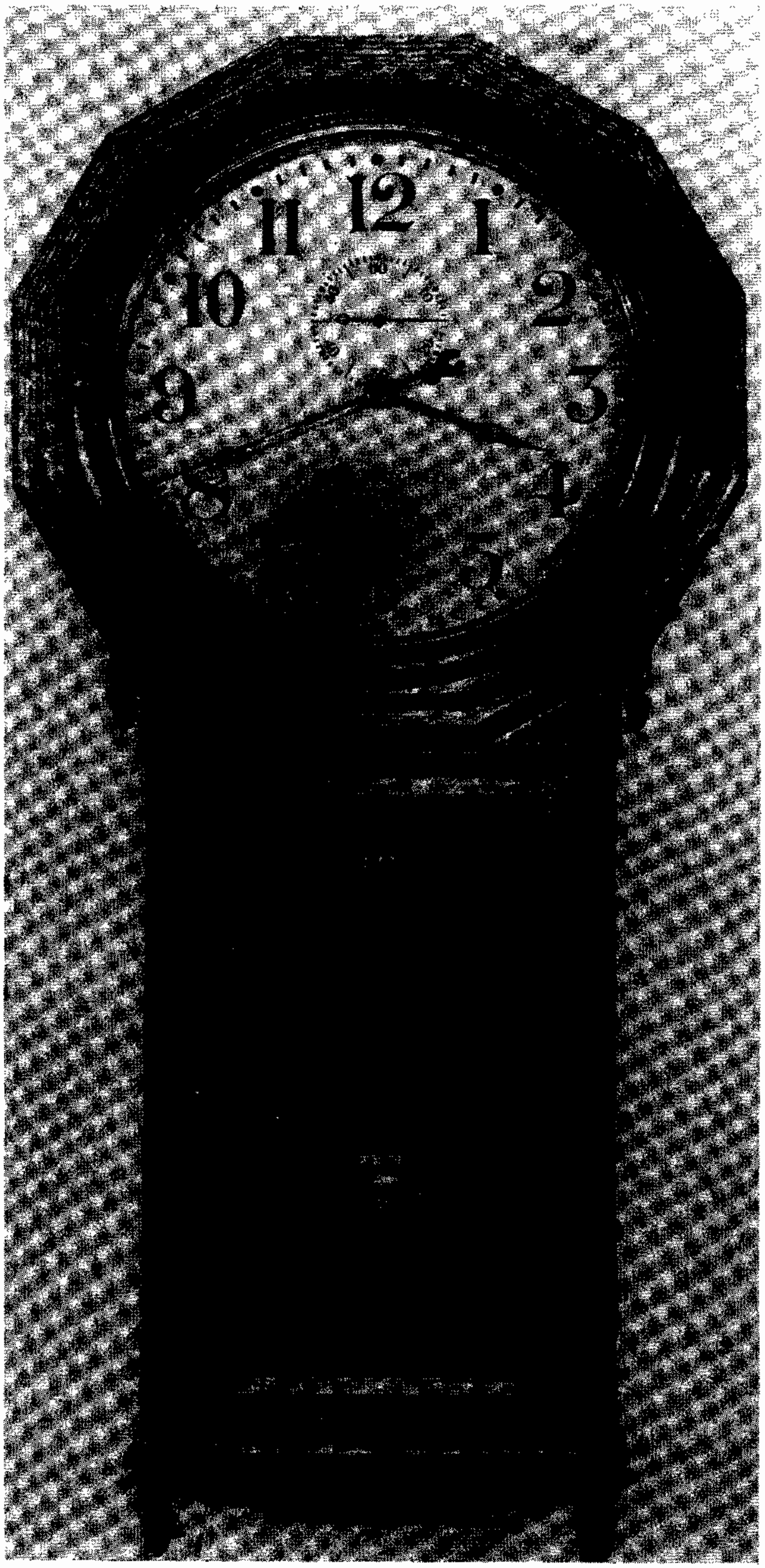
"From graphs of the tabulated measurements it is simple to determine the proportion of the tuning capacitance that should consist of negative-coefficient capacitance to achieve optimum stability through the specified range of temperature. In designing with series and parallel combinations of capacitors that have zero and negative temperature coefficients the capacitor with the negative temperature coefficient can be regarded as having the formula $N(1 - 750 \times 10^{-6}/°C) = N(1 - D)$. For example, it will be found that a capacitor of 10 picofarads (negative temperature coefficient) connected in series with one of 10 picofarads (zero temperature coefficient) performs as though the combination were a single five-picofarad capacitor with a negative temperature coefficient of $D/2$.

"The frequency of the alternating current generated by the oscillator is divided by a digital counting circuit. The resulting quotient has the form of direct-current pulses at a frequency that corresponds to the precise period of the pendulum clock when it is keeping exact time. These low-frequency pulses of current energize a solenoid that is rigidly mounted inside the case of the clock adjacent to one limit of the pendulum's swing. The solenoid develops pulses of magnetism that correspond to the pulses of current.

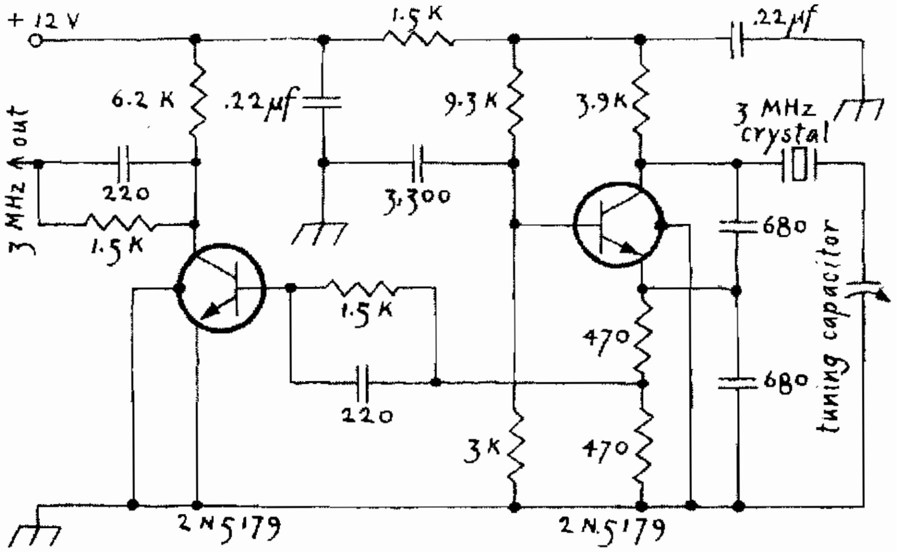
"The magnetic pulses periodically interact with the field of a small permanent magnet that projects from a slender rod mounted on the pendulum. The magnet was made with pieces of barium ferrite cut from the plastic-housed magnet of a cabinet latch. The correct direction of current in the coil to attract the magnet to its center was determined by suspending the magnet partway into the solenoid by a thread, applying current and observing the movement of the magnet. The electrically generated pulses of mechanical force speed up the clock just enough to compensate for the intrinsic slow rate to which the pendulum was adjusted and for unavoidable variations of rate caused by changes in temperature or pressure.

"The choice of the frequency of the oscillator and the details of the digital counting circuit depend on the rate at which the pendulum is designed to swing. My Seth Thomas was designed to beat 72 times per minute when keeping exact time. (The horologist's beat corresponds to the number of a pendulum's half-periods.) I selected a crystal that was ground to oscillate at three megahertz, or 180 million vibrations per minute. To obtain 36 pulses per minute, a rate that corresponds to the period of the pendulum, divide 180 million by five million.

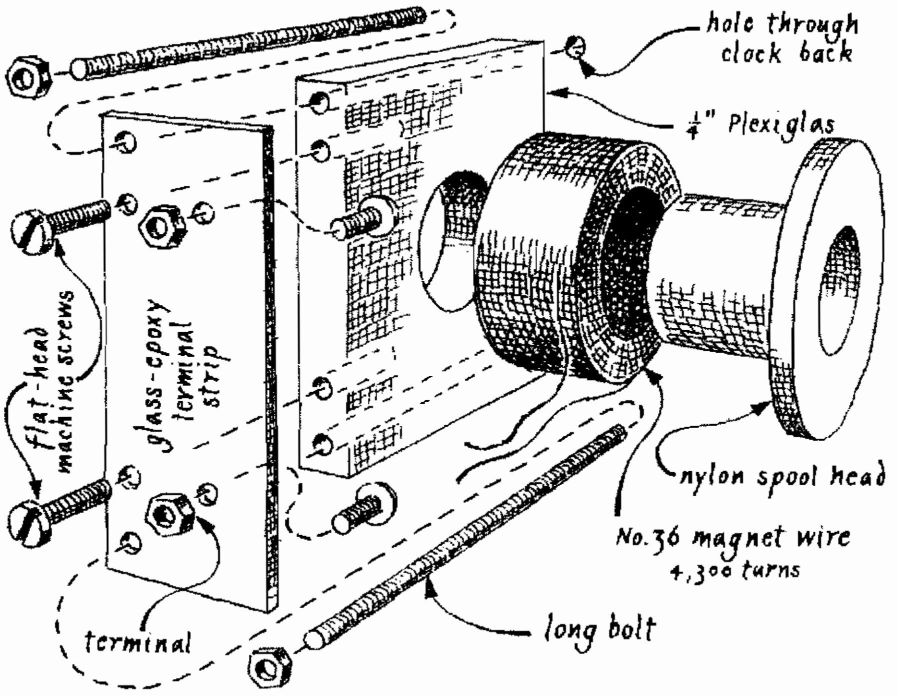
"To make the division I selected the relatively new family of complementary-symmetry metal oxide semiconductor (COS/MOS) devices. This choice was dictated primarily by the low power con-



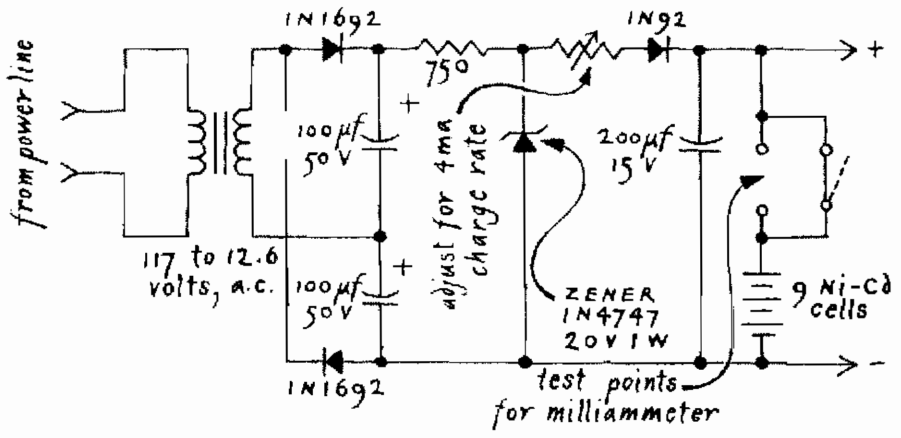
Wall clock, of Seth Thomas manufacture, modified by Laurance M. Leeds



Circuitry of the quartz-crystal oscillator



Details of the solenoid assembly



Circuitry of the power supply

sumption of the devices at low switching speeds. In my circuits the power required by the devices is in microwatts.

"The cos/mos circuit enables the clock to operate for more than 100 hours on a storage battery of nine nickel-cadmium cells. The capacity of the battery is 750 milliampere-hours. The cells are kept on a continuous trickle charge of about four milliamperes. This scheme makes the system immune to occasional power-line interruptions. An interruption of even a fraction of a second would disorganize the operation of the digital counting circuit. For this reason I regard the battery as being essential.

"A feature of my circuit is a manual switching scheme that enables me to change the divisor from five million to either 5,000,256 or 4,999,744 and thus retard or advance the clock as desired. The shift in rate, which I refer to as 'precession,' amounts to about 4.4 seconds per day. If after a month or so of unattended operation I observe that the clock does not indicate the beginning of the 60th second of each minute in exact coincidence with the time signal of WWV but is, say, a fraction of a second fast or slow, I flip the switches to alter the rate as necessary. After the error has been corrected I restore the divisor to five million. Precession has no effect on the rate at which the crystal vibrates. It merely alters the frequency of the magnetic pulses.

"Except for attaching the solenoid to the case and adding the small magnet to the pendulum, I made no significant changes in the mechanism of the clock. The driving weight continues to operate the hands through the unaltered train of gears and to supply some of the driving energy to the pendulum through the Graham deadbeat escapement. The maximum arc through which the pendulum can swing is limited to the angle at which the pallets of the escapement mechanism make contact with the roots of the teeth of the escapement wheel. In my clock the maximum swing is limited to about 3½ degrees of semiarc. A minimum semiarc of one degree is required for the pallets to sequentially release the teeth of the escapement wheel. Hence the synchronization scheme must be effective within a total excursion of not more than 2½ degrees of semiarc.

"The natural period of a pendulum is fixed primarily by its effective length and by the restoring force that results from gravitation. The effective length is determined by the distribution of the several masses of the pendulum with respect to the point from which the assembly swings. This length cannot be readily altered to change the period and thus synchronize the pendulum to the oscillator. The restoring force can, however, be increased easily by combining magnetic attraction with gravitation. The addition to gravitation of any force that tends to restore the pendulum to dead center will increase the beat, whether the added force is continuous or impulsive or whether it acts with or against the motion of the pendulum. In my arrangement pulses of magnetic attraction, which act on the pendulum tangentially between the solenoid and the magnet, are applied for .028 second once during each period.

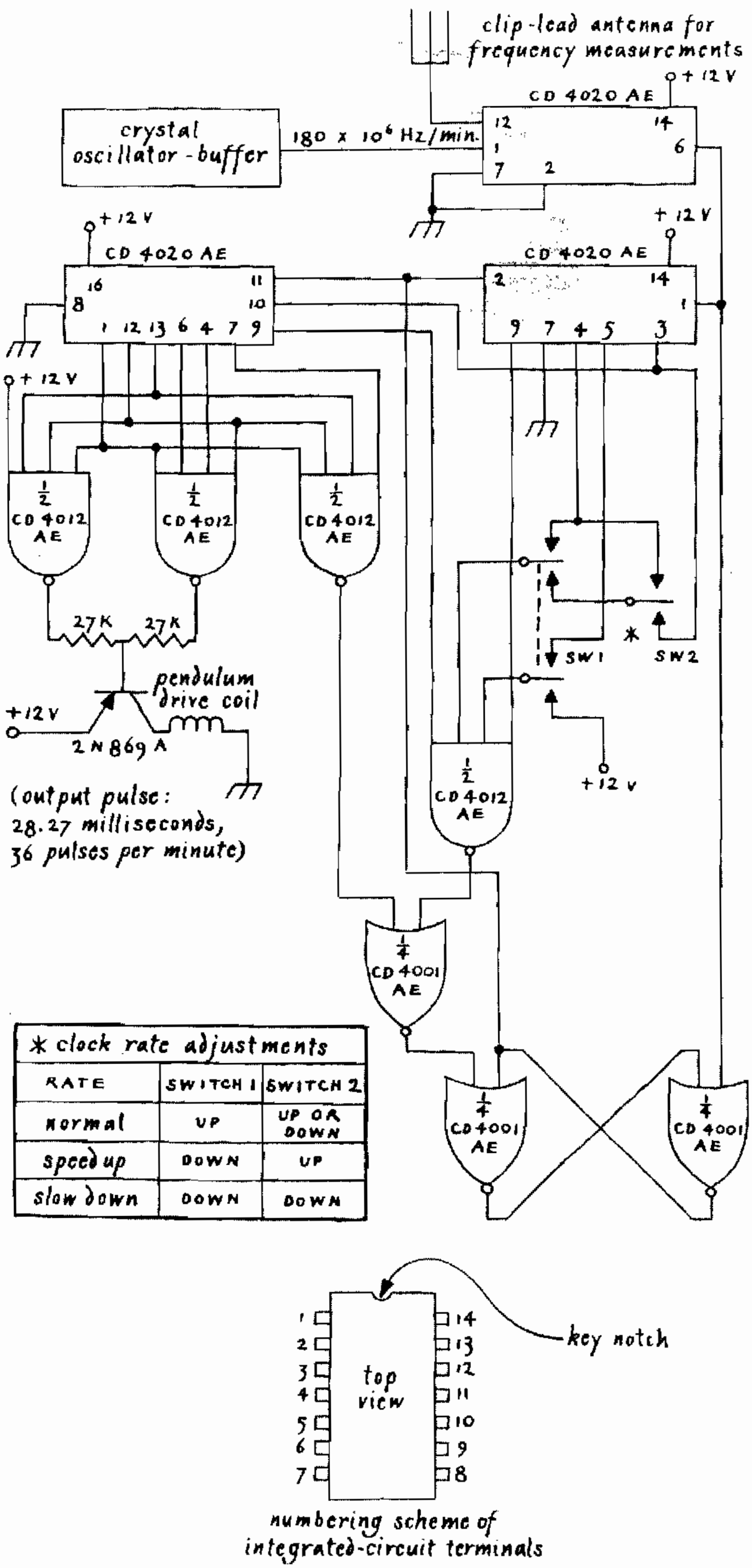
"The pulses begin as the pendulum approaches one limit of its excursion and continue through the initial portion of its departure in the opposite direction. During the interval of the pulse the position of the magnet is always beyond the magnetic center of the solenoid. For this reason the force of the entire pulse tends to speed up the clock. The intrinsic rate of the pendulum is preset slow by approximately half of the hold-in-range.

"Pendulums that traverse a circular arc, as is usually the case, have a period that increases slightly with increases in the length of the arc. This effect is known to horologists as circular error. In my clock the length of the arc changes somewhat less than 2¼ degrees, depending on variations of interaction of the solenoid and the magnet. The variations compensate for random forces that would otherwise cause the clock to fall out of step with the oscillator. It turns out that the circular error of a few seconds per day induced by this variation in arc augments the system's hold-in-range.

"I make no claim that the system is the best one that could be devised. It works. The clock has not lost synchrony during the two years it has been following the crystal.

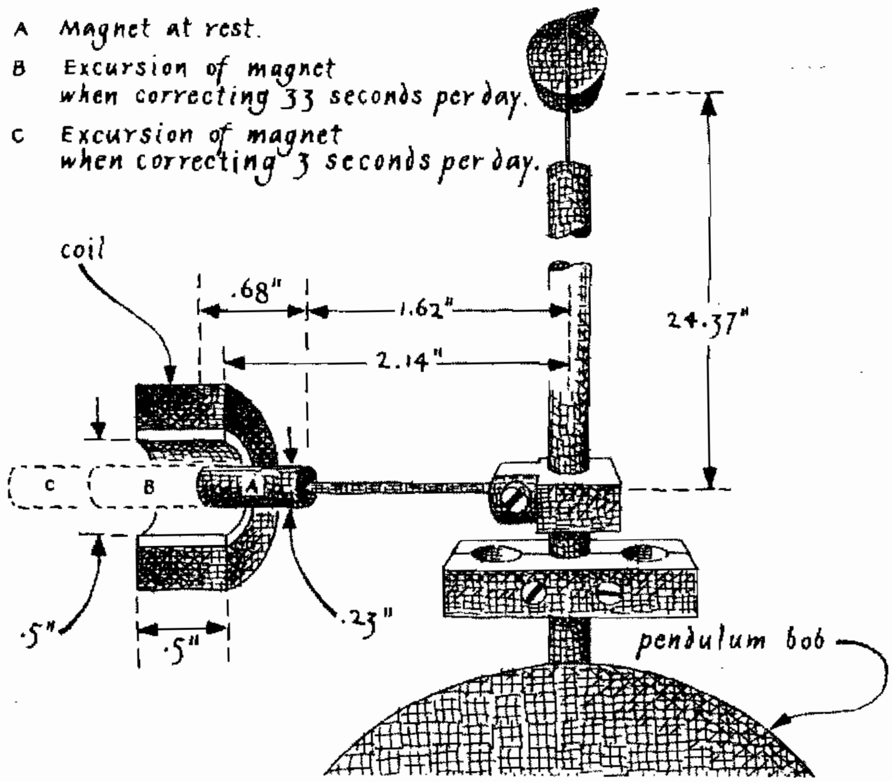
"A theory of operation that seems to explain the system's ability to converge to stable synchronization, with a very tight phase lock, has been formulated. An important aspect of the interaction is the relative phase of the pulse and the pendulum in the vicinity of one limit of the pendulum's excursion. This is the region where the pendulum slows to a stop and reverses its direction.

"Consider the duration of the pulse to consist of three contiguous parts [*see bottom illustration on next page*]. Assume that the clock is operating synchronously with the oscillator at about the center of the hold-in-range. The pulse begins as the pendulum approaches the limit of its excursion on the left side. The first part of the pulse is the

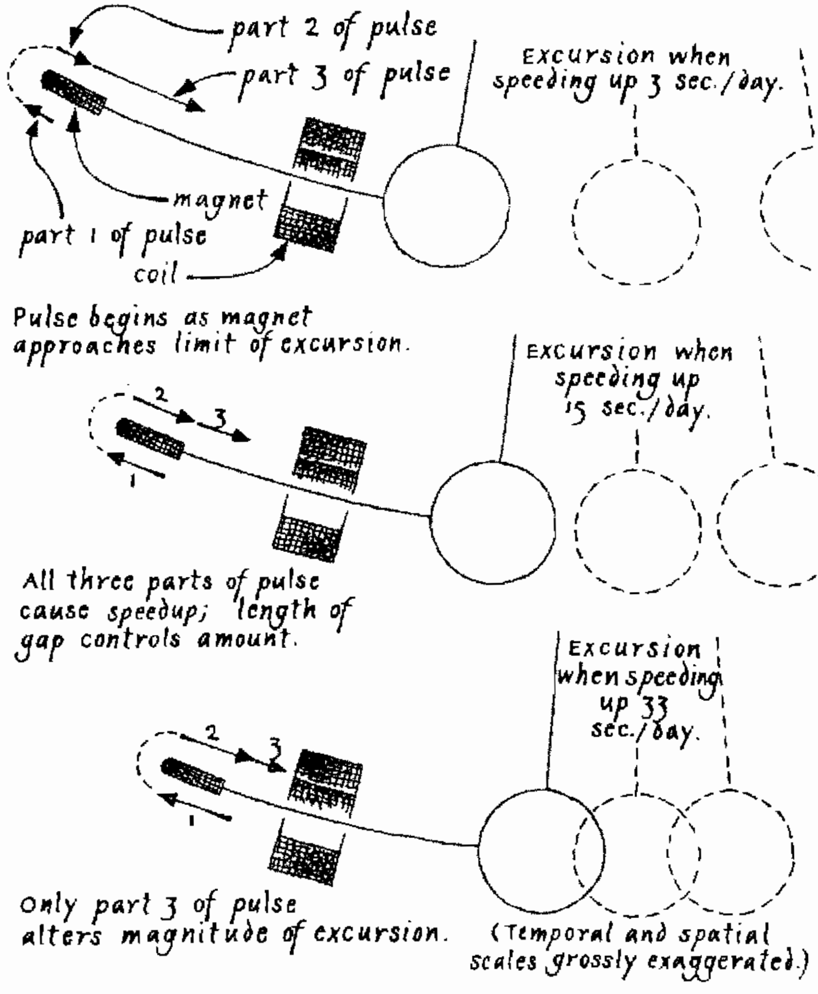


* clock rate adjustments		
RATE	SWITCH 1	SWITCH 2
normal	UP	UP OR DOWN
speed up	DOWN	UP
slow down	DOWN	DOWN

Arrangement of the digital counting circuit



Details of the pendulum assembly



Representation of the synchronizing forces

portion that extends from the onset to the instant when the pendulum comes to rest.

"The first part of the pulse would typically span about nine milliseconds. The second part begins at the instant the pendulum begins to move on its return beat and always persists for exactly the same interval as the first part. The third part is the remainder of the pulse, about 10 milliseconds. In the illustration the heads of the arrows indicate the direction of the pendulum's motion; the shafts of the arrows depict increments of the pulse. The total force of all three parts causes the pendulum to speed up, but only the third part tends to increase the length of the arc because, with respect to the arc, the forces of the first and second parts cancel.

"Assume now that the absolute phase between the pulse and the pendulum is such that the first and second parts constitute most of the pulse. The third part is therefore small and the arc will be only slightly longer than it would be if the clock were powered by its driving weight alone. Because of the reduced arc the magnet is comparatively closer to the magnetic center of the solenoid when the pulse occurs and the relative speedup force of the total pulse will be large. That is the phase in which substantially maximum speedup is being imparted to the system. Conversely, when the phase is such that the third part is relatively large, the arc is also large, as is the distance between the magnet and the solenoid. Hence the pulse exerts a lesser tendency to speed up the pendulum, which, as I have mentioned, is deliberately adjusted to run slow.

"As an example of how the system converges to stable synchronization assume that the rate is near normal at the center of the hold-in-range and that some random force of external origin tends to speed up the clock. The pendulum would respond by arriving earlier at the limits of its excursion. Hence the magnet would be closer to the limit at the beginning of the pulse.

"The first and second parts of the pulse would be shorter than normal and the third part would be extended. This part would tend to increase the arc and therefore the distance between the magnet and the solenoid, thereby reducing the tendency of the electronic system to speed up the clock. That is precisely the action required to offset the increase in the intrinsic rate.

"Conversely, if forces of external origin tend to retard the clock, the pendulum and the magnet approach the limits of their excursion somewhat behind

RCA CD4024AE 7-STAGE COUNTER

PIN NUMBER	FUNCTION
1	CLOCK INPUT
2	RESET
3	Q7
4	Q6
5	Q5
6	Q4
7	GROUND
8	BLANK
9	Q3
10	BLANK
11	Q2
12	Q1
13	BLANK
14	VDD (+12 v)

RCA CD4020AE 14-STAGE COUNTER

PIN NUMBER	FUNCTION
1	Q12
2	Q13
3	Q14
4	Q6
5	Q5
6	Q7
7	Q4
8	GROUND
9	Q1
10	CLOCK INPUT
11	RESET
12	Q9
13	Q8
14	Q10
15	Q11
16	VDD (+12 v)

RCA CD4001AE QUAD 2-INPUT NOR

PIN NUMBER	FUNCTION
1	INPUT, GATE 1
2	INPUT, GATE 1
3	OUTPUT, GATE 1
4	OUTPUT, GATE 2
5	INPUT, GATE 2
6	INPUT, GATE 2
7	GROUND
8	INPUT, GATE 3
9	INPUT, GATE 3
10	OUTPUT, GATE 3
11	OUTPUT, GATE 4
12	INPUT, GATE 4
13	INPUT, GATE 4
14	VDD (+12 v)

RCA CD4012 DUAL 4-INPUT NAND

PIN NUMBER	FUNCTION
1	OUTPUT, GATE 1
2	INPUT, GATE 1
3	INPUT, GATE 1
4	INPUT, GATE 1
5	INPUT, GATE 1
6	BLANK
7	GROUND
8	BLANK
9	INPUT, GATE 2
10	INPUT, GATE 2
11	INPUT, GATE 2
12	INPUT, GATE 2
13	OUTPUT, GATE 2
14	VDD (+12 v)

DIVISOR EXPRESSED IN BINARY NOTATION

DIVISOR	Q12 ↓ … Q1 ↓	Q7 ↓ … Q1 ↓	Q4 ↓ … Q1 ↓	SWITCH POSITION
5,000,000 =	1 0 0 1 1 0 0 0 1 0 0 1	0 1 1 0 1 0 0	0 0 0 0	NORMAL
5,000,256 =	1 0 0 1 1 0 0 0 1 0 0 1	1 0 0 0 1 0 0	0 0 0 0	SLOW DOWN
4,999,744 =	1 0 0 1 1 0 0 0 1 0 0 1	0 1 0 0 1 0 0	0 0 0 0	SPEED UP
	(CD4020AE)	(CD4024AE)	(CD4024AE)	

(ON COUNTING TO THE DIVISOR, THE CIRCUIT GENERATES AN OUTPUT PULSE AND RESETS TO 0.)

Layout of pins and circuit-division scheme

schedule. The first and second parts then persist through a longer interval, with a corresponding decrease in the duration of the third part. The arc decays. This result reduces the distance between the solenoid and the magnet and initiates the additional force required to speed up the pendulum. Thus the phase relation between the pulse and the pendulum causes the system to converge automatically to stable synchronization.

"The relative phase of the pendulum with respect to the pulse does not change by more than half the duration of the pulse, or 14 milliseconds. If the frequency of the oscillator is assumed to be constant and the system alters the intrinsic rate of the pendulum by 30 seconds per day, the indication of the clock does not actually depart from the exact time, as generated by the oscillator, by more than 10 or 12 milliseconds.

"In terms of feedback the scheme of synchronization is an open loop. Hence the pendulum does not automatically fall in step with the oscillator. To coax the two into the phase relation at which the pendulum pulls into synchrony I clip a pair of headphones, in series with a 100,000-ohm resistor, across the terminals of the solenoid. The pulses are heard as distinct clicks. I then pull the pendulum to one side and try to release it so that the click is heard just as the pendulum arrives at the left extreme of its excursion. The knack of initiating the swing correctly comes with practice. The magnet must pass to the left through the magnetic center of the solenoid before the click is heard. If this condition is satisfied, the system will pull into synchrony within an hour or so.

"During this interval it may be necessary to control the magnitude of the arc manually. I do so by judiciously stroking the bottom tip of the pendulum in the desired direction with a small camel's-hair brush. The need for this control stems directly from the theory. The beat spans 833⅓ milliseconds, whereas the pulse lasts for only 28 milliseconds. The probability of starting the pendulum by hand so that the relatively narrow pulse straddles the point in time at which the pendulum reverses its direction is exceedingly remote.

"Assume that all the pulse occurs prior to the arrival of the pendulum. The full pulse acts to reduce the arc, but an inordinate speedup of the pendulum is required before the pulse can straddle the point at which the pendulum reverses its direction. By automatically reducing the arc, however, the system indicates to the experimenter that the needed correction is pendulum speedup, which occurs when the arc is at a minimum and the distance between the magnet and the solenoid is small. Hence the experimenter should stroke the pendulum with the brush only enough to prevent the arc from falling below, say, 1½ degrees. Eventually the pendulum will be speeded up enough to lock into synchrony at the desired phase.

"Conversely, if the pulse occurs after the pendulum has departed from the extreme of its excursion, the arc will tend to become excessive. Use the brush to prevent the arc from exceeding a safe value. I have installed a stop in my clock that limits the arc to about 3½ degrees, so that no damage is done to the escapement. This synchronizing procedure presupposes that the amplitude of the pulse is reasonably adequate, but that may be unknown at the outset.

"The required amplitude of the pulse depends on several factors, such as the geometry of the system and the strength of the magnet. The amplitude must be determined experimentally and adjusted to a value that is compatible with the characteristics of the pendulum and its escapement. I proceeded as follows.

"During synchronized operation the maximum arc coincides with the minimum pendulum speedup (a correction of about three seconds per day). Hence, as the first step in determining the optimum pulse amplitude, I adjusted the intrinsic rate of the clock to be slow by three seconds per day. I then synchronized the pendulum. Next I increased the amplitude of the pulse gradually during a period of several hours until the pendulum reached a steady-state arc of maximum allowable excursion.

"With the arc so established, I determined the hold-in-range by adjusting the pendulum to swing at progressively lower intrinsic rates, resynchronizing and noting the resulting arc after it had settled into the steady state. In my clock pulses of the desired amplitude result in a semiarc of three degrees when the system is correcting at the rate of three seconds per day. The semiarc reduces to 2⅜ degrees when the system is correcting 15 seconds per day and 1¾ degrees when the correction is 33 seconds per day. The lower limit of 1¼ degrees was dictated by the fact that the driving weight acting alone causes an arc of about 1⅜ degrees.

"The clock selected for this project should demonstrate, when it is under mechanical operation, a stability or rate adequate for synchronized service. It should have a deadbeat escapement, and the second hand should make one revolution per minute. (Many European wall clocks have second hands that make one revolution in 45 seconds.)

"People who do this project but who have not worked with COS/MOS devices should keep in mind the very low power requirements of the apparatus. Since the devices operate on microwatts or less, they can be destroyed by an electrostatic discharge from the experimenter's finger. Keep them packed in their conductive plastic cases or conductive foam until they are used. Ground your body when you handle them. Avoid touching the terminals. Build the circuits with sockets that fit the devices. Switch the power off before putting the devices in the sockets or removing them.

"The terminal pins are numbered sequentially in the counterclockwise direction as viewed from the top, beginning at the notch or the equivalent mark at one end of the dual-in-line package. The accompanying table [*preceding page*] lists the terminal layout, according to function, of the CD4020AE and CD4024AE devices. All COS/MOS devices and compatible sockets are available from distributors such as KA Electronic Sales (1220 Majesty Drive, Dallas, Tex. 75247).

"One can also modify a pendulum clock that runs at a rate of 60 or 80 beats per minute. Make or obtain a quartz-crystal oscillator of appropriate frequency and synchronize the clock to it. On receipt of a stamped, self-addressed envelope I shall send circuit diagrams for generating the required pulses of current."

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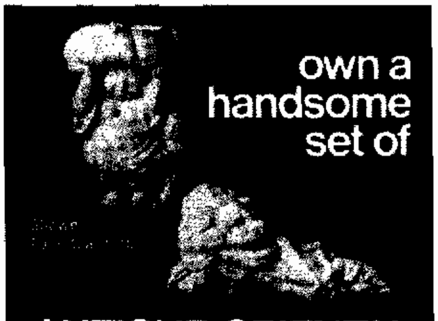

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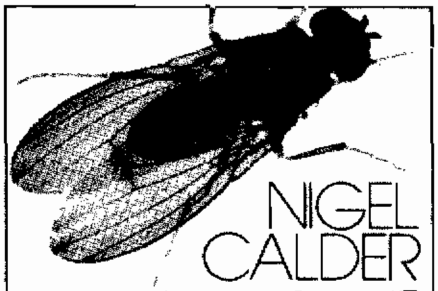

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