THE AMATEUR SCIENTIST

Apparatus to demonstrate the Coriolis force, and how to make a kymograph out of a tin can

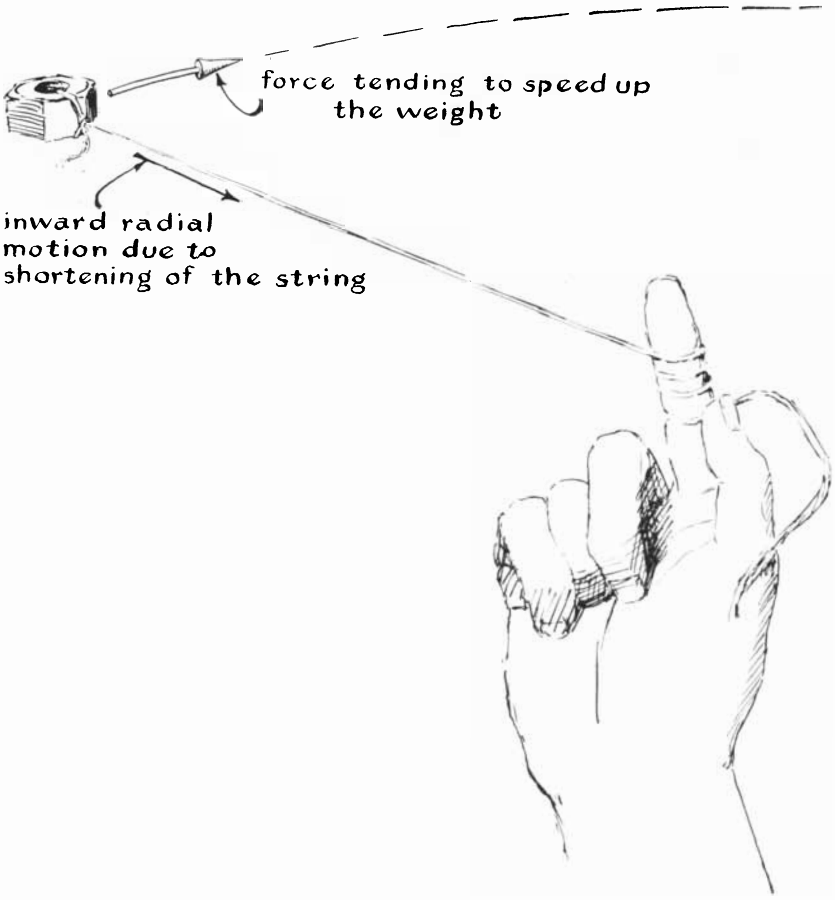
Conducted by C. L. Stong

There was a time not long ago when an amateur who had a keen interest in the physical sciences, and who liked to make things, almost always turned to physical apparatus that has a specific purpose—a telescope, say, or a short-wave transmitter and receiver. Today, with the frontiers of the physical sciences more than ever beyond the reach of the amateur, there is a new trend: the making of apparatus the sole purpose of which is to illuminate a fundamental physical principle. By the construction of such apparatus the amateur can enrich his understanding of, to choose only one example, the motions of an artificial satellite. In this vein Francis W. Niedenfuhr, associate professor of engineering mechanics at Ohio State University, writes:

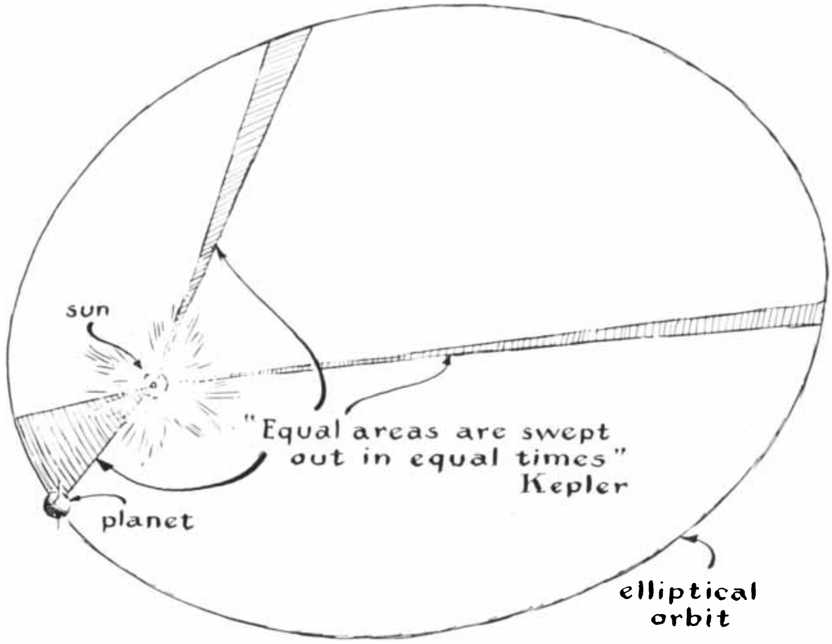
"As an engineering scientist I am always interested in finding seemingly different phenomena that are governed by a single elementary law. When a simple law of physics is well understood in a familiar situation, its application to a new situation is made easier. Moreover, when we understand the application of a law to a variety of situations, we can say that we begin to understand the law itself.

"Some months ago there was a discussion in your department of the speeding-up of an artificial earth-satellite as the radius of its orbit decreases ["The Amateur Scientist"; January, 1958, and April, 1958]. The situation can be visualized as follows. Consider the curious gait of the ticket collector on a moving merry-go-round. The fellow is not drunk; he walks that way because he is responding to a rather complex situation of relative motion. The horses near the outside of the merry-go-round have a greater velocity than those near the inside. When the ticket collector moves from the outer horses toward the inner ones, he takes some of the velocity of the outer horses with him; as he takes each step it appears to him that the floor of the merry-go-round is moving backward. Moreover, the mass of the merry-go-round, which is considerably greater than his own, slows him down and tends to throw him off balance. To be sure, the man also slightly speeds up the merry-go-round. If he weighed much more and the merry-go-round much less, the primary effect would be to speed up the merry-go-round rather than to slow him down. In any case we can observe a relative acceleration arising from the interaction of the radial velocity of the man and the rotational velocity of the platform. Formal mathematical analysis yields the same result, and we find that the acceleration is equal to twice the radial velocity multiplied by the angular velocity.

"The effect can be demonstrated by a primitive experiment that all of us have made at one time or another. Swing a small weight in a circular orbit at the end of a string, and let the string wind up on your finger as depicted in the accompanying illustration [*below*]. The result is always the same. As the length of the string decreases, the speed of the weight increases. It is a law of nature. The string may be likened to a nearly massless merry-go-round, and the weight to a very heavy ticket collector. The



A simple demonstration of the Coriolis force



A representation of Kepler's law

weight has a radial velocity toward your finger because of the shortening of the string. The radial velocity interacts with the rotational velocity to produce an acceleration that is tangential to the path of the weight and thus acts to speed up the weight. Students of Newton's laws recall that 'force equals mass times acceleration,' so that it is permissible to think of a force that causes the weight to speed up. The result is quite general. When a body in rotational motion also moves in a radial direction, a force acts to speed up the body if the radial motion is toward the center of rotation (or to slow down the body if the radial motion is away from the center). This force is called the Coriolis force in honor of Gaspard Gustave de Coriolis, a French engineer and mathematician of the early 19th century. Both the speeding-up and the slowing-down effects can be observed with the weight-on-the-string experiment, speeding up as the string winds up on the finger and slowing down as the string unwinds.

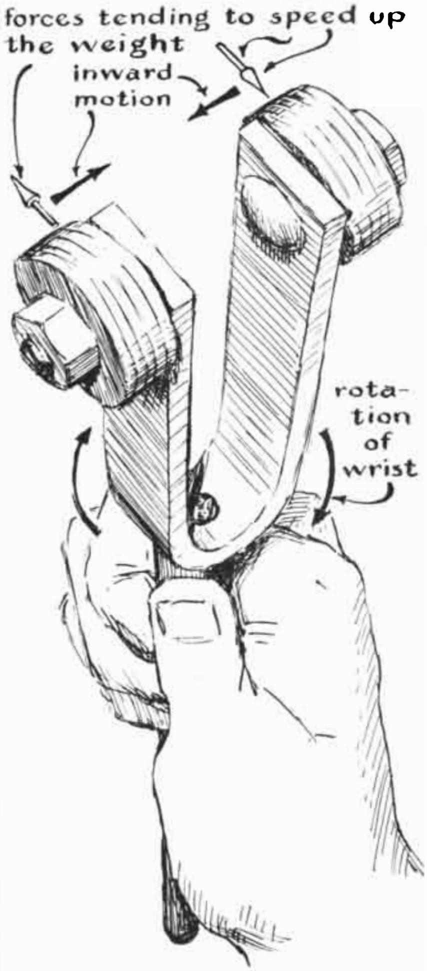
"So much for fingers, strings and weights. In the case of an artificial satellite the string is replaced by the force of gravity. When the orbit of the satellite dips closer to the earth so that the radius of curvature of its path decreases, the satellite must speed up. This effect, when observed in celestial bodies, is usually explained in terms of Kepler's law, which states that the straight line joining a planet to the sun sweeps out equal areas in any two equal intervals of time [*see illustration above*].

"The Coriolis force operates in many earth-bound ways, not the least interesting of which is the 'gyrotron.' This device is simply a tuning fork that is made to rotate on its long axis as its tines vibrate at right angles to the axis [*see illustration on page 186*]. As the weighted tines move toward the center of rotation, the Coriolis force acts to speed up the rotation of the fork in perfect analogy with the weight on a string. As the tines move away from the center of rotation, the force reverses and so acts to slow down the rotation. The effect here is just the same as the one we observed with the weight on a string, except that in this case the law gives rise to an alternating torque: a torque because the changing force tends to twist the tuning fork on its axis; alternating because the force changes with the oscillation of the tines. The tines of a tuning fork pitched at middle C oscillate 256 times per second. In consequence the alternating torque also oscillates 256 times per second.

"An important property of this alternating torque is that it grows in magnitude in direct proportion to the rate of rotation of the tuning fork. This means that if a way could be found to measure the magnitude of the torque, we would have an instrument sensitive to rates of rotation, just as a gyroscope is. This instrument would have a number of advantages over the gyroscope: it would have no continuously spinning parts or complex gimbal rings (hence nothing to wear out), and it would not need an erecting system. The puzzle of how to measure the alternating torque has been solved. One of the effects of the alternating torque is to twist the shaft or shank of the tuning fork and thus to set up a torsional vibration there. This vibration strains the material of which the shank is made, and the strain can be measured very accurately by electrical strain-gauges.

"Incidentally, electrical strain-gauges are interesting in their own right. They consist essentially of fine wires glued to the surface of the shaft. As the shaft is strained, the wires are stretched a minute amount that alters their electrical resistance in proportion. The change of resistance controls the voltage output of a constant-current power-supply. The effect can be displayed by a voltmeter calibrated to measure the strain.

"A model of the gyrotron which demonstrates the effect in terms of sound is easy to make. A conventional tuning fork of the type sold by music shops is mounted on a wooden base by means of a heavy metal bar [*see illustration on page 188*]. A lever attached to the shank



Tuning-fork demonstration of Coriolis force

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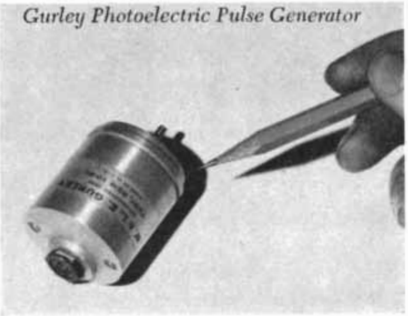

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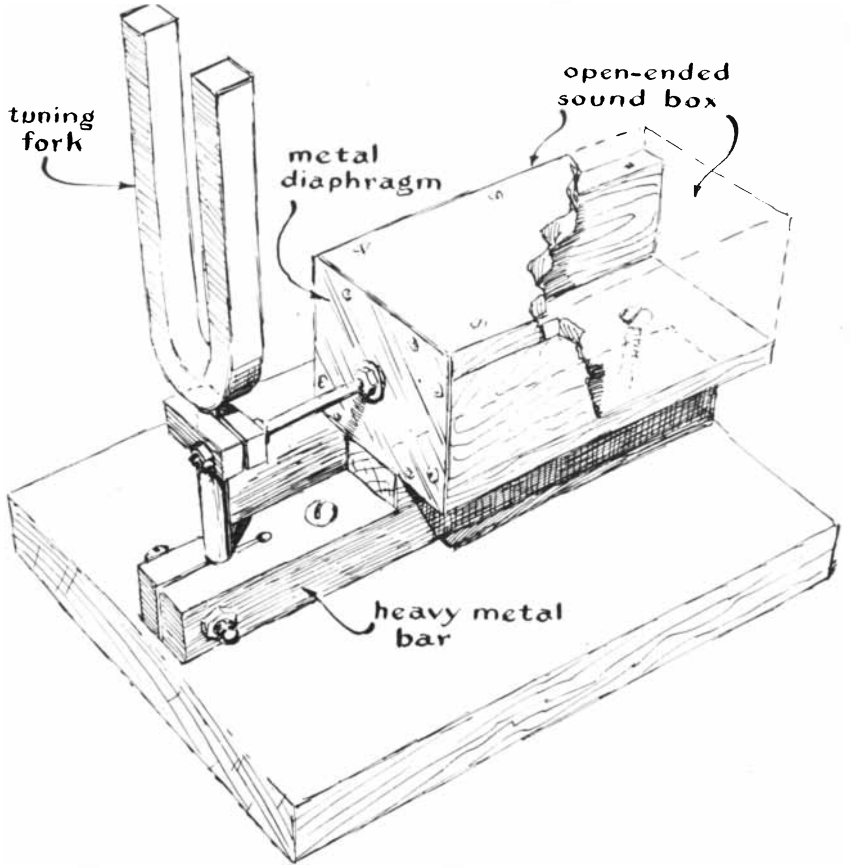
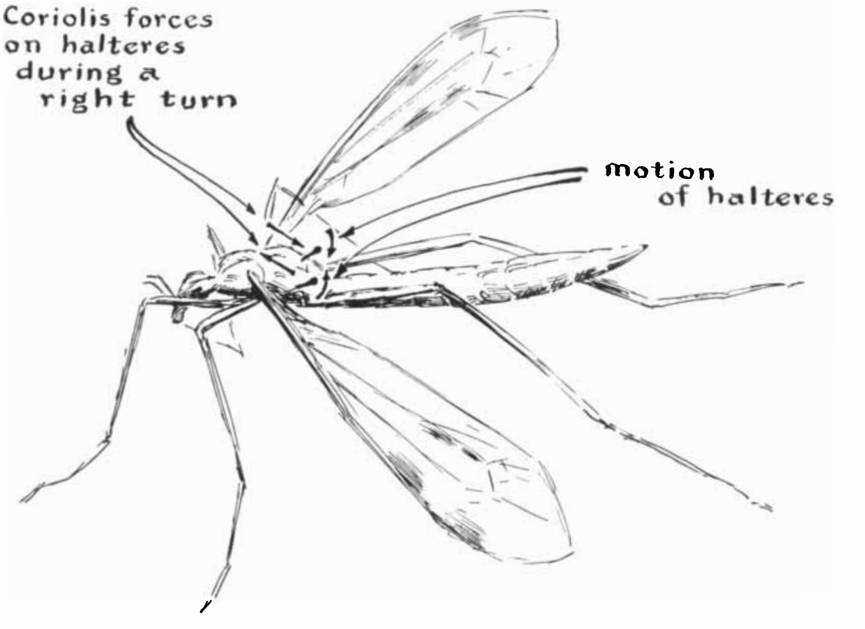


Gyrotron apparatus for sensing rate of turn

where it joins the fork communicates vibration through a steel rod to the closed end of a box. This end acts as an oscillating diaphragm. The opposite end is open. The box can therefore operate as a cavity resonator, just as an organ pipe does. If the tines of the fork are set in motion and the whole apparatus is turned about its vertical axis, the Coriolis force will set the upper end of the shank into torsional vibration. (The bottom end is restrained by the heavy metal bar.) It will be found that the volume of sound emitted by the cavity varies according to the rate at which the apparatus is turned. The best results will be obtained when the respective parts of the apparatus are tuned to the same frequency, that is, when the tines of the fork, the torsional vibration of the shank and the resonator all respond to the same pitch. These responses can be calculated, but beginners will have more fun if they cut and try until the best result is achieved. When this happy state is reached, the gyrotron will give forth a satisfying 'oowah' when given a turn.

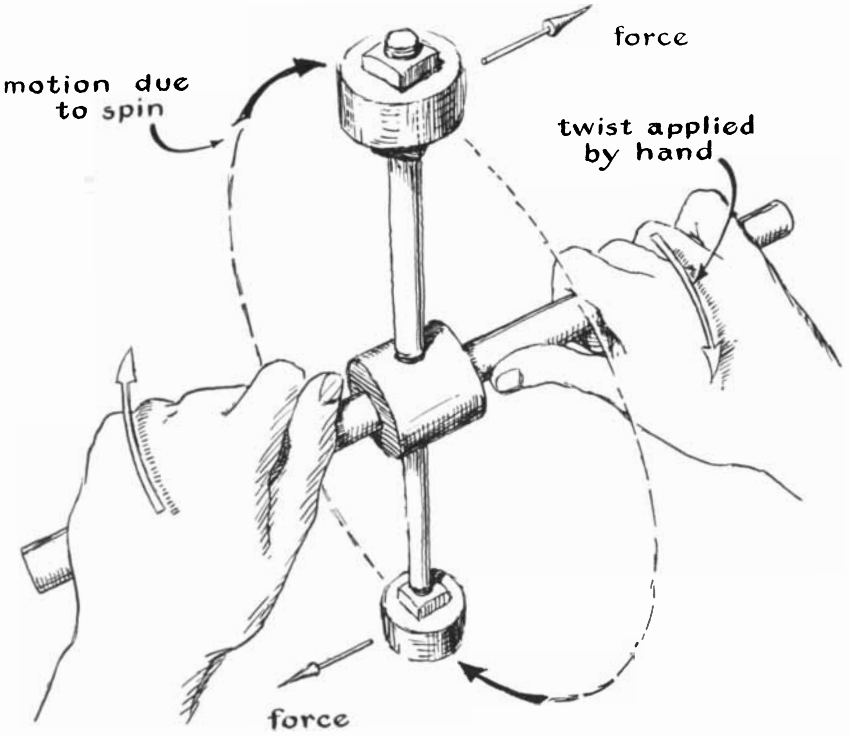
"Long before I had heard of the gyrotron, J. W. S. Pringle published in *Philosophical Transactions of the Royal Society* (Series B, 1948) a most interesting paper entitled: 'The Gyroscopic Mechanism of the Halteres of Diptera.' (Diptera are insects that have two wings.) This proved to be a discussion of the mechanism that informs the insect of changes in its flight path. All the two-winged insects, including the housefly and the mosquito, have instead of an extra pair of wings (most insects have four wings) a pair of small, club-shaped organs called halteres (singular: halter). As the insect flies about, it moves the halteres up and down in much the same way as it beats its wings. Upon making a turn, the halteres exert an alternating torque on the body of the insect. The forces and motions at one instant of a right turn are indicated by the arrows in the accompanying illustration [*top of page 190*]. Pringle's work showed conclusively that the halteres act as a 'rate of turn' sensor. The torques generated by the halteres are picked up by nerve endings at the base of each halter, transformed into an electrochemical signal and transmitted to the insect's brain. This nerve impulse tells the insect not only that it is turning but also how fast. When the halteres are removed, the insect cannot control its flight.

"The halteres can best be seen on

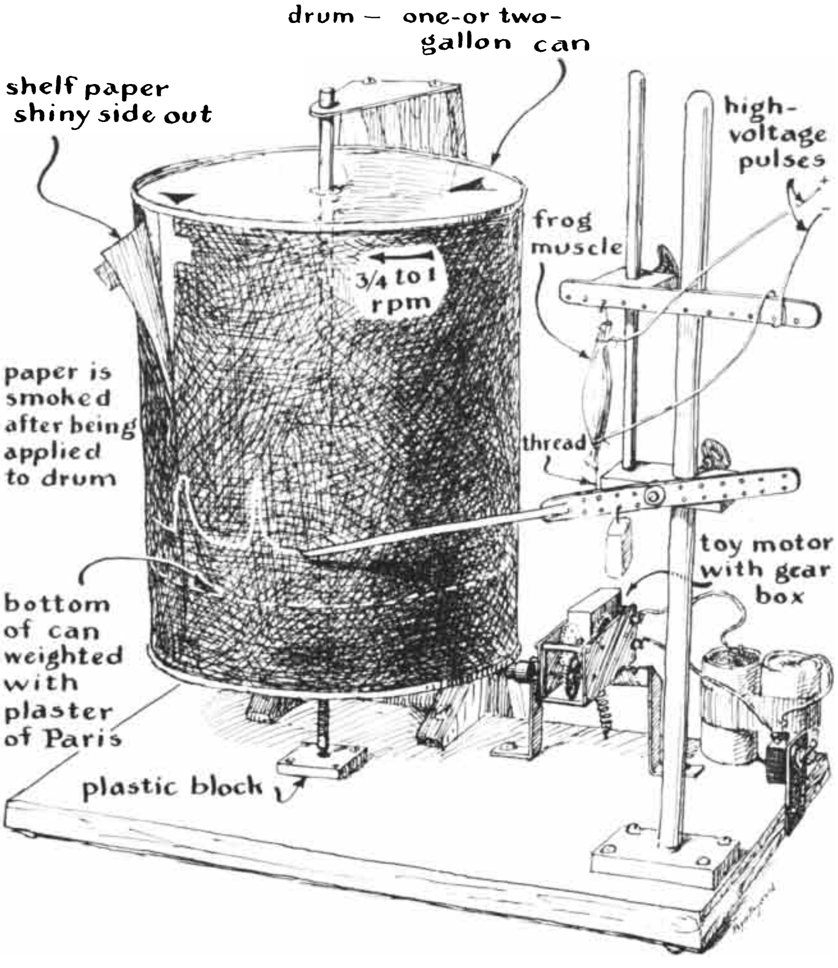


How a mosquito applies the principle of the gyrotron

some of the large species of Diptera. The crane fly is easy to catch in the garden on a late-summer day because he is a large fellow, measuring an inch or more in length. His halteres are nearly a quarter of an inch long and clearly visible to the unaided eye. If he is not pinched too vigorously when he is caught, he will oblige the amateur observer by alternately shaking and resting his halteres, thereby giving a splendid exhibition of how they operate. A mosquito is built in much the same way, but of course on a smaller scale. The observer thus needs a light touch to capture one without damaging it, and a hand glass to see the halteres in action. The housefly is easier to catch, but harder to observe. Its halteres are hidden away from the slipstream in a cavity between its thorax and its abdomen, and are protected by a pair of tiny plates called squamae. The



A simple gyroscope for demonstrating a basic law of dynamics



The tin-can kymograph set up to record the contractions of a frog muscle

squamae are located just behind the wings and cover the joint between the thorax and the abdomen. The plates must be lifted to see the halteres, and again a good magnifying glass will be needed.

"Since it is so well established that the halteres of the two-winged insects act as a turn-rate sensing device, it would be interesting to know whether the four-winged insects use their wings for the same purpose. The dynamic forces exerted on a wing are the same as those on a halter; all that is necessary is a nervous system adapted to pick up the signal. Perhaps amateurs who enjoy experiments in both mechanics and zoology will wish to explore this problem.

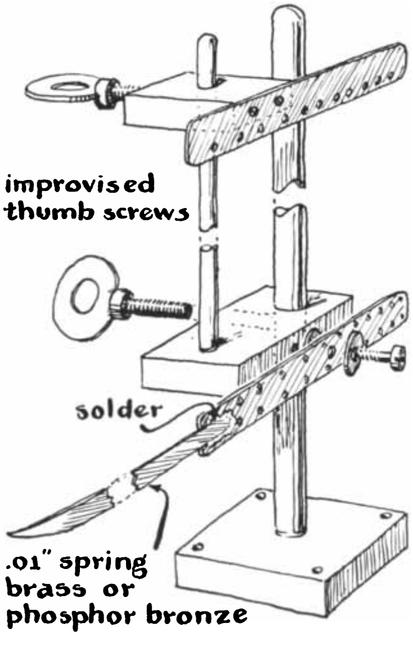
"I have mentioned gyroscopes. The combination of linear motion and turning motion in this apparatus gives rise, as always, to the Coriolis force. In the case of the gyroscope the linear motion is found in the spinning mass. Being unidirectional, this action produces a continuous—not alternating—set of Coriolis forces. A steady torque is accordingly generated by rotating the gyroscope as shown in the accompanying illustration [*bottom of page 190*]. In this gyro the mass is shown as a pair of weights corresponding to the tines of a tuning fork or the halteres of a fly. The conventional gyro uses a wheel, of course, rather than a pair of weights. The effect of the Coriolis force acting on a wheel can be obtained by adding up the effects of such forces on the elementary parts of the wheel. This is a mathematical problem called integration that I have discussed in 'The Amateur Scientist' [August, 1958]. When the necessary mathematical steps are taken, the whole set of phenomena called gyroscopic action is readily explained."

On one occasion or another most experimenters and science teachers have need for a recording apparatus that can automatically plot the movement of a pen or a stylus against time. They usually find some alternative, because the price of commercial recorders begins at $100 and has a fast rate of climb. Norman D. Weis, an instructor at Casper College in Casper, Wyo., was confronted

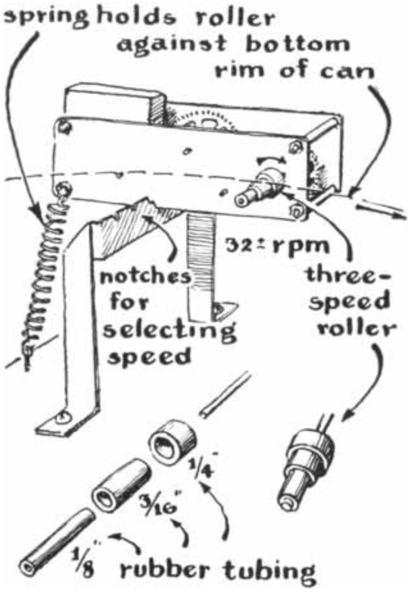
by the problem last year while he was doing graduate work at the University of Colorado, and he decided to meet it head-on. He calls the result the tin-can kymograph. Basically Weis's instrument consists of a motor-driven drum mounted vertically on a thrust bearing and fitted with a sheet of smoked paper on which the graph is traced by a mechanically actuated stylus.

"The cost of this apparatus," writes Weis, "will vary from nothing to as much as $10, depending upon the builder's talents for adapting and scrounging. The secret of the low cost is found in the method of driving the drum that transports the record sheet. Instead of coupling a motor to the axle of the drum by means of gears, as is done in conventional designs, my drum is driven at its edge by frictional contact with an extension of the motor shaft. Moreover, when the apparatus is used to chart the respiration of a human subject, the stylus is actuated by a length of thread anchored by a book instead of the expensive chest-expansion tube and tambour-needle assembly familiar to students of biology. The original model of my apparatus, which is depicted in the accompanying illustration [*page 192*], is currently employed at Casper High School.

"The stylus assembly can be moved up and down the drum as desired, thus providing for several recordings on one sheet of paper. The number of recordings per sheet is limited only by the amplitude of the stylus excursions. Although normally actuated by a mechanical link in biological observations, the stylus may be coupled to any desired sensing device and driven pneumatically, electrically or otherwise.

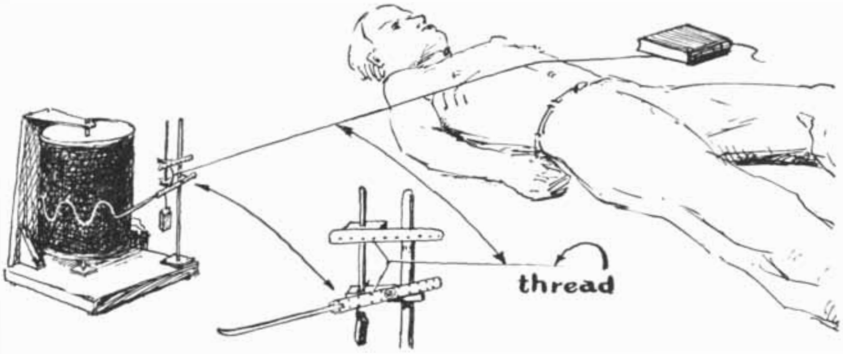


Detail of stylus for kymograph



Detail of drive for kymograph

"A gallon can of the kind used for shipping fruit juice or syrup serves as the drum. The can is weighted with about an inch of plaster of Paris. An accurately centered hole 1/4 inch in diameter is drilled through the top and bottom. One or more additional small holes in the top equalize the air pressure inside the can with that of the atmosphere. The drum turns on a shaft made of 1/4-inch drill rod, or other straight material, inserted through the centered holes of the can and soldered in place. The ends of the shaft extend beyond the can two inches at the top and 1½ inches at the bottom. The bottom of the shaft should be cut square and smoothed with a fine stone. The drum assembly is supported by a thrust bearing: a piece of plastic 1/2 inch thick drilled with a centered hole 3/8 inch deep. A steel ball 1/4 inch in diameter is placed in the bottom of the hole. The shaft turns on this ball. The upper end of the shaft is supported laterally by a simple journal-bearing: a hole through a piece of 16-gauge sheet metal screwed to a solidly braced column of plywood. The base to which the column, thrust bearing and other components are screwed, is a piece of plywood 3/4 inch thick, 12 inches wide and 16 inches long, finished with shellac. It rests on four rubber buttons of the kind used on the bottom of chair legs. The drum assembly is removed from the instrument simply by lifting it from the thrust bearing, swinging the



How the kymograph is used to chart respiration

shaft to one side and sliding it out of the upper bearing.

"Any small motor will serve for the drive, but construction is simplified by using a motor with built-in reduction gears. Mine was taken from a mechanical toy that operated from a two-cell battery. Similar motors are sold by hobby shops and toy stores for use with model-construction kits. The drive shaft should turn at a rate of about 30 revolutions per minute. The shaft is fitted with a series of frictional rollers of increasing diameter. These are made of rubber tubing; a relatively long piece that makes a snug fit with the shaft is first pushed over the shaft. Progressively shorter lengths of increasing diameter are then telescoped over the first length. My rollers were made from three sizes of tubing: 1/8, 3/16 and 1/4 inch, as shown in the accompanying illustration [*top of page 194*].

"The active components of the stylus assembly include the stylus and its supporting lever arm together with a secondary fixture that is electrically insulated from the remainder of the apparatus [*bottom illustration on page 194*]. These parts are supported by a movable block that rides on and clamps to a vertical post attached to the base by a flange. The post may be made of drill rod 3/8 inch in diameter. Any handy material, such as steel or plastic, may be used for the block. The lever arm of the stylus assembly is drilled in the middle and mounted on the block by a screw and washers. It must turn freely. The edges of the lever arm are drilled with holes 3/32 inch in diameter spaced at 1/4-inch intervals. These make it possible to balance the stylus by hooking a small weight to the bottom of the arm, and to attach specimens or apparatus to the top of the arm. A secondary post of 1/4-inch stock extends from and above the movable block. This supports a second block made of insulating plastic, to which a metal strip is attached that will hold the upper end of a specimen. The lower edge of this strip is drilled with a set of holes to match those in the upper edge of the lever arm. The blocks are secured to their respective posts by thumbscrews. This arrangement permits the entire stylus assembly to be shifted vertically merely by loosening the thumbscrew that clamps the lower block.

"I find that recordings made on highly calendered (slick) shelf paper are quite sharp and easy to read. A 25-cent roll of paper lasts for months. The paper is cut to match the depth of the cylinder and long enough to wrap around it with 1/4-inch overlap. The direction of the wrap should be chosen so that the stylus slides off the top of the overlap—otherwise it may catch and tear the edge of the paper. The overlap is stuck together by bits of Scotch tape. The paper may be smoked over almost any flame deficient in oxygen: a Bunsen burner with the air supply closed, a candle or a kerosene lamp.

"Graphs of respiration are made by stretching a thread over the chest of the subject, tying one end to the lever arm and anchoring the other under a book. (If the subject should sit up suddenly, the thread slides from beneath the book and spares the apparatus.) Variations in respiration can be observed by having the subject rest for a few minutes prior to starting an experimental run or, conversely, by having him exercise vigorously immediately prior to the run. Muscle contraction is recorded by attaching a bit of muscle from a frog or some other experimental animal between the lever arm of the stylus and the insulated fixture. Contraction is stimulated by applying a pulse of high voltage across the ends of the muscle. Warning: Do not take the pulse from a high-current source such as a 110-volt power line. To do so invites accidental shock and possible injury. Small 'B' batteries of the kind used in portable radio sets are safe and completely adequate."