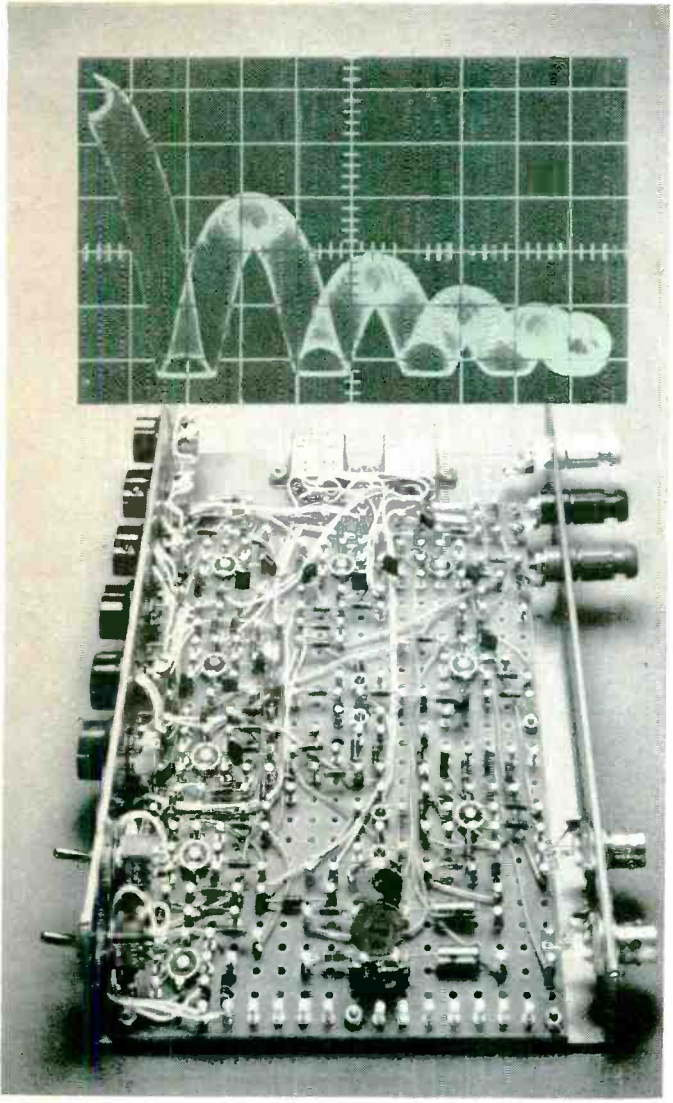


BUILD THE

"BOUNCING BALL" ANALOG COMPUTER

Displays any ball's behavior when dropped from height . . . Saves hours of higher-math calculations

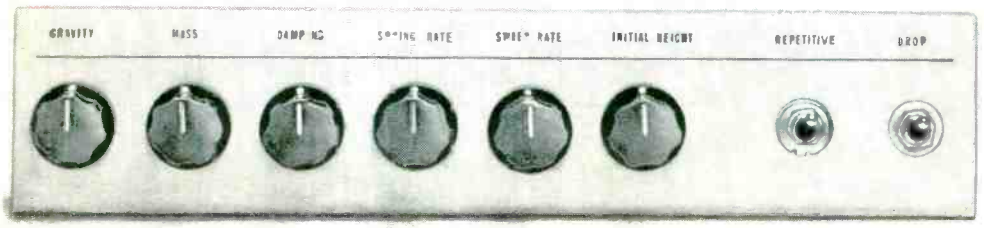
BY TERRY L. MAYHUGH

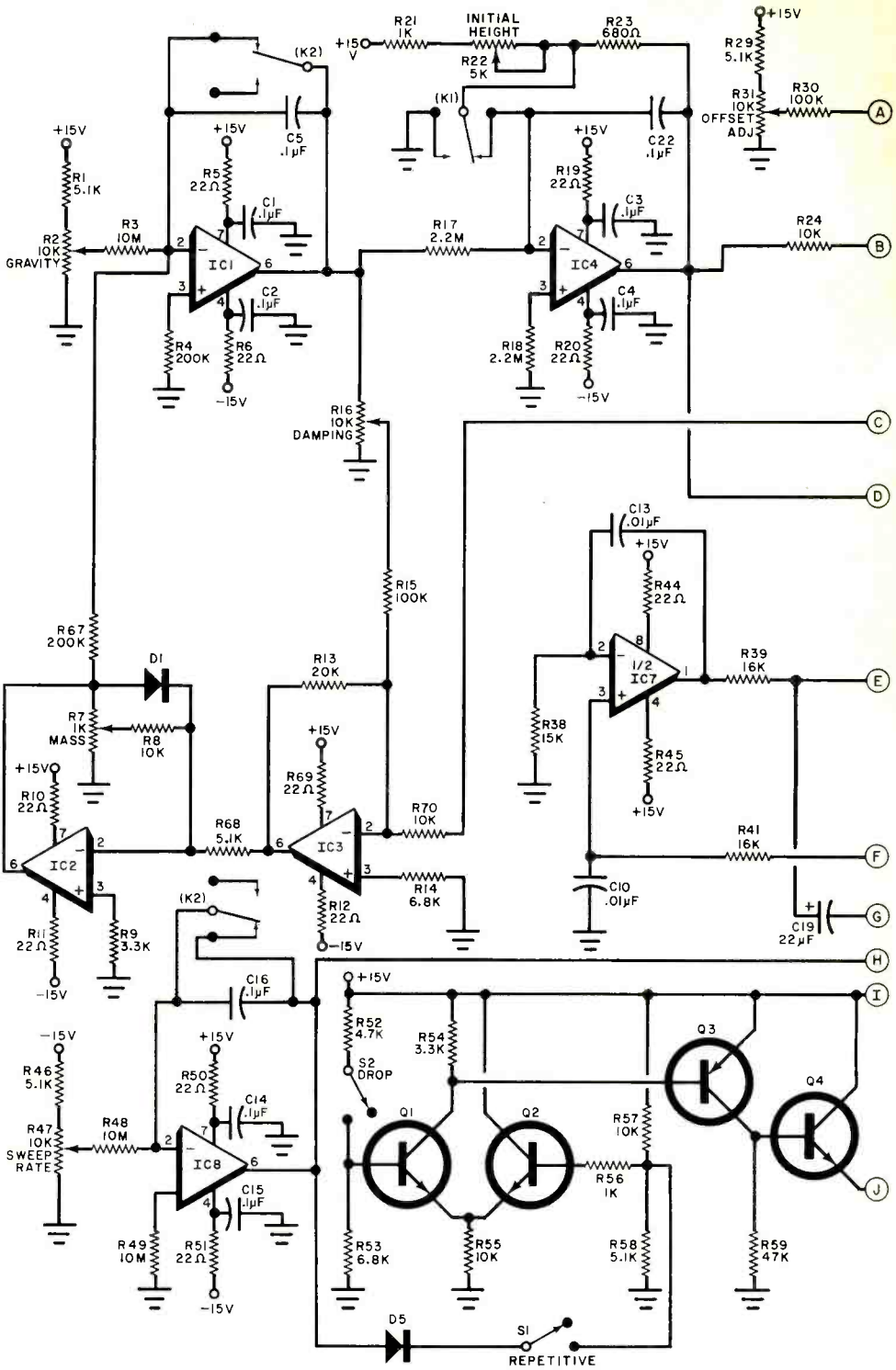
THIS Science Fair project demonstrates some principles of kinematics and how an analog computer works.

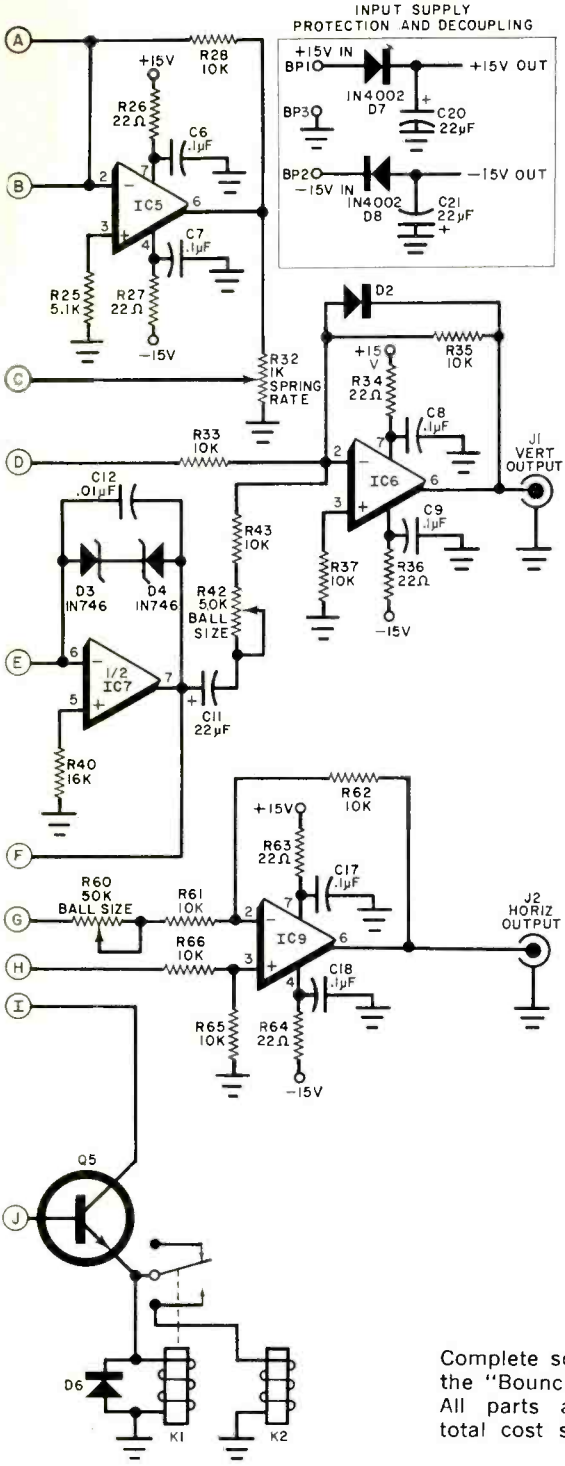
An analog computer may be likened to a slide rule. Both provide instantaneous answers on a continuous scale without *absolute* accuracy. (In contrast, digital com-

(Text continues on page 12)

Front-panel view of the analog computer. The circuit was constructed on Vector board and mounted in an aluminum tray folded from sheet rock to provide panels.




+15V
R21 1K
INITIAL HEIGHT
R22 5K
R23 680Ω
+15 V
(K2)
(K1)
R29 5.1K
R31 10K OFFSET ADJ
R30 100K
A
C5 .1μF
C22 .1μF
R1 5.1K
R2 10K GRAVITY
R3 10M
R5 22Ω
C1 .1μF
IC1
C2 .1μF
R4 200K
R6 22Ω
−15V
R19 22Ω
C3 .1μF
IC4
C4 .1μF
R18 2.2M
R20 22Ω
R17 2.2M
R24 10K
B
R16 10K DAMPING
C
D
C13 .01μF
R44 22Ω
1/2 IC7
R39 16K
E
R38 15K
R45 22Ω
R41 16K
F
C10 .01μF
C19 22μF
G
R67 200K
D1
R7 1K MASS
R8 10K
R15 100K
R13 20K
R10 22Ω
IC2
R68 5.1K
R69 22Ω
IC3
R70 10K
R14 6.8K
R12 22Ω
R11 22Ω
R9 3.3K
H
I
C16 .1μF
R52 4.7K
R54 3.3K
S2 DROP
Q1
Q2
Q3
Q4
R46 5.1K
R47 10K SWEEP RATE
R48 10M
R50 22Ω
C14 .1μF
IC8
C15 .1μF
R49 10M
R51 22Ω
R53 6.8K
R55 10K
R57 10K
R56 1K
R58 5.1K
R59 47K
J
D5
S1
REPETITIVE

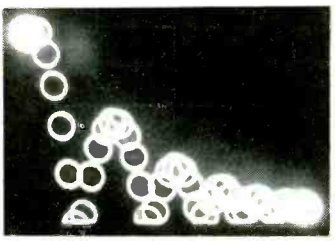


PARTS LIST

R1, R25, R29, R46, R58, R68—5100 ohm, ¼ W res. ±5%
R2, R32, R47—10,000 ohm variable panel-mounted potentiometer
R3—10 megohm, ¼ W res. ±5%
R4, R67—200,000 ohm, ¼ W res. ±5%
R5, R6, R10, R11, R12, R19, R20, R26, R27, R34, R36, R44, R45, R50, R51, R63, R64, R69—22 ohm, ¼ W res. ±5%
R7—1000 ohm variable panel-mounted potentiometer
R8, R24, R28, R33, R35, R37, R43, R55, R57, R61, R62, R65, R66, R70—10,000 ohm, ¼ W res. ±5%
R9, R54—3300 ohm, ¼ W res. ±5%
R13—20,000 ohm, ¼ W res. ±5%
R14, R53—6800 ohm, ¼ W res. ±5%
R15, R30—100,000 ohm, ¼ W res. ±5%
R16—10,000 ohm potentiometer
R17, R18—2.2 megohm, ¼ W res. ±5%
R21, R56—1000 ohm, ¼ W res. ±5%
R22—5000 ohm variable panel-mounted potentiometer
R23—680 ohm, ¼ W res. ±5%
R31—10,000 ohm variable PC-mount potentiometer
R38—15,000 ohm, ¼ W res. ±5%
R39, R40, R41—16,000 ohm, ¼ W res. ±5%
R42, R60—50,000 ohm variable PC-mount potentiometer
R48, R49—10 megohm, ¼ W res. ±5%
R52—4700 ohm, ¼ W res. ±5%
R59—47,000 ohm, ¼ W res. ±5%
C1, C2, C3, C4, C6, C7, C8, C9, C14, C15, C17, C18—0.1 μF disc ceramic capacitor
C5, C16, C22—0.1 μF Mylar capacitor
C10, C12, C13—0.01 μF Mylar capacitor
C11, C19, C20, C21—22 μF tantalum capacitor
D1, D2, D5—1N914 (or equiv.) silicon diode
D3, D4—1N746
D6, D7, D8—1N4002 (or equiv.)
IC1, IC4, IC8—Intersil 8007 FET op-amp (or equiv. such as μA740 or NE536)
IC2, IC3, IC5, IC6, IC9—741 op-amp
IC7—558 op-amp (dual 741)
IC pin numbers shown for TO-5 package
S1, S2—Spst toggle switch
J1, J2—BNC jack
K1, K2—Relay (Babcock BR12-140B2 or equiv. dpdt with 12 V dc and approx. 100-ohm coil resistance)
Q1, Q2, Q4, Q5—2N718 (or equiv. npn with beta greater than 30)
Q3—2N3789 (or equiv. pnp with beta greater than 25)

Complete schematic and parts list for the "Bouncing Ball" analog computer. All parts are readily available and total cost should not exceed $30.00.

PHYSICAL PRINCIPLES INVOLVED



When the ball is lifted above the floor, potential energy is said to be stored in it due to the work done against the gravitational field while lifting it. When released in a uniform gravitational field it falls and the potential energy is converted into kinetic energy as the downward velocity increases.

Since the gravitational field is uniform over the distance concerned and, assuming zero air resistance, the ball is uniformly accelerated (at the rate of 32 ft/sec per sec on earth). The scope photo shows the effect of the uniformly accelerated motion. Since the sequence of shots represents equal increments of time (as the scope's blanking was strobed at a fixed PRT), the vertical velocity of the ball increases as the ball falls toward the surface, as expected. Theoretically, the change in the velocity is the same in each time interval. The value of Gravity can be varied to change the acceleration and therefore the time required to reach the floor. However, as Gallileo observed, objects with different masses fall at the same rate; and this is seen from the fact that varying the mass has no effect on the fall time.

Although the acceleration is uniform if the air resistance is zero, in a practical situation the falling body will eventually attain a constant (terminal) velocity at a certain point where the drag offered to the ball becomes significant. (Drag increases with velocity.) This may be simulated by increasing the Damping which, in effect, increases the viscosity of the air, making it more "syrup-y."

When the ball strikes the surface, a portion of its kinetic energy is absorbed (dissipated as heat), leaving the remainder to be converted back into kinetic energy during the rebound. The Spring Rate determines the amount that is left for rebound. Note, again from the photo, that the velocity decreases as the ball rebounds on any particular bounce. This, again, is due to the gravitational field acting to decelerate the motion of the ball. This time the kinetic energy is changed into potential energy by the gravitational field acting against the ball. At the peak of its rebound height, vertical velocity is zero and the cycle continues. This time the remaining potential energy is converted into kinetic energy by the gravitational field and again a percentage is dissipated at the floor and the rebound gets lower and lower.

puters are essentially fast arithmetic machines that solve one problem at a time with great accuracy.) Analog computers can simulate a variety of factors by substituting electrical models. The computer described in this project, for example, can be programmed to solve an interesting problem: Given the initial height of a ball of known mass above a hard surface, the force of gravity, the viscosity of the medium, and the spring constant of the ball, how does the ball behave when it is dropped?

The computer "paints" a ball on the screen of an oscilloscope and, when given the Drop command, computes and displays continuously the path of the ball as it falls, compresses at the hard surface, rebounds, and finally settles on the floor.

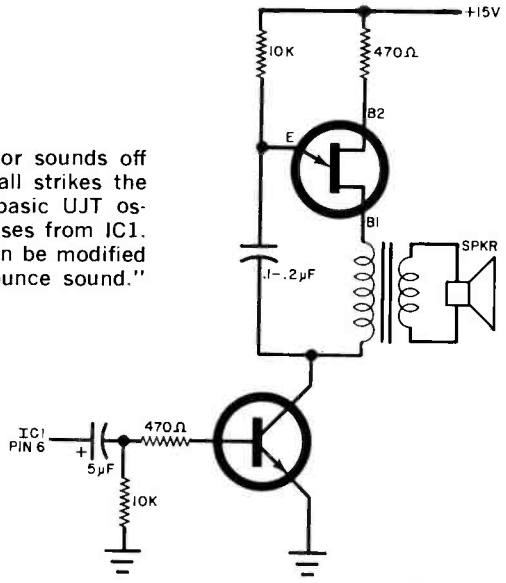
The machine quickly does the calculations for a continuous display which would take an engineer days to complete by hand and plot. The operator controls the parameters Gravity, Mass, Damping, Spring Constant, as well as the horizontal velocity across the screen. A repetitive mode is also provided for a repeating display.

Although analog computers cannot give the 15-decimal-place accuracy of their digital cousins, they are better suited for solving "real time" problems that would otherwise require a knowledge of differential calculus. More precise quantitative results than possible with the project's computer would require an expensive version of it with controlled offset errors, calibrated potentiometers, etc. Nonetheless, the unit described gives a fair approximation of what happens with a "bouncing ball."

Construction. Construction is relatively simple, as the layout is not critical. However, feedback elements should be placed near their associated op-amps. The prototype was constructed on a piece of Vector board and mounted in an aluminum tray folded from sheet stock, with front and rear panels for mounting the control pots, etc. All op-amps are of the 741 type with the exception of those used in the integrators. Here FET input amps with their low bias currents are necessary due to the high values of input resistors. Practically any FET op-amp may be used and a few suggestions are given in the parts list.

The entire project was built for less than $30. All components are readily obtainable from local or mail-order electronics parts houses.

This optional tone generator sounds off each time the bouncing ball strikes the "ground." It consists of basic UJT oscillator triggered on by pulses from IC1. The UJT time constants can be modified to create any type of "bounce sound."



How It Works. *IC7* is used as a sine/cosine generator to generate the circle. The two quadrature outputs of the oscillator are summed with the vertical and horizontal information generated by the computer in *IC6* and *IC9*, respectively.

IC8 is used as a Miller integrator to generate the horizontal sweep. The rate is determined by *R47* and the initial condition is set by one set of closed contacts of *K2*. *Q1* and *Q2* form a comparator to open the initial-condition contacts of *K1* and *K2* when the Drop switch is closed. When the Repetitive switch is closed, the relays momentarily reset the initial conditions when the sweep reaches about 9 volts, and the action repeats. One set of contacts on *K1* is used to apply power to *K2* to insure that the proper initial height is reset before the sweep begins again in the repetitive mode.

The actual computer arithmetic is done by *IC1* through *IC5* and their associated components. *IC1* is an integrator whose rate of change of output is determined by the setting of the Gravity control (ignoring, for the moment, the second input from *IC2*). *IC4* integrates *IC1's* output with initial condition set by the Initial Height control. Two feedback loops are used to control the Damping and Spring Rate of the loop. *IC2* divides the sum of these two components and divides them by the Mass to complete the path back to *IC1*.

Operation. The computer requires ±15 volts and a scope capable of X-Y mode operation (either a dual-trace scope with X-Y capability or a single-channel dc scope with access to the horizontal amp). Due to the low sweep speeds involved, it's necessary to d.c.-couple into the horizontal plates to get a repetitive display. Full-scale vertical and horizontal scale factors are about 10 V but they may be adjusted to anything less by using external voltage dividers.

With power applied, the controls set to their mid-positions, and the Drop switch "on," *R42* and *R60* are adjusted to give a symmetrical circle of convenient size for the display. *R31* is then adjusted so that the ball just "sits" on the "floor" with little or no flattening. The Repetitive switch is then closed and the ball should return to the upper left corner and automatically drop. The Gravity and Damping controls may be adjusted to change the fall as well as the rebound. The Spring Rate changes the springiness of the ball, which controls the amount it flattens when it hits the floor, as well as its rebound characteristics. The Sweep Rate can be adjusted to control the horizontal velocity of the ball, or it can be turned down to zero.

Typical results are shown in the scope photo and on the front cover. The pictures were taken by strobing the scope's beam blanking repetitively during one sweep with the shutter held open. ◈