BUILD A MODULAR ELECTRONIC

Developing music by synthesizing the tones electron-
Now it can be yours. This synthesizer is simple,

THERE IS NOT MUCH DOUBT THAT ELEC-tronic music synthesizers are the favorite toys of the music industry; hardly a record or TV commercial is produced these days without some sort of synthesizer "gim-mick." Yet despite the ubiquitous nature of these devices (or perhaps because of it) there is no other collection of electronic equipment so thoroughly misunderstood not only by the layman but by a great many musicians as well.

This article will help clear the fog sur-rounding electronic music by going beyond the "How They Work" material that has appeared in the past. Here we will present full details of the construction of a fully compatable set of voltage-controlled synthe-sizer modules.

The synthesizer that is described here has been specifically designed for construc-tion by the electronics experimenter. While some compromises have been made in the interest of improving the price/performance ratio of professionally available equipment, you will find that the equipment described is in most ways a little brother to the studio gear selling for ten times the price. There is a power supply, voltage-controlled oscillator and controller, voltage-controlled amplifier, two voltage-contolled filters, a function (en-velope) generator and control os-cillator/noise source. When the first three modules are completed you will have a playable, though limited, instrument.

Power supply

As you can tell from the photographs, the power supply does a little more than just act as a source of voltage for the rest of the modules. It also includes a patch

panel, attenuator and two sources of bias voltage that will be used to set constant fil-ter or amplifier parameters.

The schematic for the power supply is in Fig. 1. The actual power supply portion of the circuit consists of two separate full-wave rectifiers. One section (T1, D1-D4, C1, C2) provides the +18 and +9-volt supplies while the other (T2, D5, D6, C3) supplies the -9-volt side. Regulation is not included because the only module that re-quires a regulated supply (the VCO) has on-board regulation.

The series string of R2, R3 and poten-tiometer R5 provides a front panel voltage source that is variable from -5 to +5 volts while the combination of R1 and poten-tiometer R4 supplies a variable 0 to 5 volt source.

With the exception of the "condi-tional" jumpers between rows of jacks the patch panel is a straight-forward design. Referring to the schematic again we see that the switch contacts of the miniature phone jacks are arranged so that when a plug is inserted into J1 it isolates the top row of jacks from all jacks below it. Sim-ilarly, a plug inserted in J4 isolates the sec-ond row of jacks from the pin jacks below it (but not from the top row). Two sets of capacitor isolated jacks are provided at J11, J14 and J12, J13. The purpose of these jacks will become clear in a later article on using the synthesizer.

Potentiometer R6 provides a variable attenuator that can be used as a master vol-ume control or in mixing applications.

Put It together

There is nothing at all critical in the power supply circuit and any construction

method may be used, but an etched circuit board is desirable in the interest of ease of assembly and professional appearance. The foil pattern is in Fig. 2. Circuit boards may either be etched at home or purchased from the source mentioned in the parts list.

Assembly should begin with mounting the parts on the circuit board. Form and install the two wire jumpers, then the resis-tors, capacitors and diodes. Bolt the two transformers and the fuse holder to the cir-cuit board with 4-40 hardware. When they are properly installed, the transformers will be "back to back" with the primary wind-ings facing each other (see Fig. 3).

Connect the solder lugs of the fuse-holder to the circuit board with short pieces of bare wire, and before putting the circuit board aside solder in place lengths of No. 22 wire to points A through F on the cir-cuit board. Be sure to make these wires long enough to reach from the circuit board to the front panel when the two are bolted together.

From the front panel from any flat material such as aluminum, steel or even scrap copper-clad and drill or punch the re-quired holes before painting the panel and applying markings as desired. Install the pots, jacks and switch S1 as shown in the photos and wire the front panel before fas-tening the circuit board to the front panel using small "L" brackets and 4-40 hard-ware. Note that capacitors C4, C5 and C6 are wired in place on the front panel.

Make the final connections from the front panel controls to the circuit board and solder the line cord into the circuit board points marked ac Snap a ½-amp fuse into the fuse holder and fasten the knobs to the potentiometer shafts.

COVER STORY
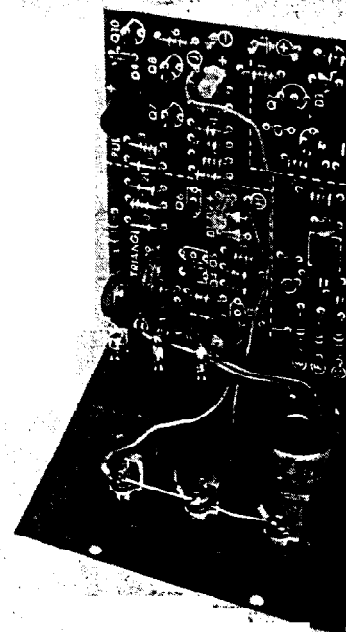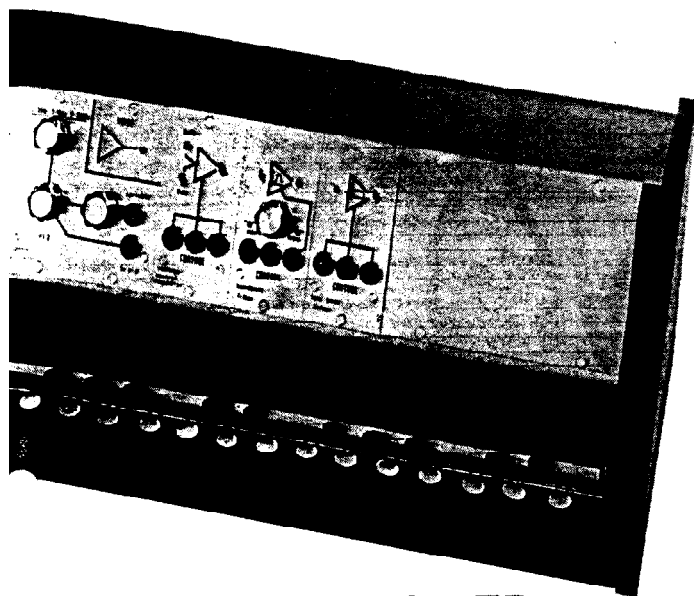
⌐ MUSIC SYNTHESIZER   by JOHN S. SIMONTON, JR.*

ically is not new but has just started gaining momentum.
inexpensive and designed for the experimenter.

Testing your work

There is really not much to test on the power supply, plug it in and use a vom to make sure that there is 18 volts between the ground and "++" points on the circuit board. Similarly check the "+" point for 9 volts to ground. Reverse the vom leads and check for -9 volts, between "-" and ground. Check the voltage output of the 0 to 5-volt and -5 to +5-volt bias supplies as the controls are rotated (all of these voltages are ±20%). Plug a miniature phone plug into J3 and check continuity between the hot side of this jack and all the other phone jacks in the group as well as the top row of pin jacks. Plug a phone plug into J1 and observe that it isolates the top row of phone jacks from the rest of the jacks. Test the switching on the second row of jacks to make sure that it isolated J4 through J6 from the row of pin jacks directly below it but not from J1 through J3.

Voltage-controlled oscillator

Unlike electronic organs—which for the most part generate a specific sound by adding together sine waves of the desired frequency, magnitude and phase—synthesizers employ "formant synthesis" in which a desired signal is formed by dropping out selected frequencies in a harmonic rich waveform.

Our VCO generates three waveforms that are particularly rich in harmonics; ramp, triangle and variable duration pulse. Frequency range of the oscillator is almost 6 octaves from 40 Hz to 2500 Hz, in a single voltage controllable range and the frequency of the oscillator is directly proportional to the sum of the voltages at three control voltage inputs. The implica-

tions of voltage control will be fully covered in another article, but for now it will suffice to say that without it you don't have a synthesizer, you have an organ.

How the VCO works

In a synthesizer the VCO is the one module that doesn't offer many design compromises. The human ear is more sensitive to variations in pitch than to any other musical parameter so even small amounts of drift and shift are objectionable.

As can be seen in Fig. 4, two precautions keep VCO drift to a minimum. First, power supply regulation is directly on the circuit board (Zener diodes D3 and D4 plus series-pass transistors Q9 and Q10). Second, control voltage is summed by the active network built around IC1.

The ramp portion of the VCO is a standard configuration consisting of a UJT relaxation oscillator (Q2, C1). The capacitor is charged by constant current source Q1. The output of the op-amp summing network is scaled by setting the gain (R7, RANGE) and offset (R4, ZERO) of the amplifier and is used to set the amount of current delivered by the current source.

The voltage ramp that appears across capacitor C1 is isolated by emitter follower Q3 and appears at the front panel jack as the ramp output. The ramp is also used to generate the other two waveforms.

The triangle waveform is shaped by the differential pair Q4 and Q5. The voltage at the collector of Q5 is in phase with the input ramp and the voltage at the collector of Q4 is 180° out of phase (inverted from the input). Diodes D1 and D2 "select" the higher of these two collector voltages and apply it to the base of emitter fol-

lower Q6. During the lower half of the input ramp, Q4's collector voltage is higher because of the phase inversion and that section of the ramp is presented in an inverted form to the base of Q6. During the second half of the ramp the collector of Q5 is higher and this portion of the ramp is applied to the base of Q6 without an inversion. The net result is a triangular wave from the emitter of Q6. Trimmer potentiometer R19 is used to balance the gains of the transistors so that the last of the wave from Q5 and the first of the wave from Q4 occur at the same dc level.

A variable-duration pulse output is derived from the ramp by applying it to the input of the Schmitt trigger (Q7 and Q8). At some point on the ramp the triggering threshold of the circuit is exceeded and the output changes from some low voltage to almost positive supply and stays in that condition until the ramp re-sets. By using R25 to vary the amplitude of the ramp, the pulse duration, as a percentage or the total period can be varied. As the amplitude is increased the duration of the pulse is also increased. Trimmer R26 provides a fine adjustment of the ramp amplitude and is set so that when the pulse duration control is fully counter-clockwise the narrowest possible pulse is produced.

Build the VCO

The VCO circuit can be assembled using any common construction technique, but an etched circuit board (Fig. 5) is recommended. Figure 6 shows parts placement on the circuit board. When all components have been mounted, solder wires to points A through K. Make sure they are long enough to reach from the board to the
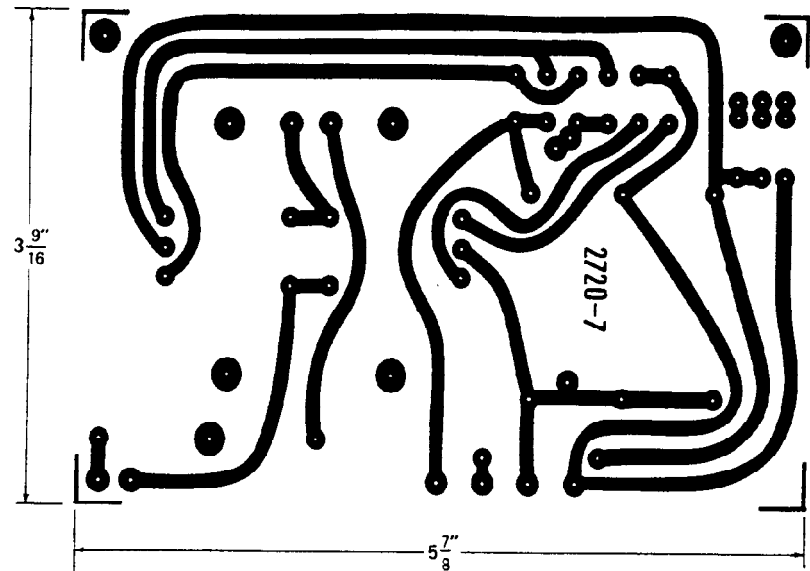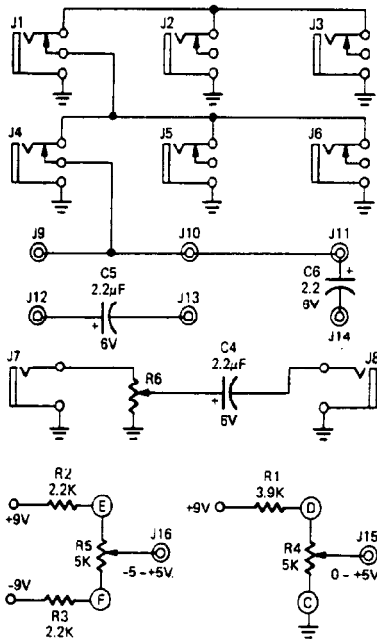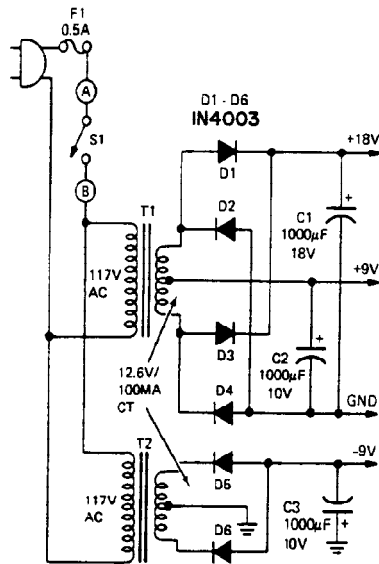
PARTS LIST
(Power Supply)

C1—1000-μF 18V electrolytic
C2, C3—1000-μF 10V electrolytic
C4, C5, C6—2.2.-μF, 6V electrolytic
D1 thru D6—1N4003
F1—0.5-amp fuse
R1—3900 ohms ½W 10%
R2, R3—2200 ohms, ½W, 10%
R4, R5, R6—5000 ohms linear taper potentiometer
S1—spst slide switch
T1, T2—12.6V 100 MA C.T. transformer
MISC: Fuse holder, line cord, (8) miniature phone jacks, (8) tip jacks, (3) knobs, hardware, wire, solder, circuit board, etc.
The following items are available from, PAIA Electronics, Inc., P.O. Box 14359, Okla. City, OK 73114
    No. 2720-7—Complete kit of parts for duplicating the prototype shown including circuit board and front panel. $22.00 plus postage for 2 lb. and insurance.
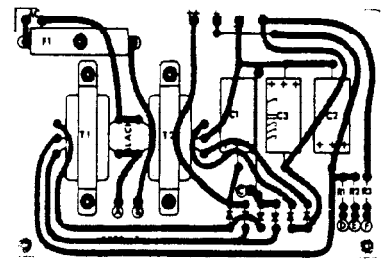   No. 2720-7pc—Circuit board only $4.00 postpaid.

FIG. 1—(far left) COMPLETE SCHEMATIC of the power supply. FIG. 2—(top of page) FOIL PATTERN for the power supply circuit board. FIG. 3—(above) PARTS PLACEMENT on the board.

front panel controls and jacks (notice that there is no point I).

Form the front panel in the same manner as for the power supply and finish and label it before installing R25 and the input and output jacks.

Fasten the circuit board to the front panel using 4-40 screws and small "L" brackets and make the final connections between the circuit board and front panel.

Calibration and testing

Apply power to the rear connections of the circuit board; +9 volts to "+", ground to ground and -9 volts to "-". The VCO pulls a hefty 25 mA because of the regulation, so batteries are not acceptable. Give the unit about 30 minutes to stabilize before calibration.

The primary adjustment sets up the summing network so the oscillator produces a specified output frequency for a given input control voltage. This can be done using either an audio signal generator or a tuned musical instrument as the pitch reference.

If you decide to use the signal generator method, the oscillator will be tuned us-

ing Lissajous figures. Connect the output of a test oscillator set to 260 Hz to the horizontal input of an oscilloscope and the triangle output of the VCO to the vertical input. Apply power to the VCO and jumper the 0 to 5-volt bias output of the power supply to the left hand control voltage input jack. (The input summing resistors can not be trimmed so unless matched resistors are used only one of the three inputs can be precisely calibrated.) Monitor this control voltage with a vom set to 2.5 or 5 volts dc full scale. Adjust the bias output for 0.625 volts as indicated by the vom (errors caused by inaccuracies in the vom movement will cancel when the keyboard is calibrated to the VCO.) Use VCO ZERO trimmer R4 to produce a Lissajous figure on the scope that indicates that the frequency of the signal generator is exactly twice the frequency of the VCO. Do not be overly concerned with a slow rotation of the pattern at this point.
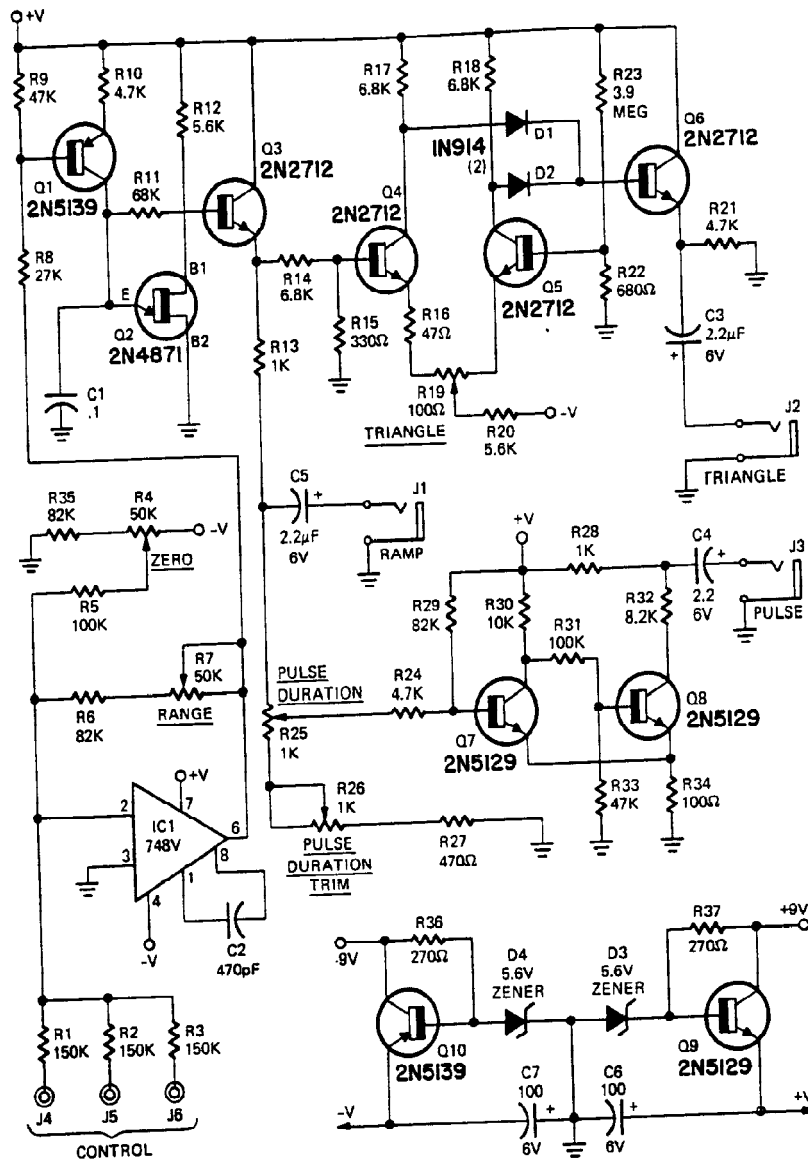
Adjust the bias supply until the scope shows the *sideways 8* pattern that indicates that the output of the signal generator is half the frequency of the VCO. Read the vom. If the reading is *Less* than 2.5 volts, rotate RANGE trimmer R7 about 1/10 of a turn clockwise. If the reading is

greater than 2.5 volts, rotate the trimmer about 1/10 of a turn counter-clockwise. Reset the bias output for 0.625 volts on the vom and once again adjust the "zero" trimmer to produce the Lissajous figure.

Repeat the previous adjustment for the *sideways 8* pattern and adjust the RANGE trimmer accordingly. After several passes through this procedure the vom should read exactly 2.5 volts when the Lissajous pattern indicates that the frequency of the VCO is twice that of the signal generator. At this point summing network calibration is complete.

A second method for calibrating the VCO is approximately the same as the first except that the ramp output is jumpered to the high level input of a hi-fi or musical instrument amplifier and the tone is "zero beat" against the C below middle C for an input voltage of 0.0625 volts; and C above middle C for an input of 2.5 volts. The same technique of *successive approximations* that was used with the signal generator still applies with the ZERO adjusted for zero beat with C below middle C with a control voltage of 0.625 volts. The bias supply is then adjusted so the oscillator is zero beat with C above middle C and if the vom reads more than 2.5 volts the "range" control is rotated 1/10 turn counter-clockwise. Go back and forth through these two steps until the vom reads exactly 2.5 volts when the VCO is zero beat with C above middle C.

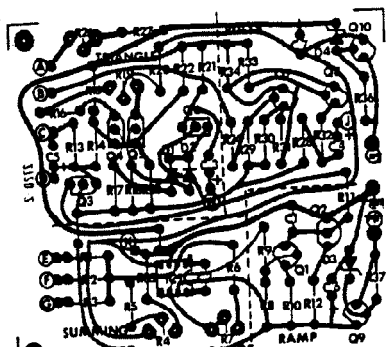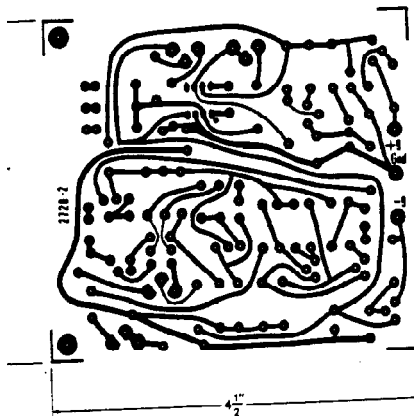When the linearity of the summing network has been calibrated you can set the

That's about all we have room for in this issue. Next month we will present details of the third module for the synthesizer and you can then start using your unit. We would appreciate your comments on the types of additional modules you would like to see for this instrument. We'll pass them on to the author and he may be able to provide them at a later date. See you again next month. R-E

FIG. 4—(top) SCHEMATIC of the voltage-controlled oscillator. FIG. 5—(above left) FOIL PATTERN for the VCO. FIG. 6—(above right) PARTS PLACEMENT on the VCO board.

spectral purity of the triangle wave. If only an amplifier is available this adjustment can be made by jumpering the triangle output to the input of the amplifier and adjusting TRIANGLE trimmer R19 for the mellowest sound. If a scope is available you can look at the triangle output and adjust R19 so the two sides of the triangle meet at the top of the waveform.

The PULSE DURATION trimmer can also be adjusted using either an amplifier or an oscilloscope. If a scope is used rotate PULSE DURATION control R25 fully counterclockwise and adjust internal trimmer R26 so that the narrowest possible pulse appears on the screen. If an amplifier is used, adjust the trimmer so you can just barely hear the buzz of the pulse.

BUILD

A MODULAR

Part II: The

this unit

tempered musical scale. Adjustable wire contacts make the connections between the resistance element and the key springs.

There are two contacts associated with the controller as indicated by the lines above and below R_k in Fig. 7. The upper line corresponds to the voltage pick-off spring that is the first to be contacted by the key spring when a key is pressed. The second line represents the key-down detector strip which contacts the key spring/pick-off spring combination when

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THIS ISSUE WE WILL SHOW YOU HOW THE electronic controller circuit of the synthesizer works and how to build it. The project is relatively simple and results in an additional module for your instrument.

Controller/case

Since the primary pitch sources in synthesizers are voltage controlled, a wide variety of controllers ranging from automatic sequencers to joy sticks are possible.

The controller that we will describe is a keyboard arrangement that is designed to be built from materials commonly available in hobby shops and variety stores. If you are able to locate a standard organ keyboard it can probably be adapted to the electronics package but since keyboards vary from one manufacturer to another it is impossible to give specific details that will apply to all keyboards.

The controller circuit

Reduced to basics the controller is nothing more than a switch controllable voltage divider but it starts to get a little more complicated as "housekeeping" functions are added. In addition to the voltage divider the circuit includes a constant-current source, trigger circuit and sample/hold circuitry.

The constant-current source is a standard design built around Q1 and using the voltage drop across the series combination of D1 and D2 as a reference. The output of the current source is regulated by changing the dc feedback with emitter resistor R20. The current source feeds the voltage divider shown in Fig. 7 as R_k.

In practice the resistance is a strip of conductive vinyl having a resistivity of 377 ohms/square. One edge of the vinyl strip is cut along a curve causing the total resistance to any point on the strip—and consequently the voltage at that point—to be exponentially related to the distance from that point to the low voltage end of the strip. The need for the exponential voltage will be fully covered in another article, but for now it will suffice to say that it relates to the exponential nature of the equally

*President, PAIA Electronics

FIG. 7—(far right) COMPLETE CIRCUIT of the controller electronics. Two IC's and six transistors are used. FIG. 8—(below) PARTS PLACEMENT on the circuit board. FIG. 9—(bottom) FOIL PATTERN of the controller circuit board.
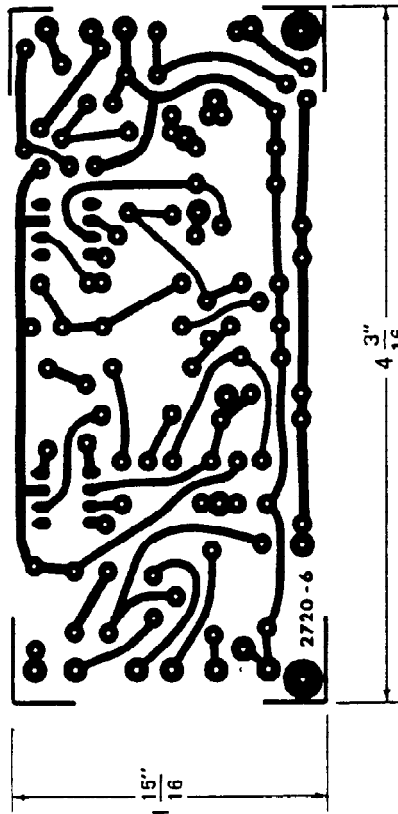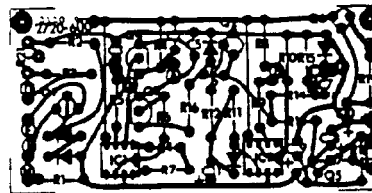
PARTS LIST
(Controller Electronics)

C1, C7—.01-μF disc
C2—.001-μF disc
C3, C11—2.2-μF 10V electrolytic
C4—100-pF disc
C5, C6—.1-μF mylar
C8, C9, C10—33-μF 10V electrolytic
D1 thru D5—1N914
IC1, IC2—748 op-amp
Q1, Q6—2N5139
Q2, Q5—2N5129
Q3, Q4—MPF-102
All resistors—½W 10%
R1—470 ohms
R2—10,000 ohms
R3, R17, R18, R19—680 ohms
R4—15,000 ohms
R5—100,000 ohms
R6—68,000 ohms
R7—82,000 ohms
R8—1 megohm
R9, R16, R22—3.9 megohms
R10—150,000 ohms
R11—22,000 ohms
R12—4700 ohms
R13—20,000 ohms, 5%
R14, R15—33,000 ohms
R20—linear taper potentiometer, 1000 ohms
R21—pc mounting trimmer pot, 1000 ohms
MISC: Case, circuit board, hardware, control panel, wire, solder, etc.

KIT SUMMARY

The following items are available from, PAIA Electronics, Inc., P.O. Box 14359, Okla. City, OK 73114

No. 2720—Kit of all parts for duplicating the complete synthesizer. Includes all parts, panels, circuit boards and detailed instructions. $139.00 plus postage for 18 lbs and insurance

No. 2720-2—VCO kit including circuit board. $24.95 ppd.
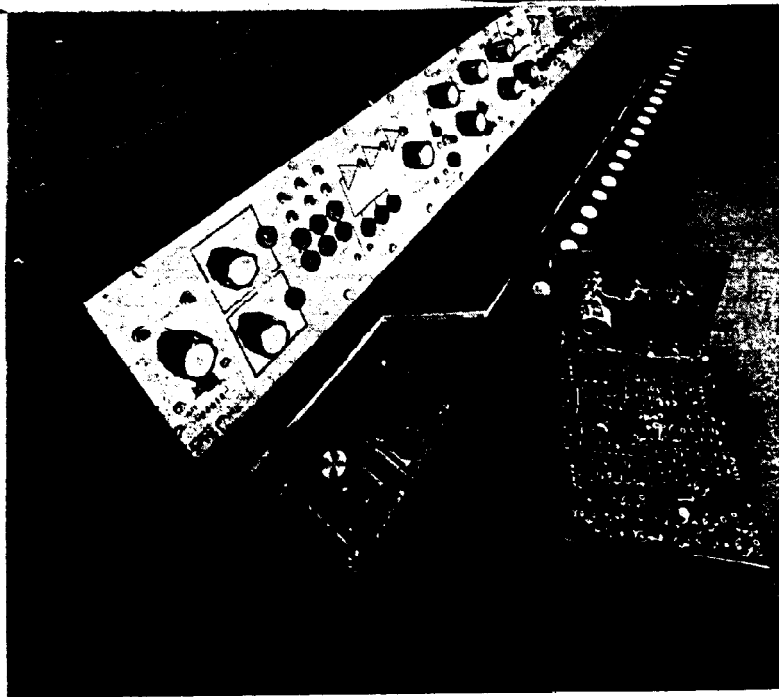
No. 2720-2pc—VCO circuit board only. $4.00 ppd

No. 2720-6—Controller/case kit. $37.00 + 18 lbs. postage

No. 2720-6pc—Sample/Hold circuit board. $3.50 ppd.

No. 2720-7—Power Supply kit. $22.00 + 2 lbs. postage

No. 2720-7pc—Power Supply circuit board. $4.00 ppd.

A controller kit featuring a professional 3 octave organ keyboard is also available. Details available on request.

ELECTRONIC MUSIC SYNTHESIZER

controller electronics is the primary pitch source for
It is a switch controllable voltage divider

by **JOHN S. SIMONTON, JR.***

the key is fully down to play a note.

When a key is depressed, C3 begins to charge or discharge. This capacitor is simply an integrating capacitor to bypass noise from dirty or corroded contacts. Almost simultaneously, the key-down detector strip is raised from near negative supply (where it is held by R22) to whatever voltage is on the key spring being pressed. Since this new voltage is always greater than the -1-volt reference at the "+" input of op-amp

comparator IC2., the output of the comparator switches from its normal high state to a voltage near negative supply. After a time determined by the discharge rate of C11 (20 ms typically) Q2 switches off causing the voltage at its collector to go from near ground up to "++" supply. This voltage charges C6 through D4 and turns on Q3.

The sample-and-hold circuit can be further broken down into comparator IC1,

high input impedance FET source follower Q4, and switch Q3. The comparator is constantly comparing the input from the voltage pick-off spring to the output which appears across the load resistor of the source follower R4. The state of this comparator has no effect on holding capacitor C5 (and consequently the source follower for which this capacitor is an input) until Q3 is turned on. With Q3 on, the comparator acts to make the voltages at its "+" and "-" inputs identical and when the voltages are identical the circuit is balanced. Since Q4 is effectively in the feed-back loop of IC1, a FET with practically any specs can be used.

When the key is released, comparator IC2 switches and immediately turns Q2 on (C11 discharges through D3 and the low output impedance of IC2 almost instantly). When Q2 switches it "pushes" the end of C6 that is connected to the anode of D4 down to about -15 volts, the voltage C6 charged to when Q2's collector was high, causing D4 to reverse bias and thereby removing all discharge paths other than stray leakage. This large negative voltage allows for considerable variations in the parameters of Q3 so that an inexpensive device may be used here.

With Q3 off, holding capacitor C5 is isolated from any discharge paths but still serves as the source follower input so that the output voltage does not change.
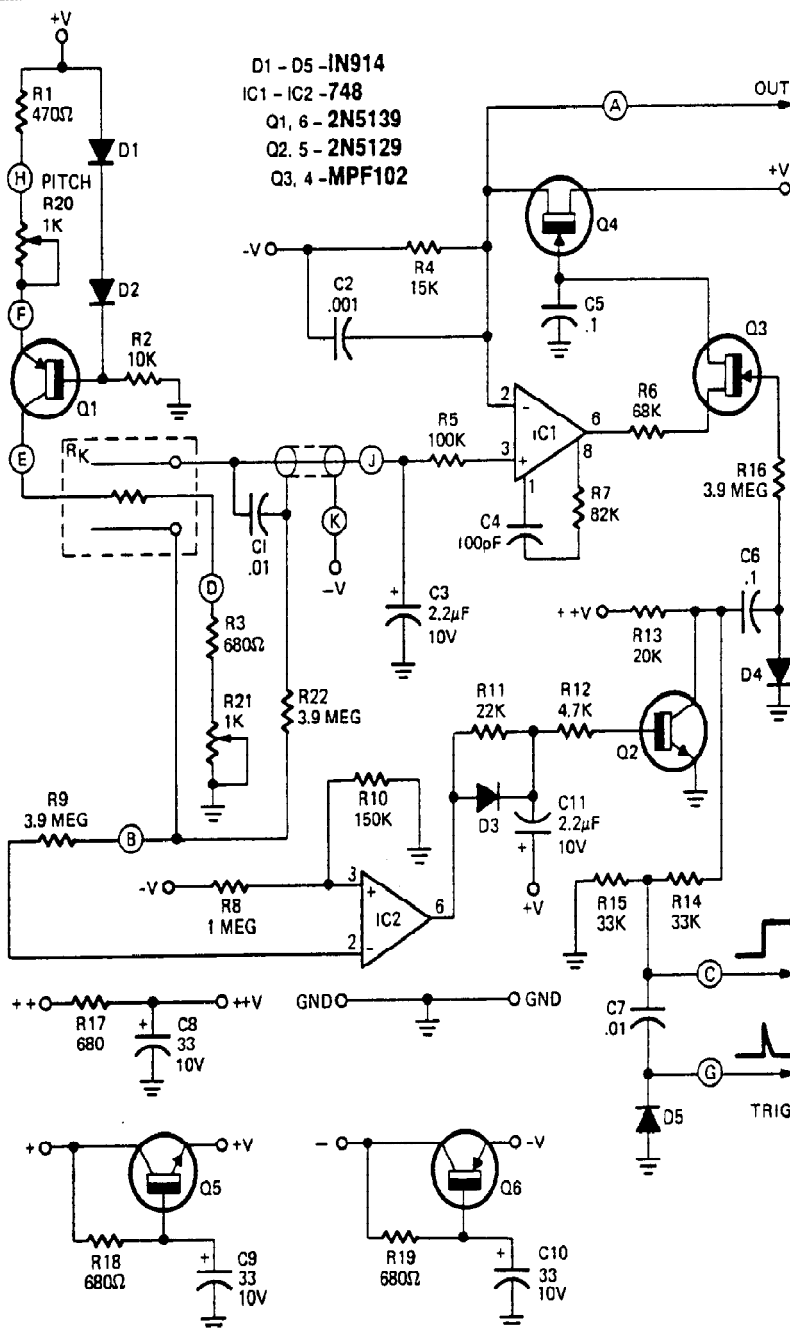
The voltage step trigger output is derived from Q2 through voltage divider R14 and R15 and the pulse trigger output is formed by differentiating the step through C7. Diode D5 clamps the negative voltage spikes to ground. Q5 and Q6 serve as capacitance multipliers for the filter capacitors C9 and C10.

Put It together

The assembly of the electronic portion of the controller is pretty straightforward but because of the high gain characteristics of the two operational amplifiers you will be ahead using an etched circuit board. The etching guide is in Fig. 9.

Be just as careful with this circuit as you were during VCO assembly. Note that not all of the parts associated with the sample and hold circuit are mounted on the circuit board. Resistor R22 and ceramic disc capacitor C1 are mounted at the end of the coax that connects the sample/hold input to the voltage pick-off wire on the keyboard. Also note the two wire jumpers on the circuit board.

Next month we will show how to build the keyboard for the synthesizer and how the modules connect into the case and main-frame. You will then have a basic synthesizer and will be able to start playing it. R-E

D1 – D5 –1N914
IC1 – IC2 –748
Q1, 6 – 2N5139
Q2. 5 – 2N5129
Q3, 4 –MPF102

the heads of the rear screws that hold down the key springs and then touches the vinyl strip.

Temporarily place the keyboard assembly in the case and mark the location of the 22" × 1" piece of copper-clad that acts as the key-down detector strip. When the exact location has been determined fasten the strip in place with seven No. 4 × ¾ wood screws and 5/16" spacers. Place a soldering lug under the right-most screw head.

Roll the excess vinyl under the keyboard assembly and fasten the assembly in place with a single No. 4 × ¾ wood screw through each end.

Make the final adjustments on the keysprings by bending them slightly or by loosening the screws and sliding them back and forth until they are all even and level. Bend the voltage pick-off springs slightly so that in their normal position they touch neither the key springs nor the key-down detector strip.

Build up the power bus assembly as shown in the photos using four 4-lug terminal strips and four 17" lengths of .032 music wire. Solder the music wire through the holes that cinch the lugs to the insulating support. Use four wood screws to fasten the assembly in place. For convenience, designate the upper rod of the power but

By now you have completed the synthesizer electronics from details in the May and June issues and are now ready to finish the project. The keyboard—usually the most expensive part of a synthesizer—is simple and inexpensive. Parts for its construction are easy to find.

Form the key springs from .032 music wire (available from hobby shops) to the dimensions shown in Fig. 9-a. Exact dimensions are not critical but for the best appearance of the finished unit all the springs should be identical. You will need 36 of the springs and of this number, 15 will be further bent as shown in Fig. 9-b so they can be used for the sharp and flat keys.

The white and black buttons at the end of the key springs are just that—shirt buttons that come with a small stud on the back. The buttons are positioned on the springs so that the stud fits into the curve of the key spring and are fastened in place with clear household cement.

Fasten the key springs to a 22" × 3" piece of ½" plywood using two No. 4 × ¾ wood screws and two washers on each spring as shown in Fig. 10. The holes for the two screws that hold down each spring as well as the single screws that will fasten down the voltage pick-off spring in a later step are all on ½" centers along the edge of the support block. Note two things in particular; the keys are arranged in groups of 5 and 7 corresponding to a piano keyboard with 1" spaces between the groups and the final key on the right hand end is fastened down by the slim strip of scrap copper-clad so that will also clamp and make contact with the resistance element.

Mount the conductive vinyl to the keyboard assembly. Secure the right hand end with a single No. 4 × ¾" wood screw through the copper-clad strip which fastens down the right hand key spring. Secure the left hand end of the strip with a second shorter scrap of copper-clad and two wood screws. Makes sure that the copper side of

the strips are facing down against the vinyl. Two notes; the copper-clad strips extend about ½" beyond the back of the key spring support block and serve as soldering points for the connections to the strip. Also, the rear edge of the vinyl strip extends beyond the rear edge of the support block and rolls under the block and is clamped when the assembly is installed in the case.

When the vinyl strip is in place, form and install the wiper contacts shown in Fig. 11. One of each of these springs goes under
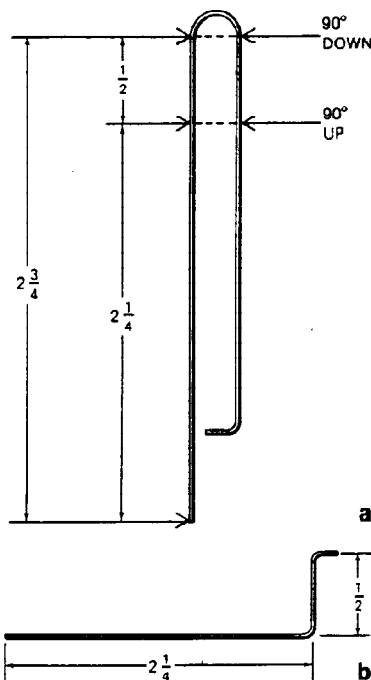
FIG. 9—THE BASIC KEY SPRING (*a*) is formed from music wire. Make 36. For the black keys, take 15 springs and make 90° bends ½ inch apart at the 2½ and 2¾ inch points so side view is as shown at *b*.
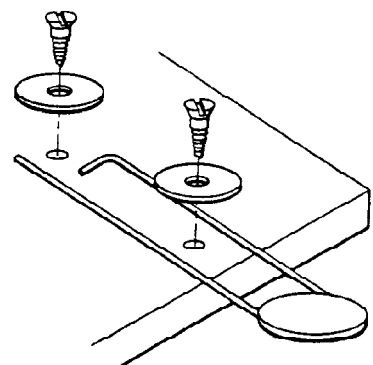

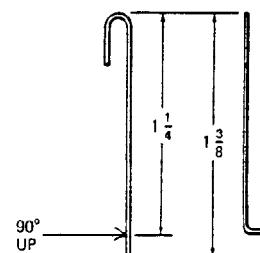FIG. 10—TWO WASHERS AND WOOD SCREWS on ½-inch centers hold key springs in place.

FIG. 11—WIPER CONTACT springs are formed to connect conductive strip to the keys.

ELECTRONIC MUSIC SYNTHESIZER

the keyboard and tune the electronics to synthesizer. Here are the details you'll need.

by JOHN S. SIMONTON, JR.*

"++", the second rod "+", the third ground and the fourth "-".

Cut, drill, paint and label the control panel and install potentiometer R22 and three pin jacks. Install the control panel in a cut-out in the case using four wood screws. Use two small "L" brackets to fasten the controller circuit board to one end of the case as shown and make the connections from the various labelled circuit board points to the power bus, controls, jacks and solder lugs. Note that circuit board point E goes to the right end of the vinyl strip.

This is a convenient point to stop assembling and make the final adjustments between the VCO and the keyboard. Temporarily connect the output of the power supply and the VCO to the power supply bus. Jumper the s/h OUT to the left input jack of the VCO and the VCO pulse output to an amplifier.

Press and hold the extreme right hand white key and use the PITCH pot to zero beat the resulting tone against the second C above middle C of a tuned musical instrument (at this point it does not matter that the right hand key is actually E, this is simply a preliminary adjustment).

Connect a clip lead to the piece of copper-clad that is holding down the left end of the vinyl strip and use the other end

of the lead to clip the voltage pick-off spring and key-down detector strip together. The tone from the oscillator is now zero beat against C below middle C using trimmer resistor R21 on the controller circuit board.

Release the jumper and repeat the tuning of the right hand key with the "pitch" control. Go back and forth between these two steps until the right hand key produces the second C above middle C whenever it is pressed and the jumper from the low end of the controller produces C below middle C.

Press and hold the seventh white key of the controller (E) and use the adjustable spring wiper to zero beat this tone against middle C. Press the fourteenth white key (also E) and zero beat this note against C above middle C. With this done, the lower end of the strip, seventh white key, fourteenth white key and last white key should be at 0.625, 1.25, 2.5 and 5 volts respectively.

In the absence of a tuned pitch source roughly this same procedure can be followed using Lissajous figures to indicate a frequency of 130 Hz, 260 Hz, 520 Hz and 1040 Hz for the four points calibrated above. Set the reference signal source for 260 Hz and do not change it during tuning (since you are tuning to exact multiples of

the reference you eliminate non linearities in the frequency generator from consideration). Once the octave intervals have been set up, the notes in between can be tuned amazingly accurately by ear.

Press and hold the seventh key and using the "pitch" control zero beat this tone against the E above middle C. Complete the tuning of the remaining controller keys by simply adjusting the wiper springs so that each note is zero beat with the equivalent note on the reference instrument.

With the controller fully calibrated the decorative keyboard cover and lower module support strip may be permanently installed using No. 4 X ¾ wood screws and ¼" spacers where needed. Make sure that not more than one screw passes through both the module support strip and the vinyl strip otherwise a portion of the strip will be shorted out. The upper case cover can also be installed at this time.

Connect the power supply output terminals to the power bus rods and install the module using No. 4 self-tapping sheet metal screws. In a similar manner make the power connections from the "+", ground and "-" power bus rods to the VCO power input points and fasten this module in place. **R-E**

KIT SUMMARY

No. 2720—Kit of all parts for duplicating the complete synthesizer. Includes all parts, pan-

$139.00 plus postage for 18 lbs and insurance.

No. 2720-2—VCO kit including circuit board. $24.95 ppd.

No. 2720-2pc—VCO circuit board only. $4.00 ppd.

No. 2720-6—Complete kit of all parts for duplicating the prototype shown including case, preformed springs, front panel, circuit board electronics, vinyl strip. $37.00 plus postage for 12 lbs. and insurance.

No. 2720-6pc—Circuit board only. $3.50 ppd.

No. 2720-6v—Pre-cut conductive vinyl strip. $2.50 ppd.

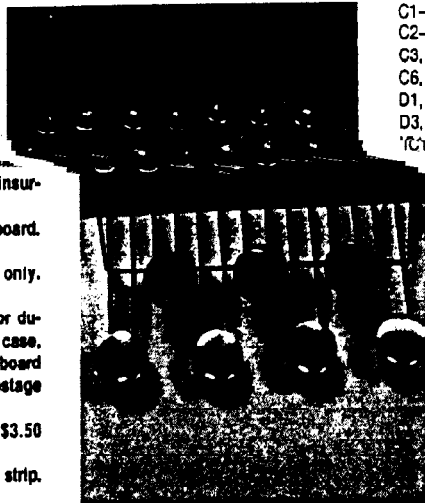No. 2720-6pc—Sample/Hold circuit board. $3.50 ppd.

No. 2720-7—Power Supply kit. $22.00 + 2 lbs. postage.

No. 2720-7pc—Power Supply circuit board. $4.00 ppd.

A controller kit featuring a professional 3 octave organ keyboard is also available. Details available on request.

The items listed above are available from, PAIA Electronics, Inc., P. O. Box 14359, Okla. City, OK 73114.

KEYBOARD CONSTRUCTION is shown in photo above. Photograph below shows synthesizer chassis with just the keyboard in place.

PARTS LIST
(Voltage-Controlled Oscillator)
For Fig. 4, May '72

C1—.1-μF Mylar
C2—470-pF disc
C3, C4, C5—2.2-μF 6V electrolytic
C6, C7—100-μF 6V electrolytic
D1, D2—1N914
D3, D4—5.6V Zener
IC1—741b op-amp
Q1—2N3819 fet
Q2—2N4871
Q3, Q4, Q5, Q6—2N2712
Q7, Q8, Q9—2N5129
All resistors ½W 10%
R1, R2, R3—150,000 ohms
R5, R31—100,000 ohms
R6, R29, R35—82,000 ohms
R8—27,000 ohms
R9, R33—47,000 ohms
R10, R21, R24—4700 ohms
R11—68,000 ohms
R12, R20—5600 ohms
R13, R28—1000 ohms
R14, R17, R18—6800 ohms
R15—330 ohms
R16—47 ohms
R22—680 ohms
R23—3.9 megohms
R27—470 ohms
R30—10,000 ohms
R32—8200 ohms
R34—100 ohms
R36, R37—270 ohms
R4, R7—trimmer potentiometer, 50,000 ohms
R19—trimmer, 100 ohms
R26—trimmer, 1000 ohms
R25—linear taper pot, 1000 ohms
MISC: Circuit board, front panel, knob, hardware, (3) tip jacks, (3) miniature phono jacks, wire, solder, etc.

more SYNTHESIZER modules

Part IV: You've built the keyboard and the basic electronic circuits. Here are four modules to enhance your instrument.

by JOHN S. SIMONTON, JR.*

BY NOW YOU SHOULD HAVE A GOOD START on your synthesizer. You've built the VCO, keyboard controller and power supply from articles in May, June and July issues. Now we will finish the basic package by assembling a voltage-controlled amplifier, two types of voltage-controlled filters, a noise source, envelope generator and low-frequency control oscillator.

Rather than go through the same tired old warnings about soldering and component polarity for each module, let's just get them all out of the way at once. These same precautions and assembly details apply to all the modules.

As you might expect, there is nothing really critical about the assembly of any of the modules we will look at. There are no

high frequencies involved so other than standard rules of good practice for audio assembly work lead dress and component arrangement are not critical. Keep outputs and inputs separated as much as possible and avoid outrageously long input and output lines.

Any of the standard assembly techniques from perf-board to etched circuits may be used with extra points for professional appearance and ease of assembly going to the etched circuit boards. Boards may be etched at home using the layouts shown or are available commercially.

As with any semiconductor circuit, heat is a major enemy so stick to as small a soldering iron as possible (no larger than 35 watts in any case) and wherever possible

heat sink semiconductor leads while soldering. Do not use a soldering gun. The induced EMF generated when they're turned on and off has crunched more than one previously healthy transistor.

Like electrical assembly, the mechanical assembly techniques used can be adapted from whatever you have available. Our standard module is 2 inches wide by 4 inches high with double and triple modules being 4 and 6 inches wide respectively. Front panels may be made of whatever materials you have handy from sheet aluminum to scrap copper-clad. Paint and mark the panels before installing any controls, jacks, etc. In prototypes the front panels are attached to the circuit boards with 4-40 hardware and small "L" brackets.
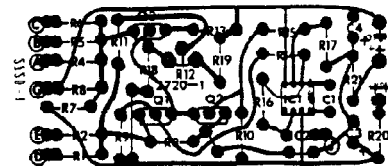
voltage-controlled amplifier

The two most important characteristics of natural or synthesized sounds are their attack and decay times—how fast they build up and die away. Taken together, these two parameters are ordinarily referred to as loudness contour or dynamics. In a synthesis, they are produced by an amplifier which has its gain determined by one or more control voltages. Ordinarily the control voltages are added together and the gain is proportional to the sum so that any control input that is not connected represents zero voltage and does not contribute to the sum.

Since many sounds require that the amplifier be switched from an essentially isolating condition to full gain in 2 ms or less, the primary concern in designing a VCA is that none of the control voltage appear as part of the audio output. If it does, the result is at best annoying "pops" and "clicks" and at worst blown loudspeakers. In my VCA (Voltage Controlled Amplifier) this problem is eliminated by using the control voltage to set constant current source (Q3) common to both emitters of a differential pair Q1 and Q2. Since the gain of a transistor is proportional to its collector current, increasing the current increases the gain of the pair.

Increasing the collector current also increases the voltage drop across load resistors R9 and R10. Since these two voltages are equal for matched transistors they ap-

pear as a common mode voltage at the inverting and noninverting inputs of the operational amplifier IC1 and are rejected at the common mode rejection ratio of the amplifier (about 90 dB for the 748 op-amp). The audio signal on the other hand is applied to the base of Q1 and appears 180° out of phase between the two collectors of Q1 and Q2. When these out of phase signals are applied to the inputs of the op-amp they are slightly amplified and appear at the output.

WHERE PARTS ARE LOCATED on the PC board for the voltage-controlled amplifier.
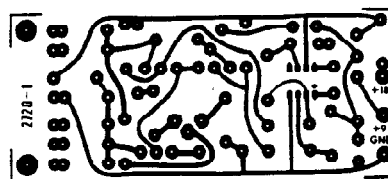
PC BOARD PATTERN for the voltage-controlled amplifier is half-size.

Control voltages are summed using a simple passive summing network (R4, R5 and R6). R1 and R2 allow the VCA to be used as a two-input audio mixer. Circuit values are selected so that when the inputs add up to 5V there is unity gain between the "0 dB" input and the output while there is a 3 dB power gain between the "3 dB" input and the output.

Test the completed module by connecting an audio signal source to one of the inputs and jumpering the output to an amplifier. Apply a variable 0 to 5V supply (such as one of the power supply's bias outputs) to one of the control voltage inputs and observe that varying the control voltage varies the gain. Note that there is no provision for dc isolation of the audio inputs so if a signal source other than the VCO is used in this test, an external isolation capacitor must be provided.

Of the modules described in this article, the VCA is the only one that requires any sort of calibration. Potentiometer R12 must be adjusted so that the characteristics of the differential pair Q1 and Q2 are as nearly identical as possible. The quickest and easiest way to perform this adjustment is to use the output of the control oscillator (described later) as a control voltage input source. With both audio inputs to the VCA open, jumper the 5V peak-to-peak output of the control oscillator to one of the VCA

control voltage inputs. Jumper the output of the VCA to the input of an amplifier and set the control oscillator for it's maximum frequency. At this point you will probably hear a "popping" from the amplifier at the same frequency as the control oscillator signal. This is the control voltage being coupled into the audio channel. Simply adjust R12 for minimum pop, indicating that the two transistors are matched.

All resistors are ½W 10% unless noted
R1, R8—22,000 ohms
R2—47,000 ohms
R3, R13—2,200 ohms
R4, R5, R6—150,000 ohms
R7—680,000 ohms
R9, R10, R14, R15—6,800 ohms
R11—10,000 ohms
R16, R17—15,000 ohms
R18—82,000 ohms
R19—100,000 ohms
R20—470 ohms
R21—1,000 ohms
R12—50,000 ohms. trimmer potentiometer
C1—100-pF ceramic
C2—.1-µF disc or mylar
C3, C4—100-µF 25V electrolytic
IC-1—748 op-amp
Q1, Q2—2N2712
Q3—2N3391
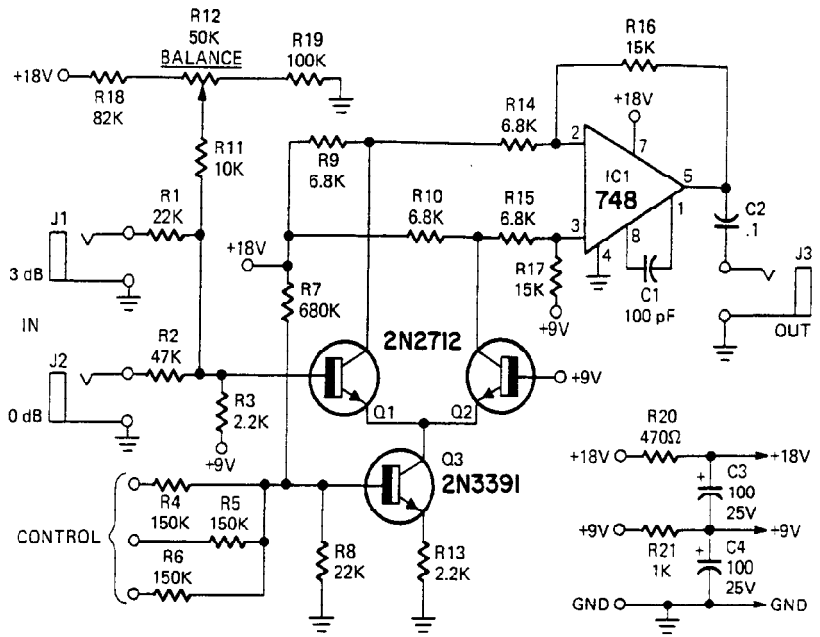
VOLTAGE-CONTROLLED AMPLIFIER uses a differential-pair fed from a constant-current source to drive the IC op-amp. Control voltages are summed in Q3's base circuit.

band-pass filter

Next to dynamics, a sound's most important property is timbre. Everybody has a feeling that timbre in some way relates to the body that a sound has, but in technical discussions this term refers to the constant or time-varying harmonic content of the signal.

Synthesizers produce various timbral properties using formant synthesist techniques. This is a fancy way of saying that instead of summing together a bunch of sine waves to arrive at a desired sound you start out with a waveform that has more harmonics than you need and use filters to eliminate the ones you don't want.

If the timbre is to be time-varying, as it should be to produce musically interesting sounds, there must be some convenient way to change the characteristics of the filter being used. Once again, voltage control comes to the rescue by allowing us to turn the job of varying the filter parameters over to automatic function generating circuitry.

In our band-pass filter, resistors R8 and R9 in combination with capacitors C3, C4 and C5 and the equivalent impedance of diode D1 form a parallel-T notch filter in the feed-back loop of the common emitter gain stage Q1. The combination of a gain block with a notch filter for negative feed-back produces a band-pass circuit.

Voltages applied to the three control voltage inputs are summed by resistors R10, R11 and R12 and cause a current to flow through diode D1. As the current flow through the diode increases, the diode's equivalent ac impedance decreases (because of the slope of the diode curve) and causes the center frequency of the notch filter to be raised.
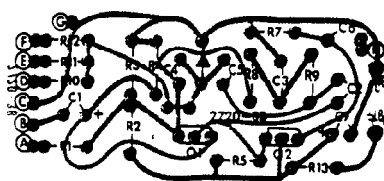
Potentiometer R6 varies Q1's gain by decreasing or increasing the emitter by-pass. As the amplification provided by the gain stage is increased it tends to overcome
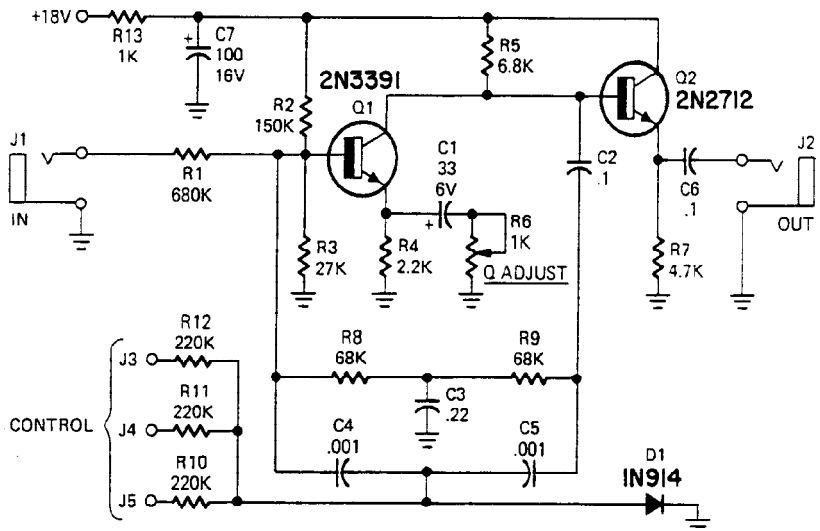

IN THE BAND-PASS FILTER, diode D1 replaces the shunt resistor in the parallel-T filter. Control votages vary D1's impedance and modify the filter's center frequency.

All resistors ½W 10% unless noted

R1—680,000 ohms	R6—1,000 ohms, linear taper potentiometer
R2—150,000 ohms	C1—33-µF 6V electrolytic
R3—27,000 ohms	C2, C6—.1-µF Mylar or ceramic
R4—2,200 ohms	C3—.22-µF Mylar
R5—6,800 ohms	C4, C5—.001-µF disc
R7—4,700 ohms	C7—100-µF 16V electrolytic
R8, R9—68,000 ohms	D1—1N914
R10, R11, R12—220,000 ohms	Q1—2N3391
R13—1,000 ohms	Q2—2N2712

WATCH TRANSISTOR LEAD PLACEMENT when wiring the band-pass amplifier board.
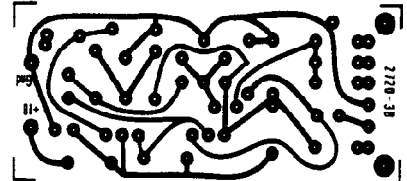
HALF-SIZE FOIL PATTERN for the active band-pass filter. Direct wiring is OK too.

more of the losses in the notch filter which has the overall effect of increasing the "Q" of the filter.

The filter is tested by supplying its input with a harmonic rich waveform—the pulse output of the VCO with the duration control at minimum is ideal—and listening to the output as a control voltage variable between 0 and 5 volts is applied to one of the control inputs. As the control voltage increases you should hear the unmistakable waa-waa of a band-pass filter being swept up and down. Advancing the Q control should make the effect more pronounced. It is one of the peculiarities of this type of filter that as the Q control is advanced the overall gain of the module is also increased but this is not particularly objectionable in a low-priced unit.
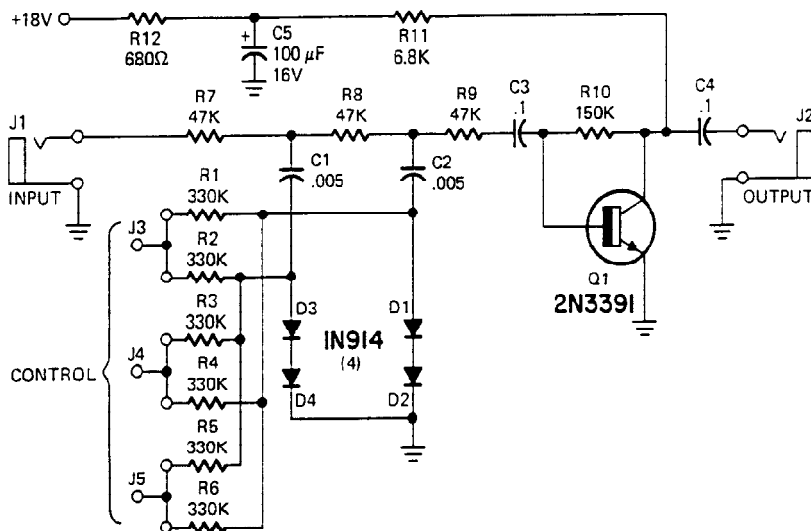
The biggest drawback of this filter is that it will "pop" if the control voltage is stepped very rapidly but you can rationalize this drawback away by reasoning that you really don't ever need to step the control voltage anyway. The nicest thing about the filter is that it's cheap. Several can be built for the cost of the next best design.

low-pass filter

Here we have a rather un-elegant, but low-priced, solution to the filter problem. While the bandpass filter is used to select a particular frequency from a harmonic rich source, the low-pass filter is used to eliminate all frequencies above some cutoff frequency.

The actual filter part of this circuit is the pi-section composed of resistors R7, R8 and R9. capacitors C1 and C2 and diodes D1 through D4. As with the bandpass filter, the equivalent impedance of the diodes is decreased by increasing the current flow through them. As the impedance of the diodes decreases the cutoff frequency of the filter rolls back. The gain stage Q1 is used to compensate for losses in the filter section.

Like the bandpass filter this module may be tested by supplying it with a harmonic-rich source and listening to the results as the voltage applied to one of the control inputs is increased from 0 to 5V. Unlike the band-pass the sound of this filter will lack the "resonant" quality and be more like the operation of a tone control turned toward accentuated bass.

All resistors ½W 10%
R1 thru R6—330,000 ohms
R7, R8, R9—47,000 ohms
R10—150,000 ohms
R11—6,800 ohms
R12—680 ohms
C1, C2—.005-µF disc
C3, C4—.1-µF ceramic or Mylar
100-µF 16V electrolytic
J4—1N914
Q1—2N3391

THE LOW-PASS FILTER IS A PI NETWORK feeding the base of Q1. Series diodes tune the filter by varying the impedance of the shunt (capacitive) legs.
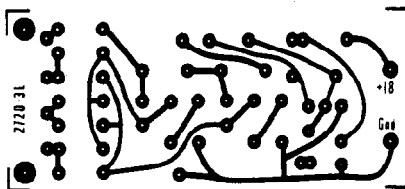
FOIL PATTERN for the low-pass filter. It should be copied twice the size shown.
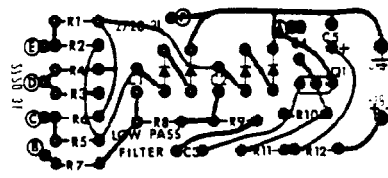
DIODE POLARITY IS IMPORTANT in the low-pass filter. Follow layout carefully.

envelope (function) generator

Now that we have built up a few of the basic synthesizer processing modules we need some way to perform all these automatic control functions we have been talking about.

The primary controller is of course the manual one, the keyboard controlled voltage source that we built last month. But that controller will most often be used to set the pitch of the VCO and what we're after now is producing desired loudness contours and all those terrific time-varying timbrel changes.

The most important automatic control voltage source is the envelope generator. Essentially this is a module that, on command, produces a voltage that rises to a pre-set level in a pre-determined time, sustains that level for a controllable length of time and then takes a pre-set length of time to decay back to zero. Obviously, this module will generate the attack and decay times required by the VCA to produce dynamics
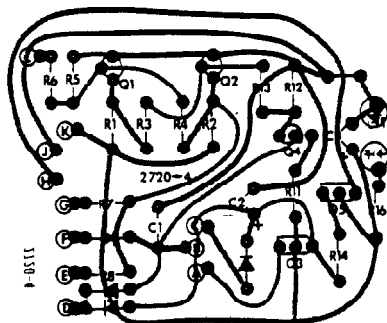
ENVELOPE GENERATOR parts layout is above. It's half-size foil pattern is at right.

but as we will see it also meets innumerable other needs.

When a short-duration pulse is applied to the input of the circuit shown, it causes bistable Q1 and Q2 to switch so that the collector of Q2 goes high. In this condition
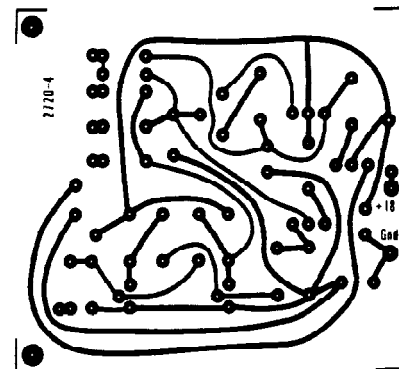
capacitor C1 charges through the "attack" control and forward biases diode D1. When the voltage reaches the triggering threshold of UJT Q4, a pulse appears across R12 which resets the bistable so that C1 dis-

SYNTHESIZER MODULES

charges through DECAY control R10 and diode D4.

The EXPAND switch is included to provide for the wide range of attack times that are useful in electronic music production. In the off position of this switch, capacitor C2 is charged by the current supplied by emitter follower Q3 and this voltage is in turn isolated by emitter follower Q5 and appears at J2 and J3 as the control voltage output. C2 discharges through D3 and the now grounded collector of Q2 during the decay portion of the output.

When longer attack times are required, switching S1 to the EXPAND position causes C1 and C2 to be paralleled thereby expanding the attack time by a factor of approximately 20. Decay times are not affected by this switch.

If a voltage step rather than a pulse is used to trigger the circuit the bistable is unable to reset until the input voltage is removed so the output voltage remains high until the triggering step is removed.

This module may be tested with a vom by reading the voltage between the output jacks and ground. The MANUAL trigger pushbutton can be used to trigger the generator for test purposes. With the expand switch on and both attack and decay controls rotated fully clockwise the output should take about 1 second to climb to 5V and another second to fall back to zero. As the attack and decay times are shortened the vom will be unable to follow them but an oscilloscope should show an attack time variable from 2 ms to 40 ms with the EXPAND off and 30 ms to 1 second with it on. Decay times should be variable from 5 ms to 1 second and there should be no interaction between the controls. When the MANUAL button is pressed and held the output voltage should rise to 5 volts and hold as long as the button is held down.   R-E
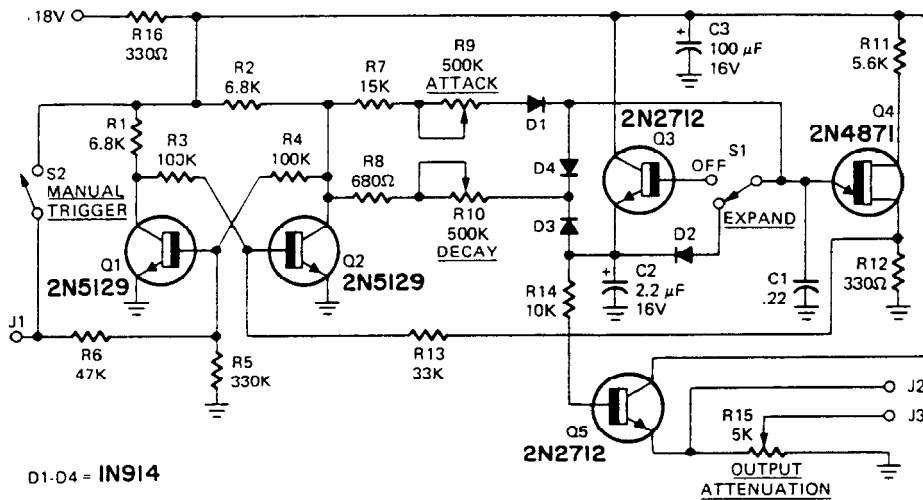
BISTABLE MULTIVIBRATOR, Q1-Q2, is the heart of this function or envelope generator. Fixed and variable outputs are at J2 and J3, respectively.

All resistors ½W 10% unless noted

R1, R2—6,800 ohms
R3, R4—100,000 ohms
R5—330,000 ohms
R6—47,000 ohms
R7—15,000 ohms
R8—680 ohms
R11—5,600 ohms
R12, R16—330 ohms
R13—33,000 ohms
R14—10,000 ohms

R9, R10—500,000 ohms, linear taper potentiometer
R15—5,000 ohms, linear taper potentiometer
C1—.22-µF Mylar
C2—2.2-µF 10V electrolytic
C3—100-µF 16V electrolytic
D1-D4—1N914
Q1, Q2—2N5129
Q3, Q5—2N2712
Q4—2N4871

More to come

One more module will be described next month. It is a special control oscillator used to produce such unusual effects as tremolo (a slow cyclic variation in the amplitude of a signal) and vibrato (cyclic variation in the frequency of a signal). A white-noise source is included as an integral part of this special control oscillator. White noise is indispensable for creating the sounds of wind, surf, snare drums, cymbals, and various assorted sounds of explosions.
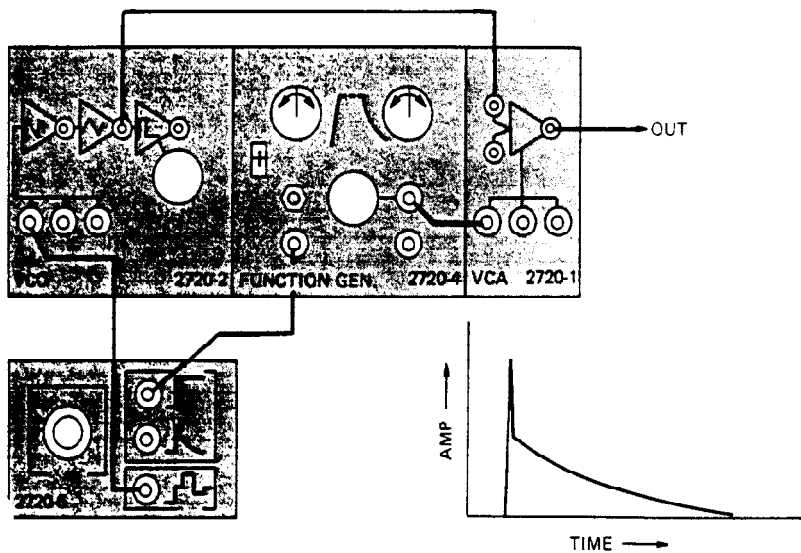
FIG. 4—WITH MODULES CONNECTED AS SHOWN the output of the function generator (see waveform) rises to its sustain level and remains there until the controller key is released.
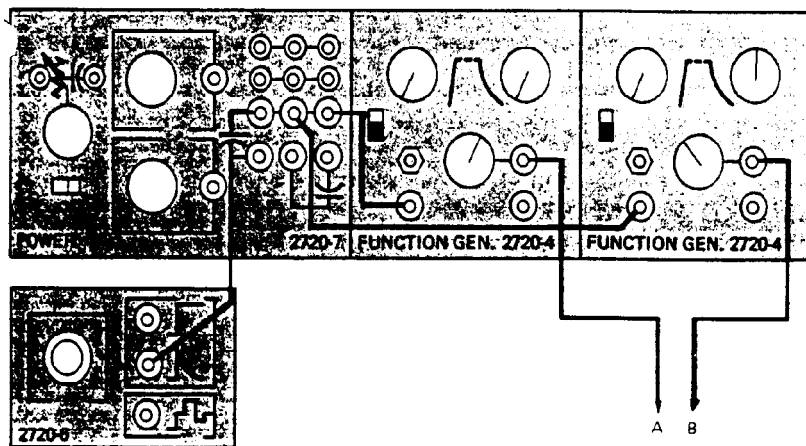

FIG. 5—TWO FUNCTION GENERATORS ARE CONNECTED as shown, to simulate certain percussive sounds. The resulting waveforms are determined by attack and decay settings.
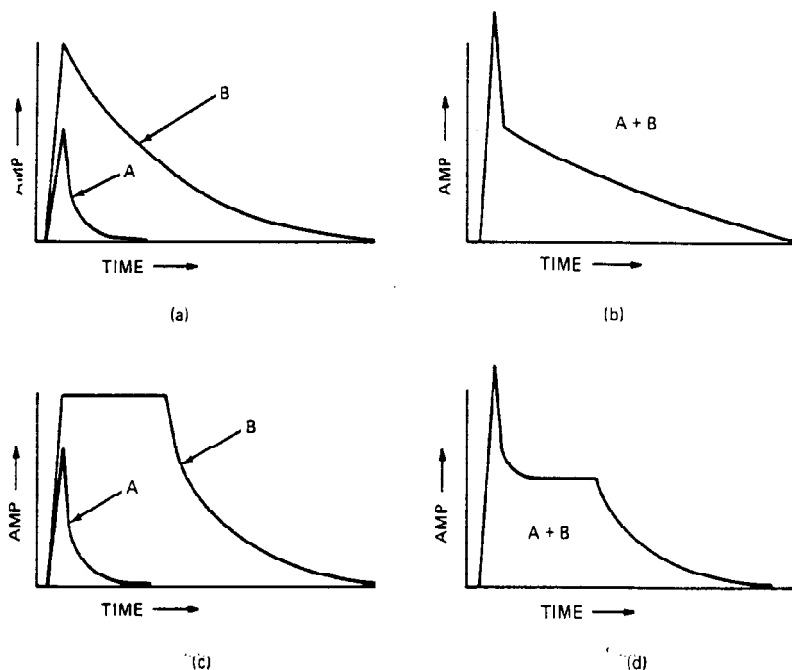

(a)

(b)

(c)

(d)

FIG. 6—HOW THE TWO FUNCTION GENERATORS, triggered by the common output of the controller are summed together to form the desired percussive waveform. Diagrams (a) and (c) show how the decay controls can be adjusted to develop various percussive effects.

generator being triggered from the controller's step output. (The operation of the controls for each module were covered in the first parts of this series. In the interest of brevity this information will not be repeated.) In this configuration the output of the function generator will rise to it's sustain voltage at a rate determined by the setting of the attack control, remain at that level as long as any one of the controller keys is held down and then decay at the rate determined by the setting of the decay control.

A little experimentation with the settings of the attack and decay controls will quickly show the importance of these parameters to the total effect that the sound produces. To completely eliminate the sustain portion of the envelope, switch the trigger input of the function generator from the controller's step output to it's pulse output. The short trigger pulse causes the function generator to cycle through the attack and immediately advance to decay.

Remember that we said that the arrangement of Fig. 4 could produce *almost* any imaginable envelope? Here's the exception. Fig. 5 shows a situation that is quite common for percussion instruments, it illustrates a case in which the instrument is played particularly hard. So hard that what can be thought of as an "overload" occurs. a short time during which the instrument is incapable of dissipating in a uniform exponential manner the applied energy.

As is shown by the envelope, the result is a brief time during which a large amount of energy is dissipated followed by the normal exponential decay. The function generator that we assembled doesn't provide for this type of envelope primarily because of cost but also because the envelope can be generated using two function generators with the added advantage of being able to, at other times, use the two modules separately. Our example illustrating this coincidentally makes a good point of the advantages of control voltage summation.

Fig. 6-a shows two function generators being triggered by the pulse output of the controller. Notice that **A** is set for the shortest possible decay while **B** is set for a significantly longer period. The outputs of these modules are routed to two of the control inputs of a single processing module—typically the VCA—where they are summed together to produce the equivalent envelope shown in Fig. 6-b.

If function generator **B** is triggered from the step rather than the pulse output of the controller the result is individual envelopes as shown in Fig. 6-c which sum together to produce another envelope that would be rare to the point of impossibility in a natural instrument.

There is one important point to note regarding multiple function generator arrangements and that is that the peak amplitude of the equivalent envelope is the sum of the amplitudes of the individual waveforms. For most of the equipment we've built this sum should not exceed the 5-volt design limit placed on control voltages. This same consideration also applies to any multiple control voltage situation.

How to add timbre

As important as pitch and dynamics are, they pretty obviously don't account for all the differences between the sounds of
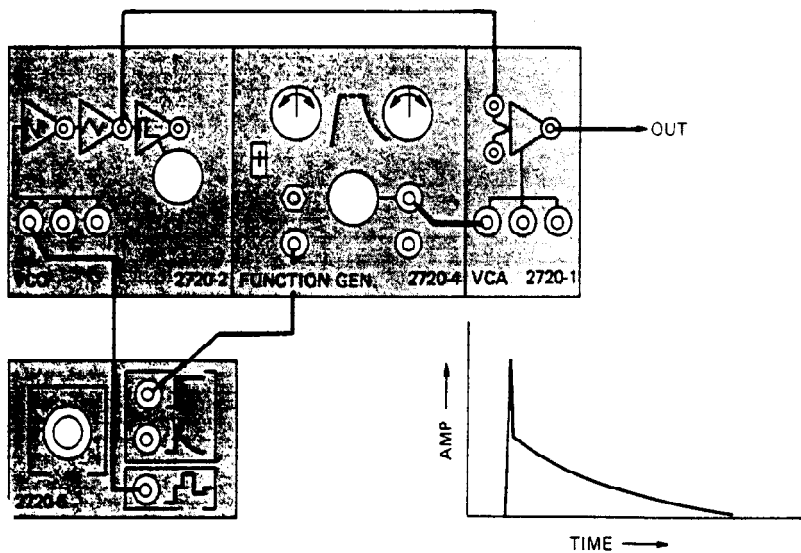
FIG. 4—WITH MODULES CONNECTED AS SHOWN the output of the function generator (see waveform) rises to its sustain level and remains there until the controller key is released.
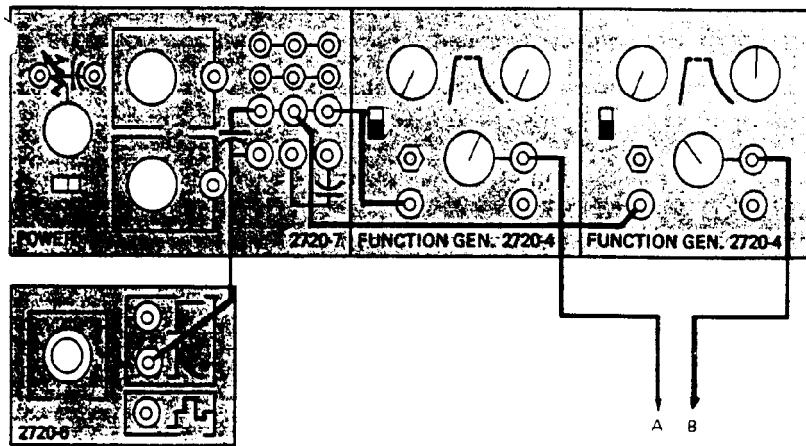

FIG. 5—TWO FUNCTION GENERATORS ARE CONNECTED as shown, to simulate certain percussive sounds. The resulting waveforms are determined by attack and decay settings.
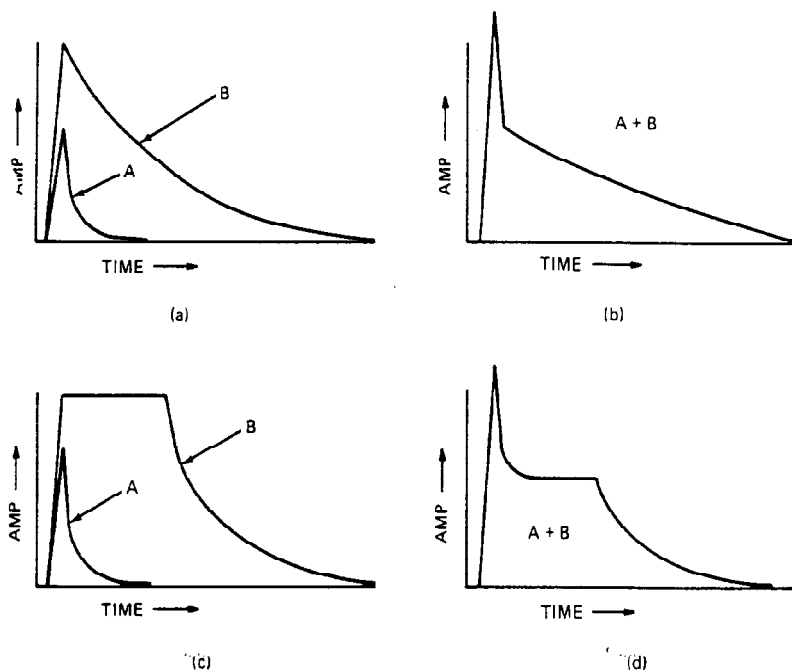

(a)

(b)

(c)

(d)

FIG. 6—HOW THE TWO FUNCTION GENERATORS, triggered by the common output of the controller are summed together to form the desired percussive waveform. Diagrams (a) and (c) show how the decay controls can be adjusted to develop various percussive effects.

generator being triggered from the controller's step output. (The operation of the controls for each module were covered in the first parts of this series. In the interest of brevity this information will not be repeated.) In this configuration the output of the function generator will rise to it's sustain voltage at a rate determined by the setting of the attack control, remain at that level as long as any one of the controller keys is held down and then decay at the rate determined by the setting of the decay control.

A little experimentation with the settings of the attack and decay controls will quickly show the importance of these parameters to the total effect that the sound produces. To completely eliminate the sustain portion of the envelope, switch the trigger input of the function generator from the controller's step output to it's pulse output. The short trigger pulse causes the function generator to cycle through the attack and immediately advance to decay.

Remember that we said that the arrangement of Fig. 4 could produce *almost* any imaginable envelope? Here's the exception. Fig. 5 shows a situation that is quite common for percussion instruments, it illustrates a case in which the instrument is played particularly hard. So hard that what can be thought of as an "overload" occurs. a short time during which the instrument is incapable of dissipating in a uniform exponential manner the applied energy.

As is shown by the envelope, the result is a brief time during which a large amount of energy is dissipated followed by the normal exponential decay. The function generator that we assembled doesn't provide for this type of envelope primarily because of cost but also because the envelope can be generated using two function generators with the added advantage of being able to, at other times, use the two modules separately. Our example illustrating this coincidentally makes a good point of the advantages of control voltage summation.

Fig. 6-a shows two function generators being triggered by the pulse output of the controller. Notice that A is set for the shortest possible decay while B is set for a significantly longer period. The outputs of these modules are routed to two of the control inputs of a single processing module—typically the VCA—where they are summed together to produce the equivalent envelope shown in Fig. 6-b.

If function generator B is triggered from the step rather than the pulse output of the controller the result is individual envelopes as shown in Fig. 6-c which sum together to produce another envelope that would be rare to the point of impossibility in a natural instrument.

There is one important point to note regarding multiple function generator arrangements and that is that the peak amplitude of the equivalent envelope is the sum of the amplitudes of the individual waveforms. For most of the equipment we've built this sum should not exceed the 5-volt design limit placed on control voltages. This same consideration also applies to any multiple control voltage situation.

How to add timbre

As important as pitch and dynamics are, they pretty obviously don't account for all the differences between the sounds of

various instruments. For example, the trumpet and French horn are both brass instruments with approximately the same attack, sustain and decay characteristics. They even overlap in pitch range but there would be little danger of mistaking the blaring, brassy sound of the trumpet for the muted, mellow tones of the French horn. The difference between the two is what we ordinarily call timbre and as was stated earlier, differences in timbre are essentially differences in the harmonic structure of the sound the instrument generates.

Since any imaginable waveform can be constructed by summing together sine waves of the proper frequency, amplitude and phase, the most obvious way to impart timbral differences to an electronic musical instrument is to get a bunch of oscillators going and sum their outputs together as needed to produce the desired waveform. This technique is known as frequency synthesis and is most often employed in electronic organs. Fig. 7 shows the result of summing a fundamental with its half amplitude second harmonic to produce the wave form shown by the solid line.

Mother Nature has developed a different method that she uses in what is probably the most versatile of all synthesis systems, the human voice. Most electronic music synthesizers employ the same technique, known as formant synthesis.

In formant synthesis the starting point is not a group of oscillators producing precisely time-related sine waves but a single oscillator that is cranking out a waveform rich in harmonics from the start. Rather than adding in sine waves as needed to produce a given voice, component frequencies are removed from the source as needed.

As an example, Table I gives the harmonic content of the three common waveforms that our VCO produces; ramp, triangle and square wave. Referring back to the wave in Fig. 7 again and comparing it to Table I we quickly see that if we remove all of the harmonics above the second that are present in a ramp the result will be the same as summing together a fundamental and it's second harmonic. Granted, this is a specially chosen, simple example but the basic principle applies to any waveform.

Some people will read that last paragraph and disagree because of the phase differences that cause one waveform to look entirely different from another even though the harmonic contents are identical. The answer to that is that as far as the sound produced is concerned constant phase differences have no effect. As evidence of this we offer the fact that a sawtooth that ramps up as time goes on sounds the same as one that ramps down even though the phase differences between the harmonics are as great as any you'll find. We can further state that phase differences cannot be heard unless they are changing in which case they are perceived as an apparent frequency shift.

Filters on the job

To use formant synthesis there must be some way of eliminating those unwanted harmonics and this is where our filters come in. Probably neither of the filter types we've built needs any explanation but briefly, the band-pass filter allows for attenuation of frequencies outside of a given frequency band while the frequencies
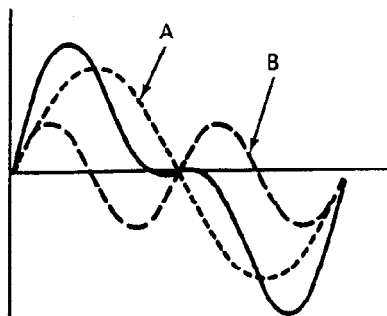
within the band are passed without alteration. In our filter the "Q" (how well the filter does it's job of attenuating out-of-band signals) is adjustable with a front panel control while the sum of the input control voltages determines the center frequency of the filter. Likewise, the low-pass filter attenuates all frequencies above the frequency of interest while allowing frequencies below that point to pass unaltered. In our low-pass filter increasing the control voltage simultaneously lowers the cut-off frequency and increases the rate at which higher frequencies are attenuated.

Due to space limitations we will leave the more subtle uses of the filters to the experimental discovery of the user and con-

centrate instead on some of the more spectacular effects that can be achieved. Fig. 8 shows a module arrangement that for lack of a better name we will call the "automute" connection. The arrangement is such that the control voltage from the keyboard sets the pitch of the oscillator while either of the controller trigger outputs (pulse works better than step) are used to key the function generator. As in the previous example the function generator output controls the VCA to provide appropriate attack and decay times. Unlike the previous example, however, the output of the VCO is routed through the band-pass filter before it passes through the VCA. The filter is also

FIG. 7—SUMMING A FUNDAMENTAL with its half-amplitude second harmonic produces the waveform shown by the solid line.

TABLE I

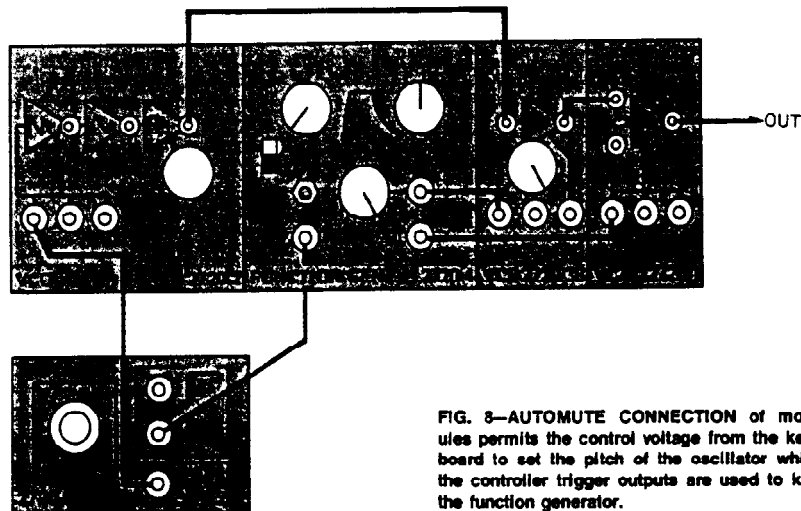| wave / harmonic	$\bigwedge\!\!\bigvee$ triangle	$\bigwedge\!\!\bigwedge\!\!\bigwedge$ ramp	$\prod\!\!\prod$ square
fundamental	$8/\pi^2$	$2/\pi$	$4/\pi$
2nd	— —	$1/\pi$	— —
3rd	$8/9\pi^2$	$2/3\pi$	$4/3\pi$
4th	— —	$1/2\pi$	— —
5th	$8/25\pi^2$	$2/5\pi$	$4/5\pi$
6th	— —	$1/3\pi$	— —
7th	$8/49\pi^2$	$2/7\pi$	$4/7\pi$
8th	— —	$1/4\pi$	— —
9th	$8/81\pi^2$	$2/9\pi$	$4/9\pi$

FIG. 8—AUTOMUTE CONNECTION of modules permits the control voltage from the keyboard to set the pitch of the oscillator while the controller trigger outputs are used to key the function generator.
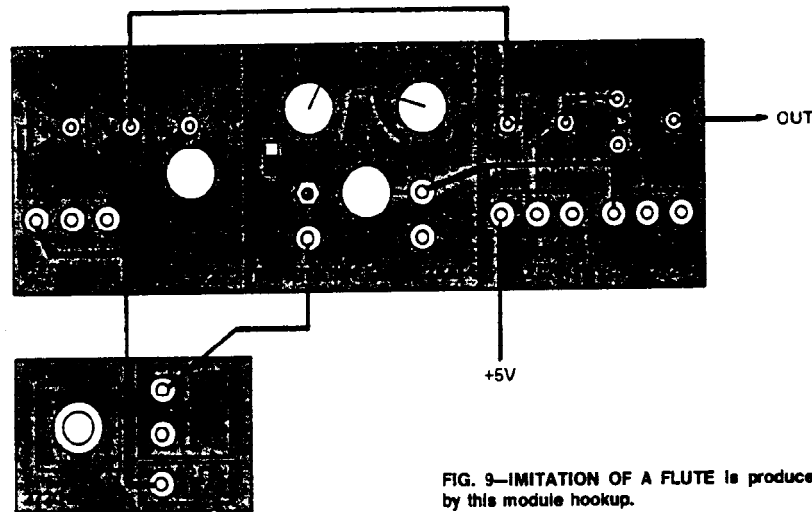

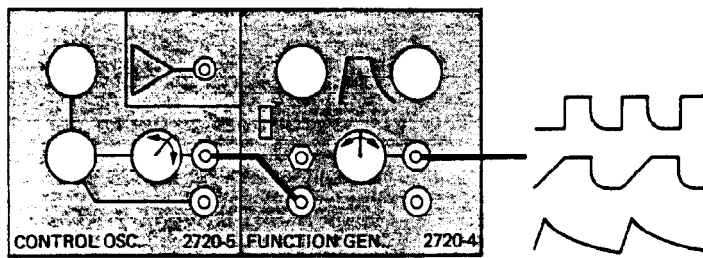FIG. 9—IMITATION OF A FLUTE is produced by this module hookup.

FIG. 10—FOR A LOW-FREQUENCY REPEATING WAVEFORM for percussion repeat effects, use this wiring arrangement. The sinewave output of the control oscillator can't do the job by itself.

under the control of the function generator. A pulse waveform of minimum duration has been chosen as the signal source in this example because of the evenly balanced, harmonic rich spectrum.

When any note is played with the above connection the function generator attacks rapidly and causes the VCF (voltage-controlled filter) to be resonant at some high frequency. During the decay portion of the note the center frequency of the filter slowly slides down through the frequency spectrum of the VCO's output pulses. The result is something like a performer muting a harmonica with his cupped hands but since the spike is a better source of harmonics than the predominantly square wave output of a harmonica and the filter is a more effective resonator than cupped hands the effect is quite naturally more spectacular.

A more standard sound can be achieved by increasing the pulse duration and backing off on pulse filter's Q control. You might also try using the function generator's output attenuator to lower the control voltage to the filter thereby lowering the upper limit of the resonant frequency. Also try summing a constant voltage from the power supply's bias sources into the control inputs of the VCF.

In Fig. 9 we have a simple arrangement that gives a convincing imitation of a flute. The connections are straight-forward; controller to VCO, step trigger to function generator, function generator to VCA. The triangle VCO output goes through the low-pass filter and then to the VCA for envelope shaping. In this example the filter is simply turned on by one of the bias supplies on our power supply module so that it attenuates the higher frequency content of the triangle. In it's fully "on" condition the filter rolls off at the rate of about 12 dB/octave and since there is no second harmonic in a triangle and the third harmonic is already 19 db down from the fundamental there is a total attenuation of the third harmonic of 43 dB. The output of the low pass filter is for all practical purposes a sine wave, the classic flute-like voice. Attack and decay times are adjusted to correspond to those typical of a flute.

Control oscillator/noise source

There is one remaining module that we've treated as an orphan child so far, the Control Oscillator/Noise source. This module is peculiar to the R-E synthesizer because in most other equipment the VCO is flexible enough to be used at very low frequencies. Our cost objectives were best met with a separate low-frequency oscillator. Among the effects produced using a low-frequency control voltage source are vibrato—a slow, rhythmic pitch variation—and tremolo, a slow variation in amplitude. These effects are produced by using the output of the control oscillator as one of the control-voltage sources for the VCO and VCA respectively.

There are times when you need a low-frequency repeating waveform with a shape other than a sine wave. For example, percussion repeat effects similar to staccato banjo picking require that the VCA be driven by a waveform such as the one shown in Fig. 10. The sine wave output of the control oscillator won't hack it by itself but it can be used as a repeating trigger
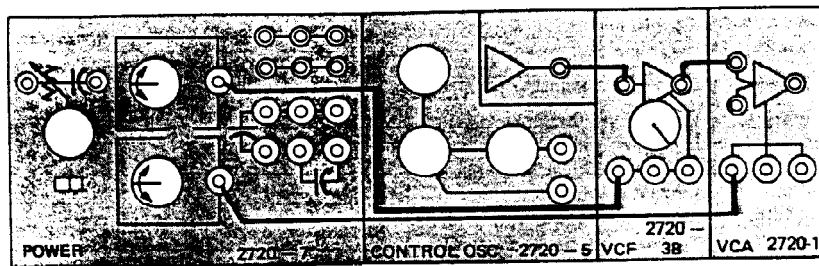
FIG. 11—NOISE IS USEFUL IN MUSIC SYNTHESIS. This hook-up generates wind sounds.

source for the function generator as shown. With this arrangement the attack and decay controls of the function generator control the attack and decay of the final output while the sustain is a function of the point on the sine wave at which the generator triggers and consequently of the settings of the control oscillator's output attenuator.

When Harry Oslon first started work on the old RCA Mark I and Mark II synthesizers back in the 1040's he was pioneering in a number of areas and not the least of these was the first use of noise in an electronic musical instrument. Up until that time the Ondiolines, Martinots, Theremins, etc. had without exception used only pitched sound sources. Because of that they produce less than natural sounds.

There are a number of stock phrases that accurately describe noise, phrases like "white noise is an equal probability distribution of all frequencies" or "pink noise is a Gaussian frequency distribution". While these are answers that display great erudi-

tion on the part of the explainer they don't do a lot for the 'splainee. Simply put, if you tune an FM radio to a spot between stations what you hear is noise in the tech-

nical sense. If you then play with the tone controls you are "coloring" the noise.

Noise as sound

It's easy to see why the first artisans of electronic music missed the signicance of noise. As you listen to it on the radio it doesn't appear to be the sort of thing that would be musically useful. But to illustrate it's use Fig. 11 shows an arrangement for producing the sound of the wind.

In other words, try everything. We've done a fair job of covering the basics involved but you have at your disposal a complete synthesis system. A few hours constructive play with the machinery will teach you more than a hundred written pages. **R-E**

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