Composer Emmanuel Ghent in the studio of the Independent Electronic Music Center. The paper-tape reader at the right is being used to program the voltage-controlled instruments at the center. The frequency counter, which is located at the left, is employed to check on the accuracy of the program that is used.

By

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ELECTRONIC MUSIC—
Its Composition & Performance

Introduced less than 20 years ago, this new type of music is rapidly assuming increasing importance to contemporary composers. This article describes the circuitry of some recently introduced electronic music-composing instruments and shows how these are employed to articulate this new musical language.

THE technology of electronics is ideally suited for application to the production (composition and performance) of music, as well as to its reproduction (broadcasting and recording). Music is, after all, a medium of communication between composer and listeners; it should permit the composer to produce any sound, or series or combination of sounds, to convey his musical message. The parameters of the sounds composers wish to control are basic to electronics: frequency, waveform, formant, amplitude, and duration. Oscillators, filters, amplifiers, and other electronic circuits capable of controlling musical parameters have been used extensively in all applications involving the generation and processing of analog (continuously varying) signals: radio and TV, analog computers, medical electronics, and many more. With some straightforward engineering and a little imagination, one can adapt familiar electronic circuits and systems concepts to the design of musical instruments, thereby greatly expanding the range of available sounds and increasing the composer's ability to control the sound parameters.

However, the language of music—the way in which sounds and sound patterns are used to convey messages—develops and changes slowly. The musical tastes of most of us are geared to the composers who lived and worked before this century. "Modern" music may tend to sound dissonant or unpleasant because the "meanings" of the sounds are generally different than those of earlier music.

A direct result of this reluctance to depart from established musical values is that musicians and the listening public have generally been slow in accepting new electronic musical instruments. Early instruments such as the Theremin, played by the free movement of the performer's hands in the space surrounding it, and the keyboard-controlled Ondes Martenot have been successfully used as solo instruments in the performance of orchestral music, but these instruments have not been accepted as the important additions to musical-instrument technology that they in fact are.

Actually, with very few exceptions, the only electronic musical instruments which have achieved commercial importance are those which are direct imitations of traditional instruments. These include monophonic (single-voice) instruments, such as the "Solovox" and the "Ondioline," and polyphonic instruments such as electronic guitars and the vast number of electronic organs now so aggressively competing with the piano for the place of honor in the home living room. Although we are generally familiar with these instruments, we would not say that they have revolutionized the language of music.

While the listening public is slowly adjusting its musical tastes in response to new developments, creative musicians are experimenting and pioneering in still newer musical languages. One of these new languages, the development of which began less than twenty years ago, is called "electronic music" and is assuming rapidly increasing importance to contemporary composers. This article will define electronic music and reveal how it is composed. It will also describe the circuitry of some recently introduced electronic musical instruments and show how they are employed in the articulation of this new musical language.

Classical Electronic-Music Composition

The introduction of the magnetic tape recorder immediately after the Second World War gave the composer the ability to store previously produced sounds and to physically shape and arrange them (by tape editing) into a musical composition. Recording media other than tape (disc and wire recording) existed before the tape recorder. However, no recording medium provides the high fidelity and editing ease of tape.

The tape recorder, used as a composing instrument, opened the door to electronic-music composition as it is usually practiced today. For the first time, the composer could create an entire finished composition and would not have to depend on performers to interpret his "message." He could use any sound that could be recorded or electronically generated. He could electronically process natural sounds in many different ways. He could compose series of sounds more closely and accurately spaced in time than any live performer could possibly produce. And finally, he could listen to his completed composition and change portions of it until he was satisfied with the finished product. Each of these possibilities could not have been conveniently realized before the advent of the tape recorder. Together, they constitute an entirely new and expanded means of musical expression—the central feature of electronic music.

At the present state of development, electronic music is defined as *the electronic generation and processing of audio signals, or the electronic processing of natural sound, and the manipulation and arrangement of these signals via tape recorders into a finished musical composition.* Although new techniques (to which the above definition may not apply) are being developed, the present definition specifically excludes the performance of traditional music on electronic instruments.

An electronic-music composer works in a studio which usually contains electronic signal generators (audio oscillators, white-noise generators), signal modifiers (filters, modulators, amplifiers, reverberation units, etc.), mixers, and at least two tape recorders. In general, all inputs and outputs are brought to a patch panel or other signal-routing facility so that the composer can set up connections between his instruments according to his requirements. A good set of power amplifiers and speakers, which enables the composer to hear exactly what he is producing, completes the basic studio equipment.

The first studios established in the United States were designed around instruments then commercially available. Laboratory test oscillators, white-noise generators, and filters, as well as commercial audio mixers, patch panels, and recorders, were installed. Variable gain amplifiers and assorted modulating devices were built from designs based on circuitry originally developed for communications equipment.

In order to work with such equipment, a composer carefully and patiently sets the operating parameters of each instrument (*e.g.*, frequencies of the oscillators, bandwidths of the filters, etc.) to achieve the desired sound and then records the sound. The segments of tape containing the sounds are then spliced together, one at a time, to produce the finished composition. This method of composition is now called "classical studio technique." A simplified block diagram of a typical classical studio is shown in Fig. 1. The University of Illinois electronic music studio, which is basically a classical studio, is shown in Fig. 2.

Voltage-Controlled Instrument Techniques

Classical studio technique has the advantage that composers can easily understand and master the processes involved. These include electronic tone and white-noise generation, filtering, modulation, amplitude control, reverberation, and tape manipulation—the "alphabet" of the new language of electronic music. However, classical composition tends to be tedious and time-consuming because each sound event must be generated and recorded individually. Moreover, it is difficult to produce complex, dynamically varying sounds with conventional laboratory and commercial audio equipment. New developments in equipment for electronic-music composition have therefore been directed at reducing the limitations of classical studio technique.

Engineers and composers now acknowledge that the consistent and systematic use of *voltage-controlled* instruments simplifies both the generation of complex, dynamically varying sounds and the arrangement of these sounds into a composition. *A voltage-controlled instrument has one or more operating parameters determined by the magnitude of an applied control voltage rather than by the settings of the panel controls.* It is generally easier to change a voltage rapidly and precisely than it is to reset panel controls with equal speed; also, the problems of changing the operating parameters of the instruments are reduced to the simpler problem of changing the control voltages determining the values of the parameters. Of course, in order to take full advantage of the benefits of voltage control, controlled instruments must have a fast speed of response and an accurate relationship between the magnitude of the control voltage and the controlled parameter.

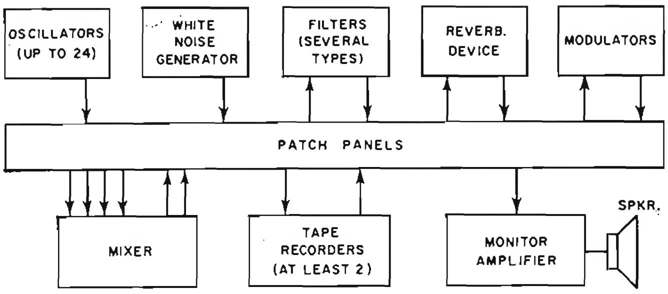
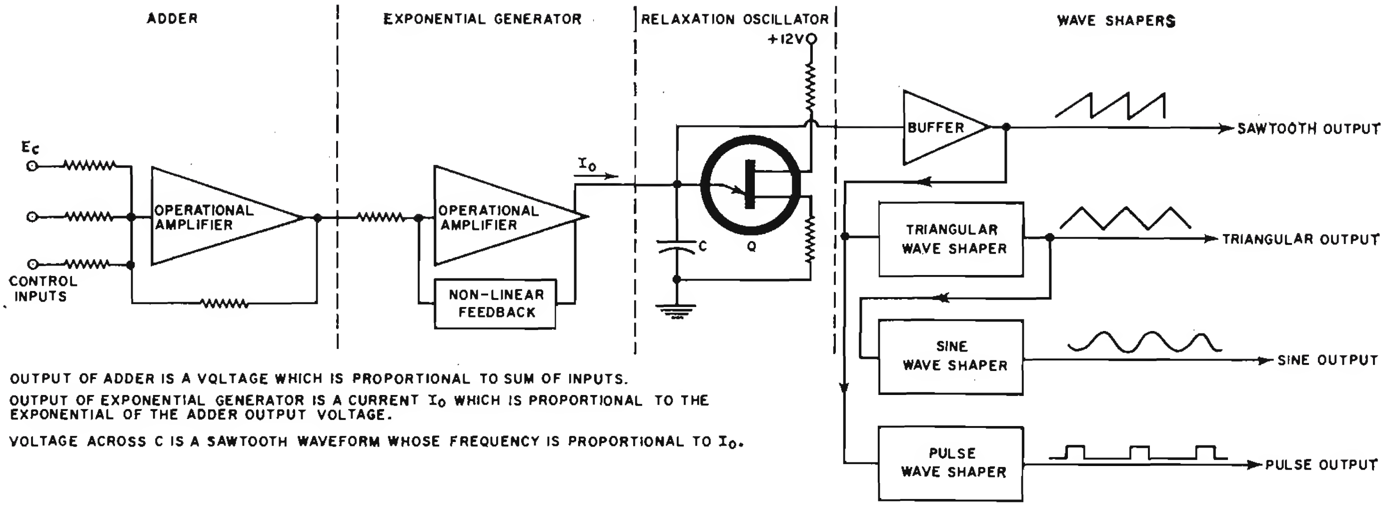


Fig. 1. Block diagram of a classical electronic music studio. Most such studios have used standard lab or audio instruments.

Three important classes of voltage-controlled instruments are now widely used by electronic-music composers: *oscillators, filters*, and *amplifiers.* A voltage-controlled oscillator (v.c.o.) may produce *audio signals* whose pitch is determined primarily by the frequency of oscillation and whose tone color is determined by the waveform and type of frequency modulation. V.c.o.'s are also used as *control-voltage* generators to periodically modulate other voltage-controlled devices. Finally, timing of musical events may be achieved by using the output of a slowly oscillating v.c.o. to *trigger* (initiate) the events.

Fig. 3 shows a simplified schematic diagram of a wide-range, high-quality v.c.o. Several control inputs are provided so that more than one type of frequency variation may be accomplished simultaneously. For instance, a slowly varying periodic voltage may be applied to one control input while the voltage at another input is stepped in fixed increments. The resulting output would then sound like a musical scale with vibrato (frequency modulation). The control voltages are added and a current I_o proportional to the exponential of the control-voltage sum is derived by two operational amplifiers. These circuits, which are shown in block form in Fig. 3, borrow their design concepts from analog computer technology. The exponential dependence

Fig. 2. University of Illinois Experimental Music Studio. Generating and processing equipment is on left, mixing and routing controls are in center, and the recorders are at the right.



OUTPUT OF ADDER IS A VOLTAGE WHICH IS PROPORTIONAL TO SUM OF INPUTS.

OUTPUT OF EXPONENTIAL GENERATOR IS A CURRENT I_0 WHICH IS PROPORTIONAL TO THE EXPONENTIAL OF THE ADDER OUTPUT VOLTAGE.

VOLTAGE ACROSS C IS A SAWTOOTH WAVEFORM WHOSE FREQUENCY IS PROPORTIONAL TO I_0.

Fig. 3. Diagram of a wide-range, fast-response voltage-controlled oscillator along with the output waveforms.

of the output current I_o upon the control-voltage sum means that I_o will change by a certain *ratio* for a given *increment* in control-voltage input change.

In virtually all musical uses of periodic signals, frequency ratios rather than absolute frequency differences are important. In fact, a given musical pitch interval is nothing more than a fixed frequency ratio. An interval of an octave is a frequency ratio of 2:1; an interval of a semitone (the smallest interval in the common tempered scale) is a frequency ratio of 1.059:1 (1.059 is the twelfth root of 2). Musicians can easily understand this constant of proportionality between control-voltage change and frequency ratio: a one-volt increase in the control voltages will double the frequency (increase it an interval of an octave); a $^1/_{12}$-volt increase in the control voltages will therefore increase the frequency one semitone. Thus, all tones in the tempered scale will be generated by integral numbers of $^1/_{12}$-volt increases in the control voltage. Other scales can be generated with different patterns of control-voltage change.

The output current I_o is used to charge timing capacitor *C*. This capacitor is discharged by unijunction transistor *Q* whenever it reaches the unijunction's breakdown voltage. The resulting voltage across *C* is a linearly rising saw-tooth whose frequency is proportional to I_o and therefore proportional to the exponential of the sum of the control-voltage inputs. With careful design and component selection, it is possible to build v.c.o.'s whose exponential-frequency/control-voltage relationship is musically accurate over a 6-octave (64:1) frequency range and still useful over a 10-octave (1000:1) frequency range.

The saw-tooth waveform appearing across *C* is itself extremely useful in synthesizing musical sounds, since it contains all of the integral harmonics of the fundamental frequency of oscillation. Subsequent filtering, which attenuates some harmonics and boosts others, is generally used to impart one of a wide variety of tone colors to the signal. However, additional waveshaping may be employed to change the saw-tooth waveform into entirely different waveforms.

Three waveforms which are also musically useful are the sine, triangular, and pulse waves. The sine ideally contains no harmonics other than the fundamental frequency. Its sound lacks brightness and, in terms of harmonic structure, is the simplest of any signal. The harmonic content of the triangular wave is only 12% of the total and consists entirely of the odd harmonics. Its sound is muted and hollow like that of a flute. Finally, the spectrum of the pulse waveform depends upon the relative widths of the positive and negative portions of the wave, but it is characterized by the absence of certain harmonics within the spectrum. For instance, when the positive and negative portions of the wave are of equal width (*i.e.,* when the waveform is a square wave), then all the even harmonics drop out, and the spectrum consists only of odd harmonics. The pulse may be used in synthesizing a wide variety of orchestral colors, from the violin to the clarinet, depending upon the relative widths of the two parts of the waveform.

The triangular, sine, and pulse waveform circuitry are indicated in block form in Fig. 3. All the waveform outputs are available simultaneously and additional timbral effects may be achieved by mixing two or more waveforms.

Voltage-Controlled Amplifiers

After frequency and duration, amplitude is the most important musical parameter. A voltage-controlled amplifier (v.c.a.) capable of varying an audio or control voltage is shown in Fig. 4. Like the v.c.o., the v.c.a. shown here incorporates an adder and exponential generator to process the control inputs. The amplitude-controlling elements are *Q*1 and *Q*2, a matched pair of junction transistors. These transistors are driven by an input buffer with very low output impedance.

Junction transistors have the characteristic that a given base-to-emitter voltage change will result in fixed *percentage* collector current change, regardless of the magnitude of the average collector current. Thus, as the standing current in the transistor is increased, the absolute collector current change for a given base-to-emitter voltage change will increase proportionally.

In the circuit in Fig. 4, the constant base-to-emitter voltage is assured by the low output impedance of the input buffer. The combined standing current through *Q*1 and *Q*2 is I_o. The collector current variations appear across *R*1 and *R*2 as voltage variations and are amplified further in the output buffer stage. Thus, the gain from signal input to signal output is proportional to I_o, which in turn is proportional to the exponential of the sum of the control input voltages. This means that the gain will increase by a given ratio for a certain incremental increase in the control input voltage. The relation between gain and control voltage is set so that a one-volt increase in the control sum will increase the amplifier gain by 12 dB. With careful selection of components, the v.c.a. control characteristic will be accurate over an 80-dB range.

The signal portion of the v.c.a. is entirely balanced so that rapid gain changes can be affected without common-mode level shifts appearing at the output. This is especially important in synthesizing percussive sounds or other sounds which change rapidly in level. In addition, the v.c.a. is entirely direct-coupled so that slow-moving control signals as well as audio signals may be processed.

Voltage-Controlled Filters

With slight additional circuitry, the v.c.a. shown in Fig. 4 can be converted into a voltage-controlled filter (v.c.f.). One very useful type of v.c.f. is shown in Fig. 5. The adder, exponential generator, input buffer, and control transistors $Q1$ and $Q2$ are the same as those in Fig. 4. The collector currents of $Q1$ and $Q2$ may be thought of as passing through four more transistor pairs ($Q3$ to $Q10$).

The inputs to each of these pairs are shunted with fixed capacitors C. At low frequencies, the reactance of the capacitor is much higher than the emitter-emitter resistance of the transistor pair, and the signal passes up the "ladder" of transistors with little attenuation. At high frequencies, however, the signal is shunted around the emitter-emitter input and is sharply attenuated by the time it "emerges" from the collectors of $Q9$ and $Q10$. Thus, the filter in Fig. 5 is a low-pass filter.

The cut-off frequency is that at which the reactance of the capacitor is equal to the emitter-emitter resistance of the transistor pairs. The capacitors are fixed and the input resistances of the transistor pairs are varied by changing the control current I_o. The filter is capable of accurate variations of cut-off frequency over a *three-decade* (1000:1) frequency range. The relationship between the cut-off frequency and the control voltage is exponential and is set so that it will be exactly the same as the relationship between the v.c.o. oscillation frequency and control voltage: a one-volt increase in the sum of the control voltages will double the cut-off frequency.

The signal currents are "read out" across the emitter-emitter resistance of $Q9$-$Q10$. The variation of this resistance with I_o is just right to ensure that signals of frequencies below the cut-off frequency remain constant in amplitude as I_o changes. The gain of the output buffer is set so that the "insertion loss" of the v.c.f. as a whole is zero dB.

The addition of feedback resistor R_F introduces a narrow resonant peak in the response of the filter at the cut-off frequency and thus converts the v.c.f. from a low-pass to a resonant filter. When a "noisy" sound with many frequency components is passed through a resonant filter, the output sounds pitched, the apparent pitch being close to the resonant frequency of the filter. A voltage-controlled resonant filter thus allows the composer to work with virtually any sound in producing pitch patterns.

Control-Voltage Generators

With voltage-controlled oscillators, amplifiers, and filters, it is possible to synthesize virtually any musical sound merely by generating a few simple control-voltage waveforms. A modern electronic-music composition system contains, in addition to the voltage-controlled devices, a variety of control-voltage generators.

The most important of these are the *transient generators*, which produce voltages which rise to a specified level with one time constant and later decay back to zero with another time constant. These transient control voltages are of great value in producing rapid changes in frequency, formant, or amplitude. In synthesizing a trombone sound, for instance, it is essential that the sound start off with low harmonic content. This is produced by applying a rising transient control voltage to the v.c.f. so that the filter first allows through only the fundamental of a waveform of high harmonic content and then allows through the harmonics. Conversely, the sound of a plucked string (for instance, a guitar sound) is synthesized by beginning with a tone of high harmonic content and then rapidly reducing the amplitudes of the harmonics. A falling transient control voltage is applied to the voltage-controlled filter in order to produce this effect.

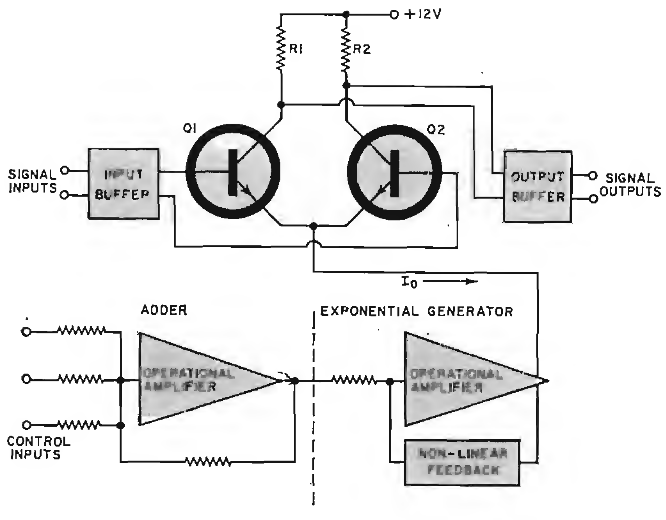


Fig. 4. Direct-coupled, balanced voltage-controlled amplifier.

In addition to transient control voltages, periodic control voltages (from oscillators) are useful in imparting frequency modulation (vibrato, trill, and other less conventional effects) to a v.c.o., and amplitude and formant modulation to a v.c.a. and v.c.f., respectively. Random control voltages, derived from white noise, are used to introduce uncertainty to any of the voltage-controlled parameters, thus adding aural interest to an otherwise steady tone. Finally, specialized function generators, such as staircase generators, are used as control voltages to create distinctive patterns of parameter variations.

Control-voltage changes from transient generators, oscillators, random voltage generators, and special-function generators create an enormously wide variety of dynamic parameter variations.

Fig. 5. Voltage-controlled low-pass filter. The introduction of R_F changes filtering mode from that of low-pass to resonant.

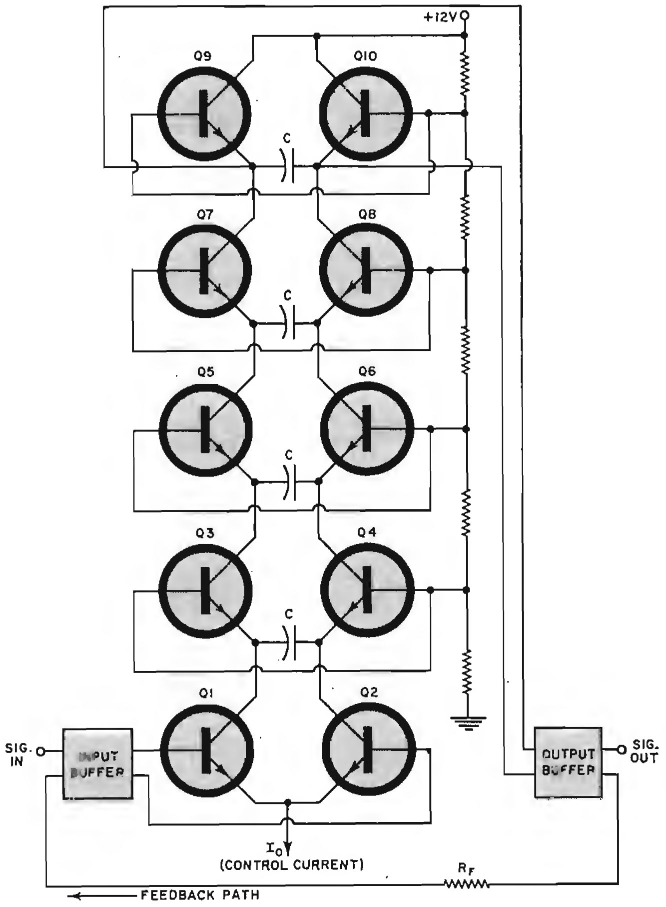


Fig. 6. (Top) Keyboard controller. Although the keyboard itself is a standard organ keyboard, the control-voltage output may be employed to control musical parameters other than the pitch. (Bottom) Linear controller. The musician slides his finger along the taut band to determine the control-voltage output.

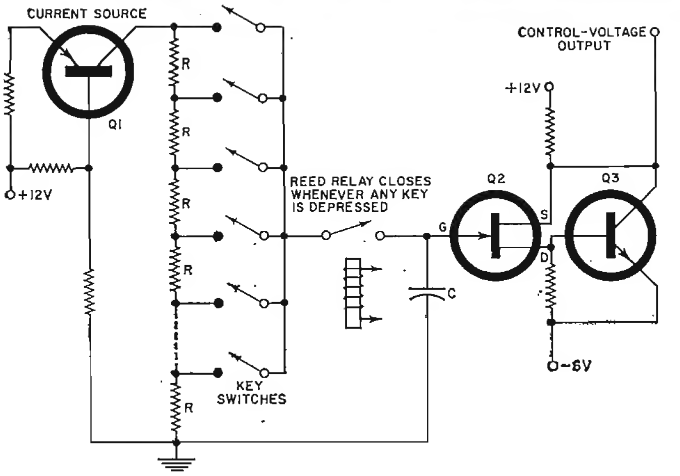


Fig. 7. Electronic circuitry of keyboard controller in Fig. 6.

The use of rapid, regular control-voltage patterns results in sounds which are perceived as having characteristic complex qualities rather than clearly varying parameters. Only slowly varying control voltages result in distinct changes in musical parameters.

Devices for producing these all-important control voltages may be either manually operated or pre-programmed for automatic composition. Two types of manually operated control devices are shown in Figs. 6 and 7. Fig. 7 is a schematic diagram of a manual controller which produces one of 61 discrete, equally spaced control voltages. A constant-current source consisting of *Q*1 and its associated components supplies current to a series of resistors *R*. Each key switches in one tap on the divider string. The voltage at the tap is used to charge capacitor *C* through the reed relay which closes whenever any key is depressed. When the key is released, the reed relay opens and the capacitor holds its charge until the next key depression recharges it to a different value. A very high input impedance unity-gain amplifier, consisting of field-effect transistor *Q*2 and junction transistor *Q*3, delivers a control voltage equal to the voltage across *C* to any of the voltage-controlled devices. A photograph of a keyboard controller incorporating this circuitry is shown in Fig. 6 (top).

Fig. 8. The Moog Synthesizer II shown below is an audio-signal generating, processing, and controlling facility for electronic-music composition. The keyboard controller and the linear controller just above it permit control of the circuits by composer.

Fig. 6 (bottom) is a photograph of a manual controller which produces a continuously variable control voltage rather than a series of discrete voltages. The circuit is the same as that shown in Fig. 7, except that the series string of fixed resistors is replaced by a long strip of resistive material, and the bank of key switches is replaced by a single taut contact band which is positioned over the resistance ribbon. The composer moves his finger along the taut band to produce continuous changes in the control-voltage output.

Fig. 8 shows a modern signal-generating, processing, and controlling system for electronic-music composition. Except for the controlling devices, all the instruments are modular and are mounted in a single console cabinet. In addition to a full complement of v.c.o.'s, v.c.a.'s, and v.c.f.'s, this system contains a white-noise generator, a bank of half-octave bandpass filters, a reverberation unit, a multi-channel mixer, and a bank of transient control-voltage generators. The system uses silicon solid-state devices exclusively and is powered by a single regulated power supply. Interconnections between the instruments are set up by patch cords. Levels and impedances of the inputs and outputs are set so that the composer can establish all the basic interconnections simply by patching between the appropriate jacks. Thus, the composer is able to think in terms of "operations" (*e.g.*, frequency modulation, filtering, mixing, etc.) and does not have to concern himself with the details of the instrument circuitry that is used.

New Trends

The early development of classical studio composition technique has focused largely on the tape recorder as the means of assembling and manipulating sounds. While this path of development has given composers immediate access to the advantages of electronic signal generation and processing with simple audio equipment, it has also pointed up the relative inefficiency of tape editing in the composition of music. A piece of music composed in a classical studio may take months or even years to realize, and much of this time is spent in tape manipulation.

The most important applications of tape editing are the arrangement in time of a series of sounds and the changing of the time scale of individual sound events. Both of these functions can be performed by applying the appropriate control-voltage variations to a system of voltage-controlled instruments. The control-voltage variations can be programmed in advance of the actual signal generation or can be determined by the musician while the signal generation is in process. The first is called *programmed composition*, while the second is called *real-time performance*.

The first important device to

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Electronic Music

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be built for programmed composition is the *RCA* synthesizer, illustrated in Fig. 10. A punched paper tape, much like a piano roll, is used to specify a set of parameters every 1/30 second. The *RCA* synthesizer does not use voltage control but employs passive component switching to achieve the parameter variations. This device is located in one of the studios of the Columbia-Princeton Electronic Music Center and has been used for the realization of several important electronic-music compositions. The high cost of the instrument is one of the reasons why more devices of this particular type have not been built.

Using Voltage Variations

Instruments for programmed composition employing control-voltage variations are inherently less expensive than those employing component switching and consist of a modest collection of voltage-controlled devices and one or more programmable control-voltage generators. A simple programmable control-voltage generator, called a sequencer, is based on a ring counter. A block diagram of a typical sequencer is shown in Fig. 9. Only one stage of the ring counter is "on" at a time. A timing pulse turns that stage "off" and the next stage "on." When a given stage is "on," it applies a fixed direct voltage across one or more programming potentiometers associated with it; when it is "off," the voltage across the potentiometers falls to zero.

The voltages at the wiper arms of all the programming potentiometers are added by a d.c. adder circuit. All these voltages are zero except the voltage of the "on" stage; the sequencer output is thus a voltage which changes from one preset value to another upon receipt of a timing pulse. The composer is able to set the programming potentiometers in advance to produce a given sequence of parameter variations, and he can produce the sequence simply by initiating the timing pulses. A control-voltage sequence can further be used to control a v.c.o. which is connected so that it produces timing pulses, thus facilitating the programming of event timing as required.

Paper-Tape Programming

The sequencer can be pre-programmed for only as many events as the number of sequencer stages, after which it repeats the sequence. Thus, the sequencer can eliminate much, but not all, splicing. The next step in programming capability is the continuous

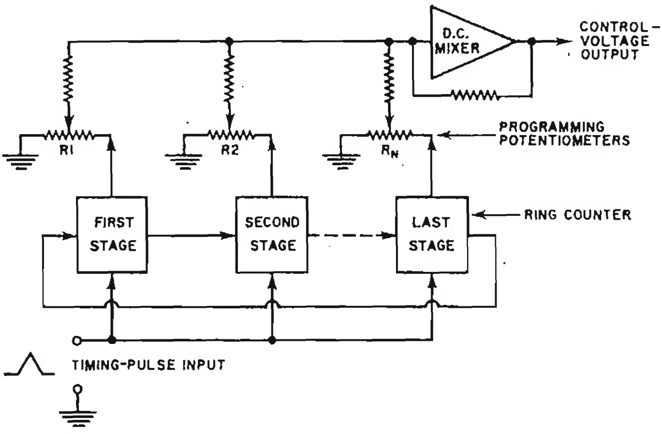
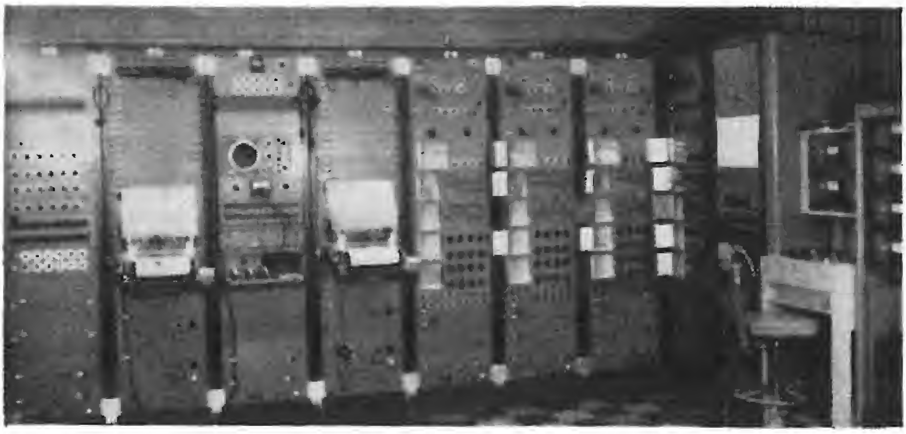


Fig. 9. Block diagram of a simple control-voltage sequencer.

Fig. 10. The RCA synthesizer, located at the Columbia-Princeton Electronic Music Center. The rolls of paper at the center of the photograph are employed to program the entire instrument.



programming of control voltages *via* paper tape. We have used conventional 8-track paper-tape readers to program passages of several thousand sound events. The passage is recorded in real time in its entirety, and this almost completely eliminates the necessity of splicing. Programmed composition of fast, intricate passages *via* paper tape generally takes about one-tenth the time of classical studio composition and, because the program is in digital form, is inherently accurate. The lead photo illustrates a portion of a typical studio in which a simple paper-tape reader is being used to program a bank of voltage-controlled oscillators and voltage-controlled amplifiers.

Using Computers

A further increase in programming capability, which has recently been developed, is achieved by using a small digital computer and a digital-to-analog converter to produce the control voltages. The converter itself can be programmed to accept coded information from the computer and speeds the composition process to a point where it is nearly as fast as composing traditional music in conventional notation. Prices of small computers are now in a region such that programmed performances of electronic music without tape recorders are entirely feasible.

Real-time performance instruments based on voltage-controlled circuitry have also been developed in recent years and have been played in public concerts of new music. The "ultimate" performance instrument, on which the performer can produce any sound or combination of sounds in real time, is yet to be developed. The main problem is the design of manual-control devices which permit the performer to continuously specify all the parameters of the sounds. This problem is one of "human engineering" and will undoubtedly take years of experimentation, on the concert stage as well as in the laboratory, to solve completely. However, even the simple performance instruments which have already been built have opened new musical horizons to composers and performers alike, and a new type of electronic music, composed for live performance, may develop apart from recorded electronic music.

Note: The Independent Electronic Music Center, a non-profit educational membership corporation, engages in several activities related to electronic music. One of these is the publication of the Electronic Music Review, *a quarterly magazine devoted to matters of interest to electronic-music composers, engineers, performers, and listeners. Interested readers are invited to send for further information to the Independent Electronic Music Center, Trumansburg, New York 14886.* ▲