and a random vibrato, respectively. The amplitudes and frequencies of the periodic and the random vibratos can be controlled separately, and thus these amplitudes and frequencies constitute four additional input parameters. The random generator is a unit whose average amplitude is controlled by its upper input, and whose bandwidth, or average rate of variation, is controlled by its lower input.

Each of the unit generators consists of a block of a few computer instructions. By assembling particular groups of generators, almost any desired properties of the output sound wave may be achieved and controlled. The computation time is roughly proportional to the number of generators, and the number of input parameters tends to increase with the number of generators. Thus, complexity of the instrument-unit is paid for both in terms of computer time and in terms of the number of parameters the composer must supply for each note. In general, the complicated instrument-units produce the most interesting sounds, and the composer must make his own compromise between interest, cost, and work.

In supplying specifications for an instrument-unit, the composer does not have to be concerned with the computer instructions represented by each unit generator. A simple language is available by means of which he can supply the specifications in a manner no more complicated than drawing a diagram such as that of Fig. 2. About ten different types of generators are available, and new ones may easily be defined. However, the generators most frequently used are those shown schematically in Fig. 2. Most composers wish to use a number of instrument-units, and these are distinguished simply by identifying numbers. If two or more instrument-units are to play simultaneously, the samples they generate are simply added together. This operation corresponds to the addition of the sound pressure waves from several sources in air.

The Score

Once the composer has supplied specifications for the orchestra, he must prepare a score giving the parameters of the notes he wishes played. An example of a score is given in Table 1. It corresponds to the conventional musical score of Fig. 3. Two instrument-units, of the type shown in Fig. 2, are assumed to be available; these are designated instrument 1 and instrument 2. Column 1 of Table 1 is an operation code which indicates that a note is to be played; column 2 designates the instrument-unit on which the note is to be played; column 3 gives the starting time of the note; column 4 gives the duration of the note; and columns 5 to 10 supply the input parameters required by the instrument-unit. Both the number of these parameters and their arrangement depend entirely upon the specifications the composer has supplied.

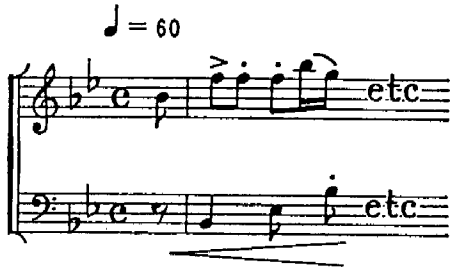

Fig. 3. A conventional score, corresponding to the computer score of Table 1.

To play the music, the computer reads a line from the score, at the appropriate time inserting the parameters given in the score into an instrument-unit and activating the instrument-unit so that it may generate numbers equivalent to the duration of the note. The entire sequencing process is automatically taken care of by the program and need not concern the composer.

Musical Examples

The best way to form an opinion about computer music is to listen to some. A commercial record is now available (*4*). However, a certain amount of discussion may be useful. A large number of compositions have now been produced by computer. They range from 16th-century music for the recorder to 12-tone music; from classical to popular music; from serious compositions by professional composers to acoustic experiments by psychologists; from pieces formed entirely of conventional tones to pieces formed entirely of random noise.

An outstanding advantage is the precision of the computer. Effects are exactly reproducible. Very complex effects, such as simultaneous synchronous tremolo and vibrato of two notes, can be obtained. Exact rhythmic patterns, such as the playing of seven notes in one voice against five notes in another voice, are as easy to produce as any other note sequence. Chords can be shifted in frequency with a glissando while the frequency ratios of the various voices are maintained.

The computer is also very flexible. When sufficient effort has been expended in supplying specifications for

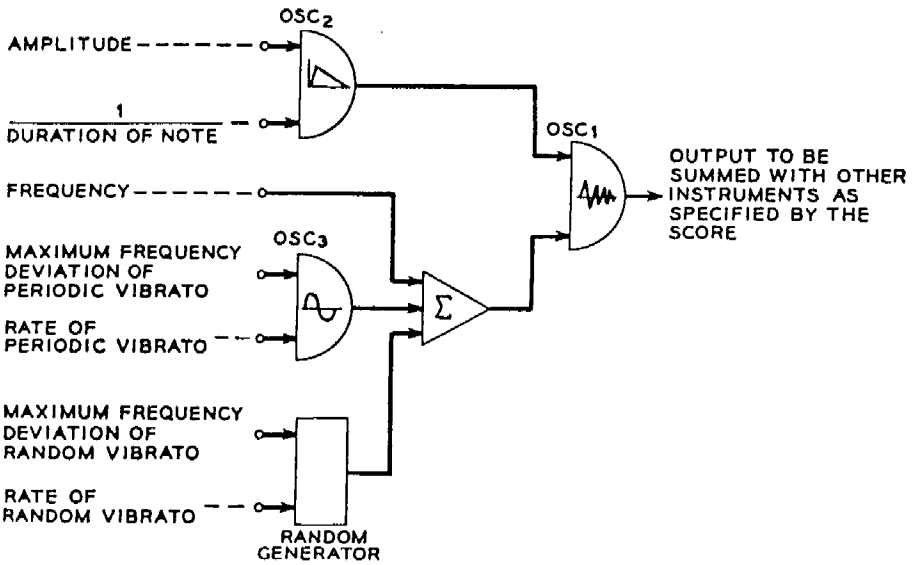

Fig. 2. Schematic diagram of a typical instrument-unit in the computer orchestra. The diagram represents a section of the computer program. In order for the computer to produce a note, numerical values for the note parameters shown at the left of the diagram are stored in the program. The program then generates samples of the sound pressure wave form.