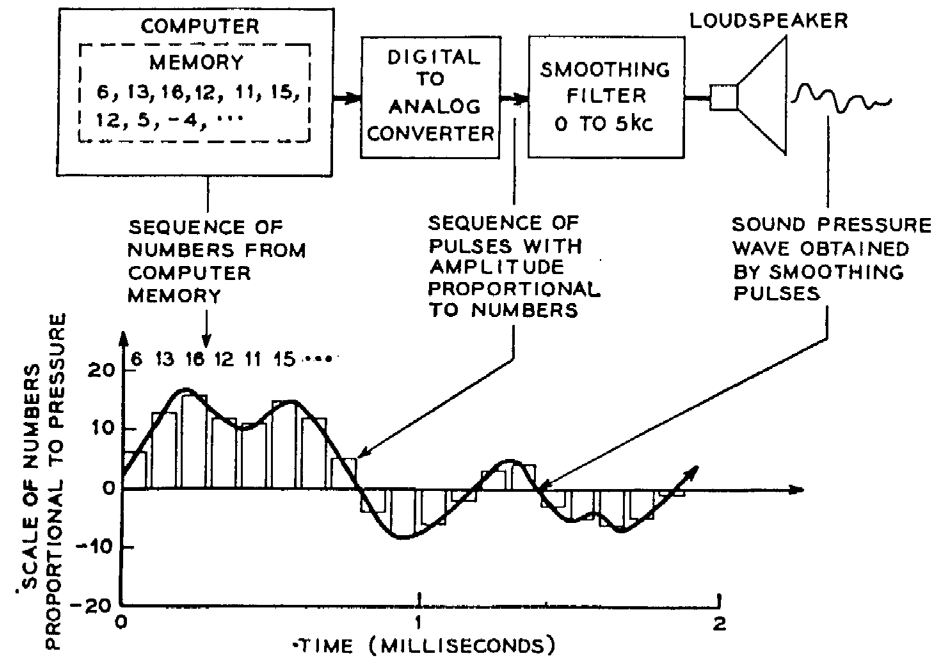

Fig. 1. Schematic diagram depicting the conversion of a sequence of numbers stored in a computer memory to a sound pressure wave form. The sampling rate is 10,000 numbers per second to yield a bandwidth of 5000 cycles per second for the sound wave.

of output is required from the computer, and hence the computation costs are less. The disadvantage is that the only sounds that can be generated are those produced by the particular electronic apparatus employed, and hence the generality of the sampling process is not attainable.

The work described here, which was done at the Bell Telephone Laboratories, is based entirely on the sampling method.

Playing a Computer

To specify individually 10,000 to 30,000 numbers for each second of music is inconceivable. Hence, the numbers-to-sound conversion is useless musically unless a suitable program (set of computer instructions) can be devised for computing the samples from a simple set of parameters. The central contribution of the Bell Telephone Laboratories to computer music is a program for computing the many samples in a note from the few parameters characterizing it. The details of the program determine the limits of the sounds now obtainable (from the standpoint of practicality) with a computer. The program represents a compromise between a general procedure, through which any sound could be produced but which would require an inordinate amount of work on the part of the composer, and a very simple procedure, which would too greatly limit the range of musical sounds obtainable. In order to give the composer flexibility between these two extremes, the program is divided into two parts. In the first part the composer specifies, in computer language, the characteristics of a set of musical instruments. The program unit that represents the instrument (or the "instrument unit") may be as simple or as complex as he desires. He then prepares a score consisting of a list of notes to be played on the instrument-units he has created. The samples of sound wave are generated by putting the score, in a form the machine can read, into the computer, together with the instrument-units, and turning on the computer. The numerical output is recorded on a digital magnetic tape for subsequent conversion to acoustic form.

The interconnected blocks of program which make up the instrument-unit are called unit generators. There are a number of different types of unit generators, each of which has a specific function. A typical instrument-unit is shown in Fig. 2. This instrument-unit is composed of five unit generators; three of them are oscillators, one is a random-number generator, and one is a summing circuit. Each oscillator has two inputs and one output. The upper input specifies the amplitude of the output; the lower input specifies the frequency of the output. The wave shape of the output need not be sinusoidal and can, indeed, be any one of 20 arbitrary functions stored in the computer memory. In the example given, the wave shapes are sketched on the oscillators, oscillator 1 producing a damped sinusoid, oscillator 2, a triangular attack-and-decay function, and oscillator 3, a sinusoid.

This particular instrument-unit produces notes with controlled attack and decay and with a frequency variation or vibrato. Oscillator 1 produces the main frequency, which, for example, for note A of the musical scale would be about 440 cycles per second. The amplitude of the output of oscillator 1 is modified by oscillator 2, which imposes a desired attack-and-decay function. The frequency of oscillator 2 is such that it goes through exactly 1 cycle of oscillation per note. Such low frequency operation is quite feasible for oscillators used in computer programs. The amplitude of the note is controlled by the upper input to oscillator 2, and this amplitude is one of the input parameters which the composer must specify for each note. The frequency of oscillator 1 is the sum of three components, one being the center frequency of the note (an input parameter), the other two being a periodic

Table 1. A typical computer score. The corresponding conventional score is shown in Fig. 3.

Operation code	Instrument No.	Starting time (sec)	Duration (sec)	Loudness (arbitrary units)	Frequency (cy/sec)	Periodic vibrato		Random vibrato	
						Amplitude (cy/sec)	Frequency (cy/sec)	Amplitude (cy/sec)	Bandwidth (cy/sec)
Play	1	0.0	0.25	1	466	0	0	7.0	6
Play	1	.5	.25	3	698	0	0	10.5	7
Play	1	1.0	.125	5	698	0	0	10.5	7.5
Play	1	1.5	.125	7	698	0	0	10.5	8
Play	1	2.0	.25	9	932	0	0	14.0	8.5
Play	1	2.25	.125	10	784	0	0	11.7	9
Play	2	0.5	.50	1	116.5	1.7	6	0	0
Play	2	1.5	.25	5	156	2.3	7	0	0
Play	2	2.0	.125	10	233	3.5	8	0	0