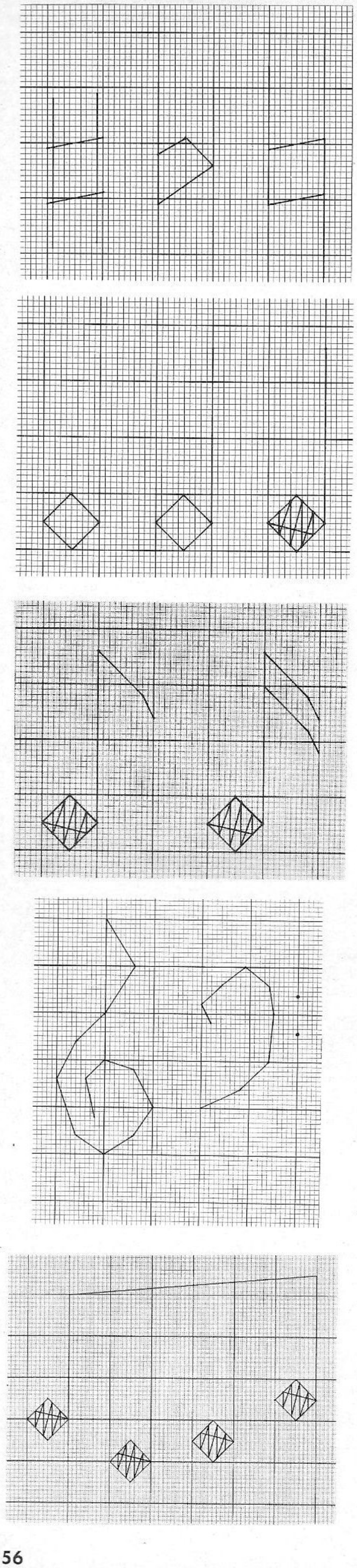


Reading from the top down, the first four illustrations at the left show how music symbols are constructed from a small number of lines to minimize flicker on a refreshing display. Because the coordinates are in hundredths of inches, the note heads of quarter, eighth, and sixteenth notes appear to be filled in when drawn to scale.

The last illustration shows the beam for a grouping of eighth notes anchored at one end to the top of a stem 0.3 inches in length on the highest note in the group. The slope of the beam is obtained from the vertical positions of the first and last notes of the group. The stems of the remaining notes are drawn to meet the beam as shown.

One product of a university project combining a computer and peripherals with an organ keyboard is the output of musical notation

Capture and Display

For more than a century various attempts have been made to obtain a written record of music as it is played at the keyboard. This problem has proven to be so difficult that the various inventors have chosen to dispense with traditional music notation and to produce a simplified graphical record. Attempts to produce music notation mechanically have been generally unsuccessful. Even today, music is printed by offset photolithography, with the master copy prepared by hand.

As part of an on-going research project at the Univ. of Utah, a music system has been developed which brings together a DEC PDP-8 computer, a CTC Datapoint 3300 terminal, a Tektronix 611 display, and a Schober electronic organ. As shown in Fig. 1 (photo at far right), the organ, display, and terminal are arranged to permit convenient interaction between the user and the system. Fig. 2 (page 58) illustrates information flow through the system—from printed score via a music description language through a terminal, or from keyboard activity, to printed score via the Tektronix display or hard copy plotter, or to an actual performance of the music via the organ tone generators. Within the computer various transformations upon the music are possible, including key transposition and tempo modification.

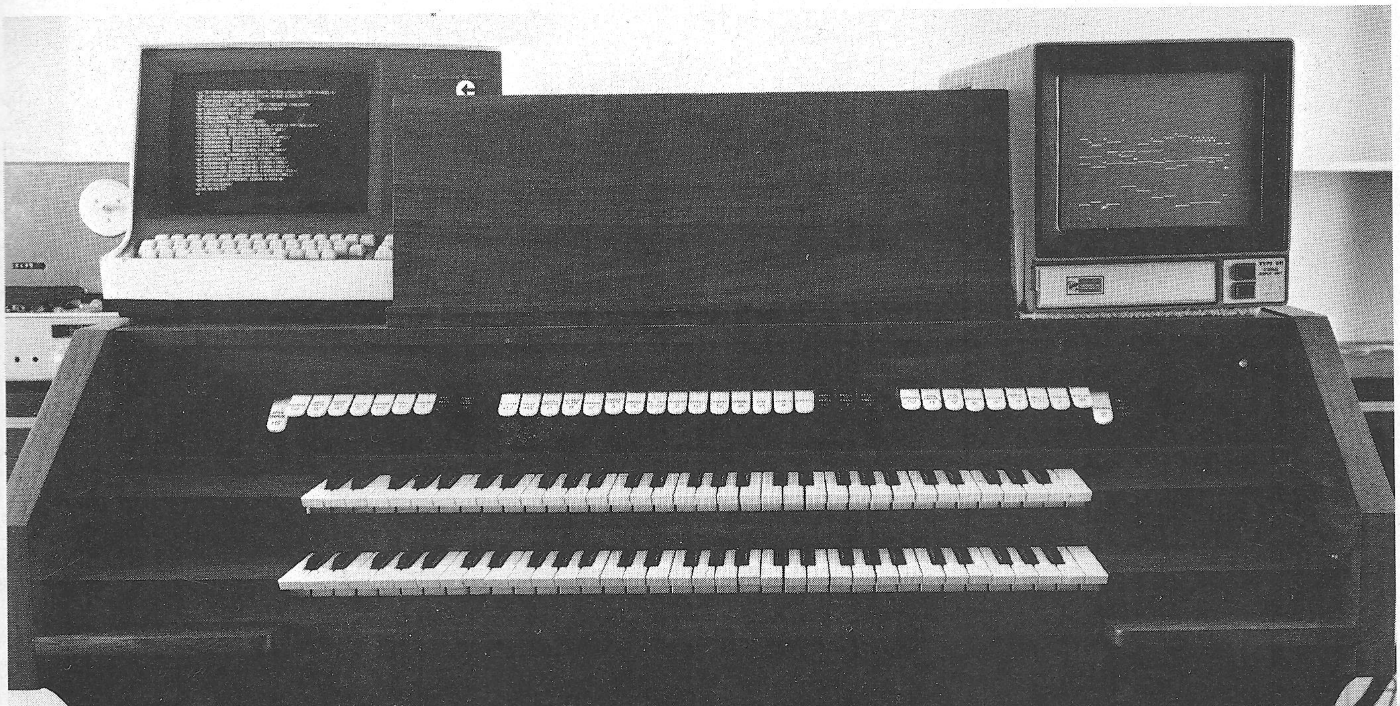
In seeking to advance the techniques of keyboard recording originally put forth by the developers of the player piano, an isomorphic internal computer representation of the paper roll was developed. Fig. 3 (page 58) illustrates a simplified fragment of a piano roll placed in a coordinate system. The times are arranged such that $t_n < t_{n+1}$. The frequencies or pitches are arranged such that $f_n < f_{n+1}$.

In order to obtain this information with the computer, two useful items are continuously available: (1) time, and (2) the state of the keyboard. The

# of Keyboard Music

by Prentiss H. Knowlton

state of the keyboard is a sequence of bits, in which 1 indicates that a key is currently depressed, and 0 indicates that a key is currently not depressed. In order to determine when a change takes place, the keyboard is sampled to determine its current state. The EXCLUSIVE-OR of this state with the previous state is performed. If the result is non-zero, the non-zero bits indicate which keys have *changed*. When a change has been detected, it is added to an event table, preceded by how much time had elapsed since the last event had taken place. A typical event table is shown in Fig. 4 (page 58). In order to conserve computer resources, the keyboard is sampled at discrete time intervals. From practical experience, 20 samplings per second suffice to capture even very complex keyboard activity. This can be verified by closely examining a typical piano roll, which consists, not of continuous slits, but rather of rows of perforations, which serve the additional function of keeping the roll intact horizontally. Each small, perforated hole can be thought of as a "clock tick" for the key it controls. Thus, the rate of the holes past the



player piano's "read head" represents the rate of the "clock." From many observations of player-piano rolls, the rate of 20 ticks per second is a reasonable estimate. Nuances of phrasing, for example, in which progression to the next note implies retarded release of the previous note, can be visually observed on piano rolls, in which two adjacent rows of perforations slightly overlap. In spite of the preference for this sampling rate, it is possible to sample at lesser and greater rates by varying the speed of the clock.

To illustrate an application of the event table, Fig. 5 represents the event table which would result from the keyboard activity represented in Fig. 3. The symbolism "$+f_n$" represents the depression of the key which has frequency f_n. Similarly, the symbolism "$-f_n$" represents the release of the key which has frequency f_n. Regarding Fig. 3 as the keyboard activity for one measure, the transformation of the resulting event table of Fig. 5 into traditional music notation will be considered.

In order to determine the point in a measure when a note of pitch f_n begins, all the Δt's in the event table which precede "$+f_n$" are added. In order to determine the duration of a note of pitch f_n, all the Δt's in the event table between "$+f_n$" and "$-f_n$" are added. From this formalism, f_1 begins at time $5+5=10$, having duration $5+15+5+5=30$; f_2 begins at time $5+5+5=15$, having duration $15+5=20$; and f_3 begins at time $5=5$, having duration $5+5+15=25$. These calculations can be verified graphically from Fig. 3.

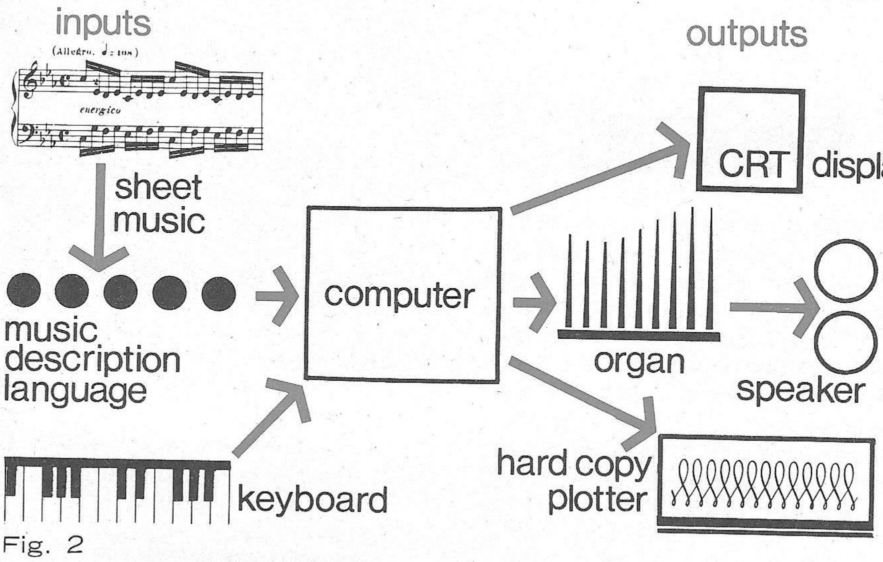


Fig. 2

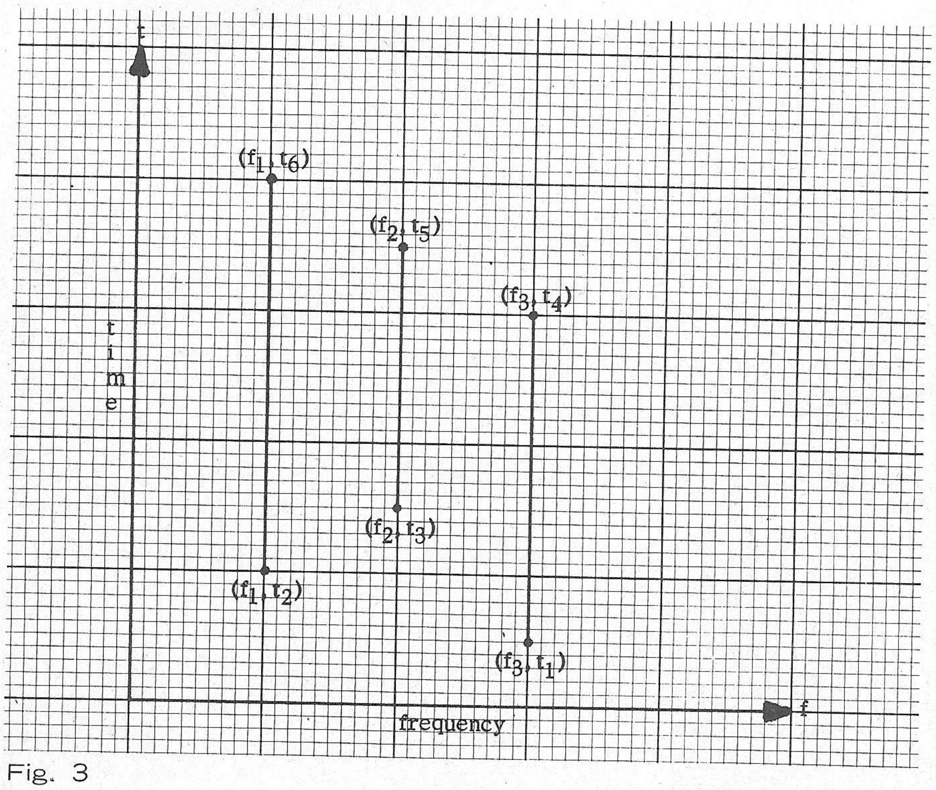


Fig. 3

For the purposes of this example, each note shall be considered a separate and independent voice, which means that the rests for each note will be individually indicated. In addition, it shall be assumed that f_1 corresponds to D below middle C, that f_2 corresponds to G above middle C, and that f_3 corresponds to D above middle C plus one octave. Finally, it shall be assumed that 5 units of time correspond to a sixteenth note. This implies that 10 units, 20 units, 40 units, and 80 units of time correspond respectively to eighth, quarter, half, and whole notes. A graphical representation of these time value assignments is shown in Fig. 6. Fig. 6 illustrates that precise timings are not required to obtain the desired note value. The principle is to define all the discrete note values for intended use along with their related "ideal" time value assignments. Subsequent to this definitional procedure, the requirement for obtaining note N_n which corresponds to the ideal time, T_n, is to produce a note duration, D, which satisfies

$$(T_n - T_{n-1})/2 < D \leq (T_{n+1} - T_n)/2, \qquad T_n > T_{n-1}$$

Compare this to Fig. 6. Clearly, the fewer the number of discrete time values, the greater the reliability in achieving the desired note symbols interactively from the organ keyboard. An additional refinement to this note assignment technique involves continual redefinition of ideal time values for note symbols. For example, when note N_3 is satisfied for durations D_i through D_j ($i<j$), the ideal time, T_3, is redefined to be the average of D_i through D_j. Subsequently, when N_3 is

Δt_1
E_1
Δt_2
E_2
.
.
.
Δt_n
E_n

Fig. 4. A typical event table.

$t_0 = 5$
$+f_3$
$\Delta t_1 = (t_2 - t_1) = 5$
$+f_1$
$\Delta t_2 = (t_3 - t_2) = 5$
$+f_2$
$\Delta t_3 = (t_4 - t_3) = 15$
$-f_3$
$\Delta t_4 = (t_5 - t_4) = 5$
$-f_2$
$\Delta t_5 = (t_6 - t_5) = 5$
$-f_1$

Fig. 5. Event table from Fig. 3.

satisfied for duration D_{j+1}, T_3 is redefined to be the average of D_{i+1} through D_{j+1}. Using this approach, the system is made to adapt to slight changes in tempo.

Going back to the example of Fig. 3 and applying the table of Fig. 6 to the results of the calculations on Fig. 5, it follows that the time preceding f_1 corresponds to an eighth rest; the time preceding f_2 corresponds to an eighth rest plus a sixteenth rest; and the time preceding f_3 corresponds to a sixteenth rest. The time duration of f_1 corresponds to a quarter note plus an eighth note, or a dotted quarter note; the time duration of f_2 corresponds to a quarter note; and the time duration of f_3 corresponds to a quarter note plus a sixteenth note. Assuming a time signature of 2/4, two quarter notes per measure, the time subsequent to f_1 is zero; the time subsequent to f_2 corresponds to a sixteenth rest; and the time subsequent to f_3 corresponds to an eighth rest. Gathering all this information together, the measure of music notation obtained is shown in Fig. 7.

The display of keyboard music

By the time printing technology had advanced the state of the art of music printing and engraving to a point of perfection, the desire began to increase for a means of obtaining musical text of high quality more rapidly. Composers desiring such a facility recognized the advantages of (1) being able to express their musical ideas in notation more rapidly, (2) being able to immediately interact with their ideas once expressed in notation, and (3) being able to provide high enough quality manuscript for immediate reproduction by means of photolithography.

At the Univ. of Utah, three mechanisms for displaying keyboard activity have been developed. The first mechanism, shown in Fig. 8, represents keyboard activity as a series of horizontal lines emanating from the right edge of the graphic display. Vertical position is based on pitch, and horizontal length of line segments indicates note time durations. The moving result is analogous to a player-piano roll moving horizontally. The second mechanism, shown in Fig. 9, represents the state of the organ keyboard at any moment on the musical staff in the key of C. The solid lines represent the musical staves, and the dashed lines represent ledger lines. Squares correspond to naturals or white keys, and diamonds correspond to sharps or black keys. The third mechanism, shown in Fig. 10 (page 60), is computer-generated music notation of "Praeludium II" in C minor from *The Well Tempered-Clavier, Book I* of Johann Sebastian Bach. Fig. 11 (page 60) gives the original sheet music, and Fig. 12 (page 60) illustrates the internal symbolic representation of the score, as entered into the computer through a terminal, or as obtained from an analysis of a keyboard performance of the score.

Conclusions

It has been shown that an interactive keyboard music system using an electronic organ, computer, and display

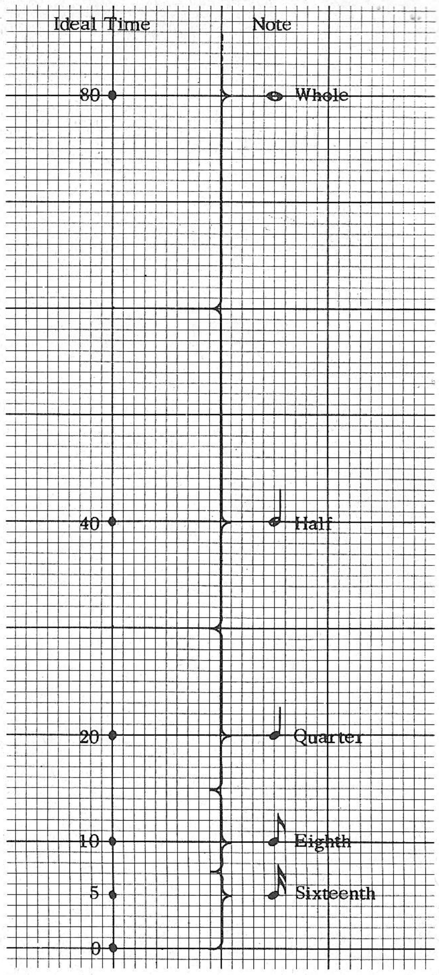


Fig. 6

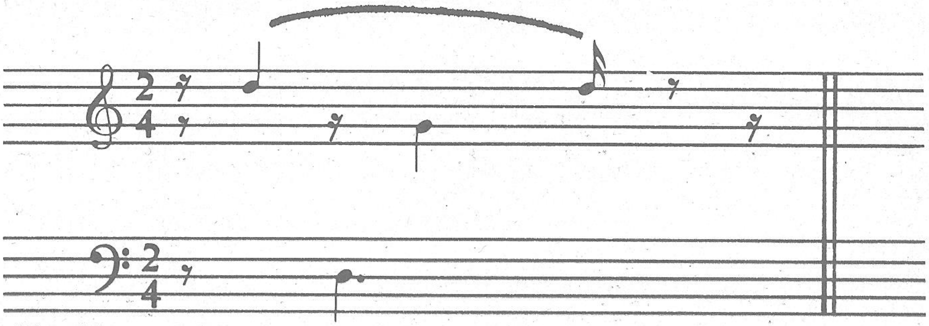


Fig. 7

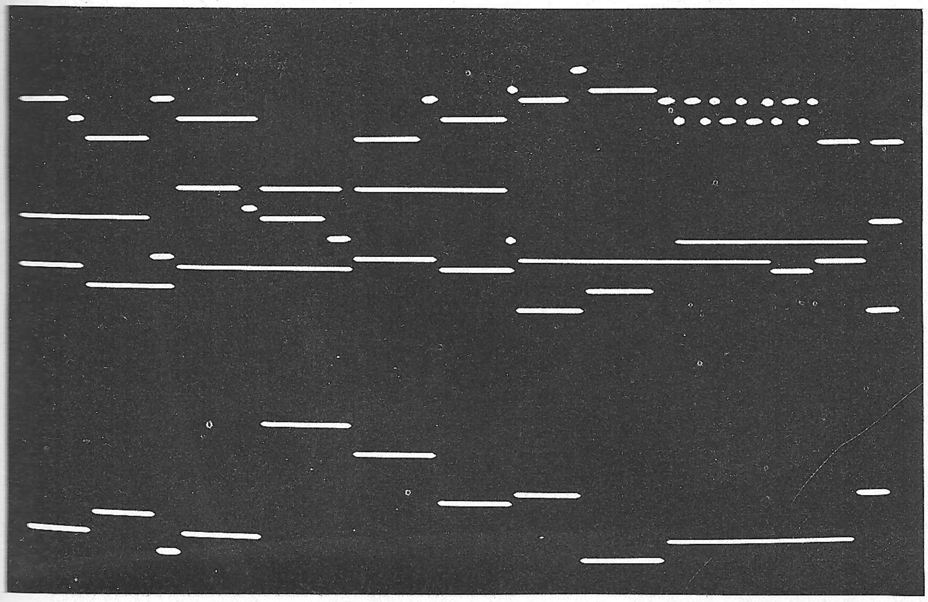


Fig. 8

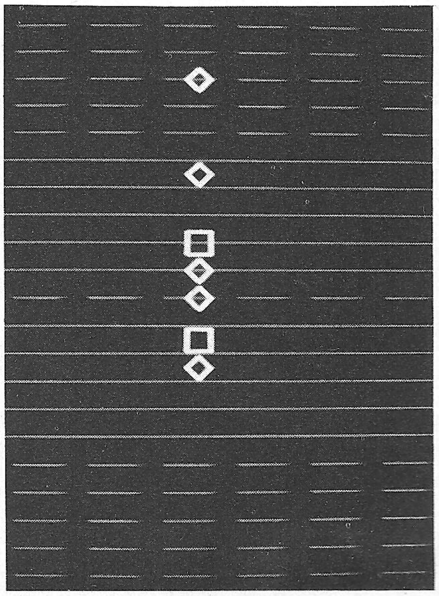


Fig. 9

can be realized. In the future, such a system might assist composers in the same way that typewriters assist writers today. Experience indicates that computer preparation of sheet music can provide significant cost savings to the music publishing industry. In addition, individual copies can be obtained from the Tektronix display for less than 8¢ each.

Acknowledgments. I wish to thank Professor William Viavant of the Univ. of Utah, who directed my research in this area. I wish to also thank Professors Robert Barton, Charles Seitz, Vladimir Ussachevsky, and Dale Harris, who served on my committee. Finally, I am indebted to my colleagues: Alan Ashton, who designed the music description language depicted in Fig. 12; David Ashton, whose initial development efforts led to Fig. 8; and to Robert Bennion, who designed, built, and maintained much of the hardware.

For further reading. Two doctoral dissertations and one masters thesis have come out of this work and are given below:

1. Ashton, Alan Conway, "Electronics, Music, and Computers," PhD dissertation, Univ. of Utah, Salt Lake City, August, 1970.
2. Ashton, David, "Teaching Music Fundamentals Using a Computer Controlled Organ and Display Scope," Masters Thesis, Univ. of Utah, Salt Lake City, August, 1971.
3. Knowlton, Prentiss Hadley, "Interactive Communication and Display of Keyboard Music," PhD dissertation, Univ. of Utah, Salt Lake City, August, 1971. ☐

Fig. 10

Fig. 11

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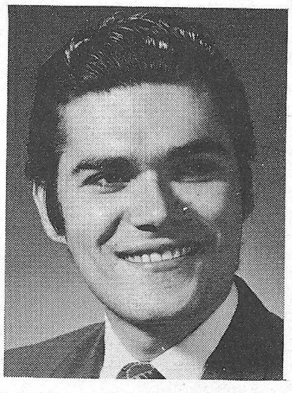
:J. S. BACH, PRAELUDIUM II, C MINOR:
K3!$4-4
:1:SC5E4DECEDEC5E4DECEDE;SC3GFGEGFGCGFGEGFG/
:2:SA4F%EFCFEFAFEFCFEF;SC3AGAFAGACAGAFAGA/
:3:S%B4FEFDFEFBFEFDFEF;SC3AGAFAGACAGAFAGA/
:4:SC5G4FGEGFGC5G4FGEGFG;SC3EDEGEDECEDEGEDE/
:5:SE5A4GAEAGAE5A4GAEAGA; SC3C4B3C4A3C4B3C4C3C4B3C4A3C4B3C4/
:6:SD5#F4%EFDFEFD5F4EFDFEF;SC3%AGA#FAGACAGAFAGA/
:7:SD5G4#FGD5G4FGDGFG;SB2B3%ABGBABB2B3ABGBAB/
:8:SC5%E4DECEDEC5E4DECEDE;SB2G3FG%EGFGB2G3FGEGFG/
```

Information enclosed in colons is treated as commentary and ignored by the system. "K3!" denotes that the key signature has three flats. "$4-4" indicates a time signature of 4/4. ":1:" is commentary that measure number 1 is about to be encoded. "SC5" means a sixteenth note of C in the fifth octave, where C in the fourth octave is middle C. "E4" means a sixteenth note (by default) of E in the fourth ocave. Subsequent letters denote subsequent sixteenth notes in the fourth octave by default. Thus, octave and time designators remain in effect until respecified. The semicolon starts the first measure over again for another voice, and the slash defines the end of the measure. In the second measure, "%E" specifies E natural, since in a key signature of three flats E is normally flat. Similarly, "#F" in the sixth measure denotes F sharp. Like time and octave designators, accidentals remain in effect until respecified, or until the beginning of the next measure, in which case the accidentals specified in the key signature go back into effect.

Fig. 12



Dr. Knowlton is a systems analyst at the Jet Propulsion Laboratory in Pasadena, Calif., where he is exploring new applications in computer graphics and programming languages. He has a BS in mathematics from California State College at Los Angeles, an MS in applied mathematics from Harvard Univ., and a PhD in computer science from the Univ. of Utah.