# *Glass Games* by David Worrall: an analysis of the integration of the instrument and tape parts, with particular reference to the compositional processes employed.

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## ANALYSIS OF *GLASS GAMES*

*Glass Games* is scored for chamber ensemble and computer generated tape, and was commissioned by the Seymour Group in 1980. The ensemble consists of flute, clarinet, violin, cello, percussion (one player), and piano. The tape part was composed using the Music Programming Library (MPL), a computer composition environment invented by American composer Gary Nelson. The purpose of this analysis is to examine the compositional processes operating within the work, and more specifically how the processes employed in the composition of the instrumental part are reflected in the MPL environment. Although the tasks of composing for an instrumental ensemble and computer generated tape require different methods and modes of work, in *Glass Games* it is the compositional processes that are the common element to these two operations, thus enabling the composer greater control over the integration of these diverse media.

This analysis is in three parts: the first examines the work as a whole; the second is an examination of the notation used in the work; and the third is a detailed explanation of the MPL facilities implemented in *Glass Games*.

The title, *Glass Games*, suggests a concept that is fundamental to the work: namely the interplay of colour and light. The creation and evolution of blocks of sonic colour form the basis of the work. The title itself is derived from the novel *The Glass Bead Game* by Hermann Hesse; a novel that has greatly influenced the composer. This work reflects the aesthetic sense found in the novel.

## STRUCTURE

The work begins with a Prologue for instruments only. Here the concept of changing and emerging colours is first introduced. This section consists of a series of chords which present the basis of the pitch material for the whole work. After the Prologue the tape begins, and this area of the work is in three main parts. The first and longest part is for the whole ensemble, the second is an improvisation for piano and percussion, and the third is an improvisation for the whole ensemble. This is followed by the Epilogue, a refrain of the Prologue.

| **part** | **section** | **description** |
|---|---|---|
| Prologue | | for instruments only |
| 1 | 1 - 14 | the tape begins - for the whole ensemble |
| 2 | 15 - 21 | improvisation for piano and percussion |
| 3 | 22 | improvisation for the whole ensemble |
| Epilogue | | for instruments only |

An important aspect of the work is the way the sounds on the tape, and the various instrumental timbres, blend and contrast. Musical ideas are heard to move from the tape part to the instrumental part and vice versa. Often the two sound sources are indistinguishable from one another: the timbre of a particular instrument will emerge for a period of time, then be absorbed back into the body of sound. The individual parameters, pitch, rhythm, timbre, and so on, cannot be isolated. They all play an integral role in the creation of particular textures and colours. In this respect, the compositional techniques and language employed in the work are more akin to the French, rather than German, tradition.

The work is divided into many sections, each of which is defined by a particular textural block, from here on referred to as a sound mass. A sound mass is the product of the combined instrument and tape parts; it focuses on a particular sonority, timbre and texture, and has its own length and dynamic shape. Larger units within the work comprise several separate sound masses containing various unifying elements.

## SONORITIES

A group of pitch structures, or sonorities, is a most important element in the creation of the sound masses of *Glass Games*. The particular sonorities in this work are made using a method based on the construction of pitch structures derived from the arrangement of three interval classes (giving each structure three different pitches).[1] By eliminating duplications due to inversion, it is possible to produce twelve different pitch structures using this method, with each structure having its own particular sonority.

This example shows the construction of a sonority.

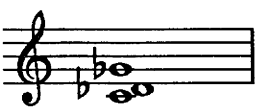


Figure 1

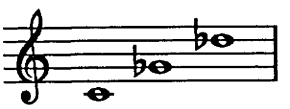


Figure 2

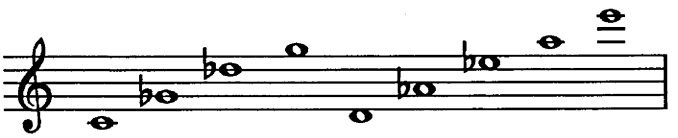


Figure 3

[1]See Allen Forte, *The Structure of Atonal Music*, Yale University Press, 1973. Appendix 1.

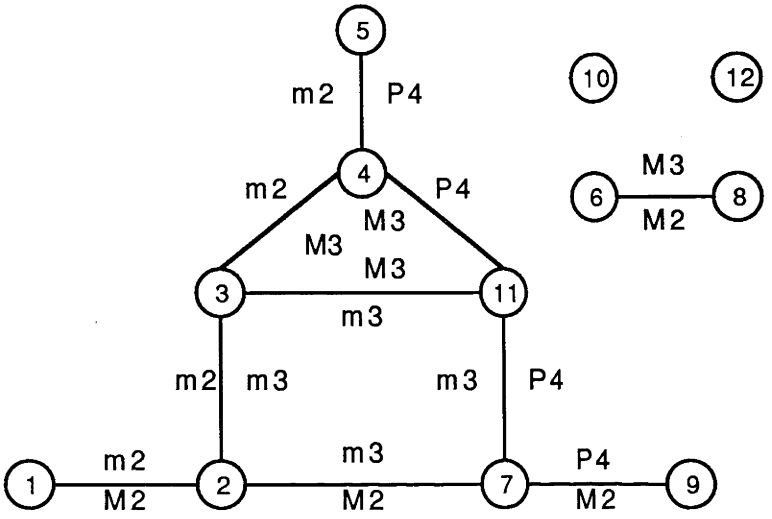
Figure 1 shows a pitch structure using the intervals of a minor 2nd, a perfect 4th, and a tritone. Figure 2 shows this structure expanded. Figure 3 shows the extension of this structure creating a sequence of pitches with a particular sonority.

From any point in the pitch sequence, a group of pitches may be taken to form a chord. This chord may contain different pitches to other chords taken from the same sequence, but they will all have the same sonority because they are made with the same interval classes.

Within the work, these sonorities are arranged according to the concept of maximum similarity. Two sonorities that have two interval classes in common, are said to have maximally similar sonorities. A transition from one sonority to another will tend to sound abrupt or smooth depending on the similarity of the sonorities with respect to interval class.

| sonority# | min 2nd | maj 2nd | min 3rd | maj 3rd | per4th | tritone |
|---|---|---|---|---|---|---|
| 1 | 2 | 1 | _ | _ | _ | _ |
| 2 | 1 | 1 | 1 | _ | _ | _ |
| 3 | 1 | _ | 1 | 1 | _ | _ |
| 4 | 1 | _ | _ | 1 | 1 | _ |
| 5 | 1 | _ | _ | _ | 1 | 1 |
| 6 | _ | 2 | _ | 1 | _ | _ |
| 7 | _ | 1 | 1 | _ | 1 | _ |
| 8 | _ | 1 | _ | 1 | _ | 1 |
| 9 | _ | 1 | _ | _ | 2 | _ |
| 10 | _ | _ | 2 | _ | _ | 1 |
| 11 | _ | _ | 1 | 1 | 1 | _ |
| 12 | _ | _ | _ | 3 | _ | _ |

This chart shows the interval classes in each of the twelve possible pitch structures.




This chart shows the relationship of maximum similarity between the twelve sonorities. Also shown are the two intervals which any sonority pair have in common. Note that sonorities 10 and 12 have no maximally similar sonority.

**TAPE EVENTS**

The tape part is divided into twenty-two short sections, or tape events. Each tape event corresponds to a section in the instrumental part of the work. When combined, a tape event and instrumental section produce a unique sound mass.

The tape events were generated on a computer using a combination of algorithms operating on each of the individual event's parameters. As an example, the same algorithm was used in each tape event to determine the selection of pitches from one of the several precompiled pitch groups. This same algorithm may be used again to determine other parameters of an event. The result of this process of event generation is that all the particular elements needed to produce a tape event are linked at a low level of the

composition. There are sixteen different tape events in the work, numbered e0 to e17, with e8 and e11 absent. The tape events occur contiguously, with several being repeated at various stages during the work.

Although each tape event comprises many elements, the element of pitch is important in distinguishing one tape event from another, or, conversely, it is used as a unifying element between several tape events. There are seven different pitch groups in the work, and of these, four are used only once. Each pitch group is attached to a consecutive number of tape events; the repetition of a tape event is coupled with the repeat of a particular sonority, and therefore of a total sound mass.

The following chart shows the three parts, their sections, and corresponding tape events. Also shown are the phrase divisions of the first part, and the pitch groups used in each tape event.

| part | section | tape event | phrase | pitch group |
|---|---|---|---|---|
| 1 | 1 | 0 | 1 | A |
| | 2 | 0 | 1 | A |
| | 3 | 1 | 1 | A |
| | 4 | 2 | 1 | A |
| | 5 | 3 | 1 | A |
| | 6 | 4 | 2 | B |
| | 7 | 5 | 2 | B |
| | 8 | 6 | 2 | B |
| | 9 | 7 | 2 | B |
| | 10 | 4 | 2 | B |
| | 11 | 9 | 3 | C |
| | 12 | 10 | 3 | D |
| | 13 | 4 | 3 | B |
| | 14 | 12 | 3 | E |
| 2 | 15 | 13 | | E |
| | 16 | 2 | | A |
| | 17 | 1 | | A |
| | 18 | 14 | | E |
| | 19 | 1 | | A |
| | 20 | 15 | | E |
| | 21 | 16 | | F |
| 3 | 22 | 17 | | G |

**PROLOGUE**

The Prologue consists of twenty-one individual chords. The pitch material for the chords is taken from one, or a combination of, the twelve sonorities. Throughout this section six different sonorities are used, with several being used only once. The Prologue takes the form of a gradual crescendo, juxtaposed with an increase in density as instruments enter one after another. There are four phrases in the Prologue, each of which is shaped by the use of rhythm and timbre, as opposed to a melodically controlled phrase structure. Each phrase has an increase in both density and rhythmic intensity, followed by a sustained chord or period of silence.

| **phrase** | **# of chords** | **sonorities of each chord** |
|---|---|---|
| 1 | 4 | 5 5 5 10<br>11 |
| 2 | 7 | 5 5 5 5 5 5 5<br>5 5 5 5 |
| 3 | 5 | 5 5 5 5 5<br>5 5 5 5 5 |
| 4 | 5 | 2 7 5 9 5<br>7 5 |

This chart shows the sonorities used in each chord of the four phrases of the Prologue. Each column of numbers in the section marked *sonorities of each chord* represents an individual chord, the numbers indicating the sonority used. In some of the chords one sonority appears twice, which indicates that the pitches in the chord come from two separate areas of that particular sonority's pitch sequence.

The first three chords of the first phrase are all three note chords using sonority 5. This, the most commonly used sonority in the work, has an interval structure of a minor 2nd, a perfect 4th, and a tritone. The final chord in this phrase is more complex, being constructed with a combination of sonorities 10 and 11, with the F# being common to both sonorities. The particular timbre, or colour of the phrase, is produced by scoring the clarinet above the flute and violin.

The second phrase is the longest and most rhythmically complex. Sonority 5 is used in every chord. Here the sounds of the cello and vibraphone are added to the palette; the flute playing above the rest of the instruments gives the overall timbre of the phrase a much brighter sound.

In the third phrase the piano is used for the first time, which has the effect of further blending the timbres of all the other instruments. In this phrase all the chords are constructed using the same method. Each chord contains two groups of pitches taken from different places in the pitch sequence of sonority 5. Occasionally one pitch group is duplicated from one chord to the next.

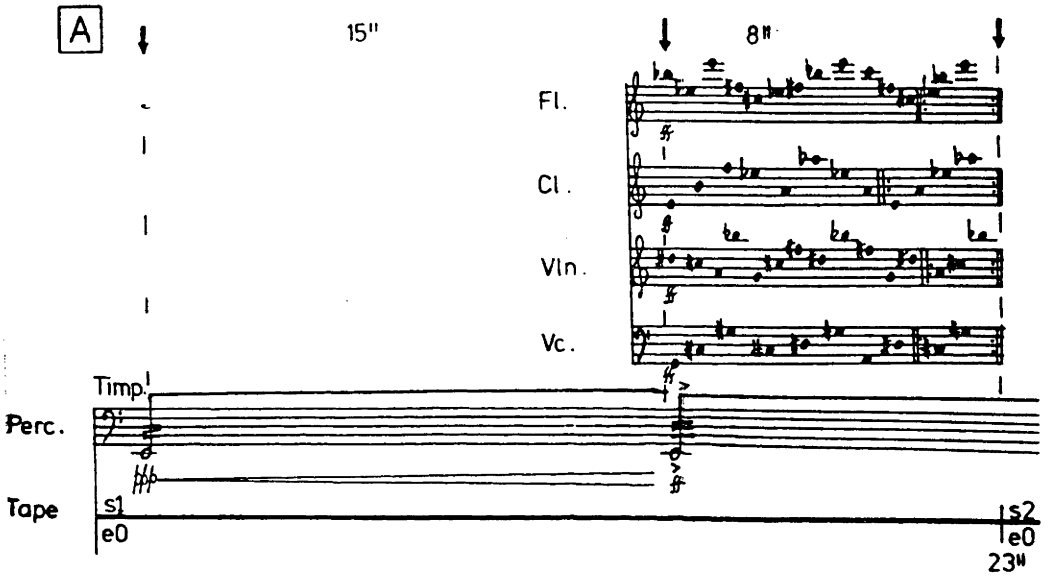
The fourth and final phrase differs from the others in that the chords are constructed using the widest range of different sonorities. The first chord uses sonority 2, the second uses sonority 7, the fourth uses a combination of the sonorities 5 and 9, and the third and fifth chords use sonority 5 only. As the phrase becomes louder, the timbre becomes brighter with the flute, clarinet and violin playing in their upper registers; creating also a rise in tension. The increase in density is emphasised in this phrase when, for the only time in the whole Prologue, all the instruments play a chord together.

This particular chord also covers a wide pitch range, producing a very full tone.

The Prologue ends with a chord using sonority 5 played by the flute, clarinet, and violin. This is the same instrument combination that began the work, though this time the flute is scored above the clarinet. The difference in tone colour of this chord is also achieved by the instruments playing loudly in their upper registers.

**PART 1: For tape and whole ensemble.**

This part of the work contains fourteen separate sections, which can be grouped into larger units, or phrases, which focus on particular elements, giving a sense of unity among the sections. The first five sections of this part all use the same pitch group, and four different events (e0, e0, e1, e2, e3). The part begins with only the tape and timpani playing. A gradual crescendo and acceleration are combined with a gradual increase in pitch; then after sixteen seconds, the flute, clarinet, violin, and cello all enter playing material identical in pitch, rhythm, and articulation to that of the tape.



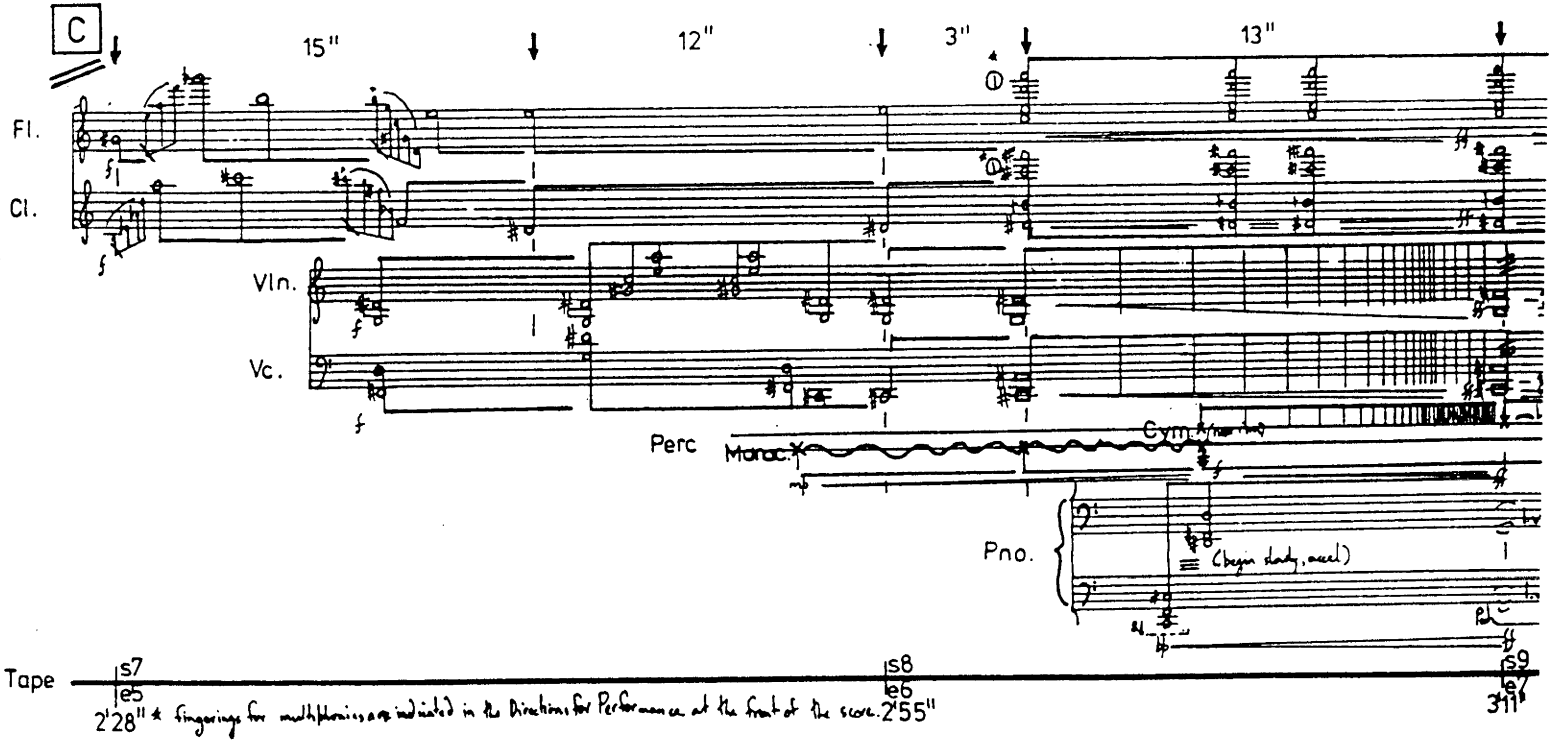

**Section 1, Event 0**

This is the first example of the sounds of the instruments mirroring those of the tape, causing the listener to focus on the colours and textures which were evolving in the tape part. Section 1, event 0, is immediately repeated. This repeat is not an exact copy of the previous section: rather, the computer has produced two separate sections of music using an identical combination of processes and algorithms. The sections, therefore, are not identical, though they share common sonorities, textures and timbres.

A common pitch group is not the only unifying element of the first five events. There are two distinct textures that are used alternately in this section. The first is a rapid staccato texture, the second is a slower moving legato texture. All the instruments combine to create a solid sound mass using one of the two different textures. At this point in the work the textures for

each event are quite static, with little variation in timbre or texture occurring within each event. The sounds of the instruments blend very closely with one another, and these sounds are further absorbed by the sounds of the tape.

The following five sections (e4, e5, e6, e7, e4) all use pitch group B. In this area of the work the sound masses start becoming more complex, as the unique qualities of the various instruments are emphasised. The first event of this section is for tape alone. When the instruments re-enter at the beginning of the next event, they are grouped according to timbre, the woodwinds, strings and percussion each having different material to play. The effect of this is to give the sound mass of the individual sections a more dynamic shape.

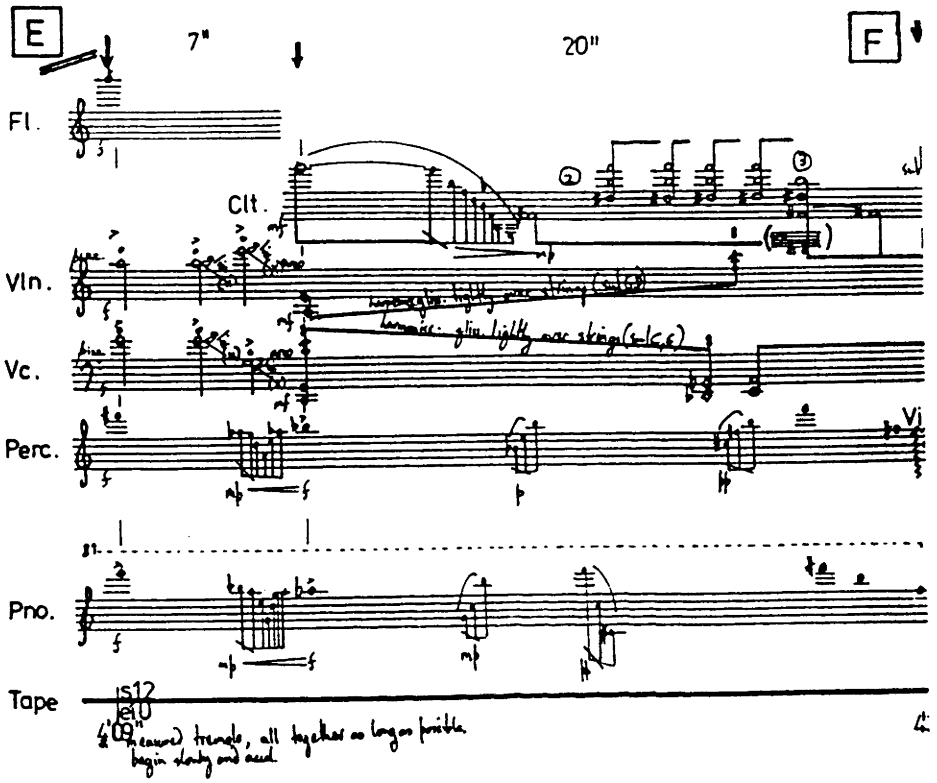



* fingerings for multiphonics are indicated in the Directions for Performance at the front of the score.

**section 7, event 5**

More unusual methods of playing the instruments are an important source of colour in the work. In several sections of this part, the flute and clarinet play chords using multiphonic techniques. In a following event, the main sound source comes from a bowed cymbal and tamtam; in another, the strings play harmonics and glissandi.

The last four sections of this part (e9, e10, e4, e12) each use a different pitch group, and the shape and textures of the events are now more complex and refined. It is also interesting to note that at this point in the work, the pitch material of the instrumental part rarely corresponds to that in the tape part, thus giving the sonorities of the events more complexity and depth. Each player now has more diverse material, and more freedom to improvise. This means the players must be careful not to stand out too far above the total sound mass. These sound masses now comprise several layers: the tape; the flute, violin, and cello harmonics; the clarinet multiphonics, and the xylophone and piano playing short, brisk passages. The sounds of all these layers are continuously overlapping, and the distinction between the instrumental timbres and the electronically produced sounds on the tape is very difficult to make.



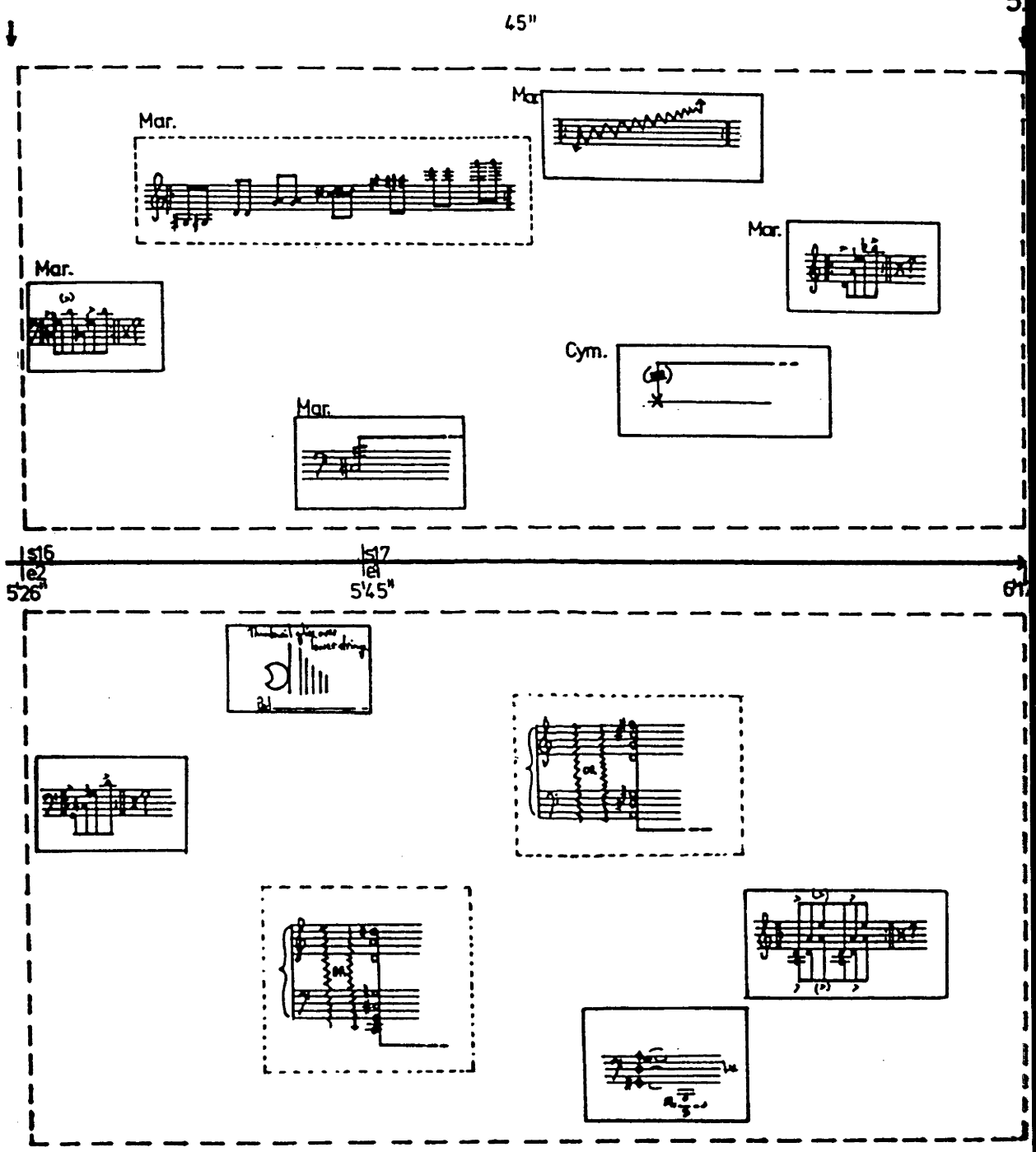

**Section 12, Event 10**

The last two events of this part combine some new sounds with sounds that are distinctive to earlier sections. The new sounds are produced by measured and unmeasured trills played by the woodwind and strings. Repetitions of a fast ascending passage from earlier in the work, the slow legato texture of section 3 and the repeat of event 4 effectively bring this part of the work to a close.

**PART 2: Improvisation for piano and percussion.**

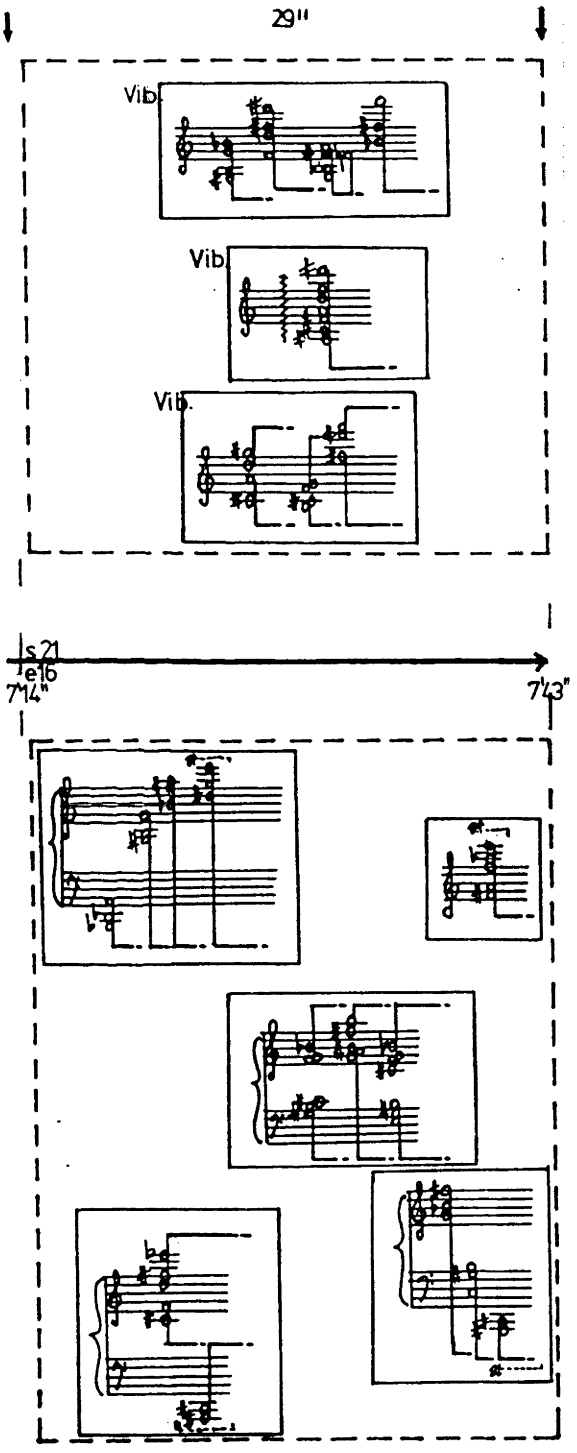
This part is divided into six sections of widely varying lengths. Improvisation is a method well suited for achieving the interaction of various sonorities and textures between the performers and the tape. The performers can, and must, listen to all of the sound happening around them in order to produce a more integrated sound mass. Improvisation also allows the performers the space to adapt freely their playing, in ways they think suitable, to blend or contrast with the sounds on the tape. Each performance of the work can be different, giving the sound textures a fresher and more interesting quality.

In each section of this part of the work, the pianist and percussionist have a collection of fragments to play. Within each fragment, the notation used consists of symbols and techniques similar to those used in the rest of the work. However, incorporated into the presentation of these fragments is the information on when and how they are to be played. A limited number of directions concerning the interpretation of the notation is given to the performers, enabling them to interact with each other and the tape. Although each player is given different material to play, there is a compatibility between the parts which gives each event its own particular quality.




**Sections 16 and 17, Events 2 and 1**

In this part all the events use one of two pitch groups, and only at section 21, e16 is a new pitch group heard. Much of the instruments' pitch material does not match that of the tape part; however, there is a greater similarity in pitch between the tape and instruments towards the end of this part. The density of the sections become progressively greater as each section has an increasing number of fragments to be played within its duration. As the difference between the fragments within each section becomes less distinctive, the sections become more static. The combined effect of the instrument and tape parts is to create a very blurred texture as their timbres merge. This particular sound quality is the main aspect of the next section of the work, an improvisation for the whole ensemble.




**Section 21, Event 16**

**PART 3: Improvisation for the whole ensemble.**

This part, the last to include the tape, consists of just one tape event, and lasts for over two minutes. The tape part uses a new pitch group that contains many pitches which have not been used at all in the rest of the work. The durations of the individual notes in the tape part are also very long: in fact, there are only thirteen individual notes in the whole section.

The instrumentalists are provided with a very small amount of material. The part begins with loud glissandi played by the vibraphone and piano, the sounds of which are sustained, and left to decay for the duration of the event. The violin and cello each have two notes a fifth apart, on which they play harmonics. They have the option to play these notes double stopped, when they wish. The flute and clarinet each have four separate multiphonic chords, the duration and order of which are left up to the players. Subtle changes to the timbre and texture occur continuously in this section as a flute or clarinet chord changes, or a new note starts in the tape, while all the time the more static sound of the string harmonics and the decaying vibraphone and piano are heard. Very gradually all the sounds merge, decay and finally disappear.

**EPILOGUE**

As the sounds on the tape fade, the Epilogue, for ensemble only, begins. This section consists of the last eight bars of the Prologue. The sound of all the instruments playing closely in rhythm and pitch again has a startling effect: the quality of the combined timbres and textures is much clearer here than in the previous parts, and this is also the first occurence of an obvious repeat. The main difference between this part and the Prologue, is that, for the entire part, the intensity of the sound is maintained at the level of piano. There is no diminuendo at the end, and therefore, no change in tension.

Combined, these factors bring the work gradually to a close; this repetition has brought the work full circle. The repeat, however, is not exact, emphasising the sense of time having progressed, while providing the listener with a reference point.

The creation of the sound masses and the gradual transition from one sound mass to the next are the fundamental ideas of this work. In order for these to be achieved all the elements of the music must blend; timbre, pitch, rhythm and articulation are fused to form a sound mass, and in this task each element must play an equally important role. The juxtaposition of computer generated and instrumental sounds allows for a very wide range of timbres, with many of the infinite possible combinations being incorporated into the sound masses. Throughout the work it is often difficult to distinguish the sounds of the instruments from those on the tape; nevertheless, this is not a listeners problem, as it is the nature of the work to integrate these sounds. In the domain of timbre the importance lies in the sonic quality, not the in method of production.

## NOTATION IN *GLASS GAMES*

In *Glass Games* notation is the important link between the techniques of improvisation and the creation of the various sound masses; in parts 1, 2 and 3, there are many aspects of improvisation in the notation. *Glass Games* uses a temporal form of notation, as first seen in works such David Bedford's *Albian Moonlight*, and Luciano Berio's *Sequenza* series of works. Except for the Epilogue, which returns to the traditional notation used in the Prologue, the use of improvisation in the instrumental sections of *Glass Games* increases progressively.

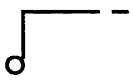
## PITCH

Because the sonorities are such an important aspect of the work, the composer maintains a strong degree of control over the element of pitch throughout. There are only a very few instances where the choice of pitches is left up to the players (beginning of section 14, piano in section 16, marimba section 17, piano and vibraphone section 22). Most of these examples are various types of glissandi, or fast implied glissandi. Except for the Prologue and Epilogue, which are barred, accidentals apply only to the pitch to which they are prefixed.

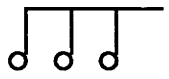
## DURATION

A number of techniques are used to notate the duration in this work. In the Prologue and Epilogue, the use of rhythm is traditional. For the remainder of the work, rhythm is used as an element of texture, and therefore the information for duration and articulation is often combined.

The notation symbols used are versatile enough to provide an adequate graphic indication of the composers intentions, eg.



The duration is left to the discretion of the performer. The duration of this type of note can be determined proportionally by the distance on the score to the next note, or end of section. Sometimes when it is stated specifically, the duration is as long as the performer can play. This type of direction is given predominantly to the wind instruments.

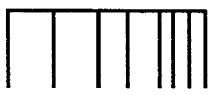
 Note heads which are left open are to be played legato.



● Filled note heads are played staccato. If there is a group of these, the amount of time between each note can be determined by the density in the score.

–
● mezzo staccato.

 Notes which are beamed and have a slash, are to be played as fast as possible. If the note heads are filled, they are to be played staccato. If the note heads are open, they are to be played legato.

 This indicates a gradual accelerando. When there is no pitch given for each attack, the performer should repeat the most recently indicated pitch.

From sections 15 to 22 a new notation is added, enabling more improvisation from the performers. Gestures now appear in small cells and boxes, which indicate when and how the various fragments are to be played.



Fragments enclosed in a solid box are to be played in the order specified.



Fragments enclosed in a broken box may be played in any order.

All the information for one section of the improvisation is enclosed in one or other of the above two types of boxes. Within these boxes there may be any number of boxes, of either type, containing small fragments. This is hierarchical notation. The fragments can be as little as a single note or chord, or as long as a series of pitches or chords. Unless stated, each cell may be repeated any number of times.

In sections 8, 12, and 22, the flute and clarinet have a number of chords which are produced using multiphonics. The relevant fingering for these multiphonics is stated in the Directions for Performance section at the beginning of the score. These fingerings are those used in Bartolozzi's *New Sounds for Woodwind.*

## MUSIC PROGRAM LIBRARY

The tape part of *Glass Games* was composed using a system called MPL (Music Program Library), which is a collection of functions and variables designed for operating on numbers representing musical ideas in musically useful ways. MPL was constructed using the programing language APL. Several features of APL make it ideal as a language environment for composition, and it provides many powerful primitive functions for operating on musical data at the conceptual level.

MPL was conceived and designed by US composer Gary Nelson. The system used in *Glass Games* was derived from his implementation and documentation of MPL during his periods as visiting scholar at the University of Melbourne, firstly in August in 1979 and later in January 1981. MPL is part of the Computer Music Project system at the University of Melbourne. At the time *Glass Games* was composed it was interfaced to Music-C, a software sound synthesis program written in C. This version of Music-C is based on the IRCAM Music-V system of 1976.

Using this system the computer can be presented with data relating to many aspects of the composition, ranging from instructions detailing the components of constituent sounds to the information needed to construct an entire work. This data may be in the form of a set of highly detailed procedures, or may consist of boundaries from within which selections are made using a range of deterministic, semi-deterministic or aleatoric processes.[2]

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[2]Worrall and Harris, *MPL Reference Manual*, The University of Melbourne, 1983. Introduction.

The computer music system is capable of providing a variety of facilities: an interactive graphics program allowing the display and modification of Music-C functions; a program for transferring the data on music disk files to the sound synthesis equipment; a music disk file editor; an interactive program for controlling the analog to digital converter and a collection of sound analysis programs. *Glass Games* utilises the compositional and Music-C sound synthesis facilities of MPL.

This part of the analysis will first examine the main MPL devices which were used in the composition of the tape part. This is followed by a detailed analysis of the code which produced one tape event for *Glass Games*. A basic understanding of some computational concepts and the data requirements for sound synthesis using frequency modulation techniques is needed.

**EVENTS**

The tape part of *Glass Games* is divided into many sections, each of which is one MPL event. An event is a separable entity or idea, the product of one set of algorithms and processes performed by the computer. Theoretically an event can be as short as one note, or as long as a whole piece. In *Glass Games*, the events are the building blocks of the work, and the work consists of 17 different events arranged to follow each other in a particular order.

**NOTE MATRIX**

The data for each event of the tape part is stored in the form of a note matrix. Each row of a matrix contains all the information for one note, and each column contains the information for one parameter; the number of columns in the note matrix is determined by the number of different parameters. A note matrix has a minimum of three columns, representing the start time of a note, the note's duration, and its pitch. The note matrices for

each event comprise thirteen columns, each one of which specifies values for parameters in the following order:

| | | |
|---|---|---|
| column 1 | - | start time |
| column 2 | - | instrument number |
| column 3 | - | duration |
| column 4 | - | pitch |
| column 5 | - | dynamics |
| column 6 | - | spacial location (in stereo) |
| column 7 | - | distance |
| column 8 | - | reverberation depth |
| column 9 | - | envelope |
| column 10 | - | blank (used for calculating local reverberation) |
| column 11 | - | FM ratio |
| column 12 | - | FM index |
| column 13 | - | FM envelope |

Here is an example of part of a note matrix from *Glass Games.*

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.131 | 2 | .113 | 293.65 | 50.33 | 82.529 | 0 | .5 | 59 | 0 | .762 | 8.441 | 33 |
| 9.291 | 2 | .167 | 155.55 | 51.975 | 83.187 | 0 | .5 | 59 | 0 | .732 | 8.373 | 24 |
| 9.525 | 2 | .055 | 58.27 | 54.46 | 84.149 | 0 | .5 | 58 | 0 | .719 | 8.273 | 22 |
| 9.601 | 2 | .214 | 554.33 | 49.705 | 84.463 | 0 | .5 | 60 | 0 | .722 | 8.241 | 29 |
| 9.899 | 2 | .053 | 65.4 | 54.81 | 85.687 | 0 | .5 | 57 | 0 | .733 | 8.114 | 22 |
| 9.972 | 2 | .104 | 739.93 | 49.68 | 85.986 | 0 | .5 | 57 | 0 | .735 | 8.083 | 21 |
| 10.115 | 2 | .204 | 207.64 | 52.67 | 86.574 | 0 | .5 | 59 | 0 | .74 | 8.022 | 21 |
| 10.393 | 2 | .05 | 1396.8 | 49.62 | 87.719 | 0 | .5 | 60 | 0 | .75 | 6.302 | 23 |
| 10.461 | 2 | .197 | 138.58 | 54.085 | 87.998 | 0 | .5 | 60 | 0 | .753 | 7.874 | 28 |
| 10.727 | 2 | .048 | 391.97 | 52.255 | 89.091 | 0 | .5 | 60 | 0 | .762 | 7.761 | 27 |

This example shows 10 rows, in other words 10 notes, taken from the matrix of section 1, event 0. Note matrices in this form are converted into score cards for the Music-C software synthesizer.

## RANDOM NUMBERS

Random numbers are often used to initiate event parameters. The random functions are used to generate a specified number of integers or real numbers within a specified range.

## LOOKUP TABLES

The numbers produced using the random functions are often then referred to one of several types of lookup tables. Lookup tables are used to convert one set of numbers into another, and in *Glass Games*, are used many times during the computation of a note matrix. Lookup tables have two columns and two or more rows, and an in-coming number (an index), is

"looked up" in the first column of the lookup table (the pointers). When that number is found in the first column, its corresponding number in the second column replaces the old number.

Using these tables, it is possible to perform lookups in two different ways: truncation or interpolation. A truncating lookup will locate the closest pointer at or below the index, and return the value pointed to. An interpolating lookup will locate the closest pointers on either side of the index, and linearly interpolate a value in proportion to the ratio of the division of the pointers.

**Example of a truncating lookup table**

| | |
|---|---|
| 0 0<br>10 20<br>20 5 | lookup table |
| 5 10 15 20 30 | in-coming numbers, or indices, from the note matrix |
| 0 20 20 5 5 | result of the truncating lookup |

In this example, the first index (5), falls between the 1st and 2nd pointers (0 and 10). In a truncating lookup table the lowest of the two pointers returns its corresponding value, in this case, 0. The second index (10), is equal to the second pointer: therefore the value returned is 20. Index values which exceed the range of the pointers will return the first or last value in the second column depending on whether the index is smaller or greater than the pointers.

**Example of an interpolating lookup table**

| | |
|---|---|
| 0 0 | |
| 10 20 | |
| 20 5 | lookup table |
| | |
| 5 10 15 20 30 | indices |
| | |
| 10.0 20.0 12.5 5.0 5.0 | result of the interpolating lookup |

In this example, the value of the first index (5), falls exactly half way between the first and second pointers (0 and 10). The value returned, (10), lies exactly half way between the two values pointed to (0 and 20). Again, if the index values exceed the range of the pointers, the first or last value in the second column will be returned, depending on whether the index is smaller or greater than the pointers. An example of a musical use of lookup tables is in computing the column which will contain the data for amplitude: a truncating lookup would be used if the composer wanted sudden changes in the dynamics; an interpolating lookup table would be used to produce crescendos and diminuendos.

## LOOKUP TABLE USAGE

Lookup tables can be used very flexibly, and in *Glass Games* they are used in three distinct ways. A general lookup table is a type designed before the note matrices are computed. These can be used in one or more individual events, and are generally designed to represent a specific parameter, eg. pitch. Several different lookup tables may be used for one parameter; for example, *Glass Games* has seven different lookup tables for pitch. A group of events may use a common lookup table for the parameter of dynamics, but may all use different lookup tables for pitch.

Another way of making a lookup table is by using controlled randomness. A random lookup table is generated during the process of computing a note matrix; it is only used once, and for a specific purpose. These tables are generated in the following manner: the composer specifies the range of the values for the two columns of the lookup table, and the number of rows (or the number of reference points in the lookup table). The necessary number of values in between these limits is calculated randomly. Here is an example of the MPL rantab function, which is used to create random lookup tables:
executing the comment:

```
4 rantab 0 10 4
```

produced the following lookup table:

```
0.0000      72.0000
2.8571      57.6000
5.7143      48.0000
10.0000     67.2000
```

In this example, the range of the pointers is from 0 to 10, and the range of the second column is from 48 to 72. The number of the rows is given as 4, the numbers in the first column are sorted in ascending order, and the values for the remaining rows are calculated randomly within the specified limit of 48 to 72.

Lookup tables may be used to perform calculations on one parameter in an individual event. They can also be used to perform the same function on the scale of the entire work. These global lookup tables can be used for tasks such as regulating the dynamics of the whole work.

## TRANSITION MATRIX

A transition matrix, or directed graph, can be used to determine transitions between values in a set; it provides a method of controlling the sequence of values. A transition matrix has an equal number of rows and columns, containing the numbers 0 and 1. The number of rows and columns is determined by the number of different values in the particular set. A column and its corresponding row (eg the first row and first column) represent one value of the set. As each new value is chosen, the previous choice is known. The previous choice determines from which row of the transition matrix the next choice will be made. The new value can be chosen from any column which contains the number 1 in that particular row. Here is an example of a transition matrix for a set of three values.

| | **1** | **2** | **3** |
|---|---|---|---|
| **1** | 1 | 1 | 1 |
| **2** | 1 | 0 | 1 |
| **3** | 1 | 1 | 0 |

Say the initial value chosen is 3: according to the data in the 3rd row, the number 3 may be followed by either the number 1 or 2, but not the number 3. If the number 1 was then chosen, it could, in turn, be followed by the number 1 2 or 3. The values in a transition matrix need not be only 0s and 1s; other values could be used to indicate the probability of making one choice over another.

Following is a description of the code that produced a note matrix for event 2, which is first used at section 4 in *Glass Games*. The ASCII version of APL, not the special APL character set, is used here.

```
[0]     event2  k;r;n;p;pr;m
[1]     pr { getevent k-1
[2]     Finsno { ins 'freqmod'
[3]     scoreout 'com ', (eventname k) ,' made with event2'
[4]     } (~null pr) /Fnn
[5]     pr {  (0,12) R 0
[6]     Fnn:m { 0S`1Yper pr
[7]     m { m,14
[8]     n { 1+Dm[2] X ranab 3  5
[9]     p { nR epoly pitseqmod26 n,8,begseq epoly
[10]    p { lookup35 lookup p
[11]    r { 0 seq rhymatev1 sequen n,1
[12]    pr { minmax r[; 1]
[13]    r { r,p
[14]    n { 3 rantab pr , 60  480
[15]    r { n warp r
[16]    r { m moveaug r
[17]    pr { minmax r[;1]
[18]    n { 3 rantab pr, 1.1  4
[19]    r { n den r
[20]    r { r col 4 set 4 divdyn dyn ilookup r[; 1]
[21]    r { r col 5 set 3 rantab pr , 0  90
[22]    r { r col 7 set .5
[23]    r { r col 8 set 3 rantab pr , 1  11
[24]    r { r col 10 set 2.001
[25]    r { r col 11 set 3 rantab pr, 3  10
[26]    r { r col 12 set 3 rantab pr, 1  11
[27]    r { [; 2] { 2 S r[; 1]
[28]    r [; 4] { (dbdyn r[; 4]) + afp ilookup r[; 3]
[29]    r [; 4] { limitdbs r[; 4]
[30]    r [; 8 12] { Fenvconst - Dr[; 8 12]
[31]    r [; 11] { r[; 11] Dr[; 10] maxfmi r[; 3]
[32]    r [; 3] { cpspit r[; 3]
[33]    Finsno notecards r
[34]    r [; 3] { pitcps r[; 3]
[35]    k putevent r
```

*[0] event2 k;r;n;p;pr;m*

This is the function header for the event; *k* is the ordinal number assigned to the event. *r*, *n*, *p*, *pr*, and *m* are APL temporary variables that are used in the computation of the event.

*[1] pr { getevent k-1*

Fetch the previous event *k-1* if it exists, and assign it to the variable *pr* for future reference during the construction of the event.

*[2] Finsno { ins 'freqmod'*

This establishes that *freqmod* will be the instrument to play the note matrix being generated.

*[3] scoreout 'com ', (eventname k) ,' made with event2'*

Place the comment *made with event2* at the top of the score cards for this event, to help locate the beginning.

*[4] } (~null pr) /Fnn*

Check the result of *getevent* (line [1]). If there is a previous event go to the line labelled *Fnn* (line [6]).

*[5] pr { (0,12) R 0*

There being no previous event, *pr* is initiated to 12 columns and no rows.

*[6] Fnn:m { 0S`1Yper pr*

*Per* returns the beginning and end time of the previous event *pr*. These values are assigned to the variable *m*.

*[7] m { m,14*

Catenate 14 to *m*. The period of the present event, represented in beats, is now stored in *m*.

*[8] n { 1+Dm[2] X ranab 3 5*

Calculate the number of notes in this event: Generate a random real number between 3 and 5, multiply it by *m* (14). Floor (truncate) to produce an integer, add 1 to the result (to prevent a 0 value).

n (max) = 1 + (14 * 5) = 71

n (min) = 1 + ( 14 * 3) = 43

*[9] p { nR epoly pitseqmod26 n,8,begseq epoly*

Generate a sequence of n values, with a minimum of 8 values before a value may be repeated. The transition of these values is determined by the matrix; *epoly*, *begseq* finds a starting element for the transition matrix. This array is assigned to the variable *p*.

*[10] p { lookup35 lookup p*

The values in *p* are looked up in the table *lookup35*. This is one of the pitch lookup tables. The 3 indicates that the pitches in the table come from a sonority set made using three interval classes, and the 5 indicates that they are from the 5th sonority of the set.

*[11] r { 0 seq rhymatev1 sequen n,1*

*Rhymatev1* is a transition matrix for rhythm, through which *n* values are generated. There is a redundancy index of 1, meaning that a value can be repeated immediately. These values represent durations. The function *seq* constructs the first two columns of a note matrix (start times and durations).

*[12] pr { minmax r[; 1]*

The first and last start times are found, and assigned to *pr*.

*[13] r { r,p*

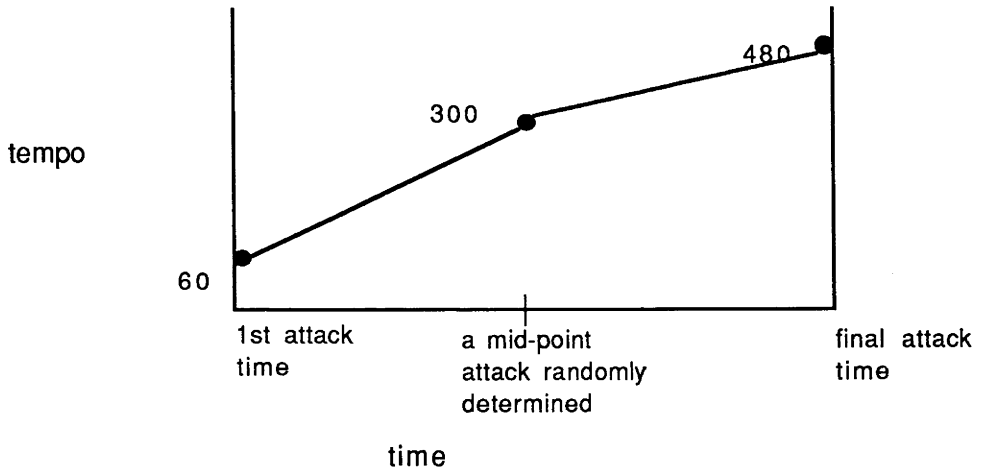
The pitch values in *p* are catenated to the start time and duration columns in the matrix *r*.

At this point the matrix consists of three columns and *n* rows (43< n <71). Column 1 contains the data for start times, column 2 has durations, and column three contains pitch data, in the form of MPL pitch numbers (48 = middle C). The matrix at this point is a series of contiguous notes.

*[14] n { 3 rantab pr , 60 480*

A random table for tempo control is created. This table has three rows. The first and last attack times (from *pr*), and one randomly determined breakpoint time, are each assigned a tempo value whose range will be between 60 and 480 inclusive. For example, if the third tempo value randomly determined was 300, the tempo table may look like this:

| | |
|---|---|
| 0 (first attack time) | 60 |
| breakpoint | 300 |
| final attack time | 480 |




*15] r { n warp r*

The attack times and corresponding durations (first and second columns of *r*) are augmented or diminished to comply with this tempo table *n*.

*[16] r { m moveaug r*

The note matrix is manipulated to fit within the period of the event. The start times and corresponding durations *r* are augmented or diminished, so that they will begin at the predetermined start time and fit into the period of the event *m*.

*[17] pr { minmax r [;1]*

Store the new first and last attack times, from the first column of the matrix *r* in *pr*.

*[18] n { 3 rantab pr, 1.1 4*

A random table for density control is created. This table has three rows. The first and last start times *pr*, and a third randomly determined breakpoint are assigned a density ranging between the values 1.1 and 4 inclusive.

The value representing density indicates how long a note will continue to sound into the duration of the next note. If the density is 1, as soon as one note ends another will begin; if it is less than 1, there will be a period of silence before the next attack. The length of this silence is determined by how close to 0 the value is. If the value is 0.5, the duration of the note will be cut in half, with the same amount of silence following as there had been sound. If the density is 2, the note will continue to sound for double the note's duration. The value for density, in this event, will always be greater than 1, producing legato articulation.

*[19] r { n den r*

*Den* augments or diminishes the durations (2nd column of *r*), but not the attack times, to comply with the density control table.

*[20] r { r col 4 set 4 divdyn dyn ilookup r[; 1]*

Add a fourth column to the matrix *r*, containing the data controlling the amplitude of each note. *Dyn* is a global lookup table. *Ilookup* returns a linearly interpolated amplitude level. The pointers to the lookup table are taken from the start times in column 1 of *r*. *Divdyn* adjusts the amplitude of each note according to the current density, with the maximum density set at 4. The purpose of this is to prevent distortion caused by the sum of simultaneous amplitudes exceeding that used by the digital-to-analog converters. The actual values for dynamics are dependent on the number of bits of the digital-to-analog converters. The Computer Music Research Project used 14 bit digital-to-analog converters.

*[21] r { r col 5 set 3 rantab pr , 0 90*

A fifth column is added to the matrix *r* dealing with the location of a sound in stereo space; these values are generated by a random lookup table. The first and last attack times *pr*, and a randomly determined breakpoint, are each assigned a value (representing location in degrees) between 0 and 90 inclusively. A location value of 0 degrees means that the sound will emanate only from the left speaker, a value of 90 means that the sound will emanate only from the right speaker. When the location value is 45 degrees, the sound will emanate from both speakers equally, giving the illusion that the sound is between them.

*[22] r { r col 7 set .5*

The seventh column is for reverberation depth. The values may range from 0 to 1. 0 means no reverberation, and 1 means maximum reverberation, or total feedback. In *Glass Games*, the reverberation depth is 0.5, with the exception of section 14 - event 12, whose value is 0.6.

*[23] r { r col 8 set 3 rantab pr , 1 11*

For *Glass Games* there are 11 predetermined envelope shapes used in the synthesis of individual notes (see appendix 3). Column 8 contains the envelope numbers for the note amplitudes. The values in this column are generated using a random lookup table. The method used to produce this lookup table is the same as was used to produce the tempo change lookup table.

*[24] r { r col 10 set 2.001*

The tenth column contains the data relating to the frequency modulation ratio for each note. In this event the frequency modulation ratio is 2.001 for all notes.

*[25] r { r col 11 set 3 rantab pr, 3 10*

The eleventh column contains the frequency modulation indices. These values are generated using a random lookup table. The method used to produce this lookup table is the same as that used to produce the tempo change lookup table.

*[26] r { r col 12 set 3 rantab pr, 1 11*

The twelfth column contains the frequency modulation envelope numbers. The envelopes used are the same predetermined envelopes mentioned in relation to the amplitude envelope of individual notes (line [23]). These values are generated using a random lookup table. The method used to produce this lookup table is the same as that used to produce the tempo change lookup table.

*[27] r { [; 2] { 2 S r[; 1]*

This ensures that the minimum duration is not less than .2 of a second.

*[28] r [; 4] { (dbdyn r[; 4]) + afp ilookup r[; 3]*

*Afp* is a lookup table where the index set is derived from the pitches (column 3). The resulting values from this linear interpolation lookup are added to the values in column four, the amplitude of each note. These values, whose range is between 1 (pppp) and 10 (ffff), are now converted by *dbdyn* into decibels.

*[29] r[; 4] { limitdbs r[; 4]*

The function *limitdbs* further adjusts the intensity levels. The values are scaled to within a specific limit so as to avoid producing values out of range for amplitude which would cause distortion.

*[30] r[; 8 12] { Fenvconst - Dr[; 8 12]*

The values in columns 8 and 12, both relating to specific envelope numbers, are floored (truncated) to ensure they are integers which range from 1 to 11. These values are then subtracted from *Fenenvconst*, a constant whose value is 61. This makes the envelope numbers range between 50 and 60.

*[31] r[; 11] { r[; 11] Dr[; 10] maxfmi r[; 3]*

The function *maxfmi* is used to calculate the maximum frequency modulation index of individual FMR/pitch pairs before foldover will occur. Foldover occurs when the frequency of the sidebands is higher than the sampling rate. The two arguments to *maxfmi* are the column of frequency modulation ratios and the column of MPL pitch values. The result is the maximum frequency modulation index possible; these values are floored and placed in the eleventh column, as the frequency modulation index.

*[32] r[; 3] { cpspit r[; 3]*

The function *cpspit* converts the values in column 3, which are MPL pitch numbers (48 = middle C), into cycles-per-second (Hertz).

*[33] Finsno notecards r*

The function *notecards* converts the matrix *r* into a set of Music-C note statements using the instrument *Freqmod.*

*[34] r[; 3] { pitcps r[; 3]*

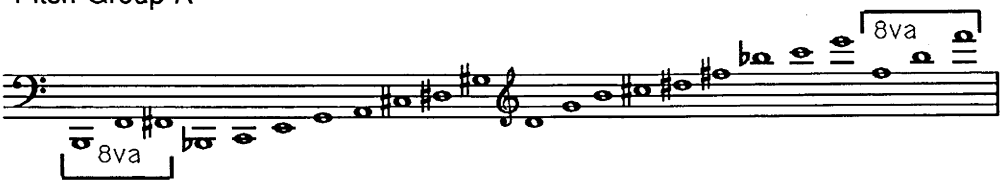
The values in column 3, which are presently representing cycles-per-second, are converted back into MPL pitch numbers.

*[35] k putevent r*

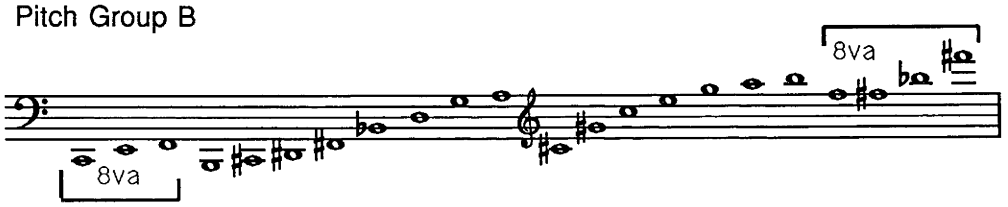
The matrix *r* is stored in binary format in the file *k*.

**Appendix 1** The seven pitch groups used in the tape part of *Glass Games.*

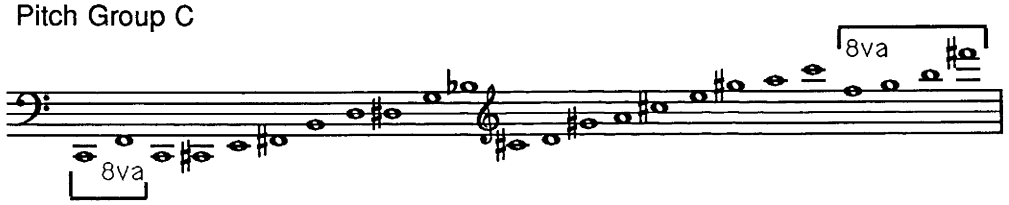
Pitch Group A



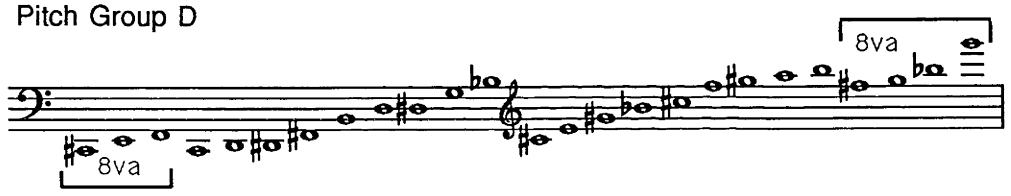

Pitch Group B



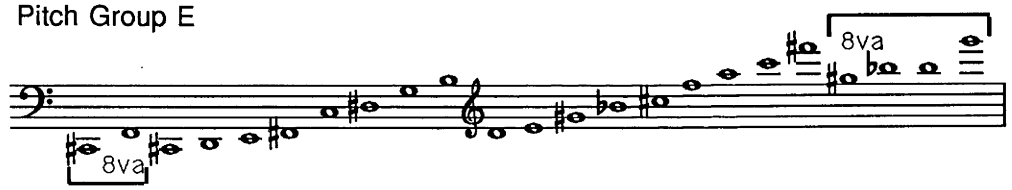

Pitch Group C



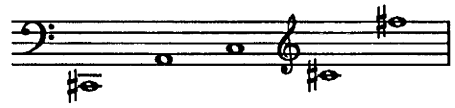

Pitch Group D



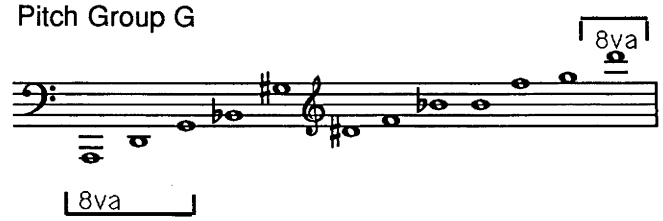

Pitch Group E



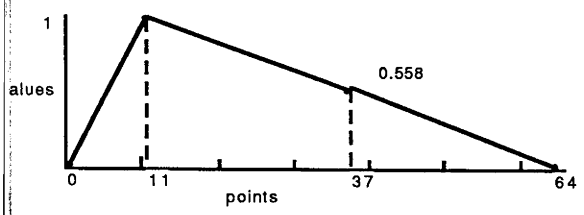

Pitch Group F



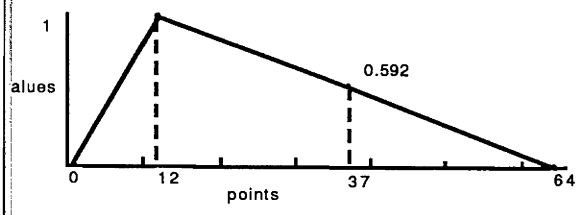
Pitch Group G



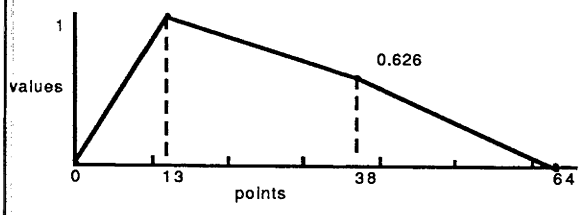
**Appendix 2** The eleven envelope shapes used in the sound synthesis process.



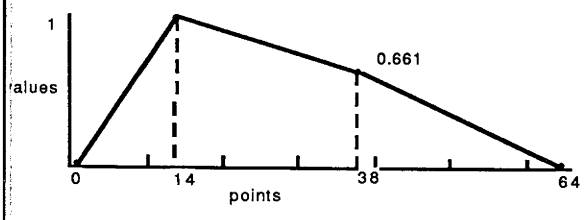
Envelope 1



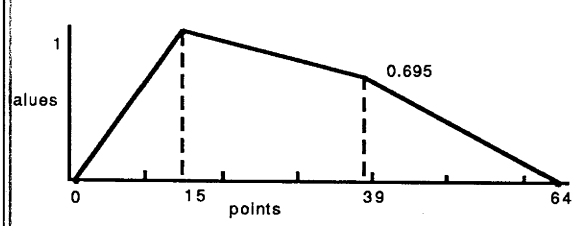
Envelope 2



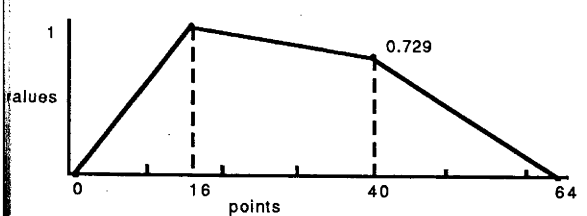
Envelope 3



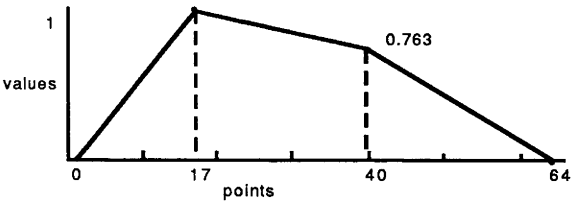
Envelope 4



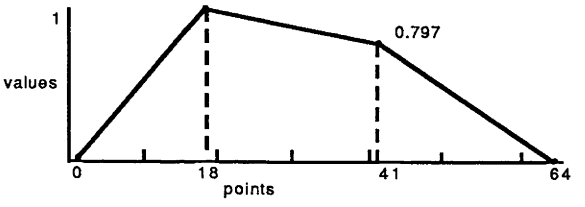
Envelope 5



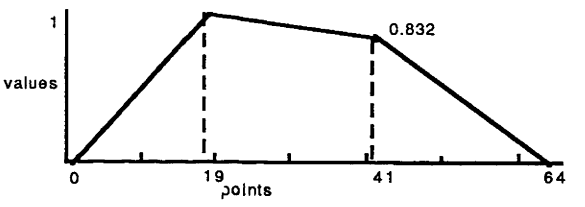
Envelope 6



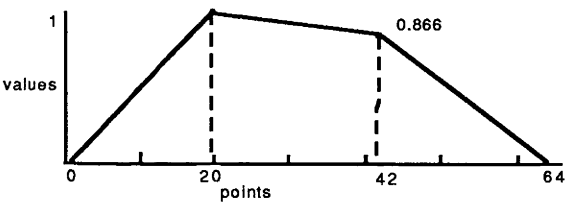
Envelope 7



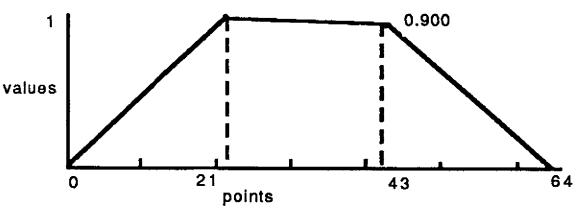
Envelope 8



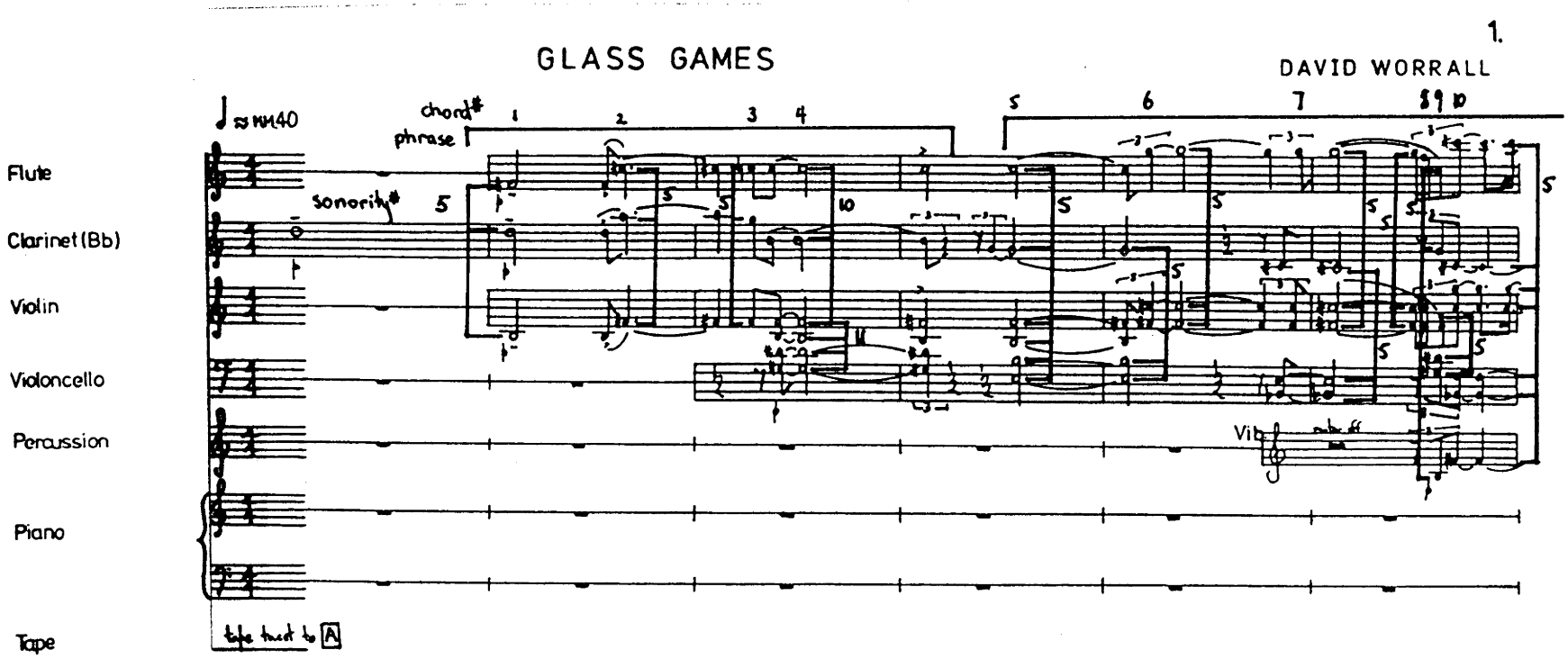
Envelope 9



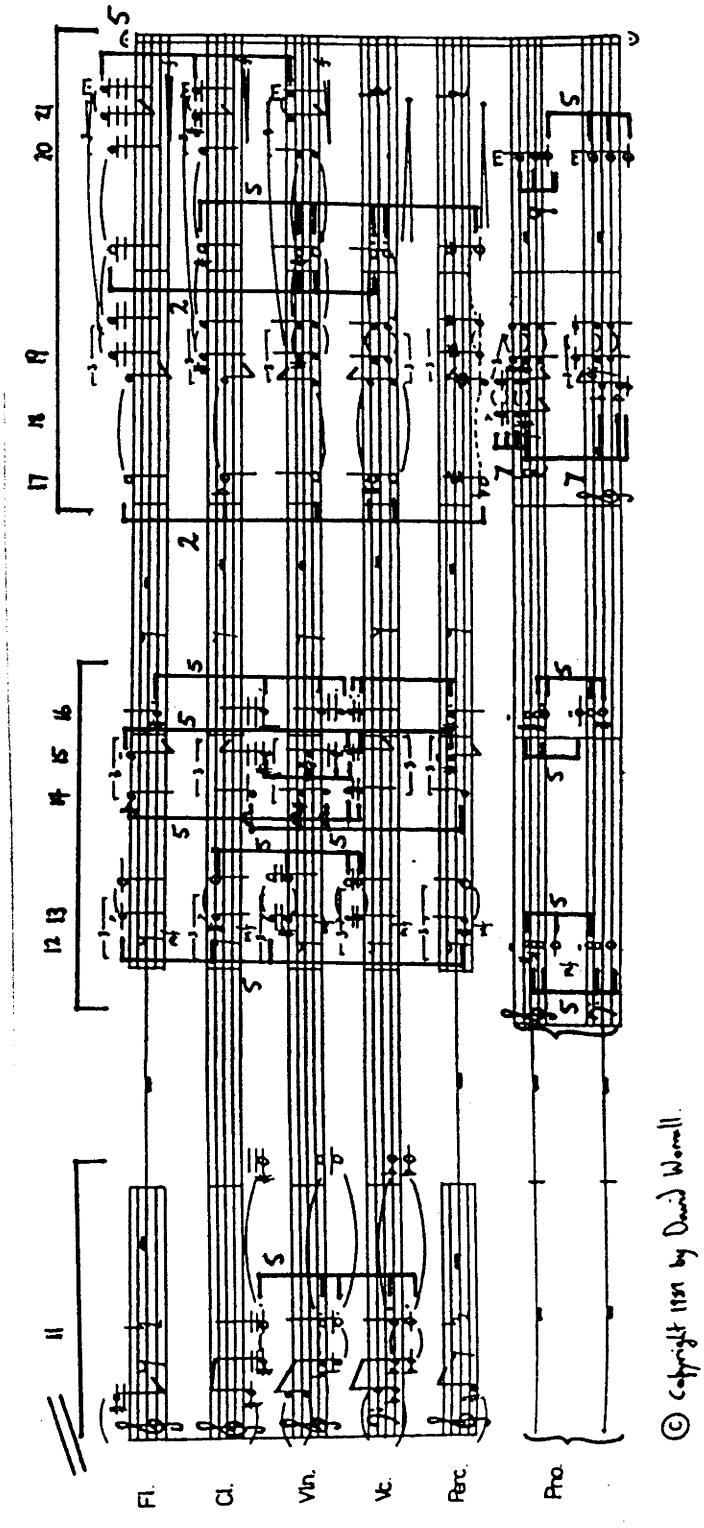
Envelope 10



Envelope 11




**Appendix 3** Analysis of the sonorities in the Prologue.


11
12 13
14 15 16
17 18 19
20 21
Fl.
Cl.
Vln.
Vc.
Perc.
Pno.
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