Composing with Chaos; applications of a new science for music

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In this paper the author shows where concepts and mathematical models derived from the developing field of Chaos Science can be applied to electroacoustic and instrumental composition. Examples of non-linear dynamics include Lorenz's model of fluid behaviour, Verhulst's model of population growth, Hénon's analysis of the multiple celestial body problem, Barry Martin's Algorithm which produces quasi-organic forms, and the 'Baker' mixing function. Besides broadening the numerical techniques available for electronic music generation, concepts such as fractal structure, feedback process and iterative function can be applied to 'ordinary' composition as well. For example, in designing melodic curve, defining meter, planning instrumentation, manipulating symbols, creating ornamentation and elaboration, etc. Some suggestions as to mapping are made, the critical boundary between science and art. Musical examples are used from the following works by the author: Harpsi-Kord for harpsichordist and tape, Fractal Piano for computer-guided pianola, The Five Seasons for 6 percussionists and tape, Brain-Wave for recorder-players, Modi-Fications for marimba & tape, and Hyperion's Tumble for tape.

300 years ago Newton formulated the laws of motion which laid the ground-work for a clockwork view of the universe. By the late 18th century the French astronomer Laplace optimistically stated that intelligent creatures could know any past or future state of the universe, if they only knew well enough its present state, what direction it was heading towards, and had powerful enough calculating methods. This deterministic world view has proved to need revision. Scientific and mathematical developments of the last 30 years have led to new insights into subjects, which because of their complexity, had previously been swept under the rug by the scientific establishment. Intractable problems in weather forecasting, the modelling of wildlife populations, the geometry of nature, the understanding of turbulent flow and bio-rhythms gave startling new results when revolutionary methods of analysis were applied. As a result, words such as "chaos", "order", "simple" and "complex" have been redefined; and a new concept formed: "fractal".

Ironically, it took the advent of the deterministic tool *par excellence* namely the computer, to cause many contemporary scientists to rethink the whole matter. With mathematical models they had been able to make accurate predictions of planetary motions and tides, for example. Everyone had thought that long-range weather prediction should also be possible; you just had to make much more calculations. In 1961 the meteorologist Edward Lorenz managed to model the Earth's weather on a computer; one could follow recurrent "rain storms", or "cyclones", etc. Only there was a problem: if he started the program with slightly different initial conditions of wind speed and temperature, the artificial weather would be the same as in a previous run only in the beginning. After a while, the "weather" would diverge from the previous run, and eventually end up completely different! (See fig. 1.) To appreciate what this means, one must remember that the computer model was using proven physical laws of gas and water behaviour; and the computer ran completely deterministically with no additional input after it was started. With Lorenz dawned the idea that long-range forecasting was impossible. Small errors in measurements would multiply, cascading upwards in the scale of turbulence: from a puff of wind to continent-sized spirals. Lorenz called it the "Butterfly Effect"- theoretically, a butterfly stirring its wings in Peking could start a storm over New York the next month!

Lorenz later developed a more general mathematical model of fluid behaviour. It describes the flow of heated fluid, called convection. For example, when a pan of water is heated, the hotter water at the bottom tends to rise, because it is less dense. At the top of the pan it comes into contact with air which cools it off somewhat. Then the cooled denser water sinks back to the bottom of the pan. This circulation of fluid is called a convection cell, and remains smooth and orderly as long as the heat under the pan is moderate. However, if the heat is high, the water moves to fast to cool off very much; the convection cell breaks up and flow is turbulent, as portions of the water compete with each other to get to the top. Lorenz took the Navier-Stokes equation which describes fluid flow, and simplified it to get an equation to model convection, using three variables in non-linear relationship. (A linear relationship is where a change in one variable is mirrored by a proportional change in another variable: its graph is a straight line. A graph of a non-linear relationship, on the other hand, might show breaks, reversals, bends, etc.)

$$x_{new} = x + d*a*(y-x)$$
$$y_{new} = y + d*(x*(c-z)-y)$$
$$z_{new} = z + d*(x*y-b*z)$$

a, **b**, **c** and **d** are constants with the values 10, 8/3, 28, and .003 respectively. A new value is calculated for each variable, dependent on its previous value and the other variables in various proportions. A loop is set up by plugging the new values from a calculation into the variables for the previous state (e.g. $x = x_{new}$). Then we can run the calculations all over again. The change in values of the variables with time can be traced out in what's called a phase diagram (See fig. 2.) A point on the diagram represents the physical state of a system, actually in three dimensions. If a system heads toward a stable final state, its phase diagram would tend to localise to a point, called the attractor. For a periodic system, the phase diagram would tend to be a closed loop of some kind. Lorenz's model appears to be chaotic, with a kind of infinite complexity; it has a *strange* attractor! The trace of the model loops endlessly without repeating or crossing itself, flipping unpredictably from one side to the other. It does remain within bounds, however, and is not random; a pattern emerges resembling butterfly wings. Indeed, a new kind of order was discovered which was to reveal itself in analysis of many different natural phenomena; order within chaos. Lorenz's work started the revolution which was, like his "Butterfly Effect" to spread to many fields outside of meteorology.

At this point I'd like to describe pieces of mine which use some of the ideas just described. **Harpsi-kord** for tape and harpsichordist was composed in 1988. In this piece the central idea is order within chaos. Compositionally, it swings between the poles: regular/irregular, loud/soft, atonal/harmonic, the use of timbre from an ancient instrument or electronically generated. The middle ground is sought for by transformations sometimes possible only through new techniques: 'samples' of harpsichord sounds were adapted electronically. Sometimes techniques were turned on themselves; having sampled a tone-cluster, it was available on each note of a synthesizer. Clusters of clusters were made. Similarly, rhythmic or melodic structures were nested in several layers at times. For example, one samples not a single tone, but a melodic motive, and loops it. By holding several keys with the same sample, one generates a polymetric texture, because the same loop at higher pitch plays faster, hence is shorter. One can sample this whole texture, and repeat the process, achieving very soon the limits of human perception regarding detail! The harpsichordist relates to the tape in a quasi-improvisational manner. Although the timing and pitch material is exactly notated, he/she is given considerable freedom in performance. For example, only the pitches were notated in a square, with the rhythm and ordering "randomly" improvised. (See fig. 3.) In this way a "feedback loop" is created; the improviser must use his/her ears and think fast in order to create a proper "dialogue" with the tape.

The next two pieces, **Shuffle** and **Fractal Piano 6** (both from 1988) were realised with the help of the "Vorsetzer". The Vorsetzer is a new form of pianola developed by the technicians of the Electronic Studio of the Sweelinck Conservatory, Amsterdam. It has 88 electromagnets mounted over the keys, which can be triggered with varied degrees of force by a computer. The obvious advantage of this system over the old method of punching out rolls of paper is the inherent flexibility and compactness of data storage with computers. In addition, the use of the computer offers new compositional possibilities.

To make **Shuffle**, an 88-note chromatic scale was produced and manipulated by a computer. The scale accelerates smoothly from relative note values of quarters in the lowest register to 32nds in the highest. It has a dynamic curve of p<f>p with the loudest part occurring in the middle of the piano. MIDI-data for each note is stored in three separate memory-allocations: for pitch, timing/length, and loudness. The data for some notes are then "shuffled" around a bit by a computer program I made: the contents of two randomly chosen (but nearby) memory units for pitch, for example, are exchanged. Likewise, length or loudness data for a few other different pairs are exchanged. Then the memory-allocations are combined, and "performed" by the Vorsetzer: one hears a slightly flawed chromatic scale. The memory-allocations of this flawed scale are then subjected to the same process; data pairs are exchanged. Output is used for input for many cycles in a kind of feedback process. With each cycle, the scale becomes audibly more diffuse and irregular: notes migrate slowly away from their original position in the scale. The original perfectly ordered chromatic scale slowly "degenerates" into a "super-serial" shuffled mix. The final state is complex, and much dependent on the cumulative effect of many small random choices. In chaos theory, one would say that there is sensitive dependence to initial conditions. As such, **Shuffle** is a musical model of the butterfly effect. Here it should be added that it also resembles a 2-voiced canon in contrary motion: a descending chromatic scale enters with the 1st "shuffled" version of the ascending scale, and receives similar treatment.

Fractal Piano 6 is one of a series of studies in which a computer program I developed was used in combination with the Vorsetzer. The heart of this program is a mathematical model of population growth, first derived in 1845 by P. F. Verhulst. (It is often referred to as the logistic equation.) I'd like to describe it in some detail because although simple, it contains profound implications.

The Malthusian Model describes the unbounded growth of a population (of fruit flies, for example) with $x_{new}=a*x$. This formula tells us that we can find the population of a new generation by multiplying the number in the last generation with a productivity factor. Suppose the population doubles each generation; then **a=2,** and starting with 2 parents, we'd get the series: 4 children, 8 grandchildren, 16 great-grand children, etc. It's easy to see that before many generations have been bred, we have a gigantic number. By the 10th generation that is 1024 siblings!

In order to make a more realistic model, Verhulst considered that in nature, the larger a population grows, the less productive it becomes, perhaps because of lack of food or other overpopulation problems. So in creating his (abstract) model, he says, let's set the upper limit of a population at 1. (Think of it as 100% of the room available for growth). Then the room left over by the environment for a new generation is **1-x.** This can be seen as a correction factor to unbounded growth. The Verhulst Model for limited population growth then becomes: $x_{new}=a*x*(1-x)$. The population of a new generation is equal to the malthusian growth factor times the old population, and scaled down by the amount of room available for growth. In spite of its simplicity, it proves to be a fair model of what happens in nature. If the productivity factor **a** is 2, then starting the formula with a low seed value like 0.001, we see the population **x** rise and level off at 0.5. This is what we might expect in nature with animals with a healthy productivity. After an initial period of fast growth, the population stabilises.

If we set the productivity factor **a** to higher values, strange things happen. If **a** is 3.2, **x** grows rapidly at first, but then doesn't stabilise to one value; rather it alternates between two values endlessly. (See fig. 4a.) It doesn't matter what the seed value was, **x** ends up alternating between the same two values. If **a** is set a little bit larger than 3.4495, we find the values for **x** orbiting between four values eventually. Carefully increasing the value of **a** for still more trials, we find that the number of values that **x** seems to land on keeps bifurcating (to 8, and 16) until there is a value for **a**, 3.569946, just beyond which **x** fluctuates chaotically from one value to the next. Sometimes it bounces back and forth between a couple of values for a while, only to spin off again. (See fig. 4b.)

This type of chaotic behaviour is also observed in nature, for example by an animal with a productivity so high that it overreaches the ability of the environment to support it. The population crashes, only to build up again. The interesting thing about the model is that it does show a kind of regularity, with **x**-values jumping up and down, but it *never repeats itself exactly.* This simple, deterministic mathematical formula can be just as erratic as measurements of real populations in nature!

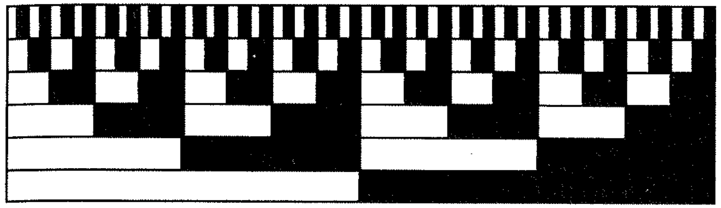
There are more mysteries lurking here. While searching for the exact values of **a** where the behaviour of the model changed-where **x** values would settle down eventually to one, two, four or eight values-the physicist Mitchell Feigenbaum recently discovered a constant ratio between the **a** values. Still more astonishing was the discovery that other quite different mathematical formulas (still using an output-input loop to calculate a new value from an old value), and also experimental data exploring the onset of turbulent flow, also showed the doublings, *and the same ratio between them,* 4.6692... In short, a new universal constant was discovered by Feigenbaum, like the constant of gravity, the speed of light, or the weight of an electron.

We're not yet finished with Verhulst's model. If **a** is increased to 3.83, the chaotic behaviour eventually stops, and **x** circles eventually between only three values. (See fig. 4c.) Increasing **a** in small amounts for new trials results in period doubling of the values where **x** eventually settles down to- 6,12; and again chaotic behaviour sets in, up to **a**=4. (See fig. 4d.) (We cannot set **a** to a number greater than 4, because that would produce **x** values greater than 1, or exceeding our original definition of the maximum population). With the help of a computer, a graph can be made of how Verhulst's formula behaves for all settings of the **a** value. (See fig. 4e.) We see the doublings of **x** at so called bifurcation points, followed by chaotic regions, then windows, where **x** again has a low number of stable values. We get a shock of recognition when we magnify the region where **x** splits up again; the whole pattern reveals itself in miniature! (See fig. 4f.) Indeed, it seems that the pattern contains nested within itself, its own replica! This kind of nested pattern is now called a "fractal". The Polish-born mathematician Benoit Mandelbrot derived the term from the Latin adjective *fractus,* meaning irregular or broken. Fractals are characterised by intricately nested patterns within patterns, with self-similarity on any scale. Fractals can be recognised in a wide range of natural phenomena and shapes, such as trees and clouds. Analysis of Indonesian Gamelan music reveals fractal structure. (See fig. 5). The rhythmic punctuation fits a pattern based on the series 2,4,8,16, etc.; and the nuclear melody is performed simultaneously on several instruments at different speeds.

To compose **Fractal Piano 6,** values obtained from iteration of the Verhulst formula where encoded

using non-linear mapping (with a partially "shuffled" scale, or with a selected or weighted element set) into pitches, lengths and loudnesses. This MIDI-data was edited with the help of a commercial sequencer program; stretched and squeezed time-wise, and layered in various ways, using "fractal" structures. For example, the on/off pattern shown in fig. 6 was used as a mask to create fragmented density in one part of the piece. Say the upper register of the piano turns on and off at intervals of 2 sec. When this register is "on", material is audible within this register. When it is "off", it is silent. In a register just under the highest one, the mask turns on and off every 4 sec.; in a register just under it, every 8 sec.; and so on. By applying such a mask over the (potentially endless) chaotic material, I find a kind of musical tension is generated. Notice that the whole mask pattern produces all possible on/off combinations for the chosen number of registers. It is related to the I Ching, with its 64 possible combinations of 6 solid or broken lines.

FIGURE 6 Combinational Scheme for Fractal Piano 6



Flocking animals co-ordinate in a remarkable and still incompletely understood fashion. The reaction time of a group in danger, or in making turns is considerably faster than the reaction time measured of isolated individuals. In order to maintain the proper distances between neighbours without collision, some sort of multi-sensory positive-negative feedback mechanism is in operation. Neural physiology has revealed that the massively interconnected neural network in the individual brain operates with feedback processes. A neuron cell has a main body, an axon from which it receives signals, and treelike extensions called dendrites which branch off in hundreds to make contact with other cells. Connections between axons and dendrites are effected across gaps, called synapses. Neurons send out impulses spontaneously at a rate of about 10 per second. However, the rate of firing changes, and depends on the sum total number and strength of the impulses it receives. There are both excitatory and inhibitory synapses: signals from the former tend to increase the firing rate of a cell, while the latter tend to reduce the firing rate of a cell. The picture of ceaseless electrical activity; signals amplifying, muting, modulating, crossing each other, and returning in loops; all in incredibly complex and indecipherable wave-like patterns: this picture gives us an idea how thought and memory are possible. Recent investigation of the physiology of perception has led to the discovery of chaos in the brain: complex behaviour which seems random, but has a hidden order. Vast collections of neurons shift quickly from one complex pattern to another, in response to the smallest of inputs (remember the butterfly effect). An organism as a whole acts in its environment with feedback mechanisms. The brain seeks information, and sends signals to muscles to place sensory organs in position, and to sensitise parts of the brain which will process signals. A burst of collective patterned activity from all sensory organs is combined to form a gestalt. Then a fraction of a second later, another search for information is demanded. It seems that chaos in the brain is not pathological, as one might expect; but instead is the basis of healthy functioning, indeed explains how the brain can respond quickly and flexibly to an ever-changing outside world. Even what we experience as a original idea (brain-storm) may be derived from a chaotic neural firing pattern triggered in an ever-widening cascade from a small initial impulse.

In my piece **Brain-Wave** for at least 3 recorders of any kind, (1989), I wanted to set up a self-regulating musical situation. All musicians improvise on the same basic material, which is arranged in four cycles, each with four events. (See fig. 7). Performers should stand or sit spread out around the hall, possibly on different levels. Each player should face an arbitrarily chosen direction. Emphasis is placed on influences which performers take from their neighbours. Players(s) in front of an individual give positive influence, and player(s) in back give negative influence. Here is a table summarising these influences:

	Positive influence	**Negative influence**
If:	player(s) in front are playing,	player(s) in back are playing,
one may:	start to play. play louder.	stop playing. play softer.

play more repeats of an event.	stop, or go to next event.
attempt to imitate style of other player(s).	attempt to play in a style opposite to other player(s).
try to match the speed(s) of other player(s).	play fast when other player(s) are slow, and vice versa.

The object is not to synchronise exactly with the other players, but to correlate what a player does with what the others do. Since there is no conductor, each player must partly assume that function, being attentive to the ensemble sound, and taking initiative to lead that sound were he/she thinks it should go. The aim is to create an interactive situation such as is found in nature, among flocks of birds, or in brain neurons, for example.

In 1989 I completed **The Five Seasons** for 6 percussionists and tape. My inspiration source was an ancient Chinese theory, in which the Seasons, Emotions, Colors, Elements and Directions were grouped as follows:

Spring	Anger	Green	Wood	East
Summer	Joy	Red	Fire	South
Aftersummer	Sympathy	Yellow	Earth	Center
Fall	Grief	White	Metal	West
Winter	Fear	Black	Water	North

This piece incorporates several techniques which were derived from Chaos Science. My adaptation of the Verhulst Model was used to derive some of the rhythmic material for the piece, as in **Fractal Piano 6.** Fractal structures define the form of several sections. Some of the electronic sounds on the tape were made using feedback loops for frequency modulation. The performers are called on to improvise in one section. I'd like to go into more detail with this piece to show how these techniques work.

The first part, **Spring**, begins with accelerandos of accelerandos. First a pulse plan was worked out; the distance between pulses starts large, with successive pulses scaled by a ratio such as 2/3rds down to small (fast) intervals. Then an accelerating figure was fitted to each of the pulses. (A similar slowly accelerating roll is found in Chinese opera and Korean ceremonial music.) There are three layers, played by wood blocks, temple blocks, and log drum. (See fig. 8). Later on, a 16-note theme in quarter-notes is introduced in the bass marimba. The melodic curve of this theme is a projection of a fractal graphic design I made. Here a 4-note melodic motive is fitted or transposed into a blown-up version of itself (See fig. 9). Such nested patterns with scaled elements are characteristic of fractals, as already described. There follows a metric canon; the theme enters in eighth notes, then triplet eighths, and finally sixteenths. (See fig. 10). One can consider the whole construction as a fractal of a fractal, since the theme pattern (itself a fractal) occurs simultaneously at different speeds and octaves. After another metric canon and a section with controlled improvisation, this theme returns with a different treatment. It is split up into 4-note fragments, and given a peculiar "doubling": not parallelism, but an exaggeration of the melodic curve, using multiplication. Again, such "scaling" is a common method of constructing geometrical fractals (See fig. 11).

In the second part, **Summer**, a wiring scheme which includes two feedback loops was used for electronic FM synthesis: the output of any generator provides input control voltages for two other generators. In one loop, when the voltage output of a Low-Frequency-Oscillator (LFO) is high, it causes its neighbour LFO to oscillate at a higher rate. In the other loop, inverted signals are sent out: in this case a high output voltage of a LFO causes a lower rate of oscillation in a cross-connected LFO. The output of all LFO's was used to control other electronic devices, to synthesize a sound. Because of the interconnectedness, and the complex interaction of positive and negative feedback loops, the results of such a circuit can be unpredictable and chaotic.

The **Summer** is divided into four sections, each with a clearly defined instrumentation. Each section and all instruments have similar material rhythmically, generated from the Verhulst Model. There are different scaling factors applied to the material for different instruments playing together in an ensemble, controlling the relative densities of attack.

The third part, **Aftersummer**, uses an on/off masking scheme like that used in **Fractal Piano 6.** Here, not registers on the piano, but six different percussion timbres (all with a sharp decay) are "turned on or off". As in **Fractal Piano 6**, we get all 64 possible combinations of the six elements, and a kind of fractured crescendo. Rolls and repeated notes of various tempi, but always in decrescendo, provide "thematic" self-similarity. (See fig. 6 again.)

The fourth part, **Fall**, depicts musically the "Butterfly Effect", previously described. In the last measures of **Aftersummer**, all six players have finally come together. In the first measure of **Fall**, they play all together again (this time on metal instruments); and then disperse. Sometimes 2 or 3 players synchronize for a while, but small deviations lead to larger separations, and this part ends fragmented and scattered. Loosely spoken, this part is an inversion of how **Spring** begins: **Fall** contains a ritardando of ritardandos.

For the fifth and last part, **Winter**, I used a technique I call "nested repeats" to create the metric structure. Difficult for a human, perhaps, but a computer can easily carry out the following set of commands:

j+[h+[f+[d+[b+[a]+c]+e]+ g]+ i]+k
=jhfdbaacbaacedbaacbaacegfdbaacbaacedbaacbaacegihfdbaacbaacedbaacbaacegfdbaacbaacedbaacbaacegik.

Here, the [ ] signs indicate a simple repetition. **[a]=aa**, for example. The nesting of the repeats makes that **a** gets printed 32 times, **b** and **c** 16 times, **d** and **e** 8 times, **f** and **g** 4 times, **h** and **i** 2 times; and **j** and **k** get printed only once each. Whether you look at a small or large part of the list above, it displays the self-similarity typical of a fractal. For **Winter**, I desired a metrical structure with many changes but internally consistent. First I decided what was going to happen in each measure, in terms of instrumentation and so on, and then let the length in eighth-notes of a measure be determined by substituting the numbers **2-12** for **a-k** in the fractal pattern.

Modi-fications for large marimba and tape (1990) makes use of what I call "transposing modes". These are constructed like fractals, with an interval structure repeated indefinitely. For example, take the interval cell [1,4,2] (a semitone=1). Starting with a low E and repeating the cell, we get E,F,A,B,C,E,F#. Notice that because the elements of the cell add up to 7, two cells don't complete an octave, but overreach it. Indeed, we must repeat the cell 12 times before we get the same pitch-names. Playing "scales" up and down through this mode, we get continuous transposition through the cycle of fifths.

The ordering of much of the material in this piece was achieved with a computer program I worked out called "statistical feedback". A weighted random choice between a string of elements; only the order of preference among the elements is always changing, depending on previous choices. What it does is make a "chaotisation" of serialism. I have used this program on several different element sets in composing the marimba part as well as the tape part of this piece. Pitch, note length and dynamics; as well as larger structures: mode, section length, and electronic timbre; all material and forms are subject to *modification.*

In 1993 I made **Hyperion's Tumble** for tape, using computer algorithms. Observations of Hyperion, a small, irregularly-shaped moon of Saturn, provided some of the first evidence that celestial motion is not merely giant clockwork. With an eccentric orbit phase-locked in 3/4 ratio with Titan (Saturn's largest moon), Hyperion tumbles end-over-end in sometimes periodic, sometimes chaotic fashion, subtly influenced by gravitational forces.

Newton had solved the problem of 2 bodies interacting gravitationally: depending on their energy and mass, they move in perfect curves: a circle, ellipse, parabola or hyperbola. The problem of 3 bodies interacting gravitationally has proved to be surprisingly difficult, and mathematician Henri Poincaré has shown that in the long term, their motion can only be approximated, and is in essence unpredictable. He invented a method to visualise the complicated behaviour of such a system, now called a Poincaré map. A 2-dimensional slice of a three-dimensional phase space will show either one or a few points if the system is periodic, and a complicated figure if it is chaotic. An object with a chaotic phase space might have a degenerate or unstable orbit, causing it to crash into another body, or fly off into infinite space. Close examination of these figures, called strange attractors, proves that they are fractals. Curves are folded into themselves, with infinite regress: increasing magnification shows evermore detail, but with recurring proportional patterns (see fig. 12).

French astronomer Michel Hénon has also demonstrated the theoretical possibility of chaos in the cosmos, when he modelled stellar orbits in galaxies, with the computer. Depending on how the model was set up, stellar orbits would show different behaviours: at low energy levels, orbits were regular ellipses. Higher energy levels gave more complicated orbits, which never exactly repeated themselves, and beyond a certain energy level, the orbits became unstable and unpredictable. He wrote a simple equation to explore the folding and remapping of an oval onto itself, which produces an archetype of strange attractors (see fig. 13).

$$x_{new}=y+1-1.4*x\hat{\ }2$$
$$y_{new}=0.3*x$$

Blowing up a strand of the attractor reveals tiny strands within it, spaced from each other in the same ratios as the parent strands.

Two computer programs I wrote based on chaos theory enabled me to generate voltage fluctuations for synthesis. A formula discovered by Barry Martin generates chaotic orbits, two-dimensional plots of which resemble organic structures such as cells under a microscope (see fig. 14).

$$x_{new}=y-SQRT(ABS(b*x-c))*SIGN(x)$$
$$y_{new}=a-x$$

Different initial values for the constants **a**,**b**, & **c** result in different patterns and periodicities.
I call the second program the "Baker function". A string of integers is folded into itself recursively, mixing the integers completely. However there are strange periodicities occurring, and eventually the original string mysteriously re-occurs. For example, imagine picking up the integer-string in the first row, below, by the middle. You have the '5' between your fingers, and two ends dangle below. Read off the numbers, starting at your fingers and alternating between the string ends as you move down, to get the second row. Repeat the process to generate the other rows. This process is similar to the one a baker uses to mix dough: flatten with a rolling pin, fold over a half, flatten again, fold again, etc.

1	2	3	4	5	6	7	8	9
5	6	4	7	3	8	2	9	1
3	8	7	2	4	9	6	1	5
4	9	2	6	7	1	8	5	3
7	1	6	8	2	5	9	3	4
2	5	8	9	6	3	1	4	7
6	3	9	1	8	4	5	7	2
8	4	1	5	9	7	3	2	6
9	7	5	3	1	2	4	6	8
1	2	3	4	5	6	7	8	9

Irregular motoric sounds resulted from the transcription of the output of these algorithms. A chaotic sound lies in a spectrum between a sinus-tone, which is perfectly periodic, and white noise, which is perfectly aperiodic. It can have a maximum of complexity, always producing more detail, or information, within certain limits. In principle, computer chaos can be used to model on any level, from musical structure to musical sound.

What holds our attention in listening to music? Music from Bach to Bartók, Josquin to Xenakis, from Bali to Bolivia has some special kind of pattern which hovers in a phase space between repetition and randomness, between association and breaking-away, between order and chaos. Does a *strange attractor* underlie a piece which gives us a feeling of anticipation & resolution, of simplicity within complexity? Do its patterns show resemblance to the fractal geometry identified in nature? Does the new definition of chaos- that dynamics can be paradoxically both deterministic and unpredictable- help us understand how a particular sequence of sounds gives us the feeling both of inevitability and surprise? Perhaps composers as well as scientists may do well to take a new look at Chaos.

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Stewert, Ian: **Does God Play Dice? The Mathematics of Chaos;** 1989 Basil Blackwell Ltd.
Watson, Lyall: **The Dreams of Dragons;** 1987 Morrow, New York

Figure 1 The Butterfly Effect

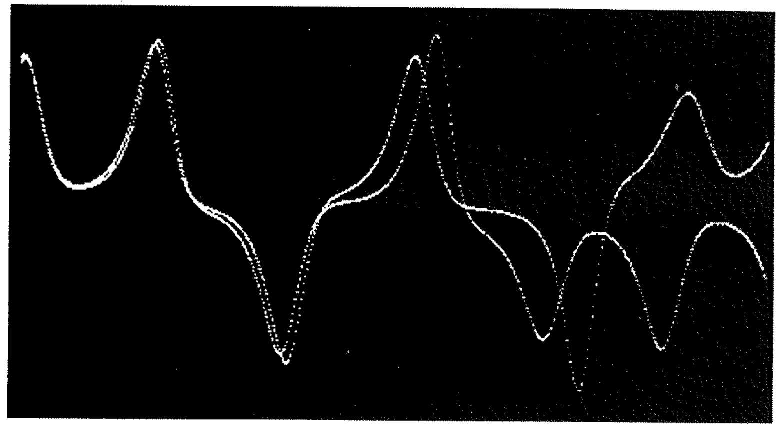


Figure 2 Lorenz Function

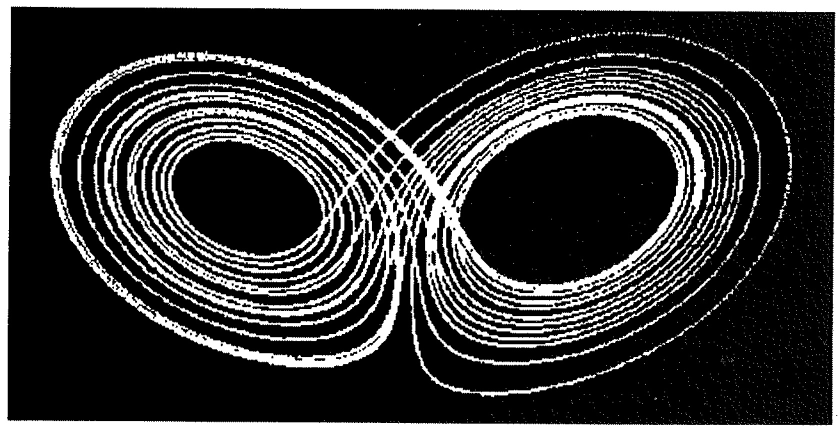
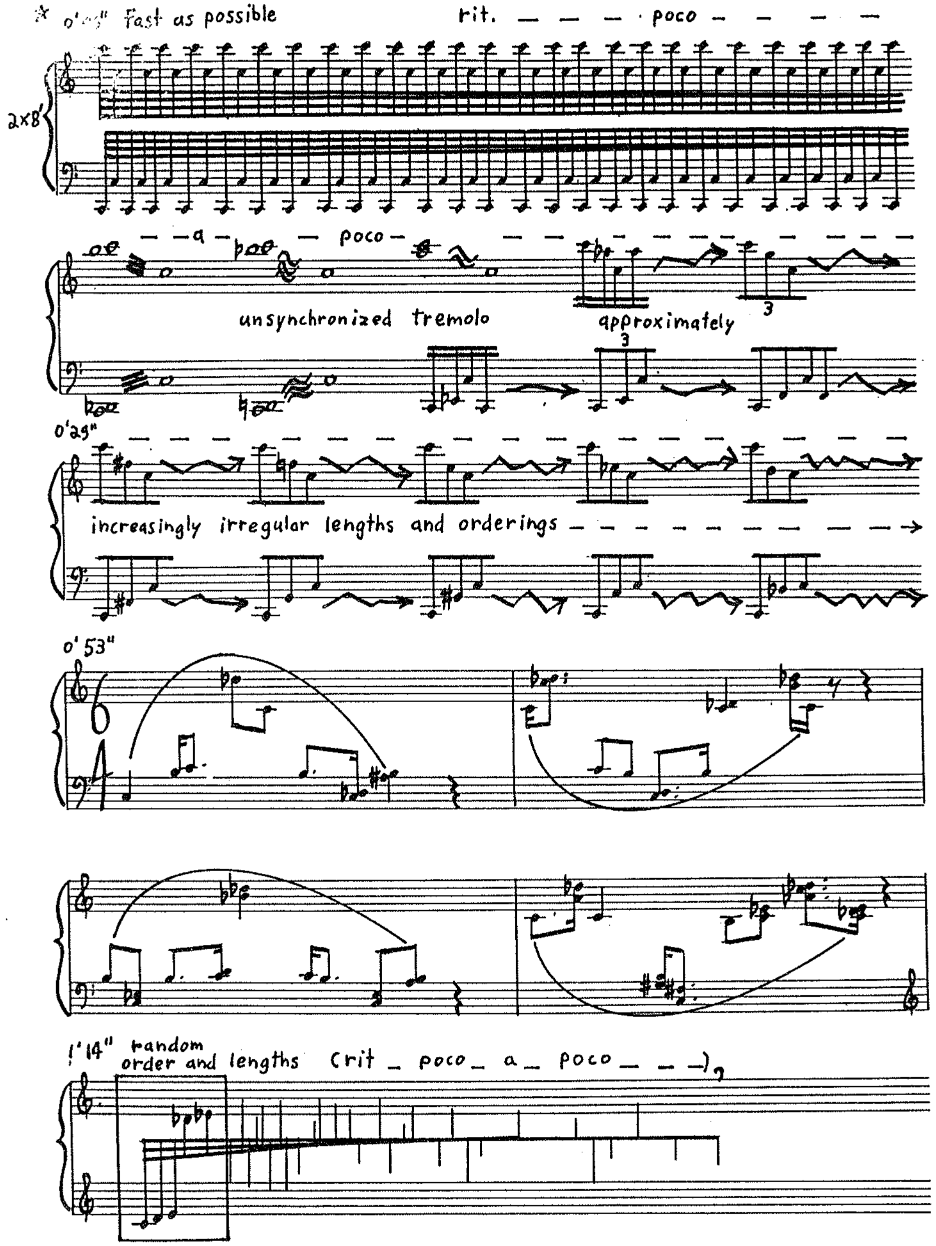


FIGURE 3 Harpsi-Kord p.1



* leave 6-Sec. rest before sound on tape: Harpsichord and tape sounds begin together at 0'06"

FIGURE 4a-d Verhulst Model

Figure 4a, Verhulst model, a=3.2

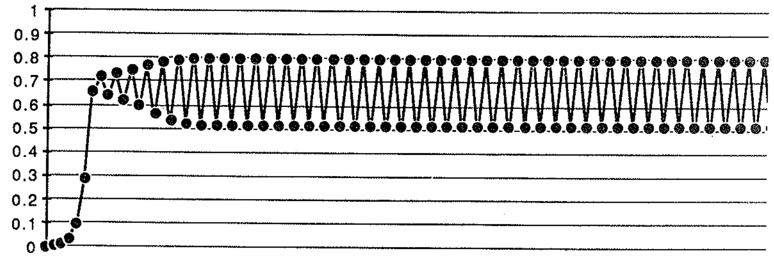


Figure 4b, Verhulst model, a=3.68

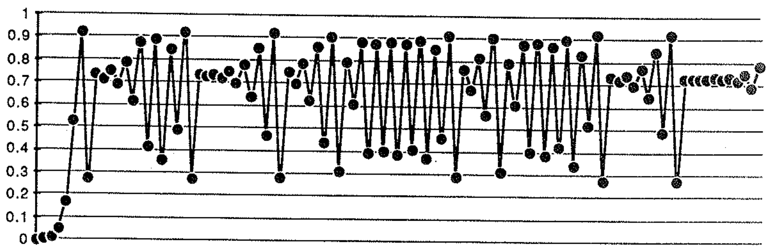


Figure 4c, Verhulst model, a=3.83

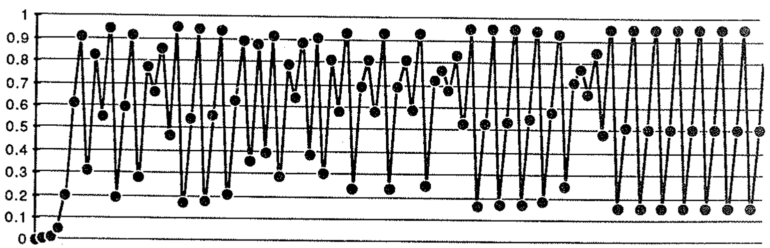


Figure 4d, Verhulst model, a=4

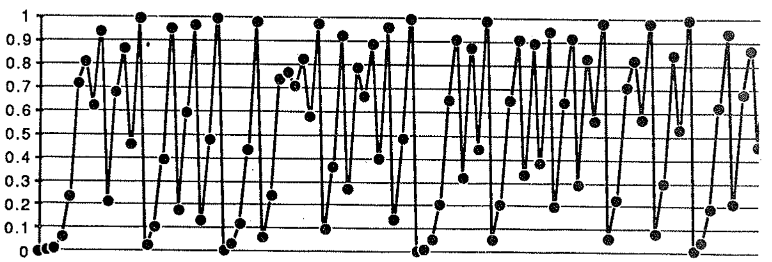


Figure 4e Verhulst Model: all "a" values along x-axis

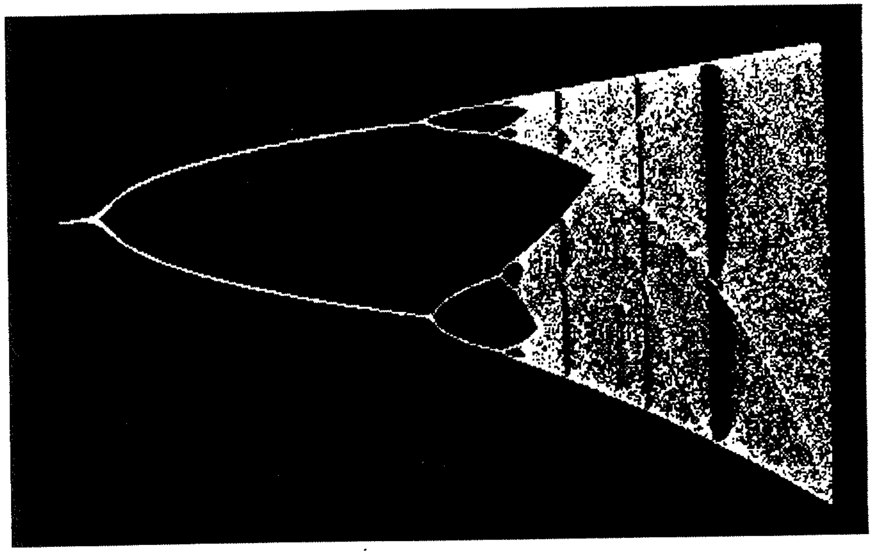


Figure 4f Verhulst Model: all "a" values along x-axis (detail)

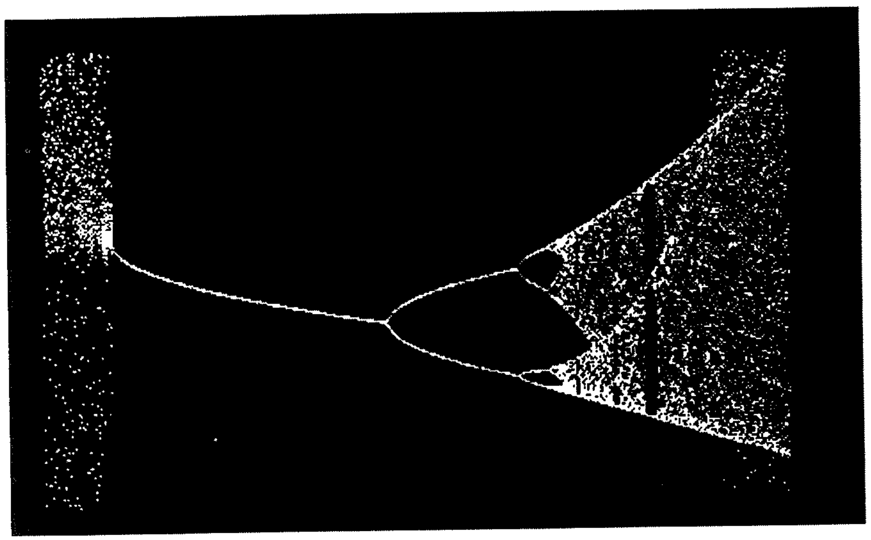
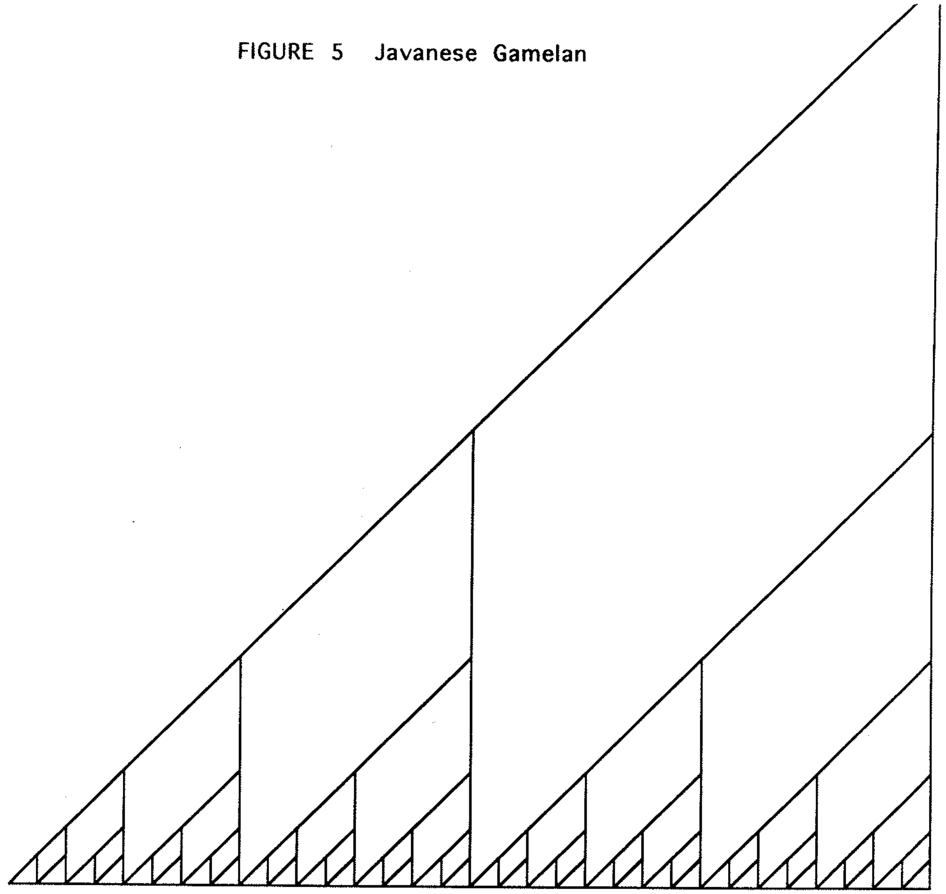
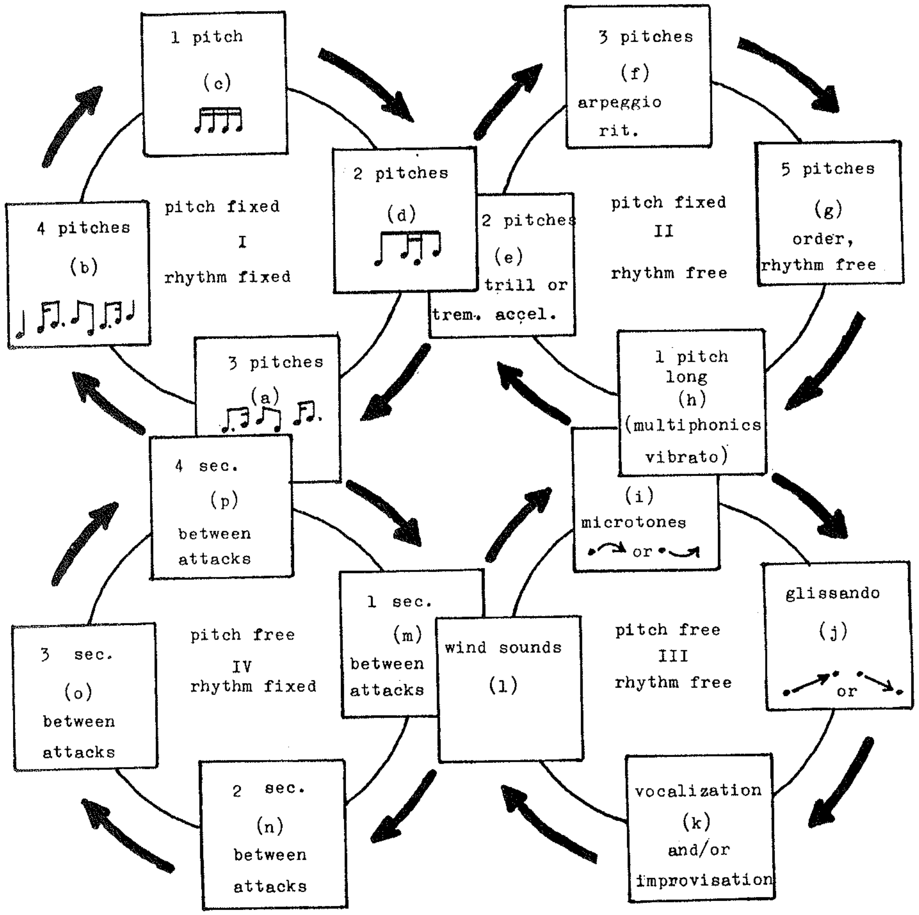


FIGURE 5 Javanese Gamelan



2 1 2 etc. =Balungan (nuclear melody) played on Saron/Slentem
t =Ketuk
P =Kempul
Kn =Kenong
G =Gong

FIGURE 7 Brain-Wave



1990 David Little

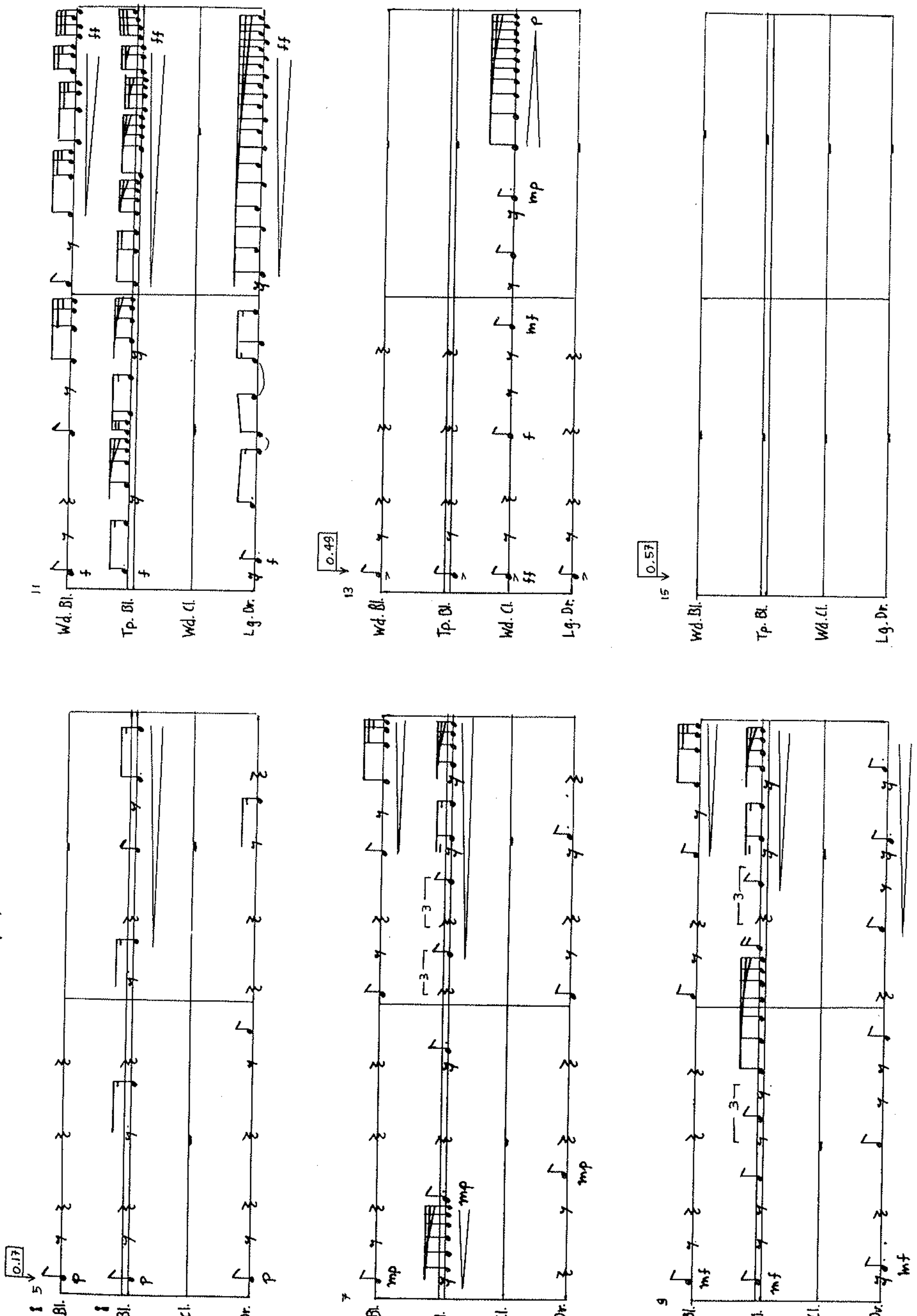


FIGURE 8 The Five Seasons p.2,3

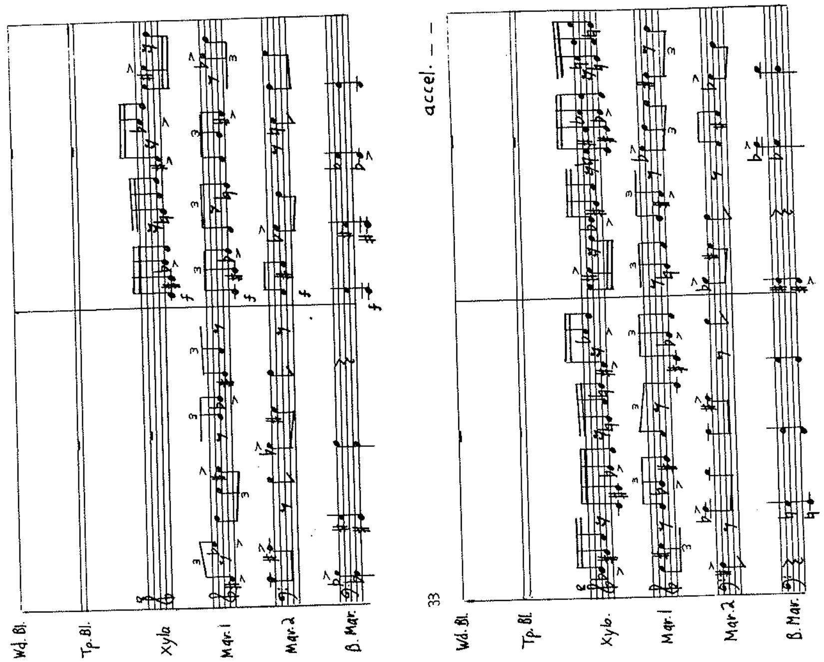


FIGURE 10 The Five Seasons p.7

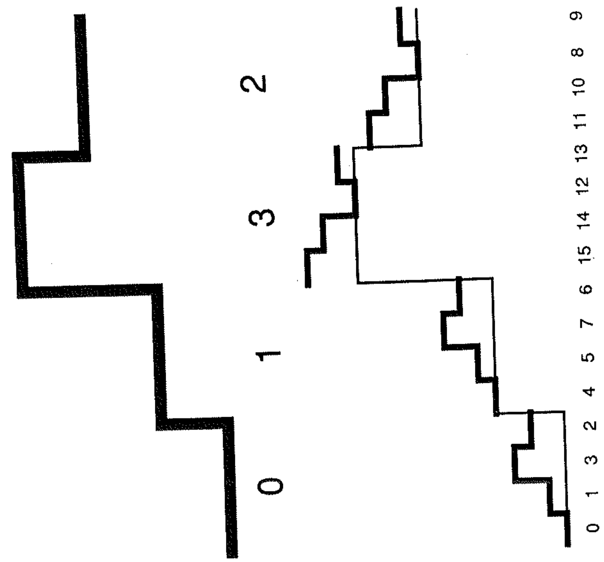


FIGURE 9 The Five Seasons (theme)

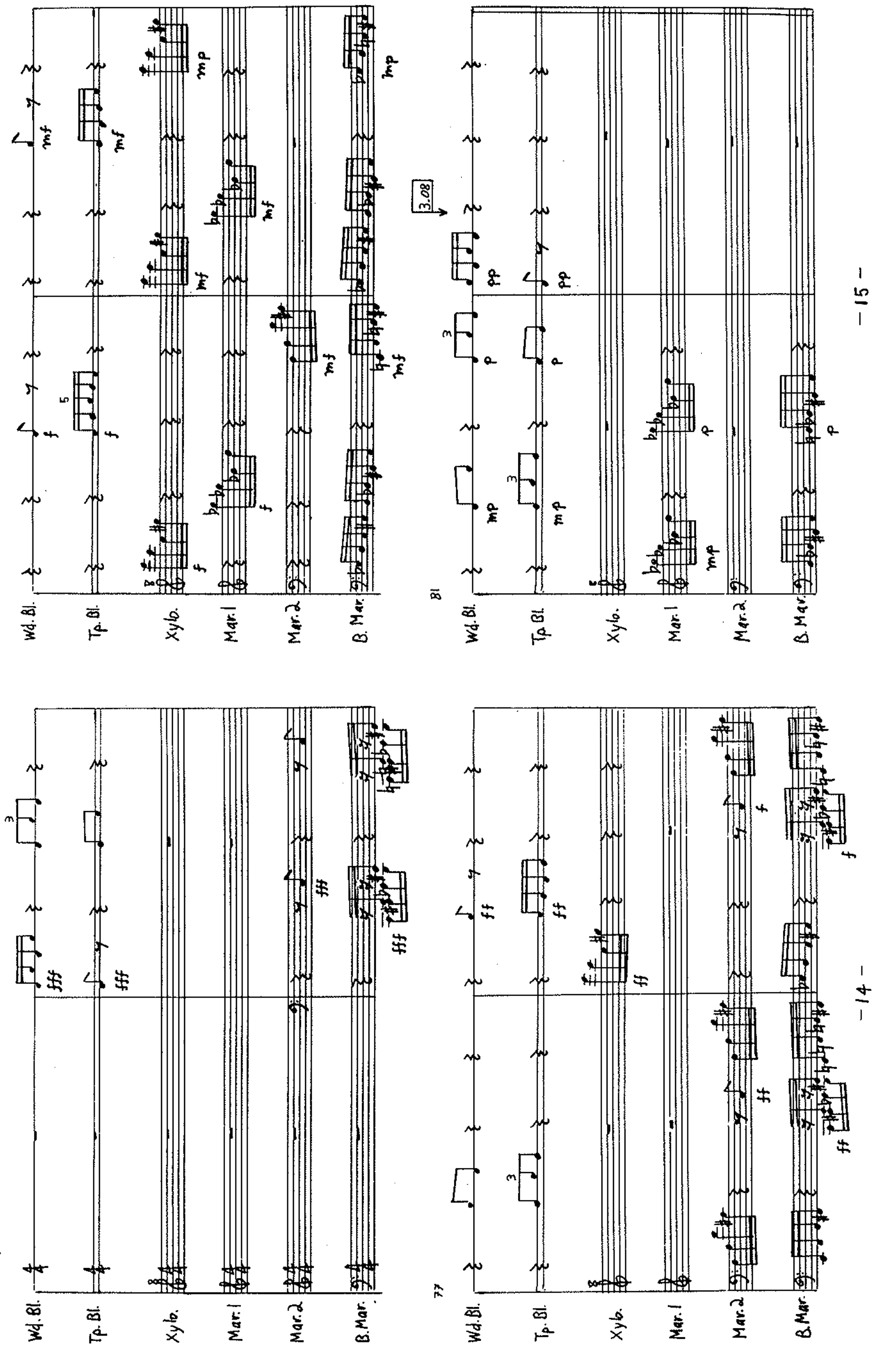


FIGURE 11 The Five Seasons p.14,15

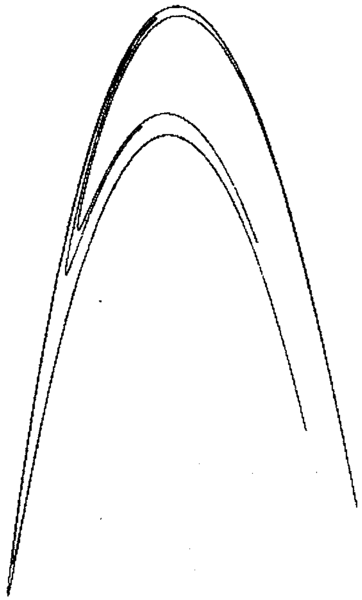


Figure 13 Henon Attractor

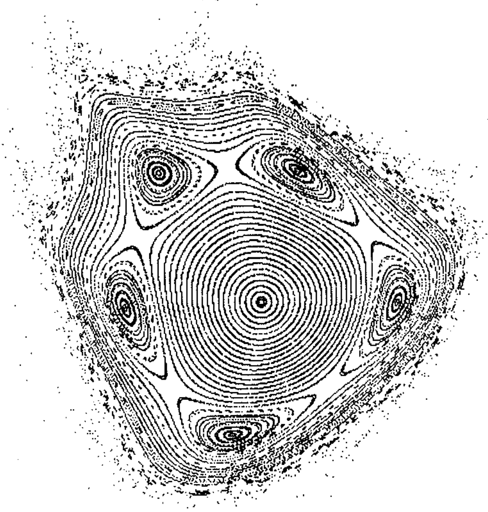


Figure 12 Poincaré Map

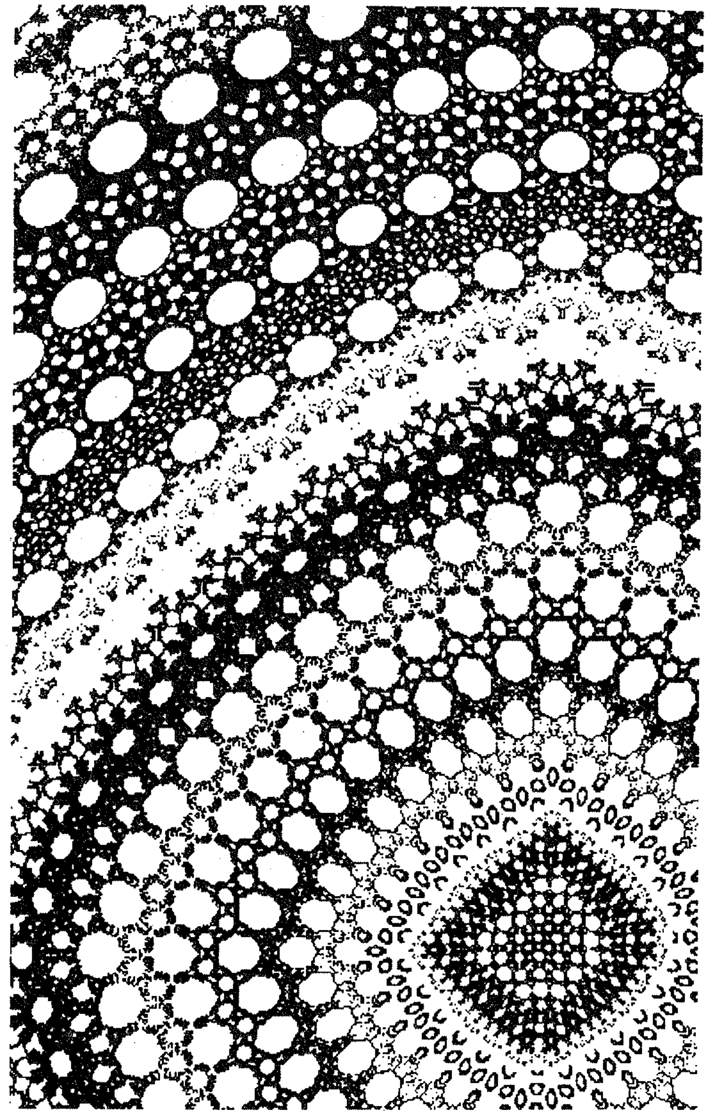


Figure 14 Barry Martin Formula