

A molecular collision model of musical interaction

Peter Beyls

KASK, University College Ghent, Belgium &
ICCMR, University of Plymouth, UK
peter.beyls@plymouth.ac.uk

Abstract

This paper speculates on the potential of a limited set of interacting particles to produce interesting temporal structures in a two dimensional world. Particles exchange information locally though global complex behavior emerges spontaneously. The imaginary physics of the world is described in an ensemble of 2D arrays. An autonomous genetic algorithm continuously aims to optimize the arrays in an effort to maximize diversity. In addition, an external user may interfere in a subtle way; external gestures are integrated into the arrays in proportion to their strength. A quite elaborate mapping scheme creates relationships between complex system behavior and parametric MIDI events.

1. Introduction

The present paper formulates a generative system featuring native internal dynamics open to disturbance by unpredictable actions from an external user. It follows the general working hypothesis of much Alife research; life-like phenomena can be studied by building distributed systems composed of many interacting components. Complex global behavior emerges spontaneously from a collection of simple local interactions between the constituting elements. These elements vary widely in dimension and character; consider for instance, communicating newsagents living on the Internet, social forces between people in a given society or molecules engaged in a chemical reaction. The behavior of such systems cannot be envisaged from a critical analysis of its components; in particular, the mutual relationships between components will force a global unpredictable functionality.

In addition, various cognitive abilities have been characterized as distributed, self-organizing systems (Minsky, 85). The fluid dynamics approach of (Hofstaedter, 95) suggests the study of cognitive processes, including creative decision making, as processes of molecular interaction. Again, coherent structures appear from the random flux of continuous interactions amongst molecules. Our work adopts the metaphor of colliding molecules as a first principle and thus also relates to recent work in artificial chemistry (Dittrich, Ziegler & Banzhaf, 01).

Our application proposes a model of musical man-machine interaction based on the real-time interpretation of particles interacting in a closed container. The container may be either of imagined toroidal shape or feature reflective walls. The internal physics of the system, i.e. what happens when any two particles collide, is represented in a 2-dimensional array. The array instructs particles to move in particular directions. The user interferes with this innate behavior by modifying the array through physical gestures. The user does not exercise explicit control but rather disturbs the expression of an otherwise autonomous, internal physical law. The basic idea here is to synthesize families of waves of variable coherence and periodicity. The complexity of the waves follows a law and the user has only limited and indirect instrumental control over the quality of the wave propagation process.

2. Motivation

The present experiment grew from earlier work with cellular automata [Beyls, 04]. CA are idealized systems to study complexity in natural and synthetic phenomena but as models they are discrete both in time and space. However, one could actually interpret embedded particles in CA as interacting molecules [Hordijk, Crutchfield & Mitchell, 96]. This work interprets domain borders of space-time diagrams in one-dimensional automata as particles. Still earlier work by Ed Fredkin suggests CA as models of ballistic computing. The billiard ball model has great musical potential since its novelty consists in focusing on the detailed evolution in time of an individual microscopic state – in contrast to studying macroscopic quantities based on a statistical distribution of states [Toffoli & Margolus, 86]. This collision model successfully performs logical operations using mirrors as routers.

Now, in an effort to generalize, we may think of particles as responsive objects of arbitrary complexity and even equip them with some form of long-term memory. Consider, for instance, people meeting and interacting in a public space. Social behavioral patterns will surface spontaneously. However, the work described here takes the atomic route to complexity engineering; the objects we use feature a single instance variable – the angle of movement -- and cannot remember former actions (no memory).

Related work

The discipline of artificial life has spawned many incarnations of distributed computational models. According to the field of application we speak, for instance, of particles, molecules, agents or artificial creatures. Particle systems have a long history in the computer simulation of complex natural phenomena. They are instructive, early examples of studying complexity by considering relationships amongst small building blocks – in contrast to using differential equations. More recent work by [Reynolds, 87] describes the flocking of birds (boids) as an emergent process. The Swarm simulation environment developed at the Santa Fe Institute [Minar, Burkhart, Langton & Askenazi 96] is also a significant example.

The swarm and boids ideas was recently adapted for musical purposes by [Blackwell & Bentley, 02]. Swarmmusic is an interactive music improviser. It maps the positions of particles/boids to positions in MIDI space. An external human improviser may act as a temporary target for the swarm. Style-scripts provide additional parametric control over the nature of the interaction thus further conditioning the musical output.

Earlier work of the present author has addressed the potential of real-time man-machine interaction in virtual worlds. Four different agents oriented systems aimed at interactive composing are documented in [Beyls, 97].

3. Formal definition

For our purpose, a molecular system is characterized as a tuple $\{M, R, A\}$ where M is a finite and fixed size collection of basic molecular building blocks and R denotes all possible interaction rules. A specifies an algorithm incorporating additional parameters conditioning how and when the rule R will be applied. Note that the interaction vessel itself is assumed to remain fixed, it is of no qualitative concern to a formal description.

We consider the density of molecules to be fixed (8 in our implementation) and, for clarity; we shall modify a molecular feature (the angle) instead of changing the concentration and/or type of molecules.

The system activity is formally summarized as:

$$system = \{M, R, A\}$$

$$A = S = array_{(12,12)}$$

$$M = \{m_1 \dots m_8\}$$

$$a_m \in \{0 \dots 11\}$$

$$D_{(m_1, m_2)} < S_{(a_{m_1}, a_{m_2})} \Rightarrow (a_{m_1} \leftarrow R_{(a_{m_1}, a_{m_2})}, a_{m_2} \leftarrow R_{(a_{m_2}, a_{m_1})})$$

The algorithm A is equivalent to S , a sensitivity matrix. It holds numerical values expressing a threshold for interaction between any two types of molecules to take place.

The vessel contains 8 molecules defined by M . All molecules move in a direction defined by their momentary angle. The state space of angles is discrete and has a resolution of 30 degrees, so relative angles range between 0 and 11 to cover full circle. Note that angles are spread out evenly in that circle. Note also that the angles resolution has a very strong impact on the potential temporal complexity of the system as a whole; higher resolution will expand the state space in an exponential way. (This will be addressed in future implementations).

Interaction rules R are also described explicitly as regular arrays of 12 by 12 elements. The angles of interacting molecules receive specific interpretation. Both angles are interpreted as to index locations in the array -- to retrieve the new values of both respective angles. The array is a simple and compact way to represent how 12 different types of molecules potentially interact. The state space of all possible matrix rules is huge (12 expt 144 is a 156 digit number!) and thus considered virtually infinite.

The effect of the rule array is qualitative control over molecular collisions. Now, interactions between molecules become effective when their physical distance is less than their mutual interaction threshold defined by array S . When interacting, both molecules will update their angle.

For clarity, sensitivity values S are symmetric in the current implementation, though unequal sensitivity values would certainly add higher degrees of non-linearity to the system.

4. Implementation

The array

The above figure shows the systems architecture. The central 2-dimensional array acts as a lookup-table rule, which molecules in the vessel address. Interacting molecules modify the vessel as a whole thus conditioning posterior interactions. This creates a complex dynamical system; a simple simulated universe is tightly coupled with the expression of a virtual physics defined in an array. For simplicity, we assume the initial conditions (molecular positions) to be random. Also note that we are dealing with a non-reversible system (Prigogine, 84). The future is captured in a deterministic device (the array) though the global system behavior may appear to feature chaotic attractors.

Once set in motion, the couplings between rule array and the vessel -- completely disconnected from the user -- may orchestrate the sustained synthesis of interesting waves for hundreds of generations. The array values (0~11) are mapped to 12 different colors in a private GUI (see fig. 3)

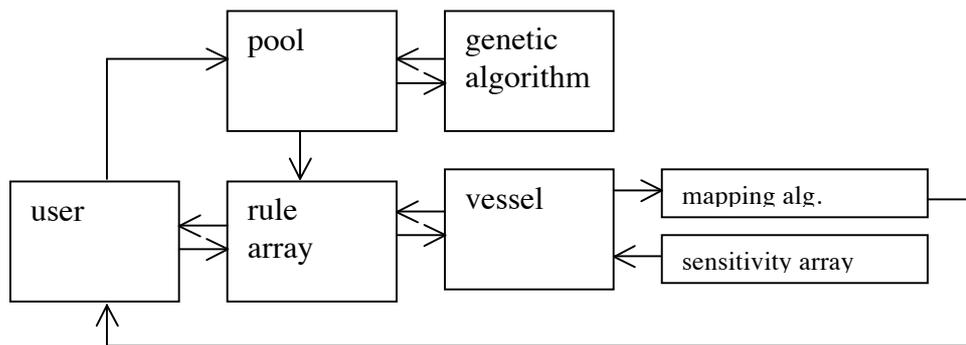


Fig. 1. Global system architecture. Observe the two loops incorporating the user.

The user

The actions of the external user speculate on the possibility to issue qualitative control over this global behavior albeit in an unusual, indirect way. A user provides gestures in 2D space; consider MIDI input of a sequence of (pitch, velocity) events interpreted as a trajectory (x, y) in 2-dimensions. The current implementation uses mouse input; the user draws some gesture (limited to maximum 100 coordinate pairs). The gesture is analyzed instantaneously when a mouse-up event occurs; analysis includes relative length, angularity, traversed distance, total surface used and acceleration/deceleration. Given a fixed sampling rate, we obtain information about the character of a gesture, and consequently, about the motoric personality of a given user.

Now a gesture modifies the current array plus some of the other arrays in the pool. The amount of change plus the number of arrays modified is stochastically proportional to the total length of all segments in a gesture. In addition, the change in an array is computed following an interpolation algorithm. That is, the previous contents of an array strays partially into the future. Therefore, arrays also function as long-term memories.

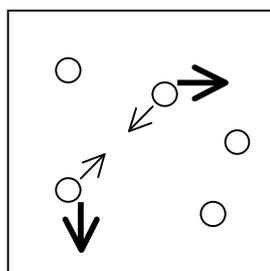


Fig. 2 Prototypical example: two objects interacting according to their current angle of movement. Thinly drawn arrows denote angles at time T , thick arrows denote angles at time $(T+1)$.

The vessel

The simulated vessel is the environment holding molecules moving in a given direction at constant speed. At every cycle, every molecule checks whether any other molecule is within its sensitivity range. If positive, the angles of both objects are viewed as (x,y) pointers in the array. The retrieved value $(0\sim 11)$ will set the new angle $(0\sim 330)$ of that molecule. In case we are dealing with asymmetric affinities, some of the neighbor molecules will change their angle if their sensitivity is high enough. When more than two molecules are within interaction

distance, all neighbors will be evaluated sequentially, the last value retrieved will finally affect the new angle.

The sensitivity between any two angles is expressed in a 12 by 12 sensitivity array. However, most of the experiments reported here use a fixed sensitivity value for all angular affinities.

The pool

There is a small critical mass of 8 arrays, one of which is copied into the currently exploited array. A background algorithm switches continuously between the arrays when the 'delta flag' is true. During every time frame, the specific array also traces the quality of its performance; it counts the total number of interactions plus the number of unique instances of angles-histograms encountered (see Fig 5. History track of angularity histograms). The fitness of the array will be directly proportional to the diversity in histograms. Arrays are chosen at random conditioned by the number of times they were chosen before; the selection probability is inverse proportional to the number of times used in the past. All arrays are visualized in a graphic user interface (see fig. 2), small arrays on top are selected by pointing and the two numbers separated by a colon indicate respectively the nr-times-selected and the accumulated total fitness.

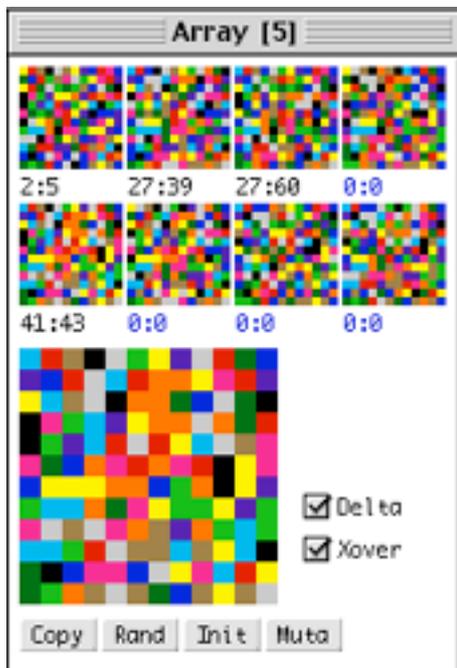


Fig. 3 Rule array selector and visual feedback interface.

The user implicitly steers a complex dynamical system from the observation of the cumulative effect of (1) rule array selection and (2) rule modification, as described above. The user's evaluation is purely subjective; one tries to discover relationships between global system behavior and spontaneous user activity.

The genetic algorithm

When the 'Xover' flag is set, an autonomous genetic process will act in parallel. The genetic interpretation and action is straightforward: arrays are viewed as genotypes subject to standard crossover and mutation operators. The arrays are first sorted according to fitness, the two fittest are considered parents in the breeding process yielding 8 fresh arrays. A small amount of mutation helps prevent premature convergence into a more or less uniform pool.

So both the user and the GA contribute to the interactive development of interesting, propagating structures. Actually, a particular type of man-machine cooperation emerges; the GA clearly aims optimization by creating arrays that often look quite similar; they converge to some spot in genetic space. On the other hand, user activity both selects and modifies some arrays, often profoundly disturbing the GA instantiated structures. The system thus permanently fluctuates producing patterns of variable regularity. User initiated actions have two effects; they tend to favor short-term disorder while also influencing long-term behavior since some of the modified arrays will survive in the next generation. Machine initiated activity can be described as background autonomy according to the single criterion of global system fitness.

The general advantage of the genetic approach is twofold. First, it allows managing the external effect of complex processes without fully understanding the internal machinery orchestrating them. Second, genetic algorithms may generate constructive material that could not be anticipated by an external observer -- so they function as generators of surprise in an otherwise stable system.

For musical continuity, we rely exclusively on the arrays. The system as a whole exhibits a certain inertia; arrays are modified by interpolation and the genetic activity spawns offsprings that inherit features of their parents as they were living in the previous generation. In other words, the perceived melodic continuity is an implicit byproduct of the global systems behavior – it does not result from any form of melodic memory. Consequently, coherent melodic form issues from the accumulative forces of explicit physical gesture and implicit genetic evolution.

5 Mapping procedures

The mapping process defines an imagined relationship between an abstract pattern generating system and an evolved, elusive cultural system we call music. It is the most crucial yet the most difficult component of any generative music generator. We could view molecules as interacting harmonics articulating some complex sound, we could view the molecules as controlling a black box sound synthesis algorithm of arbitrary complexity. However, we shall try to map system dynamics into a melodic sequence with given tonality. The mapping process avoids momentary absolute values and favors using the first derivate of the current situation. In other words, the variable distances between molecules rather than their position are considered. The mapping proceeds as follows:

```
(defmethod create-melody-slice ((self cawp))
  ;; only 1 situation of max 7 events
  (clear-events (melody self))
  (loop with position-distances = (position-distances self)
        with angle-distances = (angles-distances self)
        with interacting-lists = (mapcar 'interacting-p
                                         (subviews self))
        with all-durats = '((4 2 2) (16 8 8) (2 1 1 2 1 1)
                          (8 2 2) (8 1 1 1 1))
        with durats = (take all-durats
                          (mod (loop for el in interacting-lists
                                    sum (length el)) 5))
        with ahist = (angles-histogram self)
        with maxv = (apply 'max ahist)
        with posmaxv = (position maxv ahist) ;; 0 to 11
        with countv = (count maxv ahist) ;; min/maj
        with tonaltype = (if (zerop (mod (apply '+ ahist) 2)) 0 1)
        with scale = (nth (+ posmaxv tonaltype) 24-scales) ;; global
        with st = 0 ;; start-time
        with chan = 0 ;; midi channel
```

```

with d          ;; event duration
initially (format t "~a ~a ~a ~a ~a ~%"
             ahist posmaxv countv tonaltype scale)
for i from 0
for cell in (subviews self)
for interact in interacting-lists
for p in position-distances
for a in angle-distances do ;; a is signed
(setq d (/ (take durats (+ a i)) 10))
(setq chan (if (< p 100) 0 1))
(when interact          ;; length of list > 0
 (cm::insert-object    ;; insert timed midi event
  (cm::new
   cm::midi
   cm::time st
   cm::keynum (+ 36
                (* 12 (round (/ (point-v (view-position
cell)) 40)))) ;; octave
   a) ;; angle
   cm::amplitude (if (plussp a) (+ 100 (random 20))
                      (+ 60 (random 20)))
   cm::duration d
   cm::channel chan)
  (melody self)))
(unless (< p 100) (incf st d))) ;; conditional chord

```

The method *create-melody-slice*, sent to a CAWP object (acronym for *continuous automaton wave propagation*), creates consecutive short melodic sequences. The physical configuration of the cells is significant, though we avoid reading and interpreting the structural pattern as if it were a conventional musical score. Note we are dealing with two different but parallel timing processes. The first one concerns the internal clock controlling the timing of the simulation including the real-time visualization. Timing is set by the user -- up to about 10 updates per second. The second process handles MIDI events at a much slower pace; both processes are concurrent though not synchronized. The melody object sends a message when it has finished playing its current contents, this triggers the *create-melody-slice* method and this process repeats indefinitely. One could say that the mapping procedure occasionally samples the current situation of a virtual world. The (dis)similarity of the melodic output will thus reflect how much the world changes from one generation to the next. Let's address the mapping algorithm in detail.

The *position-distances* and *angle-distances* are the first derivative of the respective instance variables, *angle-distances* are signed values. *Interacting-lists* holds a list of all the current neighbors of every cell, if any.

All-durats is a local library of relative duration units, a short stylistic ensemble of building blocks to be exploited by the algorithm. *Durats* is the selected element from that library; the selection pointer equals the total sum of all neighbors of all cells, modulo 5 (i.e. number of sublists in *all-durats*). The local variable *ahist* is the current angles-histogram, 12 elements wide of which *Maxv* holds the angle that is most expressed in the current situation and *posmaxv* is the position 0~11 of that value in the histogram. *Countv* is the number of times the *maxv* value occurs in the histogram, it says a lot about how specific that value is and, in addition, it is a hint to the diversity of the histogram.

Our system is built inside a larger framework for musical experimentation (written in Lisp -- Digitool MCL 4.2) that provides many resident composition, pattern processing and analysis tools, including tonality libraries of arbitrary complexity. However, the current implementation builds on Western tonality and uses a simple global variable *24scales* holding all major and minor scales in all pitch-classes. These libraries are precomputed for computational efficiency. The algorithm decides on major tonality if the sum of all values in the current histogram (modulo 2) is even, else it is minor. A specific scale is then retrieved

from the scale library using a combined influence of pitch-class (set by *posmaxv* -- very conveniently in the range 0~11) and tonality.

The algorithm now loops through the various lists; the position-distances are considered at a threshold of 100, a value derived by trial and error. For instance, if the distance between two consecutive cells is less than 100 pixels, MIDI events will sound on channel 1 (a value of zero in the program) else on channel 2. In addition, the same mechanism exercises a grouping of events, controlling the start-time of new MIDI events. Thus, chords are always sounding on channel 1.

Finally, a new MIDI event is instantiated on the condition that the cell under consideration is actually interacting, if not, a rest is implicitly generated. The pitch of the event combines 2 forces: octave position follows the vertical position of the cell and the signed angle value adds an interval (-11 to +11) to derive the final pitch. The sign of the current angle-distance conditions the loudness of new events.



The figure above shows a short score excerpt of a typical molecular interaction sequence. The global, uniform sensitivity in this example is 15 pixels. We notice the complex interlocking of rhythmical patterns. A point attractor is passed through starting at measure 15. The expressive qualities follow exclusively from the interpretation of a small group of objects moving in 2D space.

6. Experimental results

The complexity of the temporal patterns varies widely; given fixed and uniform sensitivity, it is directly proportional to (1) the number of different angles at any moment in time and (2) the number of cells that change value at every cycle.

Our model is considered a tool to experiment with interesting temporal changes – not so much to help construct artifacts with a given finality. We focus on qualitative descriptors such as stability, diversity, sensitivity and relational affinity. Our model is built as a synthetic world with private physics, an imagined micro society. Most important, it expresses non-linear

relationships between its components. This implies coherent yet unpredictable behavior; minute external disturbances can indeed entail massive consequences. From the work of [Prigogine & Stengers, 84] we know that order can arise spontaneously out of disorder through the process of self-organization. This principle is scale invariant, it holds for ant societies as well as galaxies – we shall bring it into play in terms of an abstract social system.

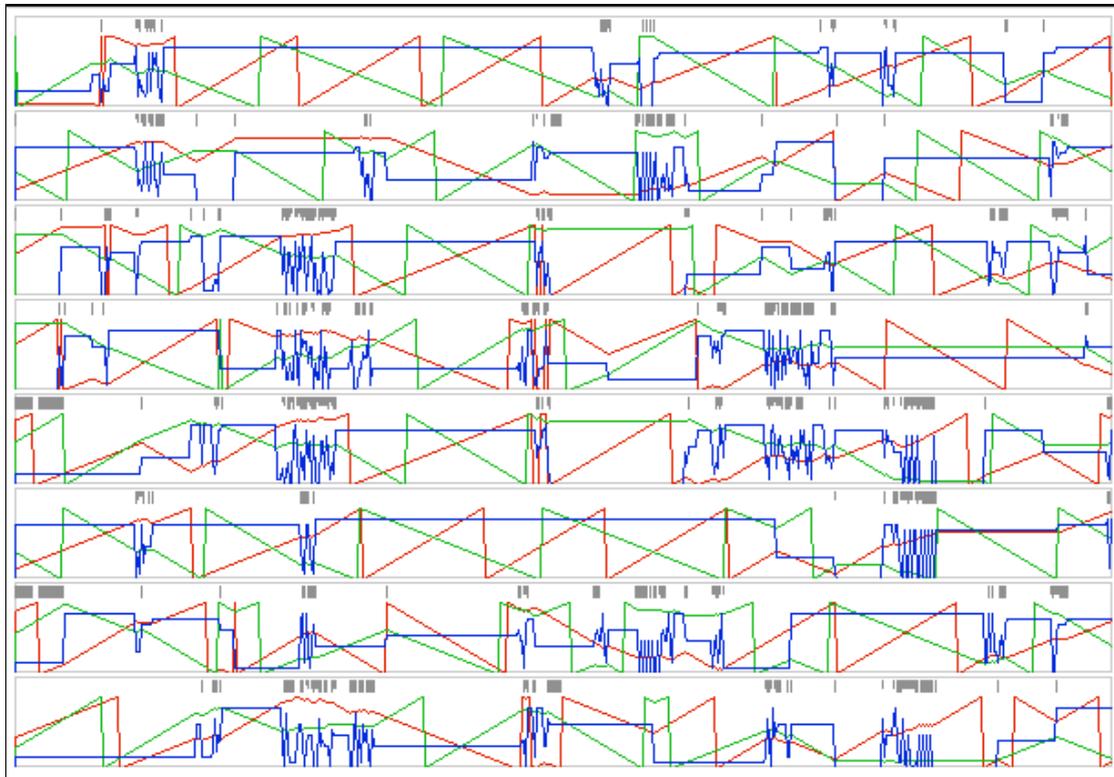


Fig. 4. History track of physical position and direction

Our experiments prove that social constructions occur spontaneously. For instance, given the right initial conditions and the right rule array, a few cells will cluster and move as a group, incidentally, similar to gliders in a 2D cellular automaton. At every process cycle, the net effect of all cells executing a private rule will be a coherent cluster of cells moving in a single direction. Now, a cell approaching the cluster may interact with its closest component and implicitly reconfigure the previous social construction. In other words, collective cycle attractor behavior is destroyed temporarily. According to the rule, communicating particles may simply bounce symmetrically, act as a catalyser in a group reaction or engage in circular motion... Many complex temporal patterns emerge that could be described formally using the notion of *temporal profiles*. A profile would capture the rule and the initial conditions and would then consider the cell's trajectories and perhaps interpret them as a collection of tightly coupled breakpoint-envelopes. These envelopes could very well control a Fourier synthesizer, the result would be the expression of social control amongst harmonics. This idea awaits further implementation.

Figure 4 documents 600 cycles of an interaction process with 8 molecules in a container without reflecting walls. A single random rule matrix is used. The sensitivity matrix holds random values in the range 1 to 30. There is no gestural input from the user, so the internal dynamics develop in isolation, as a closed system. Green and red lines respectively denote x and y coordinates and blue lines show the momentary angles. The gray patches indicate when a particular molecule is actually engaged in interaction. The gray patches at the top of each

graphic pane make it possible to detect chain reactions. Qualitative oscillations of angle values are clearly observed. So there is evidence that this type of complex dynamical systems may support modeling wave propagation. According to the contents of the rule array, the waves may either sustain or lead to a single angle value, the latter being equivalent to point attractor behavior.

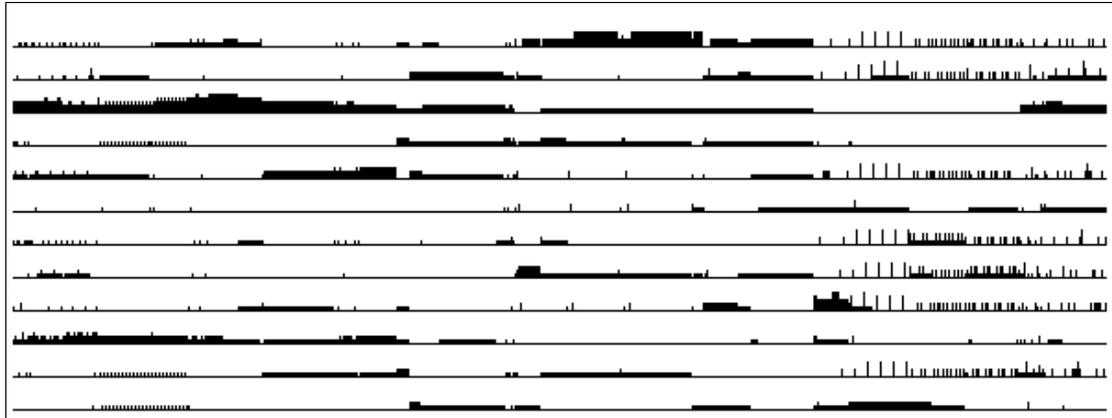


Fig 5. History track of angularity histograms.

Figure 5 shows 12 data tracks in time, 600 generations long, each track represents an angle from 0 to 330 in steps of 30 degrees. Angle histograms are computed at the end of every process cycle; this provides information of which angle values are in use, reflected in the density of the track (1) in addition to how many instances (2) of these angles are being used, reflected in the thickness of the track.

The sensitivity array is uniformly filled with a fixed value of 15, which means a global sensitivity value of 15 pixels.

A subtle user gesture at around generation 400 slightly modifies the current rule and forces a new type of waves to appear. First, past behavior is gradually acknowledged and second, amplitude and periodicity gradually build up towards a regular pattern. After a few generations, the internal dynamics will modulate that pattern and it will evolve according to the nature of the modified rule. One could say this constitutes a second kind of macroscopic behavior; waves appear to interact as bigger constellations; in effect, a neat example of emergent behavior.

7. Conclusion and outlook

This paper documents early experiments with an object oriented collision model supporting musical experimentation in real-time. It can be considered a continuous cellular automaton, a form of ballistic computing or an example of artificial chemistry. Anyway, the key notion here is *emergence*. Interesting temporal structures appear from the expression of a simple rule captured in a 2D array. These structures are thought of as propagating waves. The role of the user is quite subtle; one does not tweak a series of black-box global variables, in contrast, one shares forces with a genetic algorithm acting in parallel. So implicit autonomous actions as well as explicit user activity steer the relationships of an ensemble of objects moving in a 2D virtual world. Imagine a virtual physics of which the expression and evolution is partially controlled by an external user.

The system acts successfully as a generator of interesting waves of variable periodicity, even when operating according to the following constraints:

- (1) a fixed and uniform sensitivity range for all cells,
- (2) a fixed step size for all cells
- (3) a fixed density and energy of cells,
- (4) a discrete and small set of potential actions i.e. only angles change
- (5) no changes introduced by angle inversion when bouncing a reflective wall, and
- (6) genetic background activity is switched off.

It proves that the economy of expressing simple angular relationships in an array does indeed suffice to support interesting, non-linear dynamic behavior. However, further work is needed to classify families of automata and to study the impact of initial conditions. Automatic classification could even be addressed in an unsupervised offline algorithm since complexity criteria are explicitly available.

The work documented here is implemented in Macintosh Common Lisp using the functionality of the MIDI drivers in Common Music (Taube, 97). Our implementation challenges Lisp for real-time work. No doubt, Lisp is the most powerful symbolic programming language yet it has trouble coping with the pressure of real-time control – to the best of our knowledge, just one effort aims to connect the universal power of Lisp with the optimized number crunching efficiency of Max/MSP [Garton]. More work is needed to design robust multi-purpose, concurrent computational environments using symbolic programming languages.

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