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Composing for an Ensemble of Atoms:

The Metamorphosis of Scientific Experiment into Music[*]

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Bob L. Sturm
830 12th Ave. Apt. #3
San Diego, CA 92101 USA
sturm@ccrma.stanford.edu
http://www.composerscientist.com

ABSTRACT

Quantum Mechanics states a particle can behave as either a particle or a wave. Since sound can be described as a superposition of frequencies, a metaphor between 'particle physics' and sound synthesis is inspired. This metaphor is quantitatively developed here, suggested initially from a few similarities between the two disparate domains. Its practical use for music composition is discussed. Within these methods the distinctions between science and art are blurred, and scientific experiment becomes musical composition. The author discusses the process of using a simulated 'atom trap' to compose a piece that doesn't require a physicist to appreciate. The methods do require the composer to be trained in physical principles. It is only a matter of time before a real system of particles could be used—the particle accelerator will become an expressive musical instrument, and the particle physicist will become the composerscientist.

Keywords: physics, sonification, algorithmic composition, computer music, Art and Science.

1.0: INTRODUCTION

In quantum mechanics (QM) particles and waves have identity crises because one can act as a particle or a wave; and when not a particle, its 'matter-wave' has a frequency proportional to its kinetic and relativistic energy (hereafter referred to as the *energy* of the particle). Motivated by this, and some similarities between QM and time-frequency signal analysis (TFA), comes the idea that sound can be represented and synthesized by dynamic systems of particles. Vice versa, a sound might be 'materialized' into its corresponding system of particles, and modifications made in that domain to synthesize variant sounds.

Essentially what has been developed is a technique of sound composition using classical N-body mechanics with a quantum mechanical twist. The metaphor is developed such that the number of arbitrary decisions, e.g. 'the y-axis will determine pitch,' is kept to a minimum. Such a direct mapping of both multi-dimensional fields not only allows a cleaner interchange of concepts to enrich both, but also enables an additional level of comprehension of the underlying physical concepts. The concepts could not only be heard, but also comprehended and understood on a new level.

The music that is produced through these methods not only possesses significance for a musical experience. Because of the directness of the metaphor, the sound synthesis becomes a sonification of experiment and phenomena (Kramer, Walker, et al. 1999). The signal holds just as much meaning for a scientist who is attempting to perceive the abstract physics contained in equations and graphs. The potential usefulness of these techniques to both composers and physicists is a very interesting idea. This recalls a time when explaining music was considered as important as explaining the motions of the heavens (Cohen 1984; James 1993). Indeed, it was believed that explaining one would explain the other (Cohen 1984). And with the omnipresence of technology, it is now becoming just as important to learn the science, as it is the art.

Consequently, when using this technique for computer music composition, the composer must also possess skills in physics to even begin. Otherwise the concepts become unwieldy and misleading. Compositional and scientific concerns merge to form the 'composerscientist'—a state where doing physics and making music are the same.[1] On the other hand, it has been found that an audience need not be versed in physics to appreciate or enjoy what they hear. This points perhaps to a successful musical language.

The future of this work could culminate into using real particle systems instead of simulated ones; thus from a scientific experiment comes a musical composition. A radioactive gas, or plasma tokamak could become the musical instruments, and the scientist will improvise or follow strict directions to bring about an auditory signal that has significance on many levels. The scientific laboratories can become the concert halls; the scientific research institutes can become patrons of the arts. Indeed, these can come to pass only when it is recognized that Art has just as much good to say, as does Science; and with a clean fusion of the two, a much finer progression of each is possible.

2.0: CONSTRUCTING A METAPHOR BETWEEN PARTICLE PHYSICS AND SOUND[2]

There exist many mappings between musical and scientific domains. Well-known examples are music generated from mathematical concepts, such as fractals (Strohbeen 2001), and statistics (Xenakis 1992); or music generated from natural structures, such as DNA and proteins (Dunn and Clark 1997; Dunn 2001; Alexjander 1999), and molecular vibrations (Delatour 2000). Within any particular mapping there are numerous parameter permutations that provide rich opportunities for the composer. For instance, the flip of a coin could determine pitch, or duration, instrument, rhythm, melody, loudness, spatialization, and so on. This outcome is created by the richness of music; and with a mapping between two multi-dimensional disciplines the possibilities become innumerable.

The creation of the following metaphor found its impetus in a few similarities. Both TFA and QM use Fourier Transforms, and because of this both have uncertainty principles. In TFA one tradeoff is between time and frequency resolution of spectral components, and in QM one tradeoff is measurement uncertainty between particle position and momentum—also known as the famous Heisenberg Uncertainty Principle. Comparing the two domains at this level, i.e. a windowed signal in the time-domain, and the wave function in the space-domain, immediately leads to interpretation problems. (For instance, what relation can be created between a sound frequency distribution, to a probability distribution of momenta for a particle in some quantum state?) A circuitous route instead, remaining in the safe clutches of Classical Mechanics (CM) and borrowing the wave-particle duality of QM, proves much more profitable.

Physicist Louis de Broglie made a famous conjecture in 1923 that particles can act like waves, just as waves can act like particles. He derived an expression that states the frequency of a particle's 'matter-wave' is proportional to its energy. In simple terms, the frequency of a particle's matter-wave is related to its mass and how fast it is moving; the faster a particle travels, the shorter its wavelength becomes, and the higher its frequency goes. Using de Broglie's relation then, a particle can represent a dynamic frequency component in a sound wave. A frequency in one domain is thus a frequency in the other domain.

In light of the directness of this mapping, the amplitude mapping is not so simple. One of the peculiar aspects of particles acting as waves is that they are not *really* waves. It is some creature that has mutually exclusive properties, but not all the properties of waves or particles. Computing the amplitude of a matter-wave is not straight forward, and doing so leads to an imaginary quantity with no sensible physical interpretation. Thus a mapping between sound amplitude and matter-wave amplitude would be tedious, and perhaps altogether uninformative. Instead, invoking an observer and correlating amplitude to the physical separation of source and receiver creates a more logical and natural analogue. Though this might be a departure from the natural order of physics,[3] a true correspondence is not the aim here. Indeed it can still be seen as a one-to-one correlation when it is considered that the observer is a part of the system. This metaphor is thus no longer a sonification of a particle system, but a sonification of the observation of a particle system.

Combining these results for a system of N particles, considering that matter-waves are sinusoidal, and that superposition holds, produces the following generalized signal:

$$S(t) = \sum_{i=1}^{N} \frac{1}{1 + d_i^2(t)} \sin(2p \int E_i(t)dt) \, ,$$

where d_i is the distance between particle and observer, and E_i is the energy of the i^{th} particle. This is the 'Equation of Sonic Transformation' and it provides the means for deriving a signal from any particle system.[4]

It is apparent that this scheme is nothing more than additive synthesis. With N partials of varying frequencies and dynamics, the more complex signal $S(t)$ is created from the sum. However, unlike additive synthesis, there exists a *quantitative* metaphor that $S(t)$ is a system of N particles with dynamic energies and positions. Not only additive synthesis can be seen here. If the energy of a particle were sinusoidally varied at high enough rates, frequency modulation synthesis would occur. Similarly, amplitude modulation synthesis can occur if the separation was sinusoidally varied at a high enough rate.[5]

Using the movements of the system can enhance the metaphor—making the sounds move as do the particles they represent. This dramatically opens up the aural space so that not only are the changes in energy perceivable, but also the movements, velocities, and distances of the particles with respect to the observer. To further accentuate a sense of motion a Doppler effect can be incorporated.

The sound-particle metaphor doesn't have to stop there. Imagine an observer looking through a magic microscope at these particle systems. She can focus, or blur what is seen. She might apply a kind of filter perhaps. Real data is *always* imperfect as well; it is contaminated with noise and instrumental errors. Thus data reduction routines clean it up so that it is useful for science. In short, one is not married to the science from which this scheme has been derived. A composer, unsatisfied with the laws of nature, can create new ones for instance—a 'scientific license.'

Among the qualities of this mapping, is that there is no dependence on a predefined tempered scale, a quantized tonal language, e.g. diatonic; it uses any and all frequencies within the audible range. This not only leads to a unique musical language, but also provides a result that is quick to visualize upon audition. Like the recommended sonification mapping of representing an increasing temperature with an increasing pitch (Walker and Kramer 1996), the correspondence of higher energies with higher frequencies, louder sound with closer proximity, is common sense. Other than the metaphorical correlation of transverse matter-waves with longitudinal sound waves, there are no illogical mappings. The metaphor and its implementation suggested itself. This definitiveness, that the mappings came about so naturally, adds to the aesthetic quality of the metaphor.

2.1: THE SOUNDS OF PHYSICS

It is now possible to derive sounds from scientific principles and phenomena related to particles. Simulating particles in potentials—or ‘force-fields.’ A linear potential can be imagined as marbles rolling on a slant; a harmonic potential[6] is like the bowl in **Figure** 1. Each one produces unique sonic fingerprints, the fine details of which depend on the particular constants that shape it. A harmonic potential, unlike a linear one, guarantees a system will remain stable—though not that the sound it produces will be ‘harmonic’ in the musical sense. It can be an infinite bowl from which the marbles can't escape—an atom trap. The sonic transform of an *N*-particle, non-interacting, one-dimensional harmonic potential, with the observer at the minimum is:

$$S(t) = \sum_{i=1}^{N} \frac{1}{1+B_i^2 \cos^2(w_i t + f_i)} \sin(2p[\frac{B_i^2 w_i^2 m_i}{4} \sin(2w_i t + 2f_i) + g m_i t]) ,$$

where $w_i = \sqrt{\frac{k}{m_i}}$, *m* is the particle mass, *k* is the potential constant, is user-defined constant, and B_i and f_i are derived from the initial conditions of the particles.

The sonic properties can be surmised from the graph in **Figure** 2, which shows the displacement (position) and energy of a particle in a one-dimensional harmonic potential. As long as there are no external forces the displacements and energies are periodic, which is termed ‘simple harmonic oscillation.’

Now compare **Figure** 2 with **Figure** 3, a sonogram of fifteen particles in the same potential. The y-axis represents frequency, and the darkness of the lines represents amplitudes. Each line is a particle's energy trajectory, like a cloud chamber reveals a charged particle's path. In terms of the metaphor then, the y-axis is energy, and the darkness of the line is how close the particle travels to the observer. In this example the observer is situated at the center of the potential. Very apparent in this example is the aliasing caused by particles exceeding the ‘Nyquist energy.’

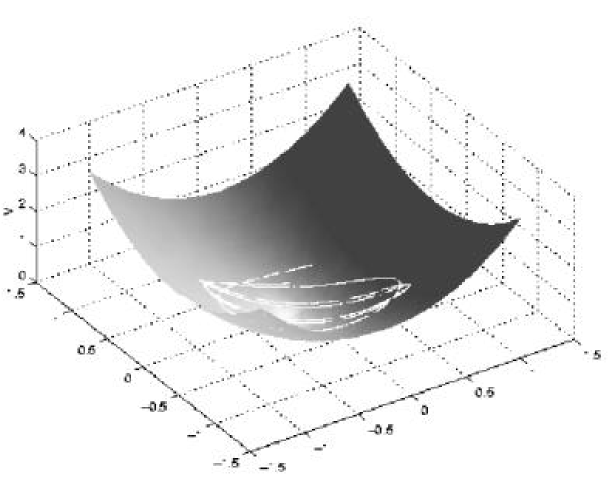
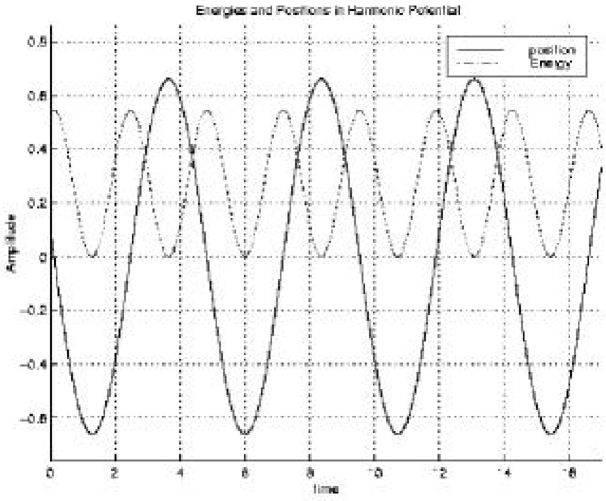


Figure 1: *A two-dimensional harmonic potential.*

Phenomena such as interactivity, radioactivity, and gas thermodynamics make for novel compositional tools via these sonification methods. With the Coulomb (electrostatic) force the particles are heard pushing each other around; sometimes one pops to a higher frequency, which means two particles got a little too close. **Figure**



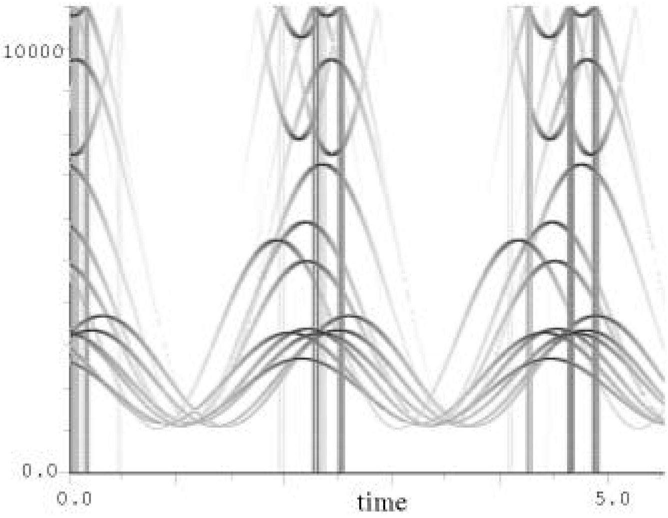


Figure 2: *Particle displacement and energy in a one-dimensional harmonic potential.*

Figure 3: *Sonogram of fifteen particles in a one-dimensional harmonic potential.*

4 shows an example of a system of charged particles in a harmonic potential. The general effects of the potential are visible, but the particle-particle interactions make the system's dynamics much more chaotic and aurally interesting.

Inelastic collisions are much different because of the abrupt exchanges of momentum and energy within the system; these create perpetual chaotic microtonal ‘organ improvisations,’ which can slowly dissipate if the collisions are elastic. Viscous fluid, and any number of mysterious forces, can be applied to a system, creating drag forces and keeping the system under, or out of, control. **Figure** 5 shows two particles radioactively decaying, which produces very distinguishable sounds. These are only a few of the many interesting possibilities that exist—a direct result of mating two rich, multi-dimensional disciplines.

It has been demonstrated so far that this union of disciplines motivates several new musical ideas, for instance quantitatively describing music in terms of a dynamic system of particles. There is also a usefulness of these ideas to physics, for instance in sonifying scientific data, or in teaching physics using sound. These have been discussed in

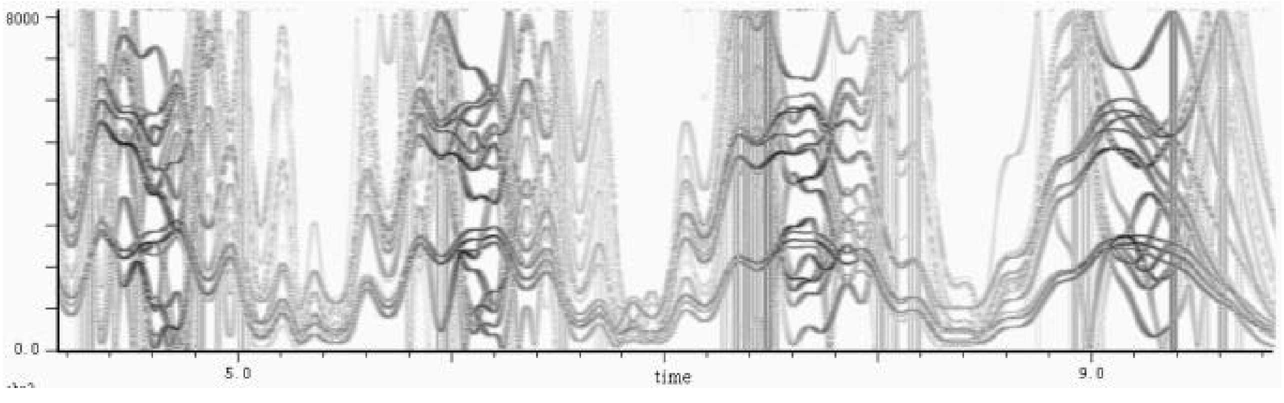


Figure 4: *Sonogram of Coulomb interactions within a harmonic potential.*

previous papers (Sturm 2000, 2001). Here the use of the system for music making will be discussed.

3.0: COMPOSING WITH PARTICLE PHYSICS

Just as in physical modeling synthesis, this metaphor puts physics at the service of the composer creating innumerable possibilities—which is a blessing and a curse. Here the composer has been restricted to the mathematics and methods of physics, and the scientist a slave to the aesthetics and methods of music. The situation however isn't that pessimistic. The physical laws one uses need not be those of the Universe; and with practice in thinking like a physicist, having the interests of a composer, the equations and phenomena become easier to massage in the directions desired. In order to employ these techniques in a musically effective way, one obviously needs practice in both disciplines. To explore the compositional usefulness of these methods, the author has composed several pieces, the first of which is discussed below.

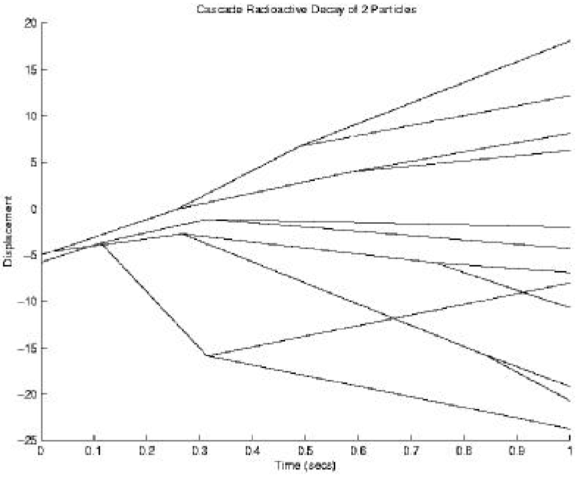


Figure 5: *A cascading radioactive decay of two particles.*

3.1: 50 PARTICLES IN A THREE-DIMENSIONAL HARMONIC POTENTIAL: AN EXPERIMENT IN 5 MOVEMENTS[7]

During the development of these algorithms many sound examples had been created, but all lacked musical coherence. This ten-minute composition was the first attempt at creating a musically coherent piece. Using the metaphor thus far described, an experiment was constructed and let run to generate the composition. The harmonic potential was chosen for this piece because it ensures the system can be controlled. The particles do not collide with each other, though they do interact in the third movement. Furthermore, there are no Doppler effects in the piece, and all particles are sine waves. Even though the system is three-dimensional, the sonification is projected in the x-y plane, with four speakers representing the four quadrants.

Since the simulation algorithms were coded for MATLAB 5.0, and 4-channel CD-quality sound was going to be produced, fifty particles was the limit if the piece was to be finished in time for its premier. (An edited version of the MATLAB code is included in Appendix A.) Before using seven hours worth of computation time to produce one minute of sound, I had to be sure that the result would be useful. To circumvent this then a practical system of experimentation was developed to predict behaviors and mold the variables—much like composers creating studies to

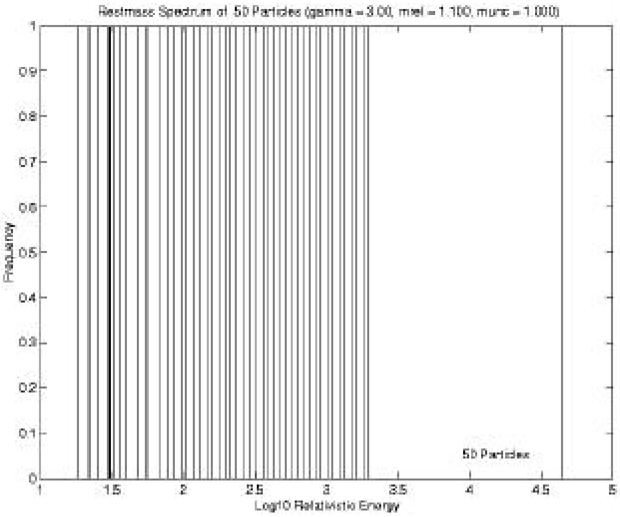


Figure 6: *The Restmass Spectrum of the fifty Particles.*

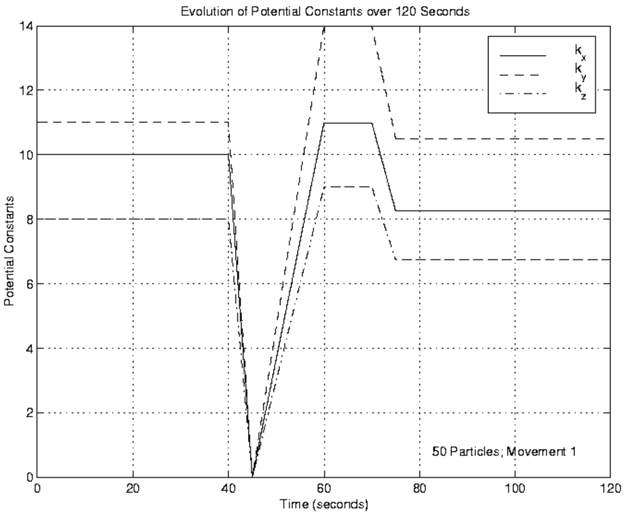


Figure 7: *The tuning of the potential constants during the first movement.*

determine what solutions exist. The ten-minute duration of this piece is far exceeded by the 150 hours it took to compute.

The titles for each two-minute movement are programmatic, describing most of what is occurring. The structure of the entire piece thus rests upon the phenomena invoked. This was worked out prior to the synthesis to provide a musically coherent structure—one with an introduction, build-up, climax, and resolution.

3.1.1: MOVEMENT 1: GRADUAL INTRODUCTION OF 50 PARTICLES INTO SYSTEM; TUNING THE HARMONIC POTENTIAL; ADJUSTING THE OBSERVATION APPARATUS

The particles come flowing from an atom source into the three-dimensional harmonic potential at times derived from a normal distribution,[8] in order of increasing mass. The observation apparatus is focused on a region that happens to include some entry points of the particles, thus clicks and pops occur from these discontinuities. The shape of the potential in which these particles exist is an integral component of the experiment, if not the most important. Initially it is ellipsoidal but changes throughout the experiment. It is described by the following generalized formula:

$$V(x,y,z,t,W) = k_x(t,W)x^2 + k_y(t,W)y^2 + k_z(t,W)z^2$$

where the potential coefficients, k_i, can depend on time and some set of parameters W—which could be mass, charge, velocity, etc. By altering these coefficient values the experimenter can thus alter the shape of the potential and consequently the dynamics of the system. If any of these constants were to become negative the result could become uncontrollable—the entire ensemble might evaporate.

Other initial conditions are also derived from statistical distributions with composer-defined limits. The particle charges, initial velocities, and the entrance positions come from using a uniform distribution rather than the

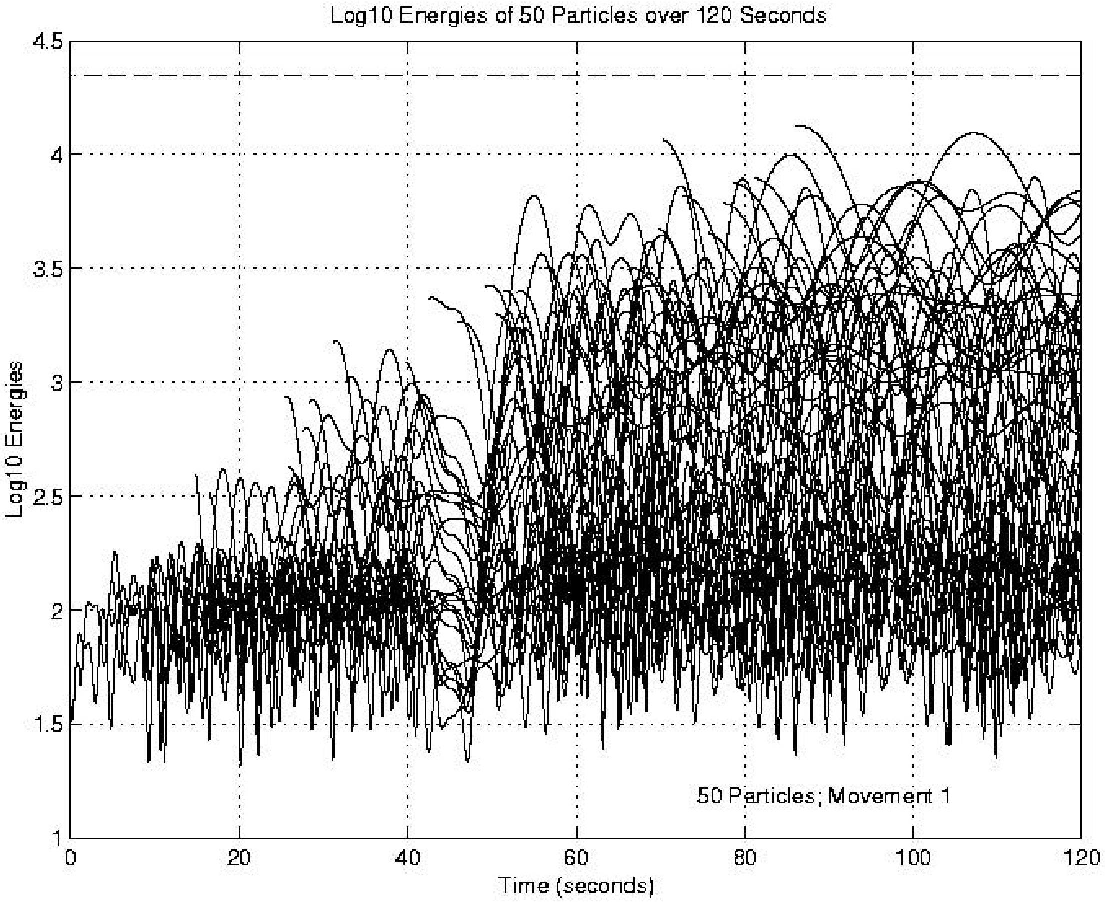


Figure 8: *Particle energies during an experimental simulation of the first movement.*

normal one used for the entrance times. This ensures a system with characteristics that don't tend toward particular values. The choice of parameter limits, e.g. the maximum initial z-velocity is 3.0 units, comes from experimental knowledge of the system. Having tested various initial conditions in the potential, these limits come from compositional preference of what the system should *not* do in the first movement.

Deciding the mass of each particle is important because that determines the frequency range of each particle. Since each particle has a minimum energy, there exists the special state of a particle system at complete rest, which produces the ‘restmass spectrum.’ In the second movement this becomes important, so the masses were chosen carefully. The restmass spectrum is shown in **Figure** 6, with the Nyquist frequency on the far right. The smallest mass will have a minimum frequency of 18.5 Hz and the largest mass a minimum frequency of 1,970 Hz. It is guaranteed then that this composition can span the entire range of human hearing. The area between the Nyquist limit and the spectrum allows a good range of non-aliasing energies that the particles can have.

During the first movement the potential is ‘tuned;’ its constants are modified. This must be done with care because any changes to the potential drastically change the system by taking or giving energy. The graph in **Figure 7** shows how the potential constants change during the first movement. When all three values become 0.0 at 45.0

seconds the potential is flat, which means there are no forces acting on the particles. This becomes obvious when listening because all frequencies become stationary; essentially energy is taken out of the system. To get back to a harmonic potential the constants are increased, with the drawback of putting energy back into the system. Now that the system for the first movement is described satisfactorily, and because computing the 120-second, 4-channel, 44.1 kHz, 16-bit, sound file takes on the order of seven hours, a test run at a 100.0 Hz sampling rate is done to make sure the system is working properly, the results will be as predicted, and no frequencies will exceed the Nyquist limit.[9] Though this is not as accurate as the 44.1 kHz sampling rate of the final product, it will give an adequate picture of what could happen. The results of this run are plotted in **Figure** 8, shown with the Nyquist 'energy limit' as the dotted line at top. This mess of lines shows each particle's energy path during the movement. The effect of the potential tuning can be readily seen at around t=40.0 seconds.

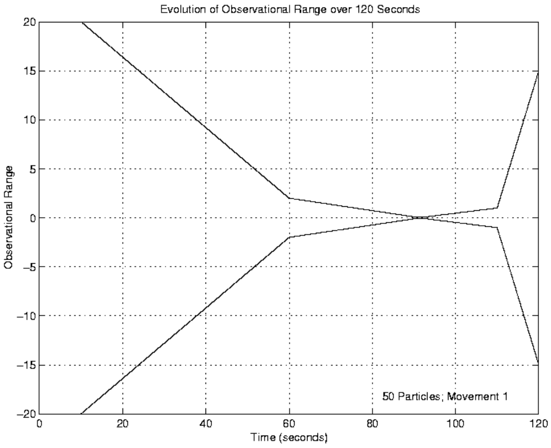


Figure 9: *The focus of the observation instrument during the first movement.*

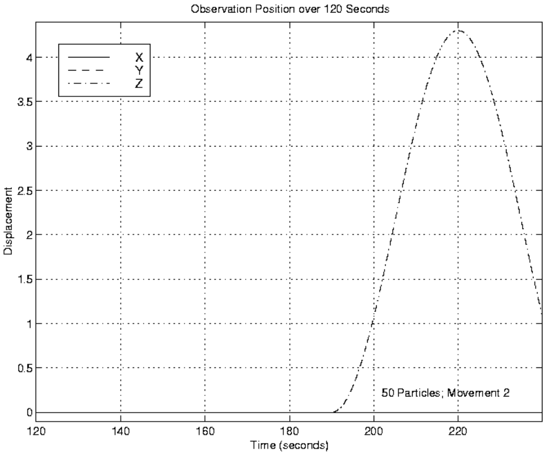


Figure 10: *Changing the observer's z-position during the second movement.*

It must be decided how the system will be observed. The position of the observer and the observational range are very important to this method because these can change global dynamics and the spatialization of the system. The observational range can be used to restrict what is heard, making more or less particles fly quickly in and out of view. In this movement the observer remains at the origin; the observational range is modified. The graph in **Figure** 9 shows the observational range during the first movement. It begins very wide but gradually becomes more focused. The aural effect of this is very interesting, providing a crescendo of activity into the second movement.

3.1.2: MOVEMENT 2: ADDING VISCOUS FLUID TO REVEAL THE RESTMASS SPECTRUM

This second movement consists of only this one phenomenon. By gradually adding a viscous fluid into the potential the particles will slow down and sink to the origin.[10] Viscosity usually acts as a damping force in proportion to the velocity of a body within it: as the body's velocity becomes higher the impeding force increases as well.

However, the viscosity of the fluid here has the unique property of being dependent on the position of the body—an invention of the scientist for compositional sake. Several experimental runs were required to ensure that the system would not come to rest too soon or too late.

It is very apparent what effect viscosity has upon this system. The process is aurally apparent as well. By the end of the movement the system will have almost reached complete rest. Since the observer is at the origin the volume of sound will accumulate as each particle comes closer. **Figure** 10 shows how the observer rises and descends in the z-dimension, which lasts into the third movement. This creates a dramatic dynamic change that emphasizes the impending explosions of the third movement.

The whole process of the second movement is seen in **Figure** 11. All the particles gradually settle to their restmass energy and finally form the spectral identity of the entire system at rest. Other than changing the observer's position and adding the effects of viscosity, nothing else is modified in this movement, e.g. the potential constants.

3.1.3: MOVEMENT 3: SUDDEN INCREASES IN THE COULOMB POTENTIAL OF THE UNIVERSE

This middle movement is the most aurally dramatic section of the piece. It extends the entire range of human hearing in an instant. This movement not only took the longest to compute, but it demanded the most time in its

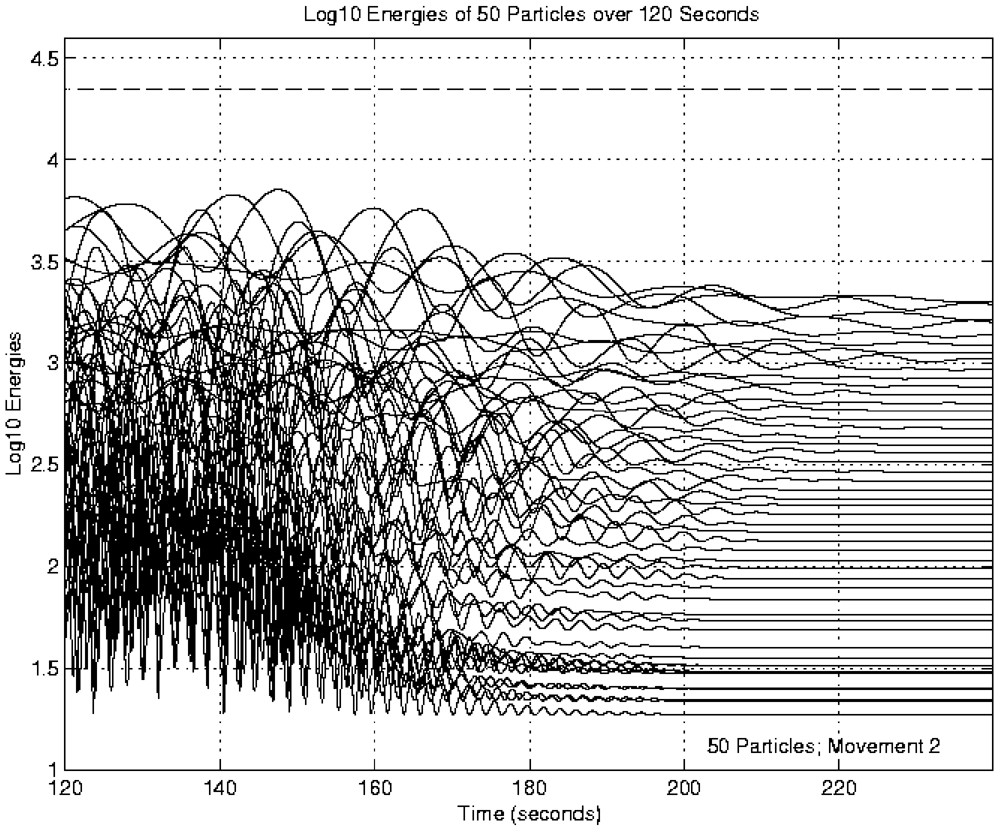


Figure 11: Particle energies during a simulation of the second movement.

experimental stages to remove anomalies and create what was desired. Far from reality, no physicist can accomplish what occurs in this movement; it is science fiction where the composer modifies nature's Universal laws and constants at will.

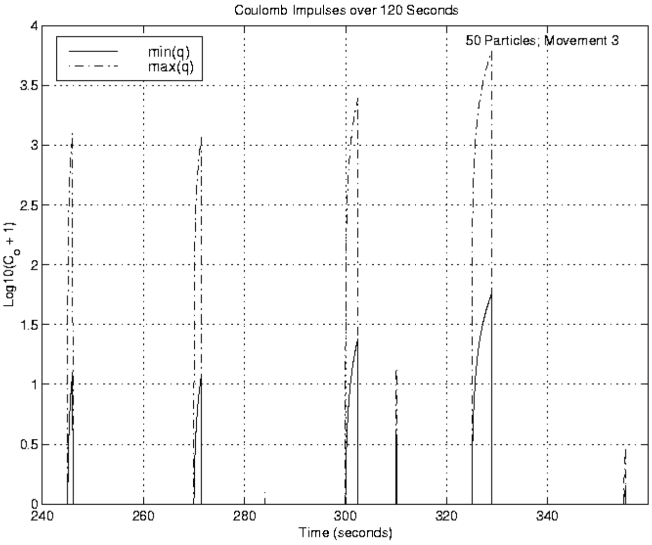


Figure 12: *Sudden changes in the universal Coulomb constant during the third movement.*

At the end of the second movement, the motionless particles are packed tightly together at the origin. Each particle has some positive charge, but because the Coulomb constant has been zero, the particles do not interact. When the Coulomb constant is suddenly increased, the closely packed particles will explode frenetically. There are four such large impulses, each having progressively longer durations.

In Nature the Coulomb force depends only on the charge and separation of particles. For this composition it was found that this provided unsatisfactory results. The larger masses would hardly be affected by the changes, and the smaller particles were flying past the Nyquist limit. By making the magnitude of interaction dependent sometimes upon the charges *and* masses involved, every particle would be similarly affected. **Figure** 12 shows the effective range of the Coulomb forces for smallest and largest charged particles in the system. The interactions are kept very brief because of the computational expense: for every sample the effect of each particle on every other particle must be computed. Even with the briefest of interactions, this movement took over 50 hours to compute—one-third of the entire computation time.

After developing the impulses and running experiments to predict the frequency distributions, the action of the viscous fluid had to be tailored so that there could be explosions and subsequent quick returns to the stable restmass frequencies. During the movement the particles gradually become more chaotic as the action of the viscosity is more relaxed. The viscosity in this movement is only time, not position, dependent.

At particular moments in this movement the potential walls are modulated. The potential constants are quickly varied sinusoidally in an attempt to create frequency modulation synthesis of the entire system. Other than near the end of the movement, its effects cannot be heard at all.

After specifying all of these details the experiment is run to check the system. The graph in **Figure** 13 shows a beautiful picture of what happens. From the first to the last, the explosions become more erratic. The particles begin to wiggle about more and more as potential modulations occur with larger amplitudes.

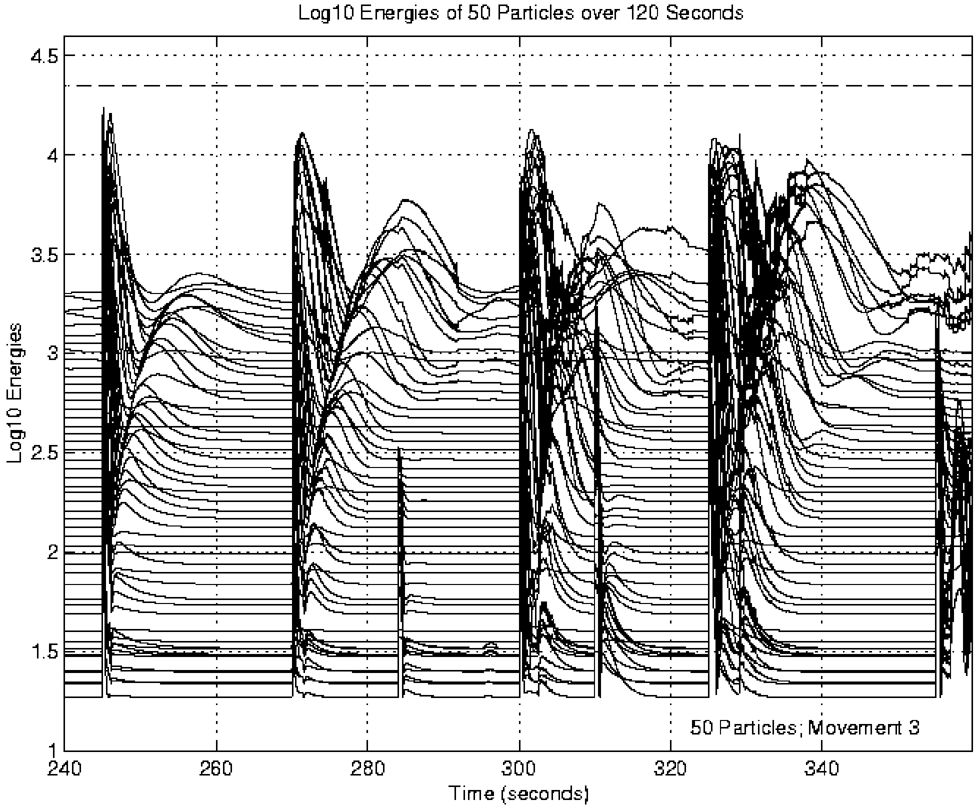


Figure 13: *The particle energies during a simulation of the third movement.*

The details of these brief interactions, which become longer as each Coulomb impulse occurs (notice the roundness of each peak), are shown in **Figure** 14 and **Figure** 15. These two details are quite different; during the fourth and last impulse, the particles interact for four times as long, and are more affected by the modulating potential. At around 330 seconds some of the higher frequencies are blurred by this frequency modulation. The effect is less noticeable than what was desired.

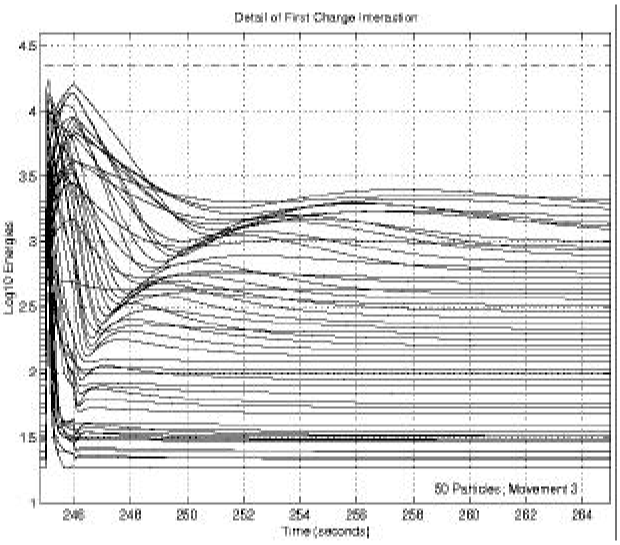


Figure 14: *A detail of the energies during the first Coulomb interaction.*

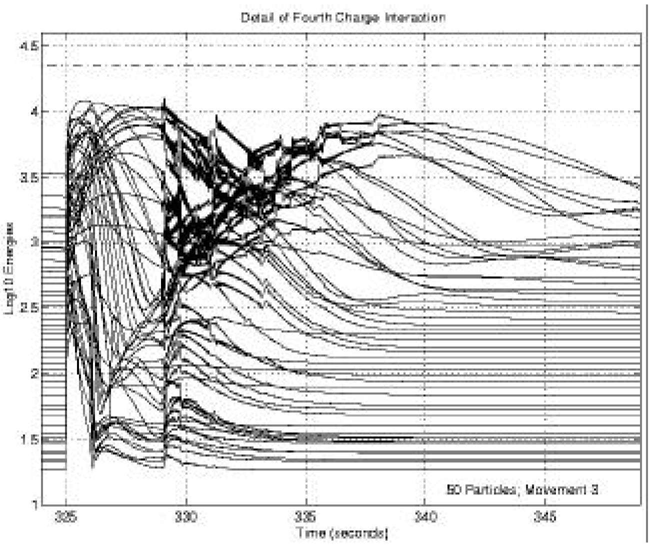


Figure 15: *A detail of the energies during the fourth Coulomb interaction.*

The observer's position changes dramatically through this movement creating very effective global dynamics. The author did not wish for the observer to pass closest at the times of Coulomb impulses. By avoiding this, and since the first explosion happened when the observer was at ‘ground zero,’ the listener is fooled into expecting another loud crash as s/he passes through the origin. This creates a very effective musical experience.

This movement by far required the most thought. Several hours were spent thinking about how to produce the effects wanted, and translate that into ‘science,’ which really became a science fiction. It was difficult at times to isolate what variables were causing what phenomena; and then to determine why certain large variations were not producing noticeable effects. This detailed work before the actual simulation was absolutely necessary since this movement took the longest to compute. Luckily the first simulation provided excellent results; the hard effort resulted in the colorful and dramatic movement that was hoped for.

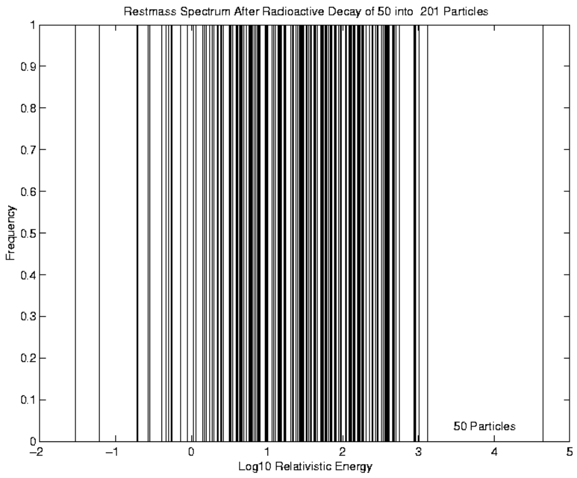


Figure 16: *The restmass spectrum of the system after decaying during the fourth movement.*

3.1.4: MOVEMENT 4: TWO GENERATION CASCADING RADIOACTIVE DECAY

Already having acknowledged the existence of a unique set of particles and heard their characteristic restmass spectrum, the particles will now undergo an irreversible decay. There will be no return to the initial system once this occurs. Over the duration of this movement each particle will split into two particles and each of those will split into two more. By the end of the movement there will be approximately 200 particles in the system. The times at which the particles decay is predetermined by a normal distribution that depends on the amount of material left to decay. Normally radioactive decay results in numerous energetic particles spilling from an unstable particle or atom. This will obviously result in energies higher than the Nyquist limit, but that is not of concern here. In several of the first sonified examples of radioactive decay, particles would blast apart with such force that soon every particle was aliasing and a band-limited noisy signal would result. These gritty effects are being encouraged in this movement.

The particles are kept from blasting too far from the system by using a high viscosity fluid which gradually decreases with the half-life of the particles. With such a high viscosity, nothing moves very far before being stopped, and so the results are nice pitched pops. Unfortunately the high viscosity limited the activity of the system and not enough chaos resulted. Toward the end the viscosity is taken away and an external force is applied in an attempt, though unsuccessful, to get the particles moving again.

Like in the first movement, the observation region is gradually focused on the potential's minimum, but since most of the particles are already at the center, this had little effect. Similar to the previous movement, the potential walls are oscillated, but again this had little effect on the system because of the high viscosity. However, the most dramatic effect comes from oscillating the observer's position very rapidly—like moving one's head back and forth quickly. It becomes so fast that the entire system is amplitude modulated by a noticeable amount. This occurs three times with varying frequencies and amplitudes. As the observer slows down, the system seamlessly modulates back into the clean sound of pure particles. At the end of this movement there are 200 particles in the system, and the restmass spectrum has changed. The new restmass spectrum, shown in **Figure** 16, is visually and aurally much more thick than the initial system. The bandwidth extends much lower than the first set of particles.

3.1.5: MOVEMENT 5: REDUCTION OF THE SYSTEM VIA LEAST ENERGIES

At randomly predetermined times the particle having the least kinetic energy is removed. It is as if it fell out of the potential through an expanding hole. This is similar to the introductory process, but instead of sequentially adding heavier particles one at a time, the least energetic particles are removed.

Since through the fourth movement the sonic material has significantly degraded to many particles with small masses concentrated at the minimum potential, a subtle means of moving the system to higher energies had to be devised. A general forcing function then was added to move the particles to higher energies, independent of mass. At times it seems the particles are on a roller coaster; the experience is visceral and disorienting. The viscosity of the fluid is rather simple. In the beginning it acts to keep the particles from getting too energetic, and halfway into the movement it is relaxed to allow for higher energies.

Figure 17 shows the result of the test run. Each vertical line represents a particle leaving the system, and is only an artifact of the programming process. Because of the increased number of particles this movement took much more computation time than usual. Finally the observer's position is gradually moved further from the system to create a decrescendo. The composition is thus brought to an end with the system evaporated.

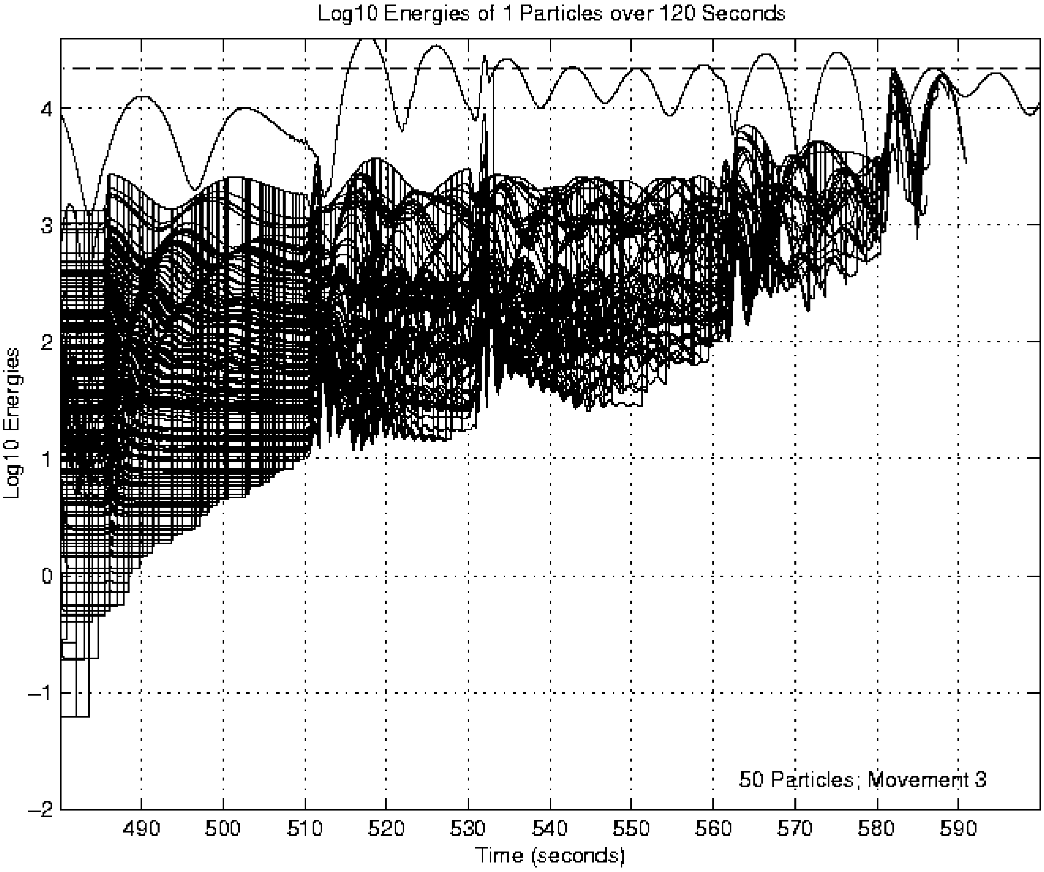


Figure 17: *The particle energies during a simulation of the fifth movement.*

4.0: ***50 PARTICLES*** **AS ART**

There is no doubt that having produced an aural experience with the intent of creating a coherent and meaningful (Meyer 1967:6) musical experience the result can be called music. The degree of its success though is debatable. Even though the macrostructure of the piece is well defined, the microstructure, the exact frequencies and amplitudes of the particles etc., are quantitatively unpredictable. Compositional concerns in this domain are limited to possibilities; pitch, melody, harmony, timbre, and rhythm are left to the particles. By using the same framework but different initial conditions, e.g. masses, a different piece will result. To what degree the musical information changes with these variations, or manifold compositions (Kaper and Tipei 1998), is questionable since the macrostructure on which the piece depends doesn't change. There was found a preference however between certain experimental runs of the movements, even when the initial parameters were the same.

Though effective use of these methods requires scholarship in both physics and music—not to mention numerical methods, programming, and digital signal processing—the audience should not be required to possess anything but an ear. Successful perception of this piece does not require the superhuman abilities of Babbitt's ideal listener—the ‘specialist’ (Babbitt 1998). The audience is however prepared for a scientific experience. By the very act of appending the name *50 Particles* rather than *Love Me Tender*, its perception and reception will be influenced (Franklin, Becklen, and Doyle 1993). Indeed the piece cannot be independent of its origin, as is all algorithmic composition to varying extents. Given a different title the piece would certainly be perceived differently—something the author is currently exploring.

It is interesting to note that most people perceive a logic underlying the sounds, as well as a process guiding the composition. Another interesting thing is that many find the piece visually stimulating. Though it is a piece for tape the world of sound becomes tangible, and many have remarked 'visceral.' Persons untrained in any scientific discipline have been fascinated; and even though at first some might have a lack of programmatic imagery, they have substituted other things—in one case a journey through the digestive system. Yet in the case of several teenagers at a science camp at Stanford, comments were 'Ten minutes of this?' and 'Sounds like a horror movie.'

From the viewpoint of the composer the piece isn't entirely successful. The sine waves aren't as blended together as was hoped, but every so often interesting timbres magically solidify and then dissipate. Disappointing were the unnoticeable effects of modulating the potential walls in the third and fourth movements. Even though these movements didn't wholly depend on the effect, it was frustrating trying to make the physics produce what was desired. The dilemma then is whether the composer should modify the algorithmic result to fit his desires.

The most negative comments received were concerning the clicks in the first movement—caused by particles suddenly entering the field of view. Computer music composers at CCRMA, Stanford, believed the clicks to be mistakes at first. The author knew exactly what the clicks were and did not consider them mistakes, but only artifacts of the experiment's design. Most composers defected to the opposite position—that the clicks are colorful, and not distracting—after more familiarity with the metaphorical explanation. Hardly anyone has had a problem with the clicks caused by the radioactive decay in the fourth movement, perhaps because that phenomenon is understood to be discontinuous. Even though there are parts lacking the intended effects, the composer has resolved not to modify this first composition—which might be seen akin to modifying experimental results.

4.1: *50 PARTICLES* AS SCIENCE

It was demonstrated above that while composing *50 Particles*, the distinction between composer and scientist was blurred. Making music and doing physics became the same thing. Each served the other in wonderful complementary ways—musical composition derived material from entities interacting with force fields, and the abstract physical concepts become tangible and aurally animated. There is definitely a paradigm shift for the composer in this new context. It can be the case that either the algorithms are at the mercy of the composer, or the composer is at the mercy of the physics. When writing this piece the author became more concerned at times with how particles were going to move, rather than what they sounded like. The piece should then be seen as much science as it is art.

Simultaneously, this piece exists as a sonic counterpart to a particle system, a sonification of a multi-dimensional data set, a composition requesting artistic merit, and an application of this physics-sound metaphor. The degree to which the composition stands as science, is arguable; but then again so is the meaning of the term ‘science’ (Chalmers 1982).

In Xenakis' introductory address in defense of his doctoral thesis, he says:

> From here on nothing prevents us from foreseeing a new relationship between the arts and sciences, especially between the arts and mathematics; where the arts would consciously 'set' problems which mathematics would then be obliged to solve through the invention of new theories (Xenakis 1985:3).

Similar to the methods presented here, Xenakis derived methods of practical sound composition from stochastic theory—an area of mathematics concerned with randomness, chaos, and complexity—as well as psychoacoustics. Instead of mapping particles to spectral components, musical events are determined and structured by probabilistic entities. For example, violin glissandi are derived from probability distributions. In Xenakis' work then the macrostructure, microstructure, and ‘metastructure’ of a composition thus find genesis in these principles.

Xenakis certainly occupies an advantageous position, as he is a composer come from architecture and engineering. Architecture is much more for him than physical construction; it is a valid proof of a scientific theory, such as material strength, or structural stability. To this end he states at the very opening to *Formalized Music* that ‘Art, and above all, music has a fundamental function, which is to catalyze the sublimation that it can bring about through all means of expression’ (Xenakis 1992:1). In other words, music is a means of demonstrating mathematical truth; in essence it is mathematics manifest.

The degree to which this is a ‘new relationship’ between the Arts and Sciences is debatable. Ever since Pythagoras, at least mathematics and music have been intimately linked in a symbiotic relationship. In his wonderful treatise on musical science during the first stage of the Scientific Revolution, Cohen states that,

> Let me point out, by way of a conclusion, that art indeed influences science; that the nature of such influences cannot be found by drawing broad analogies but only by searching for precise and detailed causation patterns; and, finally, that developments in art may effect themselves over long stretches of time, but may just as well make

> themselves felt in the development of science with surprising immediacy (Cohen 1984:252).

Cohen provides several of these 'causation patterns,' for example the problems posed to the science of music by consonance, or the justification of various temperaments. Cohen however does remark that '…beyond the domain of tuning and temperament I, for one, did not find any influence of the revolutionary changes in the science of music on the art' (Cohen 1984:253-4).

More than anything, the composition *50 Particles* was inspired by the physics it sonifies. It is certainly a wonderful thought that these sounds are from the microcosm of the quantum mechanical world. In a similar way the astronomer/mystic Kepler proposed musical scales based upon which the planets revolved (Cohen 1984:28). The impetus in creating the physics-sound metaphor was suggested by similarities in techniques, and later realized to provide an interesting way of looking at the world. And thus the composition *50 Particles* is an expression of the abstract scientific principles that it sonifies—even if the laws of its nature are not those of Nature.

5.0: CONCLUSION

It is not too far a step to conceive of the application of these methods to real experiments, rather than simulations. The composerscientist would direct the 'compositionexperiment' in 'musico-scientifically' meaningful ways. The concert space might be in the control room of a particle accelerator, with the composerscientist at the great instrument's controls bringing about hand-in-hand significant science as well as moving music, from the most elementary pieces of the Universe. A real-time simulation system has been programmed in C++, but with strict limits on the phenomena invoked. In any application the distinction between the science making and the art making is blurred.

The definitions of Art and Science become the same with only a difference in vocabulary. It is usually claimed that 'proper' science limits the influence of subjectivity. However, the practice of science is not such a simple activity (Chalmers 1982). Paul Feyerabend eloquently states in his article 'Theoreticians, Artists, and Artisans,' that,

> In a way, individual scientists, scientific movements, tribes, nations, function like artists or artisans trying to shape a world from a largely unknown material, Being. … *[Scientific] researchers are artists who, working on a largely unknown material, Being, build a variety of manifest worlds that they often, but mistakenly, identify with Being itself* (Feyerabend 1996).

Science, like Art, is a way of interpreting the world by shaping abstract mediums. By motivating a discussion of their intersections, interactions, and interrelations, an enhanced perspective is obtained which reveals the natures of both. ‘By removing the boundaries between art and science, we can open up new arenas for investigation. In doing so, greater intellectual flexibility and creative diversity—a new Renaissance—becomes possible’ (Garoian and Mathews 1996). The ‘boundaries’ will come down and reveal that the two cultures (Snow 1959) lost along the ways their common heritage, as well as their common pursuits.

In conclusion to his book *Emblems of Mind: The Inner Life of Music and Mathematics*, Rothstein offers up a wonderful similarity between artists and scientists:

> Mathematicians and musicians may spend most of their time in the mathematical world of hypothesis and reason, but the inner life of their arts is in the world of the Forms, in the processes of the dialectic and its argument by metaphor (Rothstein 1995:238).

More than anything else, Science and Art share this use of logic in their practices. Artists and scientists have utilized the power of the metaphor probably since the genesis of their disciplines. Connecting unlike entities, with adequate justification, can reveal numerous insights and applications that were previously invisible. To state some scientific or artistic idea in as many different ways possible enhances one’s comprehension of it; which might be why love is such a popular subject in the arts. This is not to say that Bach can only be fully experienced with an understanding of statistical mechanics; nor only with an understanding of Bach, can statistical mechanics be fully appreciated. But having knowledge of a metaphor between particle physics and music certainly enriches the experience of both.

APPENDIX A: MATLAB CODE

This code can be obtained from the author.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Transformation of physical particle systems into sound space.
%%Copyright 1999 Bob L. Sturm, CCRMA Stanford.
%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Harmonic (x,y) potenitial, INTERACTING particles when C != 0
%%  V(x,y) = kx*x^2 + ky*y^2 + Vo + V(Np)
%%      where V(Np) is the potential contributed
%%      by all the charged particles.
%%  F(x,y) = -(dV/dx,dV/dy) = m*a(t)
%%         = -m*(2kx*x,2ky*y)
%%  Int[a(t)]/m = v(t) + vo
%%  Int[v(t)]   = x(t) + xo
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%Sound and simulation parameters
%--------------------------------
Fs = 44100;                                          %sampling frequency
dur = 120;                                           %sound duration (seconds)
samples = dur*Fs;                                    %total number of samples
dt = 1/Fs;                                           %sample period
spatial = 4                                          %1,2,4 for # of channels
sys = zeros(spatial,Fs);                             %sound array
```

```
count = 0;                                          %iteration variable
soundsec = 10;                                      %used to avoid buffer memory problems

%%System parameters
%------------------
Vo = 0;                                             %potential offset
gamma = 3;                                          %user-defined relativistic constant
l = 2;                                              %width of ‘sonic sphere of influence’
power = 2;                                          %exponential for loudness-separation relation

%%Initial conditions
%-------------------
Np = 50                                             %number of particles
tco= 0;                                             %time offset
nu = (1/2)*m.*(vx.^2+vy.^2+vz.^2) + m.*gamma;       %total energy (frequency) of particle
E = nu                                              %Energy is initialized
mu = 0;                                             %viscosity coefficient
C = 0;                                              %initial Coulomb constant
ps = [0,0,0];                                       %initial position of observer
roo = [-20,20];                                     %initial region of observation along y-axis
A = [0,0,0];                                        %initial potential constants
f = [0,0,0];                                        %initial forcing function magnitudes
m = random('unif',0.01,0.05,1,Np)                   %create mass array
q = random('unif',0,5,1,Np)                         %create charge array
vx = random('unif',-20,20,1,Np)                     %create initial velocities array
vy = random('unif',-20,20,1,Np)
vz = random('unif',-20,20,1,Np)
x = random('unif',-0.1,0.1,1,Np)                    %create initial positions array
y = random('unif',-0.1,0.1,1,Np)
z = random('unif',-0.1,0.1,1,Np)

maximum=0;                                          %initial maximum amplitude, for sound file

data= [sprintf('final_%1.1d',round(tco))];
fid = fopen(data,'a');                              %file of raw sound data

%%Begin main loop
%----------------
for sec = 0:dur-1,                                  %Begin for each second
  for ii = 0:Fs-1,                                  %Begin for each sample
    tc = tco+ii*dt+sec;                             %iterated time.

    %%%%
    % BEGIN PSUEDO-CODE
    %%%%
    if (tc > sometime & tc < someOtherTime)
       update observer’s position: ps(x,y,z)
       update region of observation: roo(y_1, y_2)
       update viscosity: mu(x,y,z,t,W)
       update potential constants: kx(t), ky(t), kz(t)
       etc…
    end
    %%%%
    % END PSUEDO-CODE
    %%%%

    kx = A(1); ky = A(2); kz = A(3);                %set potential constants

    %%Begin Coulomb interaction
    %--------------------------
    if (Np > 1 & C ~= 0),
       Fx = zeros(1,Np); Fy = zeros(1,Np); Fz = zeros(1,Np);

       if length(C)==1,
         C = ones(1,Np)*C;
       end

       for jj = 1:Np-1,                                     %for every particle
         for kk = jj+1:Np,                                  %for every other particle
              xdiff = x(jj)-x(kk);
              ydiff = y(jj)-y(kk);
              zdiff = z(jj)-z(kk);
              rjjkk = sqrt(xdiff^2+ydiff^2+zdiff^2);        %separation between particles
              Fjjkk = C(jj)*q(jj)*q(kk)/(rjjkk^3);          %Coulomb Law
              Fxjjkk= Fjjkk*xdiff;                          %x-component of C force
              Fyjjkk= Fjjkk*ydiff;
```

```
           Fzjjkk= Fjjkk*zdiff;
           Fx(jj)= Fx(jj) + Fxjjkk;                    %update total x force
           Fx(kk)= Fx(kk) - Fxjjkk;                    %equal but opposite force
           Fy(jj)= Fy(jj) + Fyjjkk;
           Fy(kk)= Fy(kk) - Fyjjkk;
           Fz(jj)= Fz(jj) + Fzjjkk;
           Fz(kk)= Fz(kk) - Fzjjkk;
      end
    end
else
  Fx = 0; Fy = 0; Fz = 0;
end

Fx = Fx-2*kx.*x-mu*vx-ff*m;                            %total forces in the x-direction
Fy = Fy-2*ky.*y-mu*vy-ff*m;
Fz = Fz-2*kz.*z-mu*vz-ff*m;

%%Update particle acceleration, velocity, position
%-----------------------------------------------
ax = Fx./m;
vx = vx + rungekutta(ax,dt);
x  = x + rungekutta(vx,dt);

ay = Fy./m;
vy = vy + rungekutta(ay,dt);
y  = y + rungekutta(vy,dt);

az = Fz./m;
vz = vz + rungekutta(az,dt);
z  = z + rungekutta(vz,dt);

%%%%
% BEGIN RUNGE-KUTTA FUNCTION
% numerical integration scheme
%%%%
   function [integ] = rungekutta(f,dt)
     k1 = dt*f;
     k2 = dt*(f+(1/2)*k1);
     k3 = dt*(f+(1/2)*k2);
     k4 = dt*(f+k3);
     integ = (1/6)*(k1+2*k2+2*k3+k4);
%%%%
% END FUNCTION
%%%%

r = sqrt((x-ps(1)).^2+(y-ps(2)).^2+(z-ps(3)).^2);      %separation of particles and observer
E  = (1/2)*m.*(vx.^2 + vy.^2 + vz.^2) + m.*gamma;      %energy update
nu = nu + E.*dt;                                       %integrated E*dt = de Broglie’s freq*dt
s = (1./(1+r)).^(power).*sin(2*pi*nu);                 %sonic transformation of system

%%Spatialization calculation
%---------------------------------
h1 = l-(y-roo(1)-ps(2));
h2 = l-(y-roo(2)-ps(2));
peroo=real((1/(pi*l^2))*...
     (l^2*acos((l-h1)./l)-(l-h1).*sqrt(2*l*h1-h1.^2) - ...
      l^2*acos((l-h2)./l)-(l-h2).*sqrt(2*l*h2-h2.^2)));
s = s.*peroo;

%%Create channel array for sound
%-------------------------------
if spatial == 2,                               %stereo spatialization
  [I,II] = space2(x,ps,l,s);                   %function space2() can be obtained from author
  sys(1,ii+1) = sys(1,ii+1) + I;
  sys(2,ii+1) = sys(2,ii+1) + II;

elseif spatial == 4,                           %quad spatialization
  [I,II,III,IV] = space4(x,y,ps,l,s);          %function space4() can be obtained from author
  sys(1,ii+1) = sys(1,ii+1) + I;
  sys(2,ii+1) = sys(2,ii+1) + II;
  sys(3,ii+1) = sys(3,ii+1) + III;
  sys(4,ii+1) = sys(4,ii+1) + IV;

elseif spatial == 1,                           %mono spatialization
  sys(1,ii+1) = sys(1,ii+1) + sum(s);
end
```

```
  end                                               %END FOR EACH SAMPLE

  if (((ii+1)/Fs) == 1),
      count = count + 1;
      fwrite(fid,sys,'real*4');
      maxamp = max(max(max(max(abs(sys)))));        %find maximum signal amplitude
      if maxamp > maximum,
         maximum = maxamp;
      end
      sys = zeros(spatial,Fs);
      %%To avoid buffer memory problems
      %--------------------------------
      if (count == soundsec & sec ~= dur-1),
        fclose(fid);
        data= [sprintf('final_%1.1d',round(tc))];
        fid = fopen(data,'a');
        count = 0;
      end
  end

end                                                 %END FOR EACH SECOND

fclose(fid);

%%Create soundfiles from raw data files
%--------------------------------------
segments = dur/soundsec;                            %number of raw data files produced
samples = soundsec*Fs;
for i=0:segments-1,
  data = [sprintf('final_%1.1d',soundsec*i+round(tco))];
  fid = fopen(data,'r');
  S = fread(fid,[spatial,samples],'real*4');
  if maximum > 1,
    S = (S./(maximum+0.01));
  end
  wavwrite(S',Fs,[data,(sprintf('%1.1d.wav',i))]);
  fclose(fid);
end
```

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[*] This research began while the author was a graduate student at the Center for Computer Research in Music and Acoustics (CCRMA), Stanford University.

[1] The author has created an on-line resource devoted to exploring these topics at http://www.composerscientist.com.

[2] Presented here is an overview with a minimum of mathematics. For a more in depth discussion of the technical details see (Sturm 2000).

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[3] The amplitudes of matter-waves in nature are not related to the separation between particle and observer.

[4] Though this sonification is explicitly sinusoidal, it is possible that the matter-waves could be more complex sample-tables.

[5] These ideas pose a question for particle physics: can a matter-wave be frequency modulated to reveal several particles at one time?

[6] The term 'harmonic' here has nothing to do with musical sound. It is a physical term used to describe this type of potential in the same way as a pendulum is termed a harmonic oscillator.

[7] This composition for four-channel tape can be found in stereo mp3 format at http://www.mp3.com/BobLSturm.

[8] The term 'normal distribution' refers to a type of statistical distribution that describes a general trend for a large number of events.

[9] Of course, exceeding this limit means nothing traumatic, and could be used as a compositional device with unique affect. As composer, I do not wish to have these effects this early in the experiment.

[10] If the particles that are being simulated were subatomic, viscosity would not exist. Rather, here it is being used as a concept to control the system.