Composing for an ensemble of atoms: the metamorphosis of scientific experiment into music

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In quantum mechanics a particle can behave like a particle or a wave. Thus, systems of particles can be likened to a superposition of waves. Since sound can be described as a superposition of frequencies, it can also be described in terms of a system of particles manifest as waves. This metaphor between 'particle physics' and sound synthesis is quantitatively developed here, suggested initially from some similarities between the two domains. It is applied to a few fundamental physical principles to show how these can be sonified. The author discusses the process of using a simulated 'atom trap' to compose a piece that does not require a physicist to appreciate it. This metaphor blurs the distinctions between science and art, where scientific experiment becomes musical composition, and exploring a musical idea involves playing with particle system dynamics. In the future, methods like these could be used with a real system of particles – the particle accelerator will become an expressive musical instrument, and the particle physicist will become the composerscientist.

1. INTRODUCTION

In quantum mechanics (QM), particles and waves have identity crises because a particle 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). From this and some similarities between QM and time-frequency analysis (TFA), comes the idea that sound can be represented and synthesised by dynamic systems of particles. Conversely, a sound might be 'materialised' into its corresponding particle system, and modifications made in that domain to synthesise variant sounds – perhaps making two sounds collide or chemically react.

Essentially what is developed is a technique of sound-composition using classical *N*-body mechanics with a quantum mechanical twist. It is a sonification (Kramer, Walker, Bonebright, Cook, Flowers, Miner, Neuhoff, Bargar, Barrass, Berger, Evreinov, Fitch, Gröhn, Handel, Kaper, Levkowitz, Lodha, Shinn-Cunningham, Simoni and Tipei 1999), a sonic metaphor, and a synaesthesia of the physics of such systems. The metaphor is developed such that the number of arbitrary decisions, e.g. 'the *y*-position determines pitch', is kept to a minimum. Creating the most direct mapping of both multi-dimensional fields allows a cleaner interchange of concepts, for instance using electrodynamics as a compositional tool, or exploring particle phenomena using an auditory display. The potential usefulness of these techniques to both composers and physicists is a very interesting idea. It recalls a time when explaining how music works was considered as important as explaining the motions of the heavens. Indeed, it was believed that explaining one would explain the other (Cohen 1984, James 1993).

When using these techniques for sound composition, the composer must also possess skills in physics to even begin; the concepts quickly become cumbersome and misleading. It is not the intent of the author to create general-purpose compositional tools for others to use. Rather these methods are developed to explore and inform the musical and scientific curiosity of the author. Certainly these methods will find more use among physics teachers than among computer music composers, since they shows promise as a pedagogical tool for physics students (Sturm 2000, 2001).

When using these methods, compositional and scientific concerns merge to form the 'composerscientist' – a state where doing physics and making music are the same. Working out a musical idea entails deriving a system of equations and then simulating them. On the other hand, it has been found that an audience need not be versed in physics to appreciate or enjoy what they hear. Although one may not understand the physics involved, the music has been said to be visually stimulating.

The future of this work could culminate in sonifying real particle systems instead of simulated ones; thus, from scientific experiment comes musical composition. Scientific laboratories can become places for composition and performance. A radioactive gas, or plasma fusion tokamak could become the musical instruments, and the scientist will bring about an auditory signal that

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[1] This research began while the author was a graduate student at the Center for Computer Research in Music and Acoustics (CCRMA), Stanford, 1999. The composition *50 Particles* was completed and premiered there in May 1999.

Organised Sound **6**(2): 131–145 © 2001 Cambridge University Press. Printed in the United Kingdom.

has significance on many levels. The benefit of using simulated systems for now though is that no audience will be accidentally irradiated.

2. CONSTRUCTING A METAPHOR BETWEEN PARTICLE PHYSICS AND SOUND[2]

Many mappings between sound and scientific domains have been created. Well-known examples are music generated from mathematical concepts, such as fractals (Strohbeen 2001), and statistics (Xenakis 1992). Music has also been generated from natural structures, such as DNA and proteins (Dunn and Clark 1997, Alexjander 1999, Dunn 2001). Scientific sonifications include the successful Geiger counter, and the more recent sonification of molecular vibrations (Delatour 2000). Within any particular mapping there are numerous parameter assignments that provide rich opportunities for an auditory display. For instance, one parameter could be assigned to pitch, duration, timbre/instrument, tempo, loudness, or spatialisation, and so on. This outcome is due to the multidimensionality of sound and music; and with a mapping between two multi-dimensional disciplines the possibilities become enormous.

The creation of the present 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, the trade-off is between the time and frequency resolution of spectral components, and in QM the trade-off is in the uncertainties in position and momentum, also known as the famous Heisenberg Uncertainty Principle: the more precise one measurement is, the more uncertain the other must be. Initial work attempted to sonify the non-stationary wave functions derived from Schrödinger's equation, but this immediately led to interpretation problems. Specifically, what relation can be created between an energy–frequency distribution and a momentum–probability distribution for a particle in some quantum state? The mapping is not clear enough. A circuitous route instead, remaining in the safe clutches of classical mechanics and borrowing the wave–particle duality of QM, proves much more immediately productive.

2.1. de Broglie and matter waves

French physicist Louis de Broglie made the famous conjecture in 1923 that particles can act like waves (electron diffraction), just as waves can act like particles (photoelectric effect). He derived a relation which states that when a particle acts as a wave, its frequency is proportional to its energy. Specifically: $f = E/h$, where f is the 'matter wave' frequency, E is the energy of the particle, and the Planck constant $h \approx 6 \times 10^{-34}$ J s, is herein set to 1 for convenience. 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 moves, the higher its frequency goes. The energy of a particle is defined as

$$E(t) = T(t) + m_0c^2 = \frac{1}{2}\, m_0v^2(t) + m_0\gamma,$$

where T is the kinetic energy, m_0 is the particle mass at rest, and v is the particle's velocity. To simplify things, c^2, the speed of light squared, is replaced by the much smaller user-defined constant, $\gamma > 0$. The minimum frequency is determined by $m_0\gamma$, which acts as the frequency offset. Using de Broglie's relation, one particle can now represent one frequency component. A frequency in one domain is thus a frequency in the other.

In light of the directness of this mapping, the amplitude mapping is not so simple. Computing the amplitude of a matter wave leads to a function that, when squared and summed over some interval, gives the probability of finding the particle in that interval. Thus, a mapping between sound amplitude and matter wave amplitude is not clear. Instead, invoking an observer and making amplitude depend on the physical separation of particle and observer, a more logical and natural analogue is created. 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 generalised signal

$$S(t) = \sum_{i=1}^{N} \frac{1}{1 + d_i^2(t)} \sin\left[2\pi \int E_i(t)\mathrm{d}t\right],$$

where d_i is the distance between the ith particle and the observer, and E_i is its energy. This is the general equation for deriving a signal from any particle system.

It is apparent that this is nothing more than additive synthesis with control parameters derived from the particle system. The signal $S(t)$ is created from the sum of N frequencies. However, unlike additive synthesis, there exists the *quantitative* metaphor that $S(t)$ is a system of N particles with dynamic energies and positions. If the energy of a particle is sinusoidally varied at high enough rates, frequency modulation synthesis will occur. Similarly, the signal can be amplitude modulated if the separation is sinusoidally varied.

Using the movements of the system can enhance the metaphor, making the sounds move with the particles they represent. This dramatically opens up the volume of aural space so that the movements, velocities and distances of the particles are more perceivable. To further accentuate a sense of motion, a Doppler effect can be incorporated. With these additions though, a price is paid in terms of the fusibility of spectral components. A high independence of components makes it hard to perceive them as one complex sound, rather than several simple

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

sounds. If fusion is desired, the system needs to be designed to allow for that.

The metaphor can be elaborated further. Imagine an observer looking through a magic microscope at these particle systems. He or she can focus, or blur what is seen, or might apply a filter. Real data is *always* imperfect as well; it is contaminated with noise and instrumental errors. Thus, data reduction routines modify it so that it becomes more useful. In short, one is not restricted to the science from which this metaphor is derived. A composer, unsatisfied with the laws of nature, can create new laws governing a system and ways of observing it.

Among the qualities of this mapping is that there is no dependence on a predefined tempered scale, a quantised tonal language, e.g. diatonic; it uses any and all frequencies within the audible range. Furthermore, all elementary parameters of sound, and more, are derived via the metaphor: frequency from energy, loudness from distance, spatialisation from position, and hopefully timbre from the system as a whole. Other than the metaphorical correlation of transverse matter waves with longitudinal sound waves, there are no illogical mappings. The correspondence of higher energies with higher frequencies, louder sound with closer proximity, is common sense. These mappings require less aural training of the observer because they are already learned through experience. This not only leads to a unique musical language, but also provides a result that is rich in meaning. The metaphor and its implementation almost suggested itself from the few initial similarities between QM and TFA. This definitiveness, that the mappings came about so naturally, adds to the aesthetic quality of the metaphor.

As an aside, there is usually confusion of these methods with those of granular synthesis, or sound-particles. In granular synthesis (Xenakis 1992: 43), a sound is constructed from many small grains of sound – which are sometimes called particles, or acoustical quanta (Gabor 1947). These grains are usually windowed sines that synthesise a sound in swarms, or clouds. The particles here are not such entities. They act according to classical mechanics, exist continuously, and interact with the environment and each other as if they are particulate matter. Furthermore, the focus of these methods is on the sonification of physical principles and phenomena, and the use of those principles to synthesise sound compositions. However, an approximation to granular synthesis can occur if the field of observation is focused such that the particles quickly fly through.

2.2. The sound of science

Scientific principles and phenomena related to N-body particle systems can now be sonified. A linear potential can be imagined as marbles rolling on a slanted board; a harmonic potential is like the bowl in figure 1. (A potential produces a 'force field', which makes the particles move.) Each type of potential has a unique sonic fingerprint, the details of which depend on the variables that shape it. A harmonic potential, unlike a slanted linear one, guarantees the system will remain stable because the particle energies are bounded. It is an infinite bowl from which the marbles cannot escape – an atom trap. The sonic transform of a non-interacting N-particle, one-dimensional, time-invariant, harmonic potential that is a function of only position, with the observer stationary at the minimum, is

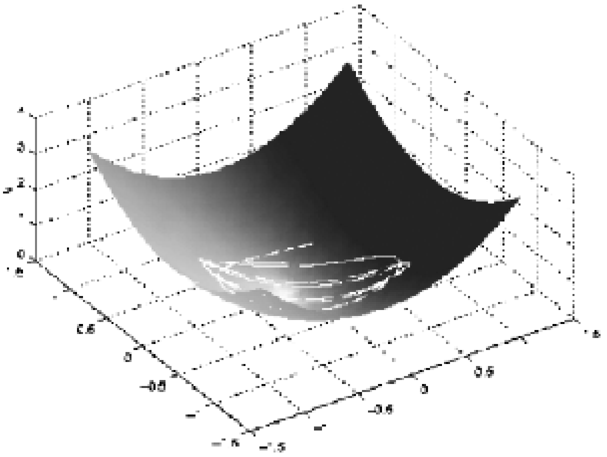

Figure 1. A two-dimensional harmonic potential.

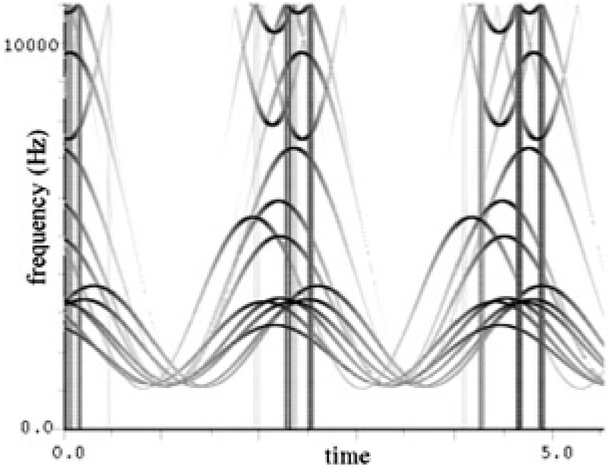

Figure 2. Sonogram of fifteen particles in a one-dimensional harmonic potential.

$$S(t) = \sum_{i=1}^{N} \frac{1}{1 + A_i^2 \cos^2(\omega_i t + \phi_i)} \times \sin\left(2\pi\left\{\frac{A_i^2 \omega_i m_i}{4} \times \left[\omega_i t + \phi_i - \frac{1}{2}\sin(2\omega_i t + 2\phi_i)\right] + \gamma m_i t\right\}\right),$$

where m_i is the ith particle mass, $\omega_i = (k/m_i)^{1/2}$, k is the potential constant, and the phases and amplitudes are derived from the initial positions and velocities of the particles: $\phi_i = \arctan(-v_{i,0}/\omega_i x_{i,0})$, $A_i = x_{i,0}/\cos\phi_i$.

The sonic properties of this system can be surmised from figure 2, a sonogram of fifteen particles in the potential. In the same way that a cloud chamber reveals charged particles, each line represents a particle's energy trajectory. In terms of the metaphor, the y-axis is energy, and the darkness of the line is the proximity of the particle to the observer. In this example, the observer is at the centre of the potential where the particle energies are maximised. Very apparent in this example is the aliasing caused by particles exceeding the 'Nyquist energy'.

It is not apparent from the equation derived above that $S(t)$ simply represents sine waves going up and down. So why go through all the rigorous mathematics for a result that could have been more easily obtained? Firstly, if something had been created more easily, then it could only be likened to the metaphor rather than quantitatively representative of it. Looking at a fossilised apple and being told it is the actual apple which inspired Newton produces a different experience than if told the apple is from a similar tree. Secondly, the example above is very simple and is only a springboard to more elaborate systems. It is a departure point rather than a programmatic note. One can begin to complexify the potential by perhaps wobbling its walls, or making one dimension dependent upon mass and another on position, and then having the particles start reacting, and so on.

Phenomena such as collisions, radioactivity and thermodynamics make for novel compositional tools via these sonification methods. Of course, if these particles were acting as waves they would interfere instead of collide. Figure 3 shows two particles radioactively decaying, which produces very distinguishable pops. The Coulomb (electrostatic) force makes charged particles push each other around like magnets; sometimes one pops to a higher frequency, which means two particles were pushed too close together. Figure 4 shows a sonogram of a system of charged particles in a harmonic potential. The general effect of the harmonic potential is visible, but the Coulomb interactions create the chaotic oscillations. The particle–particle interactions make the system's dynamics much more aurally interesting.

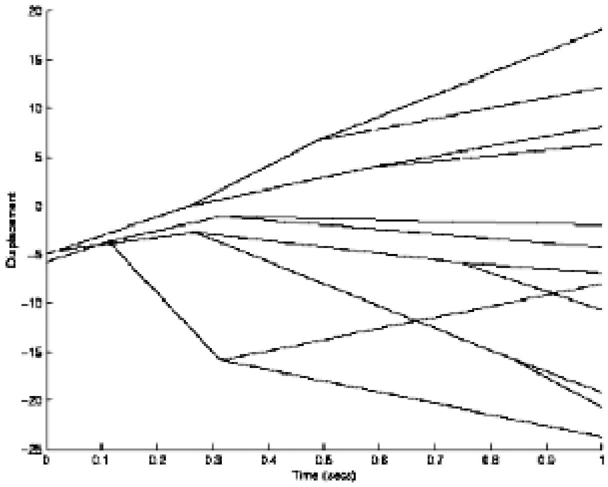

Figure 3. A cascading radioactive decay of two particles.

Collisions are much different because of the abrupt exchanges of energy within the system. This phenomenon creates perpetual chaotic microtonal 'organ improvisations', which can slowly dissipate if the collisions are inelastic. 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. (At the atomic scale, viscosity is senseless because it is a macroscopic phenomenon, but the particles can be treated as macroscopic entities.) Systems can also be heated or cooled, expanded and contracted, pressurised or exploded. These are only a few of the many interesting possibilities that exist – a direct result of combining two rich, multi-dimensional disciplines.

3. COMPOSING WITH PARTICLE PHYSICS

Just as in physical modelling synthesis, this metaphor places physics at the service of the composer creating innumerable possibilities – which is a blessing and a curse. The composer's tools are now the mathematical methods of physics, and the scientist must now heed musical aesthetics. However, the situation is not bleak. The physical laws one uses need not be those of the universe; and with practice in thinking like a physicist, with the interests of a composer, the equations and phenomena become easier to massage in the directions desired.

3.1. 50 Particles in a Three-Dimensional Harmonic Potential: An Experiment in 5 Movements

During the development of these algorithms, many sound examples were created, but all lacked musical coherence. This ten-minute composition for four-channel tape was the first attempt at creating a musically coherent piece using the metaphor thus far described. A simulated experiment with an atom trap was planned with five sections, and then let run to generate the composition. The harmonic potential was chosen to make the system more controllable. The particles do not collide with each other, though they do interact in the third movement. It was felt that for this first piece it was necessary to keep the metaphor in its purest form, so all particles are kept as sine waves. Even though the system is three-dimensional, the sonification is projected in the x–y plane, with the four speakers representing the four quadrants.

Since the simulation algorithms were coded in MATLAB 5.0, and 4-channel CD-quality sound (16 bit,

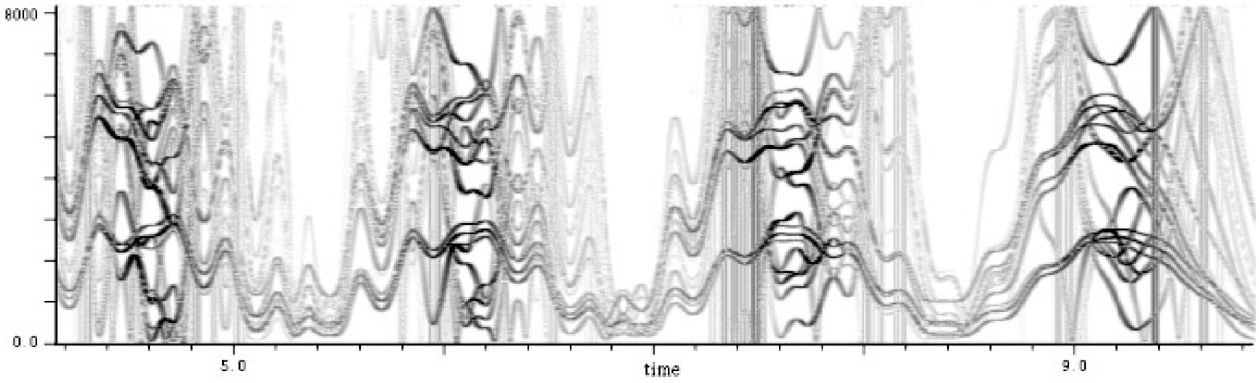

Figure 4. Sonogram of Coulomb interactions within a harmonic potential.

44.1 kHz) was going to be produced, fifty particles was the limit if the piece was to be finished for its premiere. Trial and error was limited because one minute of sound took at least seven hours of computation time. The ten-minute duration of this piece is far exceeded by the 150 hours it took to compute. (Current algorithms are coded in C++ and take much less time to run.) To guarantee the output will be useful the system is tested without producing sound, at a sampling rate of $f_s = 100$ Hz, and the particle energies are plotted – much like a composer creates studies to explore possibilities and solutions.

The titles for each two-minute movement describe most of what is occurring. The structure of the piece is created from the phenomena invoked. This was all worked out prior to the synthesis to provide a musically coherent structure – one with an introduction, development, climax and recapitulation. The following sections discuss the design of each movement. There are many more details than can be presented here, so only the most critical are discussed.

3.1.1. Movement 1: Gradual Introduction of 50 Particles into System; Tuning the Harmonic Potential; Adjusting the Observation Apparatus

From the least to the most massive, the particles come flowing into the potential at sequential times derived from a normal distribution. 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 it changes throughout the experiment. The following generalised formula describes the potential:

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

Here, the potential coefficients, $k \geq 0$, 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 alter the shape and thus the effects of the potential. If any of these constants were to become negative, the result could become uncontrollable – the entire ensemble might evaporate.

In addition to entrance times, other initial conditions are derived from statistical distributions. The initial velocities and the entrance positions come from a uniform distribution rather than the normal one used for the entrance times. A uniform distribution gives results that do not tend toward predictable values. The limits on these parameters, e.g. the maximum possible initial z-velocity is 3.0 units, comes from prior experimenting with the system. These limits give the most musical results.

Choosing the mass of each particle is important because this determines its frequency range. Since each particle has a minimum energy, there exists the special state of the particle system in its lowest energy state, which produces the 'rest-mass spectrum'. This becomes important in the second movement, so the masses were chosen carefully. The rest-mass spectrum is shown in figure 5, with the Nyquist energy 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

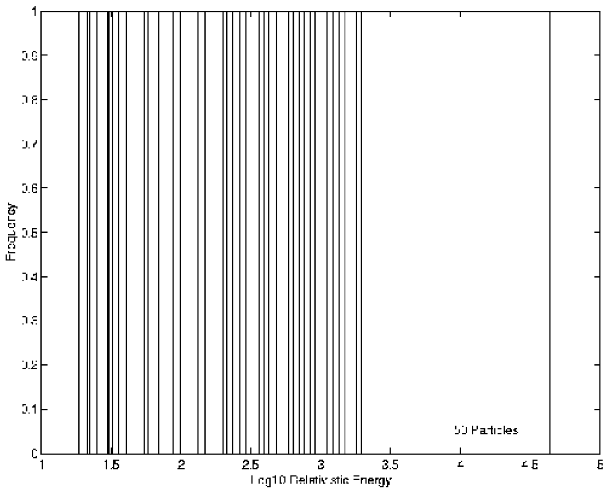

Figure 5. The rest-mass spectrum of the fifty particles. The Nyquist energy is at far right.

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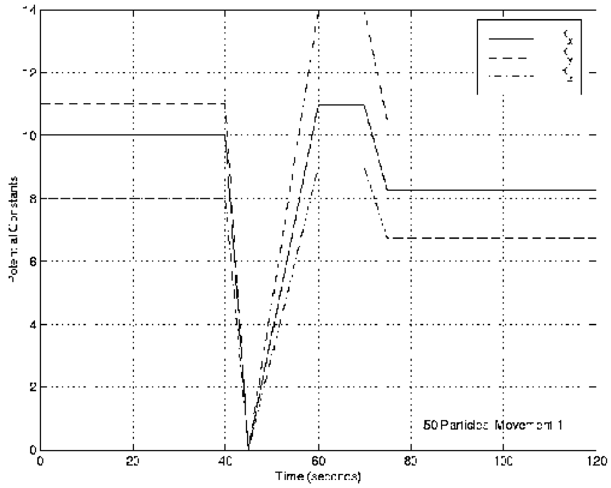

Figure 6. The tuning of the potential constants during the first movement.

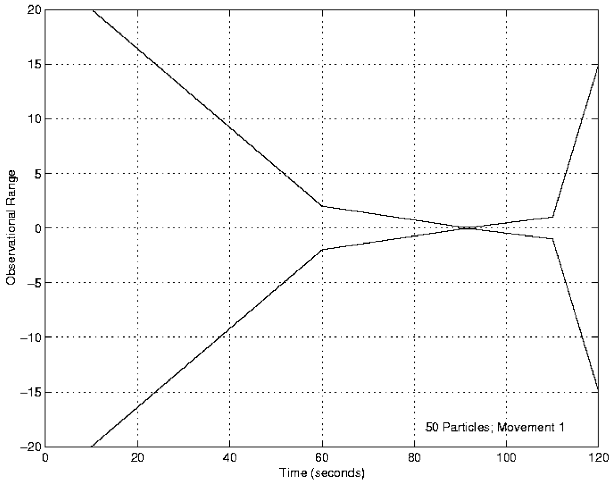

Figure 7. The focus of the observation instrument during the first movement.

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 possess.

During the first movement, the potential is 'tuned' by modifying its constants. This must be done with care because any change to the potential drastically changes the particles' energies. The graph in figure 6 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 stop changing. When the constants are increased, the drawback is putting energy back into the system.

Now 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 it restricts what is heard. In this movement, the observer remains at the origin and the observational range is gradually squeezed. The graph in figure 7 shows how the view develops during the first movement. It begins very wide, gradually becomes more focused, and then zooms out to reveal the entire system. This provides a crescendo of activity into the second movement.

Now that the system for the first movement is described satisfactorily, the system is tested to make sure it works as predicted. The results of this are plotted in figure 8. The mess of lines shows each particle's energy path during the movement. The effect of the potential tuning can be readily seen between $t = 40.0$ and 50.0 seconds.

3.1.2. Movement 2: Adding Viscous Fluid to Reveal the Rest-Mass Spectrum

The second movement consists of only one phenomenon. By adding a viscous fluid into the potential, the particles will slow and sink to the minimum potential at the origin. Viscosity acts as a damping force in proportion to the velocity of a body: as the body's velocity becomes higher, the impeding force increases as well, until the net effect is zero and the body reaches a terminal velocity. In order to produce what was compositionally desired, simple viscosity was ineffective. Instead, it was found that the viscosity of the fluid should be dependent on the position of the body as well as its velocity. Several experimental trials were required to ensure that the system would come to rest at the desired time. 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 increases as each particle descends. Figure 9 shows how the observer rises and falls in the z-dimension to create a crescendo into the third movement. A test of the second movement is seen in figure 10. All the particles gradually settle to their rest-mass energy and form the spectral identity of the entire system at rest. Other than changing the observer's position and adding a viscous medium, nothing else is modified in this movement.

3.1.3. Movement 3: Sudden Increases in the Coulomb Potential of the Universe

This middle movement extends the entire range of human hearing in an instant. It not only took the longest to compute, it demanded the most time in its experimental stages to remove anomalies and create what was desired. Far from reality, no physicist can do what is done in this movement; it becomes fantasy when the composer modifies nature's universal laws and constants.

At the end of the second movement, the motionless particles are packed tightly together at the origin. Each

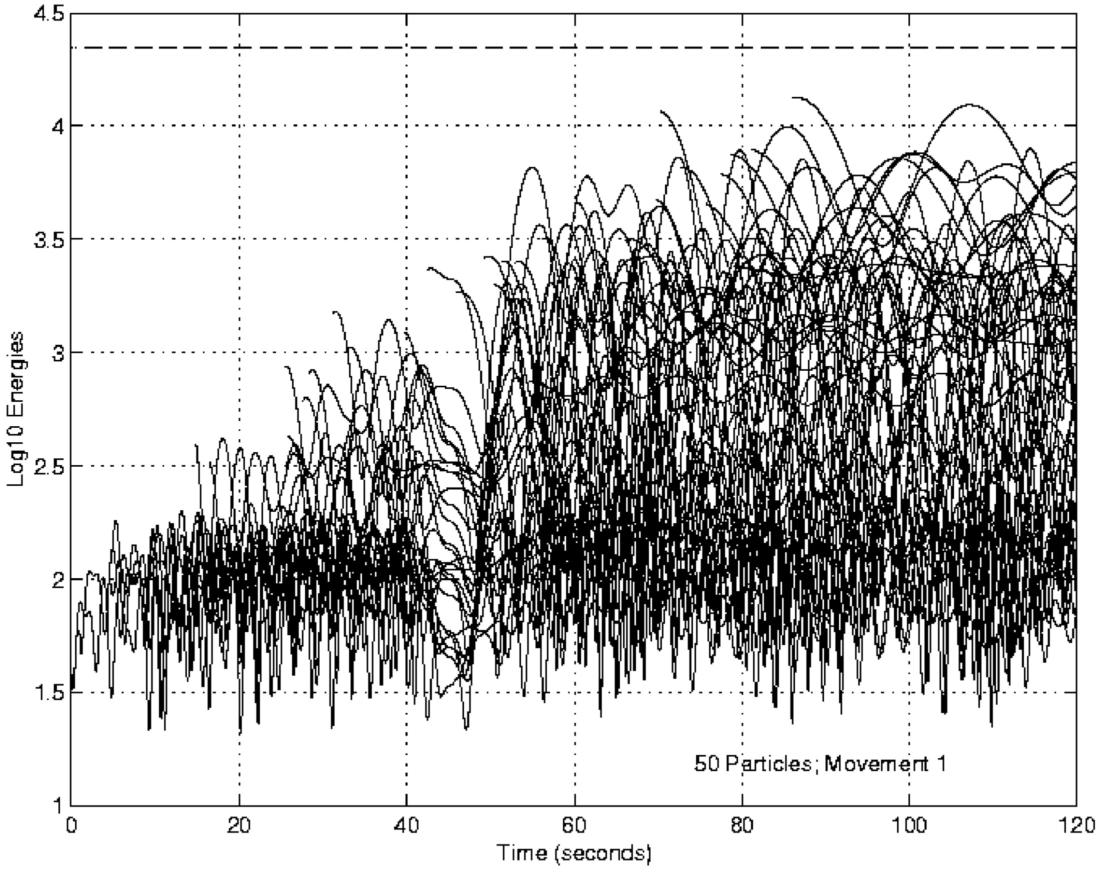

Figure 8. Particle energies during a simulation of the first movement. Nyquist frequency is the dotted line at top.

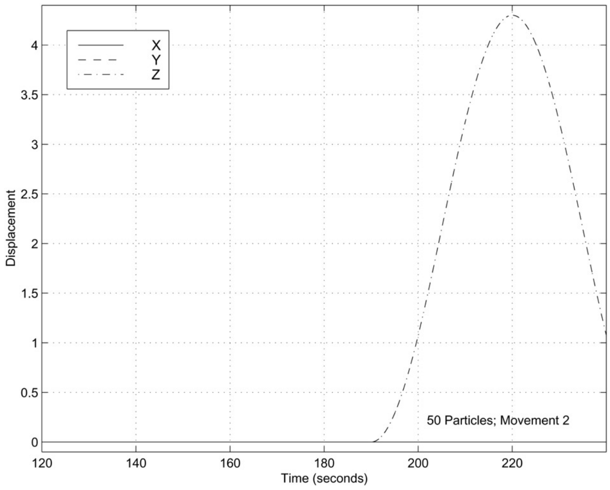

Figure 9. Changing the observer's z-position during the second movement.

particle has some negative charge, but since the Coulomb constant has been zero, the particles have not interacted. When the Coulomb constant is suddenly increased, the closely packed particles 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. This provided unsatisfactory compositional results. The larger masses were hardly affected by the changes, and the smaller particles flew past the Nyquist energy. By making the Coulomb 'constant' a function of mass, every particle could be similarly affected. Figure 11 shows the values of the Coulomb coefficient for the smallest and largest 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 these brief interactions, this movement took over fifty hours to compute.

After developing the impulses and running tests to predict the frequency distributions, the action of the viscous fluid had to be tailored so that there could be expansive explosions but quick returns to a low-energy state. The particles gradually become more chaotic as the action of the viscosity is relaxed, which is now time, not position, dependent. At particular moments, the potential walls are modulated quickly in an attempt to create a frequency modulation synthesis of the entire system. Other than near the end of the movement, its effects cannot be heard.

After specifying all of these details, a test is run to check the system. The graph in figure 12 shows a beautiful picture of what happens. Details of these brief interactions, which become longer as each Coulomb impulse

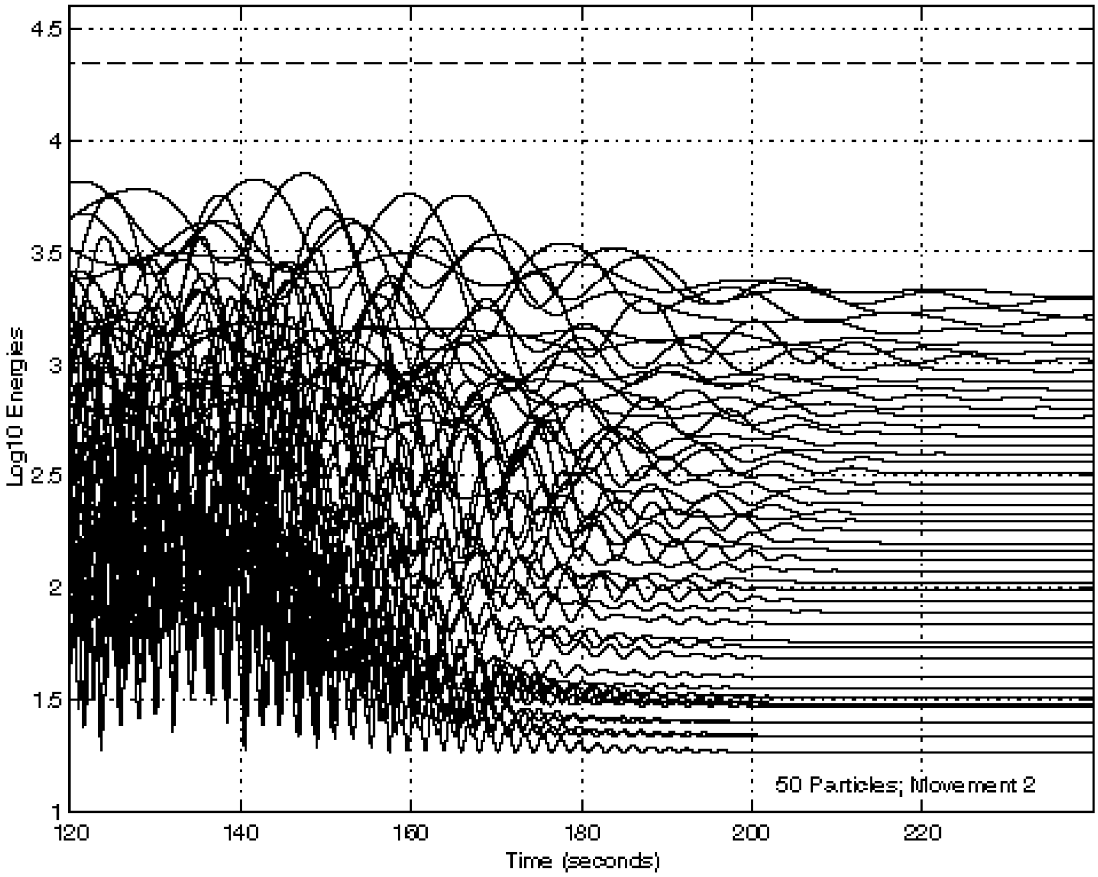

Figure 10. Particle energies during a simulation of the second movement.

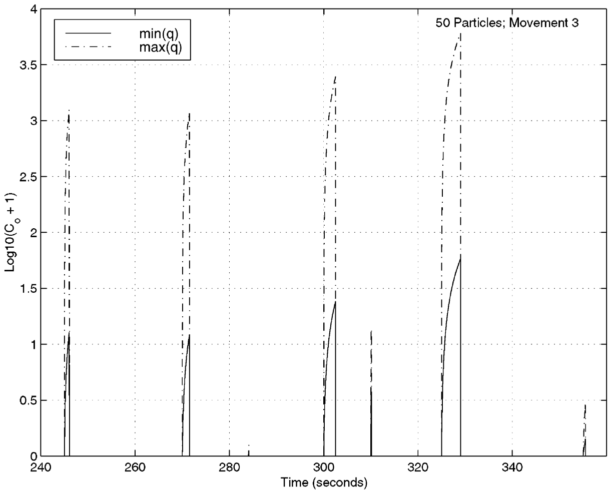

Figure 11. Sudden changes in the universal Coulomb constant during the third movement, for the largest and smallest particles.

occurs (notice the increasing roundness of each peak), are shown in figures 13 and 14. During the fourth major impulse, the particles interact for four times as long, and are more affected by the wobbling potential. At around 330 seconds, some of the higher frequencies are blurred by this frequency modulation. Figure 15 shows how the observer's position changes during this movement to create contrasting dynamics and spatialisation.

This movement required the most thought and design. Several hours were spent thinking about how to produce the desired effects, and translate that into 'physics'. 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 colourful and dramatic movement that was hoped for.

3.1.4. Movement 4: Two-Generation Cascading Radioactive Decay; Position Modulation of Observer

The particles will now undergo the irreversible decay of radioactivity. This phenomenon results in numerous energetic particles spilling from an unstable particle or atom. Over the duration of this movement, each particle splits into two particles and each of those split into two more. By the end of the movement, there are 200 particles in the system. The times at which the particles

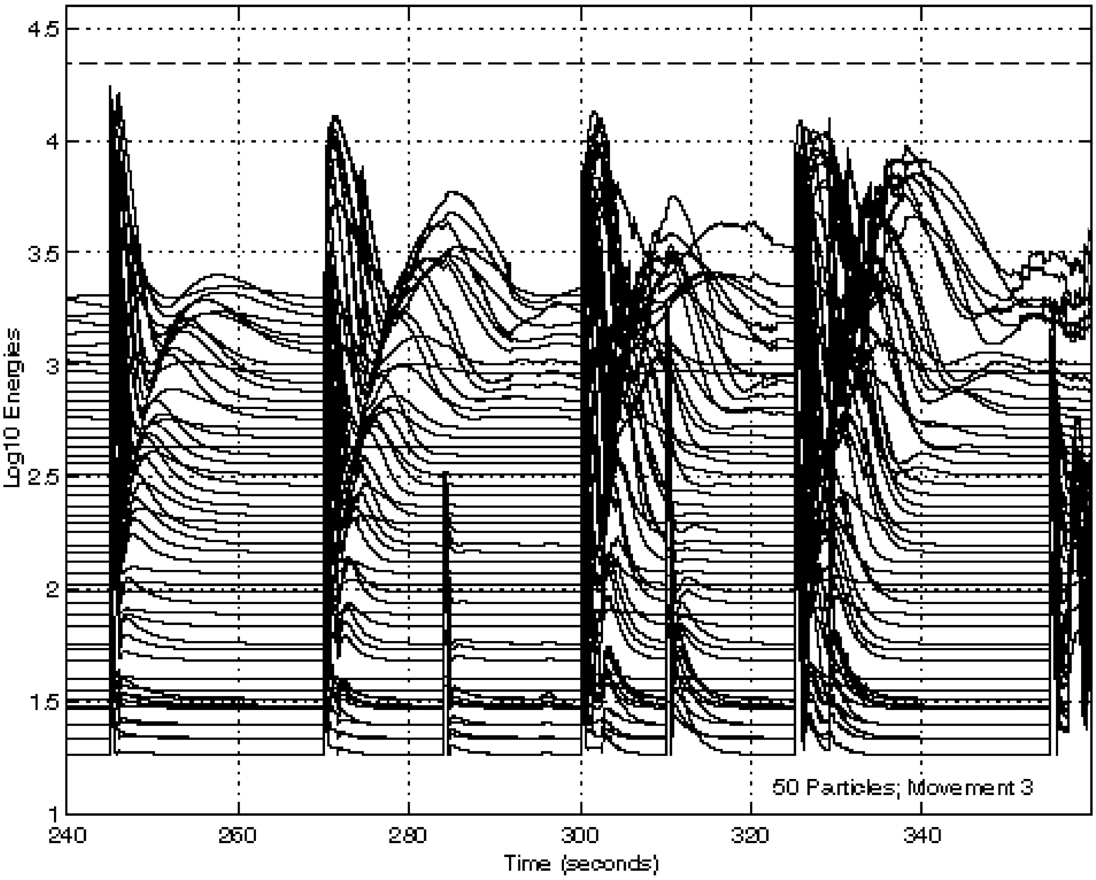

Figure 12. The particle energies during a simulation of the third movement.

decay is determined by a normal distribution that depends on the amount of material left to decay – how radioactivity naturally occurs. The resulting particle masses were randomly determined from the energy of the particles, kinetic and relativistic combined.

The particles are kept from blasting too far from the system by using a high-viscosity fluid that gradually relaxes over the half-lives of the particles. With such a high viscosity, nothing moves very far before stopping, and so the results are pitched pops. Unfortunately, the high viscosity limits the activity of the system and not enough chaos results. Towards the end, the viscosity is taken away and an external force is applied to get the particles moving again.

Similar to the previous movement, the potential walls are oscillated, but again this has little effect on the system because of the high viscosity. However, the most dramatic effect comes from oscillating the observer's position very rapidly. It becomes so fast that the entire system is amplitude modulated by noticeable amounts. This occurs three times with different 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 new rest-mass spectrum, shown in figure 16, has drastically changed. The bandwidth now extends much lower than the first set of particles.

3.1.5. Movement 5: Reduction of the System Via Least Energies

At predetermined random times, the particle having the least kinetic energy is removed. It falls out of the potential through an expanding hole at the origin. 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 means of moving the system to higher energies had to be devised. A general forcing function was then added, like an external electrostatic field, to move the particles to higher energies. To affect all particles similarly, the force was made independent of mass, like gravity. At times it seems the particles are on a roller coaster.

Figure 17 shows the result of the test run. Each vertical line represents a particle leaving the system, and is only an artefact of the programming process. The observer's

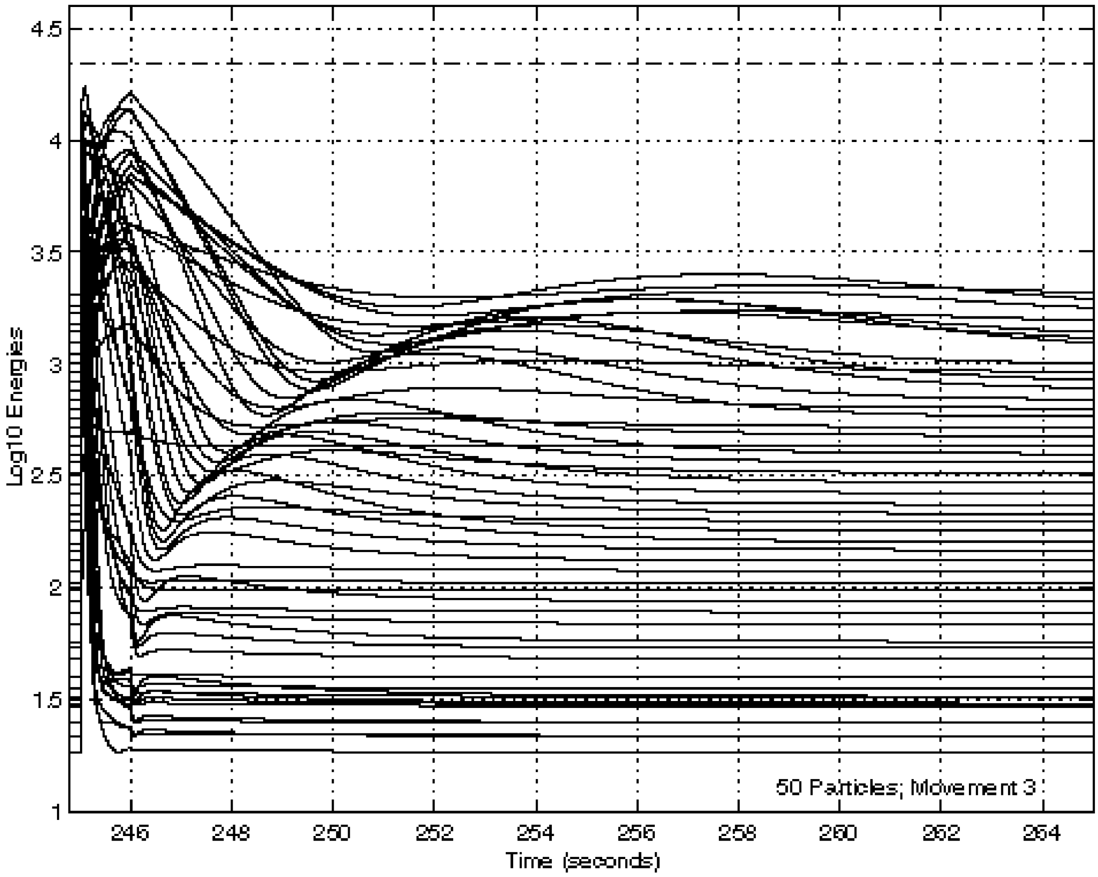

Figure 13. A detail of the energies during the first major Coulomb interaction.

position is gradually moved further from the system to create a fade-out. The composition is brought to an end as the potential flattens and the system evaporates.

4. *50 PARTICLES* AS MUSIC AND SCIENCE

For the author, *50 Particles* is alien and beautiful. Even before hearing the piece, its programmatic aspect – that it is a sonification of 'particle physics' – creates a profound impression. It is a piece of music created by making ideal particles move, react and interact; a piece that reveals what the universe at the quantum scale might sound like. At moments it becomes a glimpse of a universe that could never exist. As a metaphor for nature, this piece is very successful. As a musical composition, however, its success is limited.

The foremost problem is the lack of interesting timbre. The sine waves are not as blended together as was hoped, but every so often interesting timbres magically solidify and then dissipate. With an integration of Fletcher-Munson equal-loudness scaling, the sines might blend more often. Adding harmonics to the particles or using a complex wave-table would make the sound more aurally interesting. But it was felt that for this first composition, the metaphor in its purest form should be demonstrated.

Even though the macrostructure of the piece is well defined, the microstructure – the frequencies and amplitudes of the particles – is quantitatively unpredictable. Compositional concerns in this domain are limited to possibilities; pitch, loudness and timbre 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 within these variations, or manifold compositions (Kaper and Tipei 1998), is questionable since the macrostructure on which the piece depends does not change. A preference was found between certain experimental runs of the movements, even when the initial conditions were hardly modified.

Though effective use of these methods requires scholarship in both physics and music – not to mention numerical methods, scientific programming and digital signal processing – the audience should not be required to possess anything but two ears. Successful perception of this piece does not require a physicist. The audience is, however, prepared for a 'scientific experience'. Appending the name *50 Particles* rather than *Love Me Tender*, in addition to the verbose movement titles, influences its perception and reception. Indeed, the piece cannot be independent of its origin, as is the case for all algorithmic composition to varying extents.

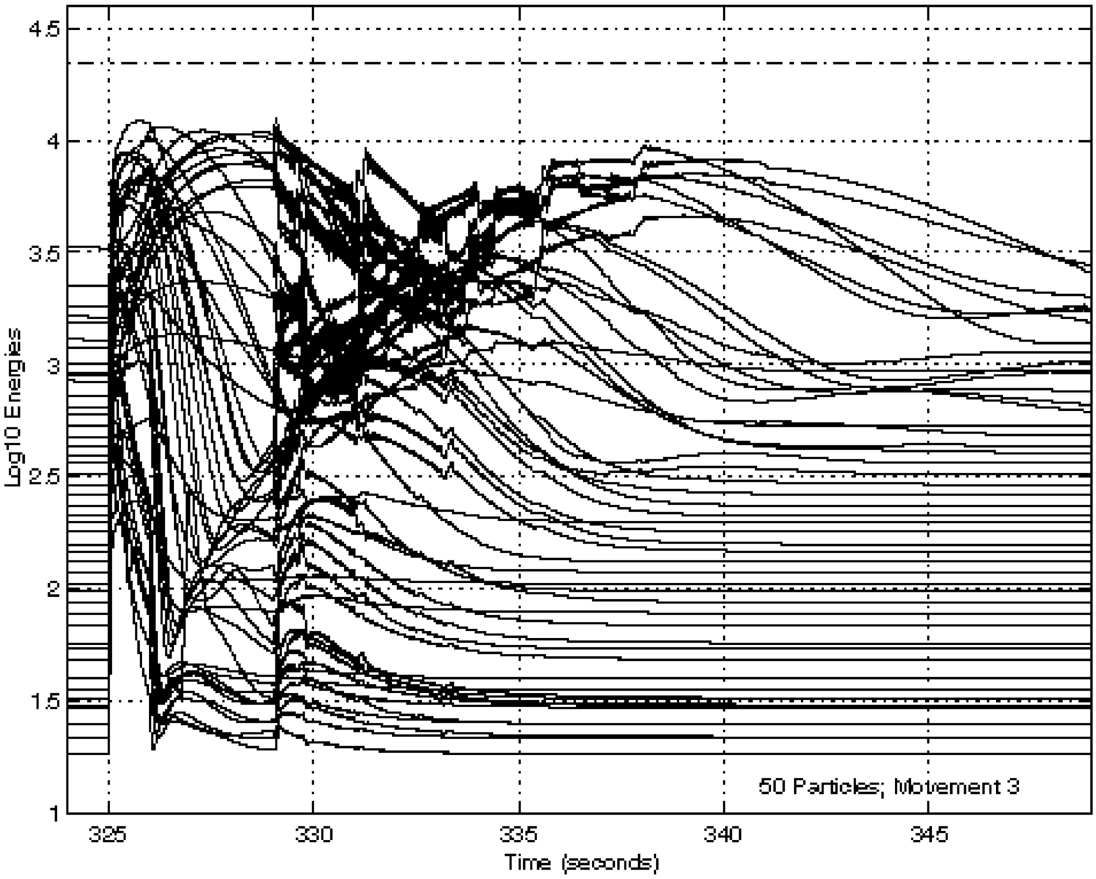

Figure 14. A detail of the energies during the fourth major Coulomb interaction. Potential modulation is visible at the higher energies.

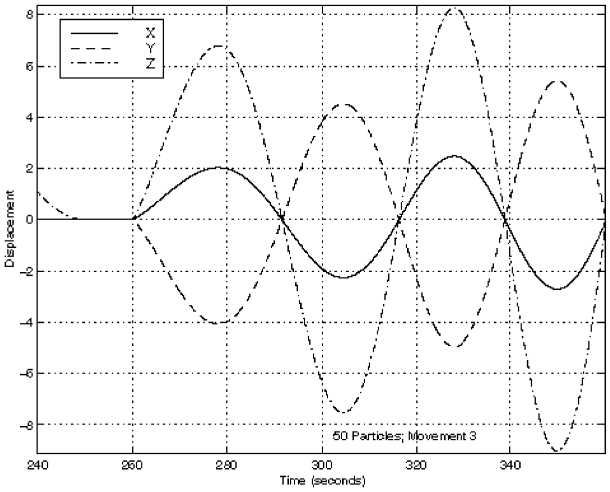

Figure 15. The position of the observer during the third movement.

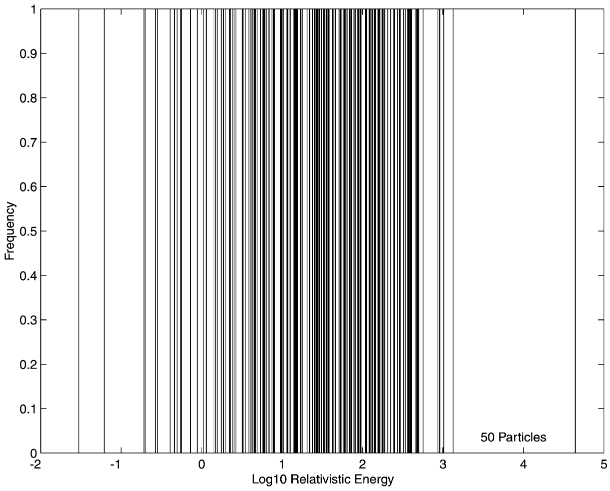

Figure 16. The rest-mass spectrum of particles after radioactive decay during the fourth movement.

It is interesting to note that most people perceive a logic underlying the sounds, as well as a process guiding the composition, even without knowing the title or its background. Many people have found the piece visually stimulating, and are excited at the prospect of seeing a visual representation of the particles with the music. 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

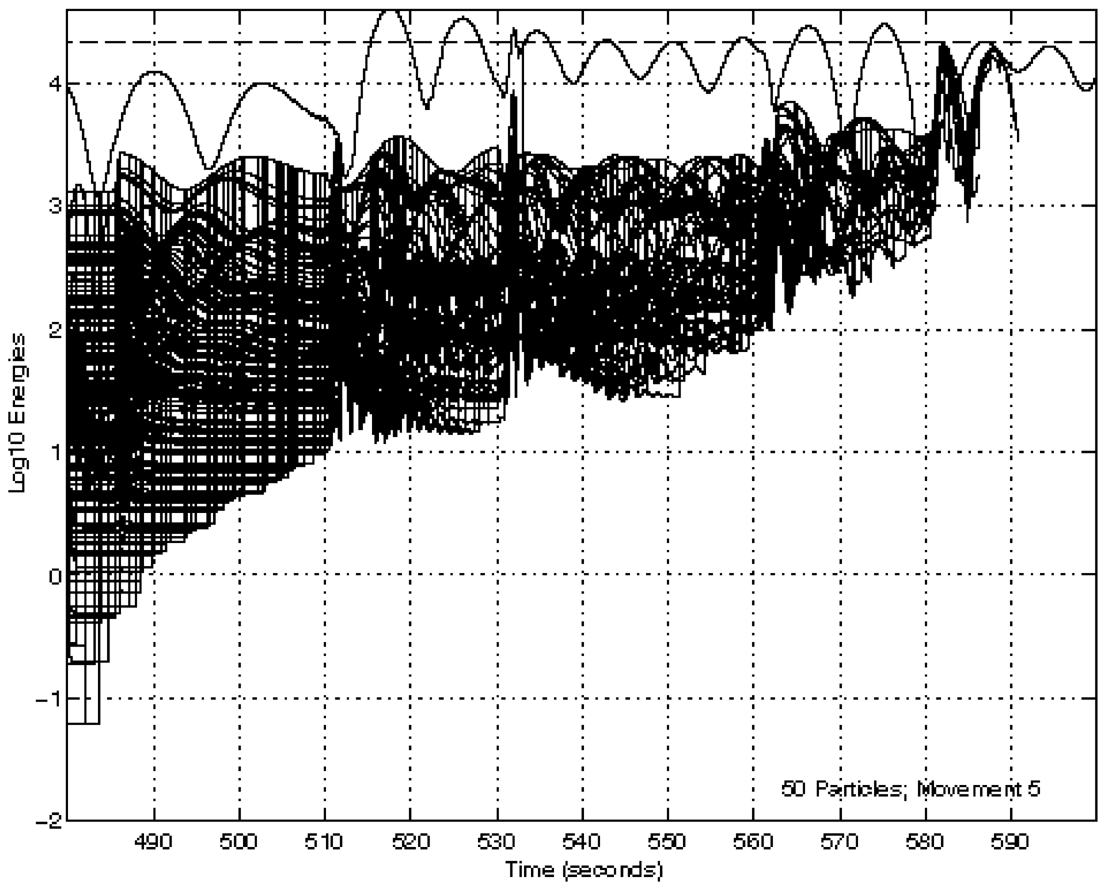

Figure 17. The particle energies during a simulation of the fifth movement.

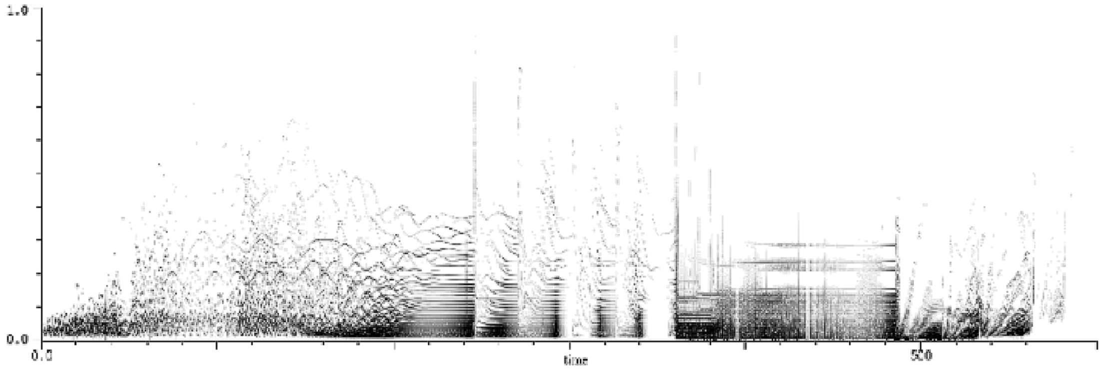

Figure 18. A sonogram of the entire composition, *50 Particles*.

system. Yet in the case of several teenagers at a science camp at Stanford, who were not prepared beforehand as to what they were listening to, comments were, ‘Ten minutes of this?’ and ‘Sounds like a horror movie’.

Many comments concern the clicks in the first movement. Some believe the clicks to be mistakes at first, such as clipping. The author knew the clicks were a consequence of the experiment’s design: particles popping into existence in the observation view. After more familiarity with the metaphorical explanation, most become comfortable with the clicks. Hardly anyone has a problem with the clicks caused by the radioactive decay in the fourth movement – perhaps because that phenomenon is understood to be discontinuous by nature.

Disappointing were the unnoticeable effects of modulating the potential walls in the third and fourth movements. Even though these movements do not wholly depend on the effect, it was frustrating trying to make the physics produce what was desired. There are also problems with spatialisation. Unless the speakers are set far enough apart, the sines do not spatialise well. More complex sample-tables will address this problem. The dilemma then is whether the composer should modify the algorithmic result to fit his or her desires. In this particular piece, the motivation was to keep the composition a pure reflection of the metaphor. All composition takes place before the experiment, and the music is then the direct result of the experiment and the science that produces it.

4.1. *50 Particles* as music–science

It is demonstrated above that while composing *50 Particles*, the distinction between composer and scientist blurs. Making music and doing physics became the same thing. Exploring a compositional idea meant constructing a system and solving its equations of motion. At times during the compositional process there was more concern with how the particles were moving than what they would sound like. This was the case in the last movement, attempting to make particles fall through the expanding hole.

The methods of each, music and physics, complement each other in wonderful ways – musical material is derived from entities interacting with force fields, and the abstract concepts of physics, compressed into esoteric, inanimate equations, become aurally tangible and animated.

In Xenakis' introductory address in defence 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 for sound composition from stochastic theory – an area of mathematics concerned with randomness, chaos and complexity. 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 his work *Pithoprakta* (Xenakis 1992: 15). 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.

For Xenakis, music is a means of exalting mathematical truth. As he is a composer also trained in architecture and engineering, he has an advantageous multidisciplinary background. For him, architecture is much more than physical construction; it is a valid proof of scientific theory, such as material strength, and equilibrium. Like flat blueprints, the physics presented herein is only thrilling to a select few in the form of mathematics. With this sonification, it acquires an impact for many more people, like a tangible scale model, or even the actualised building. Physics done well should be as visceral as music done well – an understanding that reaches to the gut.

Art and science here have become similar with only a difference in vocabulary. 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, italics in original)

For Feyerabend, then, a scientist interprets the world in much the same way an artist does. 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. The boundaries between the two will come down and reveal that the two cultures (Snow 1959) have forgotten along the way their common heritage and their common pursuits. This is important because, as Garoian and Mathews say in their article entitled, 'A common impulse in art and science': '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)

5. CONCLUSION

Inspired by a few similarities, a metaphor has been created that links together sound composition and classical mechanics, with the quantum mechanical notion of particles acting as waves. The parameter mappings between the two domains seem to magically fall into place, forming an auditory display of particle phenomena that is quick to comprehend and visualise for physicists and non-physicists alike. Thus the sound that is produced through these methods possesses significance for musical *and* scientific experience. The sound synthesis becomes a sonification of and composition from the observations of the phenomena of N-body particle systems.

Through the use of this system for composition, it is seen that the traditional role of the composer is replaced by the composerscientist. Much work was required in both musical and scientific domains to compose *50 Particles*. Musical gestures became particle interactions; and equations of motion hinted to musical development. More than anything, this composition was inspired by the physics it sonifies, satisfying the author's curiosity for what the subject of his undergraduate study sounded like.

It is a wonderful thought that these sounds are from the microcosm of the quantum mechanical world, a place too small for the imagination. The astronomer/mystic Kepler created musical scales for each planet based upon the eccentricity of its orbit (Cohen 1984:

28), crudely sonifying a realm too large for the imagination. And thus the composition *50 Particles* is inspired by these 'musics' of the spheres, attempting to make conceivable the inconceivable. It is an expression of the abstract scientific principles that it sonifies – even if the laws of its nature are not those of Nature. In the end, the composition is a successful application of the metaphor, providing promise for future developments – especially linking visual particle animations with the sound.

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

> 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)

Science and art share this use of logic and metaphor in their practices. Artists and scientists have utilised the power of the metaphor since the genesis of their disciplines. Metaphors 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 can certainly enrich the experience of both.

It is not too far a step to conceive of the application of methods like these to real particle experiments. The composerscientist would direct the 'compositionexperiment' in 'musico-scientifically' meaningful ways for attending observers. The concert space could be the control room of a particle accelerator, with the composerscientist at the great instrument's controls bringing about significant science as well as moving music using the most elementary pieces of the universe.

APPENDIX. SOUND EXAMPLES

1. Linear potential, 100 particles
2. Mass-dependent linear potential, 100 particles
3. Harmonic potential, 20 particles
4. Mass-dependent harmonic potential, 20 particles
5. Harmonic potential, 50 particles, Doppler effect
6. 20 particles in a box, elastic collisions
7. Heating a gas of 1,000 particles in a square box
8. Cooling a gas of 1,000 particles in a square box
9. Gas of 1,000 particles in a circular box
   In this example, the observer at the centre is closely surrounded by 1,000 particles. At the very beginning, the particles explode radially away from the observer. The particles then bounce off the boundary of the box and return, flying through the observer to the other side of the box, bounce and return.
10. 5 particles in a square box, sudden increase in Coulomb coefficient, return of Coulomb coefficient to zero
11. Example 1 of radioactive decay
12. Example 2 of radioactive decay
13. 50 Particles in a Three-Dimensional Harmonic Potential: An Experiment in 5 Movements
    i. Movement 1: Gradual Introduction of 50 Particles into System; Tuning the Harmonic Potential; Adjusting the Observation Apparatus
    ii. Movement 2: Adding Viscous Fluid to Reveal the Rest-Mass Spectrum
    iii. Movement 3: Sudden Increases in the Coulomb Potential of the Universe
    iv. Movement 4: Two-Generation Cascading Radioactive Decay; Position Modulation of Observer
    v. Movement 5: Reduction of the System Via Least Energies

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