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Composing for an Ensemble of Atoms:

The Metamorphosis of Scientific Experiment into Music[*]

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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.

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

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.'

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:

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

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.'

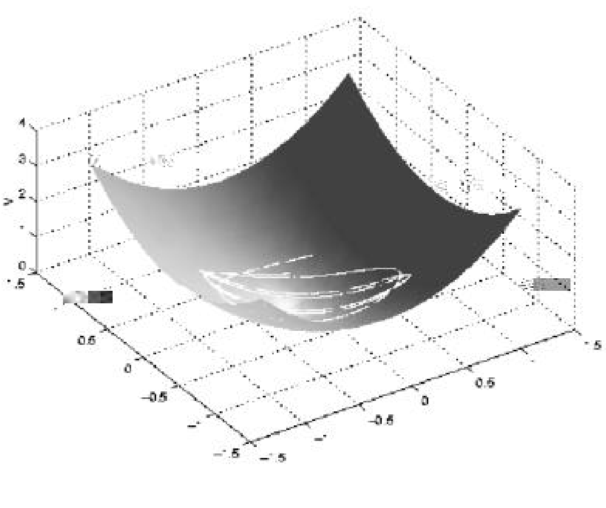


Figure 1: *A two-dimensional harmonic potential.*

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**

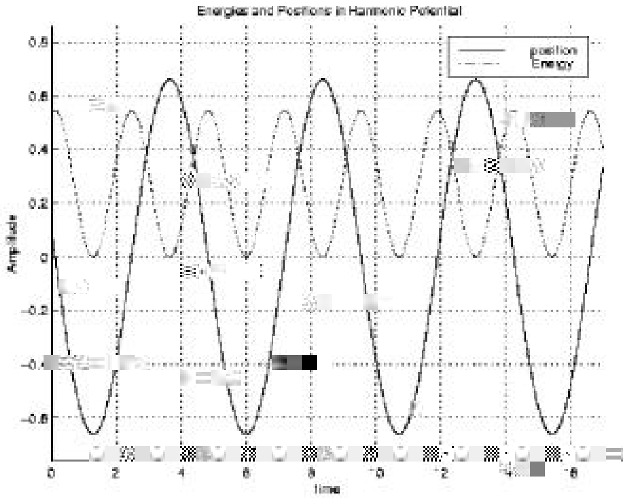


Figure 2: Particle displacement and energy in a one-dimensional harmonic potential.

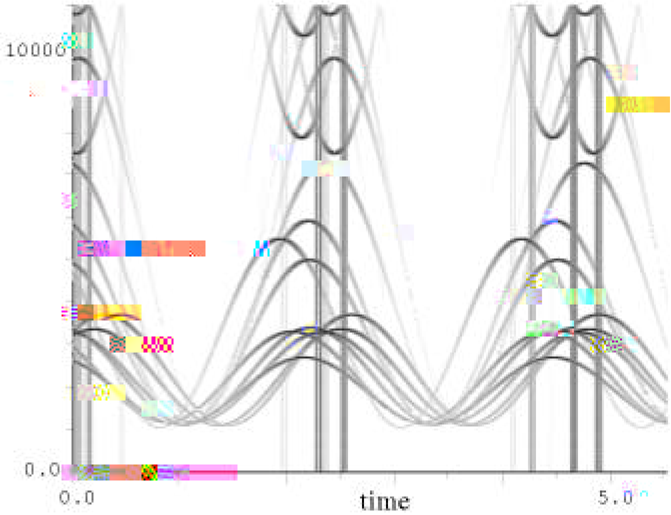


Figure 3: Sonogram of fifteen particles in a one-dimensional harmonic potential.

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

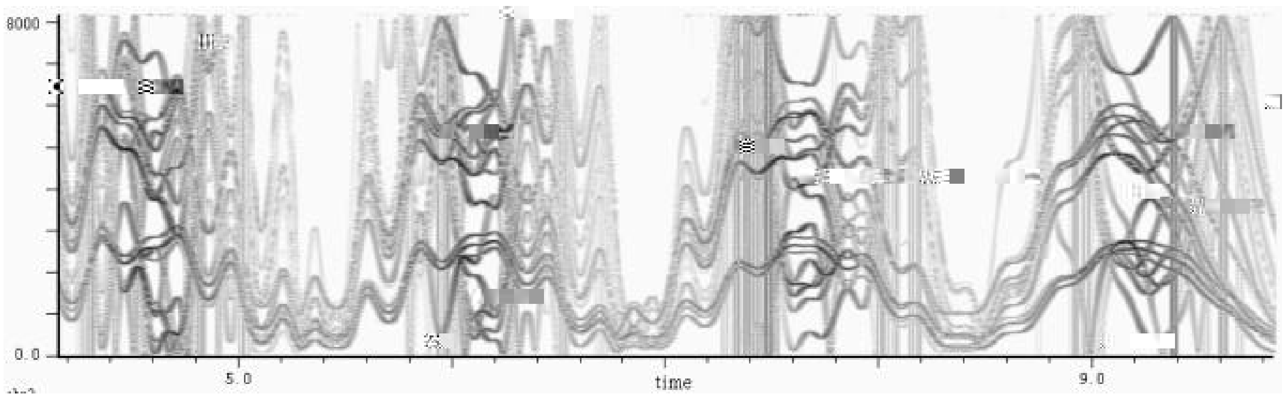


Figure 4: Sonogram of Coulomb interactions within a harmonic potential.

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.

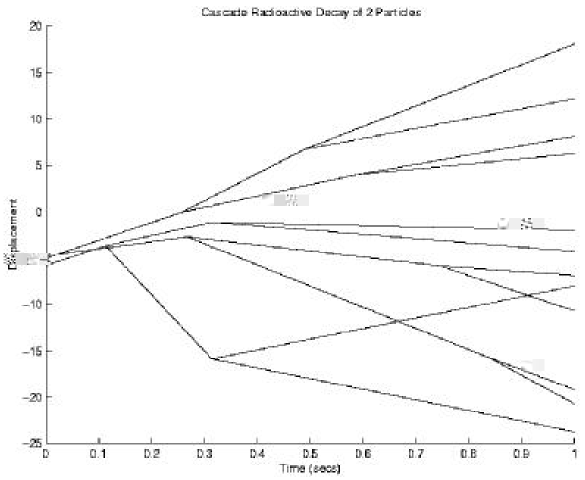


Figure 5: *A cascading radioactive decay of two particles.*

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

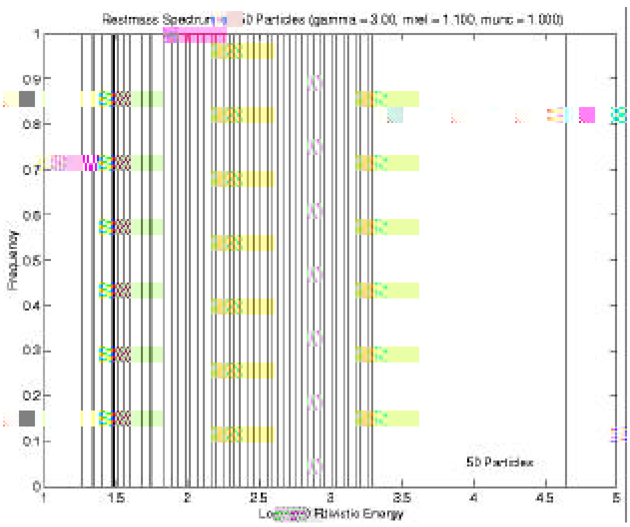


Figure 6: *The Restmass Spectrum of the fifty Particles.*

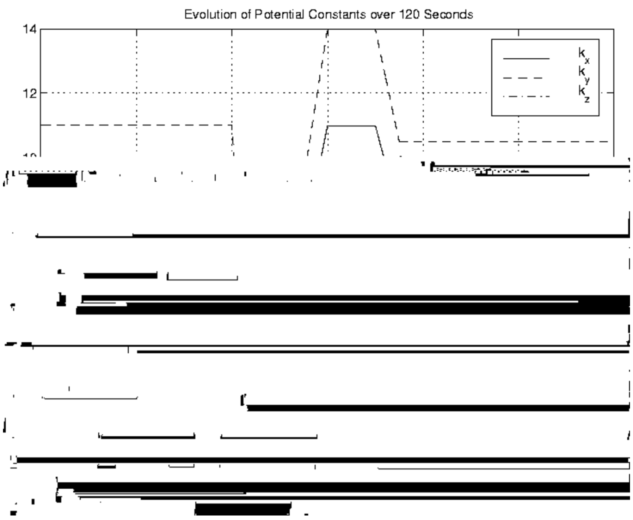


Figure 7: *The tuning of the potential constants during the first movement.*

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 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** 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*=This me8st as acc537k 0 0 00 Tverm. mporhe d e

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

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.

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

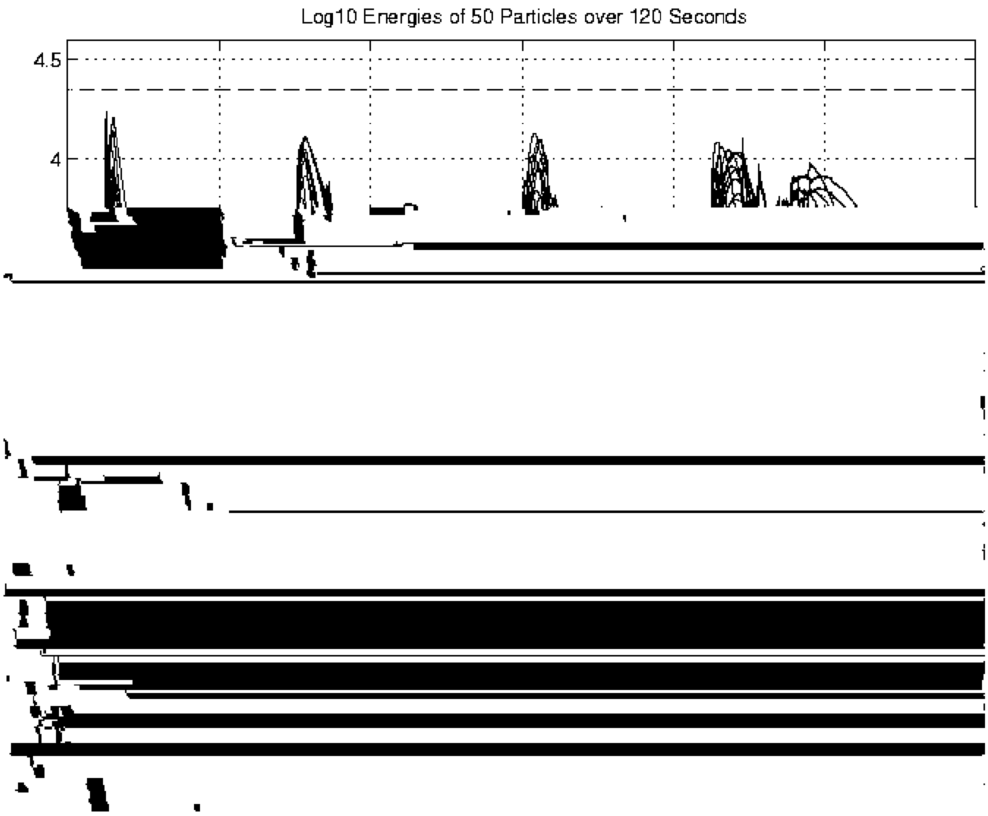


Figure 13: *The particle energies during a simulation of the third movement.*

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.

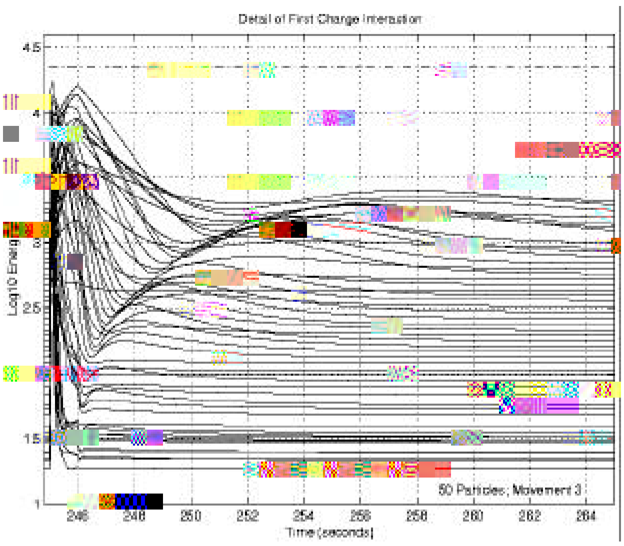


Figure 14: *A detail of the energies during the first Coulomb interaction.*

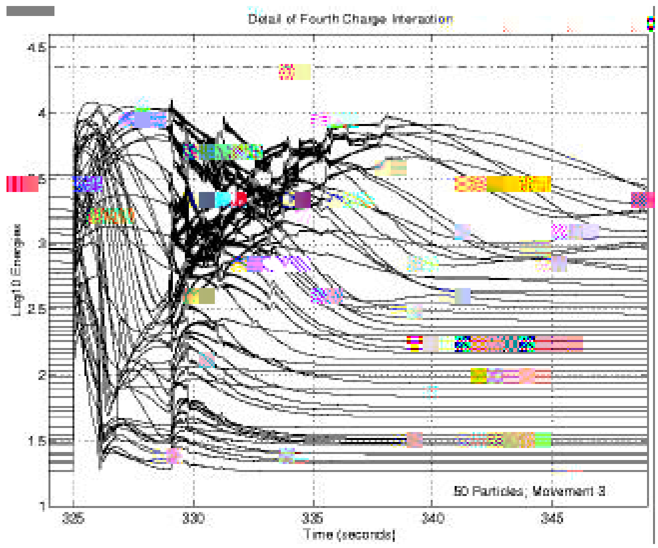
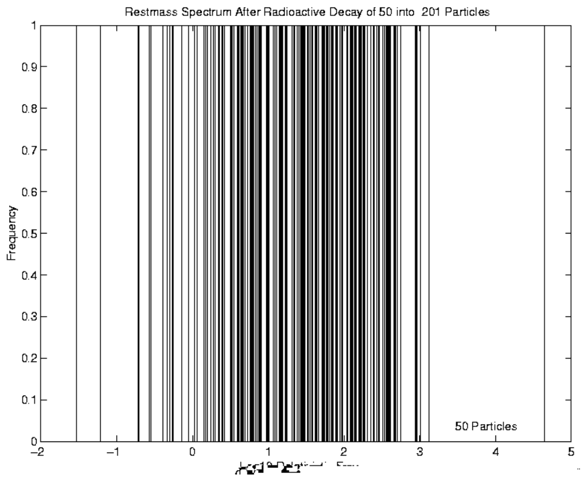


Figure 15: *A detail of the energies during the fourth Coulomb interaction.*

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.



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

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

of appending the name

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 stand0392 4g6we it isguable; butuld thagaitioo it w (theanesticy of tounm ‘92 4g6w’The) Tj   02.8

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> 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

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;                                            %visco
```

```
           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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BIBLIOGRAPHY

Alexjander, Susan. 1999. The Infrared Frequencies of DNA Bases: Science and Art. *IEEE Engineering In Medicine and Biology*, 18:2. Available on-line at: <http://www.healingmusic.org/SusanA/>.

Babbitt, M. 1998. Who Cares if You Listen? In E. Schwartz, and B. Childs (eds.) *Contemporary Composers on Contemporary Music*. New York: Da Capo Press.

Chalmers, A. F. 1982. *What is this thing called Science?* Indianapolis: Hackett Publishing Co.

Cohen, H. F. 1984. *Quantifying Music: The Science of Music at the First Stage of the Scientific Revolution, 1580-1650*.

.5ohen,

Franklin, M., R. Becklen, and C. Doyle. 1993. The Influence of Titles on How Paintings are Seen. *Leonardo*, 26:2.

Garoian, C., and J. Mathews. 1996. A Common Impulse in Art and Science. *Leonardo* 29:3.

James, J. 1993. *The Music of the Spheres: Music, Science, and the Natural Order of the Universe*. New York: Grove Press.

Kaper, H. G., and S. Tipei. 1998. Manifold Compositions, Music Visualization, and Scientific Sonification in an Immersive Virtual-Reality Environment. In *Proceedings of the 1998 International Computer Music Conference*. Ann Arbor: International Computer Music Association.

Kramer, G., B. Walker, et al. 1999. *Sonification Report: Status of the Field and Research Agenda*, ICAD, Santa Fe. Can be found at <http://www.icad.org>.

Meyer, L. B. 1967. *Music, the Arts, and Ideas: Patterns and Predictions in Twentieth Century Culture*. Chicago: University of Chicago Press.

Rothstein, E. 1995. *Emblems of Mind: The Inner Life of Music and Mathematics.* New York: Avon Books.

Snow, C.P. 1959. *77per, H.9177nd: ThSturm 199 87.62000.*

[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.