CHAPTER SEVENTEEN

Immersed in Unfolding Complex Systems

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Our Multimodal Arena

What would it be like to walk into a real-life "Holodeck" or "Cerebro" and experience a stunning new world unlike anything seen before? Beyond this, what if we were able to experience hitherto unobservable aspects of nature, as environments into which the body cannot actually venture? In fact, these questions are on the minds of scientists and artists working together, right now, in the AlloSphere located in the California NanoSystems Institute at the University of California, Santa Barbara. We have in our hands an instrument that allows us to explore and interact with complex, high-dimensional data and systems—whether they be sub-atomic particles, the human brain, or entire synthetic ecosystems—as if they were fully immersive worlds.

The AlloSphere is one of the largest scientific/artistic instruments/laboratories in the world for immersive visualization, sonification, and multimodal data manipulation. It is a three-story sphere finely tuned for perceptual experiences with a 360-degree, super-black, non-reflective screen surrounded by a multi-channel loudspeaker array, all housed in an echo-free chamber (see Figure 17-1). Multiple users standing on the central bridge (Figure 17-2) can interact through myriad multimodal devices as they experience stereographic projections and spatial audio.

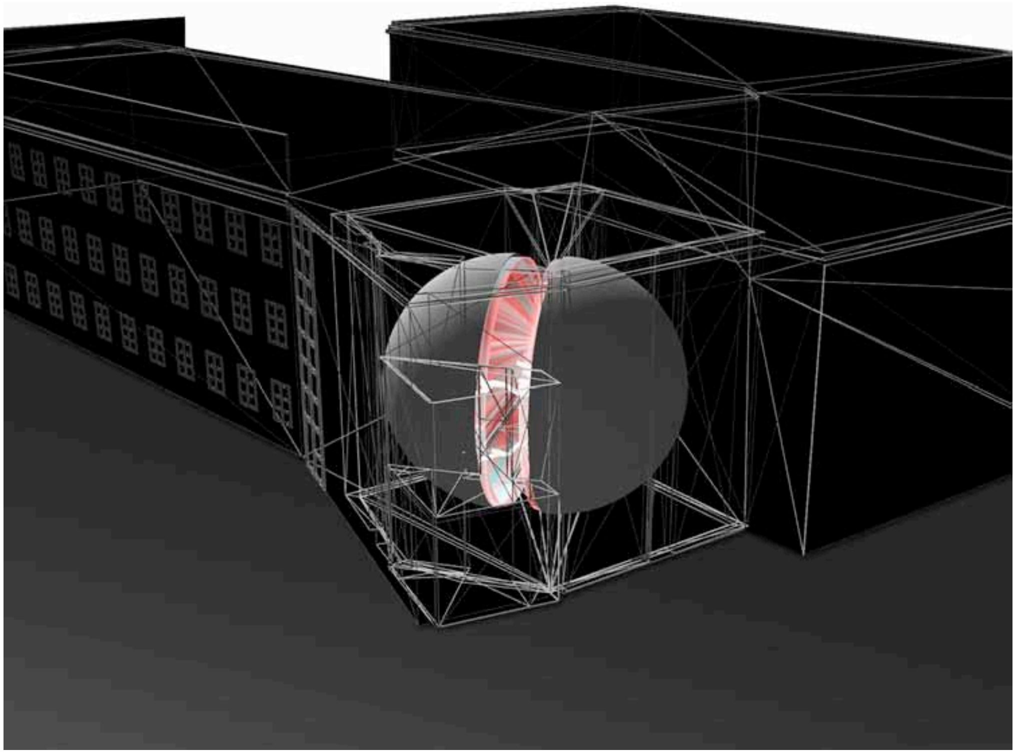

Figure 17-1. *A virtual real-scale model of the AlloSphere*

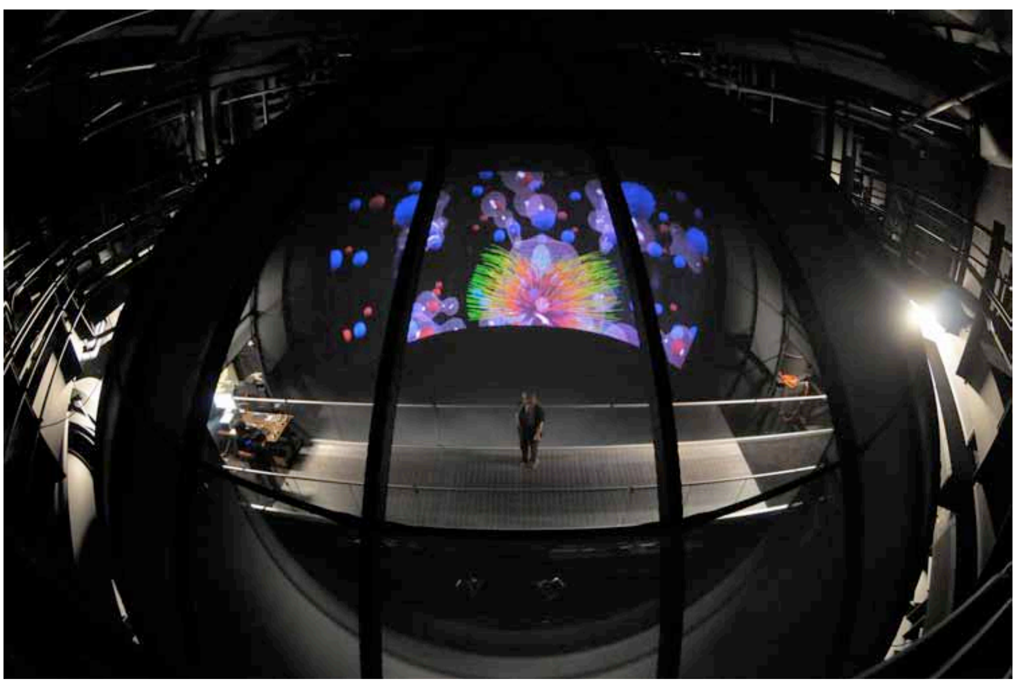

Figure 17-2. *A full-scale photo of the AlloSphere*

The AlloSphere was conceived by composer JoAnn Kuchera-Morin as a general-purpose eye- and ear-limiting multimedia instrument for both new modes of artistic expression and scientific discovery. Her intention was to provide a common meeting ground where diverse researchers can share insights and pursue similar fundamental questions about symmetry, beauty, pattern formation, and emergence. Our attitude to this unique opportunity is to establish a frontier of research that is grounded in both art and science, but not constrained to either one. This has required a holistic rethinking of the fundamental aspects of our creative medium: computation, data, process, perception, interaction, immersion, and evaluation.

With artists, scientists, and engineers working together in the AlloSphere to uncover new worlds through unique and compelling simulations and visualizations, we are implementing our concept of beauty as truth. We help researchers find this truth through the visualization and sonification of intriguing equations. These visualizations offer elegant solutions in their unfolding, allowing us to discover symmetry—and broken symmetry—as it unfolds in these equations.

Our Roadmap to Creative Thinking

The AlloSphere indeed provides a compelling interactive, multimodal environment for a new type of interdisciplinary research that, from the start, tightly integrates quantitative and qualitative approaches to problem solving and discovery. It also offers a unique opportunity for experiencing, using all of our senses, how complex systems unfold over time. We have begun to uncover common themes in how these systems are described in terms of computational constructs and how they can be represented in terms of beauty and symmetry. Our challenge and opportunity in composing beautiful visualizations is thus to strike a balance of both mathematical truth and perceptual expression, and to introduce a new form of art and research as epistemological experiment.

Beauty and Symmetry

Beauty no doubt plays a central role in our perceptual engagement, as it is closely related to symmetry. In fact, beauty and symmetry have shared an intimate relationship since the time of the ancient Pythagoreans, who stated that the key to beauty lies in the proportions of parts and their interrelationships, and that symmetry and harmony are the interrelationships in the domains of sight and hearing, respectively (Tatarkiewicz 1972). This theory has been one of the most enduring throughout our cultural history.

Indeed, symmetry—and its more formal definition as "invariance to transformation" (Weyl 1952)—is the basis of some of the most profound scientific theories of nature, including special relativity, the laws of conservation, and string theory. Symmetry has also played a less acknowledged but vital role in computational simulation. In ancient times, we could only observe the patterns in nature around us; today, through the control over proportion afforded by computation, we can compose systems that generate complex natural patterns with precision and autonomy. At the heart of these complex patterns, we do indeed find symmetries. In fact, symmetry often helps guide our search for significant patterns in the data.

The Computational Medium

Computation and mathematics provide an alluring common language between scientific models and aesthetic practice. Computation is a vital tool for scientific simulation and also an open-ended material for art. By designing and instantiating complex autonomous systems, we open the door to a new kind of knowledge based on synthesis of parts.

Regardless of the questions we want to ask, computation necessitates a formal and discrete description of the basic components of the data and a consideration of the limits of real-time processing. We have found, particularly for physically based models, that the data we work with consists primarily of values associated with positions in space and/or time. Values represent particular internal intensities, such as velocity, flux, frequency, or complex phase, and are typically correlated to positions in space and/or time. Many of the visualization techniques we apply involve filtering out values at a certain position (such as a cross-section) or positions at a certain value (such as a contour line).

How the values and positions are instantiated during a program's execution varies. The values can be explicit (given at regular sampling points or as position/value pairs) or implicit (computed on the fly using an equation or algorithm). Likewise, the positions can be explicit (as position/value pairs) or implicit (determined from the dimensions of a regular lattice).

In working with various computational models, we have observed three general paradigms in how data is represented for storage and processing:

1. As a regular lattice of sampled values
2. As a collection of position/value pairs
3. As a function of position

The difference between the first two is the same as the two general ways images can be represented on a computer—raster-based (as a matrix of pixels) or vector-based (as a set of points connected with curves). The third paradigm is more like a black box that takes in a position and outputs a corresponding value.

With each paradigm, there are specific tradeoffs. A lattice permits models consisting of unexpected signals and local interactions, but it requires sampling, leading to aliasing and the need for potentially large amounts of memory to model systems at an appropriate level of resolution. In contrast, the position/value and function paradigms allow fine or arbitrary spatial resolution, but make it computationally difficult to model interactions between entities.

A natural conceptual division that follows from these paradigms is between spatiotemporal fields and sets of free agents. *Fields* are a type of regular lattice in space (possibly time-varying) and serve as the substrata of complex systems. They provide the underlying architecture of structure and dynamics within a system. Fields represent things like density distributions, fluids, and waves. The concept of a field exists in many disciplines: developmental biology has the morphogenetic field and epigenetic landscape, evolutionary biology has the fitness landscape, and physics has quantum fields and wavefunctions. *Agents* are collections of position/value pairs and serve as the superstrata of complex systems. Agents represent actual discrete entities, possibly mobile, in continuous space. They allow us to observe fields more clearly by focusing finely on parts of the entire system and filtering it to see its patterns of invariance. In addition, agents often interact with one another by reading and writing values in a field.

Interpretation As a Filter

Our work involves not only the design and instantiation of complex systems, but also—and just as importantly—the composition of a filter that reduces the overwhelming vastness of the computational/mathematical spaces into forms that we can perceive and draw meaning from. In other words, visualization and sonification involve both the organization of materials (composition) and the presentation of the patterns we are trying to reveal (interpretation).

We often ask ourselves the question "what are we looking for in the data or system?" To begin answering this question, we can say that we are looking for the interesting patterns that reveal essential aspects of the system as it unfolds. Furthermore, we find that utilizing symmetry helps guide our search for significant patterns. The visualization techniques we commonly apply, such as isosurfaces, contours, streamlines, and particle flows, show aspects of a system where its values (or a derived quantity of them) are equivalent or invariant. These "pockets of symmetry" show the similarities in the system and tend to provide a good starting point for more deeply understanding its behaviors and patterns. We know that too much symmetry reduces significance, while too little symmetry is overwhelming; the filter must fall between these extremes of order and disorder. This also applies to time: patterns of interest must maintain identity long enough to be recognized, but also change sufficiently to capture attention.

Composing a filter is an adaptive process that occurs within a modality just as much as across modalities. We find that multimodal representation is important for revealing otherwise hidden or non-obvious symmetries and asymmetries in data. Sometimes, the most natural sensory modality of a dataset or process will not fully depict important aspects of its structure. For example, we find that symmetries of waveforms are better seen and that slightly broken symmetries in spatial data are better heard. We use the transformational capacities of computation to map amongst and between modalities, searching for a balance that will give a more complete mental picture of the phenomena at hand. In fact, there is evidence that the brain's memory system consists of an "episodic buffer" that integrates visual and aural sensory information into a multidimensional code that interfaces with long-term memory and can subsequently affect long-term learning (Baddeley 2000).

The agent-based model has played a dominant role in our filtering and presentation of data and systems. Agents are appealing from both a visual and an aural sense since they can have smoother and more continuous movements, versus being restricted to moving on a discrete lattice. In return, they allow us to observe dominant patterns in systems through coherent structures, thus reducing noise. One example is using agents to show flux across a coarsely sampled field using smooth and continuous curves.

Project Discussion

In this section, six research projects will be discussed that span areas ranging from artistic/scientific mathematical abstraction to precise multimodal representation of computational models based on real scientific data and theories. We'll move from real biological data through bio-inspired evolutionary developmental algorithms, to the world of atoms; then, moving from the atomic level down to the electron level in one single hydrogen atom, we will finally arrive at a project that represents the coherent precession of an electron spin.

Allobrain

By Graham Wakefield, John Thompson, Lance Putnam, Wesley Smith, and Charlie Roberts (Media Arts and Technology)

Faculty Directors: Professor JoAnn Kuchera-Morin and Professor Marcos Novak (Media Arts and Technology)

In the Allobrain, we fly through the cortex of the human brain (Figure 17-3). Structural components of functional magnetic resonance imaging (fMRI) data are used to create a space that can be experienced as a "world" through which we can navigate. The raw data maps density values of cerebral metabolic activity across a lattice of spatial coordinates throughout the brain; the visualization contains two isosurfaces through this dataset, selected by the intensity of brain tissue response to the fMRI scan. (An *isosurface* is a 3D contour representing points of a constant value.) Inside this world are "search agents" that navigate autonomously to mine the data, indicating their presence spatially and visually, clustering in regions of interest and reporting back to us through musical sound. "Wanderer agents," color-coded to specific brain regions, take a random walk through the data looking for high blood density levels. They alert large packs of "cluster agents" to do finer detailed analysis and visualization in these regions of interest. The wanderer agents can also be commanded to report back to the center of the screen and sing blood density levels, where higher pitches correlate to higher levels.

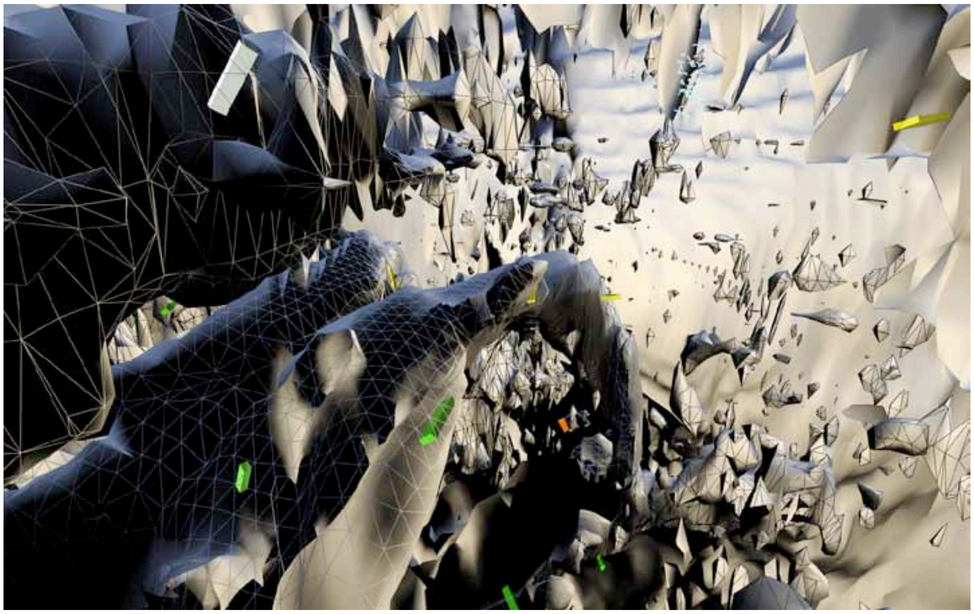

Figure 17-3. *Inside the Allobrain*

One can imagine applications not only for medical diagnostics but also for psychological studies in cognition and perception: by revealing many dimensions of information in a single viewing, Allobrain facilitates early discovery of cellular disorder and understanding of how the brain functions. In fact, visual artist and trans-architect Marcos Novak—the creator of this world, and whose brain it is—conceived the project to engage with the neurological bases of aesthetic appreciation. He describes his work as follows:

> When we say that something is "beautiful," what parts of the brain are involved in that assessment, and how? Since there is such great variation among people in aesthetic matters, a better approach to the question of beauty may be to study one or few instances as closed systems, learn as much as possible about them, and then [determine] if what has been learned can be generalized to others.
>
> In particular, this work aims to construct a situation in which most of the elements that pertain to the making of something beautiful are accessible to investigation. Specifically:
>
> - the work to be appraised as beautiful or not
>
> - the method and mechanism of its generation
>
> - the creator, appraiser, and investigator of the work

> Furthermore, the aim (scientifically and artistically) is to create a feedback loop in which the art affects the brain and the brain generates new data that creates new art, that in turn affects the brain, that generates new data, and so on.
>
> To seed the process, I wrote a generative algorithm that produced stimuli that I could not anticipate in detail, and that triggered in me the reaction of beauty (in terms of visual and spatial composition). The stimuli consisted of either a) an interactive/generative moving/changing image, [or] b) video recordings of this so that they could be used in the fMRI machine. While in the fMRI machine, I was presented with this video (which I had not seen previously). Whenever I felt that the visual compositions were beautiful to me, I pressed a button. The pressing of the button was timed, so that it could be correlated with the activity of the brain at that instant. The fMRI data was converted into an immersive environment, or "world." This step allows two parallel possibilities: from a scientific viewpoint, it permits the structural and functional data to be perceived from within in ways that conventional visualization techniques do not allow. From an artistic viewpoint, it proposes a novel art form in which the brain (and subsequent mind) produces the world, and the world alters the mind, which in turn produces another world, and so on. In both cases, a feedback loop can be constructed in which the user's response itself helps generate the stimuli that trigger that response, thus amplifying the effect.

Presently, the Allobrain reveals one static snapshot of a thought. As we move the project forward, real-time interactive fMRI data will allow researchers to be immersed in their own thoughts and watch them transform and change, as in Novak's description. The brain will perceive the world and then transform the world through its perception.

Artificial Nature

By Haru Ji and Graham Wakefield (Media Arts and Technology)

http://artificialnature.mat.ucsb.edu

We move now from raw biological data to the processes and systems at the roots of life. Artificial Nature is a transdisciplinary research project and bio-inspired immersive art installation based on generative models drawn from systems biology, artificial life, and complexity sciences rather than empirical data. The computational world of Artificial Nature is an ecosystem consisting of populations of organisms interacting within a dynamic environment, with which spectators interact.

The environment is a spatial field based upon equations of fluid dynamics. Simple particles flowing within it represent different nutrient types (hue) and energy levels (brightness), and interact kinetically with one another. These particles provide the metabolic fuel for the organisms, which are modeled as autonomous agents. Both ingestion of nutrients and disposal of waste products are necessary for organisms to survive and reproduce.

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The appearance and autonomous activity of organisms is determined through the interpretation of their genetic descriptions according to local (spatial and historical) conditions. For example, sufficient accumulation of energy triggers some organisms to generate children by asexual reproduction, with small chances of mutation. The shape of these organisms is based upon the Boy surface equation (Boy 1901) and is gradually varied over their lifetimes to indicate gradual growth and development, while health is represented by opacity.

Activities such as ingestion, reproduction, and detection of neighbors are accompanied by different varieties of chirp-like songs, which are fully spatialized in the AlloSphere. These sounds are bright, transient-rich, and tightly clustered, making them easier to distinguish from one another, localize, and connect to visual events.

Spectators can explore this world freely and endlessly using a six-degrees-of-freedom navigator device and can influence it indirectly, creating turbulence just as they might have playing in a stream or sandpit in their childhood. Sensory data collected through a camera-eye and microphone-ear, and sometimes through touch, become the environmental conditions to which the organisms must adapt. The turbulence of the fluid also feeds back to influence the navigation of the spectators. The entire ecosystem, including the spectators themselves, generates continuous patterns of emergent beauty (Figure 17-4 and Figure 17-5).

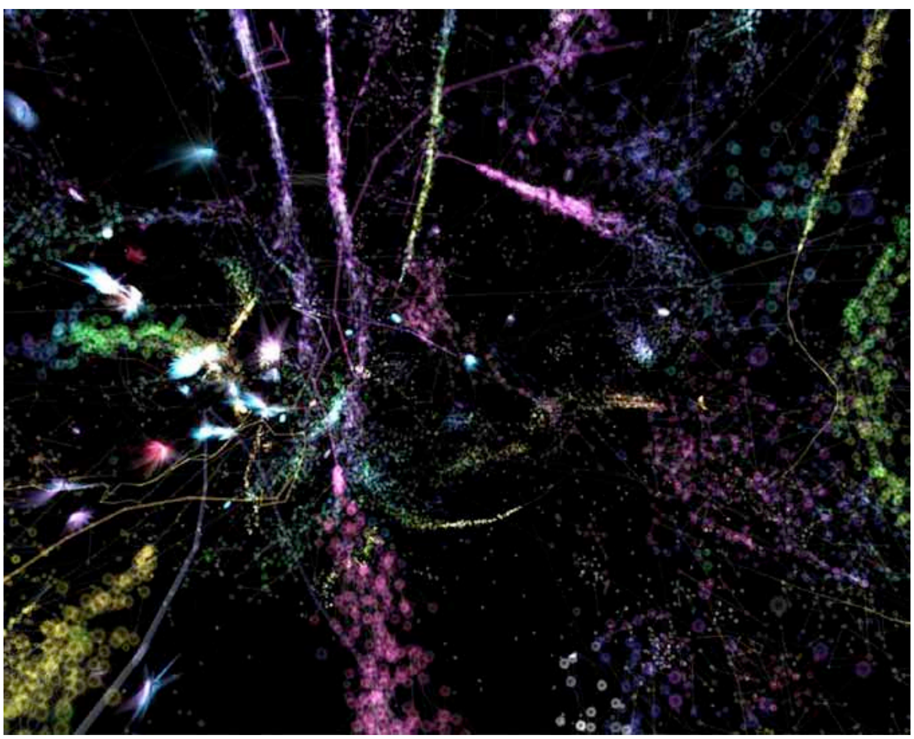

Figure 17-4. *Artificial nutrients being produced and dispersed in the fluid fields of Artificial Nature (version 1: Infinite Game)*

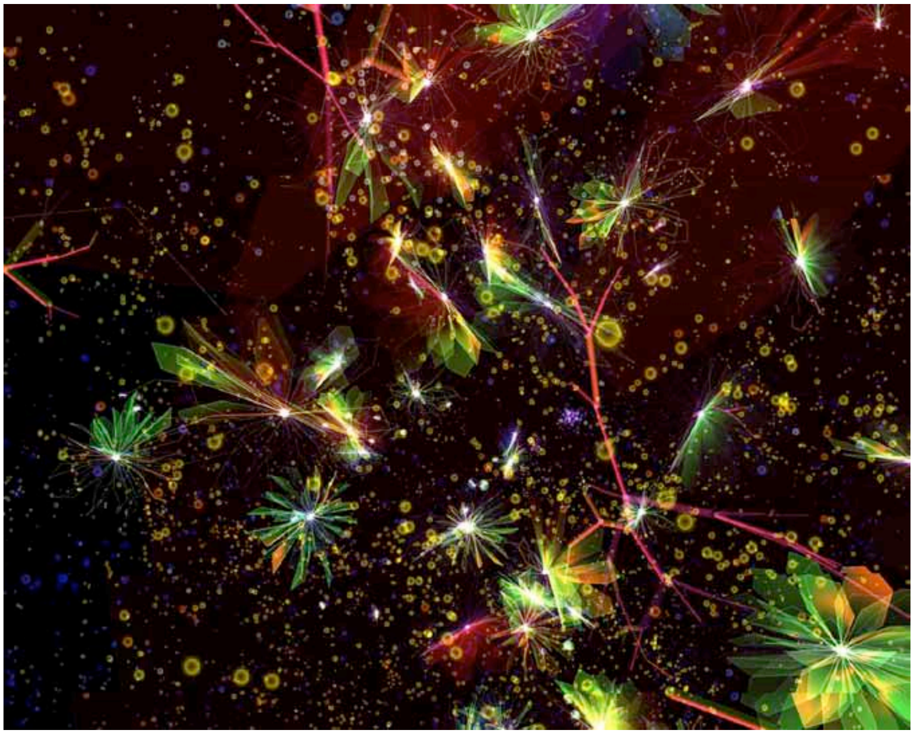

Figure 17-5. *Artificial organisms growing and interacting in Artificial Nature (version 2: Fluid Space)*

We asked what form of art could evolve in the space of the AlloSphere. Artificial Nature responds consciously to this challenge as an immersive artwork, a new kind of experience within an alternative environment—an infinitely unfolding possible world. The open-ended nature of Artificial Nature is grounded in the embodiment of complex adaptive systems drawn from artificial life. These agent-based techniques lend themselves to real-time simulations, and multimodal interaction embeds spectators into the ecosystemic network.

Artificial Nature is itself a project within a larger evolution. As we embed more dimensions and relations into it, new potentials for pattern, structure, meaning, and beauty emerge.

Hydrogen Bond

By Basak Alper, Wesley Smith, Lance Putnam, and Charlie Roberts (Media Arts and Technology), and Anderson Janotti (Materials Research Laboratory)

Faculty Directors: Professor JoAnn Kuchera-Morin (Media Arts and Technology) and Professor Chris G. Van de Walle (Materials Research Laboratory)

As we move from the biological and macroscopic world, we enter the world of atoms and a new materials compound for clean technology, the multicenter hydrogen bond. This is a very important step for the fabrication of transparent solar cells and low-cost display devices. Normally, hydrogen forms a *covalent bond* with other elements (meaning that it bonds by sharing a pair of electrons—since hydrogen has only one electron, it can only form one covalent bond at a time), but in a zinc-oxide lattice it bonds anomalously to four zinc atoms, forming a tetrahedral bond structure.

Our materials science colleagues in the Solid State Lighting and Energy Center at UCSB discovered this unique type of bond structure and requested that we represent their simulation data visually and sonically in ways that their existing tools would not permit. The data we received was a three-dimensional lattice of electrostatic charge density at the site of the hydrogen bond. Visualizing this kind of volumetric data poses a significant challenge as there is no natural way to see inside a solid shape.

A common way of visualizing volumetric data is to draw isosurfaces to reveal internal curvature. By applying isosurfaces to the charge density, we made the shape of the bond structure more clearly visible in a way similar to how contour lines are used on a map to reveal changes in height. Locating local maxima/minima in the data field was also an important goal for the scientists, as it would help them identify critical regions in the bond. We solved this problem by interpreting the gradient as a volumetric data field. Initially we couldn't get any results, because the sampling distance of the data was much larger than the regions we were looking for. We explained how the visualization algorithm worked and convinced the scientists to generate higher-resolution data. Once we got the high-resolution data, drawing zero-value isosurfaces in the gradient field successfully showed the local maxima/minima regions.

To reveal more of the field's shape, we used a visualization technique called *streamlines* that produces curves that run along the flow of a vector field. We started the streamlines near the center of the hydrogen atom and allowed them to flow outwards "down" the gradient, where hue indicated fast (red) and slow (green) movement. Although our science partners initially regarded the streamlines as strange, they proved themselves effective by converging upon critical locations in the bond structure.

We extended the standard visualization tools by adding the ability to choose between different visualization modes and overlay selected visualizations in a single view (see Figure 17-6). Conveying different layers of information in one view requires drawing a picture where clutter and ambiguity is minimized. To this end, we utilized a custom lighting algorithm that is less diffused and therefore highlights the curvature of the isosurfaces. We composited both transparent and wireframe renderings to ease perception of multiple transparent surfaces. We found that streamlines and isosurfaces were natural visual complements as they had the ability to show information in perpendicular directions. Showing streamlines and isosurfaces together was not perceived as being as problematic as showing multiple layers of isosurfaces, since they were easier to visually differentiate.

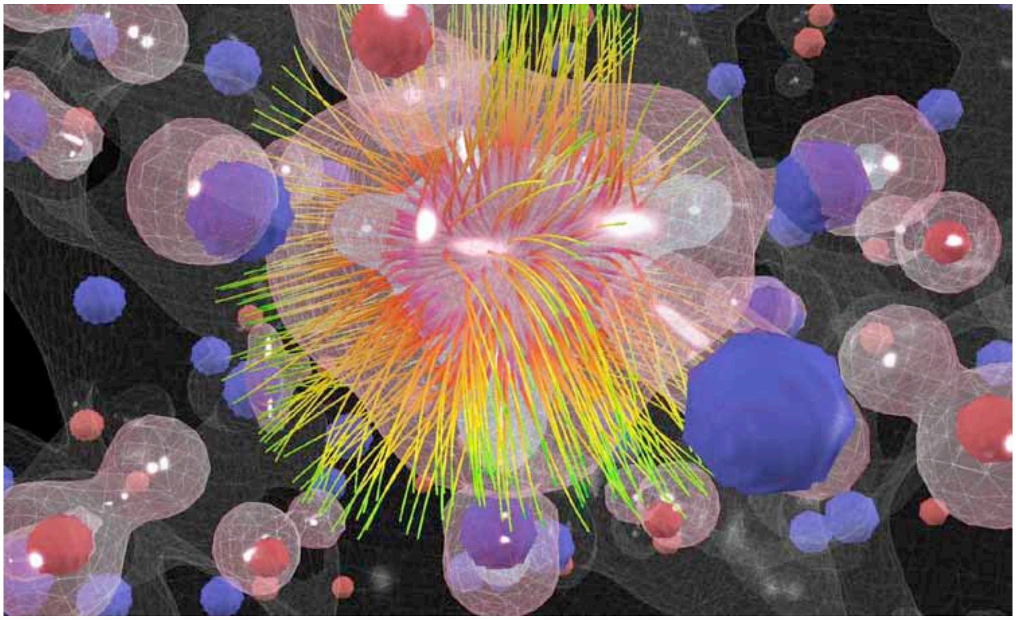

Figure 17-6. *Closeup view of hydrogen in a tetrahedral bond with four zinc atoms (blue)*

In addition to visuals, we used spatial audio for localizing the bond location and the user's position in the lattice (Figure 17-7). In order to give a sonic identity to the atoms, we sonified the *emission spectra* (the relative electromagnetic radiation) of hydrogen, zinc, and oxygen by pitch-shifting their respective emission frequencies down 10 octaves to the audible range.

Figure 17-7. *Researchers immersed in the hydrogen bond*

Given the time-invariant and three-dimensional nature of the data, deciding how to sonify it was a challenge. One solution we came up with was to scan through the density field along a parametric curve. We used a Lissajous curve, since it exhibits a high degree of spatial symmetry and smoothness, minimizing sonic distortion. While this technique had no visual complement, it produced characteristic sounds and helped localize the bond, producing a more complete multimodal experience.

Hydrogen Atom

By Lance Putnam and Charlie Roberts (Media Arts and Technology)

Faculty Directors: Professor Luca Peliti (Kavli Institute of Theoretical Physics) and Professor JoAnn Kuchera-Morin (Media Arts and Technology)

We now move from a lattice of atoms down to the electron cloud of a single hydrogen atom. Much is known about the shapes of single hydrogen atom orbitals, and physicists have little trouble picturing them in their minds. However, when two or more time-varying orbitals are mixed together in superposition, the resulting electron cloud is complex and not readily apparent from the individual equations. Furthermore, mathematical equations and static images do not capture the dynamics of its complex temporal evolution.

Our aim with this work was to create a multimodal experience of a "hydrogen-like" atom through interactive visualization and sonification of its electron wavefunction. We modeled the atomic orbitals as solutions to the time-dependent Schrödinger equation with a spherically symmetric potential given by Coulomb's law of electrostatic force. In this model, the relationship between the nucleus and electron are akin to a bowl (the nucleus) filled with liquid (the electron), with the difference that the liquid can have many different resting shapes and extend outside of the bowl. For computation, the time-invariant structures of the single orbitals were precomputed and stored in a 3D lattice; then, during the simulation, they evolved individually and were mixed together spatially. We programmed several preset orbital superpositions to observe dynamic behaviors such as photon emission and absorption.

The first visualization technique we tried was to render the electron cloud as a 3D volume. This made it easy to see the global, outer shape of the wavefunction, but it was difficult to see its inner and more local structure. To address this, we superimposed collections of agents on the volume rendering that moved along different flows in the wavefunction. This way, we could simultaneously get a sense of the global and local structure of the cloud. We found that using colored lines provided a reasonable compromise between number of mapping dimensions, visual complexity, and computational efficiency (Figure 17-8). Colored line agents gave us three internal dimensions of color and four spatial dimensions of orientation and length that we could use for mapping purposes. We used hue to distinguish different types of flow and orientation to show direction. In addition, the brightness and length of the lines were varied to smoothly fade agents into and out of the scene.

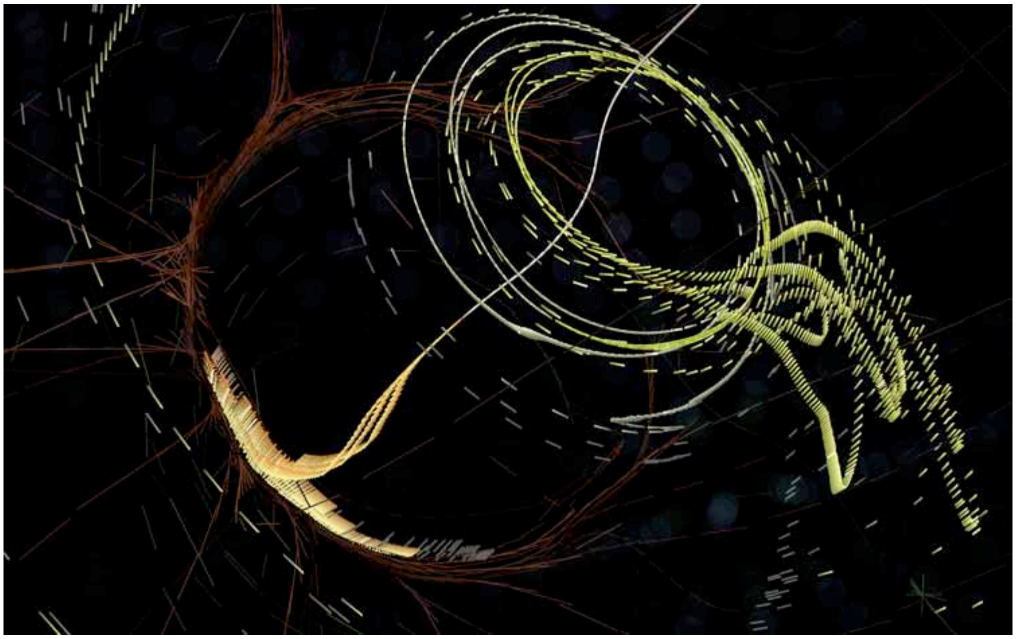

Figure 17-8. *Light emitting configuration of a hydrogen atom*

We also wanted to use sound as a way of notifying us of certain types of events—such as the emergence or dissipation of certain types of shapes—occurring within the cloud. To do this, we used a slight variation on a synthesis technique called *scanned synthesis*. We scanned along the agents like a read head on an audio tape loop and listened to the wavefunction amplitude at their locations. By changing the scan rate, we could change the pitch of the sound. Lower pitches worked best at revealing the local variations in shape, while higher pitches worked best at indicating global characteristics. We also found it effective to assign different pitch classes (pitches a whole number of octaves apart) to the different types of agents so that they could be sonically distinguished from one another. This scanning method was successful in alerting us when and where a cluster of agents formed at a singularity or attractor basin, but did not work so well at informing us about the particular shape formed. Our solution to representing the system more holistically was not to augment single modalities, but to take a multimodal approach, leaving overall shape to visuals and emergence of local structures over time to sound.

An unexpected outcome of doing this representation was seeing a drastic change in the complexity and richness of the wavefunction patterns going from single orbitals to mixtures (Figure 17-9). The composite patterns that emerged had no obvious relation to the parts and were not at all evident from the mathematical equations. We found that interference of waves, a simple and well-known physical mechanism, can serve as a powerful construct when thinking about the creation of complex patterns and emergent behavior.

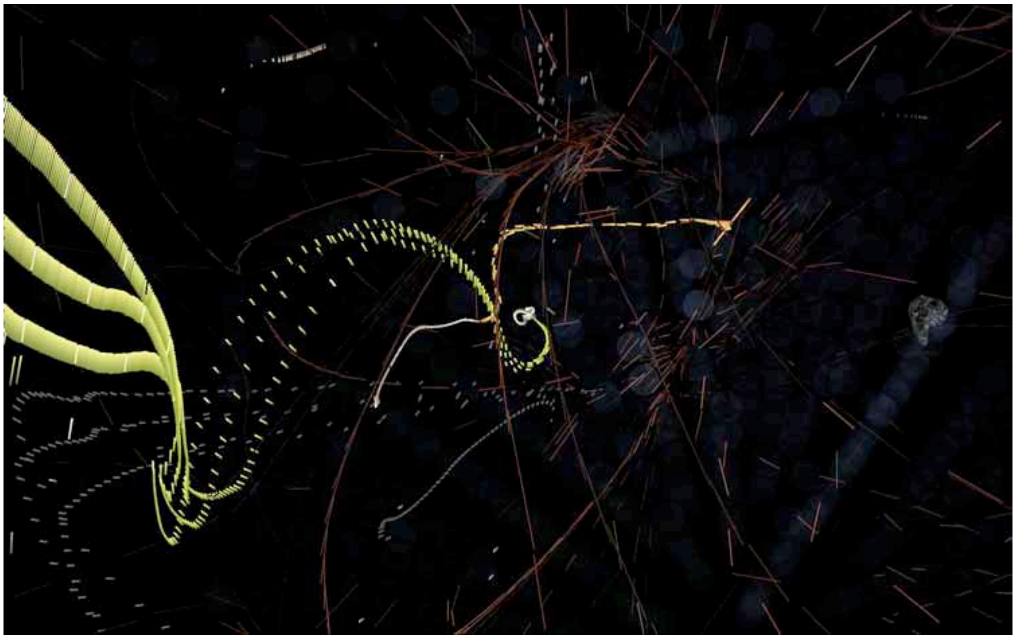

Figure 17-9. *Higher-order orbital mixture of a hydrogen atom*

Hydrogen Atom with Spin

By Lance Putnam (Media Arts and Technology)

Faculty Directors: Professor Luca Peliti (Kavli Institute of Theoretical Physics) and Professor JoAnn Kuchera-Morin (Media Arts and Technology)

With this project, we desired to expand on the previous hydrogen atom project by using a more complete physical model that included the spin quantum number. We also wanted to move away from the regular sampling in space of the wavefunction toward something with finer spatial resolution. We decided it would be best to not precompute and store the orbitals ahead of time, but instead to compute everything on the fly so that we could get the exact values of the wavefunction at all points in space. In this sense, the computational representation of the wavefunction changed from a lattice of values to a function of position. This new approach also gave us a new perspective on agents as a *general-purpose* visualization and sonification tool. The agents could not only show the derived flows of the wavefunction through their individual movements, but also represent something about its state, such as its oscillation phases. Furthermore, the agents could be programmed to act in an ensemble-like manner to create smoother and more connected shapes.

We started by positioning the line agents on a grid and then modifying their orientation and length based on the underlying wavefunction amplitude. While this gave us a good sense of global characteristics, we found the spatial artifacts (Moiré patterns) due to their regular positioning in space to be visually disturbing and misleading. To avoid these artifacts, we next tried to randomly position the agents within a cube. This succeeded in eliminating the artifacts, but uncovered two more serious and fundamental problems. First of all, we found it difficult to visually fuse all the individual agents into a coherent form from their individual line shapes. Second, we found that distributing the agents uniformly in 3D space does not lend itself to a natural method of sonification. While we could use separate spatial structures for visualization and sonification, we had found in previous projects—namely, the hydrogen bond project—that an underlying connectedness between aural and visual representation is important for comprehending the scene.

Our solution to these connectivity problems was to arrange the line agents into a loop and keep the agents connected to one another by putting springs between them. This gave us an elastic ribbon that would remain smooth and connected, but still have enough freedom to move through the space and show local properties of the measured field. The width of the loop was mapped to the probability density so that sharp spikes would indicate a high probability of finding the electron at that position (Figure 17-10). The loop also worked well for showing wavefunction states that were more distributed throughout space (Figure 17-11).

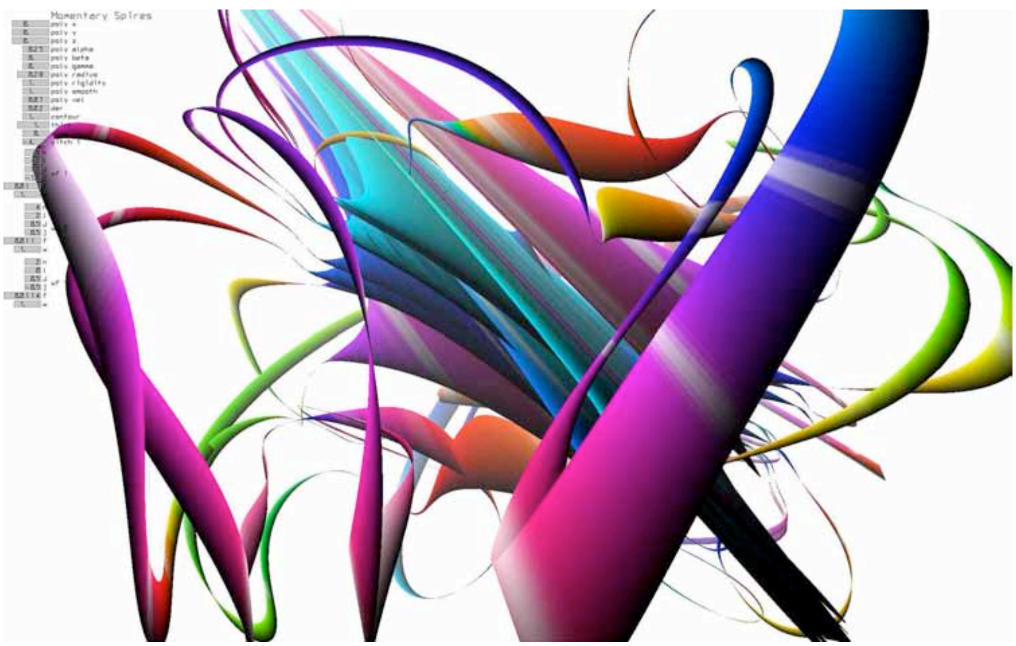

Figure 17-10. *Constructive interference between orbitals of a hydrogen atom with spin*

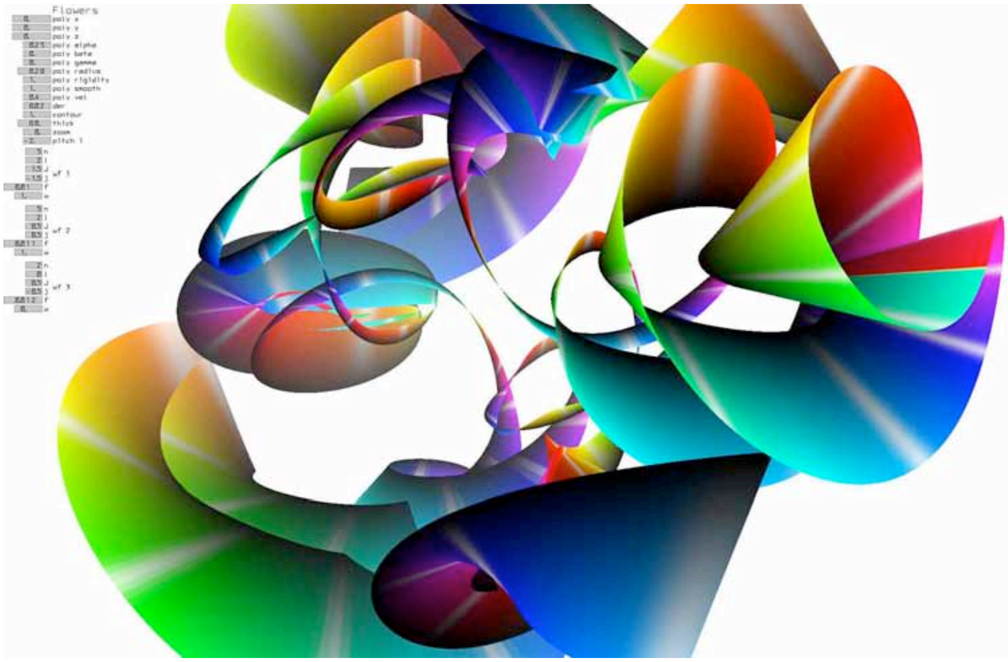

Figure 17-11. *Outer shell mixture of a hydrogen atom with spin*

The loop, being smooth, also permitted a desirable shape for scanning through the agents for sonification, as was done with the spinless atom. Visually, the loop provided a good compromise between transparency, coherency of shape, and depiction of global and local attributes.

Coherent Precession of Electron Spin

By Dennis Adderton and Lance Putnam (Media Arts and Technology), and Jesse Berezovsky (Center for Spintronics and Quantum Computing)

Faculty Directors: Professor JoAnn Kuchera-Morin (Media Arts and Technology) and Professor David Awschalom (Center for Spintronics and Quantum Computing)

The goal of this project was to represent the *coherent precession*, or change in rotation, of an electron spin within a quantum dot. Seeking out the most capable apparatus for measuring the result of quantum coherence in just such a nanoscale device, we visited the spintronics lab in the UCSB Physics department to learn about Kerr rotation microscopy. This is an optical experiment wherein a very fast laser pulse is focused onto a semiconductor quantum device. The polarization of the pulse induces coherent precession of a single electron spin in the quantum dot. A subsequent pulse measures the rotating polarization of the quantum dot to capture a picture of the precessing spin. From this measurement, it is possible to quantify a characteristic decay time for quantum coherence in the device. Decoherence of the quantum state marks the transition from the quantum to the classical world.

To represent the phenomena of the experiment through sonification, we slowed it down one million times. This allowed us to hear the tone of the electron and the buzz of the pulsing laser. To visualize the phenomena of spin precession, we plotted phase angle on the Bloch sphere, a standard graphical tool for physicists. At this point we relied on a simple equation from a published experiment (Berezovsky 2008) to give the three-dimensional dynamics (Figure 17-12).

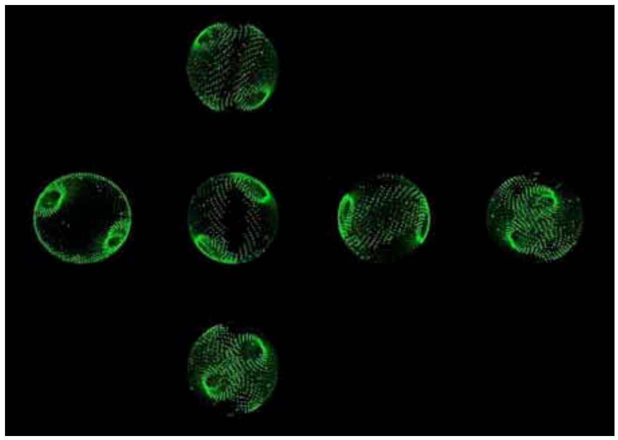

Figure 17-12. *Multiple perspectives on Bloch sphere showing spin precession*

This rudimentary test stimulated our senses but immediately revealed an overly simple aspect of the model that was not obvious from the outset. Although the precession made interesting spherical patterns visually, its temporal components were predominantly sinusoidal and quickly became boring to listen to. It became clear that a more complex system was required to immerse us in a quantum reality.

To engage our senses, we require a more complete quantum mechanical model of nature, rather than a simplified model of the experiment. Representing a theoretical model requires interpretation. Aural and visual analogies are made. As an artist, there is a need to construct an artifact so that something tangible can be discussed. The artwork becomes a philosophical apparatus in the discourse of truth—a truth connected directly to the mathematics that are being visualized and sonified.

These works serve as a basis for our philosophical premise that beautiful visualization is connected to the visualization and sonification of complex mathematical systems that make and break symmetry.

Conclusion

In the AlloSphere, visualization transforms into beautiful immersive multimodal representation, transformation and creation, resulting in the evolution of a unique field. This new field merges the different criteria and metrics of art and science—art as speculation, generation, and transformation, and science as model/theory building and validation. As we move forward with our research, a new, yet "classical" style of thought is unfolding that integrates science and art into a new environment: a place where new art and new technology emerge in mutual adaptation. As this emerging field and its computation-driven medium develop, the distinction among artists, scientists, and engineers begins to disappear and we realize that we are all engineers, scientists, and artists—we all design, analyze, and create.

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