Endogenous Biologically-Inspired Visualization Immersed within an Art of Complex Systems

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Figure 1: Selected installations in the Artificial Nature series. Left: *Time of Doubles* (curved screen, projectors, loudspeakers, RGBD cameras). Photographed at the *type:wall* exhibition, Seoul Olympic Museum of Art (SOMA), Korea (March 31–May 29 2011). Center: *Endless Current* (head-mounted display, loudspeakers, RGBD cameras). Photographed at the *Artience Project* exhibition, Korea Research Institute of Standards and Science (KRISS), Korea (Aug 26–Sep 4 2014). Right: *Archipelago* (kinetic sand, carved styrofoam, projectors, loudspeakers, RGBD cameras). Photographed at the *Capitaine Futur* exhibition, La Gaîté Lyrique, Paris, France (Oct 18 2014–Feb 8 2015).

Abstract

We document techniques and insights gained through the creation of interactive visualizations of biologically-inspired complex systems that have been exhibited as mixed-reality art installations since 2007. A binding theme is the importance of *endogenous* accounts: that all perceivable forms have dynamic ontological capacities within the world; that the simulated world is able to autonomously originate; that as a result interaction can lead to exploratory discovery; and that visitors become part of the ecosystem, both through immersive display and through interactions that induce presence. Details of how each of these components have been applied in the visualization, sonification, and interaction design are given with specific examples of prototypes and exhibited installations.

1 Introduction

Since 2007 we have been engaged in a research-creation project defined by the creation of a series of *"artificial natures"*: interactive visualizations of biologically-inspired complex systems that can evoke aesthetic experiences we know from nature, but within mixed-reality art installations [10]. By "mixed-reality" we refer to the spectrum of augmented virtual reality (VR) to augmented reality (AR), that is, blending elements from the real world into a virtual space and/or elements from a virtual world into real space [21]. Our visualizations are displayed at high-levels of sensory immersion, through the use of large-scale displays, wide fields of view, stereoscopic rendering, high frame-rates, and spatialized audio.

Each artificial nature presents a computational world with its own physics and biology, within which visitors interact to become essential participants within the system. As artists we are motivated to use the open-ended mechanisms and processes of life to evoke extended aesthetic experiences that recapitulate something akin to the child-like wonder regarding the complexity, beauty, and sublimity of nature. The resulting installations have been exhibited and presented at more than thirty international events and have received national and international awards.[1]

Developing these works has involved many of the techniques and challenges characteristic of interactive data visualization in general, however some of the specific implications of their goals have led us to unique solutions and principles of development. In comparison to the principles outlined in Tufte's landmark text [34], we find convergence in the emphasis of showing the data above all else; in maximizing the "data-ink ratio" (avoiding the use of "non-data-ink"); in revealing multiple levels of detail in large or complex data; and in inducing the viewer to think about the substance of the data and the relationships between its elements. However our working principles diverge by eschewing the integration of statistical or verbal descriptions of the data; nor do our works serve clear analytic purposes of data description, tabulation, or comparison. In this paper we show how these differences are derived from development principles specific to our problem domain, and detail how they are applied in the visualization, sonification, and interaction design of prototypes and exhibited installations. We hope that documenting our progress in this paper will positively inform data visualists and computational artists in the broader community engaging similar challenges.

1.1 Form and function

Tufte's first principle of "show the data", to induce the viewer to think about its substance [34], in our case becomes "show the system", to induce the viewer's attention toward its substantial qualities. And echoing Friedman, both aesthetic form and functionality must go hand in hand, providing insights by communicating key

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[1] The project is also documented at http://www.artificialnature.net

aspects of the world in a more intuitive way [7]. But here lies an important subtlety. Since the system realizes a model world, the principle must be followed more exclusively–to a principle of *endogenous visualization*. This requires that *every perceivable element must have dynamic ontological*[2] *capacity in the world, playing an active role in multiple world-level processes with other such elements*. If one views this as a restricted subset of Tufte's concept of "data-ink" (the non-erasable, data-dependent core of a graphic), the principle implies a corresponding requirement to maximize the the ratio of "endogenous-ink" to total ink.

In terms of visualization this poses some interesting challenges. It implies that "non-diegetic" media[3] should be avoided: no secondary or symbolic notations, none of the well-researched statistical graphical devices familiar to data artists, etc. Instead, all processes of the world must be conveyed through the sensory displays of components of the world itself. For example, although prototypes may feature textual annotations, such as property labels spatially attached to agents, we cannot include such non-diegetic elements in an exhibited work as they have no ontological capacities in its process. Whatever salience such annotations communicate to us must instead be conveyed through intrinsic perceivable features of the agents themselves. So, just as in nature we perceive the wind by how it moves the leaves, in our virtual world we perceive the fluid simulation by how it moves suspended particles. Just as the fallen leaf's color describes its state of decay, a virtual organisms texture imparts information about its internal changes over time.

In practice, as will be detailed below, this also means that the development of the visualization and the underlying system (or, in software-engineering terms, the *view* and the *model*), evolve hand-in-hand. There is no separation of concerns here: instead they become increasingly interdependent with neither side interchangeable.

1.2 Becoming part of the system

Data visualization and interactive art are both deeply concerned with machine-mediated experience. The meaning of a particular work depends essentially upon what we can experience through its responses, what we can do within it, and how this reflects critically upon ourselves and our environment [13]. In the case of artworks, what we can do may be purposefully left quite open-ended; unlike canonical data visualizations, participants are not executing specific analytic tasks, and the work is not designed to satisfy user-driven goals or convey specific ideas effectively; rather the meaning is typically multi-layered and often contextually-derived.

In our case, as artists we are deeply motivated to create computational environments that draw more from nature's sense of open-ended continuation, than rational senses of utilitarian closure. Our challenge is to design interaction such that the visitors may explore an open-ended space, drawing meaningful responses, while indirectly influencing its adaptive conditions, and thus partaking in each others living time as a fulfilled aesthetic experience [5].

We believe this is made possible by considering the visitors as fully-integrated components within the simulated world. In this regard we concur with interactive art pioneers Sommerer and Mignonneau, who stated a goal that "a visitor must become part of the system to realize that *there are no pre-defined solutions of what to do and what to see*, and that instead the artwork develops through his or her interaction...the longer one interacts the more *one becomes part of the system*" [32] (emphasis added).

In order that visitors feel that they are part of the system, we have focused upon methods of display and interaction that emphasize immersion, presence, and agency. We prioritize indirect modes of interaction that integrate with the complex network of feedback relations in the world, which tends to reduce simplification into a task-oriented or pre-defined roles. Moreover, to support exploratory discovery, we choose simulation strategies that can engender open-ended behaviors.

1.3 From immersion to presence, driven by agency

The success of our works depends in part on the extents visitors become absorbed within the generated world and find meaning in the actions they perform. We can address this through concepts of immersion, presence, and agency, which contribute to the intensity of the experience. Presence is generally understood in terms of a subjective sense of being there, or being engaged such that the artificiality of the situation becomes suppressed. Lombard and Ditton describe it as the continuous illusion of non-mediation, with humans behaving as if the mediation was not there [17]. Naturally, immersion is conducive to presence, but is not the sole factor. Presence appears to also depend on interactivity, and crucially on how successful actions are supported; experience in general is grounded more in functionality than appearance [30]. Moreover, presence has been found to correlate very strongly with agency, a subjective property defined as the satisfying power to take meaningful action and see their results [9], that is deeply rooted in bodily experience.

In that regard our interaction inputs have gradually shifted away from hand-held devices oriented to direct active control, toward ambient sensing with microphones, infra-red and RGBD range cameras capable of low latency natural "transparent UI", and a wider spectrum of embodied interaction. This also signals a shift from voluntary control to forms of interaction in which continuous nuances have more value than discrete commands. By eschewing pre-defined tasks it also lends weight to the world, which appears less in need of human action for its reason to exist, and in fact will continue its life without human presence. Moreover it is chosen to permit a much more open-ended range of possible interactions to be discovered, such that visitors can discover behaviors and reveal the emergent relationships between elements by interaction and observation, as a child learns by playing in nature.

1.4 Open-endedness

The richer the resolution, speed and flexibility of interaction, the more integrated its evolution can be, and the more humans and machines can cohere into new awareness. But for this to be possible, the simulated world itself must carry the capacity to continuously adapt and generate new patterns of behavior. To that end we turn to biologically-inspired complex systems, as found in the field of artificial life. In particular, almost all iterations of our work are models of ecosystems in which large numbers of mobile agents (evolving populations of organisms) interact with a dynamic environment.[4] Evolution in the ecosystemic approach features an endogenous selection criterion, such as maintaining sufficient energy levels to survive and reproduce, which differentiates it from evolutionary approaches 'steered' evolution by fitness functions that are either defined in advance or actively directed at run-time by a user.

The ecosystemic approach to evolutionary art is well-established. Antunes et al. provide a detailed review comprising forty artworks (including three artificial natures) using evolutionary

[2] In this paper we use the term "ontological" with its original philosophical meaning–regarding the nature of existence, being, reality, or ultimate substance–rather than the usage it has taken on in information science, which specifies categories and relationships of entities within a domain of discourse.

[3] This terminology is borrowed from film theory: diegetic images and sounds emerge from within the space of the story world, whereas the sources of non-diegetic media, such as the sounds of narrator commentary, appear to come from outside the story world [3].

[4] We note the similar set of concerns and methods (sustaining interest with endlessly fascinating interaction by means of passive interaction and an agent-based complex adaptive system within a liminal space), but applied on a level of social rather than ecosystemic dynamics, in a recent art installation [19].

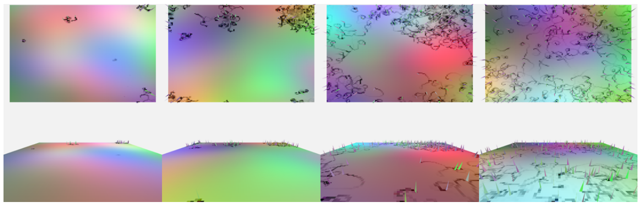


Figure 2: Early 2D prototype visualizing agent-environment interaction (2007).

computational ecosystems produced since the mid-1990s [1]. An important observation made is that, perhaps surprisingly, very few of these biologically-inspired works attempt realistic representation of life as we know it; instead, abstraction and/or alien surfaces and volumes are dominant. Similarly, the majority of works eschew pre-recorded naturalistic sounds in favor of algorithmically synthesized audio. To an extent this echoes the "life-as-it-could-be" motto of artificial life research [15], apparently liberating artists from realism. Nevertheless, as Whitelaw previously noted ([39]), artificial life art remains representational, and still owes a debt to "organicism" in the arts. Though is not a mirror to the *appearance* of nature, it nevertheless represents the way life *operates*: "an aesthetic that is largely focused around *visualizations of processes of life*." [5]

2 Visualizing dynamic environments

The strength of a particular ecosystemic model derives significantly from the richness of the environment that supports it [20]. The environments used in artificial natures are dynamic, incorporating physically-inspired processes that conserve matter-energy, save for some entropic loss, in every transaction. Moreover the environments are dissipative, subject to the kinds of energetic gradients that keep them away from equilibrium, and the varying rates of diffusion that can lead to naturally-occurring self-organized structures [23].

2.1 2D and 2.5D

In our earliest two-dimensional prototypes, the environment is modeled as a discrete field of cells spanning the space through which organism-agents may move. Each cell stores a concentration of each of three pseudo-chemical substances, simply visualized beneath agents as red, green and blue intensities (see Figure 2).

Each agent continuously extracts from this environmental field the quantities of each chemical it requires; in effect leaving a darkened trail behind as it travels. With sufficient nutrition and appropriate age agents may reproduce, but in regions of scarcity they perish. In addition to motile behavior, the agents' genetic structure also specifies the relative mixture of chemicals it requires to subsist, which we visualize in the color of the agent. Reproduction incorporates a degree of genetic mutation by which organisms can adapt to the environment, often resulting in clusters of similarly-colored agents occupying specific regions of the world. The environment itself is a continuous process incorporating an energetic gradient–each cell gradually accumulates a location-specific nutrient chemicals (akin to photosynthesis)–as well as a process of diffusion gradually smoothing out the chemical landscape. Population cycles and explosions, evolved searching behaviors, nomadic migrations, genetic distributions, and the dynamics of the environment itself are all readily visible through this direct visualization.

We extended this model to attach to each cell a rate of nutrient recovery. Following our principle of deriving form from function, we extruded the visualization into 3D by displaying this rate as *height*.

[5] In fact, as Shanken noted, it would be more accurate to describe them as visualizations of *current theories of* the processes of life [31].

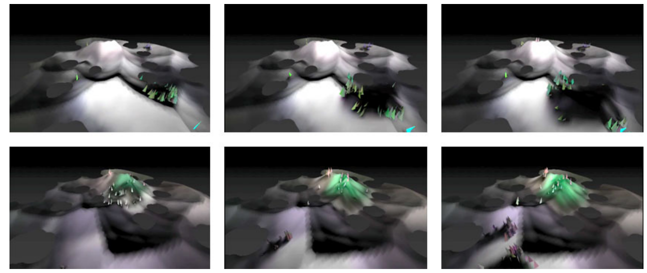


Figure 3: Visualizing fertility of the environment as altitude, and mapping its gradient to tendencies of diffusion, led to more complex population dynamics.

In effect, this created an easily understandable "2.5D" topography in which the higher altitudes are the most fertile. Then, in a reverse step of creating function from form, we used the gradient of the landscape to skew the rate and direction of environmental diffusion. These simple modifications led to immediate increases in behavioral complexity. Rival populations compete for dominance of the rich mountain peaks, but once there the increased availability of resources leads to decimation by overpopulation, allowing more nutrients to drain through valleys to the more sparsely populated lowlands, inviting other groups toward the peaks again (see Figure 3).

This topographical approach to the environment was reprised several years later in *Archipelago* (see Figure 1, right). In this work the visualization is projected from above onto a physical landscape constructed of sand, whose topographic height map is derived through the use of ceiling-mounted RGBD cameras. The simulated environment comprises a larger number of fields, including chemical traces left by a variety of different species of organisms (see Figure 4).

2.2 Immersive 3D

A number of our works have emphasized the immersive qualities of 3D virtual world, with a navigable viewpoint embedded inside the system (*Infinite Game*, *Fluid Space* and *Endless Current*). In moving to a fully three-dimensional, first-person environment we faced the challenges of how to both simulate and visualize an dissipative environment that occupies all surrounding space.

The most obvious 3D equivalent of our 2D prototypes would be cloud-like volume rendering. However in this approach local densities filter or occlude more distant features, and in lacking discernible edges, depth and motion are more difficult to accurately perceive (see Figure 5). Data visualizations often refine volume rendering by extracting isosurfaces from level sets or using coloring algorithms to categorize areas, but these refinements would subvert our principle that all visible elements have ontological reality in the world. An isosurface is an abstraction of the underlying data that filters out all but an arbitrarily *chosen* isolevel, whereas the organisms in the world perceive the full continuum of levels.

We also experimented with lattice-like structures such as grids, trees and networks, to provided sharper features for depth cues while being more visually porous, at the cost of requiring an ontological role within the world. Some artificial natures have retained these components as weed-like organisms drifting in space, through which nutrients can be transported (see the purple vines in Figure 8).

Our most widely-used method of visualizing the dynamics of the 3D environment has been through particles. Particle movement can display the rich complexities of fluid flow and turbulence, particle color can display variations in pseudo-chemical constitution, particle quantity conveys concentration without unduly obscuring dis-

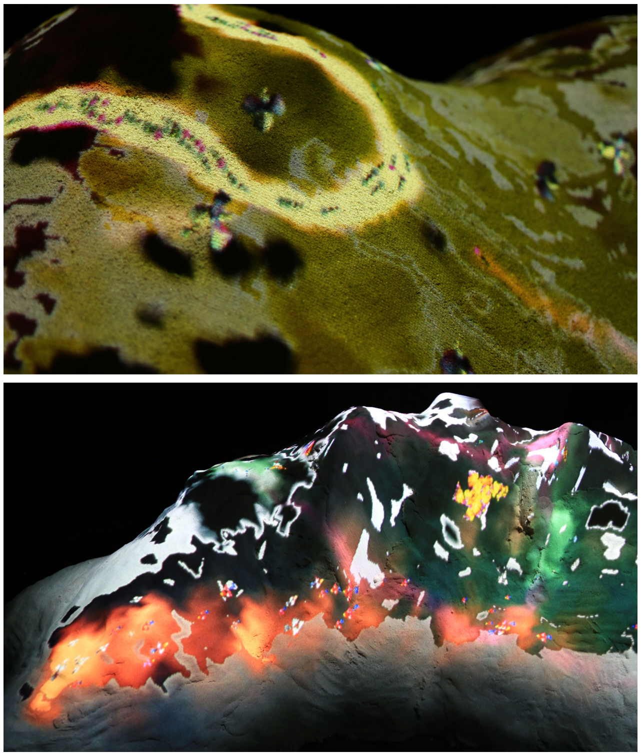


Figure 4: Close-up details of *Archipelago*. Top: A trail of ant-like creatures (pink and green) is following and replenishing a stigmergetic path of pheromones (yellow). In the lower-right area of this image a lone forager is depositing a new pheromone trail. Bottom: A flocking group organisms (red bodies, blue tails) in the lower altitudes have over-consumed the white mould-like species covering many parts of the landscape and are now dying out, leaving pale carcasses surrounded by a diffusing field of decay (red), which may attract the scavengers visible in the higher altitudes.

Figure 5: Prototype visualizing the dynamic environment in 3D via raycast volume-rendering. Note that even with accurate depth occlusion with other objects, cloud depth remains difficult to apprehend.

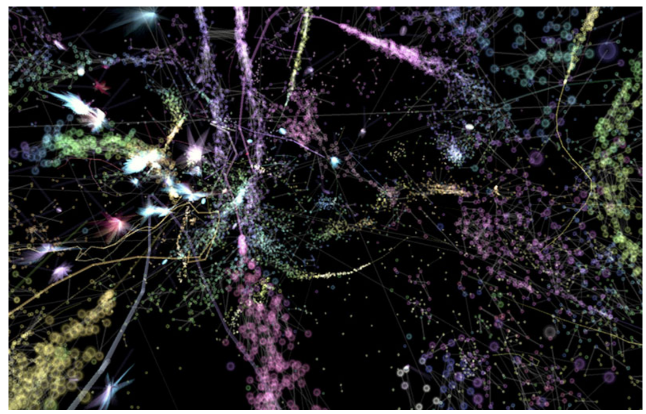


Figure 6: Visualizing the dynamic environment via particles (Infinite Game, 2008).

tant regions, and particle size serves as a cue for distance (see Figure 6). As a result particles reveal properties of the world at several levels of detail, from broad overview to fine structure. Moreover assigning an ontological role to the particles, as carriers of chemical nutrients, is trivial.

3 Visualization with Agents

Multi-agent systems are well-established model for simulating complex systems. Although they are perhaps less familiar as a tool of visualization, they have been a recurrent visual and sonic feature of works in the AlloSphere immersive instrument [36]. The model is closely-related to particle-based visualization: like particles, agents are mobile entities that visualize and respond to local features. However where particles generally follow physically-inspired, simple, global rules, the rules agents follow are often more biologically-inspired, showing autonomous, stateful, individual, and even intelligent behaviors. Populations of agents can support higher-level macro-behaviors such as flocking [27].

Some software visualization toolkits, such as *Behaviorism*, include support for attaching behaviours to visual and data elements (and to other behaviours), effectively supporting the construction of agent-based visualizations [6]. With toolkits such as Repast [24] and MASON [18] the assumption is that agents are an integral part of the simulation model being visualized. In some cases however agents are being used as a supplementary method for visualization, such as computer-assisted distribution of data exploration roles [33], or the intelligent and autonomous distribution of textual annotations [8]. These examples demonstrate the use of software agents to augment human capabilities by focusing users' attention to relevant information elements [29].

In our work, each agent is an evolved artificial organism traversing the dynamic environment, seeking nutrition to survive and reproduce. Following our principle of endogenous visualization, we attempt to show key aspects of the underlying processes of the organisms and their relations to other elements of the world. For example, in our work *Fluid Space* it is possible to watch organisms gradually mature from spherical-like eggs into fully-developed creatures with undulating petal-like appendages, and up close it is also possible to observe inside them the food particles that they have eaten, also gradually changing in color as they are metabolized, until they are ultimately ejected back into the environment.

Evolution acts upon not just *phenotypic* properties but also behaviors of the agent, through the development of a unique program according to a *genotypic* process of inheritance and mutation. For example, in *Time of Doubles* the agent's phenotype program is the evolutionary product of an intermediate metaprogram derived from the individual's genome tree, in a variation of genetic programming [11]. This program will be invoked repeatedly through the organism lifespan (see the much-simplified example in Figure 7), using a subsumption architecture [4] to blend decision-making with metabolic viability constraints. It takes a number of inputs (external and internal sensors), applies a series of expressions, and according to applicative predicate conditionals may produce a number of side-effects including motor actions, growth, reproduction, and memory storage, along with their energetic cost. To side-step the halting problem, backward control-flow is not permitted; looping behavior must be implemented in terms of memory stores and reads distributed over successive invocations of the program (more details in [35]).

The longer-term organism-environment relationship is one of knowledge gathering: species must adapt to extract inferences from the complex data set in which they are immersed–a fluid simulation in which nutrient-particles are suspended. The evolutionary model has no fitness measure, but the viability requirement that organisms must locate and consume food in order to reproduce imparts an endogenous selection pressure that can only drive the gene pool toward developing agent-programs that result in superior search strategies. In this regard, the agents form a distributed, adaptive search algorithm within a data-set of nutrient distribution, and each individual organism is an *improvised* proposal for its solution. But again, this is a search without end, circular rather than linear, as the environmental data-set is itself modified (depleted) by the agents' activities.

We note here that Ware defined information visualization as the interface connecting the human perceptual system–understood as a flexible pattern finder coupled with an adaptive decision-making mechanism–with the calculating power and information resources of a computer [38]. Of course the domains of artificial intelligence and artificial life explore purely computational mechanisms of pattern-finding and decision-making. Our own integration of visualization with evolving autonomous agents is suggestive of the potential of a hybrid spatial interaction merging both human and digital forms.

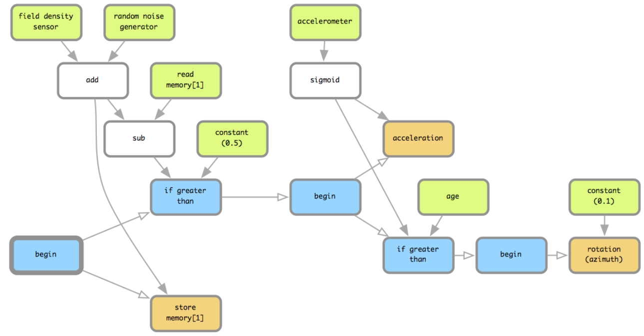
4 Implementation Efficiency

The combination of high-resolution, high frame-rate display, and low-latency, high-bandwidth sensing puts tremendous pressure on the efficient implementation of our works. We generally use standard languages and software techniques to maximize the capabilities of hardware, however there is one aspect particular to our work that warrants further explanation.

The simplicity and homogeneity of particle-based visualizations lend themselves to optimized implementations that can support vast numbers of particles. Agent-based models as described above however are much more challenging, due to the increased complexity of and diverse heterogeneity between phenotype programs. There have been examples of using GPGPU programming to address the issue of program complexity [28], but this is less able to resolve the issue of heterogeneity: the ahead-of-time, massively parallel optimizations that GPGPU computing can provide are generally incompatible with the characteristic tendencies of open-ended phenomena away from invariances (the breaking of symmetry).

We therefore utilize dynamic code generation and just-in-time (JIT) compilation to avoid unnecessary compromises, and have been able to support thousands of unique yet concurrent agents at immersive simulation rates. Agent programs are dynamically compiled to efficient machine code at birth, using the LLVM compiler infrastructure [16]. In this way we can leverage the open-ended space of genetic programming with far greater efficiency, creating new machine code components at high frequency and in parallel.

For *Time of Doubles* were able to maintain a frame-rate consistently above 50Hz with a population of 2000 concurrent unique organisms of 40 or more intermediate operations each, replacing on average 30 individuals per second (measured on a 2GHz Intel Core i7 processor with 2GB RAM). Genetic processing and dynamic compilation occur in background threads to avoid rendering stalls during population explosions, and careful garbage collection permitted continuous uptime over several months. We hope to extend this open-endedness to include the processes of genetic mutation and development within the phenotype program, and broader aspects of the system in future installations.




```
extern "C" void update(Organisms& self, Environment& env ) {
    /* used sensors */
    const float density = env.field_density;
    const float noise0 = noise();
    const float memory1 = self.memory[1];
    const float accelerometer = self.accelerometer;
    const float age = self.age;

    /* operators */
    const float add1 = density + noise0;
    const float sub2 = add1 - memory1;
    const float sigmoid3 = sigmoid(accelerometer);

    /* applicative predicates */
    if (sub2 > 0.5) {
        self.acceleration = sigmoid3;
        self.energy -= sigmoid3 * ACCELERATION_COST;
        if (sigmoid3 > age) {
            self.rotation_azimuth = 0.1;
            self.energy -= 0.1 * ROTATION_COST;
        }
    }
    self.memory[1] = add1;
}
```

Figure 7: Above: A simplified example of a phenotype program (simplified for legibility; actual graphs approximately 10x larger). Outline arrows show control-flow, solid arrows show data-flow. Blue nodes are control-flow blocks, white nodes are data operations, green nodes are terminal sensor, memory, or constant inputs, orange nodes are side-effect operations. Note that the resulting phenotype program structure is a graph, not a tree. Below: The same program translated to equivalent C code, for explanatory purposes (in the running artwork, the genomes generate LLVM bitcode directly, for more efficient translation to native machine code).

We note that although bytecode generation is well explored in artificial life [25, 26], run-time machine code generation has rarely been explored for interactive generative art. We have elsewhere indicated the potential for exploratory data visualization within the constraints of immersive performance [36].

5 Sonification

Augmenting visual display with sound allows events to be apprehended even if the corresponding visual objects are occluded, and affords an unlimited "field of regard". Furthermore humans can detect much finer temporal structures over a wider range of frequencies in sound, and more readily perceive and process audio in parallel [12]. Accordingly, all artificial natures have utilized algorithmic approaches to sound generation at microsonic time scales to fluidly reflect subtle changes in the ongoing simulation.

For example, in *Fluid Space*, sound is used to reveal lateral gene transfer. When an agent detects another close by, it may emit its genetic information through a characteristic song, synchronized with a visual flash to precisely identify the source agent. The sonic design is also algorithmic, a frequency- and amplitude-modulated grain parameterized by the genetic data. Nearby agents may absorb this genetic information, with errors (mutations).[6]

The agents in *Time of Doubles* are sonified using a granular process inspired by cricket chirps, where each sound event consists of a brief train of narrow-band pulses followed by a longer resting interval. These chirps are spatialized with direction and distance cues according to the agent location. The agent's genome is used to parameterize the various properties of the pulses, including pulse frequency, burst rate, burst length, envelope shape, etc. We note here the promising strategy of biological inspiration for data sonification. Since many organisms have evolved sounds specifically adapted to be easily localized and identified, even in a noisy environment. In our case, the cricket-inspired chirps are readily localizable due to the bursty envelope, while the narrow frequency range used allows many individual voices to be concurrently identified. Moreover, as populations grow and collapse the soundscape develops from isolated pulses to dense clouds of sound, whose timbres vary with the evolving gene pool. Evolutionary events (such as the discovery of a better search program) cause rapid and readily perceivable changes to the timbre of the clouds. As with visual particles, this approach to sonification reveals properties of the world at multiple levels of detail.

Sound enhances the sense of presence, most dramatically when the sound is properly spatialized as surround audio. As a metaphor for information display [22] agents are well-suited to spatialized sonification.[7] Arbitrary sound sources can be attached to agent locations and trajectories, using directional cues of amplitude and phase differences over multiple loudspeakers or head-related transfer functions (HRTFs) with headphones, and further modulated with physically-based cues according to distance and velocity including amplitude attenuation, high-frequency absorption, Doppler shift, and reverberation mix. We have utilized all of these techniques for our exhibits of *Fluid Space* and *Time of Doubles* in the AlloSphere immersive instrument [14], and for *Endless Current* on the Oculus Rift head-mounted display (see Figure 1, center); and have adapted them to the degree possible for multi-channel gallery exhibits.

6 Installation and interaction design

Each artificial nature installation invites participants to become part of the ecosystem through a responsive environment utilizing immersive or mixed-reality audiovisual display. Our first installations utilized a typical immersive format, projecting on walls or large screens within darkened rooms. Navigation devices allow visitors to explore the worlds with six degrees of freedom. This direction naturally has found its best expression in deeply immersive facilities such as the AlloSphere (see Figure 8).

However we found that the first-person egocentric perspective has a tendency to create a distanced objectivity due to disembodiment, weakening presence. To bring the body back into the world we began exploring mixed realities of augmented virtuality (bringing the body into the virtual world) and augmented reality (projecting the world back into a body-centric spatiality).

In *Time of Doubles* we removed navigation and began projecting onto curved, architectural/sculptural objects mounted in the middle of gallery spaces (see Figure 1, left), creating a mixed reality emphasizing continuity between the real and virtual spaces. The mixture of real and virtual is augmented by the projection of visitors' "double" into the ecosystem (see Figure 9). These doubles are not avatars, but mirror existences that closely reconstruct the shape and movements of participants as volumes of high-density, high-energy particles, by means of an array of RGBD cameras. The presentation of a recognizably human double induces an immediate psychological link with the otherwise alien virtual world. (This design is addressed in terms of presence and agency in [37]). However the doubles in the virtual world have quite distinct behaviors, which extend visitors into alternate roles within the network of relations as energetic sources and kinetic disturbance. Participants thus see, hear, and feel how they are fed to unknown species, bringing forth a meaningful tension.

[6] Although we describe this as lateral gene transfer, we could equally recast it as social knowledge sharing. The net result is the same: behavioral changes can propagate through populations faster than population regeneration.

[7] Not surprisingly, they have also been utilized in interactive art, see for example [2].

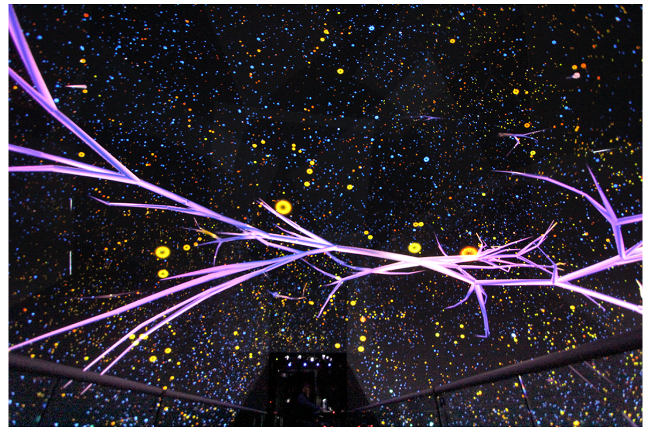


Figure 8: Wide-angle photograph of *Fluid Space* taken from the bridge of the AlloSphere, University of California Santa Barbara, 2012. This version of the *Fluid Space* application is distributed over 16 computers and 26 projectors covering an almost completely spherical screen, and 54 loudspeakers mounted behind it.

In *Archipelago* the format becomes more sculptural: we project from above onto an archipelago landscape constructed of sand. From above, an array of RGBD cameras is used to determine the topography of the landscape, shaping the adaptive conditions of the species below. The choice of an archipelago reflects the necessity of niche conditions to support divergent evolution, and also echoes the environment in which Darwin's theory of evolution was inspired. The sensors also track visitors in the space in order to mirror their actual shadows over the landscape with virtual counterparts in the simulation. Shadows are re-projected in black, ensuring that visitors are never themselves illuminated by the patterns of the land. All life in regions of the world under shadow is destroyed, yet the land is simultaneously refertilized. The interaction becomes more subtle and sensitive when visitors reach down to touch the land. The landscape itself is malleable, using a special kind of "kinetic" sand that does not dry, allowing visitors to reshape the topography or even to destroy and create new islands. Moreover, participants may also watch organisms creep onto their hands, from where they can be carefully carried to other islands, as tracked by optical flow (see Figure 10).

Human presence and activity has primarily indirect influences on the evolving life, which is predominantly realized by diffuse effects on the shared environment: as a source of turbulence (in *Fluid Space*); as a source of high-energy particles (in *Time of Doubles*); or the removal primary foodstuffs and gradual reshaping of topography (in *Archipelago*). In each case, consequences of actions are easy to perceive, but ultimately difficult to predict; thus encouraging exploratory behavior.

Figure 9: Participants and their virtual "doubles"–emanations of yellow nutrient particles fed upon by the organisms in *Time of Doubles (Flux)*. Photographed at the Microwave International New Media Festival, City Hall, Hong Kong (Nov 3 to Nov 25, 2012).

Figure 10: Transporting virtual organisms by hand from one island to another in *Archipelago*. Note also the shadow underneath the hands, which is replicated by the projection of black: cast shadows annihilate the white mould-like species below, but also refertilize the land.

7 Conclusion and Future Directions

The apparently oxymoronic terminology "artificial nature" reflects a conjunction of anthropocentric (subjective, authored) and cosmocentric (objective, universal) values. As a cultural artifact (an artwork) it reveals "nature as it could be", through endogenous processes at the level of her operation. Accordingly, our speculative visualizations of possible natures need not be true to any original data set (or simulation). Thus in contrast to the clear directionality in the development of most data visualizations, from the data itself to the communication of its most significant aspects, in our case both model and view evolve in tandem as the work is developed (and to a lesser extent continue to evolve as they run).

In keeping with the theme of endogeny, an important strategy for future work is to replace statically aggregated systems with genealogical processes that may generate them: that is, fully-working accounts as to how every structure and function emerges from simpler initial elements. We hope that, in this regard, our exploration of code generation and rewriting systems opens a path to a broader diversity of worlds. But we must also acknowledge that we are attempting to engender nature-like complexity on vastly smaller scales of space, time and complexity. For example, the number of operations in our agents' programs are less than 1% of the neurons of a *C. Elegans* nematode worm.

Despite the whole-world mechanics, each artificial nature remains a work that is oriented to human experience. Nevertheless, for us, deep interaction implies the growth of both the world and the participants. This means the possibility of providing continual variation and new potentials for new patterns of behavior in both visitors and world. To liberate this experience, an artificial nature must grant freedom to participants as to what they see, observe, feel, and do. For example, both a three-year old child and an an eighty-year-old scientist can enjoy playing with waves, a swell, a wash, and a breaker at the same time, yet each learns and plays with quite different values. The medium with which participants interact, and in which they are immersed, must share with nature its multi-dimensionality, multi-modality and dynamic complexity.

In our work, all four of the components of endogenous visualization–form and function, human as part of the system, design for agency, and open-ended generativity–are chosen to intensify primary aesthetic and exploratory experience. Reflecting upon a cultural context that is increasingly immersed in computation, we hope the continued development of artificial natures will grant more transformative experiences, and stimulate more creation and open-ended thinking in terms of nature and artifice.

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