Swarm Aesthetics

A Critical Appraisal of Swarming Structures in Art Practice

Daniel Jones

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Student ID:

M00105600

Tutor:

Nye Parry

Contents

Chapter 1

Introduction

Precisely two decades prior to the time of writing, in September 1987, the inaugural conference on Artificial Life was taking place, marking the inception of a field of study which had finally coalesced sufficiently to be named. Just a few months earlier saw the publication of a milestone paper by Craig Reynolds [30], describing a method of graphically simulating the collective behaviour of a flock of birds from a stunningly frugal set of rules. In the time elapsed since, it has become clear that the qualities exemplified by this swarming system are fundamental to our conception of artificial life: simple, local interactions giving rise to complex, co-ordinated and lifelike global behaviours, which cannot be understood simply as a compound of their parts.

Indeed, the swarming behaviour as formulated by the Boid algorithm remains amongst the most elegant formulations of these core properties, and a well-suited lens through which to explore their aesthetic and scientific significance.

This paper is a critical appraisal of the aesthetic values of swarm-theoretical practices, with specific reference to the domain of sound art and composition. We approach this by attempting to contextualise this work along a number of axes – as a generative, emergent and self-organising ecosystem – and present a skeletal history of artworks exhibiting swarm-like structures, drawing on each of the cross-disciplinary fields that constitute the basis for the study of a-life. In the final chapter, we describe AtomSwarm, a platform developed by the author for sound-based composition using swarms, and attempt to position it along each of these axes, with the intention of developing a basis for critical reflection in a still-emergent field of work.

Chapter 2

Characteristics of a Swarm

The types of swarm that we shall take as paradigmatic are those found in the world of social animals: bees, ants, fish, birds. For the sake of generalisation, we shall examine only the attributes common to all of these species, and omit those qualities only exhibited in unusual cases[1].

The Boid model described by Craig Reynolds [30] demonstrates all of the properties with which we are here concerned, and does so by recourse to an exceptionally spartan ruleset. Each agent, located in (say) 3-dimensional space, follows just three instructions:

cohesion – remain close to nearby agents

separation – avoid collisions with nearby agents

alignment – match velocity with nearby agents

Remarkably, this is sufficient to create a rich and compelling representation of a natural swarm, resembling the unified movements of a flock of birds or school of fish. Granted, it will not exhibit the goal-finding or complex adaptive capabilities present within the heterogenous, hierarchical societies of a functioning bee colony, but it is an elegant exemplar of all of the key qualities that we perceive a swarm to possess.

It is first useful to assert precisely what these qualities are, and what constitutes the concept of a 'swarm'[2]. We shall proceed on the basis that a swarm is a *distributed collection of similar agents, situated in a Euclidean space, each of whose behaviour is determined by its local neighbourhood*. Though this definition broadly applies to thermodynamically self-organising systems, we shall take 'agency' to imply a degree of intentionality, whether modelled or otherwise. The implication here is that we are concerned with networks comprised of living organisms; the recurring paradigms we are to deal with are from the domain of biology rather than physics.

The crucial elements of this definition, however, are the fact that it is *distributed* – inherently comprised of a multiplicity, hence operating in parallel – and operating purely through *local* interactions. As in a flock of birds, there is no source of top-down control, and the seemingly

[1] Including the structure-building capabilities of termites and ants, for which see [12], and the useful act of 'stigmergy', or indirect communication via environmental modification [5]

[2] Or 'flock', 'herd', 'shoal', etc; we adopt the term 'swarm' as it is arguably most species- and behaviour-agnostic, and the most commonly cited of the terms in cultural practice.

co-ordinated global behaviour arises without any form of global communication. We shall return to both of these properties later.

Over the course of this paper, we intend to extend the depth of discussion by identifying the qualities that imbue swarm-like structures with their aesthetic richness. We address each of these qualities in depth, examining their historical and conceptual context, and critically explore how they are drawn upon by existing artworks.

We first position swarms within the broad heritage of biologically mimetic artworks, and address their status as living or *lifelike* entities. We then examine the usage of swarm structures as *generative* systems, subsequently narrowing the field of focus to explore the *self-organising and emergent* dynamics expressed when such systems are transferred from a serial (singular) to a parallel (multiple) domain. Finally, we address the implications of a swarm's *spatiotemporality*, and conduct a brief cross-section of how swarm space is expressed in current artistic practices.

2.1 The Lifelikeness of Artificial Forms

Invoking natural forms for artistic ends is a practice that dates back to humankind's earliest modes of of artisanship. The ancient Greek *daidala*, as a prominent example, were intricate artefacts modelled on the animal or geological kingdom. Numerous references can be found in the literature, including the Trojan Horse, the wood and leather cow built for Pasiphae, and the ill-fated wings crafted by Daedalus and Icarus to escape imprisonment; indeed, the word's etymological root is linked to that of *Daedalus*[3].

Alberto Pérez-Gómez observes that this mimetic act was thought to bestow "mysterious powers" upon the object:

> "The principal value of 'daidala' is that of enabling inaminate matter to become magically alive, of 'reproducing' life rather than 'representing' it". [26].

The same "fundamental act of mimesis" [14] similarly characterises the methodologies adopted by a-life art: practitioners take models of natural forms as their palette, and attempt to invoke through them an alchemical transformation, to create works to which we could attribute the nebulous quality of 'life'. Through these activities, the boundary point between alive/unalive has become increasingly blurred, and it no longer seems as clean-cut as the distinction between carbon-chain and silicon.

Christopher Langton identifies 'life' as an essentially formal construct, the product of a complex set of relations between simple components [20]. In the wake of a generally accepted rejection of vitalism, the theory that there is some hidden essence within animate matter that imbues it with a life-force, the normative scientific stance is that living creatures are "nothing more than complex biochemical machines" [20, p5]. This complexity is manifest in a massive parallelism, enabling the adaptive, self-organising behaviours recurrent within biological systems.

But how complex does such a machine have to be to be alive? Additionally, if we were to recreate the formal structure of a natural organism within a digital simulation, would this therefore be an instance of 'life'? Langton suggests that even a minimally complex symbolic system, demonstrating a suitable functional architecture and displaying emergent properties, could be

[3] from 'Daidalos', "the cunning worker'; Daidallein, "to work artfully".

justifiably qualified as alive. Whether or not this is the case is a philosophical issue, and one that we shall not address here.

In the context of artistic production, we are more concerned with *lifelikeness*, and works which exhibit the "vital presence" that Berry and Dahlstedt [1] cite as motivating their work with artificial life. If we are able to evoke the broad "confluence of signs" that suggests an animate form, then we can proceed to explore the requirements and properties of such forms. Perhaps subsequently, it will become possible to synthesise new, potentially alien forms that remain within our expanded conception of 'life'.

2.2 Swarms as Generative Systems

In contemporary terminology, a generative artwork broadly includes some system, independent of the artist, that is used to create multiple different results. The artist typically constructs this system out of rules or procedures through which the finished work can be created (assuming that such a final point exists), and then commences their execution. These procedures may alter during execution; they may be executed by the artist herself, or by a third party, or by a mechanistic system; they may be comprised of very precise instructions, open choices, or broad, ambiguous suggestions. All that is essential is that some such system is present as an intentional component of the work.

This practice dates back to Mozart's dice games[4] [15, 17], via the chance compositions of Cage [7], Stockhausen and Riley, through early computer artists using fractals, chaos and cellular automata [25, 12], to the intricate ecosystems of contemporary a-life art. Indeed, the use of autonomous systems to complete an open work is found across the gamut of artistic agendas: conceptual, visual, sonic, and beyond. Given the inherent a priori order imposed by geometric forms, Philip Galanter [13] goes so far as to identify primitive tile-etchings as 'generative', on the basis that the artist has no moment-to-moment input as to how to place the following piece; the construction is determined wholly by the structural properties of the chosen tiling system.

The degree to which the artist imposes control over the resultant output varies enormously between these works, as does the complexity of the ruleset and variables affecting the execution of the instructions. In the recent decades, the exponential increase in available computing power has been mirrored by the growth in complexity of these structures; Craig Reynolds' graphical swarming simulations [30], for example, would have previously required manual calculations for every agent in every frame. For a complex, interconnected system such as this, in which every agent's movement is affected by that of every other, this is an impossible task.

For a modern computer, of course, Reynolds' algorithm is trivial to execute in real-time, and – in testament to its elegance and abstract generality – it has worked frequently as a building block in constructing ever-more sophisticated generative pieces. Daniel Shiffman's 'Swarm' (2002, [33]), shown at SIGGRAPH 2004's Emerging Technologies exhibition, acknowledges the organic paths created by the agents' individual movements by treating them as painterly strokes, automatically sketching segments of a live video input onto the visual display. The basic ruleset is left

[4] Many such *Musikalisches Würfelspiel* were published during the 18th century; whether Mozart did author those attributed to him is the subject of some dispute [15]. Samuel Pepys is known to have constructed a less well-known combinatorical method of composition over one hundred years earlier [18, p37].

unchanged, and so the paths followed by each agent are entirely determined on their relational position to those around them. Shiffman has effectively constructed a drawing machine which blindly takes input from its video input and displays it in a manner governed by iterative number-crunching. Yet, a viewer would never deny that it truly does look 'painterly'.

In mathematical modelling, deterministic multi-agent environments of this class are named *Markov systems* [21]. Every aspect of the system's configuration at time $t + 1$ can be calculated from inspecting its state at time t; it is time-independent, unaffected by its prior events (except insofar as they sequentially led to this particular state at t). The only random variable is the initial position of each of the agents. This means that, given the same starting position, precisely the same organic, 'painterly' set of strokes will always be executed, pixel for pixel. Of course, the video input will differ entirely from case to case, but this is the only element of the piece that is truly open and indeterminate.

Even if the swarm's basic ruleset were supplemented with a slight random variance, such as in the interactive video installations of Boyd et al's SwarmArt (2002, [6]), it is important to understand that its realization as a purely digital system still reduces it to being essentially deterministic: the pseudo-random number generator used by the operating system is actually taking a fixed, predictable series of numbers in order. If we know the 'seed' value with which this sequence starts (usually automatically derived from the time at which the system is initialized), we can cause the swarm to reproduce precisely the same complicated sequence of 'random' paths and jitters.

2.2.1 Implications of Symbolic Representation

This inherent determinism is one of many interesting phenomena that arise when we consider the pure digitization of swarm space. In contrast with cybernetic bio-mimetic systems, which use feedback sensors to respond to their physical surroundings, these "pristine" [39] digital environments operate solely using blocks of self-generated binary data. The advantages to this are manifold: foremost is the inherent malleability of these information structures, which can be easily transformed and transmitted. It is trivial, for example, to transfer the temporal structures of a swarm's collective motion into parametrised events in the acoustic domain. It is likewise simple to reproduce these software environments on other compatible hardware platforms, transmit them to other locations, and create interconnected systems spanning geographical locations.

Tara Rodgers [32] suggests that there is also a structural resonance in the codification of biological processes. In object-orientated programming, data is encapsulated into functionally separate objects, which exchange messages and form relations with those linked to them. To perform a complex task, exchanges must often take place between many such objects on a number of structural levels. She implicitly likens this to a connectionist web of "cells", suggestive of the hierarchical model of the brain, from lower-level synaptic interactions between neurons to the division into higher-level organisational areas.

The symbolic, state-based nature of a purely digital system, however, places an inherent limit on its structural complexity. Accordingly to Peter Cariani [8], an inherently finite state-space and granularity have vital consequences for the potential of truly emergent behaviour. We shall return to this in section 2.3.

2.2.2 Roles and Intentions of Generative Works

In the same way that much 'sound art' has its critical gaze set on the phenomenon of sound itself (its transmission, role and cultural status), generative art is often concerned with revealing to us the generative procedure itself, which unfolds as the work is executed. It can be situated as an essential, perceptible process of development, in the tradition of process music exercised by composers such as Steve Reich, who states his desire "to be able to hear the process happening throughout the sounding music" [29]. The form becomes entwined into the content: the process of following the composer's structural rules itself becomes an expressive device, intended for the audience to perceive at the time of listening rather than as a consequence of prior/posterior study.

This same focus can be seen throughout many of of the generative software systems used in current practices, applying tools such as Processing [28] and VVVV [37] to synthesise abstract geometric forms which can then be set into trajectories of motion and mutation. The pleasure instilled in the observer is a virtually intellectual joy, through the ongoing comprehension of this continual flux, in a system so complex that it takes close scrutiny to fathom its internal logic. And indeed, it is this logic that is explicated through the application of its rules. We can see this as a mathematical storytelling, an exegesis of the inner workings of a world constructed from scratch by its artist-creator.

Returning to the SwarmArt video installations [6], the only visual content is a rendering of the swarm space, with which users are invited to gesturally interact via video hardware. The aesthetic basis lies in perceiving the interactions between the swarming agents, and between the viewer's gestures and their resultant effects in swarm space. The inherent complexity of this system, distributed between a collection of individual agents and their human counterparts in the physical world, is sufficient for it to be a rewarding subject of continued play and apprehension.

Lev Manovich suggests that it is this complexity of process that bestows such self-organising generative systems with their aesthetic richness [23]. A digital generative world is an expression or response to the complexity of the accelerated, information-driven society we inhabit, with events operating in parallel and organising their spatio-temporal structures through emergent properties. Many artists are currently working with methods of visualising or otherwise recreating such information structures; Manovich observes that around half of the Net Art projects at the 2002 Whitney Biennale presented various methods of mapping data to aesthetic forms [22]. Swarm-theoretical art could be seen as a more tacit response to these structures, embodying their behaviours without explicitly referencing the same conceptual content. In fact, if we were inclined to draw on the radical constructionist viewpoint, we could assert that both animal swarm and socio-economic structures are both simply instances of large parallel-processing machines, whether composed of carbon compounds or social units.

A second, contrasting direction of creative research using swarm behaviours is that exemplified by Tim Blackwell and Michael Young's composition systems [2, 4], which make use of the formations of cohesive groups and path-following capabilities to generate musical notes or textures based on a parametrisation of swarm space. This takes a more macroscopic view, with larger swarms seen from afar and treated in the same method as used in scientific problems of search and optimization. The emphasis is placed on the "swarm intelligence" exhibited by the unified aggregate, and on the resultant output of the system rather than in the mechanistic details of its execution.

As used in this context, the swarm acts as an autonomous performance agent, capable of generating coherent yet frequently unexpected output. The intention is that it can play a role in a musical ensemble alongside human performers, complementing their output and generating potential new aesthetic directions. Blackwell is careful to state that the goal of such systems is not to simply take the place of human performers, but to aid in exploring new forms of expression, augmented through algorithmically-driven processes.

2.2.3 How Autonomous is Autonomous?

In all of the above cases, we are treating the swarm's output as an autonomous method of creation. But is this genuinely the expression of swarm intelligence, or just another form of the artist's own expression? In terms of the sonic domain, to what extent are we justified in making such claims as "this is the sound of a swarm"?

Two difficulties are encountered here. The first is that, given our epistemological and technical limits, we are only working with an abstract model of a swarm; though its behaviour looks similar in basic cases, it is still merely an approximate representation, and its absolute 'swarmlikeness' cannot be tested and reproduced. A digital swarm remains a human-constructed simulation, and though it is compelling to interpret this generative composition as what a biological swarm would sound like, it remains a symbolic abstraction from a biological process. This question of abstraction and representative granularity is addressed further in the following section.

More critical in this context, however, is the fact that the creative interpretation of a swarm's dynamics is itself a highly open and subjective process. In the case of sonification, the assignment of properties of movement to musical events can be configured in an astronomical number of permutations. To ensure the aesthetic coherency of the output, the selection of how to assign these will inevitably be a subjective process, imposed by the artist when developing the work. Alternatively, it could be left to an internal evolutionary system, but this is difficult without an aesthetic 'fitness function', which would likewise be devised by the artist.

The work may now be identified as a system for composition, rather than as a single composition itself, but the products of this system are still essentially aesthetically ordered by the architectural decisions of the artist. This is the simultaneous peril and wonder of generative a-life systems: a phenomenally rich range of output may be produced, but it remains the product of a relatively simple, deterministic system. It is only through our epistemological limitations that we see the system as exercising its own creative faculties. In fact, to use the words of Peter Cariani, these are actually methods of amplifying our *own* creativity [8].

2.3 Self-Organising and Emergent Properties

It is perhaps due to two intertwined behaviours that swarm theory is currently the subject of such fascination: *self-organisation*, the spatio-temporal development of coherent structures without any centralised control mechanism; and *emergence*, the phenomenon of high-level behaviours arising from many simple lower-level interactions, yet whose properties do not appear to be reducible to the sum of their constituents.

We shall take an ant colony as a relevant example. No centralised decision-making force is present; each ant reacts only to its surrounding neighbourhood, aware of a localised group of its nearby peers. As each ant moves through its environment, it deposits trails of pheromones, which have an attractive quality to other ants. Upon successfully finding a food deposit, an ant retraces its trail back to the nest, now depositing a much greater quantity of pheromones to indicate its find. This trail is then subsequently located by other ants, which, perceiving its concentration, can themselves locate the food and return it to the nest, strengthening the pathway further in doing so.

In developing these spatial pathways and structures, the collective colony is exhibiting *self-organising* capabilities. The structures that are formed – between each food deposit and the nest, and in more complex situations, in the activity of building the nest itself – are the result of multiple interactions occurring in parallel, with a degree of random variance to encourage diversity of exploration, plus positive feedback between agents to amplify positive behaviours [5]. In this case, this leads to the *emergent* behaviour of path-finding in search of food, a capability which is clearly not found within the functional programming of any single ant in the colony.

Though we must be careful to distinguish between the concepts of self-organisation and emergence, they are strongly related in their manifestations. Both are reliant on the plurality of their underlying substrate, and involve a form of order or coherence that emerges from this plurality. Both involve multi-planar structures or models, at least on an epistemological level, and this emergence manifests itself on successive hierarchical levels of these models. Both often take place over a period of time, as in the case of swarming dynamics, though this is certainly not a condition for emergence. Moreover, both are intrinsically concerned with *form*, and the configuration of relations between their constituent components. But why are they so aesthetically rich and relevant?

2.3.1 Emergence and the "Something Extra"

Christopher Langton, in the inaugural declaration of 'Artificial Life' [20], identifies emergence as the key concept and methodology of the field as a whole. In the wake of two decades of embryonic a-life art, Mitchell Whitelaw has more recently cited the emergent 'payoff' as the motivation behind artists employing a-life concepts in their work. What is its appeal?

It is difficult to define precisely, but Whitelaw suggests, based on interviews with a number of a-life artists, that it is the unexpected discovery of "something extra", something that comes from within the workings of a computational framework but manifests itself in a creative or richly subtle manner. It is described in reverent terms that evoke the nebulous, mystical properties cited by vitalists to differentiate the living from non-living, and is generally characterised by a sensation of surprise and delight.

The implication of coming across this sensation is that the system somehow possesses its own autonomy: it has made a behavioural leap that seems to exceed the limits of its deterministic programming. Taking a closer examination of descriptions of this 'leap', an analogue becomes apparent within the domain of artistic production – it is discussed in similar terms to those used to describe the creative impulse, wherein a sudden, unexpected connection is made between elements or concepts, forming new, emergent aesthetic constructs. Whitelaw characterises creative development in this same manner, as an iterative, evolutionary sequence of self-modification, leading to a singular moment of radical emergence, which seems to exceed the cognitive and creative frameworks in place up to this point.

A similar resonance with the creative process is described in Tim Blackwell's observations of free improvisation [2], which, he asserts, is structurally self-organising. No prior agreements are made on form or structure, which consequently emerge from the local interactions between players. This is a form of pure creative play, based on moment-to-moment expressive forces, lacking any form of centralised control – and the parallel with a-life systems is clearly evident.

Returning to Whitelaw's commentary, we are met with a powerfully compelling hypothesis:

> What if a-life involves a recapitulation of the cognitive structure of human creative processes, albeit in a tightly constrained, formal medium? Perhaps this would account, in part, for the enthusiasm with which a-life has been embraced by new media artists. Perhaps artists recognize something in the systems and techniques of artificial life that replays that moment of emergence, surprise or excess characteristic of creative processes. [39, p231]

2.3.2 The Limits of Emergence

Given that we have already established that a digital system is deterministic, and thus can only perform functions made possible by its initial programming, it is natural to inquire as how truly novel, emergent behaviours can occur within such a system. In a definitive paper by Peter Cariani, the accepted conclusion is that, in short, they cannot: any apparent emergence is simply the result of our insufficient knowledge of a system.

Through the course of 'Emergence and Artificial Life' [8], Cariani performs a systematic analysis of symbolic state machines – that is, digital systems – and their potential for emergent behaviours in comparison with biological organisms. Based on the fact that a digital system can only have a finite number of states, and its environment can only possess a finite degree of granularity (a functional consequence of its program code), he points out that seemingly emergent behaviour is tightly bounded by both of these limitations. Furthermore, because of the previously-discussed innate determinism of a digital system, this behaviour remains only *seemingly* emergent. Were we to be aware of the state of all of the machine's finite number of registers, we could systematically derive the system's subsequent behaviours, and any apparent 'emergent' behaviour would be revealed as a tautological inevitability. It is only due to our ignorance of the mechanistic system, and the conceptual error of shifting to a different frame of reference, that a swarm's synchronised behaviour appears to have such spontaneously subtlety and richness, rather than simply as a series of banal low-level operations.

Cariani thus draws a distinction between the real functional emergence of biological systems with this, what he classes as 'computational emergence'. Yet this line is not drawn disparagingly; he recognizes that its inherent bounds does not render computational emergence as worthless. On the contrary, he asserts that "the interesting emergent events that involve artificial life simulations reside not in the simulations themselves, but in the ways that they change the way we think and interact with the world" [8, p790]. These computationally emergent a-life artworks might be rebuffed if they were to claim themselves exemplars of "strong" emergence, but they certainly all do encourage reflection on the nature of bottom-up organisational processes, and the implications of the power of such systems in contemporary cultural and political spheres.

This neatly returns us to the reflexivity of generative art, turning in on itself and pointing the viewer at its own generativity. Aesthetic forms founded on emergent processes, it seems, follow a similar heritage, pointing the viewer at the very process of emergence itself.

2.4 The Spatiotemporality of a Swarm

By the working definition that we are using, a swarm is a collection of agents located within Euclidean space, bounded or otherwise. Each agent has a neighbourhood of nearby peers, and through local interactions within this neighbourhood, global swarming behaviours arise. These self-organising behaviours are, therefore, intrinsically tied in with the spatial distribution of the swarm population, and could not occur within a serial, one-dimensional system.

Similarly, self-organisation is an iterative process, in which changes are amplified and reinforced in response to previous states, and so must take place over a period of time. Analogous to the phenomenon of sound, which is emergent from fluctuations in air pressure levels, swarming is wholly bound up with the notion of *change*. Indeed, in 1911, William Morton Wheeler wrote of an ant colony that it is "neither a thing nor a concept, but a continual flux or process, and hence forever changing and never completed" [38].

It is as a necessarily time-based procedure that swarming has seen recurrent adoption within the fields of video, sound, and interactive installation art. In an early and influential emergent work, titled 'The Flock' (1993)[5], Kenneth Rinaldo [31] assembles a swarm from a number of jointed mechanical arms, suspended from the ceiling of the gallery. Each arm reaches several metres towards the ground, and is equipped with sensors and actuating motors to respond to its surroundings. The arms are programmed to reach slowly towards the voices of visitors, but to be repulsed if they move within a certain proximity. Furthermore, each arm can communicate with its nearby peers through telephone tones, conveying positional information of the surrounding participants.

The interactions between these local behaviours are described as giving rise to a "graceful, responsive" [39] choreography, embodying the self-organisational properties described above. As well as remaining faithful to the biological basis of the project by giving the arms an uncannily organic visual form, Rinaldo's installation is one of a rare class of swarm-based artwork that is realized in physical space. The more recent Bacterial Orchestra [9] is another, which likewise incorporates the idea of local communication to distribute behaviours between its population. Here, however, the behaviour is an aural mimicry, using microphones to record snatches of the environmental sound and speakers to replay their recordings with modulated pitch. The effect is a chorus of vocal imitation and mutation, which spreads endemically across the installation.

In both of these examples, the participant is genuinely immersed within the space of the swarm itself: no mapping to or from a digital domain is required. However, due to the technical requirements of developing a hardware-based swarm, alongside the limits imposed by sensing and actuating events in physical space, this remains a relatively infrequent practice, predominantly limited to scientific research.

[5] Later developed and extended as 'Autopoeiesis', whose greater size (15 arms, as opposed to 3) perhaps more aptly justifies the label of a 'flock'. Both are described by Whitelaw [39].

2.4.1 Symbolic Representations of Swarm Space

A more common method of realizing a swarm environment is through software-based simulations, which are almost universally based on the axioms of Reynolds' Boids [30]. Works by Shiffman [33], Boyd [6], and Spector & Klein [35] all take this approach, with a 2D or 3D rendering of swarm space presented on a visual display. In the case of Boyd et al's SwarmArt, the virtual swarm space is not isolated from the real space of the participants, but linked via a gestural input device, which captures physical movements and translates them into events in the software environment. In this way, the participant is able to virtually enter into the swarm world.

Davis & Rebelo [10] adopt the method of representing the swarm space sonically, through multiple loudspeakers positioned around the audience. Spatial panning is used to virtually position sound sources relative to the position of the listener, and so the swarm's self-organisation is rendered audible. The novel use of space here is that the swarm environment is isomorphically mapped onto that of the audience; in their words, the listener "becomes an inhabiting agent rather than a voyeur".

Finally, Unemi & Bisig [36] likewise provide a gestural mapping from real space into a 3-dimension virtual swarm space, but extend this by allowing two separate participants to interface with the same swarm space, connected remotely by a network. In 'Flocking Messengers', two users can communicate by using a webcam and microphone to converse with the flocking system, which then relays the messages to the other party. Essentially, this virtual space is providing a bridge between physical spaces, mediated by means of the swarm's interactions. Though the focus of this work is not on the emergent swarming behaviours per se, it is certainly a creative approach to spatial mapping, not to mention a charming method of communication.

Chapter 3

AtomSwarm

The AtomSwarm framework is a platform for sound-based composition and performance using swarming behaviours within a dynamic, metabolic environment, developed by the author at the Lansdown Centre for Electronic Arts, London. After earlier prototypes, the system is now composed of two key elements: the graphical swarming engine, powered by Processing[1] [28], and the sound synthesis engine, comprised of a number of combinatorically-produced SuperCollider synthesis objects [24].

3.0.2 Swarming Engine

Working from the basis of Reynolds' Boid algorithm [30], the swarming engine is extended in complexity by introducing a series of variable *hormones* to each agent, whose behaviours are modelled on the metabolic systems of animals. Each hormone is modulated by certain interactions and programmatical cycles, and in turn modifies the rule set for local interactions that each agent follows as it traverses the swarm space.

Testosterone (h_t) - Increases with age and crowdedness; decreases upon giving birth. Causes an increase in the likelihood of reproduction.

Adrenaline (h_a) - Increases with overcrowding; decreases as a result of internal regulation over time. Causes a greater rate and erraticness of movement.

Serotonin (h_s) - Increases during 'day' cycles; decreases during 'night' cycles, and as a result of hunger. Causes a greater social attraction towards other agents.

Melatonin (h_m) - Increases during 'night' cycles; decreases during 'day' cycles. Causes sluggishness of movement.

Leptin (h_l) - Increases upon eating 'food' deposits; decreases steadily at all other times. Signifies how well-fed an agent is, and causes downwards regulation of serotonin when depleted, plus greater attraction to food deposits.

In addition, each agent has a fixed *genome*, comprised of a number floating-point values g_n. These encode various qualities of the agent's behaviour, which remain invariant over time. These include:

[1]Processing is a graphically-orientated extension of Java, incorporating a programming language and standalone IDE.

Colour (g_{col}) : The hue of colour used to visually depict the agent

Age (g_{age}) : The rate at which the agent 'ages'

Introspection (g_{int}) : The degree to which the agent is attracted to social groups, or otherwise

Perception (g_{perc}) : The range at which the agent can perceive and respond to its peers

Sonic parameters (g_{son_x}) : The sonic behaviours exhibited by the agent, described in the following section

Hormone cycle amplitudes (g_{cyc_x}) : The strength or speed of each hormonal cycle; for example, g_{cyc_s} determines the amount in which the agent's serotonin level h_s increases during a 'day' cycle.

Hormone uptake responses (g_{up_x}) : The increase in hormone level experienced when uptake occurs; for example, g_{up_a} determines the amount of adrenaline increase following a collision with another agent.

The latter two genes, determining hormonal cycles and sensitivities, are critical to the ecosystem's diversity and evolution. As a consequence of their effects, a particular agent may be prone to sudden increases in adrenaline levels, resulting in it 'fleeing' an overcrowded area and locating new food deposits. The swarm is thereby able to moderately adapt to a continuum of states.

Thus, in distinction to the time-invariant behaviour of the original Boid algorithm, there are now a number of feedback mechanisms in place: the genotype of an agent determines its hormonal fluctuations; the genotype and hormone levels co-determine its response to each of the set of physical rules (cohesion, separation, etc); and events caused by following these rules (eating, colliding, becoming overcrowded) feed back to modulate hormone levels. The interactions between these three planes of codification quickly become very complex, and result in diverse and shifting collective behaviours over time. Moreover, they create the ability for the ecosystem to adapt and self-regulate its population, as outlined below in Section 3.3.

The size of the population is also affected by the reproduction and death rates. The agents are asexual, and give birth to a single offspring after their testosterone levels reach a threshold. The genome of the offspring is a duplicate of its parent's, subject to minor variance and a random degree of genetic mutation, and so its behaviour is usually similar but may occasional exhibit radical alterations, opening up the possibility of advantageous anomalies. Deaths can be caused by hormone imbalances (representing starvation, depression and testosterone overload) or simply by old age, determined relative to the g_{age} gene.

As referenced above, the system also introduces the concept of 'food' - an arbitrary resource, placed in scattered collections over random intervals - and day and night periods, which cycle over the course of a few minutes. These are purely programmatical constructs to modulate the swarm's hormonal levels, in a fashion analogous to natural metabolic systems.

3.0.3 Sonic Mappings

The sound generation components of AtomSwarm are handled by SuperCollider's powerful synthesis engine, communicating with the swarming process via Open Sound Control [41]. As the system's design requires fine-grained control over the musical output from the ground up, sonic behaviours are also codified extensively in the swarming engine itself.

In terms of the swarm's population, this begins at the creation of each agent's genome. This describes the structure of the synthesis graph that the agent will utilise – which can essentially be thought of as a generator and processor unit, combined in serial – plus a 'trigger' mode and threshold, which together determine the point at which the synth is instructed to generate output. This may be, for example, upon collision with another agent, or when the agent reaches a velocity of 10 pixels per second.

In addition, the genome encodes a fixed mapping from the agent's movements to a given property of its synthesis graph; for example, its velocity may be mapped to the generator's amplitude. In a more complex case, the doppler-shift parameter, reflecting the rate at which the agent is moving towards or away from a peer, could be assigned to the frequency parameter of an oscillator. This creates an approximation of the Doppler effect, exemplified by the familiar drop in pitch of a passing ambulance siren. In testing, this was found to also give a convincing approximation of the pitch oscillations of a swarm of buzzing bees.

In contrast with the approach taken by Tim Blackwell's melody-based Swarm Music system [2], AtomSwarm is orientated towards the composition of textural and quasi-rhythmic forms, often making use of repetitive cycles of short, non-tuned sound objects. The single pitched synthesis class is a pure sine wave, with an amplitude envelope for gradual onset and release. However, combined with the potential combinatorical complexity of a genetically-selected processor unit and motion mapping, even this can give rise to a startling range of output.

3.1 ...as a lifelike ecosystem

Despite its relatively sparse ontology and clean, geometrically-rendered forms, AtomSwarm frequently demonstrates surprisingly lifelike qualities. The heterogoneity of the swarm's behaviour grants it a significant perceptual richness, in contrast with the homogenous (though complex) movements of the original Boid algorithm. Despite the eye's powerful pattern recognition system, subtle alterations of a base genome are sufficient to create a compellingly non-uniform and organic unified movement.

The scale at which it is displayed also allows the spectator to easily pick out and follow individual agents. From this, it is a natural step to mentally attribute distinct personalities to each, with some agents moving erratically and sociably, others operating as nomadic explorers, and still others drawing smooth, regular orbits around distant neighbours. This natural anthropomorphism has been shown to induce a significant empathic response in audiences. One public performance was concluded with two agents seemingly engaged in a form of dance, pursuing each other in swooping curves. This was left to continue until, eventually, one reached its natural lifespan and died, disappearing from the display. Clearly recognising the situation, some viewers audibly sighed in an expression of loss.

This willingness to emotionally engage with a symbolic community, whose structure bears merely a resemblance to that of a living system, is an indicator that concepts are being applied beyond those of an abstract generative system. Using the terms of Mitchell Whitelaw [40], a "system story" is being imposed through the the spectator's imaginative faculties, seeing the underlying biological ontology of the system. The audience takes joy in this familiar-yet-strange image of "life as it could be" [20].

3.1.1 Biomimetics in Sound Design

Sound synthesis in AtomSwarm is accomplished with a palette of generator and processor components, each of which consists of a number of primitive synthesis units. For a newborn agent, these are selected and combined based on its genome, and a compound of one generator and one processor provides it with an identifiable sonic signature – or to use the language adopted by Dennis Smalley, its "physiognomy" [34].

With the accompanying visual flash whenever an agent generates sound, the suggestion is that each sound object signifies an utterance, communicating to its peers or expressing its physical state. Through perceived vocal exchanges between agents, this sonic physiognomy thus serves as another device to individuate and characterise the swarm

The sound design for the generator components was a broadly biomimetic process. An earlier incarnation of AtomSwarm used sound recordings of a number of natural phenomena: human bodily functions, cicada calls, and metallic, drip-like impulses. The transition to pure synthesis was made by observing the spectral qualities of these classes of sound, and translating them into functions of basic oscillators and DSP units. Each generator component thus has a distinct morphological identity, texturally modified by its processor, but retaining sufficient qualities to be identifiable as being from the same source.

Why was this approach taken? Rather than simply using the ordered structures of motion for composition within an existing framework, like the melody-orientated generative composition of Tim Blackwell's early research [2], a conscious decision was made to evoke the qualities of an ecosystem "as it could be" – supporting the existing visual and conceptual narratives, suggesting immersion within a possible, quasi-biological world. The intention was that, even without the visual depiction of the ecosystem, the sonic design alone would suggest that the source of the sound is organic in nature. With the addition of heavily synthetic processor units, this reference is warped and distended to suggest a bio-technological hybrid.

3.2 ...as a generative work

In a performance context, AtomSwarm is projected onto a screen visible to the audience, with audio distributed via a multi-channel speaker system. Control over the environment is limited to a basic MIDI interface, through which the human 'conductor' is able to create and destroy agents, add food deposits, and manipulate the weightings of the physical rules governing the swarm's movements. Thus, the only control mechanism is wholly indirect, with no scope for determining its sonic behaviours, nor even manipulating the individual agents themselves[2]. Three layers of interactions serve to mediate the conductor's influence over the soundscape: between the rule weightings and the swarm's hormone levels; between the relative positions of each of the agents; and between each agent's motion dynamics and the sonic mappings described by its genome.

[2]It is for these reasons that the term 'conductor' has been adopted: as in an orchestra or choir, the conductor maintains real-time control over the unified ensemble, gesturally influencing its flow and dynamics en masse.

Through these layers of mediation, it is often the case that that attempts at influencing the system go unheeded; increasing the 'Cohesion' rule, for example, may be ignored entirely by a swarm made up of highly introverted agents.

As far as modulating the current behaviour is concerned, therefore, the conductor's role is limited by constraints imposed within the system. A constant tension emerges between order and chaos, with the human input in continual threat of being outweighed by the balance of internal forces. This is the same "dynamic network of relations" as described by Lev Manovich [23], in which current trends are vulnerable to being swept away by amplified oscillations towards a new structural equilibrium. The resultant experience is almost game-like, in that the aesthetic 'fitness' of the collective sonic output may be at odds with the fitness criteria of its constitutive agents. For example, a clustered group may be generating a rich, compelling timbre, but this cannot be sustained if its collision rate is too high (wherein testosterone overload will kill many of the agents), or hunger levels rise to the point at which the agents ignore the 'cohesion' rule and depart to seek food.

The alternative approach to performance is to allow the ecosystem to develop and regulate itself independently, and engage in total autopoeisis. In the absence of human intervention to supervise its growth, the swarm will still engage in self-regulating behaviour as a consequence of its hormonal requirements, limited resource supplies and aging processes. Evolutionary narratives unfold according to the interconnected rulesets that determine the genome-hormone-ruleset interactions; spectators can select whether to engage on a macroscopic scale, with the synchronised movement and sonification of the swarm as a whole, or on a microscopic scale, in the interactions of individual agents.

3.3 ...as an emergent, self-organising system

The introduction of metabolic constructs to AtomSwarm was followed by several manual iterations of fine-tuning the interactions between rule weightings, hormonal levels and environmental events. As a consequence of this tuning, it is now demonstrably capable of exhibiting a range of significant self-organising behaviours, many of which were not even anticipated when these interactions were first implemented.

On one level of resource flow, each agent attempts to maintains an internal homeostasis: as a hormone quantity is amassed or depleted, its rule-following behaviours will be slowly weighted towards those actions that will assist its regulation (eating, reproducing, seeking isolation). Above this, on the macro-scale of the swarm as a whole, a "homeorhesis" [14] occurs, or the *regulation of flow* of resources between agents, with only a limited quantity of food deposits available. If the population grows too large, insufficient food supplies result in downwards regulation due to deaths from starvation. If it shrinks, food is abundant and the population is free to increase. Yet, this is no guarantee of survival: agents which are excessively sociable risk death from the testosterone overload caused by excessive collisions; a nomadic tendency may be useful for finding isolated deposits of food, but can result in serotonin depletion and a lack of testosterone, and thus the inability to reproduce.

Another emergent surprise, and one which genuinely instilled the rewarding, unexpected sensation of the "something extra" that Whitelaw describes [39] in his cross-section of a-life art, is the swarm's demonstable capability of effectively discovering food deposits. Each deposit comprises of up to 10 food particles, each of which is sufficient to satiate an agent's hunger for a short period. In one pertinent case, a fairly tight-knit swarm was located far away from any food resources. One agent was moving more nomadically, with sufficient random motion to come across a food deposit quite quickly. After consuming a particle, it lingered near the deposit. The remainder, following the rule of cohesion to the swarm's centre of mass, gradually moved across the space to join the nomad, and in doing so discovered and consumed the food deposit.

This food-finding ability through nomadic exploration is certainly not something that was programmed into the individual actions of the agents. It is purely the result of a circular feedback loop between the ecosystem's internal levels, via positive feedback through the regulation processes of the individual agents. To return to the conclusions of the previous chapter, we accept that this behaviour is merely classed as computational emergence, resulting from our limited insight into the massively complex parallel interactions taking place as the system unfolds. And yet, accepting this fact does not impede the often startling pleasure in observing and anthropomorphizing the on-screen population.

3.3.1 Sonic Self-Organisation

Because each agent's sonic behaviours are encoded in its genome, which is passed down to child agents and selected through generations of fitness-driven evolution, a significant degree of sonic ordering can be perceived through focusing on the auditory representation of the environment. The sonic spatialisation, described in detail shortly, gives a richly accurate sense of movement and change from within the swarm's frame of reference. Given an agent with a distinctive sound signature, we can hear the result of its reproduction through the sudden introduction of a similar-sounding signature. Population growth is accompanied by an increase in the density and spectral depth of the output.

This is supplemented by the presence of viral *memes*[3], a recent evolution to the AtomSwarm framework itself. An agent will very occasionally develop a meme from one of its sonic synthesis chromosomes, which can then infect nearby agents through collisions, with statistical probability based on the meme's arbitrary 'strength' rating. An infected agent will adopt this same genetic trait, and so its sound signature will immediately be transformed to resemble that of the infector. If the population's density is sufficiently high, a strong meme can spread between the agents extremely rapidly, and so the sonic landscape may suddenly switch to a chorus of unified chirping.

Is this sonic self-organisation? Insofar as the sonic terrain frequently orders itself into spectral unison, from a chaotic starting point, then it could certainly be classed as such. Moreover, consider the fact that the population of the swarm is bounded by the limited availability of resources. As the production of sound objects is directly proportional to the swarm's population size, this same bound is placed upon the sonic density; a period of high activity (expressed by high amplitude levels across the spectrum) cannot be sustained.

However, one of the critical principles for non-trivial[4] self-organisation is that of positive feed-

[3] Taken from the terminology of Richard Dawkins [11]

[4] Francis Heylighen draws a continuum between simple and complex instances of self-organisation; certain traits "will only be exhibited by the more complex systems, distinguishing for example an ecosystem from a mere process of crystallization" [16]

back: a circular interaction between components that proceeds to amplify a change [16]. In the example of the ant colony, this is manifest in the increase in pheromone trails after locating food. As further ants proceed to follow the pheromone gradient and arrive at the food deposit, the trail is strengthened, amplifying the feedback loop.

Through the interaction of metabolic systems within AtomSwarm, this class of feedback occurs at several points, such as in the example described in the previous section wherein the swarm can discover food deposits based on its shifting centre of mass. Though these interactions do have a direct result on the sonic output, this cannot be classed as *sonic* self-organisation for the fundamental reason that the this feedback *does not occur in the same frame of reference* as the relations that constitute the plane of sound generation. For true sonic self-organisation to occur, changes in sound synthesis must be reinforced and amplified based on properties of the sound itself. The distribution of sonic artefacts via memes can be modestly viewed as an organisational process, but not one that is linked to an evaluatory procedure based on auditory criteria.

In fact, no richly meaningful form of sonic self-organisation can place without an internal concept of 'fitness' in the same frame of reference. This immediately poses the old problem of creating an objective assessment of essentially aesthetic criteria. Given that whether something 'sounds good' is an inherently subjective judgement, how can a symbolic system provide positive or negative feedback on its current auditory state?

It is out of the scope of this paper to review methods of evaluating sound-based fitness. In a similar context, however, Tim Blackwell and Michael Young provide an elegant solution by placing 'attractors' in the swarm space, whose locations are determined by the attributes of a musical source that is analysed in real-time (such as pitch, amplitude, and duration). As agents swarm towards these attractors, their output – which is parametrised along the same axes – tends towards being relationally similar to the input. Assuming the musical source is a human musician, this swarming can then be positively reinforced by playing more notes in a similar vein, or negatively reinforced by modulating playing style – say, by switching to a different pitch register.

A similar procedure could here be adopted based on timbral analysis of a sound source. However, due to the heterogeneity of each agent's sonic behaviours, no universal parametrisation of timbral qualities is possible. It is one of the future research directions of this project to consider how the output of audio analysis might result in environmental modifications of other types.

3.4 ...as a spatio-temporal environment

AtomSwarm's agents are located within a flat, 2-dimensional space, with floating-point position values (in pixels) to establish a continuous plane. Earlier incarnations of the framework used vectors of an arbitrary number of dimensions to position each agent, with faux-3D rendering. For obvious reasons, the dimensions above 3 could not be effectively depicted, and were only present in order to extend the parametric mapping space. Tim Blackwell's swarm composition systems [3] use up to 7 spatial dimensions, corresponding to amplitude, pitch, duration, note interval and three phrase-based properties; good results are reported.

However, in the case of AtomSwarm, we are less interested in positional data, instead focusing on the dynamics of the swarm movement in general and its status as a continually generating ecosystem. Furthermore, as we are not working with the traditional axes of pitch/amplitude/-

duration, we have no need to capture this number of positional values in parallel; we have a sufficiently wide combinatorical space of timbral qualities to be content with one motion mapping per agent, which quickly results in complex sonic interactions even with a relatively small swarm. Even this one mapping may not be positional, instead taking values from velocity or relative movements. In this way, we hope to express a greater range of the dynamics of the swarm. A crowded, fast-moving group may be expressed by heavy layers of high-frequency ticks, a rapidly fluctuating series of sine waves corresponding to Doppler shifts, or by frequent percussive pulses given off by collisions between agents.

The most prominent use of the swarm space, however, is in its identification with the space surrounding the viewer. The single agent present from the very start of a performance is known as the 'Listener', visually identifiable by its red outer ring. Effectively, the viewer hears the swarm's motions from the perspective of the Listener, using vector-amplitude panning [27] for simulated sound source positioning on an arbitrary number of output speakers. On a 2-dimensional multichannel speaker set, sound events to the left of the Listener are heard to the left of the viewer; events displayed above the Listener are heard straight ahead. As the Listener moves around the world, therefore, the viewer's soundscape shifts accordingly.

This encourages the viewer to identify with an agent inside the space, shifting them from a position outside of the system to one immersed within it. Indeed, 'immersivity' is intended to be key to the experience of a performance, reinforcing the empathic response detailed in the previous section.

To support the experience of space, the swarm's output is passed through a global reverberation unit. Due to constraints on processing power, it was not possible to create implement true spatial reverb. Instead, the amount of global reverberation is constantly adjusted based on the Listener's distance from its peers; as the average distance between the Listener and the rest of the swarm increases, so to does the amplitude level of the reverb's reflection parameters. Thus, a swarm distributed widely across the environment will have a heavy echo, aurally akin to being in a large enclosed space. Though this technique evidently lacks precision, it serves to support the notions of distance and proximity, both important criteria for the faithful sonification of a distributed population.

In general, these ideas are a continuation of the drive to realize a possible space "as it could be". Though this space is rendered perceptible around the audience, the system's digital manifestation indelibly marks the experience with the grain of non-reality.

Chapter 4

Conclusion: Swarming and Creativity

AtomSwarm, like any complex dynamical system, is fundamentally a staging ground for a continuous flux of interactions, between forces, agents and resources. Convoluted feedback loops arise between the multiple planes of interaction (human input, rules, hormones and genomes), with sufficient complexity to evoke the organic (in)stability of a natural ecosystem. Putting aside the question of alive/unalive, this system can, through these bottom-up interactions, autonomously regulate its own global flow, resulting in a constantly oscillating series of transient equilibrium states. Each action is subsequently subject to the system's internal methods of regulation; the ecosystem responds to sonic and visual saturation, for example, through its intrinsic scarcity of resources, which restores the population to a balanced level.

This iterative sequence of action/reaction has a direct resonance with the working methodologies of Paul Klee, who saw his practice as a constant "adventure" in balancing forms and forces as they developed on the page. In the introduction to Klee's *Pedagogical Sketchbook* [19], Sibyl Moholy-Nagy observes that, in his work:

> It is the balancing and proportioning power of eye and brain that regulate this expansion of the object toward equilibrium and harmony.

In realizing these emergent balancing powers through a self-organising ecosystem, we are effectively codifying the dictates made by Klee, subsuming the power of the eye and brain into the collective interactions of a distributed system. Our autonomous super-organism regulates its own level of equilibrium, and continues to establish responses to an ever-changing set of environmental forces. The behavioural properties of this swarming environment thus not only refer implicitly to the emergent nature of creativity, but serve to reproduce a significant facet of its practical methods.

Klee describes the final crystallization of form in an organic artwork as its "death". In realizing these continually generating machines, we are thereby eternally suspending any possibility of crystallization, enabling the forces of the system to continue to engage in a neverending play.

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Appendix A

Accompanying Media

Two discs are included with this paper: a video DVD containing a recording of the AtomSwarm framework in action; and a data CD, containing various media files, source code, and an electronic edition of this essay.

A.1 Video DVD

The accompanying DVD contains a single video track. This comprises of a single performance using AtomSwarm, created in October 2007, with a human conductor guiding the system and manipulating its population. All sonic behaviours are genetically coded.

The sound is encoded in Dolby 5.1 for true spatial listening; stereo playback is also supported. Due to limitations of DV recording, the video resolution has been downsampled considerably, and so is of poorer quality than in a typical performance environment.

A.2 Data CD

The compact disc included with this report contains the following items:

`/media` – accompanying sound and video files

`/source/processing` – the Processing.org source code for the client-side elements of AtomSwarm

`/source/synthdefs` – the SuperCollider 3 synth definitions required for the server-side audio synthesis

`/text` – a PDF copy of this essay

A.2.1 Media

The media directory contains the following items:

`atomswarm-genetic.mp4` – MPEG-4 encoded video, as on DVD

`atomswarm-genetic.aif` – stereo AIFF audio, as on DVD `atomswarm-pre-genetic.aif` – stereo AIFF audio of an earlier performance, using non-genetic sound behaviours

A.2.2 Source Code

To run the source code for the AtomSwarm package, you will require a modern Macintosh computer (G4+) running a recent copy of OS X. The distribution on this CD has only been tested with OS X 10.4.10 running on a 2GHz MacBook Pro. Up-to-date installations of SuperCollider 3 [24] and Processing [28] are prerequisites for installation.

- Copy the contents of `/source/supercollider` into the SuperCollider SCClassLibrary path.
- Start SuperCollider, and run the contents of each of the files in `/source/synthdefs` to install the synth definitions.
- Open the file `/source/processing/GenoSwarm/GenoSwarm.pde` in Processing, and run the sketch.

Appendix B

A Guide to Visual Cues in AtomSwarm

Though AtomSwarm is intended primarily as a platform for sonic performance and composition, it also provides a visual depiction of the swarming environment, which contains a great deal of information to help interpret the current state of the ecosystem. This guide provides a brief outline of these visual cues, and how they can be read.

Swarm – The environment contains a single swarm of one or more agents, each of which follows a number of basic physical rules.

Listener – The listener agent is present from the inception of the swarm, shown as a solid red circle. It generates no sonic output, and cannot be infected or destroyed. When other agents are present, we hear the sounds they emit as if from the perspective of the Listener agent.

Agents – Other agents are depicted as small, ringed circles. The colour of the inner circle is simply a product of the agent's genome, and has no function but to identify an agent and its relatives. The outer circle corresponds to the sonic generator class used by the agent; that is, the class of sound that it emits. A recently born agent is also accompanied by text describing its general class.

Trails – If selected by the human conductor, the swarms may leave visual trails. These serve solely an aesthetic purpose, depicting the path recently taken by the agent.

Flashes – Agents frequently flash to indicate certain events, including collisions, sonic triggers and infections.

Infection – Occasionally, an agent may display a green ring, which can spread to other nearby agents. This indicates the spread of a viral meme, which causes other agents to adopt the same sonic characteristics.

Reproduction – Under certain conditions, agents give birth to similar offspring. A thin red line briefly links the two together before disappearing.

Food – The grey clusters visible from the start are food deposits, subsequently created at random intervals. Each agent requires food to survive.

Controls – The sliders in the top left display the current rule weightings, which determine the physical rules governing the swarm's movements.

Day/Night – On the bottom level of the slider table is a circle which slowly transitions from yellow to black. This indicates the environment's current time state, cycling between 'Day' and 'Night'. These states affect the agents' hormonal levels and behaviours.