Disembodied Characters

by

Michal Hlavac

A.B., Computer Science and Visual and Environmental Studies
Harvard University, 1997

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences
at the
Massachusetts Institute of Technology

August 1999

Signature of Author

Program in Media Arts and Sciences
August 6, 1999

Certified by

Bruce Mitchell Blumberg
Asahi Broadcasting Corporation Career Development
Assistant Professor of Media Arts and Sciences
Massachusetts Institute of Technology

Accepted by

Stephen A. Benton
Chairperson, Departmental Committee on graduate Students
Program in Media Arts and Sciences
Massachusetts Institute of Technology

Disembodied Characters

by

Michal Hlavac

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning on August 6, 1999,
in partial fulfillment of the requirements for the degree of
Master of Science

Abstract

A colony of social insects as a whole can be regarded as an organism that reproduces, maintains its internal structure, and survives in a hostile an unpredictable environment. Such superorganism – an entity that consists of smaller component organisms – is able to perform remarkable feats, decentralized information processing among them. For instance, a swarm of bees is able to choose the best possible nesting cavity even though only a few of the individuals have any knowledge of the available sites, and no single bee has a full knowledge of the situation. This decentralized decision making is remarkably similar to that performed by hypothetical functional agents, frequently featured in decentralist theories of the human mind.

In this thesis I argue that comparing a superorganism to the mind is useful. In particular, this comparison opens up an enchanting opportunity for the creation of expressive synthetic characters that may become important incremental stepping stones on the way to complex artificial intelligence. In order to explore the space between metaphors – the human mind as a collection of interconnected mindless agents, and the superorganism as a unitary whole that exhibits functional characteristics beyond those of its component parts – I present the design and implementation of the Mask of the Hive, a character that is based on a model of a bee colony. My emphasis lies on graphic design and information visualization in order to develop a set of visuals that are informative, expressive, and artistically satisfying.

Disembodied Characters

Thesis Committee

Reader

Mitchel Resnick
LEGO Papert Associate Professor of Learning Research
Massachusetts Institute of Technology

Reader

Thomas D. Seeley
Professor of Biology
Cornell University

August 1999

Table of Contents

As a zoologist, reared among what are now rapidly coming to be regarded as antiquated ideals, I confess to a feeling of great diffidence in addressing an audience so thoroughly versed in the very latest as well as the very oldest biological facts, methods and hypotheses. I feel, indeed, like some village potter who is bringing to the market of the metropolis a pitiable sample of his craft, a pot of some old-fashioned design, possibly with a concealed crack which may prevent it from ringing true. Although in what I have to say I shall strenuously endeavor to be modern, I can only beg you, if I fail to come within hailing distance of the advance guard of present day zoölogists, to remember that the range of adaptability in all organisms, even in zoölogists, is very limited.

The Ant-Colony as an Organism
By William Morton Wheeler, 1911

introduction

CHAPTER 1

An anthill is alive. It lives beyond the lives of its component ants, since it collects food, overcomes hostilities, and reproduces as a unified whole. One can compare an anthill to an organism because the degree of organization and functional specialization of ants within a colony is similar to that of cells within an organism. Termites, bees, and social wasps do not remain far behind ants, as all these Hymenopterans self-organize into spectacularly complex and remarkably successful colonies. Conveniently, such colonies can be called *super*organisms, because they themselves consist of smaller, component organisms.

Bees make for picky swarms. Since the future prosperity of a brand new bee colony depends on finding a good nesting site, bees have developed a remarkable decision-making mechanism to ensure that they will correctly identify the best available site. No single bee has full knowledge of the situation, yet the colony as a whole seems to be able to use distributed bits of knowledge to make the right choice. Such an unusual cognitive feat of this particular superorganism is especially intriguing, because it lends itself to a direct comparison with other systems that make decisions – the brain in particular.

The human mind is appropriately complex. At a certain, very simplified level, however, the decision process performed by the swarming bees may be compared to the decision process carried out by certain subsystems of the mind. Since the two systems exhibit functional similarity – namely, the ability to make decisions – studying colonies of social insects in nature might reveal insights about self-organization in decentralized systems that may be applicable in creating generative models of the mind. In order to make a step in this direction, though, one must find a suitable working approximation of the human mind.

A Synthetic Character is an autonomous animated creature that interacts with a human user while staying "in character". It is an artificial construct designed to mimic some of the behavioral qualities of animals. While it serves as a working model of an animal brain, it has been recently refined to perform in increasingly human-like fashion. A strong graphical visualization tool that stands somewhere between a real mind and a real colony of bees, a Synthetic Character may prove to be an interesting vehicle for exploring the metaphorical space between a superorganism and a decentralized model of the mind.

I wish to argue that comparing a superorganism to the mind is useful. A controlled comparison of a decentralized theory of the mind, as described by Marvin Minsky in *Society of Mind* [Minsky87], with the concept of a superorganism, as articulated by William Wheeler [Wheeler11] and others [Seeley98, WilsonD89, Stock93], creates a fruitful domain for cognitive research. The reason I find this juxtaposition interesting is that it opens up a delightful space for the creation of expressive synthetic characters that may become important incremental stepping stones on the way to complex artificial intelligence. There are three reasons why synthetic characters are the right entities to build in this domain. First, the biological models can be implemented relatively easily under the behavioral framework designed for character creation. Second, the resulting characters can be thought of as expressive bundles of proto-intelligence, and thus may cast interesting light onto the problem of building partial models of the mind. Third, abstract three-dimensional graphics can be used to visualize complex behavior-related information in expressive and interactive fashion. In order to back up my claims, I have designed and built a synthetic character that emulates the workings of a bee colony. It is based on a descriptive model of the colony as devised by Thomas Seeley [Seeley89, Seeley99a, Seeley99b], and implemented under a generative behavioral framework as designed by Bruce Blumberg [Blumberg97, Kline99]. The character also takes full advantage of the abstract nature of the modeled phenomena and provides a set of visuals that are informative, expressive, and artistically satisfying.

Motivation

Building an artificial system that mimics natural intelligence is my ultimate goal. In order to make an imprint on a problem as challenging, as complex, and as celebrated as this one, however, an aspiring scientist must establish an interesting angle. The search for such an angle is the underlying motivation for this study. Because this work represents only an initial step in this daunting quest, I have chosen to emphasize the breadth of the material surveyed rather than the depth of the solution outlined. I attempt to bring together ideas from several disciplines and to intertwine them in a way that may result in an original insight into the problem. My choices tend to gravitate toward unusual, bizarre, and even outdated ideas, all in an attempt to break away from the mainstream of thought, perspective, and implementation.

Six primary ideas constitute the basic ingredients of the discussion. First, there is the decentralized theory of the mind developed and presented by Marvin Minsky in *Society of Mind*. Second, there is the metaphor of a superorganism as originally conceived by William Wheeler and further developed by a number of entomologists. The relationship between the two is well illustrated by a third building block, Douglas Hofstadter's account of a talking ant colony [Hofstadter79]. In order to descend from the heights of a purely philosophical argument, and to "pollute" the theoretical dispute with the nitty-gritty of implementation, I chose the following generative models for the theories: Bruce Blumberg's concept of a Synthetic Character and Thomas Seeley's description of a bee colony. Finally, I consider graphic design the sixth ingredient, since it is a tool that allows for the synergy of the two models into a single graphical visualization.

This visualization takes on the form of an interactive disembodied synthetic character, the Mask of the Hive. I chose to design a character that is a bit unusual: it is a virtual embodiment of a distributed entity, an artistic rendition of an inherently decentralized collection of organisms. The character serves as a test-bed for trying out ideas about decentralized models of the mind, collective models of bee behavior, and emergent behavioral epiphenomena of superorganisms. It is a meeting place for the models and theories; it is the common ground that has been laid out by invoking three-dimensional visuals. The character thus showcases a wealth of scientific and creative opportunities offered by a direct comparison between the mind and the superorganism.

Document Roadmap

For the sake of clarity, I present the six constituent parts of my argument in a somewhat different order. I distinguish between Concepts and Models, grouping Synthetic Character, Society of Mind, and Superorganism under Concepts and Hofstadter's Ants, Seeley's Bees, and Blumberg's Animals under Models. I start the section on Concepts with a thorough description of a Synthetic Characters, providing both an intuitive account and a more precise definition of this artificial concept. I use several examples of animated characters to illustrate one of the corollaries to my argument, that even an abstract entity may qualify as an expressive synthetic character. The description of Concepts continues with a review of the metaphor of a Superorganism. Instead of a mere recapitulation of *Society of Mind*, I present the discussion of this theory in light of a larger parent philosophy, that of a Decentralized Mindset.

The Models section proceeds from abstract to concrete as it traverses Hofstadter's description of a talking anthill, Seeley's model of a bee colony, and Blumberg's system of behavioral programming. The

Implementation section then completes full circle by returning to the description of the Character. It starts with a discussion of the particulars of the combination of the models, and then continues with a detailed description of the design practices used. The Results section then presents four demos of the real-time system, with each demo highlighting different aspects of the system's functionality. The Conclusion and Appendix follow.

Socrates: Can this be true about the soul, that one soul is more and more fully a soul than another, or is less and less fully a soul, even to the smallest extent?
Simmias: Not in any way.
Socrates: Come now, by Zeus. One soul is said to have intelligence and virtue and to be good, another to have folly and wickedness and to be bad. Are those things truly said?
Simmias: They certainly are.
Socrates: What will someone who holds the theory that the soul is a harmony say that those things are which reside in the soul, that is, virtue and wickedness? Are these some other harmony and disharmony? That the good soul is harmonized and, being a harmony, has within itself another harmony, whereas the evil soul is both itself a lack of harmony and has no other within itself?

Phaedo, Five Dialogues
By Plato, 399 B.C.

concepts

CHAPTER 2

Three concepts are discussed in this section: Synthetic Character, Superorganism, and Decentralized Mindset. I begin the discussion with an informal account of what our research group has come to accept as a Synthetic Character, and then transition to a more formal definition of the concept. Several examples of both scripted and interactive synthetic characters serve to illustrate a side argument, that the concept of a Synthetic Character is broad enough to accommodate for the challenges posed by the study of the relation of the mind and the Superorganism. The description of Superorganism involves an analysis of both an early and a modern version of this concept, and I cite several examples from biological literature that illustrate it in a number of angles. Finally, I segue into a discussion of the Decentralized Mindset and illustrate it with a description of

Marvin Minsky's *Society of Mind* [Minsky87], as well as Mitchel Resnick's *Turtles, Termites and Traffic Jams* [Resnick94].

Synthetic Character

> The goal of the Synthetic Characters Group at the MIT Media Laboratory is to understand how to build interactive characters that come alive in the eyes of the people who interact with them. Through this process we hope to tackle hard problems which have broad applicability to the design of intelligent systems and realtime character animation.
>
> **Synthetic Characters Group webpage**
>
> By Bruce M. Blumberg, 1998

If Roger Rabbit, a "toon" star of the movie *Who Framed Roger Rabbit*, became autonomous, he would make a superb Synthetic Character. He is an artificial being that comes alive in the eyes of the people that interact with him, that moves, talks, acts, and reacts "in character", and that exhibits and elicits emotions appropriate for the situation at hand. Roger interacts with the cast of the film as just another sentient creature, adhering consistently to the wacky characteristics of his role and taking both his cartoon and human co-stars through a range of extreme emotions. Lack of autonomy is the reason Roger fails to qualify as Synthetic Character, however, since his actions are carefully crafted to follow a single line of events, to exhibit a linear sequence of behaviors. To endow a creature as expressive as Roger with the ability to choose its behavior from a large space of possibilities, without compromising any of its appeal and expressiveness, is the goal of the research in the domain of Synthetic Characters. Using this account as an illustration of the concept, let us now attempt to construct a more formal definition.

A Synthetic Character is an autonomous, coordinated, and individualized system of activities that appears alive, consistent, and emotional in the eyes of the people that interact with it. The character's "aliveness" comes from its behavior, motion, and knowledge of the world. A being that never steps "out of character" is consistent in the eyes of the audience. The character's emotion grows from exhibiting desires or motivational states beyond mere requirements of survival. For example, Buffalo Bob Smith's Howdy Doody character appears alive because he behaves, moves, and perceives the world correctly. Disney's Snow White appears consistent because she would never utter a swear word. Disney's rendition of A. A. Milne's Eeyore appears emotional because he clearly communicates motivational states like sadness or defeatism. Notice that the definition relies on *perceived* aliveness, consistency, and emotion, as opposed to actual life, realized consistency or experienced emotion. While the definition requires autonomy, it also implies interactivity. For instance, both Snow White and Eeyore fail to interact with the audience in their present form, and thus they do not qualify as Synthetic Characters.

The concept of a Synthetic Character is broad. Even though we tend to intuitively cast humanoid figures into the roles of Characters (as is the case with the heavily anthropomorphic Roger), nowhere does the definition constrain the extent of the aliveness, consistency, or emotion that the character must exhibit. For precisely this reason, the concept of a Synthetic Character proves to be ideal for the exploration of the imaginary space between the metaphors of the mind and the superorganism. Because the definition is so broad and all-encompassing, it opens up a wonderful opportunity for designing the most unusual animated creatures. Before closing this point completely, let me illustrate it with several examples of multifarious animated characters. Not all of them qualify as Synthetic Characters, as some lack interactivity while others fall short of the requirement of autonomy. Every one of the examples, however, establishes a significant point of reference in the "character space" and thus suggests a possible direction for further design.

Character Menagerie

Melanie

Melanie is an angry critter. She buzzes around another creature at near-sonic speeds, every now and then exploding to ten times its normal size in a fanged fit of accumulated fury: "Craaak!" In designing Melanie, Kenneth Russell and I wanted to build a character that exhibited a single emotion well. Anger is the emotion we picked, and the character turned into a fast-moving nuisance, perfect for showcasing an extreme case of squash and stretch [Figure 1]. Watching the character act on another synthetic creature quickly becomes entertaining: it is hard not to laugh at the acerbic little monster. Fast-moving and angry, Melanie appears alive and

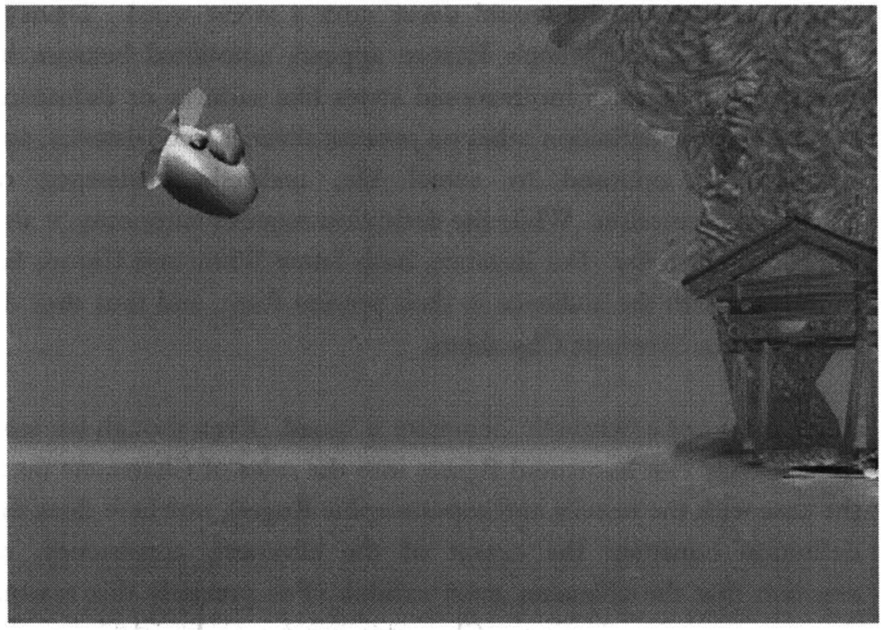

Figure 1: Melanie, an angry critter. Building Melanie was an exercise in communicating a single emotion (anger), as well as in making a fast creature exhibit exaggerated squash and stretch. Unfortunately, Melanie failed as a Synthetic Character because of its lack of interactivity.

emotional. She is also consistent, since she exhibits a limited range of actions without falling out of character or deviating from her role. The problem, of course, is that Melanie is not interactive. There is no way to direct her, and she fails to react to the changes in the environment around her.

SWAMPED! Chicken

The Chicken is a much more complex character. The protagonist of the group's first major demo installation, the Chicken is directed by the user through a plush-toy interface [Figure 2] [Johnson99]. The physical doll provides an intuitive and convenient way of controlling the Chicken on screen that acts as a virtual instance of the doll. The Chicken is consistent, since it never steps out of character. It is interactive, since it reacts to the user's actions as directed through an intuitive and tangible interface. Because it reacts *only*, however, it feels like a puppet and fails to appear alive. When left alone, the chicken simply plays out a single "moving still" animation loop, instead of running around the barnyard, soliciting input from the user, or autonomously chasing the raccoon. Further, the chicken

Figure 2: The author interacting with the *SWAMPED!* demo. The gestures registered by the instrumented plush toy direct the behavior of the chicken. The raccoon sneaks around the world, trying to juggle between its motivation to eat eggs, to explore the world, and to chase the chicken.

exhibits no emotion as its facial expression never changes. While consistent and interactive, the chicken does not appear alive and emotional.

SWAMPED! Raccoon

Perhaps the most successful character to date is the raccoon, the Chicken's nemesis in the demo. A fully autonomous creature, the raccoon follows three motivations: hunger, revenge, and curiosity. If the raccoon gets hungry, he sneaks up on the chicken's eggs and starts eating them one by one. As the chicken squawks, pecks, or kicks at him, the raccoon gets progressively more vengeful and displays his motivational state as anger. After a certain threshold, the raccoon begins chasing the chicken around the virtual world. The raccoon throttles the chicken if he catches it, an action that in turn decreases the raccoon's desire for revenge. After a minute of venting, the raccoon loses interest in the chicken and goes off to pursue some other goal. Finally, when no other stimuli present themselves, the raccoon experiences curiosity and starts exploring the world by alternatively examining the chicken coop, the farmer's house, and the Acme truck. If the chicken squawks at any point, as directed by the user, the raccoon drops what he was doing and runs after the chicken. Being thus directable (or at least prone to disturbance), the raccoon fulfills the interactivity criterion for a Synthetic Character. Furthermore, the raccoon appears emotional as he readily indulges in wild grimacing and gesturing. The raccoon's aliveness comes from his autonomy. Because of his stubbornness in the pursuit of the chicken, and his ability to fall for the same jokes over and over again, the raccoon also feels thoroughly consistent, as he never surprises the user with an action out of character.

Notion of Perceived Intelligence

The characters described in the menagerie above appear intelligent in the eyes of the observer. Of course, the reason one might want to create a character that can be perceived as intelligent is that its design will hopefully reveal insights into the workings of actual functioning intelligence. But focusing on the perception of intelligence instead of on intelligence itself simplifies the problem in two ways. First, we can identify bits and pieces of perceived intelligence and attempt to solve them in relative isolation. Single-minded characters that exhibit partial intelligence of some sort fall nicely into collective theories of the mind that postulate a heterogeneous mixture of proto-intelligent agents. Second, we can use "deceptive" tools, like the art of animation, that have been worked out over the years. Being able to use animation to fake intelligence or aliveness is a significant advantage, since it is a powerful, well-understood, and thoroughly tested tool. A wonderful description of the twelve animation principles that make good animation great is given in *The Illusion of Life* [Thomas81], a book discussing the early years of the Walt Disney animation studio. The creative influence of this book can be identified in many aspects of our group's work on characters, as well as in a number of tricks I used in order to bring the Mask of the Hive to life.

Other authors have focused on the notion of perceived life, among them Valentino Braitenberg. In his book *Vehicles* [Braitenberg94], Braitenberg describes his thought design of eleven simple robotic creatures that appear alive and emotional. His description of the first vehicle of the series, a vehicle with a single sensor and a single actuator that moves faster the more heat is senses, is especially illustrative: "Imagine, now, what you would think if you saw such a vehicle swimming around in a pond. It is restless, you would say, and does not like warm water. But it is quite stupid, since it is not able to turn back to the nice cold spot it overshot in its restlessness. Anyway, you would say, it is ALIVE, since you have never seen a particle of dead matter move around quite like that" [Braitenberg94, p5]. Braitenberg builds up his hypothetical vehicles from simple connections of sensors and actuators, giving a constructive proof of absence of life. Even though lifeless, the vehicles appear alive and emotional because of emergent complexities in the design, interaction with the environment, or mutual vehicle-vehicle entanglements. A similar argument applies to seemingly intelligent characters, where the illusion of intelligence often becomes more important than the intelligence itself. When using characters to explore theories of the mind, then, one must be careful to distinguish between the perceived and the actual.

Superorganism

No child reared on Saturday morning cartoons would be surprised if a cartoon swarm of bees assumed the form of a fighter plane and started chasing a terrified protagonist around the world. In fact, a scene just like that is featured in a Roger Rabbit cartoon *Trail Mix-Up*. The script-writers and animators have bestowed the swarm with a unified mind and a single purpose; they have gelled the swarm into a single character. While trivial, this example shows an echo of a sophisticated scientific model that popular culture has managed to preserve – the model of a superorganism.

The definition of superorganism comes in two steps. First, a colony of ants, bees, or termites can be regarded as an *organism* because it acts as a unified whole to assimilate food and resources, to reproduce, and to survive in hostile and unpredictable environment. The caste differentiation and division of labor in a colony can be compared to those of cells within an organism, as manifested most dramatically by the division between reproductive and non-reproductive units. The activities of the individual insects of the colony are mediated through intricate communication mechanisms. The unit of natural selection is the colony, rather than any individual member insect [WilsonEO90]. Second, such a colony can be called a *superorganism* because it shows two features that collections of subsocial organisms fail to exhibit: mass communication, defined as

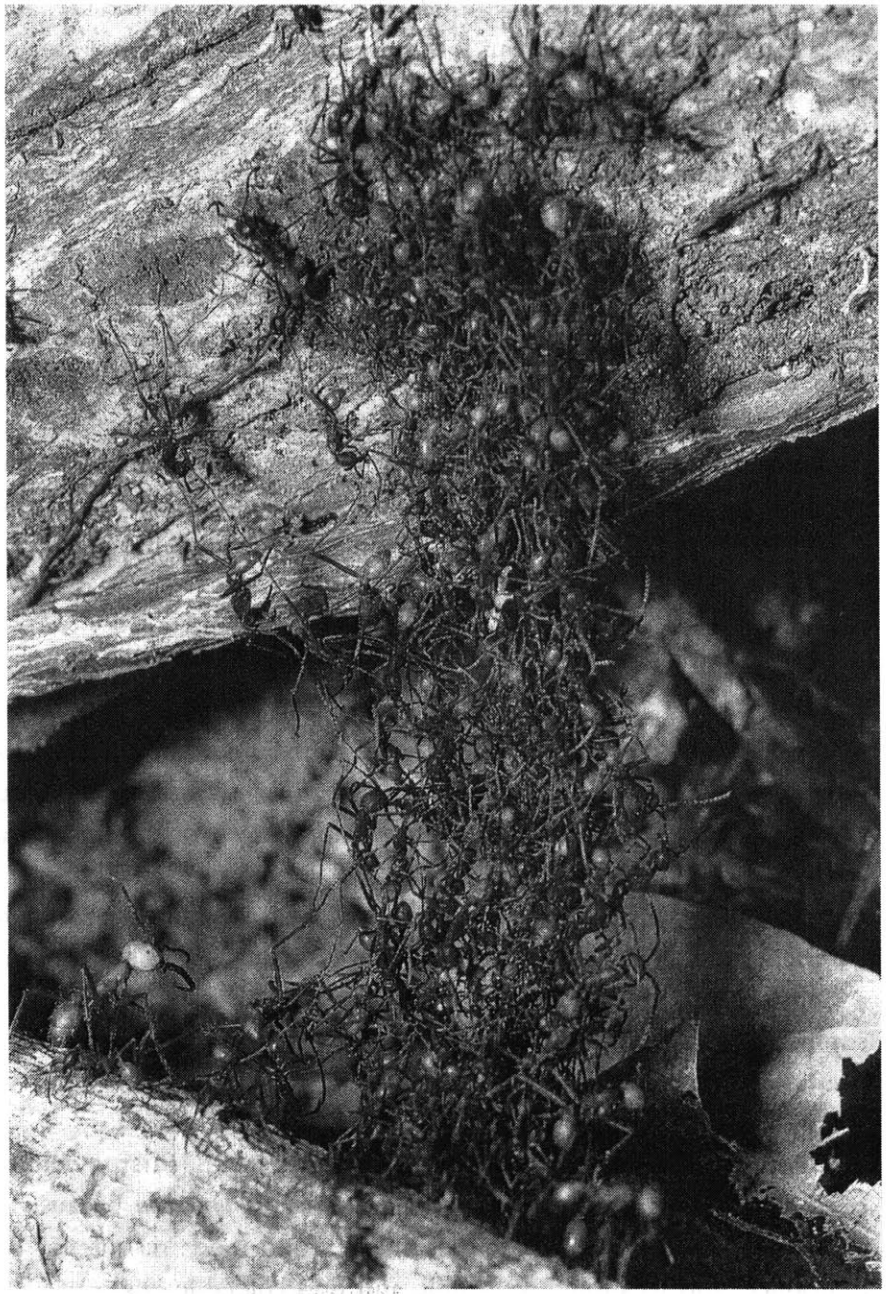

Figure 3: Raider ants *Eciton burchelli* building a bridge from their own bodies. Reprinted from Nigel Franks' journal article *Army Ants: A Collective Intelligence* [Franks98].

communication of information among groups of individuals that cannot be communicated from one individual to another, and adaptive demography, defined as controlled distribution of individual size and caste that serves to promote survival and reproduction of the colony as a whole [WilsonEO90]. It is important to point out that the prefix "super-" in the name "superorganism" does not refer to an extreme form of an organism (as in superman or supermarket), but to an entity that can be placed above the level of a conventional organism because it is itself composed of smaller organisms [Seeley, personal communication]. At the same time, while the name traditionally denotes a unit that is *larger* than its component organisms, it can also be argued that superorganisms are more fit to withstand evolutionary pressures than conventional organisms, and thus score *better* on the scale of evolutionary fitness [WilsonEO90].

Original Argument

William Wheeler was one of the first to point out the resemblance of a colony of social insects to an organism. Even though he never explicitly uses the term superorganism in his 1911 journal article *The Ant-colony as an Organism* [Wheeler11], he argues that it is helpful and illustrative to draw a metaphor between an anthill and an organism. In Wheeler's words, "the most general organismal character of the ant-colony is its individuality. Like the cell or the person, it behaves as a unitary whole, maintaining its identity in space, resisting dissolution and, as a general rule, any fusion with other colonies of the same or alien species" [Wheeler11, p310]. He further discusses the resemblance in terms of the duality between germ-plasm and soma, that, while obviously present in the "person", can also be found in an ant colony, "in which the mother queen and the virgin males and females represent the germ-plasm, or, more accurately speaking the 'Keimbahn', while the normally sterile females, or workers and soldiers, in all their developmental stages, represent the soma" [Wheeler11, p311]. But the most graphic account of this metaphor comes in his description of the colony as a whole: "Undoubtedly, if we could see it acting in its entirety, the ant-colony would resemble a gigantic foraminiferous Rhizopod, in which the nest would represent the shell, the queen the nucleus, the mass of ants the plasmodium and the files of workers, which are continually going in and out of the nest, the pseudopodia" [Wheeler11, p312].

Modern Definition

A strikingly similar picture is painted almost eighty years later by Edward O. Wilson in his work *Success and Dominance in Ecosystems: The Case of the Social Insects*: "Viewed from afar and slightly out of focus,

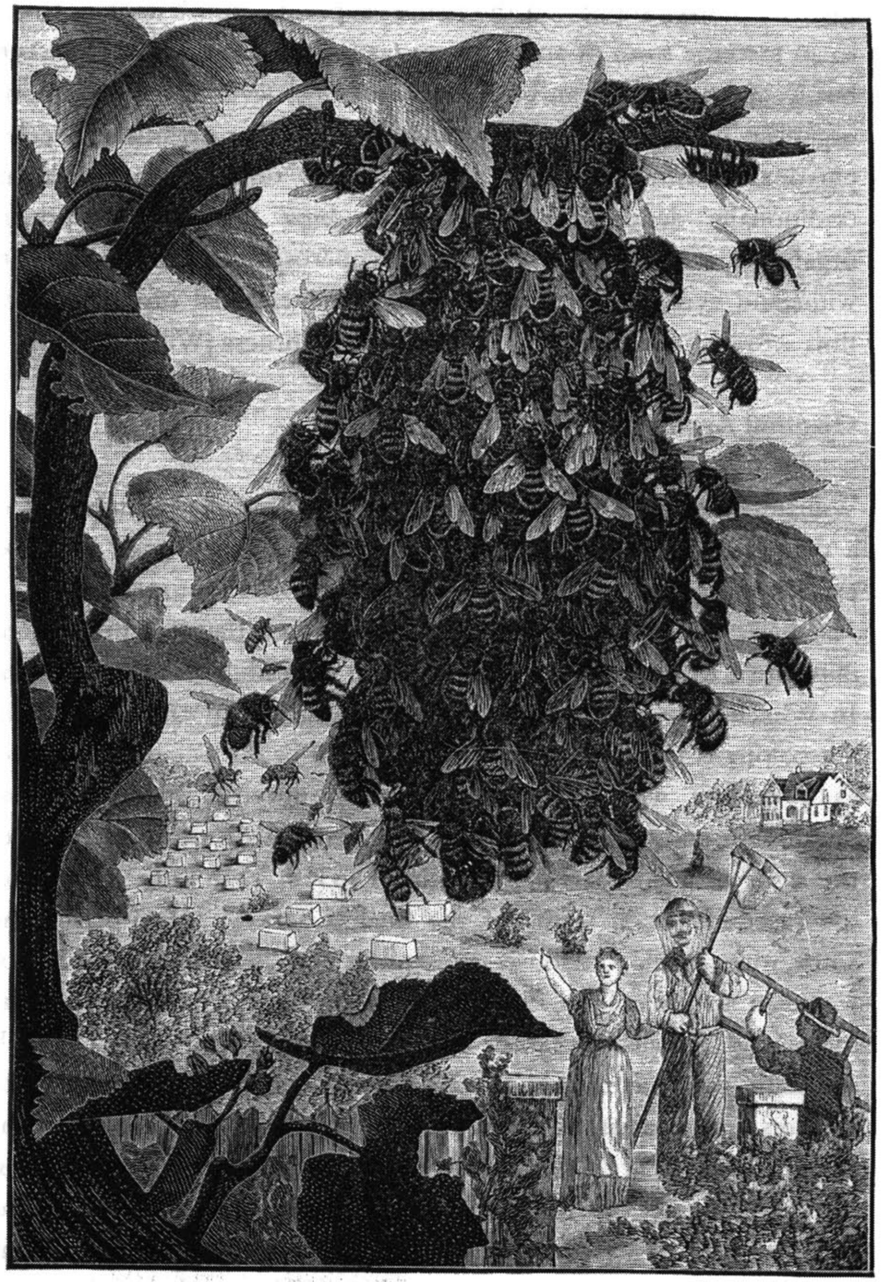

Figure 4: A small afterswarm as pictured in A.I. Root's 1912 guide *ABC and XYZ of Beekeeping* [Root12]. The cluster of bees looks remarkably similar to the "living bridge" of army ants shown in the previous figure.

the raiding column of an African driver ant colony seems a thing apart, a giant pseudopodium reaching out. A closer look discloses a mass of several million workers flowing out from the bivouac site, at first in an expanding sheet, then tree-like, with the trunk growing from the nest, the crown an advancing front, and numerous anastomosing branches connecting the two" [WilsonEO90, p55].

The comparison of an anthill to an organism is not only an amusing exercise, Wilson argues, but means of "meshing of comparable information from developmental biology and sociobiology to reveal more general and exact principles of biological organization" [WilsonEO90, p57]. Wilson distinguishes among three main sets of organismic attributes that a colony of social insects exhibits:

- The workers are equivalent to cells.
- The activities of workers are coordinated by intricate communication.
- The unit of natural selection is the colony.

Further, Wilson describes two major features that distinguish superorganisms from regular or collective organisms, and place the former above the latter in the evolutionary race, mass communication and adaptive demography. Mass communication is the "transmission of information among groups of individuals within the colony of a kind that cannot be exchanged between the individuals alone" [WilsonEO90, p72]. Wilson lists several examples from the world of formicids, among them an account of territorial "tournaments" between different colonies of the honeypot ant *Myrmecocystus mimicus*. If a colony discovers another in the vicinity of a food source, some of the foragers rush home and recruit hundreds of workers. The raiders engage all workers emerging from the alien nest in an elaborate dance, a show of force, in which the use of mandibles or formic acid, deadly weapons available to the ants, are used rarely if ever. The ritualized performance appears to be means of assessment of the colony strength. Invariably, the colony with a smaller number of foragers retreats from the scene [WilsonEO90].

The second feature distinguishing superorganisms form collective organisms, adaptive demography, is defined as "the programmed schedules of individual birth, growth, and death resulting in frequency distributions of age and size in the colony members that promote survival and reproduction of the colony as a whole" [WilsonEO90, p62]. Ordinary demography of non-social insects is a by-product of the parameters of individual growth, reproduction, and death. These parameters are shaped by natural selection operating at the level of an individual. Adaptive demography of social insects, however, is shaped by natural selection on the level of the colony, since the birth and death schedules of the worker caste make sense only with respect to the queen. It serves to produce the greatest possible number of new colonies in the next generation, not the greatest possible number of workers in the current generation [WilsonEO90]. Arguably, social insects have thus developed mechanisms that favor them in the evolutionary race against sub-social and non-social species.

Focus on the Individual

Most interestingly, the obvious unity of a colony of social insects can be explained through simple mechanisms that occur at the level of an individual. In Wilson's words, "the individual colony member does not have to perform in an extraordinary matter. Quite the contrary, it can have a simpler repertory than that of an otherwise similar solitary insect. ... The worker need operate only with cues, or rules of thumb, which are elementary decisions based on local stimuli that contain relatively small amounts of information" [WilsonEO90, p62]. Wilson even provides an algorithm that describes the activity of a single ant: "*continue hunting for a certain foodstuff if the present foraging load is accepted by nestmates, and do so avidly if the load is accepted quickly; follow an odor trail if sufficient pheromone is present; and retreat if many enemy workers are encountered in a short time, especially if a high proportion of them are large individuals*" [WilsonEO90, italics in the original]. Such line of reasoning, invoking decentralized principles that seem to result from convergent thinking in biology, artificial life, computer science, and other fields, might be able to explain many of the high-level emergent phenomena exhibited by superorganisms in nature.

Level of Emergence

> But the biologist, with his present methods is powerless to offer any solution of the living organism as a whole. He cannot appeal to the entelechy or *elan vital* however suggestive and emotionally satisfying such agencies may be to the philosophers, nor does it help him to be told that a swarm of bees or a colony of ants or termites has a 'superentelechy', 'une ame de la ruche', or spirit of the hive, to use the terms of Reaumur and Maeterlinck, concieved as controlling the entelechies of the various individuals. ... We can only regard the organismal character of the colony as a whole as an expression of the fact that it is not equivalent to the sum of its individuals but represents a different and at present inexplicable 'emergent level' ...
>
> **The Social Insects**
>
> By William Morton Wheeler, 1928

Having suggested that organismic or superorganismic features as found in colonies of social insects can be explained through descriptions of activity on the level of an individual, we should say a bit about this mysterious emergence. Wilson discusses this phenomenon in the following passage, that refers to the "rules of thumb" he postulates for each individual ant: "Each of these cues is easily followed by individual workers. The required actions are performed in a probabilistic manner with limited precision. But when put together in the form of heterarchies involving large numbers of workers engaged in mass communication, a larger pattern emerges that is strikingly different and more complicated in form, as well as more precise in execution" [WilsonEO90]. While the idea of emergent complexity is intriguing, as it stands it does little in a way of suggesting a constructive approach to building a similar system. In fact, Minsky warns us in his *Society of Mind* that "we're often told that certain wholes are 'more than the sum of their parts'. We hear this expressed with revered words like 'holistic' and 'gestalt', whose academic tones suggest that they refer to clear and definite ideas. But I suspect that actual function of such terms is to anesthetize a sense of ignorance. We say 'gestalt' when things combine to act in ways we can't explain, 'holistic' when we're caught off guard by unexpected happenings and realize we understand less than we thought we did" [Minsky87, p27]. To find a way out of trouble, let us consider the third concept, that of a decentralized mindset.

Decentralized Mindset

In the summer of 1987, a video screen flickered in front of a roomful of computer graphics enthusiasts. Flat-shaded triangle-shaped creatures floated gracefully above a virtual checkered floor, moving conspicuously like a flock of birds or a school of fish. The rules governing the strikingly realistic motion were all local to each of the creatures, argued Craig Reynolds, the author of this seminal work on "boids" [Reynolds87]. Every one of the boids simply watched other boids in its field of view, while constantly adjusting its own speed and heading to reach the center of the cluster created by its neighbors. As a result, the group as a whole exhibited motion remarkably close to that of a real flock [Figure 5]. Reynolds has thus shown in simulation that a flock of birds or a school of fish does not require a leader. To the contrary, the seemingly purposeful and centrally-

Figure 5: Reynolds' boids exhibiting flocking behavior. Reynolds was one of the first to show in simulation that no centralized control is needed to create unified and coordinated motion similar to that exhibited by flocks of birds and schools of fish [Reynolds87].

governed motion can arise from a fully decentralized set of rules. Reynold's work represents a single instance of a larger trend in today's culture – a shift toward decentralization.

Turtles, Termites, and Traffic Jams

This shift is best described in Mitchel Resnicks' work *Turtles, Termites, and Traffic Jams* [Resnick94]. Hands-on programming exercises, illustrated by examples of self-organizing phenomena, and explained through vivid commentary and classroom anecdotes, fall neatly to place under Resnick's guidance and paint a picture of the society dominated by a centralized mindset yet permeated by phenomena of completely decentralized nature. Inspired by the way simple parts are able to organize themselves into complex and sophisticated wholes, Resnick has designed an extraordinary set of tools to help children think about self-organizing systems. He offers a set of "guiding heuristics" that help the reader discover, investigate, or create a decentralized system:

- *Positive feedback isn't always negative.* Many people perceive positive feedback as being destructive, a spiral that sends things out of control. Negative feedback, on the other hand, has the image of a regulatory mechanism that damps out fluctuations and establishes equilibrium. Resnick argues that in conjunction with negative feedback, positive feedback is crucial to any decentralized system, because it "creates and extends structures" [Resnick94, p136].
- *Randomness can help create order.* Despite its negative image of an "antiorder", randomness is also important in the rise of structures. In many decentralized, self-organizing systems, random fluctuations play two roles: they "act as the seeds from which patterns and structures grow", and they "make possible the exploration of multiple options" [Resnick94, p138]. For instance, a traffic jam may not be caused by an external radar trap, but by an internal seed-like group of cars arising from random fluctuations of the speeds of individual cars. Similarly, random search patterns performed by foraging ants allow the ant colony to explore multiple food sources in parallel. While positive feedback allows for *exploitation* of a particular resource, randomness allows for *exploration* of multiple resources.
- *A flock isn't a big bird.* The idea of levels is critically important in decentralized systems. An activity of units on one level will give rise to a new type of units at another level. For instance, interactions among birds give rise to flocks. Because the two are units on different levels, it is misleading to think of birds interacting with flocks. In this sense, birds only interact with other birds.
- *A traffic jam isn't just a collection of cars.* Objects like flocks of birds or traffic jams can be thought of as "emergent objects". A traffic jam is not composed of the same static set of particular cars; it changes its composition as some cars join it from behind and others leave from the front. Resnick argues that the traffic jam remains a constant object, even though its composition keeps changing.
- *The hills are alive.* People often think of the environment as a passive entity, something to be merely acted on. In reality, complex behavior often rises from the interactions of simple creatures with complex environment. Especially in decentralized systems, the environment plays a crucial role,

since it enhances the interactions between individuals by taking away a part of the communication load. For instance, ants that lay down pheromone trails to attract other ants to a source of food rely implicitly on the evaporation of the pheromone that makes the trails disappear once they are no longer relevant. Once the source of food is depleted, the ants do not need to lay down a second trail that cancels the first one; the environment "takes care" of the trail for them.

A number of instances of several of these heuristics can be found in the implementation of the Mask of the Hive. Positive feedback plays an important role in the recruitment of forager bees. The random search pattern of both the scout and the explorer bees allows the hive to explore the space around it. The idea of levels is critical to the performance of the synthetic character, as the activity of individual bees gives rise to 'teams' that perform a given tasks. Such teams, visualized as vibrant pools of color, result in the changes of facial expression of the mask, a higher-level entity. Both the teams and the changes of the expressions can be regarded as emergent objects, since they retain a consistent presence even though their composition changes over time. Finally, the environment is the active medium through which the user interacts with the character.

Society of Mind

Armed with a framework to think about self-organizing systems, we shall examine another work stemming from the decentralized mindset, Marvin Minsky's *Society of Mind* [Minsky87]. Minsky argues that intelligence can arise from societies of interconnected, mutually interacting agents, each of which performing only a simple task that requires little or no intelligence. Across 30 chapters of 270 single-page essays, Minsky paints a picture of the mind that is composed of smaller, partially interacting units. Not all the units, groups, or hierarchies are similar, however, as the theory postulates a *heterogeneous* mixture of functional parts. While most parts communicate among each other in multiple ways, not all connections are in place and some parts do not communicate with others at all.

Society of Mind has become a flagship of decentralized theories of mind. Besides decentralism, it imposes no particular philosophy on the component parts. In fact, Minsky encourages exploration of localized ideas that may provide models for parts of the human mind and contribute to the larger mixture of ideas. He believes that it is too early to begin discarding immature or incorrect ideas and models, one must still focus on generating more of them [Minsky, class lecture]. This study attempts to make a step in that direction by identifying a particular domain of inspiration – the cross between superorganism and society of mind.

Other computer scientists have embraced decentralized theories, in particular with respect to explaining consciousness and intelligence. Rodney Brooks designed a "subsumption architecture" for controlling mobile robots. In his work, simple behavior modules execute on several layers of a hierarchy. The modules placed on higher levels have the ability to override the function of modules placed on lower levels and thus interject meaningful structure into otherwise simple behavior [Brooks85]. Daniel Dennett offers a "multiple drafts" model of consciousness, that postulates creation and existence of multiple intertwined narratives within the brain [Dennett91]. These seminal works and concepts have influenced numerous subsequent explorations.

Anteater: ...Ant colonies don't converse out loud, but in writing. You know how ants form trails leading them hither and tither?
Achilles: Oh, yes – usually straight through the kitchen sink and into my peach jam.
Anteater: Actually, some trails contain information in coded form. If you know the system, you can read what they're saying just like a book.
Achilles: Remarkable. And can you communicate back to them?
Anteater: Without any trouble at all. That's how Aunt Hillary and I have conversations for hours. I take a stick and draw trails in the moist ground, and watch the ants follow my trails. Presently, a new trail starts getting formed somewhere. I greatly enjoy watching trails develop. As they are forming, I anticipate how they will continue (and more often I am wrong than right). When the trail is completed, I know what Aunt Hillary is thinking, and I in turn make my reply.

... Ant Fugue from **Gödel, Escher, Bach**
By Douglas Hofstadter, 1979

models

CHAPTER 3

Much like the three concepts of the previous chapter, the following three models have provided a major source of inspiration for my thesis work: Douglas Hofstadter's charming account of an anteater conversing with an ant colony, Thomas Seeley's descriptive model of decentralized decision-making in swarms of honey bees, and Bruce Blumberg's ethology-inspired behavior and action-arbitration system. The models are organized from the most abstract to the most concrete, as Hofstadter's writing describes a highly inspiring, yet hypothetical and perhaps unrealistic encounter; Seeley's model provides a well-grounded and thoroughly executed evaluation of the behavior of real bees, and Blumberg's system brings in a functioning implementation based on several major ethological theories. Each of the three models thus contributes a unique nugget to the final medley: an elusive ideal, a realistic model, and a generative tool.

Talking to Ants

Hofstadter's Ant Fugue

The over-arching inspiration for this work comes from the pen of Douglas Hofstadter. A passage in his book *Gödel, Escher, Bach: An Eternal Golden Braid* [Hofstadter79] describes an anteater conversing with Aunt Hillary, an anthill, and serves to explain the difference between a holistic and a reductionist approach to a complex phenomenon. While Tortoise, Achilles, and Dr. Anteater, the heroes of the book's numerous dramatic sequences, listen to one of Bach's fugues, they indulge in a conversation that quickly gravitates toward Dr. Anteater's peculiar occupation – anthill neurosurgery.

As inquisitive Achilles bombards the anteater with a battery of pointed questions, a quaint picture emerges. Instead of becoming a mortal enemy, Dr. Anteater is actually the favorite conversation companion of Aunt Hillary. He addresses the anthill by drawing shapes into in the moist ground, and deduces her replies by reading the trails of ants that develop in response. Because of the peculiar nature of his companion, the anteater is able to point out several layers of structure that Aunt Hillary exhibits while talking to him. The bottom layer consists of ants that have limited localized knowledge of their surroundings, and are wholly unaware of any higher levels of structure. The following levels in the hierarchy are those comprised of 'signals', which are teams of ants that form in order to fulfill a particular task, 'symbols', which are active subsystems composed of lower-level signals, and 'agents', which are partially constant and partially varying systems of symbols. In the end, the faculties of thought, consciousness, and speech readily arise emergent from the multiple levels of structure, and Aunt Hillary comes across as a fully sentient being.

While perhaps a bit whimsical, Hofstadter's account of this amusing conversation describes exactly the space between the two metaphors that lies at the center of my argument. In particular, if groups of ants are capable of communicating high-level information that cannot be conveyed by any individual ant, why cannot such communication arise among groups of agents, hypothetical functional units of the mind? Even further, one could argue that consciousness or emotion are emergent phenomena arising from "transmission of information among groups of individuals within the colony of a kind that cannot be exchanged between the individuals alone" [WilsonEO90], or what Wilson calls 'mass communication' in superorganisms. This train of thought is different from the view of classical AI that often postulates a single centralized agent that solves a problem by consecutively applying heuristic rules. Quite the contrary, this view is decentralized in its nature and fits well into the framework described by Minsky, Resnick, and others.

Franks' Army Ants

While Hofstadter operates from the position of a cognitive scientist who seeks his inspiration in biology, a number of biologists have arrived at similar ideas starting from biology and casting their imagination toward cognitive science. Inspired by extraordinary feats of maraudering amry ants, Nigel Franks speculates that "it seems that intelligence, natural or artificial, is an emergent property of collective communication. Human consciousness itself may be an epiphenomenon of extraordinary processing power" [Franks89, p139]. Further, rational manipulation of symbolic information is "exactly what happens when army ants pass information from individual to individual through the 'writing' and 'reading' of symbols, often in the form of chemical messengers or trail pheromones, which act as stimuli for changing behavior patterns" [Franks89, p 139].

Franks backs up his claims with a description of a remarkable superorganism, a colony of army ants. The colonies of these insects are huge, some containing up to 20 million individuals. Army ants have evolved to prey on large arthropods and small mammals, a fact that dictates the organizational features of these colonies. Large prey necessitates large colonies, since many ants must act in concert to capture and to transport the prey to the nest. In turn, large colonies deplete their foraging areas quickly and must move in order to survive, hence the nomadic life style. Since large colonies are necessary for survival, they propagate by splitting into two rather than by solitary queens [Franks89]. The organizational patterns of such complex colony are intriguing. During a raid, a single *Eciton* *burchelli* colony will retrieve 30,000 items of prey in a single day, facing a mammoth problem of optimizing transportation costs. A specialized caste of large workers that carries out most of the transport has evolved, since transport costs decrease with increasing vehicle size. Most strikingly, Franks postulates that all workers carrying prey move at the same speed, thus avoiding traffic jams. The members of the large transportation caste will also often carry individuals of the smallest worker caste during migrations, presumably because the transportation cost is lower than if both castes traveled on their own.

However, Franks' decentralized models sometimes suffer from a shade of a centralist mindset. He explains the existence of a standard retrieval speed through a decentralized algorithm that an ant might follow: "if there is a prey item in the trail moving below the standard retrieval speed, and you are not carrying an item, then help out; otherwise continue. Once the standard retrieval speed is achieved, no other ants join the team" [Franks89, p142]. While Franks points out that "no individual chooses the team, the individuals select themselves", he assumes the existence of a centralized parameter of "retrieval speed". Drawing on the work of Resnick [Resnick94] and others, one might postulate that the "retrieval speed" is itself an emergent epiphenomenon, arising as a result of local ant-to-ant interactions. In any case, a decentralized explanation of the collective behavior of raider ants is most likely the way forward.

Dancing with Bees

Seeley's Beehive Model

> Even though the swarm as a whole is a highly sophisticated and accurate decision-making agent, the cognitive skills required of the individual bees appear to be surprisingly simple.
>
> **Decision making in Superorganisms**
>
> By Thomas Seeley, 1999

> Each mental agent by itself can only do some simple thing that needs no mind or thought at all. Yet when we join these agents in societies – in certain very special ways – this leads to true intelligence.
>
> **Society of Mind**
>
> By Marvin Minsky, 1986

The most thoroughly studied insect species on the planet, *Apis mellifera* or the common honey bee, exhibits an extraordinary range of activities. In addition to living, breathing, flying and walking, collecting nectar, and producing honey, a bee seems to be able to participate in a distributed decision-making process. In particular, towards the late spring and early summer, when a mass of bees outgrows its current hive, a swarm splits from its mother colony. The mother queen becomes one of many, a single insect in a swarm of thousands. It leaves the hive with approximately half the workers, while leaving a daughter queen and the remaining workers behind. Within 20 minutes, the swarm finds a branch and sits. A small number of scouts flies out and starts surveying the countryside for potential nesting grounds: a south-facing cavity not too small, with an entrance in the lower half. Deserted honey combs already present are also a big plus. Successful scouts return to the swarm and use the waggle dance to communicate the location of the cavity to others. As some cavities are better than others, a real 'debate' develops on the surface of the swarm. After about two days of negotiations, the swarm lifts off and heads to the best cavity found [Seeley99a, Seeley99b].

How does the swarm as a whole make a decision on a complex issue when, arguably, none of its single members have a full knowledge of the situation? How do masses of poorly informed individuals converge on an optimal decision? Thomas Seeley has studied this peculiar phenomenon for several years. In a published study [Seeley99a], Seeley describes the site-selection behavior of three distinct swarms. Each swarm was artificially created and contained a single queen together with about 4000 labeled workers. Seeley videotaped every performed dance, deciphered the location it advertised, recorded the time of the dance, the performing bee, and the number of waggle runs, and, finally, processed that mass of information into a series of plots. His analysis of this phenomenon is thorough and insightful. He describes the activities of the swarms from both a group- and an individual-level perspective.

Group-level View

Through the painstaking task of deciphering dozens of hours of video footage, Seeley was able to obtain data of unprecedented detail.

He uses the data as a basis for a behavioral model that thoroughly describes the task at hand. Seeley identifies six principles that summarize the activities of the swarming bees [Seeley99a]:

- The scout bees locate sites in all direction from the hive, and at distances up to several kilometers from the hive.
- Initially, the scouts advertise a dozen or more potential sites, but eventually they advertise only one.
- Within an hour or so of the appearance of unanimity among the dancers, the swarm lifts off.
- There is a crescendo of dancing just before lift-off.
- The chosen site is not necessarily the one that is first advertised on the swarm.
- In some swarms, decision making is fairly simple, with only one site receiving strong advertising, while in other swarms, the decision making is complex with multiple sites simultaneously receiving strong advertising.

These qualitative features serve as strong guides for building a system that attempts to mimic the behavior of a real colony. In order to stay true to a decentralist mindset, however, one must pay attention to the behaviors performed by the individuals. If an individual-based model gives rise to a qualitative performance similar to that of a real colony, it can serve as a possible explanation for the phenomena observed in nature. Of course, it may not be taken as a conclusive proof of the theory, but only as a candidate explanation.

Individual-level View

In the perspective of a decentralized mindset, a detailed individual-level view is crucial to developing a successful model. Seeley provides a precise summary of a behavior of an individual bee involved in the negotiations and backs it up by exact numbers:

- A relatively small number of bees participates in the advertising process, 2.0–4.1% of the bees, which accounts for a large absolute number of bees, 40–240, in a medium-sized swarm (2000–6000 individuals).
- While a large majority of the dancing bees (76–86%) advertises one site only, a small minority (11–22%) dances for

two sites, and only a tiny percentage (2–3%) dances for three or more sites.

- There is a high dropout rate among the dancers.
- While some bees will switch their allegiance from one site to another,
- Only a small minority of the dancers ever dances for more than one site.
- The principal means of consensus building among the dancers is for dancers advertising the non-chosen sites to cease their dancing, rather than to switch their dancing to advertising the chosen site.
- Nearly half of the bees initially advertising the *chosen* site will cease their dancing before the end of the decision-making process.

Perhaps the most striking result of Seeley's analysis is the discovery that most bees do not switch their dancing from one site to another; instead, they cease their dancing altogether. Among the bees that initially danced for the site that was not chosen, a large majority (67-80%) ceased their dancing, only a small minority (20-33%) switched to dancing for the chosen site, and none of the bees kept dancing for the non-chosen site. Among the bees that initially danced for the chosen site, however, less than half of the bees (19-48%) ceased their dancing, none switched to dancing for a non-chosen site, and more than half (52-80%) continued dancing until the lift-off. Thus, "a process of building a consensus among the dancing bees relies more upon bees ceasing to dance than upon bees switching their dances to the chosen site" [Seeley99b].

Since ceasing of the dancing seems to play a crucial role in the decision-making process, one must ask why the bees stop dancing. Seeley believes that "scout bees have an internally driven tendency to stop dancing for a site" [Seeley99b]. The data suggest that both scouts dancing for the non-chosen and scouts dancing for the chosen site exhibit a tendency to drop the number of waggle runs per dance over time. In my implementation, I chose to follow this suggestion, as a bee's motivation to advertise drops off over time. As soon as the motivation dissipates, the bee stops advertising and flies out to look for another source of nectar. Of course, my choice of this mechanism plays no role in determining whether it actually takes place in nature.

Mimicking Animals

Blumberg's Behavior Model

The synthetic creature I present in this work has been implemented under the Synthetic Characters behavioral framework, a system based on original research conducted by Bruce Blumberg and built under his direction by members of the Synthetic Characters group. In his original work [Blumberg97], Blumberg defines four major requirements for a successful synthetic creature that in turn dictate the necessary design characteristics of the supporting system: relevance, adaptation, expressiveness, and control. By 'relevance' Blumberg means that "the behavior must make sense" [Blumberg97]. At every instance, a creature must choose the action that makes the most sense, based on the creature's perception of the environment, its internal state, and its repertoire of possible actions. Adaptation means learning, as the creature should modify its behavior based on its previous experience and on its previous interactions with the user. Expressiveness is important since the most complex behavior will be lost unless it is properly conveyed to the user. This part of the work draws heavily on principles of good animation as worked out and itemized by professional feature animators over the years (see for instance, *The Illusion of Life* [Thomas81], *Principles of Traditional Animation Applied to 3D Computer Animation* [Lasseter87], or *[digital] Character Animation* [Maestri96]). Finally, the user must be in control of the creature. Although this point may sound obvious, its solution is non-trivial, since a delicate balance between control and autonomy must be established. Too much control turns the creature into a mere digital puppet, while too much autonomy leaves the user out of the loop [Blumberg97].

Any creature implemented under the Synthetic Characters behavior toolkit consists of three major subsystems: Behavior System, Motor System, and Graphics. Each of the systems is separated from its neighbor by a layer of abstraction; a layer of Actions resides between the Behavior System and the Motor System, while a layer Degrees of Freedom (DOFs) separates the Motor System from the Graphics [Figure 6].

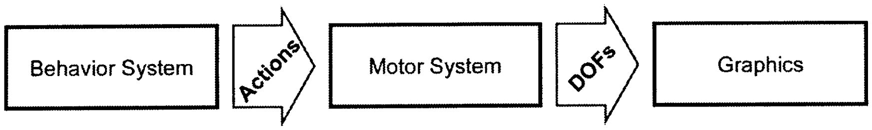

Figure 6: Behavior System, Motor System, and Graphics. Any creature consists of these three building blocks that are isolated by two layers of abstraction, a layer of Actions and a layer of Degrees of Freedom (DOFs) [Blumberg97].

Behavior System

Choosing the correct course of action when faced with an unpredictable and likely hostile environment, a wide range of possible behaviors, and a complex set of internal drives and motivations, involves a complicated decision process that every living and surviving creature must carry out routinely and with success. Blumberg's computational model that solves this problem is based on an ethologically inspired "network of self-interested, goal-directed entities called Behaviors" [Blumberg97]. Behaviors are organized into exclusion groups, in which, by definition, only one Behavior is active at any given moment. Further, Behaviors can act as parent nodes of behavior groups, and thus a tree-like network hierarchy can be built. On every update cycle of the system (every tick), every Behavior computes a single numerical value that represents the relevance of that Behavior under that specific set of conditions. This relevance value is used in the competition among the Behaviors within an exclusion group that is controlled by a mutual inhibition scheme originally suggested by Minsky and others [Minsky87, Braitenberg94]. On every tick, therefore, the system decides which chain of Behaviors is most relevant, and gives it a full control of the Motor System.

Sensors, Transducers, Accumulators

In Kline's elegant implementation of Blumberg's system [Kline99], the full behavior of any creature can be defined by using only three fundamental building blocks: Sensors, Transducers, and Accumulators [Figure 7]. A Sensor has access to all objects in the world, and it retrieves a list of relevant objects based on taxonomy or filter functions. A Transducer takes this list of objects and outputs a numerical value. For instance, a TaxonomySensor called

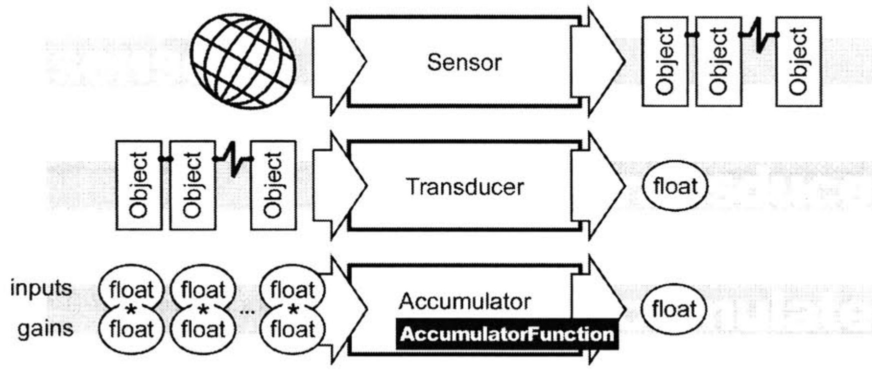

Figure 7: A schematic of the three fundamental building blocks of Blumberg's behavior system [Blumberg97] as designed and implemented by Kline [Kline99]. A Sensor looks at the world, extracts the appropriate objects and serves them in the form of a list of objects. A Transducer acts on such lists and produces a floating point number. An Accumulator then takes floats as inputs and gains, multiplies the respective pairs and applies an Accumulator Function to the resulting list. It outputs a float.

BEE_SMELL_SENSOR will output a list of all world objects that are BEEs. If the output of BEE_SMELL_SENSOR happens to be linked into the input of a COUNT_ALL_INPUTS Transducer, the output of the Transducer will contain a floating point number that corresponds to the number of all the bees in the world. Finally, an Accumulator takes a list of inputs and weights (all floating point numbers), multiplies the respective pairs, and applies an AccumulatorFunction to the list of floats. In other words, v = AccumulatorFunction($input_1*gain_1$, $input_2*gain_2$, … , $input_n*gain_n$). The most common AccumulatorFunction turns out to be a simple sum, but clamped sum, ramp, and fire-on-change are also often used. All three fundamental primitives are implemented as nodes in the behavior graph and can be connected in numerous ways as long as their input and output types match. For example, in order to connect a Sensor to an Accumulator, one must insert a Transducer to convert the list of objects that the Sensor produces as output into a floating point number that the Accumulator accepts as input.

Behaviors, Motivations extend Accumulator

Multiple nodes serving a more specific purpose can be derived from the three building blocks. For instance, a Behavior is a subclass of Accumulator, since it needs to take its inputs, multiply them by its weights and use an AccumulatorFunction to calculate its relevance on each tick. In addition to inheriting the basic Accumulator functionality, a Behavior needs to invoke action callbacks for being turned on, running active, or being turned off. The callbacks then create Actions that tell the Motor System what to do. Implementing the Behavior node as a subclass of Accumulator thus makes the most sense and reaps the advantages of elegant, object oriented design.

A bit of a shortcut, the Motivation node is another subclass of Accumulator. Given the experience of building several creatures, the group noticed that a particular way of setting up the inputs of an Accumulator became prevalent. We needed Accumulators that would sharply output a high value upon receiving a stimulus and then let the value abate over time. Instead of manually hooking up the Accumulator's own output as one of its inputs and multiplying it by 0.9, we encapsulated this functionality in a Motivation node. The output of a Motivation is then given by v_t = AccumulatorFunction($input_1 * gain_1$, $input_2 * gain_2$, ... , $input_n * gain_n$, $v_{t-1} * (1\text{-}gain)$, growth). With fire-on-change Accumulator hooked up to its input, gain = 0.1, and growth small or 0, we get an output curve that peaks quickly and then dissipates in an exponential fashion.

Motor System

The Motor System receives Action primitives from the Behavior System and insures that the creature carries them out through the most consistent and expressive motion possible. A typical Action contains the name of the Motor Skill it requires for its execution as well as a set of parameters for the skill. A Motor Skill is an encapsulation of a modular fragment of a keyframed animation that has been created by hand in an animation package, typically 3D Studio MAX. All of the animated joints of a skeletal creature (or any other animated parameters) are in turn encapsulated as DOFs. The Motor System executes blending, superposition, and interpolation of the keyframed animations in such a manner as to ensure seamless transitions between motions (for example, a standing creature needs to transition into a walk), natural layering of motions executed in parallel (a walking creature raises arm and scratches its head), and continuous interpolation of emotionally charged sample animations (a creature walking sadly gradually brightens up and starts trotting happily, without stopping or discontinuities). The Motor System is complex and well suited for creation of humanoid figures. For my implementation of a disembodied character, however, only simple animation playback was used.

Graphics

The Graphics layer resides on the very bottom of the hierarchy. Its purpose is to manage the scene graph, a tree-like data structure that contains the geometry of the creatures and the world, and to render it on screen as quickly as possible. The Graphics receives updates from the Motor System in the form of DOFs and converts them into geometrical transforms (translations, rotations, and scales) that affect the underlying geometry. A full description of the Synthetic Characters' fast Graphics layer can be found in a paper by Russell and Blumberg [Russell99].

Anger of Bees. I confess I do not like the term "anger", when applied to bees, and it almost makes me angry when I hear people speak of their being "mad", as if they were always in a towering rage, and delight in inflicting exquisite pain on everything and everybody coming near them. Bees are, on the contrary, the pleasantest, most sociable, genial and good-natured little fellows one meets in all animated creation, when one understands them. Why, we can tear their beautiful comb all to bits right before their very eyes, and without a particle of resentment; but with all the patience in the world they will at once set to work to repair it, and that, too, without a word of remonstrance. If you pinch them they will sting, and anybody who has energy enough to take care of himself would do as much, had he the weapon.

ABC and XYZ of Bee Culture

By A. I. Root and E. R. Root, 1908

implementation

CHAPTER 4

Models Combined

The implementation of the Mask of the Hive is a result of a two-way combination of models. First, I combined the models of two distinct classes of bee behavior, namely nectar collection and nest site selection, into a somewhat less realistic single simulation. Second, I combined Seeley's model of a bee colony with Blumberg's model of animal behavior by implementing the former under the latter. I shall describe each of the combinations in turn, and follow with a detailed description of the implementation of the individual bees.

Combining nectar collection with nest site selection was merely an aesthetic choice. The two activities occur at different times in nature;

only swarming bees perform the nest site selection process, while only bees well established in a nest site collect nectar. My implementations of the two processes can be run separately (as they take place in nature) or together in order to generate a wealth of information for the interactive character. It must be pointed out that the two models do not interact, as the sets of bees participating in each model fail to communicate across the model boundaries. Running the models alongside each other is therefore only beneficial with respect to providing a more complex set of parameters that the Mask of the Hive displays.

The combination of Seeley's model of bee behavior and Blumberg's behavioral framework dictated several design decisions. Every bee is treated as a behavior creature with a distinct set of drives and motivations. It has its sensors turned out onto the world as well as in onto itself, and at every tick it determines the most relevant behavior for the given configuration of sensor readings. Further, instead of implementing a single complex bee that assumes multiple behavioral roles within the colony, I chose to implement a number of simpler bees, one for each of the necessary behavioral roles. In other words, while a real bee is able to participate in all the activities of the hive (rearing the brood, collecting nectar, or partaking in the decision-making), I opted to design specialized bees that perform only a single activity each. While quite unnatural, this solution allowed for explicit enforcing of the division of labor that emerges in nature, and thus simplified the overall model. Fortunately, the modularity of the behavior system allows for defense of this design decision: since a behavior group can be placed at any level in a hierarchy, one can easily take the full behavior hierarchies of each of the individual bees and combine them into a single "omnibee" by grouping the hierarchies under a new top-level behavior group. This behavior group will then arbitrate between the top level actions of the bee, deciding whether the bee should collect nectar, search for cavities, or participate in the decision-making process. Since such an omnibee can be constructed by a mere combination of the simpler bees, I decided to keep the bees separate for the sake of clarity. I shall refer to the individual bees that fulfill separate behavior roles as *types*.

Since the implementation involves a number of simple distinct bee types, one could argue that I used the system to implement beings less complex than those for which it was designed, a higher-level

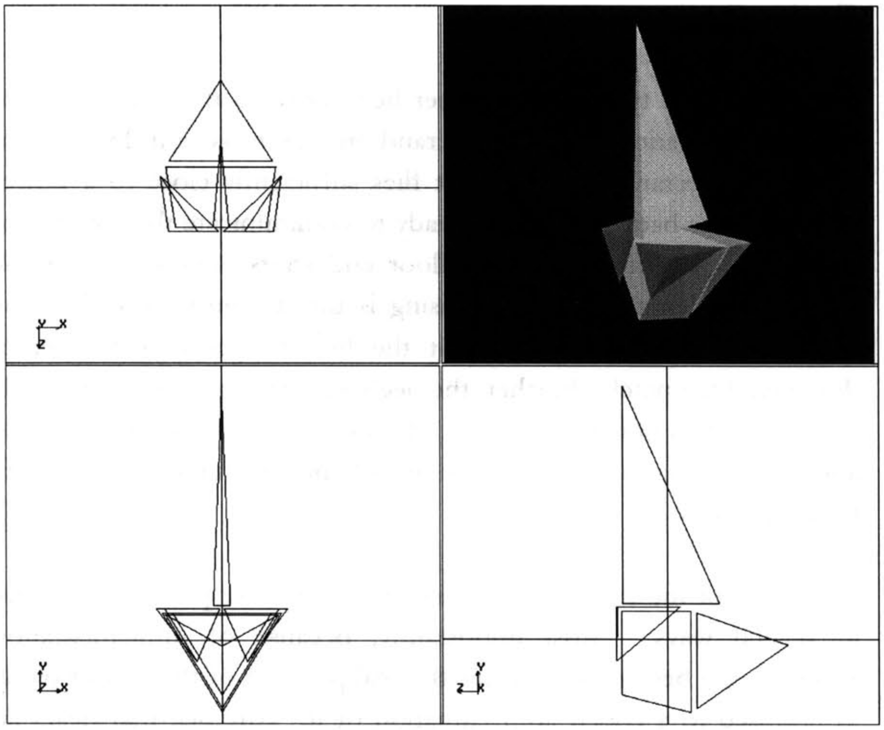

Figure 8: A three-view of the simplest bee model. In order to keep the polygon count low, the emphasis is on sparseness. The bee becomes completely expressionless as a result.

animal or a humanoid character. Using the full behavior system to implement a simple bee is overkill, the argument may continue, because a real bee does not follow animal-like drives and motivations and it is detrimental to think that it does. On the other hand, since the drives and motivations that our system simulates are simplified models of the drives and motivations of higher-level animals, one might argue in response that our behavior system is better suited to implement a simple bee than it is to implement a humanoid raccoon. Further, because insects also exhibit drives and motivations, the system turns out to be optimal for the task at hand.

Leaving theoretical polemics behind, we shall continue with the description of the individual bee types. They belong to both the nectar collection and the nest site selection model; the explorer and the forager bee take part in the nectar collection, while the scout and the decision bee participate in the choice of a nest site.

The Cast

Explorer Bee

The first of the types, the explorer bee performs the talking half of the communication. It flies in a random search pattern, looking for sources of nectar. As soon as it flies sufficiently close to a flower patch, it turns back to the hive, ready to communicate the location of the patch. It enters the dancefloor and starts advertising for the patch. The length of its advertising is directly proportional to the quality of the flower patch that the bee had estimated when it discovered the patch. Further, the bee's advertisement is audible only within a certain radius of the bee. As soon as the bee's motivation to advertise dissipates, the bee flies out of the hive in search of more flower patches.

My model of the explorer bee is simplified with respect to a real bee in several ways. Most importantly, because of implementation specifics, the bee communicates the real position of the flower patch as opposed to a coded approximation of it. Any bee that hears an advertisement will be able to find the patch even if the patch has been moved. In nature, bees communicate position through describing a flight angle and an energy expenditure that incorporates parameters like wind direction and strength [Seeley95]. Because of the chaotic nature of the real world, bees often fail to find the advertised flower patch. In this respect, my model overfits the real world slightly and fails to provide for a possibly significant source of noise. Secondly, I map the quality of the source to the length of time for which the bee advertises. In nature, the decisive parameter seems to be the number of waggle runs, and bees vary it in direct proportion to the quality of the food source advertised. Even though other parameters like pauses between the runs and the vigor of the motion might also play a role in the communication [Seeley95], it makes sense to establish a direct one-to-one correspondence between the quality of the source and the duration of the advertisement.

Forager Bee

A forager bee listens to the explorers. If it hears an advertisement, it exits the hive, flies to the source, and begins collecting nectar. If the bee collects as much nectar as it can carry, it brings its load to the hive and deposits it there. In case the source ran out, the bee re-enters the dancefloor and listens for another advertisement. Since

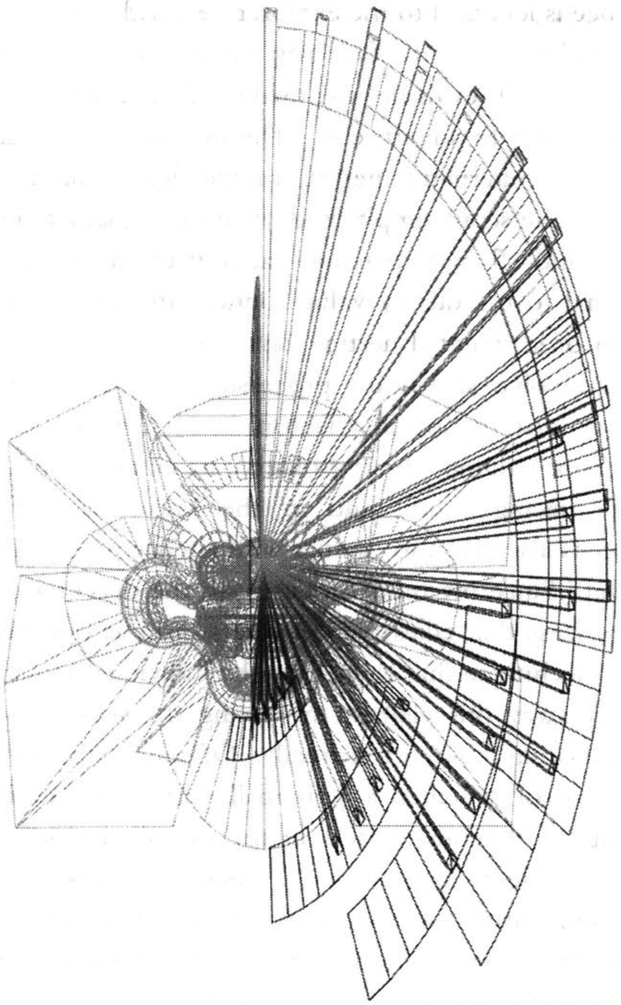

Figure 9: The model for the Mask of the Hive contrasts the bee model in several respects. Sparseness is not a necessity, since only one mask will be ever loaded into the system. The goal is to build a model as expressive as possible, using all the graphics tricks available.

the bee is modeled as a behavior-driven creature, it will take advantage of sources of nectar that it was not aiming for but that it might discover in its flight path. This feature introduces more realism into the model as a potentially noisy environment plays a role in the performance of the bees. Models that do not incorporate simulation in a virtual three-dimensional space often fail to provide such source of complexity.

Scout Bee

A scout bee is identical to the explorer bee, with the exception of the target it seeks. Instead of flower patches, it looks for alternative nesting cavities. It evaluates the quality of the cavity found, and flies back to the hive to advertise it. The evaluation process is severely simplified. All alternative nesting cavities have a hard-coded quality parameter. The scout simply reads it off and, just like in the case of explorers and flower patches, advertises in duration directly proportional to the quality value found. In nature, the process of evaluation of a potential nesting cavity is much more complex, and seems to involve significant processing power. The scout bees consider at least five distinct factors in evaluating a cavity: it must have the right volume (about 40 liters); its entrance should be of the right size, facing south, and in the lower half of the cavity. Preference is also given to cavities with already present empty combs [Seeley99a]. Since my model focuses on the decentralized decision-making process that takes place at the swarm as opposed to on the evaluation technique that is used by the individual scouts, I was able to simplify away this element by giving the scouts the benefit of always evaluating the cavity correctly. Of course, this solution avoids the question of whether a potentially erroneous evaluation of a nesting site by a scout matters in the overall decision process. It seems to be safe to assume that it does not, however, because the decentralized nature of the cavity evaluation process is likely to eliminate errors. Since the bees never rely on a single opinion, they collectively form a more error-prone decision.

Bee Decision-Maker

The decision-maker bee represents all the bees of the swarm that listen to the scouts' advertising. Since they are meant to be the mass of bees that actually carries out the decision, the crux of the decision-making problem lies here. The implementation I chose consists of two crucial mechanisms. Each bee has a number of Motivation nodes, one for each alternative nest site advertised. The bees constantly walk the floor (surface of the swarm in nature) and thus are able to hear the advertisements for numerous cavities from several different scouts. As a bee hears an advertisement, its Motivation to fly to that particular cavity rises. If one of the Motivation values steps over a certain threshold, the bee takes off and flies to that cavity. All the Motivation values drop off over time, so only a constantly repeating stimulus will send a value of any

Motivation over the threshold. Of course, this method of sampling the dance information is arbitrary, and in no way am I suggesting that it actually takes place in nature.

The second part of the algorithm is the "they fly, I fly" mechanism. If a bee sees that its neighbors are taking off, it takes off as well, and flies to the cavity that corresponds to its own Motivation with the highest value. Note that the Motivation value of the follower bee has not exceeded the threshold for take off. The highest-scoring yet under-the-threshold Motivation in one bee may not correspond to the over-the-threshold Motivation in another bee. As a result, the swarm fails to exhibit unanimity, a phenomenon that is sometimes observed in nature [Seeley99a]. In case this model fails to satisfy a purist, one might argue that real bees use some of the flocking principles that Reynolds illustrated in his boids [Reynolds87]. In other words, a bee that takes off only because its neighbors took off will not fly to the highest-scoring cavity in its own "opinion", but simply follow the crowd. In that way it shall reach the cavity that has been decided on, without contributing to the actual decision.

Other creatures - flower patches and alternative nest sites

To complete the description of the implementation, I present flower patches and alternative nest sites. Both of these are implemented as simple creatures so that they can be sensed by the bees. Any nest site contains a parameter that expresses its quality. A flower patch does a bit more; it counts the bees that collect its nectar and decreases its nectar reserve accordingly. After a patch is depleted, it recuperates, but only after a short time-out period for which it remains empty. This detail is important because it prevents a fraction of the forager bees from getting locked up in a loop that is caused by a slowly yet perpetually growing source of nectar. Flower patches and alternative nesting sites represent the environment that the user alters as he interacts with the beehive character.

The Mask of the Hive

The resulting high-level character takes on the form of a mask [Figure 9]. Musing over the question "what does the spirit of the hive look like?" I chose a Balinese wood carving (courtesy Chris Kline) as inspiration for the Mask of the Hive. The mask is able to express several grimaces that are meant to be facial expressions. Similar to *Observers* that Resnick uses in StarLogo [Resnick94, Appendix B], the behavior creature inhabiting the mask monitors the activity of the bees in a "top-down" fashion; in particular it counts the numbers of bees that are engaged in different activities at any given moment. Its facial expressions are dictated by the ratios and the changes in the ratios of the differently occupied bees. In this manner, the mask consistently communicates the state of the hive that changes in response to the user's actions. The two most distinctive grimaces are anger and happiness. A puzzled expression shows through as none of the scout bees advertise for nesting sites. An evil-looking happy grin breaks out as a high percentage of forager bees deposits nectar. In a tumultuous time, when the percentages of bees involved in any given activity fluctuate quickly and the hive finds itself out of equilibrium, the mask squirms and fidgets, going through a range of asymmetrical facial expressions. Because the mapping from the colony parameters to the facial expressions is not obvious, the Mask of the Hive appears alive and responsive.

Design Element

Visualization of Information

A significant fraction of my time went into the visuals of the resulting character. Most of the interesting activity of the character comes from proper visualization of the behavior of the individual bees. Just as Hofstadter pictures "teams" as groups of ants unified through a particular activity [Hofstadter79], and Resnick describes "emergent objects" as units appearing at different levels of a decentralized system [Resnick94], I tried to visualize such elements of structure through appropriate pieces of graphics. I used several design techniques in order to illustrate the differences between objects at different levels of my decentralized system.

The bees themselves reside at the first level of structure. They are modeled in all sparseness, with only 24 polygons each. Merely collections of tetrahedrons, the individual bees convey no expression whatsoever. Their motion is simple and functional. The bees are at a level below expressiveness, as the expression of the character must arise as an emergent property of the hive as a whole.

The teams of bees that originate as emergent objects represent the second level of structure. Rather than any particular geometrical shape, they are visualized as volatile pools of vibrant color. Every bee has a tall beam on its back that shows a scaled value of a specific internal variable of the behavior system. The motivation to fly searching for a source of nectar, for instance, shoots high as soon as a bee hears about the source and can be seen as a faint semi-transparent beam that the bee carries with it. The beam disappears as soon as the bee reaches its destination. Because more than one bee gets typically recruited for any given task, one can observe the formation of distinct trails of bees, just as Hofstadter described in his *Ant Fugue* [Hofstadter79]. In the same way, the nectar load that each bee carries is visualized through a bright red beam on its back. The beams are not meant to communicate a precise numerical measurement, but to convey a qualitative feeling for what is going on.

Finally, the mask represents the third level of emergence. It contrasts with the bees dramatically, as it is complex, richly textured, and often gratuitously ornate. It differs from the teams as it is sculpted from hard shapes and sharp edges. Its surface is fragmented into a mosaic of muted colors; its eyes are asymmetrical, and its grin terrifying. It was chosen to give the fewest possible preconceived notions of what it should do or how it should act. In this way the user can approach it with a clear mind, building anew a mental image of an entity that is not often visualized – a colony of bees. On the other hand, the mask is the anthropomorphic element of the resulting character. Even though it resembles a monster more than a human face, it still relies on a human-level perception of emotion. Because it is a caricature of a face and because it exhibits human-like expressions, it is meant to "cap off" the bee-to-bee interactions with piece of visuals that clearly represents a distinctive higher-level structure.
Additional information that is not apparent in the visualization of levels is shown through supplementary pieces of abstract geometry. The mask has a fan of concentric semi-transparent blades radiating from its forehead. Although spooky-sounding in writing, the structure is well-suited for visualization in graphics. It consists of eight "floors" containing five spikes each, and is designed to display eight different diagnostic values. The color of the blades ranges from yellow to red as the value goes from 0 to 1. The spikes pulsate and move as the bees perform their tasks in reaction to the user-controlled dynamic environment. While adding to the visual

complexity of the resulting character, the spikes also turned out to be helpful in debugging.

One Space for All

Since the character arises as a superposition of localized interactions, all the behavioral activities of the individual pieces were designed to occupy the same virtual space. In other words, while the work could be split into two separate visualizations, one showing the activities outside the hive, and one showing a close-up of the dancefloor inside, I opted to paint them both in the same space, overlapping and intertwined. The dancefloor stands perpendicular to the ground floor of outside activities. The bees must enter the hive in order to walk the dancefloor and exit it on order to fly leveled again. The bees on the dancefloor are also magnified, to distinguish them optically from the bees outside. While perhaps detrimental to conveying precise numerical description of the activities pictured, this method allows for a qualitative estimate of the interaction. Even though the user may be hard-pressed to name the exact number of bees advertising for a newly-discovered source of nectar, she will see instantly whether *many* or *few* of the bees are involved. In the framework of a dynamically changing interactive installation, qualitative communication is often dramatically more important than displaying exact numbers.

It was on a dreary night of November that I beheld the accomplishment of my toils. With an anxiety that almost amounted to agony, I collected the instruments of life around me, that I might infuse a spark of being into the lifeless thing that lay at my feet. It was already one in the morning; the rain pattered dismally against the panes, and my candle was nearly burnt out, when, by the glimmer of the half-extinguished light, I saw the dull yellow eye of the creature open; it breathed hard, and a convulsive motion agitated its limbs.

Frankenstein

By Mary Wollstonecraft Shelley, 1816

CHAPTER 5

results

Evaluation

Let us now commence reviewing the demo as it stands. It is an interactive installation endowing the user with the power to alter the environment around the beehive. In order to illustrate all the features in turn, I will describe a number of "runs" of the system, each with different numbers and ratios of the bees involved. I have included a series of images to back up the descriptions; the camera angles were picked by hand. The panes in the images are organized in a comic book fashion, and read to the right and down.

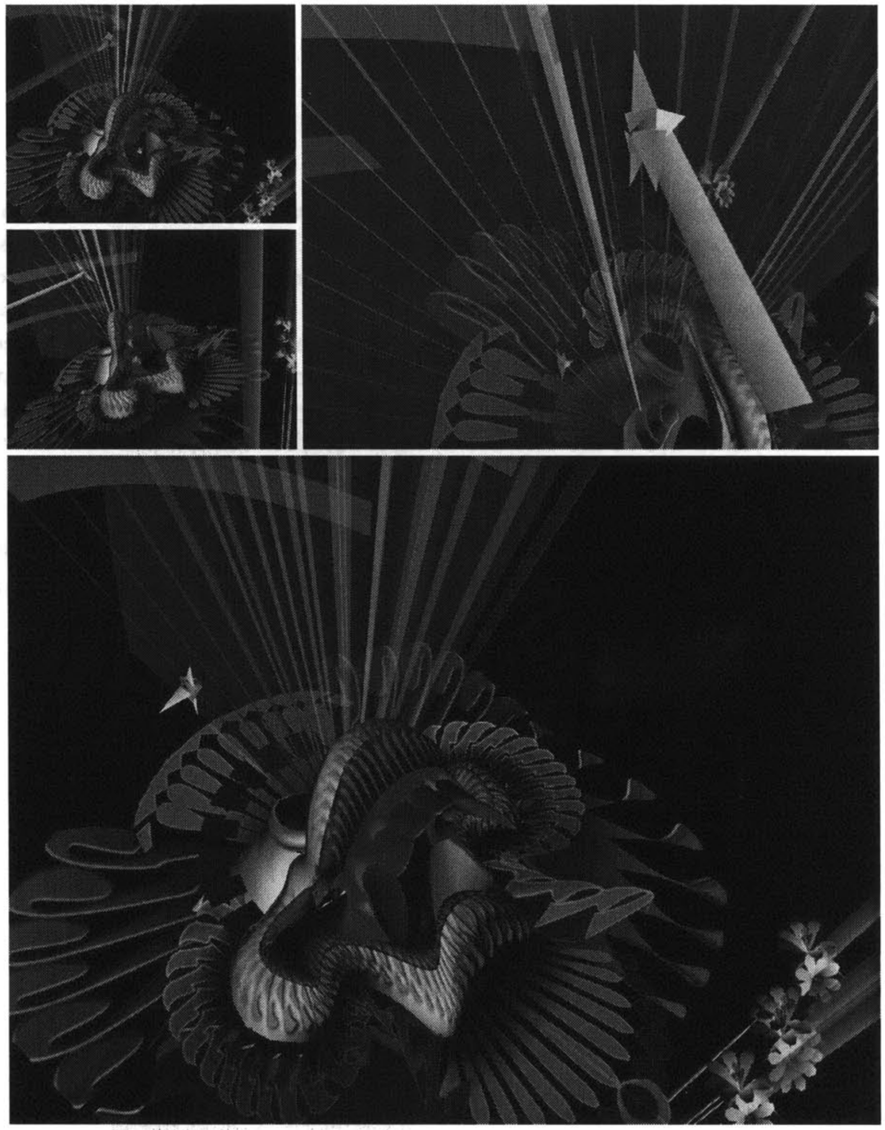

Figure 10: A comic book-like depiction of the first of the demos. Only a few explorers are active and the mask looks angry and frustrated. The panes read right to left.

Demo I: Lone Explorers

At first, only a few explorers are let into the space around the hive [Figure 10]. They wander in a random search pattern, seeking incident sources of nectar. Three of the flower patches happen to be clumped together just below the lower jaw of the mask, and the explorers discover them readily. They fly back to the hive and start advertising while walking up and down the dance floor. Pane 3 of the figure shows a close-up of one of the advertising explorers. The light blue beam, representing the quality of the source mapped onto the duration of the advertising run, shrinks steadily as the bee performs its advertising run. The dark blue ring around the bee represents the range in which the explorer can be heard by other bees. Unfortunately, there is no one to listen in this scenario, and the Mask of the Hive looks angry and frustrated. The hive is empty and the distribution of the bees allocated to different tasks has not reached equilibrium. The mask's expression remains fixed during this run.

Demo II: Explorers and Foragers

Adding half a dozen foragers to the second run of the demo spices up things: the communication loop is suddenly complete, and the sources of nectar identified by the explorers can be exploited by the colony. The first pane of the figure [Figure 11] shows a few foragers that have responded to an advertisement and located a flower patch. The cluster of red beams in the lower right half of the image denotes the nectar loads of the foragers involved in nectar collection. A few more bees are flying toward the source, carrying light, semi-translucent beams that indicate that the bees have a heard an advertisement for a destination. This group of slightly tardy foragers reaches the flower patch in the second pane, increasing the density of the pool of red in the corner of the image. By pane 3, the source of nectar has been depleted, and the bees carry their load home. The last image shows the mask smiling in a fiendish grin, as the foragers deposit their load. The bees then repeat the forage cycle, this time splitting into several distinct teams, each tending a different flower patch.

Demo III: Scouts and Decision-makers

Once we run the simulation of the decision-making process, a picture different from the foraging demo unfolds. We replace explorers with scouts, foragers with decision-makers, and flower patches with alternative nest sites. There are six nest sites in the simulation pictured [Figure 12], and the user controls the quality of the different sites. In the images shown, the hive icon on the far left represents the most ideal nest site. The scouts run into the sites at random, bringing their evaluations back to the dance floor in the form of yellow beams. The decision-makers walk the dance floor listening to the scouts. If a decision-maker hears a consistent advertisement for

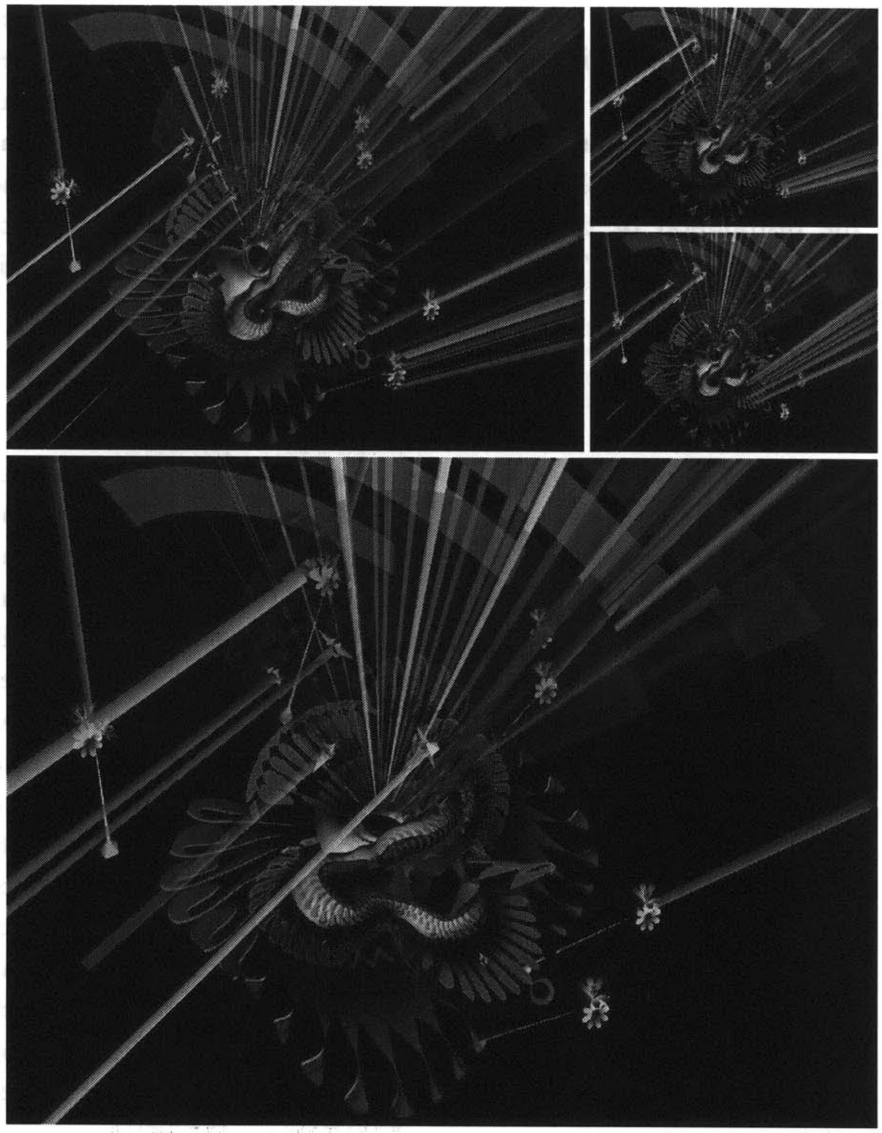

Figure 11: The second run of the system shows a complete advertising-foraging loop. Notice the development of the red team of bees that arrives at a flower patch, rounds up the nectar, and deposits it in the hive.

the same nesting site, it decides to lift off, and the signal quickly proliferates through the crowd of receptive decision bees. The bees then fly to the site and, after a while of lingering, return to the dance floor of the original hive where the decision process starts anew.

Demo IV: A Dozen Dozens

The final run of the demo documents a small stress test. It combines the two models described above and performs them with roughly 140 bees of all four types. The user is able to alter the position of the

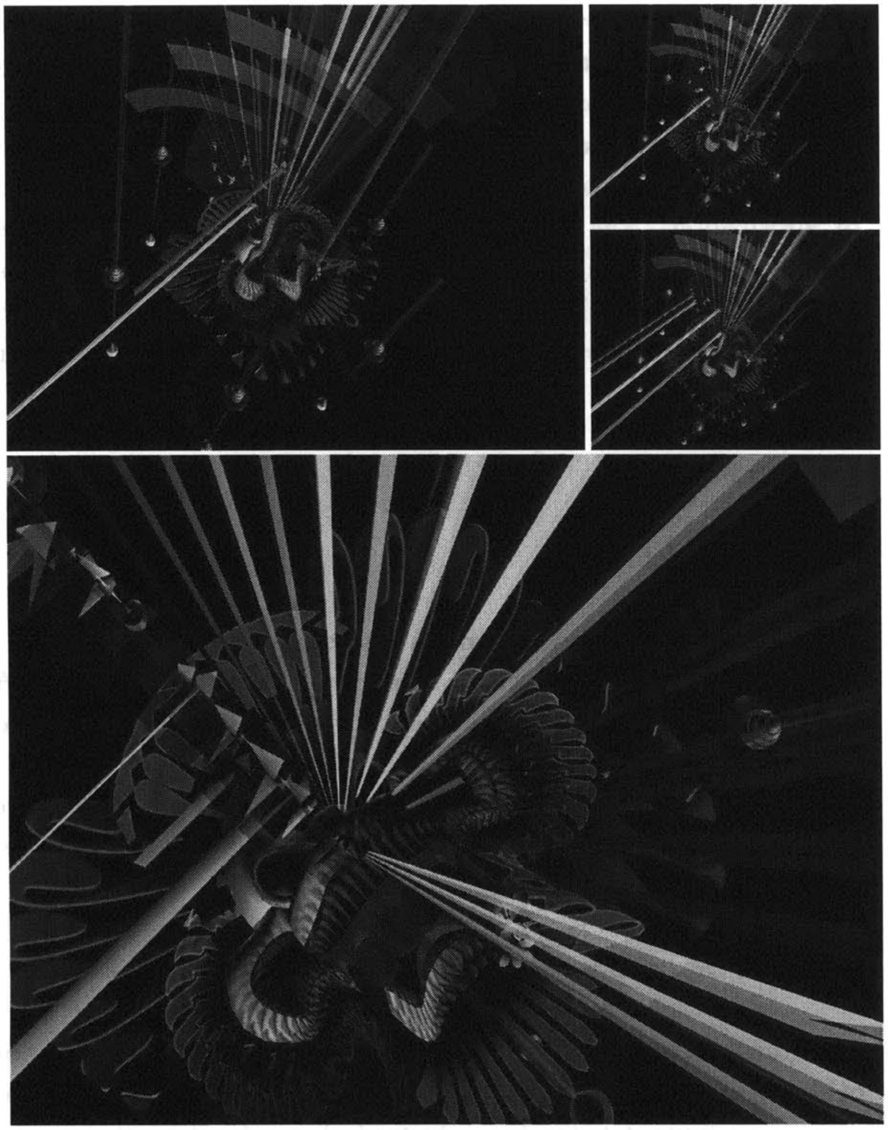

Figure 12: This demo shows the decision-making in the bees. Six alternative nest sites are represented by the hive icons positioned around the mask.

flower patches around the hive. The four panes of the figure [Figure 13] show the complexity of the resulting visuals. A light blue mass of advertising explorers mixes freely with translucent ocher of foragers that have heard an advertisement as well as with an occasional yellow of advertising scouts. In the first pane, an early explorer hits upon a flower patch right next to the mask's lower jaw. A larger group of foragers identified by translucent ocher beams follows a close second. The next pane shows a forest of red beams that sprouts around the flower patch as the rest of the bees catch up. The third pane gives a different view of the same solid column of busy foragers; the mass starts moving back towards the hive entrance as the source of nectar quickly succumbs to the numbers of foraging bees. The final image shows an overall view of the colony. The foragers are depositing their load around the hive entrance, while the rest of the colony crowds the dance floor either receiving or transmitting numerous bits of information. The radial spikes emanating from the hive center pulsate with information as different floors display the ratios of employed and unemployed bees of various types. The mask exhibits convulsive facial expressions as the activities of the bees change in response to the user's alterations of the environment.

Lessons Learned

Behavior Modeling

After having written and rewritten numerous bee behavior files, I have to come to realize several points relevant to behavior design. A description of four such principles follows as I have tried to document my experience that would otherwise go unrecorded. I have also included a description of two design primitives that I have come to use extensively in the behavior design, Behavior Couplets, and Pronome Communication.

A behavior creature is not a finite state machine

Sequential programming is the wrong mindset for the design of behavior creatures. Too often have I slipped into the pattern of designing a finite state machine. Instead of specific states that can be traversed as dictated by a value of a conditional, one must think in terms of concurrent behaviors that gain different relevance values at every iteration. In order to design a transition from one behavior to another, the author must ensure that one set of conditions drops to zero, while another rises to take the place of the active behavior. For instance, a forager bee can be thought of as performing several behavioral loops, one of which can be expressed as a simple sequence: fly to the patch, collect nectar, fly to the hive, and deposit nectar, as long as the flower patch is not empty. One can easily construct a finite state machine that encodes such behavior. Because of the mindset of behavioral programming, however, a much more appropriate method of encoding this sequence is to arrange behaviors

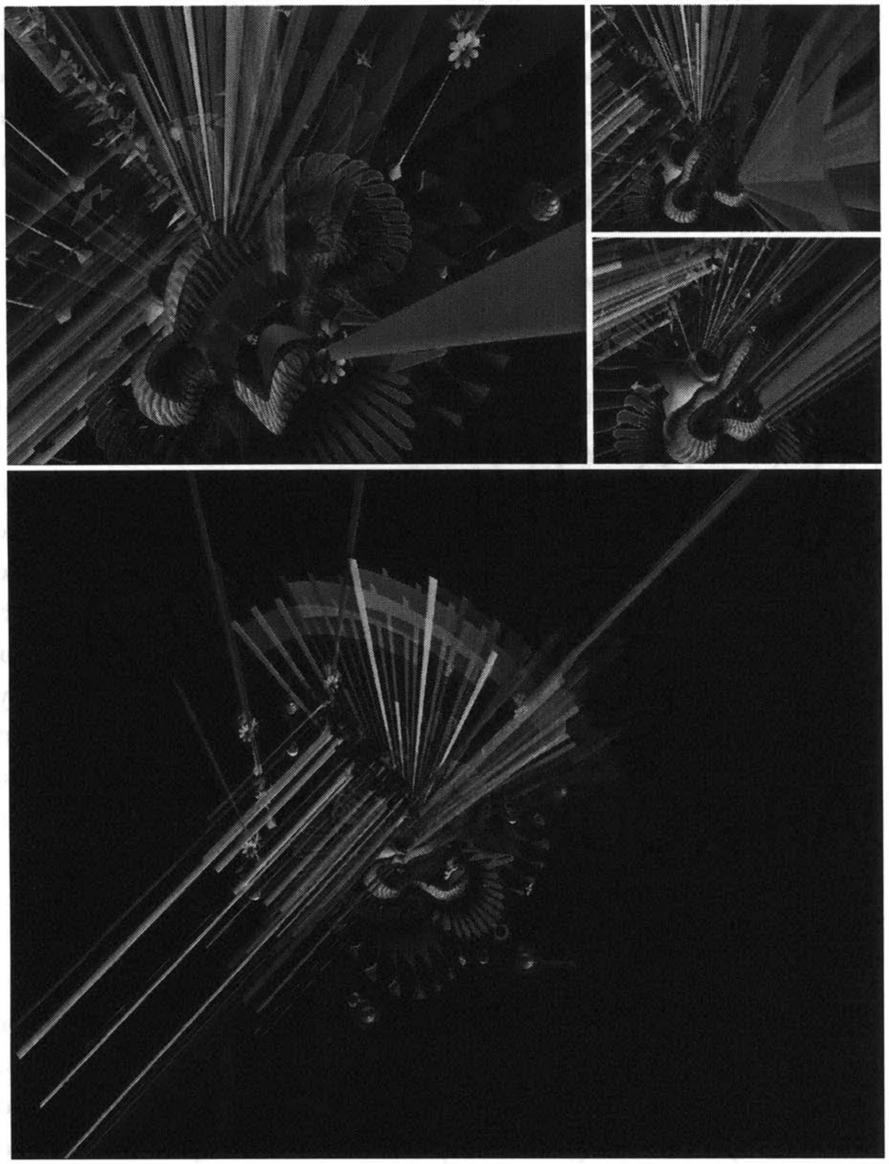

Figure 13: This demo shows the two models running alongside each other. Roughly 140 bees perform in this simulation.

into behavior groups in such a manner that only a single behavior will arise active.

Unexpected magic happens

Since we are modeling drives that are triggered by the presence of close-by stimuli, the creatures often become "opportunistic" and take advantage of what they find as they go along. For instance, a forager that seeks out a source of nectar will get sidetracked if it finds a flower patch that is closer than the one it had originally heard about. The releasers that react to the proximity of a flower will fire regardless of which flower patch they're sensing. In this respect, the bee will follow immediate stimuli and approximate a real insect more closely. Again, without building a virtual three-dimensional environment, this aspect of the behavior would be easily lost.

Simple creatures – fewer headaches

The current design of the bees is making a heavy use of behavior couplets. My earlier designs would favor more complex groupings of behaviors that resulted in flatter graphs but more complex behavior groups. For the correct behavior arbitration to happen, the behaviors had a complex forest of input nodes encoding all the possible activation conditions. The behavior tree quickly became difficult to manage, as unexpected interactions in the behavior graph gave rise to buggy behavior. In contrast, a tree built from behavior couplets is deeper, with simple exclusion groups that contain only two behaviors each. Most importantly, the set of inputs to any given behavior is much simpler, typically containing only one or two nodes. The overall design is easy to manage, as few unexpected interactions of opposing motivations conspire.

Any given problem has many solutions

Blumberg's behavior system is extremely flexible. Every behavior that can be described in words can be implemented in multiple ways. It is therefore important to work out a "bag of design tricks", since consistency of the design suddenly becomes more important than the sheer number of design primitives used. It is also easy to slip up and to implement a behavior creature that works as a collection of hacks instead of as a plausible model of a biological organism. A creature that posts and depends on internal flags that arbitrarily describe the state of the world, is highly unlikely to provide a plausible approximation of a real animal.

Behavior Couplets

Even though an algorithmic description of a particular behavioral detail may be simple, it often becomes more complex once expressed as a behavior subtree. For instance, a part of the behavior exhibited by the forager bee can be expressed as a simple implication: *if you hear an advertisement for a flower patch, fly there.* Once translated into behaviors, however, the statement quickly becomes tricky. The simple-minded solution is to take a sensor that recognizes that the bee heard an advertisement, and to connect it as a positive input into a motivation that in turn triggers the FLY_TO_PATCH behavior. While this approach captures the essence of the desired action, it will fail as soon as the graphics is introduced because the bee will jump instantly from walking around the dance floor to flying to the patch. Instead, the bee should walk to the hive entrance first and only then fly out of the hive. To remedy the situation, one can turn the FLY_TO_PATCH behavior into a behavior group that in turn contains two nodes: WALK_TO_ENTRANCE and FLY_TO_PATCH. The walking behavior will be on by default and will get subsumed by the flight behavior only as the bee passes through the hive entrance. The flight behavior will then carry the bee to the flower patch. In other words, a single behavior must be replaced by a couplet of behaviors, the first of which is the transition from the current activity to the starting point of the desired activity while the second is the desired activity itself. The transition behavior is active by default and gets subsumed by the target behavior as soon as the right conditions are met. Using such couplets, one can build a complex system from simpler parts that are easy to author, debug, and understand.

Communication of Pronomes

Pronome communication is another design construct widely used in the implementation of bee behaviors. The bees sense each other based on proximity; if an advertising bee comes within hearing range of a listening bee, the BEE_SMELL_SENSOR node in the listener will return the advertiser as one of the objects sensed. The listener is aware of the closest advertiser via identical mechanism. The listener then asks the advertiser for the target object advertised, a flower patch or an alternative nesting site, and receives the information in a form of a sensor object, or pronome. It sets the value of its TARGET_OBJECT feature to that pronome and continues walking the floor. In order for the listener to realize that it has heard an advertisement, the advertiser sets the listener's feature HEARD_SOMETHING to 1. The listener's LISTEN behavior than ceases to win the action arbitration, and the listener walks off the dancefloor in pursuit of the newly acquired target. In this fashion, a two-way communication takes place: the listener actively pulls the pronome from the advertiser, while the advertiser pushes a boolean onto the listener.

It is the custom of scholars when addressing behavior and culture to speak variously of anthropological explanations, psychological explanations, biological explanations, and other explanations appropriate to the perspectives of individual disciplines. I have argued that there is intrinsically only one class of explanation. It traverses the scales of space, time, and complexity to unite the disparate facts of the disciplines by consilience, the perception of a seamless web of cause and effect.

Consilience

By Edward Osborne Wilson, 1989

conclusion

CHAPTER 6

Designing and creating the Mask of the Hive under a real-time interactive system has been a rewarding experience. Most importantly, it provides a sliver of tangible evidence to the central claim of this work, that it is useful to compare the mind to a colony of social insects. The space spanned by such comparison provides a rich creative domain for a class of abstract synthetic characters that retain their expressive qualities.

To reiterate, the underlying motivation for this study is to find an interesting angle from which to attack the search for artificial intelligence. The angle I presented here stems from a compound metaphor, a space between superorganism and society of mind, two mental models that try to explain away complexity of two distinct phenomena by reducing it into smaller, more easily manageable pieces. Establishing a third metaphor by a direct comparison of the two then creates an interesting arena for interdisciplinary scientific inquiry. In particular, it opens a delightful domain for building synthetic characters that exhibit various forms of proto-intelligence and thus provide constructive insights into generative models of the mind.

My work on the Mask of the Hive has been guided by two opposing directives. On one hand, I wanted to stay close to a plausible model of a natural mechanism, in order to avoid venturing too far into the realm of abstract computer contraptions that exist for their own sake only. On the other hand, I wished to take a significant advantage of the fact that I was operating in a virtual space, free of the physical constraints of the real world. The Mask is a result of my attempt to reconcile these two often contradictory views. In order to stay true to reality, I based my work on a descriptive model of a real bee colony. In order to push away from reality, I took full artistic license in designing the creature and its expressions, and in using abstract three-dimensional graphics to visualize real-time behavioral information.

Future Work

Two major directions for future work can be readily identified. One lies in improving the demonstration I have created, in an effort to turn it into a well-rounded interactive installation. The other lies in continuing to explore the space spanned by the two metaphors by building more characters similar to the one presented here. Both of these directions promise to bear interesting fruit and I shall describe each of them in turn.

The presented work focuses on the visuals and on the behavior of the creature. In order to turn it into a polished demo that could be shown to uninitiated audience at a conference or a festival, one would need to address other aspects of the medium. Sound and music, in particular, present a weak spot since they are non-existent in the present version of the demo. A better interface that would occupy the physical space in front of the screen in a pervasive and tangible manner would help draw the user into the interaction, in a natural and intuitive way. Finally, learning in the character might increase the time a user spends interacting with it by an order of magnitude, since an engaging training process typically lasts much longer than a straight-through interaction with a character that is not adaptive.

The Mask of the Hive is merely an indicator pointing in a direction of future search. Numerous characters exhibiting a range of expressive qualities can be built to fully explore the space between the metaphors. A number of models of animal social behavior can be successfully combined with either Society of Mind, or with several other theories of the mind. Such exercises in constructive combinatorics shall result in a class of characters that is virtually inexhaustable and create a fascinating juncture of entertainment and science.

And one day, maybe a synthetic anthill will become alive as well.

Acknowledgements

Nonexistent would this thesis be, were it not for the constant, selfless, and loving support of my mom Olga and my dad Milos. To them I wish to express my utmost gratitude. Dakujem Vam tatko s mamkou, zo srdca Vam dakujem. My gratefulness goes also to my brother Juraj, whose wise advice showed me the way when my own compass malfunctioned, whose extraordinary strength gave me support when my own energy wilted, and whose wild frolics kept me sane when my own sense of humor fizzled out. And my boundless appreciation belongs to my dear companion, Grace Sheen, for her patience, patience, patience with my awful self.

Patient was also my advisor, professor Bruce Blumberg. To him I owe two exhilarating years of creative challenge, academic stimulation, and worldly inspiration that was ever-so-subtly offered by the illustrious Media Laboratory. My gratitude further belongs to the members of the stupendous Synthetic Characters research group, with whom I have shared many a late night: Marc Downie, Michael Patrick Johnson, Christopher Kline, Kenneth Russell, Bill Tomlinson, and Song-Yee Yoon. And my limitless thanks fly to my two thesis readers, professor Mitchel Resnick and professor Thomas Seeley, whose work and advice have provided an invaluable source of inspiration.

references

Adler92 — Adler, Frederick R., Deborah M. Gordon, *Information Collection and Spread by Networks of Patrolling Ants*, The American Naturalist, Vol. 140, No. 3, 373-400, September 1992

Blumberg97 — Blumberg, Bruce Mitchell, *Old tricks, New Dogs: Ethology and Interactive Creatures*. PhD dissertation, MIT, February 1997

Braitenberg94 — Braitenberg, Valentino, *Vehicles: Experiments in Synthetic Psychology*. MIT Press, Cambridge, MA, 1994

Brooks85 — Brooks, Rodney *A., A Robust Layered Control System for a Mobile Robot*. MIT AI Laboratory Memo 864, Septemebr 1985

Dennett91 — Dennett, Daniel C., *Consciousness Explained*. Little, brown and Co., Boston 1991

DeVries99 — De Vries, Han, Jacobus C. Biesmeijer, *Modelling collective foraging by means of individual behavior rules in honey-bees*. Journal of Behav. Ecol. Sociobiol. (1998) 44: 109-124, Springer-Verlag, 1999

Franks89 — Franks, Nigel R., *Army Ants: A Collective Intelligence*. American Scientist, Vol. 77, 139-145, March-April, 1989

Hofstadter79 — Hofstadter, Douglas R., *Gödel, Escher, Bach: an Eternal Golden Brand*. Vintage Books, New York, 1979

Johnson99 — Johnson, Michael P., Andrew Wilson, Christopher Kline, Bruce M. Blumberg and Aaron Bobick, *Sympathetic Interfaces: Using a Plush Toy to Direct Synthetic Characters*. In CHI '99 conference proceedings, 1999

Kline99 — Kline, Christopher, Bruce M. Blumberg, *The Art and Science of Synthetic Character Design*. Proceedings of the AISB 1999 Symposium on AI and Creativity in Entertainment and Visual Art, Edinburgh, Scotland, 1999

Lasseter87 — Lasseter, John, *Principles of Traditional Animation Applied to 3D Computer Animation*. In Siggraph '87 conference proceedings, 35-44, 1987

Lopez, Francisco, Jose M. Serrano, Francisco J. Acosta, *Parallels between the foraging strategies of ants and plants.* Trends in Ecology and Evolution (TREE), Vol. 9, No. 4, 150-153, April 1994 Lopez94

Maestri, George, *[digital] Character Animation.* New Riders Publishing, Indianapolis, Indiana, 1996. Maestri96

Minsky, Marvin L., *The Society of Mind.* Simon & Schuster, New York, 1987 Minsky87

Parke, Frederic I., Keith Waters, *Computer Facial Animation.* AK Peters, Wellesley, Massachusetts, 1996 Parke96

Rayner, Alan D.M., Nigel R. Franks, *Evolutionary and Ecological Parallels between Ants and Fungi.* Trends in Ecology and Evolution (TREE), Vol. 2, No. 5, 127-133, May 1987 Rayner87

Resnick, Mitchel, *Termites, Turtles, and Traffic Jams.* MIT Press, Cambridge, MA, 1994 Resnick94

Reynolds, Craig W., *Flocks, Herds and Schools: A Distributed Behavioral Model.* In Siggraph '87 conference proceedings, 25-34, 1987 Reynolds87

Root, A. I., E. R. Root, *The ABC and XYZ of Bee Culture.* The A.I. Root Company, Medina, Ohio, 1908. Root08

Russell, Kenneth B., Bruce M. Blumberg. *Behavior friendly graphics.* Proceedings of Computer Graphics International '99, Alberta, Canada, June 7-11, 1999 Russell99

Seeley, Thomas D., *The Honey Bee Colony as a Superorganism.* American Scientist, Volume 77, 1989. Seeley89

Seeley, Thomas D., *The Wisdom of the Hive.* Harvard University Press, Cambridge, MA, 1995 Seeley95

Seeley, Thomas D., Susannah C. Buhrman, *Group decision making in swarms of honey bees.* Journal of Behav. Ecol. Sociobiol. (1999) 45: 19-31, Springer-Verlag, 1999 Seeley99a

Seeley99b	Seeley, Thomas D., *Decision making in superorganisms: how collective wisdom arises from the poorly-informaed masses.* Unpublished manuscript prepared for the Dahlem Workshop on Bounded rationality: The Adaptive Toolbox, 1999.
Shelley16	Shelley, Mary W., *Frankenstein.* Charles F. Miller, Lancaster, Pensylvania, 1994; original written in 1816
Stock93	Stock, Gregory, *Metaman.* Simon & Schuster, New York, 1993
Thomas81	Thomas, Frank, and Ollie Johnston, *The Illusion of Life: Disney Animation.* Hyperion, New York, 1981
Visscher94	Visscher, P. Kirk, Scott Camazine, *Collective Decisions and Cognition in Bees.* Unpublished Manuscript, undated, after 1994
Wheeler11	Wheeler, William Morton, *The Ant-colony as an Organism.* The Journal of Morphology, Vol. 22, No. 2, June 1911.
Wheeler28	Wheeler, William Morton, *The Social Insects: Their Origin and Evolution.* Harcourt, Brace and Co., New York, 1928
WilsonD89	Wilson, David Sloan, Elliot Sober, *Reviving the Superorganism*, Journal of Theoretical Biology (1989) 136, 337-356
WilsonEO90	Wilson, Edward O., *Success and Dominance in Ecosystems: The Case of The Social Insects.* Ecology Institute, Germany, 1990
WilsonEO98	Wilson, Edward O., *Consilience.* Alfred A. Knopf, New York, 1998
Winston87	Winston, Mark L., *The Biology of the Honey Bee.* Harvard University Press, Cambridge, MA, 1987

appendix

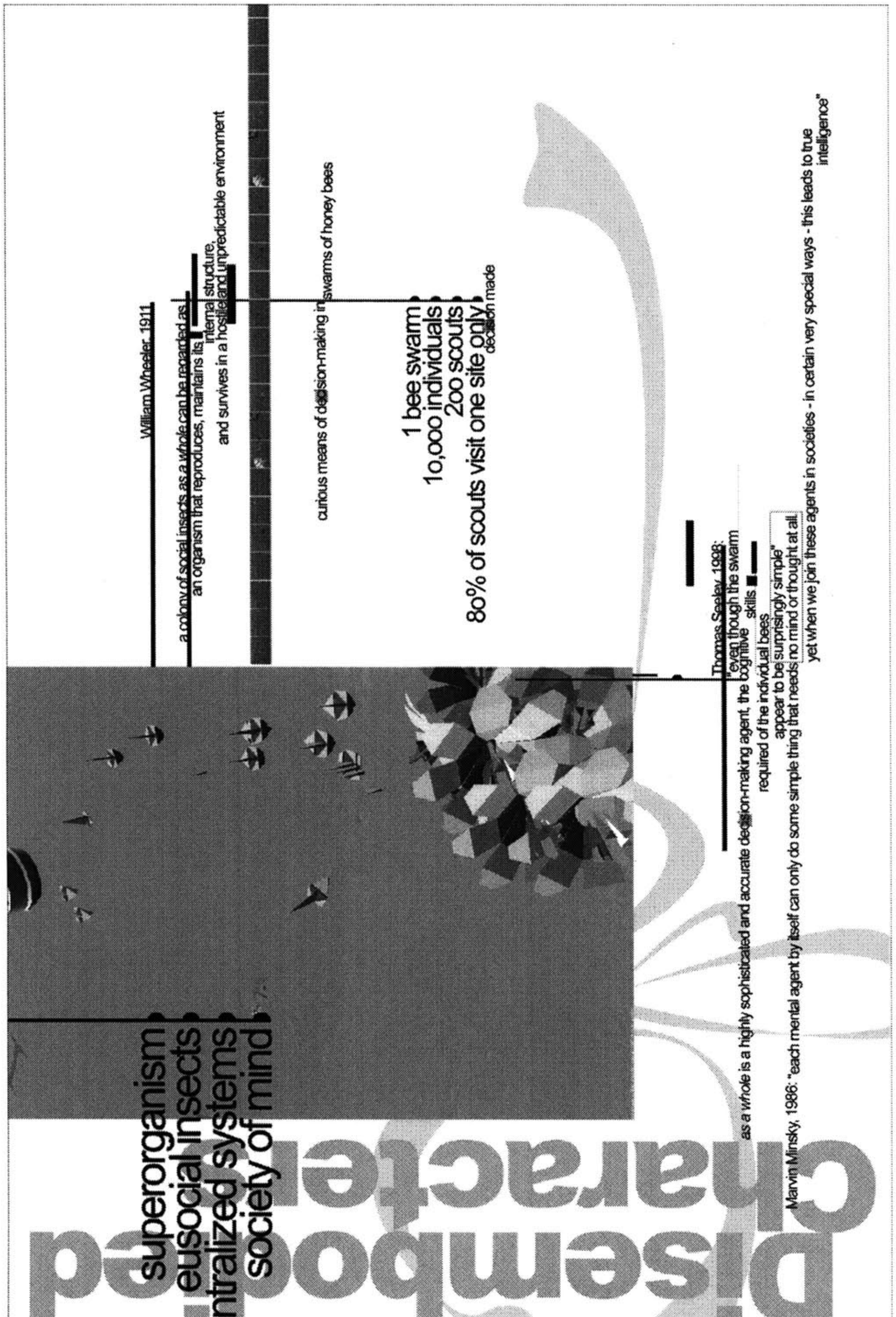

Figure 14: My thesis poster session entry, summarizing the main points of my work (February 1999).

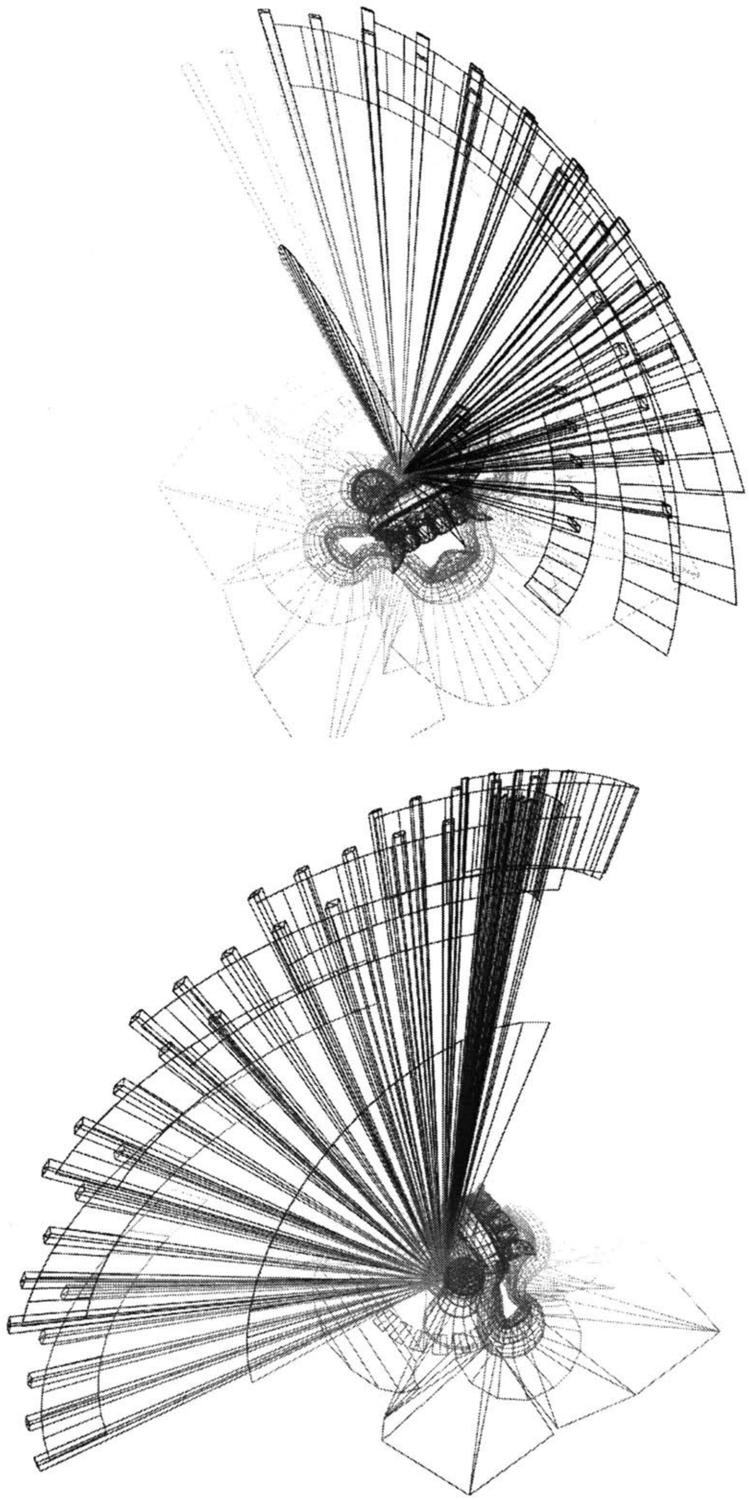

Figure 15: Two more views of the mask model in a depth-cue wireframe render.

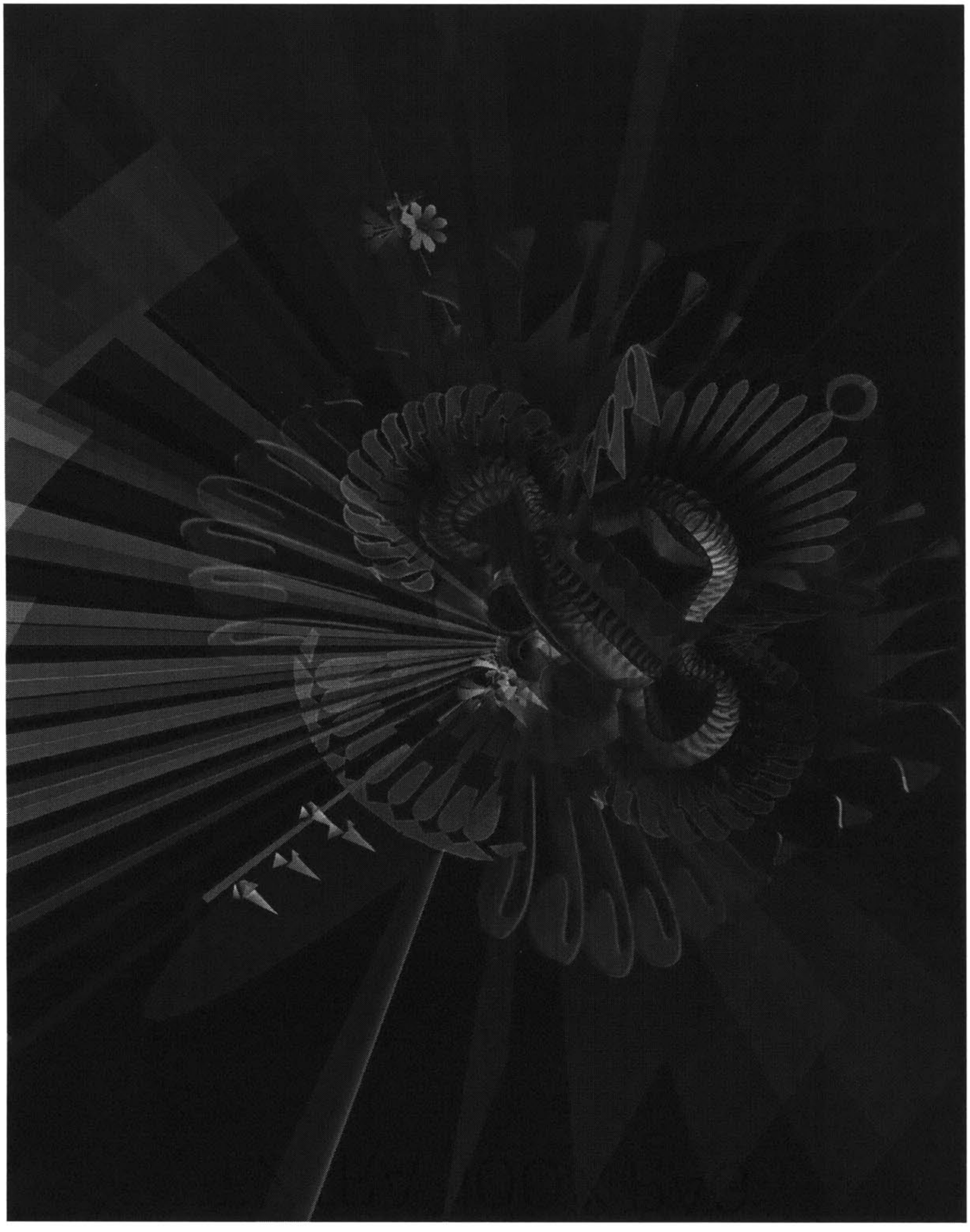

Figure 17: A top-down view of the mask. Four foragers are walking around the dancefloor awaiting advertisements. Two flower patches are in view; one of them is placed right next to the hive entrance (center). A slim golden ray representing a small nectar reserve emanates from the center, but the hive is otherwise empty. The mask shows the default neutral expression.

This and all the following images were rendered as landscape. They are best viewed rotated clockwise by 90 degrees.

Figure 17: The mask grins slightly as a single forager deposits nectar. Three "floors" of the hive repository are colored in, representing a half-full reserve of nectar. Two flower patches shown on the bottom of the image have not been discovered by the explorers; the purple beams indicate luscious reserves.

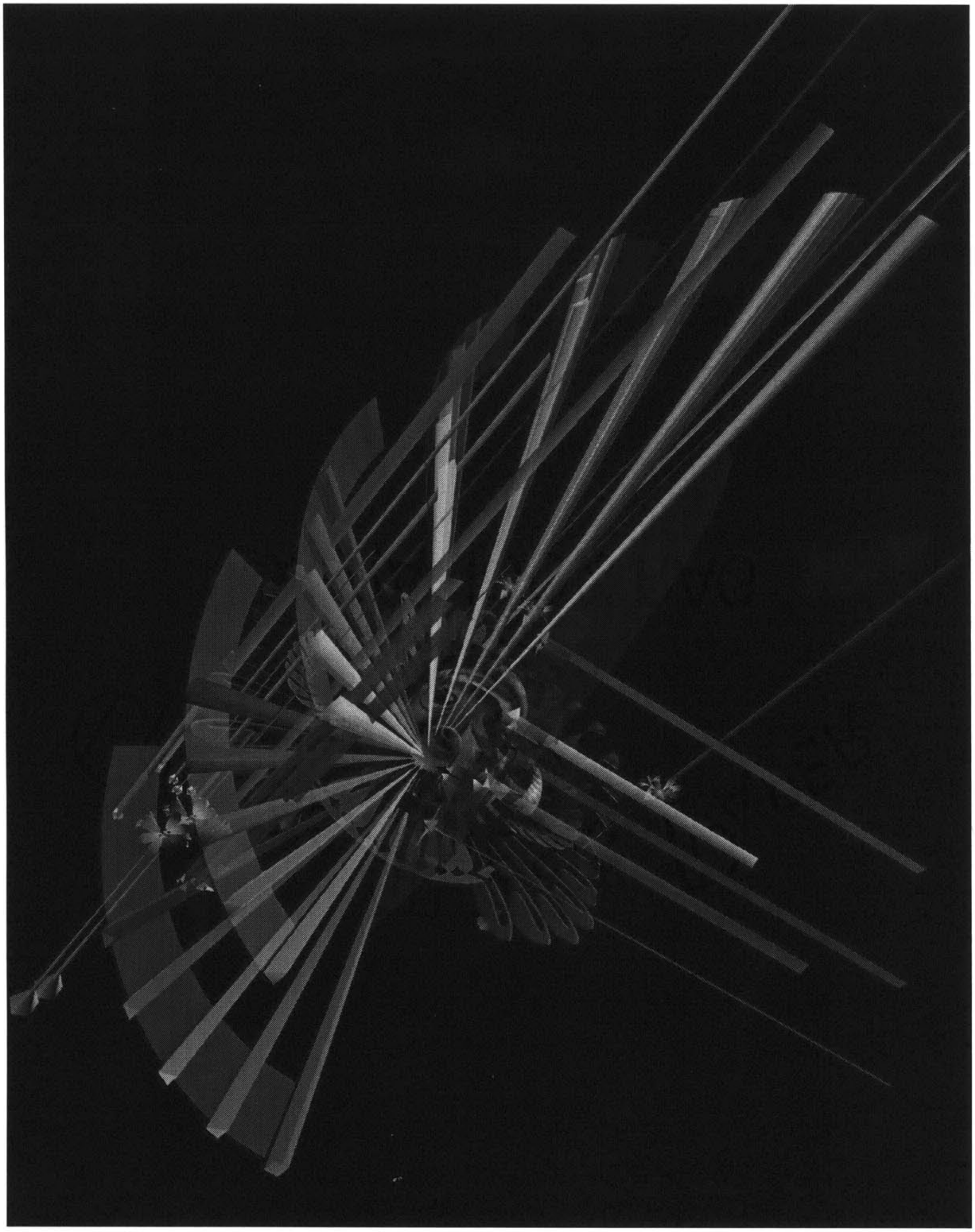

Figure 18: Chaos around the hive. An example of a situation in which the complexity of the visual design backfired: the scene is cluttered with overlapping geometry. A group of bees has been recruited to collect nectar from two sources close together. Five explorers advertise different sites on the dancefloor.

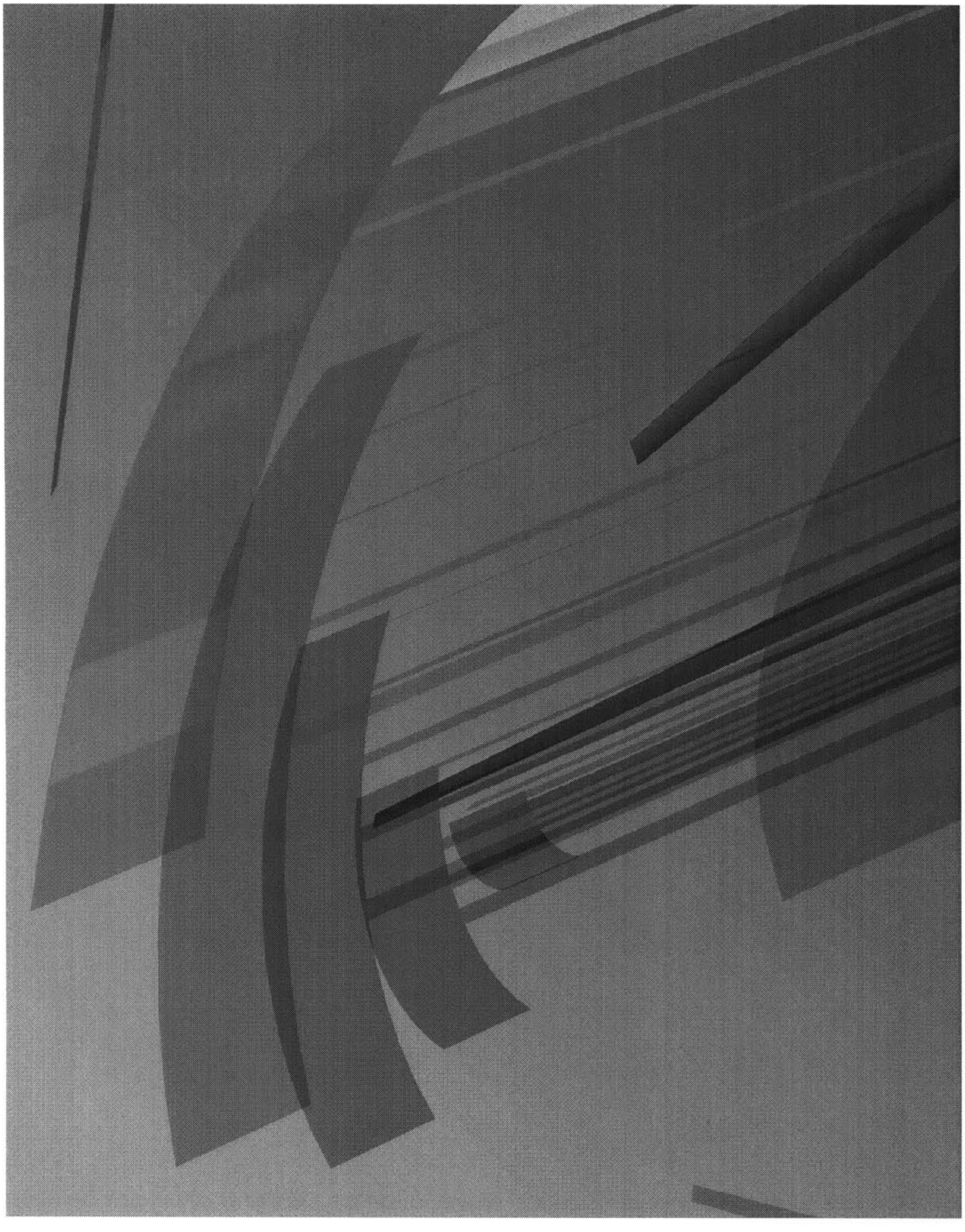

Figure 19: Translucent floors of the hive against the sky, an abstract form resulting from the visual interplay of elements.

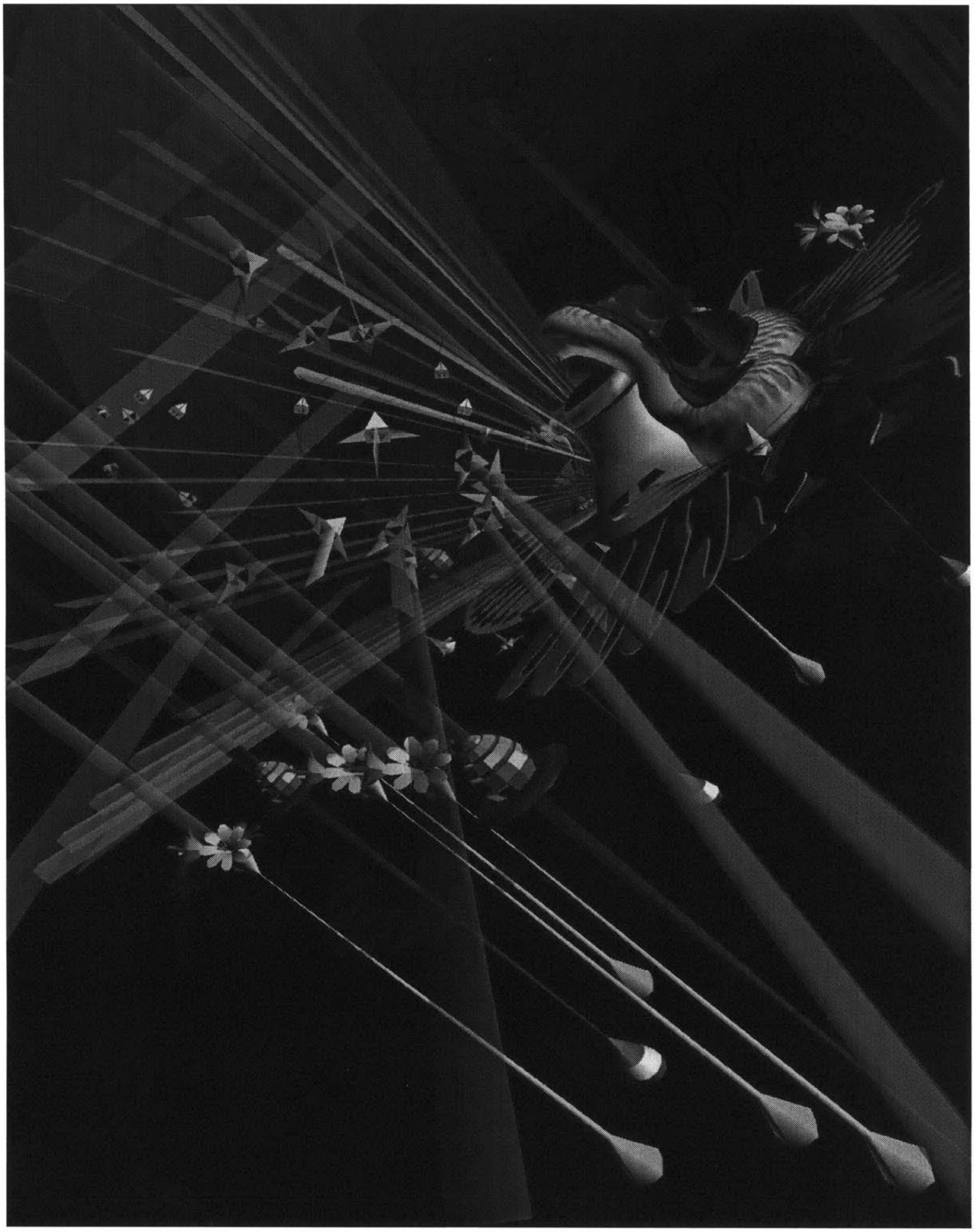

Figure 20: A top-down view of the dancefloor. One can clearly distinguish advertisers from listeners. There are four flower patches and two alternative nest sites in the upper left of the image.

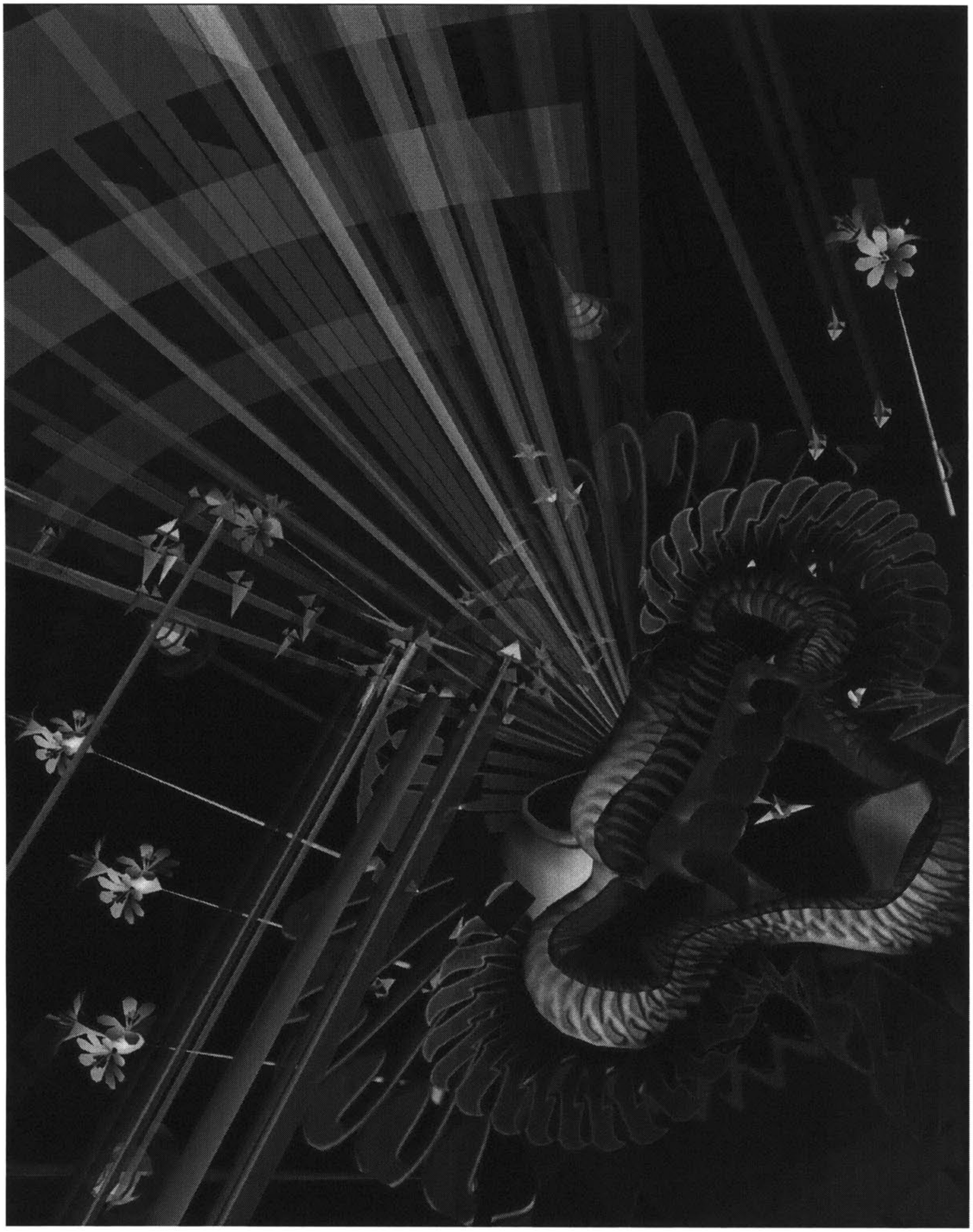

Figure 21: A detail of the mask. Three foragers heading toward an almost empty flower patch can be seen in the lower right of the image.

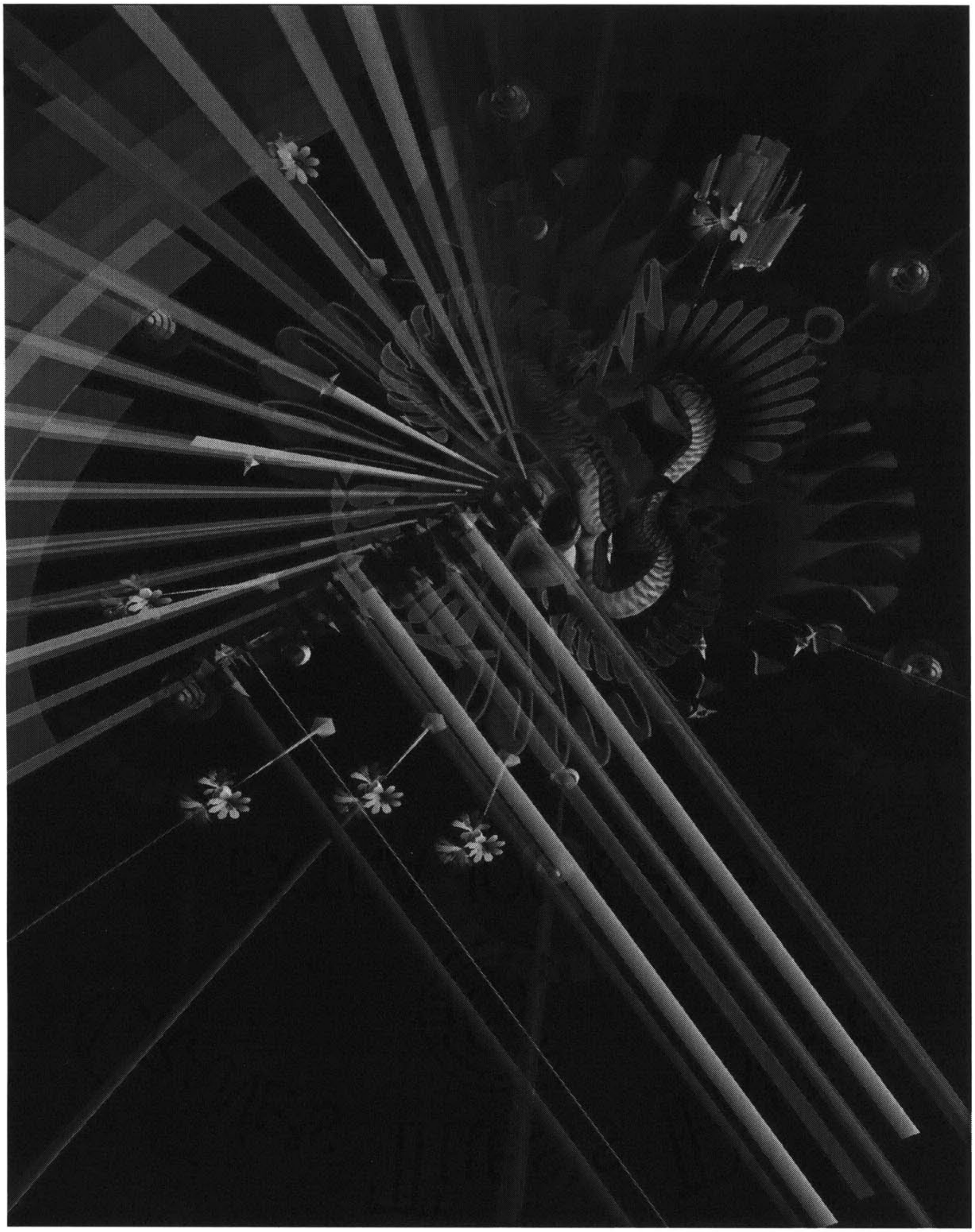

Figure 22: A view of the mask. Numerous advertisers walk the dancefloor while a team of foraging bees forms around the flower patch in the lower right.