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Habitat: Engineering in a Simulated Audible Ecosystem

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Abstract. This paper introduces a novel approach to generating audio or visual heterogeneity by simulating multi-level habitat formation by ecosystem-engineer organisms. Ecosystem engineers generate habitat by modulation of environmental factors, such as erosion or radiation exposure, and provision of substrate. We describe *Habitat*, a simulation that runs on a two-dimensional grid occupied by an evolving population of stationary agents. The bodies of these agents provide local, differentiated habitat for new agents. Agents evolve using a conventional evolutionary algorithm that acts on their habitat preferences, habitat provision and lifespan, to populate the space and one another. This generates heterogeneous, dynamic structures that have been used in a prototype sonic artwork and simple visualisation.

Keywords. ecosystem engineer, habitat, virtual ecosystem, artificial life, generative art

1 Introduction: Fleas and Smaller Fleas

A short stroll through the Australian bush, even the local urban wetlands, reveals a coherent, spatialised soundscape generated by organisms and the interactions of biota and abiota such as wind and water. Artificial life simulation can lend itself to electronic art that replicates the experience of such a stroll, by automatically generating complex, dynamic, heterogeneous patterns. In particular, virtual ecosystems appear perfect for this purpose and have been employed widely [1-4]. However, ecosystem simulation in artificial life has frequently leap-frogged aspects of ecology that are known to be responsible for generating much of the richness typical of real evolutionary systems [5]. This paper focuses on the idea of multi-layered habitat formation — habitat that appears directly on the bodies of organisms.

> *So nat'ralists observe, a flea*
> *Hath smaller fleas that on him prey,*
> *And these have smaller fleas that bite 'em,*
> *And so proceed ad infinitum* — Swift, 1733

The modern ecological terminology that encompasses this phenomenon is *ecosystem engineering* [6]. All organisms are physical ecosystem engineers to some extent. Physical ecosystem engineers alter the biotic or abiotic environment and thereby control or modulate the availability of resources to (or forces acting on) other organisms. These physical changes destroy, maintain or create habitat for other organisms.

A tree is an example of a significant physical ecosystem engineer: it provides habitat for mosses on its limbs, insects under its bark and possums or birds in its hollows and branches; its roots trap soil and leaf matter, altering the impact of wind and water erosion; its branches harbour larvae or tadpoles within pools of rainwater and they provide shade and detritus for fungi. Coral produces reefs, wombats dig holes and worms break down vast quantities of leaf litter and other materials. These species have a massive impact on organisms around them, including of course themselves, their own species, and in particular, their offspring. Of course humans are extremely significant ecosystem engineers too. Ecosystem engineers are often *niche constructors*. That is, their impact on the environment alters the selection pressures acting on themselves and their offspring [7].

This paper does not investigate all aspects of ecosystem engineering. It focuses specifically on the production of habitat that is spatially coincident with the engineer organism. For instance, the tree just described is such a habitat provider. The dynamics of simulated habitat production are used to generate patterns for a sonic artwork and visualization.

1.1 Heterogeneity in Sonic and Visual Generative Art

The composition of pattern in sonic or visual phenomena is the very basis of generative art. Algorithms may easily generate boring repetition, or with some effort, near disorder. But when they create complex structure that is emergent from simple initial conditions and dynamical processes, generative artists are liable to sit up and take notice [8]. For this reason, cellular automata [9], L-Systems [10], ant-trail formation [11], and evolutionary algorithms [12] have all been employed. One of the goals of this paper is to generate coherent, dynamic, spatial complexity that may be experienced sonically and interpreted graphically. With any luck, the generated patterns will one day exhibit a richness associated with natural evolution and real biological habitat.

Existing works that have employed virtual ecosystems to generate soundscapes include: *Living Melodies* [2], which evolves singing organisms in a grid world; *Listening Sky* [1], a globe populated by musical organisms that is experienced via an eaves-dropper under user control; and *Eden* [4], a user-aware graphical and sonic installation of agents that forage and communicate their findings with one another audibly. The work *Plague* also has a sonic component generated from the interactions of evolving disease-ridden agents [13]. This paper employs a new technique, based on the simulation of habitat formation in an ecosystem, to achieve the goal of sonic spatiotemporal complexity and coherence.

2 Habitat, a Virtual Ecosystem Simulation

Ecosystem engineers must provide habitat that is sufficiently persistent if it is to come to support the evolution and continuation of species that depend on it. This simulation is designed to generate habitats provided by one organism for occupation by another. As in real ecosystems, the aim is to allow the emergence of habitat chains that piggyback one another, supporting a range of niches.

In any real ecosystem, engineers may provide habitat for multiple dependent species (as does the tree described earlier) and the interactions between an engineer and its beneficiaries may be reciprocal. Although it is possible to extend the current simulation to permit this, our investigation leaves multiple habitat provision and reciprocal interactions as future work. An overview of the simulation appears below. Detailed parameter settings are discussed in section 3.

2.1 The Grid and Habitat Specification

The *Habitat* simulation runs on a toroidal grid of square cells. Each cell has a three-bit pattern designating the base habitat at its location. A different number of bits can be employed, however visualising the three bits as the colour components red, green and blue is effective and convenient. Any initial coloured pattern of bits across the grid cells can be established. In order to explore purely emergent structure in the absence of pre-specified heterogeneity, we generate our results from a grid with uniform white (1,1,1) base habitat.

2.2 Multi-Layered Habitat Specification

Multiple agents may simultaneously occupy a *Habitat* cell by piggybacking on one another. Each agent has a genotype specifying the habitat bit pattern it *requires* and the habitat that it *provides*. The habitat provided always has fewer bits set than the habitat that an agent requires. I.e. to occupy a cell, an agent must use one or more habitat bits that represent “slots” in the environment. The habitat that an agent provides consists of the bits that remain after its required bits have been occupied (see Figure 1). For instance, for an agent to inhabit a white grid cell, its habitat preference bits must all be set: (1,1,1). Its habitat provision bits must then clear one or more of these bits, ensuring it provides habitat that is yellow (1,1,0), magenta (1,0,1), cyan (0,1,1), blue (0,0,1), green (0,1,0), red (1,0,0) or black (0,0,0). Agents are rendered as rectangles coloured according to the habitat they provide.

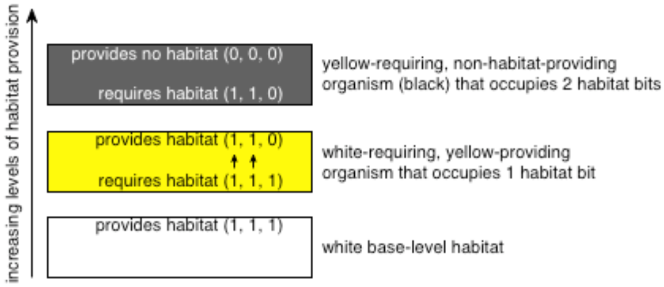

Fig. 1. A yellow agent (i.e. one that provides yellow habitat) occupies the white base and provides habitat for a black agent (i.e. one that provides no habitat itself).

An empty white cell first occupied by an agent that provides cyan habitat (0,1,1) may be occupied next by any agent with cyan preference bits. This second agent must then provide blue (0,0,1), green (0,1,0) or black (0,0,0) habitat, since it too must use one or more of the available habitat bits on the back of the cyan agent. Only a single agent type, black, can exist on top of a primary colour since there is only one bit of habitat remaining to be occupied. Hence, a complete habitat chain is always topped off with unusable black (Figure 2).

Fig. 2. Four sample habitat occupation patterns ranging between white (the empty grid cell) and black are shown. With three bits there are thirteen different habitat patterns that may arise where an agent must occupy one or more bits of the remaining habitat.

2.3 Agent Reproduction and Death

Agents do not move during the simulation. A few white-inhabiting but otherwise randomly engineered agents are scattered onto the grid at the start of a run. To avoid the need for conflict resolution, a sample of random locations on the board, and random habitat levels within those cells, are selected for update at a pre-specified rate per simulation time step. If an agent occupies the selected cell and level, this agent is updated by one time step. Otherwise this update attempt has no effect on any agent.

In addition to habitat bits, an agent genotype contains an integer *lifespan* measured in agent updates (not simulation time steps). After a fixed proportion of their lifespan agents start to reproduce asexually. Every reproductively mature agent selected for update generates a single child. Children inherit the genotype of their parents with the possibility of a mutation that completely regenerates the selected gene. If the gene selected for mutation is a habit preference or habitat provision gene, the other habitat genes in the genotype are adjusted if necessary to maintain genotype coherence — i.e.

so that the habitat provision genes contain a subset of the bits in the habitat required genes.

A potential parent randomly samples cells in its Moore neighbourhood (including its own cell), searching for suitable habitat for its offspring. If none is located in this sampling, the child dies immediately and does not appear on the grid. Otherwise, the parent deposits the offspring in the empty white cell or on top of any pre-existing agents that provide suitable higher-level habitat. Thus it is possible for a child to occupy the habitat provided by its parent if a fortuitous mutation permits this.

An agent that reaches its lifespan is removed immediately from the grid. Any agent that depended on the dead agent for habitat is also extinguished up the habitat chain of that cell. Thus if a base-level agent dies, all agents on its cell die simultaneously for want of suitable habitat and the white base level habitat will become accessible again.

3 Results

The software is coded in C++ employing the OpenGL and OpenAL APIs on an Apple Macintosh, running OSX. The basic parameters used to establish the results described here are as follows.

- Grids from 10x10 to 50x50 have been tested. Grid size doesn't make a significant impact on the behaviour of the simulation although as the resolution is reduced obviously the scope for pattern formation decreases.
- The grid is initialised with a fixed white (1,1,1) base habitat.
- The grid is initialised with 5 random, white-living agents regardless of its size.
- An agent's reproductive maturity is fixed at 80% of its lifespan.
- The maximum life span of an agent is 100 updates (lifespan is evolvable).
- 1 randomly selected level on 50% of cells is selected for update at each simulation time step. If a selected cell and level is uninhabited, nothing occurs.
- The mutation rate is set to 1/100.
- Would-be parents make 4 attempts to find local habitat for their offspring.

The simulation parameters are few in order to examine, in isolation, the potential of habitat creation as a generative mechanism of sonic and visual complexity. Hence there are many aspects of organism reproduction, movement, niche construction and ecosystem engineering that could be considered. The potential for future work is discussed below.

3.1 Visualisation and Basic Simulation Results

Figure 3 shows a typical *Habitat* visual sequence showing the rich, patchy landscape that emerges. The structure of the landscape remains spatiotemporally stable, even across large time frames, however it is anything but static. For instance, note the existence of a stable magenta habitat towards the upper-left of the screenshots. The boundary of this formation changes but the structure remains over the 20,000 time steps. Note the development of a stretch of green habitat on the lower right hand side of the images that coalesces from three discontinuous patches.

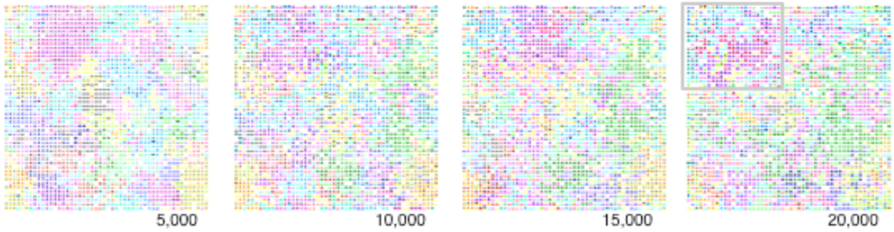

Fig. 3. Images of *Habitat* at 5000 frame intervals. The faint grey rectangle (*top left at 20,000 frames*) indicates the area enlarged in Figure 4.

Figure 4 shows a close up of the simulation at 20,000 frames. The width of the bars drawn in each cell represents the lifespan of the agent that is providing the habitat of the indicated colour at that location. A full cell-width indicates the maximum life span of 100 updates.

As the stack height increases, agents of decreasing lifespan form stable cells. A short-lived agent cannot provide a basis upon which others can depend for habitat. Reciprocally, a long-lived agent cannot live on a shorter-lived habitat provider and hope to achieve reproductive maturity. Hence, miniature *Towers of Hanoi* emerge naturally from the simulation and are only broken by a mutation that produces an unsustainable top-heavy configuration.

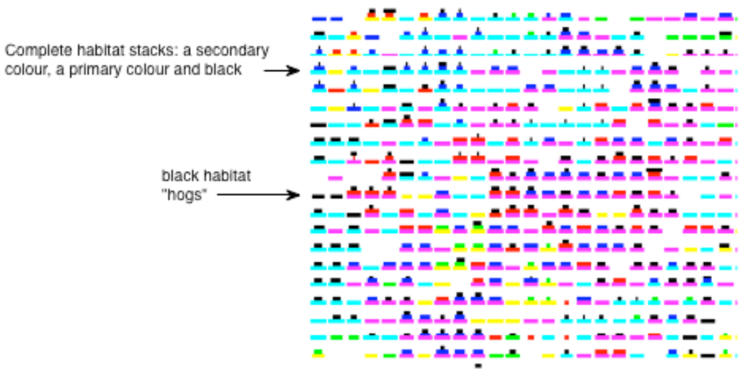

Fig. 4. Close-up (*top left corner of frame 20,000, Figure 3*) showing individual habitat layers. Agent lifespan is represented by the width of the habitat bar at each location and ranges from 0 to100 agent updates.

Over hundreds of thousands of time steps the simulation maintains stable habitat configurations. Figure 4 shows some black habitat "hogs" that occupy all bits of their white habitat. These agents appear to be at a selective disadvantage when compared to coloured agents. This is surprising given that black is barren wasteland for other agents and provides no habitat for others to infiltrate. The reasons for this behaviour are yet to be established statistically. However, the phenomenon has been confirmed by seeding *Habitat* exclusively with randomly placed white-living, black-providing agents.

One possible reason for the behaviour is that every reproducing agent samples its neighbourhood, including its own location, for a place to locate its offspring. When the local neighbourhood is densely populated with creatures of a parent's kind, a mutation will allow the offspring to survive by shifting it to the next upward layer of local habitat. This is most likely identical to the habitat provided by the parent agent itself. Unfortunately for black agents, no children, regardless of any mutation they possess, can live on its parent or its parent's kind. Thus black wastelands appear to be colonized from the edges by fitter agents that have the option of placing offspring in habitat provided by their own kind (when fortuitous mutations arise), and then opportunistically mutating back to their parent's kind when conditions allow.

3.2 Sonification Results

Habitat simulates evolutionary time periods. Our software therefore allows for the sonification of the evolutionary dynamics of habitat formation. Alternatively, a set of habitats that have evolved over a period of time may be evolutionarily frozen by the user and sonified directly.

To generate a spatialised, coherent, evolutionary sonic ecosystem from *Habitat*, each agent type is assigned audio characteristic of a real organism according to the type of habitat that it requires, and the type that it provides. These are stored as sampled audio files for playback. Agents that are occupying the base-level habitat are assumed to be autotrophs and are assigned the sound of marsh grass, bushes or trees blowing in a gentle breeze. Agents that occupy the grass, bushes or trees are assigned samples of distinct animal calls found in the wetland environment located down the street from the author's home. In the prototype described here, the plants are occupied by the Common Eastern Froglet (*Crinia signifera*), the expressively named Eastern Pobblebonk (*Limnodynastes dumerilii*) and the Spotted Marsh Frog (*Limnodynastes_tasmaniensis*). Finally, black habitat is assigned the percussive chirp of a cicada, the Alarm Clock Squeaker (*Pauropsalta mneme*)[1]. Agents generate audio only when they are reproductively mature. See section 4 for a description of the intended final soundscape.

The listener is positioned in the centre of the grid (Figure 5). The sound of the environment is spatialised around the listener according to the direction of the generating sources and attenuated according to the generator's distance from the listener. To avoid a cacophony of mature singing agents, the grid is sampled sparsely at each frame for audio generation. The current sampling density is 1 sample per frame with the simulation running at 25 frames per second. This can be altered to vary the density of sounds generated by the software. If a mature agent is located at the sampled position and habitat level, that agent voices its audio file.

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[1] Real cicadas don't depend on frogs or birds for habitat production, they live in trees! This prototype was based largely on aesthetic grounds. See section 4 for a more easily justified implementation.

Figure 5 shows a cumulative "score" generated over a one-minute period after evolution has been frozen at frame 10,000. By freezing the evolutionary process and preventing the agents from ageing, we maintain a snapshot of the habitat as it has evolved to this point. This is suitable for generating a coherent audible experience from a single habitat arrangement. Alternatively, evolution may be left running and the software will generate an evolutionary soundscape.

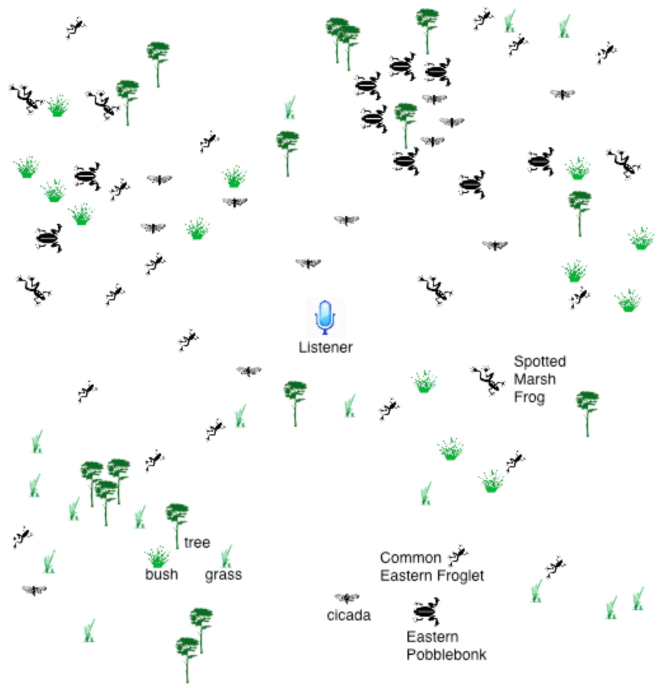

Fig. 5. An illustrative, cumulative section of the score produced by sonifications over 60 seconds with evolution paused at 10,000 time steps.

The resulting soundscape is most pleasing to the author when the grid contains about twenty by twenty cells. This gives sufficient density without overpowering the listener with too many individual sound sources. The number of organisms, in particular the number of frogs, seems to approximate the effect of the author's local wetland and the repeated calls made by particular frogs is regular enough to give the desired effect of a spatially coherent handful of callers. Although some ponds are literally hopping with singing frogs it has not been the aim to replicate this din!

4 Future Work

This simulation and visualisation could be extended in many ways. A few that are relevant to constructing a coherent habitat model and a soundscape are listed below.

An extension to the application in generative art is the inclusion of multiple habitats in a single layer within a grid cell. A white cell could provide habitat for three agents simultaneously and at the same level if they were red, blue and green, or perhaps for two agents simultaneously at the same level if they were magenta and green. The magenta agent could provide habitat for a red and a blue agent on its own back. This would more accurately reflect habitat formation by ecosystem engineers such as the tree that simultaneously provides different kinds of habitat for occupation by beneficiary species. For instance, a particular tree may harbour earwigs under its bark and possums in its hollows. The software would benefit from a longer habitat bit pattern to allow for this greater species diversity.

With a longer habitat bit pattern, it is possible to diversify the sonic material played by the software for installation in a multi-speaker environment. As well as the frogs listed above, endemic thicket-hiding and tree-dwelling birds will be added. The Noisy Miner, Wattlebird and Magpie are suitable candidates. Cicadas will be assigned specifically as tree dwelling organisms.

To sonify this intricate environment a "hierarchical listening" approach would be helpful. Rather than sonify the whole environment simultaneously (as occurs now), the listener could focus attention at different scales, from close-up to wide overview, and also move around within the grid world. Agents in a neighbourhood would then play a chorus dependent on the species present in the vicinity of the listener. In this way a walk through *Habitat* could be simulated.

It is possible to directly seed the simulation base-habitat cells with colour to structurally predetermine habitats. Predetermined habitats give specific species an advantage in some areas and not in others. For instance a cyan region could be drawn into the base-grid ensuring that no secondary coloured agents could ever inhabit this location — just as sand or water might prevent bushes and trees taking hold. Pre-established habitats like this would change the dynamics of the simulation and sonification considerably. They would act as simulated ponds or arid areas with their own characteristic sounds.

A continuous model of habitat occupation would permit agents to survive in less than ideal areas in times of hardship, even if they were not able to grow or reproduce there. This would be particularly useful if the software was applied to ecology.

4 Conclusion

This paper presents a simple simulation of an evolutionary ecosystem from which emerges stable, multi-layered habitats based on ecosystem-engineer agents. The habitats form spatiotemporally coherent, patchy environments. They are generated by asexually reproducing, immobile agents operating on a two dimensional grid. Each agent engineers a new form of habitat suited to occupation by other agents. Agent lifespan evolves within the simulation to create stacks of habitat with long-lived agents at their bases, and progressively shorter-lived agents on top.

The simulation has been used to generate a soundscape that represents the experience of a Melbournian urban wetland. It can also be operated in a mode that sonifies the simulated evolutionary process as it unfolds.

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