Creatures of Habit: A Computational System to Enhance and Illuminate the Development of Scientific Thinking

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A Computational System to Enhance and Illuminate the Development of Scientific Thinking *

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Abstract

Creatures of Habit is a computer-based microworld designed to engage middle-to-high school students in the process of scientific inquiry. The system depicts a universe of interacting programmable "creatures" whose individual behavior is guided by simple rules that may model naive psychology, physical laws, chemical affinities, and other domains. Students can create or revise creature rules and explore the resulting (and often surprising) emergent behaviors within "artificial ecosystems"; or they may employ predesigned ecosystems in undertaking more structured problem-solving activities. Our objective is for students to use these ecosystem simulations as an enjoyable introduction to a variety of scientific domains, especially the area of *dynamical systems*, a field of science where experiments with such simulations often leads theory. The system encourages a wide range of reasoning and learning central to scientific methodology — pattern observation, hypothesis formation, experimentation, data collection and analysis, and deduction. We describe the rationale behind the system, discuss some sample activities, and outline the system's potential both as a learning environment and as a research laboratory for empiricial studies of scientific thought. Finally, we briefly describe the present state of our prototype Creatures of Habit system.

KEY WORDS: microworlds; dynamical systems; scientific reasoning

Introduction

"Doing science" involves learning to use complex techniques and skills — making observations, noticing interesting patterns, forming hypotheses and theories, making conjectures, and designing and running experiments. If introducing students to scientific content were sufficient, education would be hard enough; studies show children bring ill-formed models of scientific domains such as mechanics, electricity, chemistry, and biology to school (Driver, 1985; Osborne, 1985). Students need to learn not only a body of structured beliefs, but how to participate in the processes of science, which are intimately related to content. Students must understand that scientific ideas are motivated and supported by theory, experiment, and argumentation — not authority. Beyond the content and process of science, students should also enjoy doing science. They often view science as a mysterious, unapproachable culture in which they observe rather than participate. A truly effective science education should dispel this image by giving students opportunities for designing and refining inquiries.

We describe a computational system under development — "Creatures of Habit" (henceforth, Creatures) — designed to address these science education issues by providing rich, exploratory, and enjoyable scientific experiences for the middle-to-high school years. Creatures is a microworld of programmable interacting "creatures" whose behaviors are based on rules. In exploring this microworld, students can be introduced to important content in various scientific domains, notably in the area of *dynamical systems*; moreover, the program allows for a wide range of activities central to doing science — such as conjecture, theory formation, experimentation, deduction, and communication of results. Perhaps most important, Creatures is intended to lead students toward original and creative work — to have them participate in science as fledgling researchers driven by curiosity, rather than onlookers motivated by assignment.

Besides its utility for science education, we see roles for Creatures in empirical studies of scientific thought. Because it affords activities engaging reasoning skills

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such as analysis, synthesis, and evaluation (see below), it may be used to examine how these different skills develop. The system can thus provide a uniform environment in which to design specific instructional and experimental tasks.

In the remainder of this paper, we first motivate the design of Creatures by discussing the subject of dynamical systems; we then describe the system[1], outline some learning activities that might be undertaken with it, sketch how it reflects key learning goals for science education, and propose a design for an experiment in which Creatures may be used to illuminate the development of scientific thought.

Dynamical Systems: Analytic Science, Synthetic Science, and "New Wave" Science

Since Creatures is designed to provide introduction to concepts and methods involved in the study of complex dynamical systems (Thompson & Stewart, 1986), we briefly describe the growing importance of such science. Certainly there has been an explosion of interest in this subject within the scientific community (Gleick, 1987); and this phenomenon has ramifications both for scientific methodology and for science education.

Historically, scientific thought has been characterized as either "analytic" or "synthetic" (Oldroyd, 1986). In this classic formulation, the analytic method is observing phenomena and seeking laws to account for them; the synthetic method involves confirming the validity of laws via prediction and experimentation. The advent of scientific computing has added a new texture to this division. In studying a system, a scientist may account for its behavior by constructing an abstract model that can be realized as a program; that model may then be simulated by running the program as a test of its applicability. Thus, there is an *analytic* side to computer modeling (observing real-world phenomena and designing model systems that might illuminate them); and a *synthetic* side (changing parameters in the model system to match observations or see new phenomena). Hut and Sussman (1987) describe this approach as "analysis by synthesis"; while Farmer and Packard (1986) call it "new wave science" — a methodology "characterized by attempts at synthesis rather than reduction, cutting across conventional disciplinary boundaries.... New 'effects' are discovered through a combination of insight and serendipity, and more often than not experiment leads theory....Simulations are frequently used to develop qualitative insight, often by studying highly simplified models which are nonetheless complicated enough to possess universal properties found in more complicated systems."

Developing computer simulations as experimental systems has led to a blossoming scientific literature beyond cognitive science. Simulations are employed to discover robust properties of intergalactic collisions, heat flow in solids, kinetics of chemical reaction mechanisms, evolutionary adaptation, and many other dynamical systems. These simulations enable the study of increasingly complex phenomena; but they also tax skill in developing formal models, and present students with new phenomena to understand and methods to use. Techniques of developing, studying, and documenting computer models have become an integral element of scientific method. In this context we see Creatures as having particular potential value, since it provides an engaging "introduction to complexity" and an environment in which to learn-by-doing these skills of "analysis by synthesis." As we will show below, students can construct systems of creatures that exemplify concepts such as stability, oscillations, and bifurcations. Because these systems may be of their own devising, the concepts become personalized in a way that canned demonstrations could not.

Creatures of Habit: The Basic Elements

Creatures is an environment in which students can explore "artificial ecosystems" composed of interacting programmed entities called "creatures." Inspired by Braitenberg's (1984) *Vehicles*, these creatures behave and interact on the computer screen according to sets of simple rules. The rules might be chosen to reflect physical laws, naive psychology, chemical affinities, and so on. A simple example of a group of creatures and how they might interact illustrates the system's components.

Consider the scenario illustrated by the sequence of "snapshots" in Figures 1 to 5.[2] Here we see three different creature types (distinguished by geometric shape) with the following behavioral rules:

1. *Squares* are attracted to squares, but indifferent to triangles and circles;
2. *Circles* are repelled by triangles and circles, but attracted to squares;
3. *Triangles* are attracted to circles, but indifferent to squares and triangles.

Figure 1 shows an initial "ecosystem" with five creatures, and Figures 2 – 5 demonstrate how this ecosystem evolves over time according to these rules (note that creatures leave a visible path). Even in this simple case we see many types of behavior: mutual attraction (between squares), mutual repulsion (between circles), and predator-prey relationships (the triangle "chases" the circle that is "running away" from it). Note how the interactions can be parsed into "episodes" in a naive model of animal behavior:

- The squares like each other and begin to move together. The circles, interested in the squares but oblivious to each other (and the triangle), tag along. The triangle, spying a tasty circle, starts sneaking up on it;

[1] Creatures exists in prototype form on a Hewlett-Packard Series 300 Model 320.

[2] These figures were generated by our prototype Creatures system.

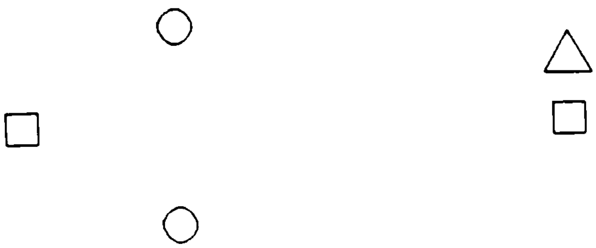

Figure 1: Initial Configuration

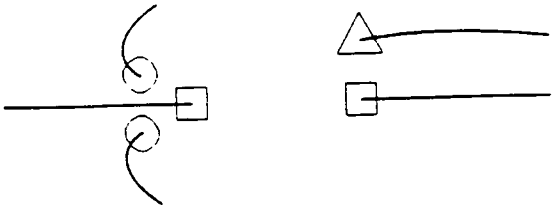

Figure 2

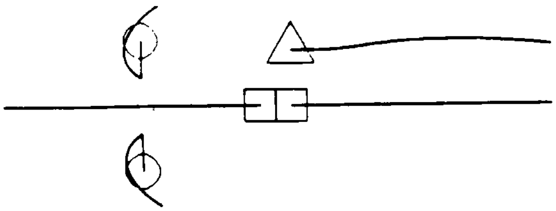

Figure 3

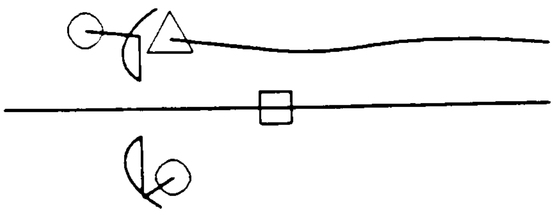

Figure 4
(Note that the two squares overlap.)

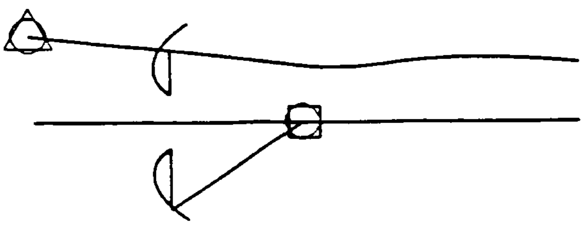

Figure 5: Final (Equilibrium) Configuration

- After noticing one another, the frightened circles flee in opposite directions;
- The triangle chases the topmost circle while the other circle, regaining its composure, heads back toward the squares.
- The creatures reach a final "equilibrium" configuration when the triangle "catches" the topmost circle and the other circle joins the two squares.

This simple scenario indicates how even a small number of creatures governed by straightforward rules can lead to interesting, varied behavior. Under slightly different situations, it is possible to observe more complex behavior and "emergent phenomena"[3]. Even this scenario suggests interesting questions to explore, e.g., how do initial positions of the creatures influence the episodic nature of the interaction or the creature "fates"? How would adding one creature to the start state affect the interaction? Given these species, is it possible to design a configuration that exhibits stable oscillations?

We now present a fuller exposition of the basic elements of the Creatures of Habit system:

Creature Morphology

Creatures are small mobile fantasy creatures that "live" on the screen. Creatures come in many "species," identified by a set of discrete characteristics. Above, creatures were distinguished only by shape, but more animal-like creatures are conceivable (a species might be identified as purple, with bobbling eyes, pointy ears, squiggly tail). Species may also be endowed with less visible properties such as mass or birth rate.

Species Rules

Creatures interact with each other and their environment by obeying a small set of species-specific rules linking perception to action. Typically, species rules indicate which properties are "attractive" or "repellent" to a species. Once a species rule-set is defined, every member of that species uses those rules to govern its behavior.

Ecosystem Rules

The complete dynamics of a population of creatures is determined by a higher-level set of ecosystem rules which specify how the creatures employ the notions of "attraction" and "repulsion" when moving. Ecosystem rules are perhaps best illustrated by example; the particular examples that we provide should be read merely as indicating a space of possibilities. Variations on these rule-sets are of course possible, and other rule-sets are computationally viable.

Ideal Gas Rule-Set. In this simple model, all creatures are regarded as indifferent to one another (i.e. properties that are attractive/repulsive to a given creature's species do not affect its motion). The ecosystem rule-set does include, however, a default collision rule

[3] For instance, an entire cluster of creatures might move as one unit due to the internal patterns of attraction and repulsion between the cluster's individuals.

specifying that collisions between creatures are elastic and momentum-conserving[4]. Note that this rule-set implicitly assumes that mass will be included among the species properties. Creatures here are regarded as inanimate billiard-ball-like objects, each with a (species-specific) mass.

Inverse-Square Force Rule-Set. This rule-set elaborates the last one. Creatures are particles upon which inverse-squared forces act. To determine the individual force of creature *C2* on creature *C1*, we sum the attractions (+) and repulsions (-) that *C1* has for *C2*'s properties. The resulting number divided by the square of the distance between *C1* and *C2* is the magnitude of this individual force; the direction between *C1* and *C2* determines the direction of the individual force. The total force on creature *C1* is the vector sum of the individual forces from all other creatures. Dividing this total force by creature *C2*'s mass determines the acceleration, or velocity change, of *C1*. (Again we assume creatures have mass as a species-specific property — and we might add some other properties, such as "charge," as well.)

Distance-Dependent "Animal Attraction" Rule-Set. This rule-set embodies a simple "naive psychological" model for creature interactions; it was the ecosystem rule-set implicitly used in the scenario depicted in the figures. To determine how much creature *C1* would "like/not-like" creature *C2* if it were one unit away, look at *C1*'s species rules and subtract the number of repellent properties exhibited by *C2* from the number of attracting properties. To determine how much *C1* *actually* likes *C2*, divide the previous result by the distance; this inverse distance dependence models a situation in which creatures pay more attention to closer objects. Thus, if creature *C1* finds three properties of creature *C2* attractive, and one repellent, then the unit-distance strength of *C1*'s attraction for *C2* is 2; if *C1* is 10 units of distance from *C2* at that moment, then *C1*'s current attraction toward *C2* has a strength of 0.2. To determine how creature *C1* should move, the system finds the creature about which *C1* feels most strongly (like/not-like); creature *C1* should then move at a constant (species-specific) speed towards that creature (if liked) or away (if not).

Encounter-Dependent Birth and Death Rates. In this rule-set based on population biology, we assume that creatures have species-specific properties of "birth and death rates." Creature movement might be governed by the rule-set above, and in addition new species members may be born or die. The birth rules might depend upon encounter rates between members of the same species. The birth rule for species *A* might be the following: on any time step, an *A*-creature has a 2% chance of giving birth to another *A*-creature, except when the previous time step resulted in contact with an *A*-creature, in which case there is a 50% chance of giving birth. The death rate of a species might be defined similarly (e.g., on any particular time step, an *A*-creature has a 3% chance of dying, except when the previous step resulted in contact with a "predator" species B, with a 60% chance of dying).

[4] It is also possible to collide with the boundaries of the screen; these collisions should be treated as elastic collisions with a stationary wall.

Interface to the System; Additional Tools

We have described the basic elements of Creatures but thus far ignored the interface. In this section, we describe several aspects of the interface design for Creatures. Many issues must be resolved to make Creatures both accessible to first-time users and extensible for use by expert scientists. We aim to first provide some beginning ecosystem rule-sets for easy access to Creatures; given a choice of ecosystems, the user may edit the properties and rules for individual species with iconic menus. The basic interface should also provide a fair amount of control over simulations: initial configurations may be specified by directly moving creatures to their desired starting positions, and individual runs may be paused, single-stepped, replayed, and stored.

The description above does not address the needs of more experienced users who wish to create or edit the ecosystem rule-sets. The range of ecosystem rule-sets may be constrained so that they might be customized via a menu interface; but more likely, a more elaborate interface to ecosystem rule-sets (verging on a special-purpose programming language) will be required.

We are working on other special-purpose tools for the Creatures system for measuring, modifying, and experimenting with configurations and rules. For example, we aim to provide multiple screen windows so the student can make two runs at once, comparing results from two systems by varying only one parameter — say the initial position of a creature. Experimentation will also be supported by "annotation windows" where students enter information obtained from the results of previous runs; e.g. to examine a sequence of runs and make deductions about the species-rules of individual creatures, structured tables help a student codify the information obtained and highlight the information needed for a solution. The system will include graphical measuring devices that enable the student to take precise measurements of distance, angle, and time; in our experience with the Creatures prototype, these variables have proven crucial in describing important features of simulations.

Sample Activities

Exploratory Activities

The most fundamental activity we imagine is exploration. Here, students are provided with sets of creatures in an ecosystem, and observe how the creatures behave and interact. Since both the species rule-sets and the ecosystem rule-sets are accessible, students can investigate the relationship between the behavior they observe and the rule-sets governing that behavior. And because the system facilitates change at a wide variety of levels (from the number and positioning of the creatures to the species and ecosystem rule-sets), students can readily explore the effects of "perturbing" a given scenario in diverse ways. Even inexperienced students could examine how the qualitative behavior of a configuration depended on the initial position of one of the creatures; more advanced students could explore the effects of "tweaking" species rule-sets; yet more advanced students could work at the ecosystem rule-set level.

Even within this purely exploratory frame, a number of important scientific ideas are introduced. To highlight, it quickly becomes apparent in working with Creatures that *complex systems may arise even from very simple rules*. Often these systems exhibit emergent properties — stability, oscillations, irreversibility — that resist explanation in terms of low-level rules. Moreover, by playing around with these systems, students can develop important skills that are usually slighted by classroom science: making conjectures, searching for patterns in data, and generating qualitative or statistical descriptions. We emphasize that although exploration is a low-threshold activity, it is not merely an introductory one; rather, it is the essential point of the design of Creatures. Indeed, although Creatures is targeted for students in middle-to-high school, issues raised by "mere exploration" could evolve into highly challenging problems at or beyond the college level.

Problem-Solving Activities

Although Creatures lends itself to exploration, it supports more structured "problem-solving" activities as well. We have used the prototype to play a "Mystery Creatures" game where users are provided with a set of creatures whose species rules are unknown and must be determined from their behaviors. The goal of the game is to design experimental runs and thereby deduce the rule-sets of the creatures. Sometimes, one well-chosen experiment can illuminate the behavior of a number of mystery creatures all at once; in other situations, the user must design a sequence of experiments. A related game, Invisible Creatures, involves several visible creatures (whose rule-sets are accessible) that interact with an "invisible" creature. In this case, the goal is to determine the identity and location of the invisible creature based on the observed actions of the visible ones. These kinds of activities stress skills of experimentation and logical deduction.

Design Activities

Many activities supported by Creatures have an important design focus. Here the emphasis is not on *why* a given system evolves as it does; rather, the goal is to *construct* a system exemplifying some desired behavior. For example, given a set of creatures, one might ask: "Is there an initial configuration for these creatures such that all the creatures will collide at once?" Design can take place at many levels, from constructing configurations of creatures to "creating new worlds" with new ecosystem rules.

A Hypothetical Scenario

The following scenario shows how a student might use Creatures. We use the same species and ecosystem rules as in the scenario shown in the figures earlier:

▷ The student begins with a screen on which a dozen creatures — some squares, triangles, and circles — move in various directions, creating intricate patterns. The student tries similar runs using the same numbers of creatures, but with different initial configurations, just to get a feeling for the kinds of phenomena that might occur.

▷ The student decides to figure out what the species rules for each of the three creature types might be. She runs a sequence of experiments in which two creatures of the same type are placed at a slight distance from each other in the screen center. She observes that when triangles are used, they stay where they began; squares move toward each other; and circles move away from each other. She concludes that triangle creatures are indifferent to other triangles, while squares are attracted to other squares and circles are mutually repelled.

▷ When she places a square and two circles in a particular initial configuration, the two circles move toward the square until, at a later time, they drift apart; then, shortly after, they move toward the square again. The student hypothesizes that circles find the square attractive, but when they are too close to each other, their mutual repulsion becomes stronger than their attraction for the square. She replays the earlier run, this time occasionally pausing the simulation and measuring distances and headings of the creatures to test her conjecture.

▷ Replaying the previous run, the student notices the square remained stationary throughout. She concludes that squares are indifferent to circles. In fact, she recalls that in her earlier simulations, whenever there was only one square on the screen, that square did not move at all regardless of how many circles and triangles were about; so she concludes that squares must be indifferent to triangles, too.

▷ During her experiments with circles, the student remembers noticing that the two creatures ended up standing still in opposite halves of the screen.[5] She decides to investigate: Does any initial configuration of any number of circles always end up in a "stationary" state; and if so, do the final states reveal some pattern?

Clearly, the scenario above could be extended in different ways. For example, the species rules could involve features besides shape; or the creatures could move at varying speeds; or the student might choose to examine whether any "stationary configuration" remains stationary if one other creature is added to the screen; or the student could design a new creature that moves away from squares, and see what happens when it is placed in a crowd of (mutually attracting) squares. From this very simple beginning, many projects — some touching on very sophisticated questions — may arise.

Creatures as Part of A Science Curriculum

A perennial tension in science education exists between teaching content knowledge and scientific

[5] It should perhaps be mentioned that, for this particular scenario, we assume that the screen on which the creatures move "wraps around" in both the x- and y-directions.

method. The flaw in overemphasizing content is that it tends to lead to rote learning, with little sense of how scientists work to develop theories. This approach typically fails to recognize students' pre-existing conceptions of scientific domains (diSessa, 1987); students are tacitly encouraged to memorize laws and results without ever engaging their own reasoning powers to see how they were arrived at, or could be tested. In contrast is "discovery learning", which emphasizes experimentation and the scientific process. The difficulty with this approach is twofold. First, the notion of "discovery" is often realized in practice by canned experiments; the "discovery," whose results are known beforehand, is superficial. In this kind of setting, students spend much of their time trying to find the "right answer," rather than what the experiment means. Second, when discovery learning is realized most sincerely, by simply letting the student explore on his or her own, the teacher is often left with questions about what the student's explorations were, and what was learned (Hawkins, 1987).

We feel that Creatures can serve as a medium for guided, exploratory discovery-type learning (cf. White and Horwitz, 1987). The worlds students can explore with Creatures are brand-new; there are few "right answers," and real discoveries can be made. But while making these discoveries, students can obtain a structured introduction to the role of conjecture, measurement, and experimentation in the scientific process. Activities such as the "Mystery Creatures" game place an emphasis on logical reasoning; these puzzle-like activities can provide the benefits of occasional settings in which a right answer does in fact exist.

An Experimental Design for Studying the Development of Scientific Thought

We have stressed the role of Creatures in science education. Here we illustrate how it may also be used for studying the development of scientific thought, proposing an experimental design we aim to undertake using the next iteration of the system. Consider the following three tasks, corresponding to three common modes of scientific thought, that a student might be asked to perform using a particular ecosystem and starting creature configuration:

1. The student watches the system run (i.e. creatures move on the screen), and is asked to infer the species rules of each creature. This *analytic* task involves working backward from observed behavior to underlying rules.

2. The student is shown the species rules for the creatures, then asked to predict the result of running the system using the startup configuration. This is a *synthetic* task of predicting behavior from a known set of deterministic rules.

3. The student is provided the set of species rules for the creatures, *and* shown the results of running the system using the startup configuration; his task would simply be to explain events observed in the scenario in terms of the species rules. This is an *evaluative*, or perhaps *explanatory*, task.

Now the very same ecosystem and starting configuration could be used for each of these three tasks, as given to three different groups of students; but the kinds of descriptions generated for each of the three tasks — and indeed, the features of a particular scenario attended to — might vary widely. By obtaining think-aloud protocols from these different subject groups, we could begin to develop a coherent picture of how the several modes of scientific thinking differ; specifically, we could begin to distinguish these modes according to the sorts of phenomena to which they typically apply.

As a possibility, we might ask whether the phenomena used to deduce rules in the "analytic" tasks are the same phenomena for which explanations are offered in the "evaluative" task. In other words, are the phenomena that people find salient for the deduction process the same as those that people find representative in the explanatory process? For example, in looking for underlying rules, subjects might tend to focus on events in which creatures reverse direction (e.g., a situation in which creature A, in moving toward an "attractive" creature B, finds itself too near a "repellent" creature C and turns around). In contrast, subjects given the task of explaining a given scenario might insist on a chronologically faithful narrative; i.e., they might pay as much attention to explaining creature A's initial direction as they do to explaining its change of direction.

Or we might try to characterize the kinds of "episodic groupings" that different task groups assign to the given scenarios: e.g., are there certain tasks in which scenarios are typically viewed as "punctuated" by changes in direction? Are there certain tasks in which the final states (e.g., the achievement of equilibrium) are attributed more importance? Under what circumstances do people reason at the "system level," talking about behaviors of larger groups of creatures, rather than at the "atomic level" of individual creatures' histories?

Yet another issue involves the possibility of an order effect between different activity modes. For example, in a different study we could ask subjects who have just predicted a scenario in the "synthetic" task to watch the actual scenario and perform the "explanatory" task; their protocols could be compared with those generated by subjects given the explanatory task alone. We could then begin to characterize how a subject's previous predictions affect the kinds of explanations generated for a particular scenario.

Finally, it is worth mentioning the issue of noticing "creature indifference" in the context of this experimental design. In our attempts at watching scenarios and deducing the rules underlying them, we found that a great deal of information is conveyed by noting which creatures are indifferent to which others. Indifference between creatures seems to be a subtler notion that attraction or repulsion; when watching a scenario, there is a tendency to attribute a creature's movements solely to attraction or repulsion without recognising that the *absence of motion* toward or away from some other creature is also informative. This tendency is reminiscent of the disinclination to use negative information in scientific reasoning (Mynatt *et. al.*, 1977; Wason, 1977). Thus another question addressable within this experimental design is whether any of the three tasks is more likely to lead subjects to confront the issue of creature indifference.

Conclusion: Present Status, Future Directions

We now have two prototype Creatures of Habit systems: one written in Scheme (a Lisp dialect), one in C. Both run on a Hewlett-Packard Series 300 Model 320 computer. The Scheme version contains facilities for developing and editing ecosystem and species rulesets, and includes features for maintaining histories of individual runs. But it is slow and at the moment unsuitable for running systems with more than 4-5 creatures. The C program is less elaborate or interactive, but its running speed is two orders of magnitude faster than the Scheme program; using the C prototype, simulations employing 16 creatures have been run at a satisfactory speed. We continue work with both systems, using Scheme as a medium for developing new tools and trying out ecosystems in the small, and the C program to run simulations quickly and experiment with properties of larger creature-worlds.

Much of our current design effort is developing a suitable interface to the system, and delineating a "starter set" of sample ecosystems appropriate for middle-to-high school students. A second theme noted above is using the system as a laboratory tool for conducting experiments in the development of scientific thought. It should also be possible to follow up with work in student modeling and intelligent "coaching" efforts to promote the various inquiry skills in science we have outlined. Ultimately, we hope that Creatures of Habit will provide an environment in which students can acquire the concepts, the methodological techniques, and — too frequently neglected — the intellectual curiosity of the working scientist.

References

Braitenberg, V. (1984). *Vehicles*. Cambridge: MIT Press

diSessa, A. (1987). Towards an intuitive epistemology of physics. UC Berkeley Cognitive Science Report #48.

Driver, R.*et. al.*, eds. (1985). *Children's Ideas in Science*. Philadelphia: Open University Press.

Farmer, J. and Packard, N. (1986). Evolution, Games, and Learning: Models for Adaptation in Machines and Nature. In Farmer *et. al.* (Eds.), *Evolution, Games, and Learning*, pp. vii-xii. New York: Elsevier.

Gleick, J. (1987). *Chaos*. New York: Viking Press.

Hawkins, J. (1987). The Interpretation of Logo in Practice. In R. Pea and K. Sheingold (Eds.), *Mirrors of Minds*, pp. 3-34. Norwood: Ablex.

Hut, P. and Sussman, G. (1987). Advanced Computing for Science. *Scientific American*, 255:10, 144-153.

Mynatt, C.R., Doherty, M.E., and Tweney, R.D. (1977). Confirmational Bias in a Simulated Research Environment: An Experimental Study of Scientific Inference. *Quarterly J. Exp. Psy.*, 29, 85-95.

Oldroyd, D. (1986). *The Arch of Knowledge*. London: Methuen & Co.

Osborne, R.*et. al.* (1985). *Learning in Science*. Auckland: Heinemann Publishers.

Thompson, J. & Stewart, H. (1986). *Nonlinear Dynamics and Chaos*. Chichester: John Wiley and Sons.

Wason, P.C. (1977). "On the failure to eliminate hypotheses..." — a second look. In P.N. Johnson-Laird and P.C. Wason (Eds.), *Thinking*, pp. 307-314. New York: Cambridge University Press.

White, B. and Horwitz, P. (1987). Thinkertools: Enabling Children to Understand Physical Laws. BBN Report No. 6470. Bolt Beranek and Newman Inc., Cambridge, Massachusetts.