Aintz: A study of emergent properties in a model of ant foraging

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Abstract

In this paper I discuss the notion of multiple levels of emergence, and motivate its usefulness as a conceptual tool. I argue that a multi agent system containing emergent properties can be divided into i) Axiomatic behaviour ii) Emergent behaviour and iii) World rules. I show how to use this division as an informal design tool, when designing and analysing emergent properties. Specifically I discuss where and why to place the axiomatic level, given the goal of the model.
Further I present an ant model, called Aintz. I show that the very simple basic behavior of the individual agents cause complicated emergent behaviors of multiple levels. I use the Aintz model to exemplify the notion of multiple levels of emergence.

Introduction

The field of Artificial Life investigates the fundamental properties of living systems and attemps to capture these in artificial media, such as computers. One of the most important concepts that have been identified is emergent behavior. This concept, and the study of it, is important because it provides an elegant way to create complex systems that are:
(i) Robust
(ii) Distributed
(iii) Extendable.
These qualities are all desirable in most types of computer systems. Emergent properties, in the context of computer programs, are often defined as being properties that are a consequence of the interactions of the behaviors programmed into the simpler parts of the system. If these properties sum up to "more" than the sum of their parts, they are said to be *synergetic*. The terminology is useful for identifying fuzzy properties of complex systems that might be hard to describe formally. This paper will address the issue of emergent behavior, introduce a simple model with a number of emergent properties, and provide some conceptual tools for the design of emergent properties.

Emergent Behavior

A formal definition of emergent properties was proposed by (Baas 1993):

P is an emergent property of S^2

iff

$$P \in Obs^2(S^2), \text{ but } P \notin Obs^2(S^1_{i_1})\ \forall i_1$$

In Baas' definition, S^2, the second order structure, is the result R of applying interactions Int^1 to the primitives, S^1, and the observable properties of the primitives $Obs^1(S^1)$:
$S^2 = R(S^1, Obs^1(S^1), Int^1)$
This means, that a Property P of S^2 is emergent iff it is observable on S^2 but not below. For instance, while observing the flightpath of a group of birds, one might conclude that the group forms a flock. If this property isn't observable by looking at individual flightpaths, the flocking property is said to be an emergent behaviour of the group.

I will adopt a less strict approach to my definition of emergent properties, and define them in terms of systems that contain a number of agents, each of which behave according to a traditional sequential program. These agents all inhabit the same world, and are able to modify it, and each other, using a set of *atomic actions*. The different agents must run concurrently, either on a distributed system, or parrallelized on a single CPU. In a system like this the *axiomatic behavior* is the code according to which the individual agent behaves. This behavior is predictable and formally describable, using normal computer science formalisms.
The *emergent behavior* of the system is the behavior arising as a consequence of the axiomatic behavior. This includes the axiomatic behavior, but much more interestingly, it includes the interactions of the individual agents, the *history of changes* that the agents leave in the environment and the interactions of the agents with this

history. This behavior is sometimes so complex and difficult to predict that the easiest way to observe it is to simulate it.

The history of changes at time t is the sum of all the interactions between the agents and the environment, and between individual agents from time 0 until t. This history defines the *state* of the system at time *t*. The state itself doesn't need to record the entire history of changes, indeed whenever it does, this part of the history becomes a part of the state. Interestingly the state of the system at time *t* quite often has dramatic impact on the behavior of the system at time *t+1*.

Some emergent behaviors have higher order consequences themselves.

I will name these consequences N-ary emergent effects. Primary emergence would thus be the direct consequences of the axiomatic behavior, secondary emergence would be the consequences of primary emergent behavior etc. It is interesting to identify these different levels since this allows us to reason informally, yet still structurally, about emergent effects.

For instance, a property P of the system that is not explicitly coded, but is deduced to be a direct consequence of the axiomatic behavior, can be classified as a primary emergent effect. Other emergent effects must be higher level emergent effects.

This definition should be used to structure the thoughts of the implementor in the design and evaluation phases of the programming process.

Thus, what "direct consequence" means exactly, is dependant on the implementor's ability to predict and deduce emergent effects.

Introducing the Aintz

To exemplify some of the topics that I have introduced in the previous sections, I will now introduce an ant model that displays many of these qualities. The model, Aintz, is inspired by biological ants. It is not a study of Ant systems, such as the one presented by (Dorigo et al. 1997). It resembles the MANTA system, as described in (Drogoul et al. 1992) and even more the system of "dock-worker" robots described in (Drogoul et al. 1993)
The Aintz system is a simulation of foraging by artificial pseudoants, here called "Aintz"[1]. There are different types of aintz, all of which employ different strategies in this foraging.
The model is based on some basic objectives:

1. Aintz shouldn't individually be able to do things biological ants can't do

2. Aintz should operate according to local rules, without global control.

3. Only the search for food is modelled.

[1]Named so to illustrate that they are not ants

Aintz can leave pheromone trails in the environment, detect them, and react to them. They always know the direction to their home. Further, pheromone trails evaporate linearly, and the infinitesimal amount of food an Aint eats is ignored. Instead of focusing on expenditure of energy, the model is focused on transformation of biomatter, specifically from food items to Aintz, and back. The total biomatter of the system is kept constant, some of the biomatter existing as food, and some of it as Aintz.

The World

The world of the Aintz is a two dimensional lattice, with a 4 neighbourhood topology. A grid cell, (here called a place) doesn't have any topological dimensionality. Anything at the same place is completely colocated. The edges of the lattice wrap around, thus forming a torus. A place can hold any number of Aintz of the same color, or race, but not two of different color. Any place can also hold exactly one scent or pheromomone. Finally a place can hold any non-negative number of food items. Some places are special places, called hills. These places serve as the home for any Aintz produced there.

Whenever a hill holds more than $\mathbf{F}_a$ fooditems, it transforms $\mathbf{F}_a$ of its fooditems into a new Aint of its own color. This is done to simulate that eggs have been laid, larvae fed etc. All of this is compacted to the single action of transforming biomatter from food to an Aint. The scent of a place may be either neutral or of a certain color. Neutral scents are ignored and handled as no scent. Colored scents have a certain strength that decreases linearly in time. Whenever a scent is added to a place it either completely replaces, combines with, or is overpowered by the scent that is already present. A combination occurs when the two scents are of the same color. Replacement/overpowering occurs when they are different, in which case the stronger scent overpowers the weaker. Scents do not dissipate in the environment.

Whenever an Aint dies, it is transformed back into $\mathbf{F}_a$ fooditems. These can be reintroduced into the world in different ways: They may be dropped at the spot where the Aint died, to simulate a carcass that Aintz might eat (cannibalistic reentry) or it may be dropped randomly into the world, either uniformly or normally around the center (Random reentry).

The Aintz

There are four different types of Aintz, identified with red, blue, cyan and white color. The generalized Aint implements the common behavior of all Aintz which mainly is bookkeeping, graphics rendering, etc.

All of the Aintz have access to a number of *atomic actions*:

- **Move**
  Moves the Aint to a neighbouring place.
- **Drop Pheromone**
  Drops a pheromone item of a certain strength and color.
- **Pick up food**
  If any food is at the same place as the Aint, the Aint picks up one food item.
- **Drop food**
  If the Aint is carrying a food item then it drops it.

In addition, the Aintz can sense the pheromone of the place on which they are standing, and of the neighbouring places. Further they can sense the direction to home.

The generalized Aintz' axiomatic behavior can be stated as a subsumption architecture. (Brooks 1987) This means that the Aint has an ordered list of core behaviors, higher level behaviors *subsuming*, taking over, in special situations.

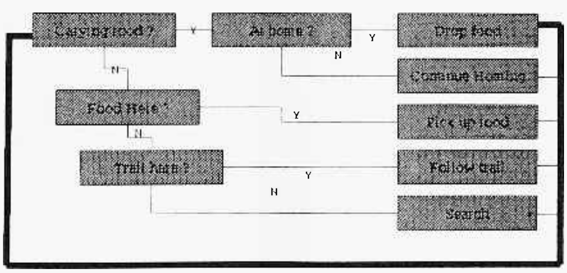

Figure 1: subsumption architecture of the general Aint

Thus an Aint will first check whether it is carrying food or not. If it is, it will check whether it is at home or not. If it is at home, and carrying food, it will drop the food. If it is not at home, but carrying food, it will "Go Home", which here means that it moves one step in the direction of home. While an Aint is homing (while carrying food) it will leave a pheromone trail pointing in the opposite direction of its current travel direction. This trail can be seen as a small arrow pointing in one of the four directions, N, S, E or W. Thus a homing Aint will leave these small arrows pointing towards wherever it found the food it is bringing back.
The "Pick up food" behavior simply removes the food from the world, and adds it to the food the Aint is carrying. The Aintz energy is then set to 250, to represent that the Aint eats a bite of the food. This energy measure should not to be confused with the biomatter, neither in the Aint, nor in the food items. It is a mechanism to ensure that Aintz die if they don't find at least one food item every 250 timesteps.
While performing the "Follow trail" behavior, the aint reads the direction of the trail it is standing on, and takes a step in this direction. The trails of different types of Aintz are identical, thus a blue Aint can sense and follow a trail left by a red Aint.
While performing the "Search" behavior, in the case of the general Aint, it simply chooses a random compas direction and moves a step in this direction. Whenever a timestep has passed, the Aint loses a unit of energy. If the Aintz energy drops to zero, it dies, to simulate starvation. If an Aint moves into a place where an Aint of a different color already stands it also dies. This rule simulates combat between Aintz. All Aintz share this architecture and basic behavior, whereas the "search" behavior differs between Aintz of different colors.
The red Aintz simply use the default behavior of choosing a random direction. (Random search).
The blue Aintz (see fig. 2) leave a pink pheromone trail while searching, and when they need to choose a direction in which to move, they choose randomly among those neighbouring places containg the least pink pheromone. Thus, they avoid the pink pheromone. (Spreading search)

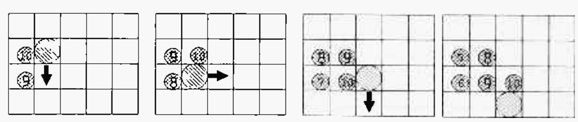

Figure 2: movement pattern of the blue Aint, avoiding the pheromone markers

The cyan Aintz (see fig. 3) have a gene-string of directions. At each timestep the genetic Aint chooses the next gene in its gene-string as the direction it will move. Whenever a genetic Aint drops food at home, it also leaves its gene-string. Whenever the anthill produces a new Aint, it performs a simple one point cross over combination of the last two gene-strings for the new Aint. There is also a certain probability[2] that the new Aint will be completely random. (Mutation) Thus Aintz that bring more food home have a better chance of spawning offspring. (Genetic search)

The white Aintz are a mixed population of half random searchers, and half genetic searchers. Whenever a

[2] 1% in the current implementation

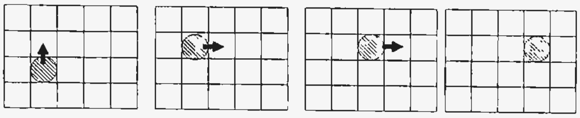

Figure 3: movement pattern of the cyan Aint, with genestring North,East,East (NEE)

new white Aint is produced, there is a 50% chance it will be a new random Aint, and a 50% chance it will be a genetic Aint. (Hybrid)

Results

The system described above has a large number of interesting dynamic properties, arising from the local interactions of the different types of agents and objects in the world. In the following section I will focus on the efficiency of the different colors of Aintz, which is equal to their ability to proliferate in competition with the other Aintz. It is important to note that this efficiency is dependant on many factors. The most important goals are summarized below.

1. Avoid starvation
2. Gather food
3. Avoid getting killed by other Aintz
4. Kill other Aintz

Points 1 and 2 are related, since whenever food is found, starvation is avoided and gathering is in progress. The reason why I list them as different goals, is that 1) is concerned with the survival of the individual Aint, whereas 2) is concerned with the proliferation of the colony. Number 3 and 4 are quite difficult to accomplish, since the Aintz cannot sense each others presence.

Example runs

Figure 4 shows a screenshot of a typical run, in which food is reintroduced cannibalistically, i.e. the dead aint is replaced by a number of food items on the place it dies. Upper left is red aintz, upper right is cyan, lower left is blue and lower right is white aintz. Note how trails radiate from each hill. Note also that blue is much more efficient than the others.

Figure 5 shows a run where food is reintroduced randomly, i.e. whenever an aint dies, F_a food items are reintroduced randomly into the world. Note the circular area around blue (bootom left) which is continually patrolled and therefore empty of food. Note also that cyan is significantly more efficient than the others under these circumstances.

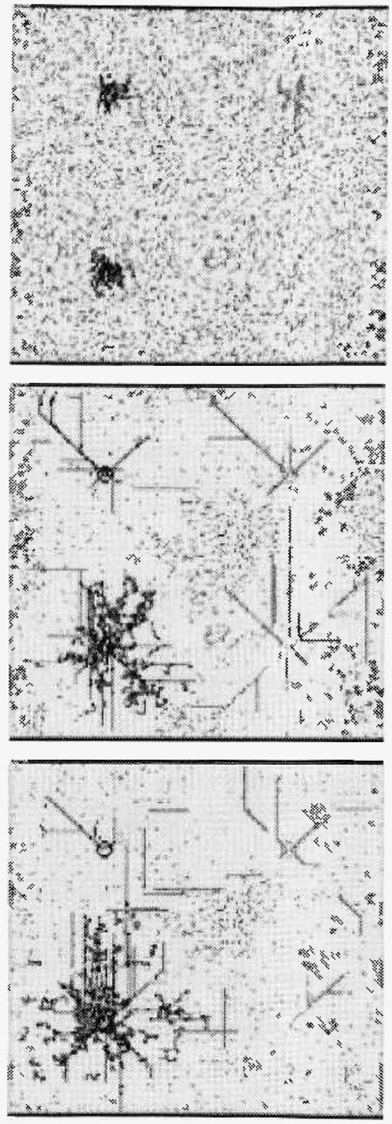

Figure 4: situation 1 after 61, 3006 and 10012 steps

The Red Aintz

The red Aintz, the random searchers, try to accomplish the goals in the simplest way compared to the other types. Whenever a red Aint is carrying food and is at home, it drops the food. Whenever a red Aint is carrying food and is not at home, it will move a step in the direction of home and leave a pheromone marker in the place it reaches, which will point towards the place it left. This is the axiomatic behavior of the red Aint carrying food. It clearly has the primary emergent effect that the Aint eventually will reach home and drop the food there. The effect that the Aint will leave a trail of

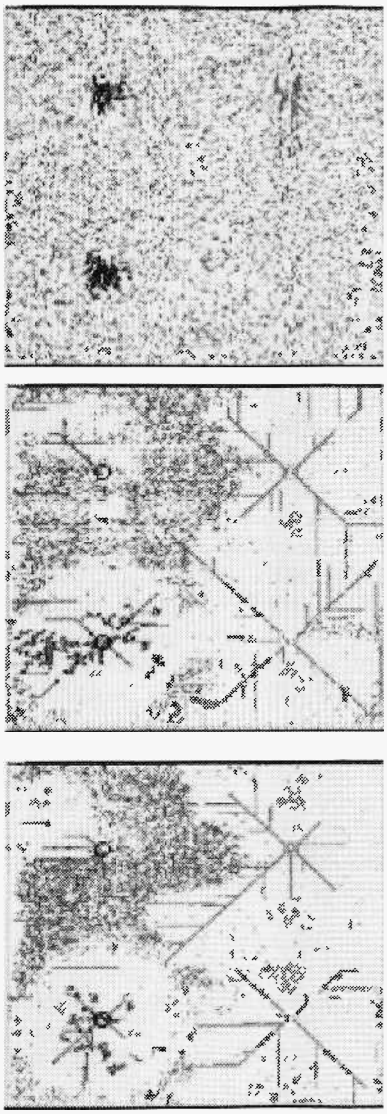

Figure 5: situation 2 after 73, 5009 and 10012 steps

pheromone markers, leading from home to wherever the fooditem was found, is another primary emergent effect. Whenever a red Aint is not carrying food and is standing on a pheromone trail, it will take a step in the direction of the trail. Whenever it is not carrying food, and is not standing on a trail, it will move a step in a random direction. This axiomatic behavior has the direct consequence that red Aintz seem to "seek" trails, albeit inefficiently, and follow them when they bump into them.

The Blue Aintz

The blue Aintz have the exact same properties as the red Aintz described above, except when they are searching for food or trails: Whenever a blue Aint is not carrying food and is not standing on a pheromone trail, it will examine the scent of all neighbouring places, and move to the place in its neighbourhood with the least amount of pink pheromomone. If several of the neighbouring places contain the same (least) amount, it will choose randomly among them. This axiomatic behavior has an interesting primary emergent effect: The individual blue Aint will tend to avoid its own footsteps. It will drive itself away from the places it has recently visited, thus tending to cover more ground than the red Aintz. It will also drive itself away from other blue Aintz, thus being less likely to examine areas that have already been examined by other blue Aintz.

The Cyan Aintz

The cyan Aintz move according to a sequence of directions in which they move one step in each timestep, and restart the sequence when they reach the end. This results in a cyclic movement pattern, for instance NNESN. This movement pattern can be reduced to the resulting movement NNE, since SN cancel each other (except of course if it runs into food or a trail). Because of this cyclic movement pattern, the cyan Aintz will tend to move in a line directly away from home, except for those that have an empty resulting movement (e.g. NS). Since all four directions initially have an equal chance of appearing in the gene-string of the initial Aintz, the cyan Aintz will initially fan out in a star-pattern.

The White Aintz

The white Aintz are composed of 50% random searchers, and 50% genetic searchers. Unsurprisingly, their behaviour is a mixture of the behaviours of the red and cyan Aintz.

Discussion of the Aintz model

The Aintz described so far have a number of emergent properties. Properties that are consequences of the axiomatic rules coded into the agents themselves. Some of these emergent properties have second order emergent properties. These properties are described in the following section.

Primary emergence

Primary emergent effects are caused indirectly by the hardcoded behavior of the single agent. It is not the behavior itself, for instance the "Homing" behavior of the general Aint that moves it one step closer to home at each timestep, is not emergent. It is axiomatic. However, the fact that this behavior leads the Aint to its home is an emergent behavior, though somewhat trivial. A less trivial primary emergent property, is the tendency of a single blue Aint to choose a certain direction, and stick to it. This property emerges from the behavior that the blue Aint will avoid its own tracks. The axiomatic behavior changes the environment and thus the basis for its own later decisions.

Secondary emergence

Secondary emergent effects are effects that emerge from (simpler, first order) emergent behaviors. An example is the tendency of cyan Aints to evolve towards higher efficiency: Cyan Aintz leave their genes at the hill whenever they bring food back home. This means that these Aintz have a higher probability of getting "offspring", in the sense that their genes are perpetuated. This in turn makes the colony as such evolve towards behaving like the most efficient food gatherers. Note that the fitness of a cyan Aint is an emergent property. It is a property that isn't recorded anywhere in the system, but it is still observable. We can see that certain directions are favoured, while others disappear.
Another example of secondary emergence is the tendency of blue Aintz to spread out to a certain radius, and then continually sweep this area around their own home (territorialism). This effect is partly a derivation of the blue Aintz tendency to avoid not only their own tracks but also those of their peers, and partly due to the fact that when a blue Aint returns home, and starts from home, it will choose the path with the least pink pheromone, i.e. the path left unused for the longest time, from home to "unexplored country". This path then becomes the path used most recently, and it won't be revisited until it becomes the oldest path again.

This primary emergent property has the secondary emergent property of territoriality, since it leads to the blue Aintz continually patrolling the areas that haven't been visited for a while.

Tertiary emergence

Tertiary effects are rarer, and less readily identified. However, the fact that blue Aintz are much more suited to competition involving mass combat than the other Aintz is primarily because the blue Aintz are territorial. If Aintz of different colors meet each other, one will die, and the other will live. This is an advantage for the colony that manages to "harvest" the cadaver and obviously a disadvantage for the colony that lost an Aint. Therefore it is an advantage to stay together, and relatively close to the hill, since the probability of harvesting the cadavers of a confrontation is then higher. Thus, the advantage in warlike scenarios for the blue Aintz emerges from their territorialism, which emerges from their tendency to avoid each other, which finally emerges from their individual tendency to avoid their own tracks. Therefore it is a tertiary emergent property.

Discussion of emergence

The classical Alife approach to the design of emergent behavior is to identify the task which needs to be solved, and then to look at nature for inspiration. Some aspect of a natural system that solves a similar task is then modelled in sufficient detail, and simulated. Hopefully, the model exhibits the same emergent properties as nature. If not, the natural system is reinvestigated, the model is refined and the cycle is repeated. This is the approach taken by people such as Dorigo et al. in solving graph-problems by ant colony optimisation (Dorigo et al. 1997). It is also the approach of the MANTA system (Drogoul et al. 1992), although in the MANTA system, the domain modelled isn't the natural world, but rather the laboratory conditions under which biological ants are studied.

This approach has the nice property that since the natural system solves the interesting task, all we need to do is to simulate nature sufficiently accurately to make the model solve the same task.
The disadvantage is that it is quite difficult to model nature "sufficiently accurately", especially since it is also a goal to model the minimum necessary to obtain the desired effects.

The "natural" system described above, does not need to be found in nature. Important lessons for real-world applications can be learned from observing artificial toy-worlds, such as for instance the Aintz model.
Assume someone wants to program a number of micro-robots to kill weeds on a golfcourse. Which of the Aintz should be used as inspiration?
The blue Aintz are territorial and will constantly patrol the area, keeping the weeds down. Therefore they appear to be a natural choice. If we wish to solve the task of unbounded exploration/mapping then territoriality becomes a problem. In that case, the simpler red Aintz seem more relevant.

Choosing atomic actions

The choice of atomic actions is closely related to the choice of axiomatic behaviour. To illustrate the differences between the two, consider the case of robotics: The atomic actions correspond closely to the physical capabilities of the robot: If the robot has wheels, one of the atomic actions of the robot could be MoveWheelForward, another might be TurnXDegrees etc. The atomic actions are the building blocks of the axiomatic behaviour. Therefore, the atomic actions are a level lower, in terms of abstraction, than the axiomatic behaviour.

The set of atomic actions is the set of interactions (i) between agents and the world and (ii) between agents and each other. Therefore, the atomic actions define the state-space of the system. For this reason, it is important to know which state-space the model should explore. I for instance, was interested in the foraging techniques of ants. To forage, it is necessary to be able to move, pick up, and drop items. I also wanted to see how much cooperation was possible by using simple non-dissipative trails. Therefore the Aintz were given the ability to lay out, and sense these trails.

Choosing axioms

In order to minimize the complexity of the model, while still being sufficiently accurate, it is crucial to identify the necessary axiomatic behaviors correctly. If a property P is wanted in the system, it should be carefully decided whether P is an Axiomatic behavior or an emergent behavior. This decision should be based on the level of modelling detail. If for instance the model is about the flocking behavior of birds then changing velocity should be an axiomatic behavior for the single bird (Reynolds 1987). If the focus is on the actual locomotion then the aerodynamics of the agent and the moving parts of the agent (it's limbs) could be modelled as axiomatic behavior (Sims 1994). This choice should be based on the goal of the research. It is useful to keep in mind that a lower level of axiomatic behavior also allows higher level emergent effects, as demonstrated in the Aintz system. For instance, it should be possible to obtain flocking results similar to the ones obtained in the boids model (Reynolds 1987), based on boids that propel themselves not by axiomatically accelerating, but by moving their limbs, thus causing acceleration, like in Karl Sims model. (Sims 1994).

However, due to the extra amount of computation, this approach will be more time consuming. It is important to know where and why to implement actions as axiomatic. It is a good idea to disregard aerodynamics and simply implement acceleration axiomatically if the focus is on unordered flocks, like swallows or gnats. However, if the focus is (evolving) ordered flocks, like for instance geese that fly in a V formation, then aerodynamic effects may indeed be crucial, and the axiomatic level should be on locomotion.

The pioneering paper "The motility of Microrobots" (Solem 1994) deals with the physical realities faced by a designer of microrobots. The interesting part here, is that the paper describes the world rules, and atomic actions possible for such microrobots. This defines the axiomatic level, and therefore the level at which the behaviour of these machines should be modeled. For instance, this investigation shows that jumping seems to be the most efficient method of transport for earthbound robots. A programmer interested in having a large number of microrobots perform some task involving movement should therefore choose jumping as an atomic action, and proceed from there.

More work of this kind is very much needed, since it allows work on the behaviour of the machines to start, even though the machines themselves are not available yet. In the context of nano and microrobotics, the concept of emergent behaviour is very interesting, since micromachines can be assumed to have limited computing ability. Therefore their control programs will probably be rather simple. However, if these simple programs are designed carefully, interesting and useful emergent effects of a large number of these robots can be obtained.

Combining Axioms

Having decided at which level to model the domain, the next step is to implement the aximatic behaviors, and to combine them in such a way that the emergent behaviors arise. Here again there are several approaches. Brooks (Brooks 1987) introduced the concept of the subsumption architecture. The idea is to decompose the behaviour of the agent (in Brooks case a robot) into functional units. Thus for instance a robot could primarily be concerned with obstacle avoidance, secondarily with exploration and tertiarly with mapbuilding.

This concept is quite useful for the designer of emergent properties, since it provides a way to structure the individual agent, and cause it to choose among a number of axiomatic behaviors based on it's current state. Even though Brooks uses subsumption architectures for reactive systems, this approach is quite valid for other types of agents as well. There is no a priori reason to restrict the use of subsumption architectures to simple Stimulus-response agents. In fact, actions may be designed to change some state of the agent and stimuli may come from the agent itself. In such a way, there may be several processes going on inside the agent, which result in a cognitive agent as an emergent effect.

The World

The agents invariably live in some sort of world. The world, in this context, is the sum of all the rules that apply to the agents, as well as the medium in which they interact. It is the "laws of nature" of the model.

In the case of the Aintz model, the world is the lattice which represents the spatial properties of the model, the rules for transformation of biomatter ("birth" in the homes and reentry of biomatter when an Aint dies), the rules of combat, and the rule of pheromone evaporation. Obviously these laws have dramatic impact on the systems behavior.

For instance, the rule of biomatter reentry: Whenever an Aint dies, $\mathbf{F}_a$ food items will be reintroduced into the system. This can happen either by depositing the food items as a pile of food where the Aint died (cannibalistic reentry) or by reintroducing the fooditems somewhere random (Random reentry).

The Blue Aintz are significantly less efficient in random reentry compared to cannibalistic reentry, but interestingly the cyan Aintz (genetic search) are *more* efficient with random reentry. Assuming the Cyan home is W and N of the center of the normal distribution of food, the cyan genepool just needs to discover that E and S are "good genes", while N and W are "bad genes". This becomes much harder to discover if the Aintz going N and W leave their carcasses N and W of the home. Then those that follow will find them, producing even more Aintz going N and W. If on the other hand, the Aintz going N and W die, disappear, and reappear as food *in the center of the world*, the "good genes" are much easier to evolve.

This is an example of how the global rules can have dramatic impact on the behavior of the system. In the context of designing emergent behavior, the interaction with the world can be used to affect highlevel emergent effects, without nescessarily altering the lowlevel effects. We can use the global rules to affect those things that are difficult to affect by altering the local rules.

Continuous vs. Discrete worlds

In the context of emergent behavior, only few people seem to be interested in continuous worlds. Most models in this area are based on two or three dimensional lattices. Notable exceptions are (Reynolds 1987) and (Sims 1994). The reason for this is obvious: It is much easier to code, and less computationally expensive.

However, there are important differences between nature and lattice worlds

I have worked with both types of worlds (continuous and discrete) and the only thing that seems clear to me is that even small changes in the "world rules" can have enormous consequences in any emergent system. When modeling nature as a discrete lattice world, important aspects of the domain might be lost. For instance, when going from a discrete lattice based world to a continuous one, the concept of extensionality is introduced into the model. In this context, extensionality is the physical body of the agent. Specifically its size and shape. The work of (Sims 1994) shows that morphology plays a role in locomotion. Morphology and extensionality in general might play a very important role in interaction between agents.

The concept of extensionality might very well lead to more natural emergent effects. The boids model (Reynolds 1987) may work in a lattice based world, but not nearly as smoothly and naturally[3]. The work of (Sims 1994) certainly becomes much more artificial, when transferred to a lattice based world. The Aintz model would have to be changed dramatically to translate the axiomatic behaviors to continuity. In fact, the very choice of discrete vs. continuous modelling poses some severe restrictions on other choices of the model later on.

The euclidian vs. non-euclidian distance problem is nicely exemplified in the Aintz model. If an Aint is at grid point (0,0) and moves 5 steps north, and then 5 steps east, it will find itself at gridpoint (5,5). If it moves in a straight line[4], from (0,0) to (5,5) it *also* moves 10 steps. In euclidian space, the shortest distance between two points is a line. In the Aintz lattice world, a line, an angle, indeed any string of steps, containing 5 N and 5 E will get the Aint to the same place.

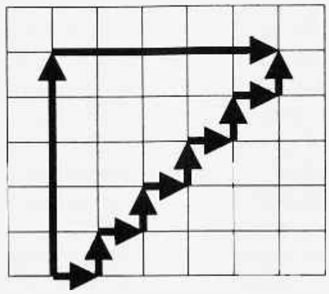

Figure 6: The geographical distance problem

If I had chosen an 8 neighbourhood topology instead of the 4 neighbourhood topology, I would have encountered similar problems.

This global rule is an artefact of the choice of a lattice world. Any lattice world will suffer these problems. Nature is not a lattice world.

Conclusions

I have addressed the notion of multiple levels of emergence, as introduced by Baas (Baas 1993), and have argued for the usefulness of this term. I have shown some ways to use the notion as a conceptual tool, when designing and analysing emergent properties. Specifically I have argued for the importance of choosing where to put the axiomatic level, depending on the goal of the model.

Further, I have discussed the differences between discrete and continuous worlds and have argued that discrete lattice worlds present serious problems with regard to geographical distances.

I have presented an ant model, called Aintz. I have shown that the very simple basic behavior of the individual agents cause quite complicated emergent behaviors,

[3] At the EVAlife workshop, Mr. Reynolds said that his primary reason for working with continuous rather than discrete models were aestetic. "It looks nicer".

[4] Or rather, the closest approximation of a straight line in this world

of multiple levels. I have used the Aintz model to exemplify the notion of multiple levels of emergence.

Future work: Evolving emergence

In the context of the Aintz model, it would be interesting to try to evolve the current axiomatic behaviours, along with others. The atomic actions would thus form the core of this new implementation of the Aintz model, along with a genetic programming algorithm to evolve the behavior of the individual Aint. In fact this amounts to choosing the basic actions of the Aintz, together with the evolutionary algorithm as the axiomatic behavior of the system, thus making the behaviors of the Aintz (the genetic code) the primary emergent effects. Another aspect to examine is the issue of discrete vs. continuous worlds. A viable approach would be to evolve the emergent behaviours as described above, first in a latticeworld, then in a continuous, and see if different strategies emerge. It is possible that the introduction of extensionality of actions (in continuous time) and agents (in continuous space) will prove to be important.

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Aintz
The Aintz system is available on the WWW as an applet.

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