Emergent Communication:
The Evolution of Simplistic Machines using Different Communication Types

A DISSERTATION
SUBMITTED TO THE DEPARTMENT OF COMPUTER SCIENCE,
FACULTY OF SCIENCE
AT THE UNIVERSITY OF CAPE TOWN
IN THE FUFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE

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January 2009

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Acknowledgements

Thank you to my parents for all the encouragement and support. You push me to become more than I could ever be on my own. Thanks to my family for tolerating all my flaws, my friends who spent much of the time asking "when it was going to be done" and telling me to hurry up already because they wanted to read it. Special thanks go to Richard and Stuart, who spent time listening to my ideas and not simply shooting them down.

My supervisor, Anet for without your knowledge this would not have turned out as well as it did. Finally, Dave, without you this would just have been research but your enthusiasm kept me motivated and our design sessions were the stuff of legend.

Abstract

The methods of transmitting information may be divided as follows: direct; and, indirect. The "direct" method occurs when a creature transmits a signal that other creatures in its local environment can receive. Word of mouth advertising is a form of direct communication. "Indirect" communication *relays* a message through the environment. This type of communication is known as stigmergy.

Both word of mouth communication and stigmergy require the existence of groups of communicators. It is, however, difficult to analyse a very large number of local interactions that occur in group behaviour. A global phenomenon known as "emergence" arises from such behaviour. The phrase –"*the whole is greater than the sum of its parts*" normally describes emergence.

In this research, we investigate how the two methods of communicating, direct and indirect (including a combination of these), result in emergent behaviour. In order to establish this outcome we employed the use of agent-based software in which we designed groups of agents to evolve over generations in response to specific situations. The manner in which these agent groups evolve is by a genetic algorithm. This is based on the consumption and collection of resources from the environment - a metric for gauging how well the population performs as a whole.

For the purpose of this dissertation, we measure and examine the performance of four styles of the two methods of communication: No Communication, Word of Mouth, Stigmergic and Both (a combination of direct and indirect). We observe the fitness arising through successive generations of agents for each of the four styles and compare the results.

The "No Communication" style is markedly the worst performer and is "the sum of the parts" in terms of the definition of emergence. The "Word of Mouth" style is marginally below the best performer but is rated well above that of "No Communication". The "Stigmergic" style is only the third best performer. Combining the direct and indirect methods yields the best result for the "Both" style.

All the communicating categories, considered "the whole" in terms of the definition for emergence, outperform the "No Communication" style. This demonstrates that emergence occurs when using these communication methods in groups.

Keywords: Communication, Emergence, Genetic Algorithms, Group Behaviour

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Chapter 1 Introduction

The world of communication may be divided into two types of communication. These divisions can be direct and indirect communication. Direct communication occurs when a single entity transmits information to another privately. A form of this direct communication is known as word of mouth advertising. This form of advertising is very effective but little understood, since it requires changing a person's attitudes to a product or service. A trusted party usually creates this attitude change.

Indirect communication occurs when a message is passed in the public domain. This means any entity that is able to view that public domain to be able to utilize the information in the message. This form of communication is becoming more prevalent in computer science (1). This transmitting of messages via the environment is known as stigmergy. Stigmergy is usually used to coordinate large groups without the group having a central command.

Large groups however are difficult to analyse and a new way of doing this is through the understanding of emergence. Emergence is a global phenomenon that needs to be understood in order to explain the general behaviours to a group of interacting entities. This can be very useful in observing whether a group of entities is acting as a group or as a bunch of single entities acting alone. There is theory behind emergence that lets us determine whether this group behaviour has occurred. The usual definition of emergence is "The whole is greater than the sum of its parts" (2; 3; 4; 5).

In this research, we examine these divisions of communication and build a simulation model in order to be able to observe the behaviour of these different types of communication in order to understand emergence. In order to create the model we had to decide how the entities, inside a simulated environment, would operate. The communicating entities (agents) were similar in design to an ant's characteristics and behaviour. The agents, like ants, try to collect and consume food. The agents start out random and with the help of a genetic algorithm, the agents become streamlined for the set tasks. Genetic algorithms are a method that is used for finding optimal parameters. We use it on the agents so that the parameters do not have to be set. This is like human beings learning the best pathways to work.

1.1 Motivation

A company might want to know whether one type of advertising is more useful than another type. This knowledge will cause a competitive advantage and save money on expensive advertising. In being able to determine how large groups of people react to a message, how it spreads and how to facilitate that spread might cause companies to rethink the design of future advertising campaigns. If group behaviour, rather than a bunch of individual behaviours, can be determined by how they communicate, then an advertising campaign can be decided on more effectively for that group.

Companies such as Google, started by creating a useful product and not advertising at all but letting word of mouth spread the usefulness of their product. This form of advertising cost almost nothing. This was the marketing campaign for Google's search engine. Pamphlet fliers are well known as a method of advertising for companies wanting to spread the name of their brand. These two styles of advertising can be seen as ways of communicating information to others. Almost no testing has been done in comparing these two types of communication, even though there is research on each separately.

1.2 Research Questions

In our research, we explored the following research questions:

- Can a large group of simplistic machines by communicating with each other be more efficient at collecting and finding resources than machines that do not communicate?
- Which type of communication in a group is the most efficient at collecting and consuming resources?
- Can different types of communication cause group behaviour or emergence to occur?
- Will a genetic algorithm cause an increase in efficiency of communicating agents?

These questions further the field of computer science; they are discussed in the following section.

1.3 Contributions of Research

The main contribution of this research would be for systems that use communication as a device for resource collection. More specifically, the research contributions are:

- We compare four different groups of agents, communicating or lacking of communication. This comparison will help when having to choose which type of communication to apply to a specific situation. It means that when confronted with a question of which communication type to use, this dissertation gives a comparison of these communication types.

- Groups of individual entities using different communication types are likely to react as a whole in certain ways; we examine the ways that this is done by agent design. This means that a general behaviour can be given to entities that communicate in the way described.
- The effect of evolving agents in terms of their efficiency, which would demonstrate agent evolution as a way of enhancing an agent instead of using a design which might not be suited for a specific environment. This also tries to mimic evolving communicators that do not become stagnant over time but adapt to their placement in an environment.
- How large populations behave according to communication type. This allows for greater understanding of crowd behaviour and thus allowing better ways to react and use these communication types effectively.

This research has several application areas:

- **Biological systems:** This would help in understanding how cells and other such structures operate with each other.
- **Crowds:** Better analysis of crowd control and information spread. An example of this is signs for people in a stadium needing the toilet.
- **Computer communication systems:** When the systems should talk to each other or leave a message that allows many systems to observe this message.
- **Games development**: for role-playing games the agents can communicate information to each other and players, demonstrating a greater immersion in the game environment.

These areas could gain benefit from knowing which communication type to use in future endeavours.

1.4 Limitations

The limitations of this research are that models are a generalisation. There are usually cases in the real world that a model does not consider. We developed scenarios for testing purposes, which might not match accurately real world situations. Since the model is very generic it can be used for describing many real systems but also has the inherent problem of not modelling any particular system closely enough. Other systems will have rules that differ from this specific system. The rules that were used in this model might be more accurately modelled but were sufficient for our purposes. Since communication is very complex, it becomes increasingly difficult to model by simple agent design. The real world has more information that is imparted at any one time and it is nearly impossible to duplicate all these sources of information.

The scenarios that were chosen will give a specific set of results but having different scenarios might produce different results. The information these scenarios impart may be useful in a general sense. The number of scenarios is limited. This means that testing more scenarios will increase the accuracy of information about group behaviour. This research is assumed to be unique as no other specifically related research was found; anything that remotely resembles this research either had the agents in direct competition with each other for limited resources or had very small sets of agents (6). No more than fifty agents were used in any other paper, whereas we used five hundred.

The next section outlines how the chapters are organized.

1.5 Dissertation Outline

The rest of this dissertation is outlined as follows

- **Section 2: Background**

  Three related background topics are presented as summaries of related work in this field. The three main topics were chosen based on how applicable the topics were to the simulation. The three topics are:

  - Chapter 2: Communication
  - Chapter 3: Emergence
  - Chapter 4: Genetic Algorithms

- **Section 3: Design**

  Using the background research a model was created in order to show the different aspects of the communication types. These chapters detail the model design. It also explains how the local level parts interact with one another.

  - Chapter 5: Environment: is a description of the world, within which agents will operate.
  - Chapter 6: Agents: this chapter outlines what the agents are and how they behave.

- **Section 4: Research**

  This section outlines the research that was accomplished using the model in section 3. The model's implementation, the way it was tested and the results are described.

  - Chapter 7: Research Methodology, how the system was implemented and would be tested.
  - Chapter 8: Results, this is how the agents performed at collection and consumption of resources.

- **Section 5: Conclusions**

This section outlines the conclusions that were drawn from the results and the future work that should be done to further this research.

  - Chapter 9: Conclusion and Future Work

Background

Chapter 2 Communication

2.1 Introduction

When examining communication an observer has to define what communication means. This is no simple task, since there are many types of communication and not all of it would be considered communication by human standards and senses. In the *Soul of the White Ant* (7), Marais describes the *toktokkie* beetle and how it answers its call even below that of human hearing range and far below what can be detected by a microphone powerful enough to hear the footfall of a fly easily. It does this without even having perceivable hearing organs. This does not mean that it is not communicating. The process of communication could be either the process that some creature communicates or the result of that communication.

Maclennan (8) states that animal interaction is sometimes difficult to define as communication and that if we define it as one organism that does something that another organism notices, then it loses all meaning since then everything is communication. He suggests a way around this by Gordon Burghardt's definition of communication (9 p. 14):

Communication is the phenomenon of one organism producing a signal that, when responded to by another organism, confers some advantage (or the statistical probability of it) to the signaler or his group.

2.2 Importance

Communication allows ideas and concepts to be transferred from one being to another. This lets some advantage be given to the receiving being. The world relies on this process to happen. In order to examine the importance of communication to the human world let us travel back through history and just look at human communication and the reach of technology and how it has impacted on communication. This report splits the advances of technology into three groups; direct, indirect and both direct and indirect (6). This corresponds nicely with being able to disseminate information to others. "Direct" is any passing of information from one source to another without the use of a medium and very little delay in time. "Indirect" is passing information via another medium and that the information persists even once the sender is no longer available. "Both direct and indirect" is a medium that allows for both types of communication to exist. The technologies for communication that will be examined taken from (10):

Direct: including for example speech, telegraph line, telephone and cellular telephone;

Indirect: writing, paper and printing press, amongst others;

Both direct and indirect: including radio, television and internet.

2.2.1 Direct

Speech started about two hundred thousand years ago. This caused coordination amongst the human race. It is easier to survive if there is communication amongst a group. This is group communication, where a local group can survive better by introducing co-operation to perform tasks. The next step was to be able to communicate over long distances.

The semaphore telegraph was a step towards long distance communication. It would use a system of shutters to communicate over long distances with a type of code. There were problems with this as anyone who knew the code could read it. This was first used in 1793 by a man named Claude Chappe. It was later replaced by long distance electric telegraph, first created in 1843 by Samuel Morse along with the Morse code eight years earlier. The next step was to make it possible to transmit the spoken word.

This barrier was broken thirty-three years later in 1876 by Alexander Graham Bell and Thomas A. Watson when they invented the telephone. The telephone allowed for transmission of the spoken word and opened up almost instantaneous communication between people causing information to become easily available over long distances. It was simply a matter of time before most homes had a telephone and was readily available for the public. These phones had to be in fixed locations though since they required wired lines in order to transmit.

In 1947, Douglas H. Ring and W. Rae Young of Bell Labs proposed a cell-based approach, which led to "cellular phones". Now people can communicate almost instantaneously over long distances to people that they know how to reach. Locality has become obsolete in terms of communication and it is now down to whom you know not how you can reach them. Due to the drop in production cost, most people can afford a cellular telephone.

2.2.2 Indirect

Writing started around 3500BC. Written forms were used to convey information. It allowed information to be passed from one generation to the next. Usually written forms were religious in nature. Cuneiform developed by the Sumerians and Hieroglyphics by the Egyptians. The problem was still how to keep this writing from becoming worn away by time.

Paper was the answer to being able to preserve written words over longer periods of times, even centuries. It was first created by a man named Tsai Lun in 105AD. This was still far from the finished product that we have today. It took time, but eventually in 1844 Charles Fenerty managed to create paper from wood pulp, this replaced rag paper, which was in short supply. The problem with paper was that it was difficult to copy information to paper form, since each document had to be copied by someone who had to write it by hand.

The Chinese first solved this problem in 1305 with a wooden block movable printing press and independently by Johannes Gutenberg in 1450 with metal block movable printing press. This caused information to be duplicated easily and allowed access by a larger population of people. Education became easier if access to the information did not die with a teacher.

2.2.3 Both Direct and Indirect

In 1901, Guglielmo Marconi transmitted a radio signal from Cornwall to Newfoundland. This allowed information to be transmitted over long distances without the use of wires. Radio is not a private means of sending communication like that of the original semaphore telegraph. Anyone who knows how to interpret the information can gain access to it. This caused the invention of codes to secure the information; this was in order to be able to send private messages. The way that was indirect was the ability to record messages, which usually came in the form of music and general announcements. The person who was sending the message was not broadcasting directly. Images still needed to be converted to a digital means in order to be displayed.

Television solved this problem and in 1925, John Logie Baird transmitted the first television signal. It was not long before television was affordable by the public. This created a visual medium instead of just an auditory one. It is direct and indirect in the same manner as radio. Messages could now be pre-recorded. However prerecording was not open to the public at large and was very expensive. The invention of the personal computer it became possible for the public to be able to utilize information and generate information far more easily. The year 1969, saw the creation of ARPANET, the ancestor to the current Internet. It allowed the sharing of information. In 1994, the USA released the Internet. This allowed the public to create websites and put them online for others to browse. Information was now being allowed to spread freely. Since people could now upload content, it was a matter of time before the purpose of the Internet changed. It has adapted and now allows for the masses of users to be able to add their own content and change their online environment. E-mail allows the sending of messages directly (11). Geography is no longer the barrier to communication. An Internet user can post a message to a forum to pass information to others.

These forms of progress in technology have allowed communication to become broader and reach more people, more easily. It is now about whom you know and not about how far away you are. Common interests bind people together instead of differentiating people by class, education and difference (12).

2.3 Types

There are a large number of types of communication, especially exploited in the field of advertising. The field of advertising involves many different mediums for trying to lure a person to a product. Examples of this range from digital (television, digital billboards, internet, etc.) to older forms of printed advertising (newspapers, classifieds, posters, pamphlets, etc.).

In this report, we discuss two methods in more depth, namely word of mouth communication and stigmergy. Word of mouth communication occurs when a signaller passes information directly to a receiver in a local manner, whereas with stigmergy a signaller changes the environment in some way and thus passes along information to the next receiver.

2.4 Word of Mouth Communication

Arndt (13) refers to Word of Mouth Advertising as "*oral, person-to-person communication between a receiver and a communicator whom the receiver perceives as non-commercial, concerning a brand, a product, or a service".*

There are problems with this definition that need to be dealt with for use in a more general sense since this report does not deal with advertising specifically, but applies more to communication in general. The first problem with the definition is that being oral, it can be said that any communication, as long as it is in close proximity, can be used in this definition. The second problem is with referring to a person, it can be said any agent that can communicate in a local manner (face-to-face) can be said to be using word of mouth. Thirdly, the non-commercial nature referred to in the definition is advertising specific and can be replaced with a trusted source. Fourthly the advertising referred to, applies to a brand, a product, or a service; instead, any resource may replace this.

We define Word of Mouth Communication as:

- Agent-to-Agent; locality is important, the receiver and communicator must be near each other;
- Communication must occur; useful information must pass from at least one agent to another;
- The receiver must trust the communicator; the message would be suspect otherwise.

Marketing is one of the best examples of word of mouth communication. Word of Mouth Advertising is also called advocacy or viral marketing. This principle is becoming extremely relevant for companies evaluating the effectiveness of their branding by analysing the advocacy using intricate market research drives. It is possible to create simulations exploiting these principles and they will be invaluable in these marketing research drives. Companies exploiting this will be able to better and sustain their competitive advantage.

2.4.1 Basic Marketing Example

A basic example is illustrated in Figure 1 below. A number of agents (light red dots) buy a product (resource) and are happy with that resource. They then tell other local agents about that resource (light blue dots).

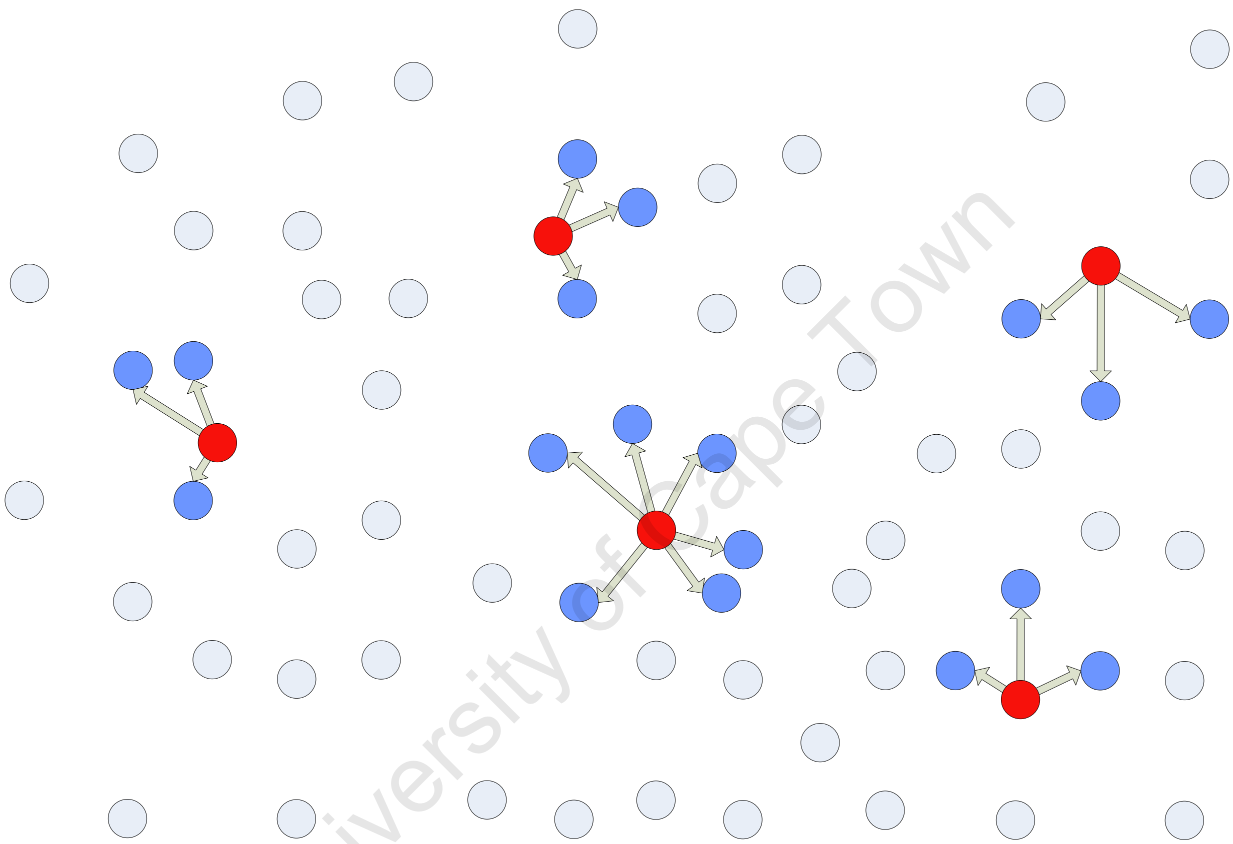

Figure 1: Information spread after one iteration

Out of the agents that have now heard about the resource some are convinced to use the resource but others are not yet convinced to use it. In Figure 2 the agents that have been convinced are now red dots and proceed to tell all their local neighbours about the resource. The agents (dark blue) that have been told about the resource from two different agents are represented as a darker blue. The original agents (dark red) that have used the resource are now darker red and no longer have connections since they have already told their neighbours.

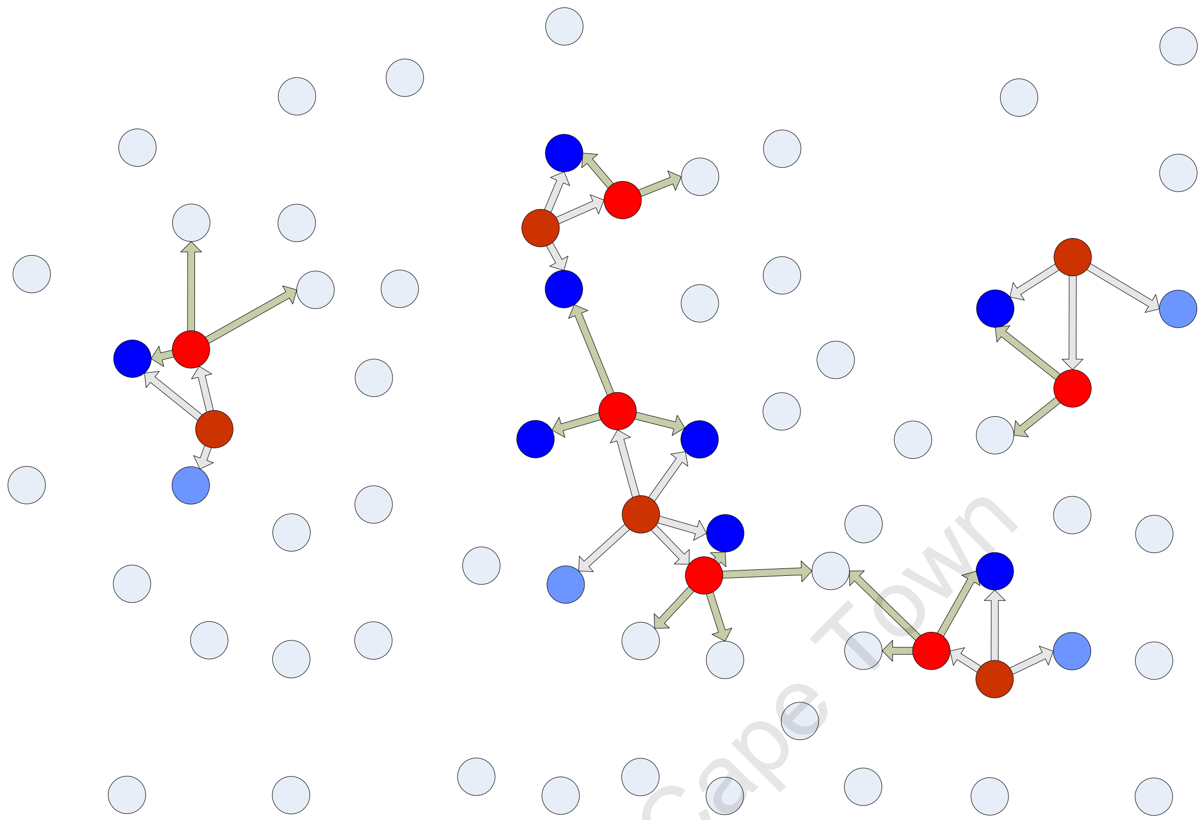

Figure 2: Spread after two iterations

For this basic example, agents that have been told twice will become convinced (light red dots). The already convinced agents in Figure 2 will now also become dark red, with the original connections turned to grey, and the newly convinced will tell other agents about the resource. This will cause agents that have already heard about the resource to become dark blue and the new agents to hear about the resource to become light blue. This spread is continued in Figure 3, Figure 4 and Figure 5.

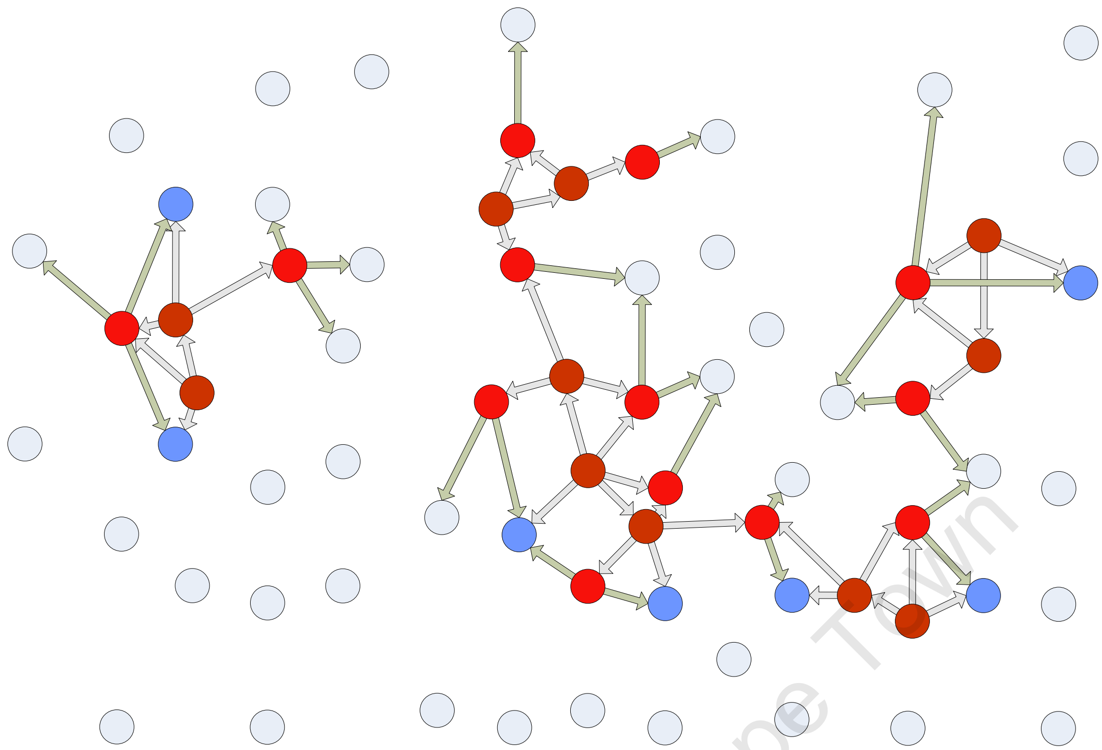

Figure 3: Further spread of information after three iterations

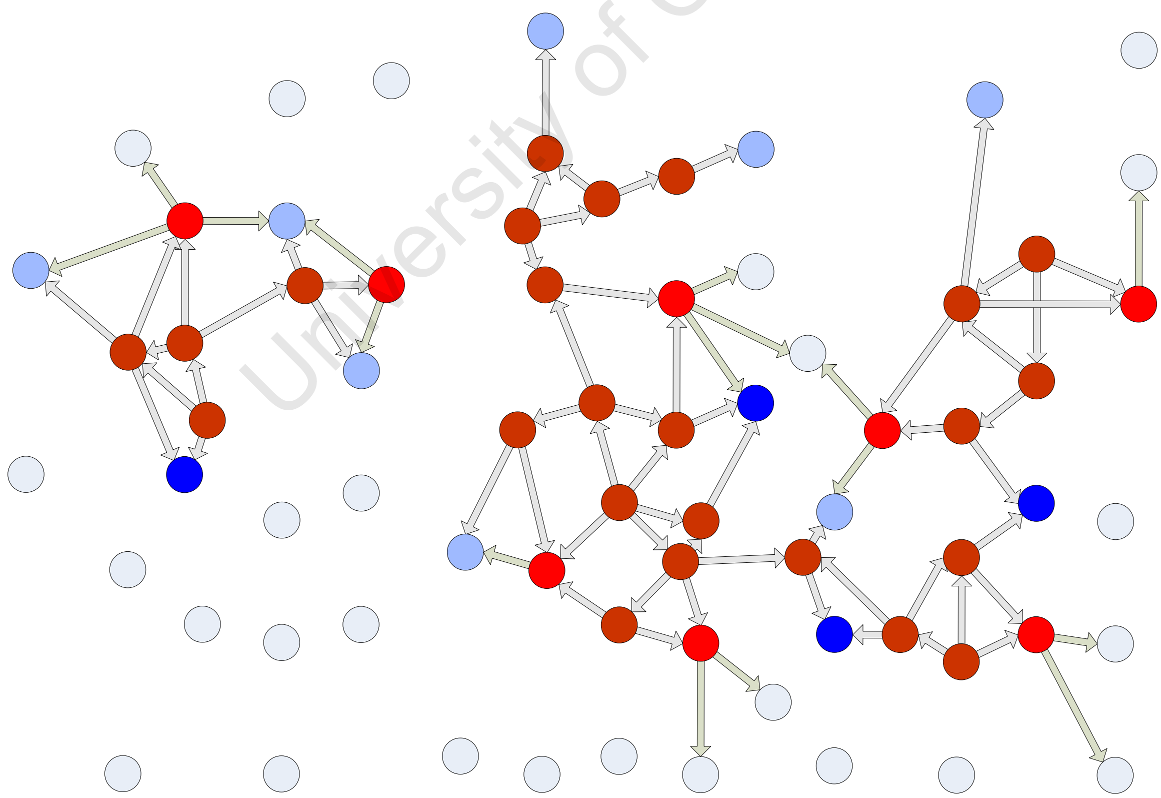

Figure 4: Information spread after four iterations

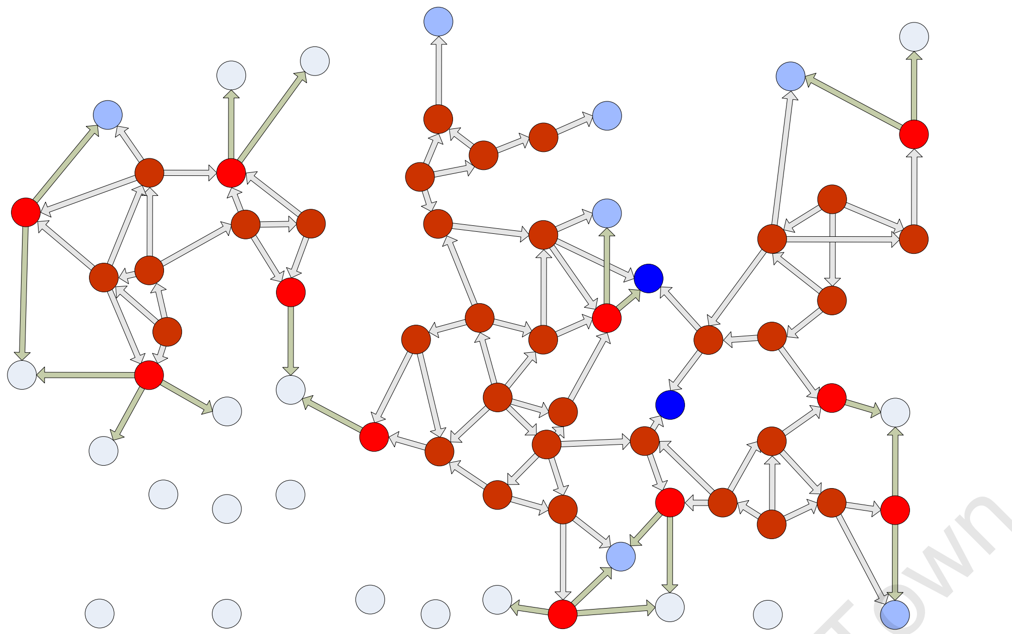

Figure 5: Continued spread

Just using this basic example the numbers showing the growth are:

Iteration	Total Number of Agents
1	5
2	11
3	24
4	32
5	43

Table 1: Continuous Growth of the above network

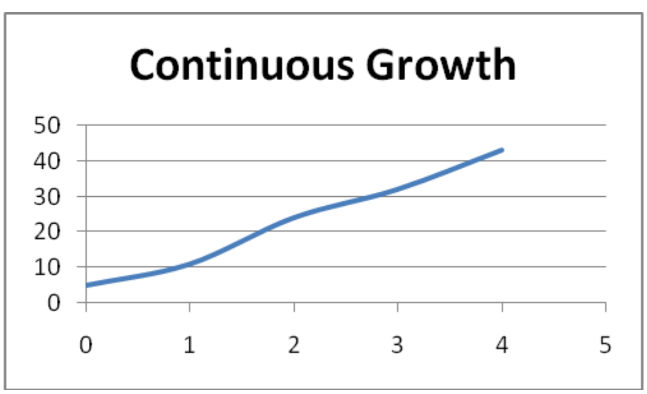

Figure 6: Graph demonstrating Continuous Growth of Table 1

2.4.2 Examples

The passing of information directly from one agent to another is an important mechanism. Humans do this often. They are one of the only creatures to have a fully developed complex language to achieve this method of message passing. A number of natural systems take advantage of this type of communication. Bees use it to describe where food is by having the "waggle dance" - a type of dance that is done around the hive informing bees of where food is located (14). This style of communication is very prevalent in swarms. A few examples of this include the coordinated behaviour of animals such as flocks, herds and wolf packs hunting prey (4; 15; 16; 17). These however are not stigmergic since they do not leave messages indirectly for others to observe in the world.

In the case of flocks, each bird is assessing where the birds around it are and adjust their own flight path to match the others. This means that if one bird on the one side of the flock changes its path slightly, this local behaviour will cause a ripple through the whole flock. The message spreads through the flock and helps coordinate the global behaviour of the flock. This behaviour happens in schools of fish and herds of animals, as in Figure 7: Flock of Birds below.

Figure 7: Flock of Birds

2.4.3 **Successful applications**

To find good applications of this principle we need go no further than marketing which tries to utilize it as much as possible (13). Companies try to create advertising that causes the brand to be spoken about by people to their neighbours. To give examples of companies that have done this, Google, Facebook, Myspace and Tupperware (11; 18) are just a few.

Google used word of mouth advertising to create demand for their e-mail accounts (Gmail). Google released only a few Gmail accounts. Since it was a very useful tool, the people who had them told their friends. This created a demand by the community to have an account. The only way a person was able to get a Gmail account was by having a friend invite you to join, at least initially.

Facebook and Myspace are social networking sites. The growth of these sites has been rapidly increasing. Once a person has signed up, they can invite their friends to join, browse for new friends with common interests, share information that can be put up by the user. On Facebook, a user can put up stories, pictures, movies and other content. A link can then be sent to friends telling them that the content is available. This allows people to share opinions and advertising about products has never been easier since it is targeting people's interests.

Tupperware has a policy of not using the Internet. However, they still use word of mouth advertising by having parties, were the host gets rewards for being a host. The reputation of products are spread by having a group of people buy products. The happy customers then host their own parties with a representative being present with the ability to place new orders.

NASA is using this principle for searching amongst the asteroid belt (16). The robots are distributed in order to search for different things. Robots are allowed to talk to one another when in close proximity to facilitate knowing which asteroids have been checked. It is much faster to have a host of robots with low capabilities searching a large area, than having one robot that has many functions try to explore the same area.

In *Conditions Enabling the Evolution of Inter-Agent Signaling in an Artificial World* (19), agents evolve to warn each other using signals about predators as well as other useful information.

2.5 Stigmergy

This method of communication occurs when the environment has been changed, leaving a message for the next agent that can use this information. Pierre-Paul Grassé in 1959 first used the term in describing termite construction. The term stigmergy comes from the Greek "*stigma*" meaning sting and "*ergon*" meaning work (12).

The following definition has been proposed by Karsai (4):

> *"Grassé coined the term stigmergy (previous work directs and triggers new building actions) to describe a mechanism of decentralized pathway of information flow in social insects. In general, all kinds of multi-agent groups require coordination for their effort and it seems that stigmergy is a very powerful means to coordinate activity over great spans of time and space in a wide variety of systems. In a situation in which many individuals contribute to a collective effort, such as building a nest, stimuli provided by the emerging structure itself can provide a rich source of information for the working insects. The current article provides a detailed review of this stigmergic paradigm in the building behaviour of paper wasps to show how stigmergy influenced the understanding of mechanisms and evolution of a particular biological system. The most important feature to understand is how local stimuli are organized in space and time to ensure the emergence of a coherent adaptive structure and to explain how workers could act independently yet respond to stimuli provided through the common medium of the environment of the colony. [Istvan Karsai]"*

Flocks are often referred to as stigmergic (4; 17) using for example the velocity and direction of the motion of other entities as signals in the environment. In this research, it is not considered stigmergic since information is exchanged directly between two entities, which would imply that all forms of agent information spread would be stigmergic, which is not the case. We define stigmergy as follows:

> *"Stigmergy is when one agent (communicator) changes the environment in such a way that another agent (receiver) of the same type can acquire information. The communicator does not need to exist locally in the environment for the information to be received."*

2.5.1 Background to Stigmergy

Entities that communicate using stigmergy change the environment in order to impart information to other entities that can interact with that environment. A message left by a single entity in the environment can have meaning to multiple entities, which is not possible in a one-to-one message exchange. Since stigmergy in nature most often occurs using scent we use this as an example for explaining the concept of stigmergy. This mechanism will be used for the current explanation. When a scent trail is left in the environment, other creatures of the same type can read this scent and interpret meaning from it. The scent fades to bring the most up to date information for that environment (20), essentially making sure that old information is cleared from the environment. This is how these agents adapt to dynamic environments. The scent trails are also spatially placed, which gives the message at least two more pieces of information (Location and time) than just having a message placed on some sort of message board, which are useful for dispersing information to wide populations, much like civic announcements to a city (12). Television is a good example of this.

According to White (4) some useful aspects of stigmergy include:

- *Agents are not goal directed; they react rather than plan extensively thus being reactive agents instead of goal orientated agents, another field of research;*
- *Agents are simple, with minimal behaviour and memory;*
- *Control is decentralized; there is no global information in the system;*
- *Failure of individual agents is tolerated; emergent behaviour is robust with respect to individual failure;*
- *Agents can react to dynamically changing environments;*
- *Direct agent interaction is not required.*

Some of the problems, as depicted by White (4):

- *Collective behaviour of a group of agents cannot be inferred from the local behaviours of individual agents* – "the whole is more than the sum of the parts" (5). *This implies that observing single agents will not necessarily allow swarm-defeating behaviour to be chosen. This can also be taken as an advantage for the group against attackers trying to understand what the group is trying to achieve*. This is depicted in the report presented by White (4) for the military.
- *Individual behaviour looks like noise as action choice is stochastic*.

- *Designing swarm based systems is hard. There are almost no analytical mechanisms for design. There are new methods for being able to design swarm based systems; most start by analyzing natural systems and using the information gathered there to help create these systems.* Genetic algorithms and genetic programming are methods that help in the design of swarm based systems. Giving a system free reign to design itself and just giving it an objective allows the system to do so. In addition, simulation allows swarms to become easier to analyse. When the local rules can be determined, it allows for greater understanding of the global behaviour. The problem lies in being given the global behaviour how to generate the local behaviour that produces that global behaviour again (15).
- *Parameters that define the swarm system can have a dramatic effect on the emergence (or not) of collective behaviour.*

2.5.1 Natural Examples

There are many examples of natural systems that utilize this principle. Insects use it to coordinate their behaviour. Large animals use this principle to mark territory, give information about them. A few examples of this principle follow:

Wasps build funnels by observing the local built environment and then adding on to that environment thus changing it for the next wasp to examine. By tweaking a couple of parameters multiple nests can be built an example of this is given by Karsai (21).

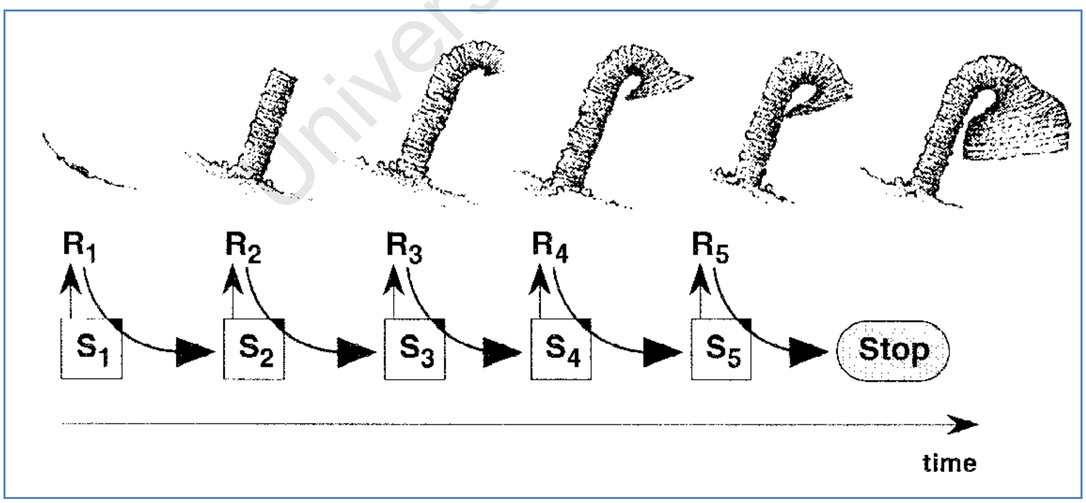

Figure 8: Stimulus-response sequence leading to the construction of the mud funnel in the nest of the Eumenid wasp Paralastor sp. Each new building stage n is completed after stimulus S_n triggers a new ensemble of building actions R_n. The completion of each building stage n gives rise to a new stimulus S_{n+1} that triggers new building actions R_{n+1} leading to the

construction of the next building stage n+1. When the fifth stage has been completed, there exists no more stimulus on the funnel to trigger new building actions and the construction stops. Taken from (12).

Bees use it while collecting pollen from flowers. Bees leave a scent on a flower letting other bees know that that flower has been visited already. This behaviour allows for quick identification of flowers that have not been visited so as not to waste time. The scent also fades such that after a period a flower can be revisited to gain maximum benefit from the flower.

2.5.2 Successful applications

A host of optimization problems uses stigmergy as its basis. In *Stigmergy, Self-Organization, and Sorting in Collective Robotics* (1) stigmergy was used to help robots sort clusters of objects. This application has uses in automated packing industries and logistics. An example of stigmergy is used with RFID tags to find forgotten-somewhere items and used digital trails of the objects in order to trace a path to the items (20).

White (4) refers to a number of applications that could make use of stigmergy:

- Routing in ad hoc networks; the paths of the routers is optimized.
- Collective robotics specially nanotechnology; it makes sense to use stigmergy in nanotechnology since the technology is very small and it is difficult to get communication technology on something that size, however if it operates according to its environment it is far easier to store this information.
- Many military applications
    - Target acquisitions and tracking
    - Intelligent Minefields
    - Autonomous Negotiating Teams
- Ant Colony Optimization problems
    - Job shop scheduling
    - Vehicle routing
    - Quadratic assignment problems

Google is a good example of stigmergy at work (22). Based on the number of links to a website it provides that website with a rating in relation to other websites. This is the core of how Google can tell which websites are valid for lookups. The stigmergy of this is that when a website is added to the environment of the internet it changes that environment by linking to other sites, this causes those other sites to prove more desirable.

Road signs are a successful application of stigmergic principles. The road signs are messages that are left in the environment in order for a car driver to know what to do in specific situations. This includes traffic lights, which regulate traffic flow (23).

Panait (24) uses pheromones in order to be able to navigate dynamic environments. This shows stigmergy as ants use it to operate in the real world.

2.6 Conclusion

In this chapter, we have seen two different communication types, word of mouth and stigmergy. Word of mouth allows communication to spread due to proximity to others; this is done in a local manner and Stigmergy that changes the environment to leave information for later use by anything that can read that environment. We saw a number of examples of each and the usefulness of each. In the next section we design a system based on these two communication types [see section Design].

Chapter 3 Emergence

3.1 Introduction

Emergence is a global phenomenon that arises from local behaviours, which are difficult to understand because of the complexity of the interactions, as a group. It is an intuitive concept and much research has been done in trying to identify what it is precisely. Emergence can most often be seen in nature with natural examples being as simple as a hive of bees collecting honey from flowers to the complex structures that make up the human immune system. The outline for this chapter is as follows:

- Definitions
- Test for Emergence, which we use in this research for discovering whether the system was emergent
- Evolution and Emergence, how evolution relates to emergence and whether evolution is considered emergent by the emergence test
- Emergence in Nature, a few examples of natural systems exhibiting emergence
- Drawbacks to Emergence Research, some drawbacks that were proposed by Kubik (25)
- Conclusion

3.2 Definitions

According to Peter Cariani (26) there are three categories of Emergence: computational, thermodynamic and relative to a model.

3.2.1 Computational Emergence

This is often used in a description of Artificial Life research. Macro-behaviours and structures arise out of local interactions. In Emergence and Artificial Life (26) it is stated that computational emergence is not actually emergence if taken from the view of the programmer of the simulation. This happens because the programmer has set up a predetermined system. Each state is dependent upon the last.

An excuse of there being a random function in a simulation is not valid since, that function is also predetermined by the system, as all random functions are predetermined in computer systems. The random functions are just given the appearance of being random as is mentioned in (27).

However, it does not stop emergence happening with respect to a model of some given real system. To illustrate an example of this we use the Boids flocking model (17). A few simple rules govern the agents in a flock, emergence being the coordinated movement of what appears to be a large animal than the single entities that make up the flock. The simulation might be explainable but it is depicting a real world example, which was until that point surprising.

According to Cariani the system is deterministic and the observer knows the entire system; this is not emergent. If an observer, who does not know the detailed processes, is now shown the system it can be that the observers depictions of the macro-behaviour or structure can be seen as emergent (2; 28).

In the research done we observe emergence even if the observer knows the entire model simulated and the interactions that can be done. If the system is complex enough (i.e. the number of interactions cannot be tracked manually) then the system can still appear to have emergent behaviour.

“The interesting emergent events that involve artificial life simulations reside not in the simulations themselves, but in the ways that they change the way we think and interact with the world.” –Peter Cariani

3.2.2 Thermodynamic Emergence

Thermodynamic Emergence can be characterized as the emergence of order from noise. An example of this is a gas. The noisy motions of the atoms or molecules within the gas create ordered properties of temperature, pressure and volume at a higher level. This is not so applicable to this research since it is a very specific form of chaos theory.

3.2.3 Emergence Relative to a Model

This is defined by Cariani as "*The emergence-relative-to-a-model view sees emergence as the deviation of the behaviour of a physical system from an observer's model of it. Emergence then involves a change in the relationship between the observer and the physical system under observation. If we are observing a device which changes its internal structure and consequently its behaviour, we as observers will need to change our model to "track" the device's behaviour in order to successfully continue to predict its actions*."

This definition relies on there being an observer and having the observer change perspective about the model. It again relies on the fact that the observer cannot see the working parts of the model and has just an idea of the behaviour of the model. We achieve this with the use of a genetic algorithm to change the inner workings of the agents.

3.2.4 Other Definitions

Emergence is simply "*the whole is greater than the sum of its parts*". This has been stated in many places (2; 4; 5; 29). This implies that a whole can be observed as exhibiting some behaviour that makes sense to an external observer. The "sum of the parts" would not be able to create a global behaviour since there are no local interactions. We use this definition in this research as it adequately describes the system and the tests that have been designed to test the system.

3.3 Test for Emergence

A simple test for emergence given by Ronald (28) is as follows:

Design: A designer can construct local interaction between components (e.g. simulated creatures in an environment) in a language L_1.

Observation: The observer is fully aware of the design, but describes *global* behaviours and properties of the running system, over a period, using a language L_2.

Surprise: L_1 and L_2 must be distinct. The language for describing the local behaviour must not be the same language used to describe the global behaviour. The causal link between L_1 and L_2 should not be obvious to the observer.

Further on Surprise: Ronald outlines three levels of surprise, *Unsurprise*, *Unsurprising Surprise* and *Surprising Surprise* (30).

- *Unsurprise*, is when it is immediately obvious how L_1 gets to L_2. For example; a rabbit eats food therefore it gets fatter.
- *Unsurprising Surprise* is when after examining L_1 and L_2 the link can eventually be explained. Ants pathway to food achieves optimum efficiency, this baffled scientists for years before pheromones were discovered. We consider this as emergent, since it still allows us to see a global behaviour given low level rules.
- *Surprising Surprise* is even after examining the languages L_1 and L_2 no link is observable that allows for L_2. We consider this to be the highest form of emergence.

3.4 Evolution and Emergence

Is an evolutionary algorithm emergent? We propose that evolution is emergent and examine it using the previously stated test.

Design: L_1 are the solutions in a specific run and how this solution performs in regard to the fitness.

Observation: L_2 is the fitness of the solutions over time. This is distinct from L_1 because L_1 cannot be described over time.

The system runs through a number of iterations checking solutions and recombining good solutions in different ways in order to produce fitter solutions. The system results are the latest fittest solution(s).

Surprise: This is the fact that better results are produced. It is unsurprising surprise. Since L_1 the single fitness of a solution has no direct link with how solutions get better over time L_2 is created, this is emergent.

This test shows that evolution is emergent. It is tricky to make sure that L_1 and L_2 are distinct and are merely a matter of perspective in the observer in this particular example.

3.5 Examples of Emergence

Some examples of emergent behaviour are found in nature. Things that cannot simply be explained even once the rules for creating this behaviour are known. We apply Ronald's test for emergence (28) to natural examples below.

3.5.1 Nests in Wasps, Bees and Ants

Design: The language L1 is the basic configurations that exist and what must be added to these configurations to form the next new configuration. If simulated, these behaviours can exist in a simple lookup table as described by Karsai (21).

Observation: The geometric description of the entire nest can be viewed as L_2, which is the result after L_1 has finished being applied.

Surprise: While aware of the interaction rules, the observer still cannot fathom all the connections that took place in order to be able to produce such a structure.

Nest structures in wasps, bees and other nesting insects can be considered emergent since based on a few simple rules an entire complex structure can be created. Examples of these can be seen in (4; 21; 28).

3.5.2 Flocks and Herds

Design: L_1 is the interactions of the animals wanting to stay near others of its species by simple rules of nearness. The animals however try to avoid collision by staying a slight distance away from nearest neighbours.

Observation: L_2 describes the coordinated whole that looks like one large animal when it moves.

Surprise: No direct correlation between the movement of the whole and the simple rules that govern it can be determined. It is almost impossible to follow what is going to happen because of the myriad interactions that occur amongst the flock and herd.

Flocking is considered emergent since the animals obey simple rules and yet move in a coordinated fashion (17).

3.5.3 Other examples

A few examples of emergence can be seen in crowdsourcing (31). Threadless.com, a t-shirt design site is a great example of this emergent behaviour. T-shirt designs can be uploaded to the website. Other users of the site then vote upon the t-shirts. The best t-shirt designers are sent the t-shirt with a prize. The site then sells the t-shirt with the design. This way the crowd decides what it likes. The likes are in terms of t-shirt design and the best designs emerge.

Ants have a nice example of emergent behaviour (3). If contained, ants will create a graveyard as far away from the nest as possible and then have a location for refuse that is as far away from the nest and the graveyard location as possible. It is not simple math to be able to work out these locations, yet simple agents can do it merely by a means of countless simple interactions.

Traffic Flow is emergent (23) as the group behaviour looks similar to water flow with congestion happening around tight points. The individuals move according to their local environment but a global picture of the traffic flow emerges.

3.6 Drawbacks to Emergence

Kubik outlines some drawbacks to the work that has been done on emergence. He lists examples of these papers in a Formalization of Emergence (25):

- *The papers treat emergence in an informal and intuitive manner. This concerns a large volume of scientific literature where emergence is explained without reference to any theory of emergence*. See Kubiks' paper (25) for a list of examples of this occurring. This could have happened due to very poor research into what emergence is and how it applies to science.
- *The definition heavily depends on the term "surprise"* (28). Since surprise is vague and subjective, using it in a test is not critical enough; there is too much scope for error. Rigorous definitions of different levels of surprise (30) are applied. The three levels of surprise help cover this problem. They are Unsurprise, Unsurprsing Surprise and Surprising Surprise. (See section 3.3)
- *The definition is too broad and so includes phenomena that are not emergent, or is too strict and so omits phenomena that are emergent.* This is true since emergence is subjective depending on the observer. It is not emergent if there is no surprise as to what has occurred.
- *The categorization is not fine enough or is based on different criteria so that we are unable to distinguish among different types of emergence or identify the source of emergent behaviour.*

Emergence is a very wide concept in narrowing the definition it removes cases that are still emergent. This problem of not being able to classify emergence should be looked into. Cariani (26) has some definitions for emergence for differing structures but does not make it any easier to classify other systems.

- *It does not refer to a unified framework for research on emergence.*
- *It fails to define "sum of the behaviours of individual parts," a crucial point in defining emergence. We know of no attempt to define this concept.*
- *There is no modeling technique to both design and study (analyze) emergent phenomena (i.e., to capture emergence constructively) in MASs(Multi Agent Systems), except computer simulations. Even by that field, no results have been achieved.* Some results have been achieved with simulations. A few examples have been given in producing better products such as crowdsourcing (31) from the Internet, which allows multiple changes to products to create new useful products. Unique solutions to problems using genetic algorithms have occurred using computer simulations, giving notable advantages in many fields.

The problems that Kubik outlines are true but nearly impossible to fix completely due to the complex nature and inability to understand all the connections that occur in this process. If one can observe and remember every interaction that takes place then nothing is emergent since it can all be traced as to how it came about. However since this is extremely difficult we label it emergence.

3.7 Conclusion

Emergence is a difficult concept to explain accurately. The interactions of many events and communications cause emergence. The whole is greater than the sum of its parts. The parts being each individual element on its own not interacting with others would create a sum of individuals' but allow them to interact and suddenly there is something different. There is a type of coordination that arises that benefits the whole. This is emergence when working together brings a benefit but no central controlling system designates this working together.

In this chapter, we examined a number of examples and saw some drawbacks to the research that has been done on emergence. We have a test for emergence and a way of describing the emergence that is observed.

Chapter 4 Genetic Algorithms

4.1 Introduction

A Genetic Algorithm (GA) is a technique used to find optimum solutions. It is based on using evolution to optimize parameters, taking only the best or surviving solutions and breeding them in an attempt to produce better results. GA's are usually implemented as computer simulations since it is far easier to measure the success of a solution when it is a virtual construct[1]. GA's are utilized extensively in fields such as Robotics, Biology and others. An Evolutionary Algorithm (EA) adapts solutions to fit specific criteria. These criteria do not have to be static and can be constantly changing. A Genetic Algorithm is a specific type of EA (32).

In this chapter, the basic design behind a GA is discussed and then the simple methods behind a GA are demonstrated in a few simple worked examples, which are given as proof of the concept. Further reading can be done into Evolution and Genetic algorithms in (32; 33; 34; 35).

4.2 Basics

A genetic algorithm starts with a random population. A formula should exist that measures the fitness of a specific solution giving it some score. This is the difference between GA's and EA's; in an EA it is merely a matter of surviving longer in order to bring a specific solutions genes forward, whereas with a genetic algorithm it selects the best genes based on some criteria, as is discussed in Bäck's book *Evolutionary Algorithms in Theory and Practice* (32) . Since there is a function that determines how good a solution is, good solutions can be chosen from the population, this is elitist selection. These solutions can be bred by utilizing biological methods. These solutions are then tested and the process is repeated until solutions that have been bred are almost the same as the previous solutions or adequate solutions are found. In Figure 9 we see a flowchart of this process.

[1] A virtual construct refers to a simulation on a computer instead of in the real world

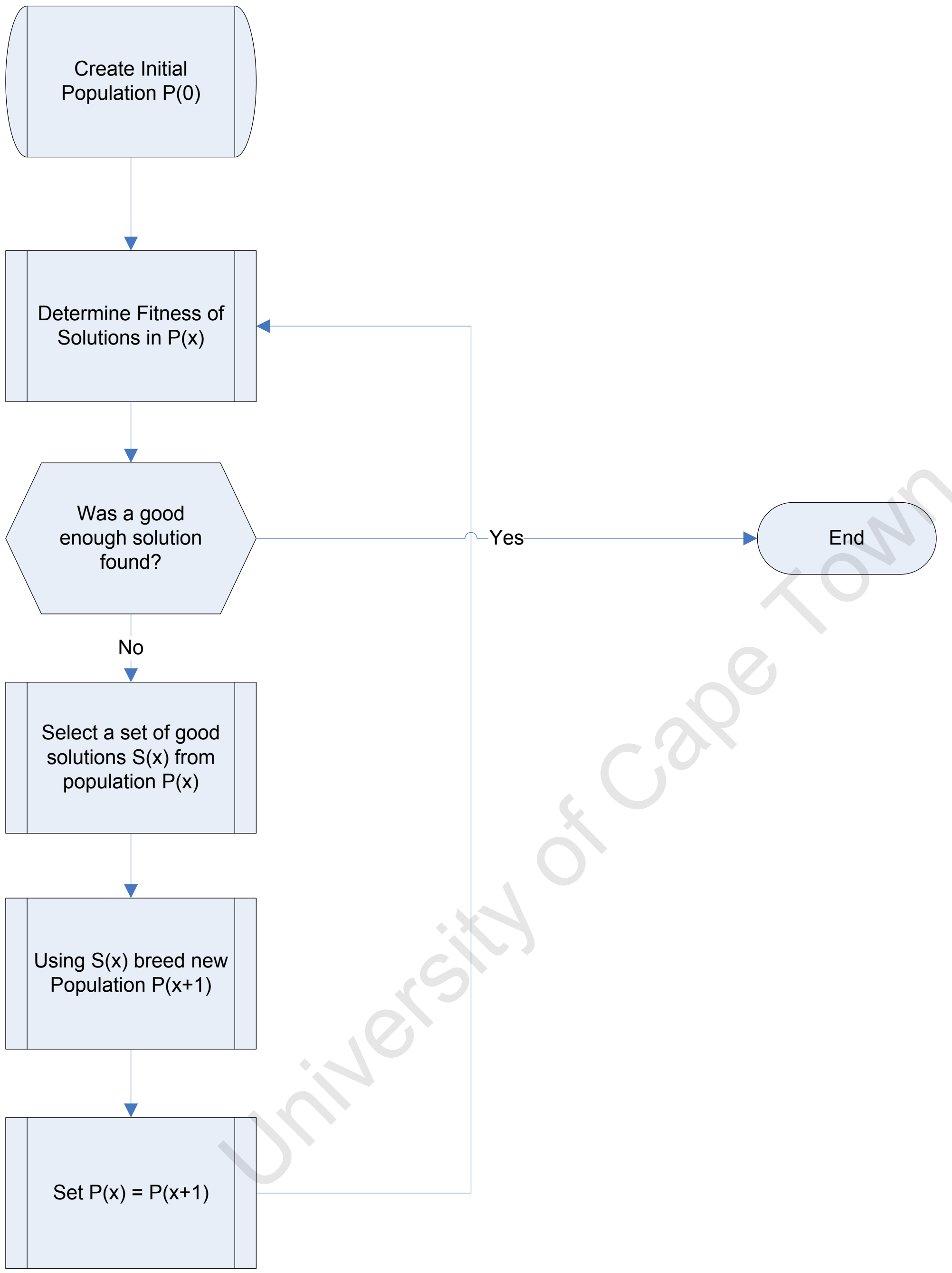

Figure 9: A flow chart describing a genetic algorithm

Koza (34) describes a GA run in three basic steps with substeps as follows:

1) Randomly create an initial population of individual fixed-length character strings.
2) Iteratively perform the following substeps on the population of strings until the termination criterion has been satisfied:
    a. Assign a fitness value to each individual in the population using the fitness measure.
    b. Create a new population of strings by applying the following three genetic operations. The genetic operations are applied to individual string(s) in the population selected with a probability based on fitness (with reselection allowed)
        i. Reproduce an existing individual string by copying it into the new population.
        ii. Create two new strings from two existing strings by genetically recombining substrings using the crossover operation at a randomly chosen point. [see 0.0.0 □ Combination]
        iii. Create a new string from an existing string by randomly mutating the character of one randomly chosen position in the string. [see 0.0.0 □ Mutation]
3) Designate the string that is identified by the method of result designation (e.g., the best-so-far individual) as the result of the genetic algorithm for the run. This result may represent a solution (or an approximate solution) to the problem.

According to Koza (34) there are four major axioms for a GA, namely:

1) The representation scheme
2) The fitness measure
3) The parameters and variables for controlling the algorithm
4) A way of designating the result and a criterion for terminating a run

The representation scheme must be able to give a solution to the problem. Standardizing the representation allows solutions to be bred together and recombined in different ways. The representation is usually in the form of bit strings (33; 36; 37; 38) but any standardized format can be used. The parts of the representation schema should be able to align due to the fixed size of the structures. Variable length structures may be used but the breeding of two solutions then becomes more complex.

The fitness function or measure is used to measure the quality of any solution. The fitness function is problem dependant and is used to rank the solutions. These functions can often be difficult to define and sometimes an interactive approach needs to be used. These were first used by Holland (33).

The axioms 3 and 4 that Koza (34) refers to are only necessary if the answer to the problem does not change. It does not hold for problems that have constantly shifting solutions. These problems occur in artificial life simulations where the problem continues to change as the situation in the environment changes (2; 8; 15).

Holland (33) uses a similar series of steps in his section on Generalized Reproductive Plans. His series of steps applies to only one structure at a time and replaces a random structure from the same set with the newly created structure. He uses probabilities to determine fitness based on performance.

4.2.1 Fitness

Fitness refers to how desirable a specific solution is to answer a specific problem. Using a fitness function, a solution can be determined closer to the optimum answer relative to other solutions. An example of this would be finding the answer to a simple equation, illustrated in the example below.

Example:

Evaluating 2X = 4

In this case a human being simply divides 4 by 2 and we get the answer of X = 2. If a fitness function is used, a number of solutions are generated and tested to see how close they are to the answer. The steps on evaluating the fitness function 2X – 4 = 0 iteratively to determine the closeness to 0, is tabulated below:

X	2X – 4	Evaluation
1	2(1)-4	-2
1.5	2(1.5) - 4	-1
2	2(2) - 4	0
2.5	2(2.5) - 4	1
3	2(3) - 4	2

Table 2: Evaluation of F(x) = 2X-4

As observed, the closer to the correct solution the closer the fitness function moves to 0. This happens due to the nature of maximum and minimum solutions. A solution that is not the minimum solution will always have a greater value than the minimum solution. The same holds true for a maximum solution concerning having no solution with a larger value.

Fitness can be used to answer simple problems. With regard to more complex problems with multiple peaks and valleys as well as the solution space being possibly infinite it becomes more difficult to find decent fitness functions. This simple solution would not be able to generate enough solutions to be able to find the correct solution. Therefore, a general best solution is sought rather than a best specific solution.

4.2.2 Breeding

As in biology, a creature (solution) wants to propagate its genes to the next generation. The idea that the best parents will produce the best offspring is used to try to achieve better results. In GA's the creation of a new solution is based upon aspects of two previous solutions. In order to find good solutions a random number of solutions is generated. This is like having a group of random people of differing strengths. In order to find the best solution at the end of the simulation we take the best solutions from our group of solutions and breed them together. Continuing with our human example if we wanted strong people, we would take the strongest people in our current population and make them breed in order to have strong offspring. This is repeated until a good solution is found or in the case of the example, the people are too strong and overthrow the government.

Solutions can be bred in many ways from previous good solutions. The most standard are combination and mutation. These shall be further discussed in the following sections.

➢ ***Combination***

Holland (33) states that crossing-over or combination generates a kind of diffusion from the pool to schemata (solutions) not represented therein. If no fitness is applied to the solutions then this type of breeding will produce a steady state of solutions, says Holland in lemma 6.2.2 in (33).

Refer to the example used to describe fitness function F(X) = 2X - 4. Multiple solutions for this problem were given in the fitness section [see 4.2.1], with trying to get F(X) as close to zero as possible.

F(1) = -2 F(1.5) = -1 F(2.5) = 1 F(3) = 2

Taking the two best solutions one from the positive side and one from the negative side gives F(1.5) and F(2.5). We combine these two solutions to generate a new set of possible solutions. As an example for combination:

Take random numbers between the smallest positive and largest negative results yields random numbers between 1.5 and 2.5 give possible solutions as follows:

F(1.7) = -0.6 F(1.9) = -0.2 F(2.2) = 0.4 F(2.4) = 0.8

Repeating the process will become increasingly closer to the solution F(2) = 0. If one of the answers is X= 2 it will have been found by our fitness function.

A few different crossover techniques can be used. Three of these techniques are discussed; they are single point crossover, two point crossover and uniform crossover. More can be used depending on the problem under discussion. These crossover techniques are just variations on the same basic techniques described previously.

Single point crossover

This method assigns a single random point in two bit strings and uses that to generate two new strings from the two old strings. This was determined to be the lowest achieving form of crossover by Eshelman et al (37)

Example:

100101 *0011101*

101100 *1110100*

Assign point 6 as the crossover point and swap the ends of the bit strings providing two new solutions.

100101 *1110100*

101100 *0011101*

Two point crossover

This method assigns two points and replaces the bits from one into the other and back again. The bits may not be at the same point in the string, so the crossover point in one string may start at the fifth bit and the other could start at the second as long as the same number of bits is swapped.

Example:

1001 *01001* 1101

10110 *01110* 100

In the first string assign point 5 and point 10

1001 *01110* 1101

10110 *01001* 100

Uniform crossover

This chooses random points along the bit string and swaps them with the other string at the same points.

Example:

10 *0* 10 *1* 001 *1 1* 01

10 *1* 10 *0* 111 *0 1* 00

Choose random points along the bit string and swap them

10 *1* 10 *0* 001 *0 1* 01

10 *0* 10 *1* 111 *1 1* 00

Uniform cross over is used in the implementation of this project. Two point crossover favours the centre of the bit string and will swap it more often than the ends, which causes less diverse solutions. Uniform crossover is superior to both one point and two point crossover for most optimization problems, states Syswerda (38), with one point being the worst, states Eshelman et al. (37)

➢ ***Mutation***

Mutations is the change in a base pair sequence in genetic material. It causes a gene or genes to change into a different form. Mutating bit strings is often done by simply flipping a number of random bits in the bit string. In structures that are more complex however, this cannot be done since it might break certain constraints and a random selection can be used to determine the new genes.

Example:

- Given the genetic bit string

  10 1 0100 0 11 1 101

- Three mutations are applied to it

  10 *0* 0100 *1* 11 *0* 101

- This creates a new genetic structure.

A more complicated structure involves three variables X, Y and Z. Where X,Y and Z represent complex structures. X can only exist between 1 and 10, Y must be between 5 and 10 and Z can be any real number.

If represented as bits the mutation does not work since it can overstep boundary conditions. A condition must then be placed upon the mutation in order for this to be effective.

There are also two ways of mutating a variable, small and large mutation as stated by Davis (39). The small way is to take the value already in the variable and offset it either positively or negatively. The large way is to replace the value with a completely new value inside the given constraints. As can be seen by the following example this is arbitrary for small sets but for large sets this can be extremely different.

Example:

X= 5

Small: give X=5 +2 = 7

Large: X= 5 replaced with X = 9

The reason for using mutation is to avoid local minima. If not in place, the genetic algorithm can become stuck in a minimum solution and give an incorrect answer. An increase in the number of mutations can cause an increase in the probability of moving away from a local minimum. This can also cause it to take longer to find an optimum solution. Mutation allows new solutions to be used and can permute all solutions in the given solution space given infinite time and high probability of mutation. Holland states these points in (33).

4.2.3 Agent Selection

There are two strategies for agent selection, *Survival of the Fittest* and *Generational*. These strategies come from (33). They are two ways in order to determine how the agents evolve using the genetic structures above and determining who is the best choice. In both strategies, there are positive and negative characteristics.

Survival of the Fittest

This is when the agents select the breeding partner on local availability. The partner is bred with and a new agent is created using the above methods. There are two ways of proceeding once breeding is accomplished. Either the two chosen to breed are replaced by their offspring or they are not and the offspring are added to the current population. This method of replacement is mentioned by Davis (39) and Stanley et al (40).

One of the drawbacks adding the offspring to the current population is that there is no way to control the growth or decline of the population. This could create interesting behaviour; however, for the sake of processing cost when a population grows too large, this type of breeding is ignored. It becomes far easier to analyse data that has been split into generations and pick agents that have done well.

Generational

Agents are grouped into generations. The starting generation is random, with the following generations becoming more and more suited to a specific environment. The best agents are removed from the population and then rebred. This may cause them to perform better. Koza (34) takes the approach of removing two agents breeding them and putting the offspring back in the agent's place.

Another approach can be taken by simply selecting the top agents and using them for breeding purposes to create a new generation. This will however cause very specific solutions to occur.

4.3 Examples of Evolutionary Algorithms

Evolutionary algorithms are often useful for find optimum solutions. This often happens much faster than traditional ways of searching a state space. Provided below are a few examples of a genetic algorithm that has worked to provide good solutions to problems.

Intelligent Detection of Anomalies in Telecommunications Customer Behaviour (41) uses a GA to be able to create distinctive models for a Bayesian Network in order to better facilitate detection of anomalies.

In *Automated Stock Trading: A Multi-Agent, Evolutionary Approach* (42), a better artificial stock trader is generated using an evolutionary algorithm.

Artificial Intelligence: a New Synthesis (43) has an example of a wall following robot that is evolved using genetic programming.

In *simulating evolutionary agent communities with OOCSMP* (44), the agents use natural selection in order to evolve liars and truth tellers and draw a correlation between scepticism and lying.

In *Evolving Neural Network Agent in the Nero Video Game* (40), the agents that play a game are evolved using an evolutionary algorithm in order to become more adept at the game.

In a *Comprehensive evaluation of the methods for evolving a cooperative team* (45), this approach is used to create cooperative soccer playing teams.

In a *Simple model of evolving ecosystems* (46) a model is described using a type of evolutionary algorithm to facilitate correct parameters for the model.

4.4 Conclusion

An EA is particularly useful in generating useful solutions to problems. If the problem is constantly changing, using this approach can be very beneficial. It is a standard for machine learning and requires feedback in order to perform. A genetic algorithm will be used for improving the designed system.

Design

Chapter 5 Environment

5.1 Introduction

All creatures have an environment that they interact with in some way. Scientists will try to observe an animal in its natural environment in order to understand how it behaves (5; 7; 17). Some creatures manipulate their environment in order to survive more ably, such as termites, ants and anything that builds a nest for protection.

Every living thing uses its environment to gather resources for itself. The ability to do so determines how well that creature can survive. Humans have changed their environment dramatically allowing them to live in very hostile conditions, such as in deserts, ice lands and other inhospitable places. This is because they can adapt living conditions to suit humans instead of adapting as animals do to the change in the environment.

In the research done we create an environment within which simulated creatures operate. It is a highly controlled environment. This environment has elements that can be setup at the beginning of each simulation run. In this section, each of those elements is detailed and how an agent may interact with them. The elements of the environment that will be discussed include:

- **Resources**, a source of energy for agents in the environment as food is for creatures in the real world.
- **Bases**, a location to return resources to for a larger return of energy to an agent simulating a benefit as would be received for having some nest in the real world.
- **Landscape**, this is where messages can be left for other agents to view information pertaining to the environment.

Each of these will be discussed in the sections that follow.

5.2 Resources

In nature, animals need resources in order to survive. This occurs in many ways. Some animals (predators) need to hunt other animals, which can be considered as resources. These resources move around. Their behaviour is influenced by predators hunting them. Certain animals are foraging animals and most do not hunt other animals. The food that they consume does not move quickly but can run out. Examples of foragers include ants, bees and cows.

In our simulation, resources are considered similar to plants. Foraging animals gain sustenance from plants. If a plant is almost destroyed, some foraging animals will leave the plant alone in order for it to grow enough to be consumed again.

We speed up the process of resource growth in the simulation. This is so as not to inhibit the agents from being able to gain resources indefinitely since they have limited life spans. The simulated plants (resources) produce five hundred food units every ten time steps[2]. Resources will not store more than one hundred thousand food units, since plants in the real world are limited in size by their own environment and resources. Resources that drop below five hundred food units disappear from the environment until that resource has reached ten thousand food units at which point it reappears in the environment, basically mimicking a real world plant being given time to grow back.

Just as animals gain sustenance from food that they consume, so do agents gain energy from resource food units that they consume. In the simulation, the food units can be taken straight from a resource and consumed directly by an agent. A food unit gives an agent thirty units of energy. This allows a change in goal [see 6.3] and the ability to move thirty steps in the environment.

Since steps are a measurement of distance it was necessary not to have agents be aware of distant cells. The agents should only operate in a local manner. Agents can see resources when they are six or less units of distance[3] away. This was to aid in computation expense as well as limiting the agents.

Since ants can carry food back to a nest, the agents in the simulation should also be able to carry food units. They can consume this food as they move giving them the ability to move to a further location. This is also useful for the task of retrieving food units and bringing it to a base location.

[2] A time step is one pass of the simulation allowing every agent to take some action
[3] A unit of distance is a single cell in the environment that an agent can occupy

5.3 Bases

Animals have many types of living places. A few examples of these are nests created by birds, burrows by larger animals such as rabbits, hives by bees and many more. These places afford animals protection whether it is in the form of physical protection from attack or the resources that the animal has gathered.

The agents can gather food at a specified location like ants; this conveys specific advantages to the agent. An agent will receive two hundred units of energy for every food unit that is drops at this location. This is done in regards to how ants use a fungus found in their nests that allow food to become useful to the ants. This is far greater than that of just eating food at a resource. This is done to offset the disadvantage of having to travel to a base. Bases cannot be spotted by an agent. It can only be told about the base from other agents. A base is the method for removing food units from the system since they continually are regenerated by the resources. Another reason the base is hidden is to provide a means for observing how well information about the base is spread by the agents. In all the figures of environment blue dots represent resources and purple dots represent bases as in Figure 12 below.

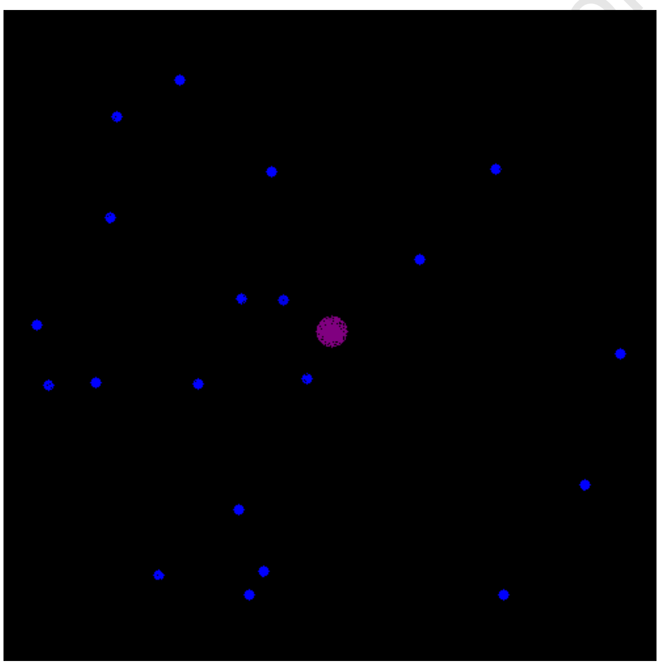

Figure 10: Example environment of resources and a base

Agents can pass information in two ways about where resources and the base is located. They can pass it directly or leave a message in the two dimensional landscape.

5.4 Landscape

When animals first settle in a territory the landscape is fresh. They leave scent trails or messages in the world. Therefore, at the beginning of the simulation the simulated landscape is empty of messages so as not to help the agents being run in the simulation. The agents may interact with the landscape in only a very limited way; they can drop a message of a resource or base location onto the landscape at the agents' current location. The messages can be overwritten in the landscape so only the most recently dropped message will be seen on the landscape. This is similar to leaving scent trails by animals and insects that do this. A stronger or more recent scent will overlap or disrupt the previous scent. The agents that use stigmergy [see 6.4] can view these messages and use the information that the messages (yellow dots in figures) represent. This is considered the environment for stigmergic principles. In Figure 13 below is an example of this process of agents walking around leaving messages.

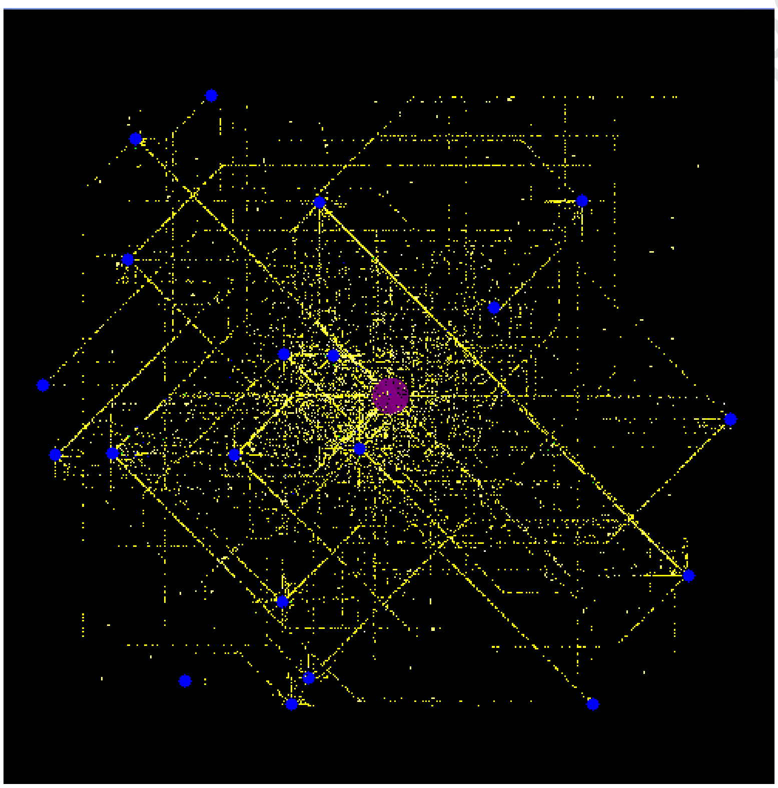

Figure 11: Environment with messages left in it

5.5 Conclusion

The environment in our simulation is simply constructed, so as not to interfere with the message passing. Environments that are more complicated could have been used but then agents that are more complicated would have to be designed. The idea is to keep it as simple as possible and see if there emergence will arise. Agents can wander this environment and interact with it, as they need to, as creatures in a laboratory would do. Resources give the agents the ability to change goals and allow actions to be carried out. Bases give the agents more energy as a semblance of advantage. The landscape is there to allow indirect message passing to exist. Our agents operate in this environment. Next, we discuss those agents and the rules that govern them.

Chapter 6 Agents

6.1 Introduction

Agents are the backbone of this research. The following section outlines the language L_1 in terms of the Test for Emergence [see 3.3]. An agent[4] is simply a simulated creature, which is kept as simple as possible in this research. The closest real world example, of these simulated animals, is possibly an ant. Our agents are however not the same as ants since ants can relay more complex messages and are able to interact with their environment far better than agents. Ants are far more complex than the agents in this simulation are. An agent can do several things that ants can do. Namely,

- Find resources, which allows them to perform actions appropriate to be able to gain energy;
- Consume food units, which gives them energy;
- Carry food units, such as an ant might;
- Collect food units, bringing them to a central location for a greater advantage;
- Communicate with other agents of the same communication type.

This chapter details what makes up the agents in this research, what they are and how they operate. The following sections are as follows

- Attributes and Characteristics, details of the agents and what they mean;
- Decision Making, the actions an agent may choose to perform and when in order to achieve the agent's goals;
- Communication, what messages mean and the different styles of communication the agents are able to utilize;
- Concluding with a summary of the agent's characteristics and behaviours.

[4] Henceforth when referring to an agent it is the simulated creature used in the research

6.2 Attributes and Characteristics

In this research, agents are modelling small creatures that live in an environment. Several things make up what an agent is and how it interacts with the environment. Attributes and characteristics store information about single agents such that they are more or less adapted for specific environments.

When operating in an environment, creatures in natural systems will have processes that change regularly and others that remain static. The amount of energy a creature has is very dependent on the amount the creature has consumed recently. Therefore, a creature's energy level will fluctuate many times in its life span. Its general strength however will remain constant with a gradual increase or decrease.

6.2.1 Characteristics

Characteristics make up part of the description of an agent. They do not change as the agent operates in the given environment. They are set from the agents' predecessors when they have been bred together.

➢ ***List of Characteristics:***

- ID
- Strength
- Fertility
- Communication Style
- Choices

The above characteristics are described in more detail in the sections that follow.

➢ ***ID***

This represents an identifier for an individual agent inside a single population. A specific identifier allows the agent to be found quickly again, when the system wants to know about a specific agent. In addition, this characteristic allows the simulation to check if one agent is different from another. When breeding is done an agent needs to be found again once the simulation section has been run. An *ID* allows the agent to be found afterwards when determining the fittest individuals. Gell-Mann refers to this characteristic of a complex adaptive system as "tagging" (5).

➢ ***Strength***

This determines the amount of food an agent can carry in one trip. The higher the value of *Strength* the more food can be carried by that particular agent. This is similar to natural systems, where the stronger an individual the heavier a load can be carried.

➢ ***Fertility***

This characteristic was originally for *survival of the fittest* [see 4.2.3]. This characteristic is not used for generating results. Fertility determines whether two agents would breed or not. The higher the fertility value would allow for a higher chance of breeding. The cost of breeding is in energy, where the more fertile the agent is the more energy it costs to breed. In a natural system, this would be depicted by attractiveness of a mate. Attractiveness would not necessarily carry additional energy costs when breeding.

➢ ***Communication Style***

One agent can communicate to another agent in this style. It is represented by a number depicting the style. 0 is *No Communication*; 1 is *Word of Mouth*; 2 is *Stigmergic*, where messages in the environment are left and 3 is *Both Styles*, where agents can gain messages from the environment and other agents. [See 6.4 for more detail]

➢ ***Goal Table***

These are the choices that an agent can make and the values that are associated with them. [See 6.3.2]

6.2.2 Attributes

Attributes also make up part of the agents description. They are the part that changes with time as the agent moves about the environment. In natural systems, many of the characteristics are also attributes since they can also be changed over time. However for the sake of the simulation we keep them static.

➢ ***List of Attributes:***

- Location
- Energy
- Life Span
- Food
- Messages

The above attributes are described in more detail in the sections that follow.

- ***Location***

This is where the agent is situated in the environment. It allows decisions to be made in relative locality. An agent must know where it is in order to be able to move towards a specific location. In the real world, this can occur in three-dimensional spaces such as birds in flight and schools of fish in water. In our simulation, a two dimensional environment is used so only an X and Y coordinate are needed.

- ***Energy***

This determines when and what actions must be taken. For every action, there is an energy cost involved. Agents acquire energy from consuming food and collecting food and bringing it to a base. This attribute is used in decision making. [See 6.3.3 Energy] This is similar to the way animals decide on when they eat and sleep.

- ***Life Span***

This is how old the agent is in simulation time steps. Agents have a life span of 1500 time steps. The more evolved agents would continue forever, so the life span is given in order to end the simulation.

A more interesting method of doing this would have been to make the agent age a factor to determine the energy to perform actions. This would provide instability in the simulation and end the simulation. This however was not implemented.

- ***Food***

This is how much food is being carried by an agent. This gives an agent more options and the ability to return food to a base for more energy. This is similar to having a knapsack, which can only hold so much space. The total amount that can be carried is determined by the agents *Strength* characteristic. The number can be less than the total amount possibly carried since an agent may have eaten some of what it carries.

- ***Messages***

This stores the location of a Resource and/or a Base. [See 6.4.1 Messages]

6.3 Decision Making

6.3.1 Introduction

This section details the process that an agent undergoes in order to make a decision as to where to go and what other actions to perform. The entire process can be broken into *Goals*, which an agent is trying to achieve, and *Actions,* which are required to achieve those goals.

The goals are as follows:

- Move towards Random Location (*Random*);
- Eat food units at a resource (*Consume*);
- Bring food units to a base location (*Collect*).

The actions are:

- Move towards a location, agent, resource, message;
- Eat food, pick up food, drop food;
- Get a message from agent or environment.

This is the decision making process for the agents. Moving has a cost associated with it, the consumption of energy. Achieving goals provides the agent with energy. The way this occurs is discussed in the following sections.

6.3.2 Goals

Goals are what the agent is trying to achieve in its current energy state. This is similar to animals who determine whether they eat, sleep, breed and play based on the different states and situations that occur. The goals change depending on how much energy the agent has currently [see Energy]. Goals are broken down by decision trees. Four main Goals need to be decided between, *Consume, Collect, Reproduce and Random*. Reproduction would have been used in Survival of the Fittest simulations. Since generational breeding is being used, *Reproduce* is not given an energy state. The other goals are described in further sections.

6.3.3 Energy

Energy allows agents to move and perform certain actions. While an agent moves around, energy is consumed. This can cause an agent to change the goal it is currently trying to achieve. This single amount grows based on how many food units are consumed or collected. It is used up as an agent moves. Agents can move to an adjacent block in the environment, each time this occurs this action consumes one unit of energy. When a food unit is consumed, the agent gains thirty units of energy. When an agent returns food units to a base location it gains two hundred units of energy for every food unit it deposits. This is to make collection more valuable than just sitting and eating food units by a resource.

6.3.4 Goal Setting

Goals have different energy boundaries associated with them. These boundaries allow the goal to be active or inactive. For an example, an animal does not want to eat once it has satisfied its need to eat, which causes it to have passed its energy boundary. Goals also have a priority which helps distinguish between which goal should be active if they have overlapping boundaries.

An example of this is:

		Energy Level	
Goals	**Priority**	**Lower Bound**	**Upper Bound**
Collect	0	250	800
Breed	1	500	600
Eat	2	0	300
Random	3	12	58

Table 3 Agent Goal Table

Now given an energy level of 100, the goal that the agent would have would be *Eat*. If the Agent manages to do this, its energy would increase until it moves out of the upper bound 300. Now it has the energy level 300 causing the goal to shift to being *Collect*. The priority of *Collect* changes to being the highest so that it will be followed until it moves out of the energy bounds. Therefore, if it does not find a resource before it has lowered past the lower bound, it does not change back to *Eat*.

6.3.5 Actions

Consume and Collect have actions that can be performed. Each flow diagram (Figure 12; Figure 13) will have its decisions explained but the result is always an action. These actions depend on the local landscape and the state of the agent. The following points describe the decision trees in the next section. The points are split into groups surrounding what the agent may interact with in the environment.

The different actions applied to different resources, bases, agents and the local landscape are listed below:

Resources: Move to resource, Eat at resource, Pick up food units and Eat food units being carried;

Bases: Move to base and Drop food units;

Agents: Move to agent and Ask for message;

Local Landscape: Move to resource message, Move to base message and Pick up message.

The actions are described in more detail below:

- ***Resources***
  - **Move to resource:**
    This has two modes one which responds to resources inside the sight range of the agent and the other to a message obtained by the agent. The sight range of an agent is up to six units of distance from the agent, allowing it to see a resource. The content of the message is a location of a resource. The agent will move towards one of these locations.
  - **Eat at resource:**
    Consume the food units directly from the resource in the environment, thus giving more energy to the agent.
  - **Pick up food units:**
    An agent can pick up food units. The number of food units it may carry at any time is based on the agent's strength. This is similar to ants being able to carry food back to a nest.
  - **Eat food units being carried:**

The agent has the ability to carry food, so the food it carries is also considered a resource that is available to that agent and that agent alone. This food is consumed providing the agent with more energy temporarily until the food being carried runs out.

- ***Bases***
  - **Move to base:**

    The agent having a message of where a base is will move towards this location.
  - **Drop food units:**

    This is taking food units that have been carried by the agent and deposited in a base thus giving the agent a large energy boost.
- ***Agents***
  - **Move to agent:**

    This only happens if the agent uses Word of Mouth communication. If the agent can see another agent, with a message, in the local landscape then it will move towards it.
  - **Ask for message:**

    This only happens when the agent is a Word of Mouth communicator. The agent will ask another agent that is at the same location as itself for a resource or base message.
- ***Local Landscape***
  - **Move to resource message:**

    If a message, in the environment, of a resource is inside the sight range of the agent, it will move towards the closest message indicating a resource.
  - **Move to base message:**

    If a world message of a base is inside the sight range of the agent, it will move towards the closest message.
  - **Pick up message:**

    This only happens under the conditions of the agent being a *Stigmergic* or *Both Styles* message passer. A message is in the environment at the agent's current location and the agent's internal message is updated, giving it a location of a resource.

6.3.6 **Random**

When a decision cannot be made or nothing in the environment gives the agent a method of gaining some advantage, it will walk towards a randomly allocated location. After a certain amount of time, the agent will stop and revaluate its local landscape and see if it can accomplish one of its goals.

In terms of the decision process, *Random* has a different lower and upper bound. These actually represent co-ordinates in the environment, which the agent will walk towards for a certain amount of time units. The reason that *Random* does not have bounds is that it is there just to move the agent to a new location away from its current stagnant one, so it can change energy level and possibly find new agents or resources. The location changes due to computer generated randomness.

When an agent reaches its location it is assigned a completely new random location somewhere in the environment. While walking in this mode, every step has a fifty percent chance of changing the location slightly and a five percent chance of changing it to somewhere completely new. This is just to force it to move around to newer locations and not move in a continuous straight line.

6.3.7 Consume

Agents hunt for and consume food by this method. This is an approximately the way an animal would go about doing so in the wild. Following is a diagram that illustrates the decision process for this action.

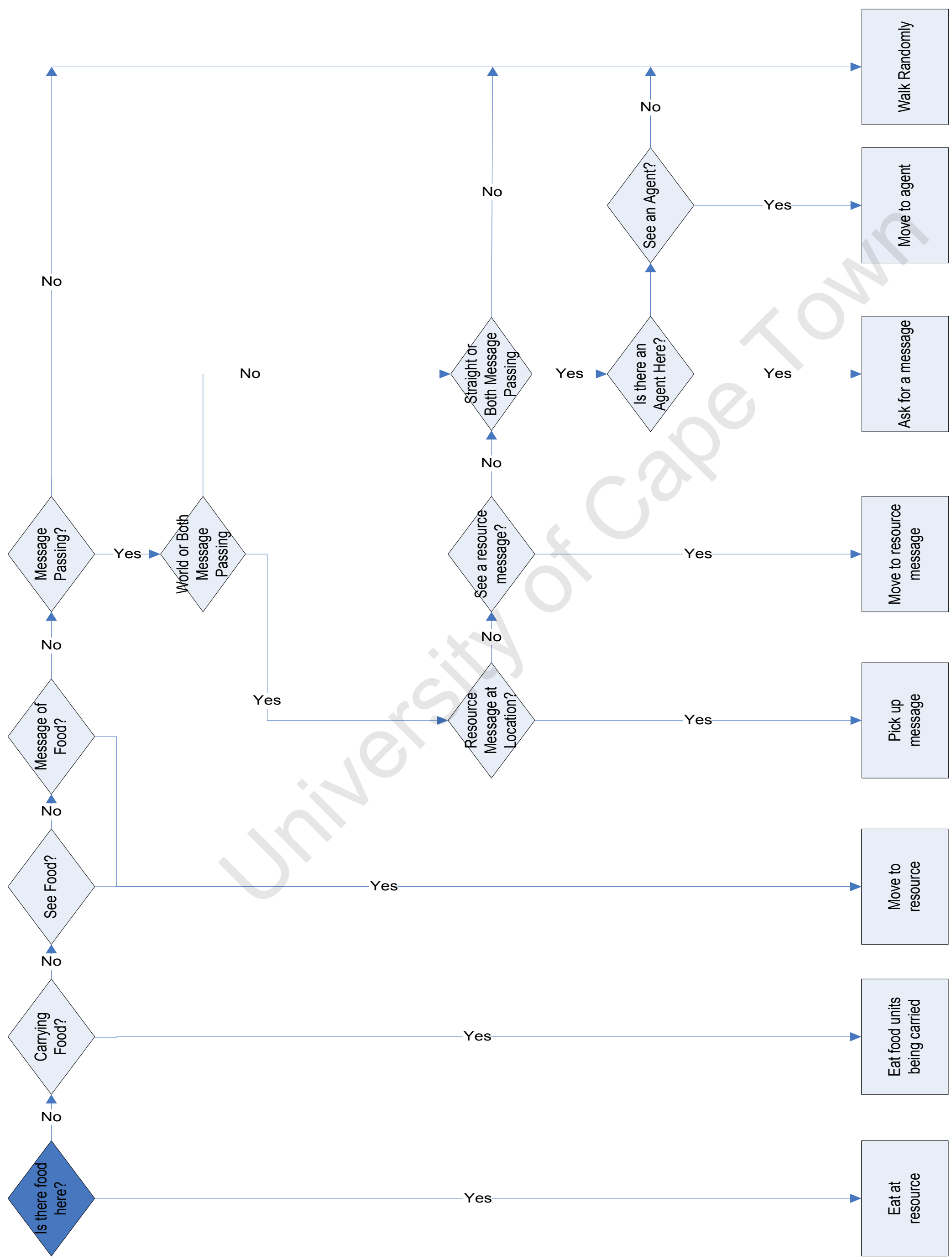

Figure 12: Decision tree for trying to consume food, starting at the dark blue diamond

6.3.8 **Collect**

The point of this decision tree is to bring food units to a base. To navigate the decision tree: yes's move down the tree and no's move across the tree. We will use a depth first traversal of the tree to describe all the steps in the tree.

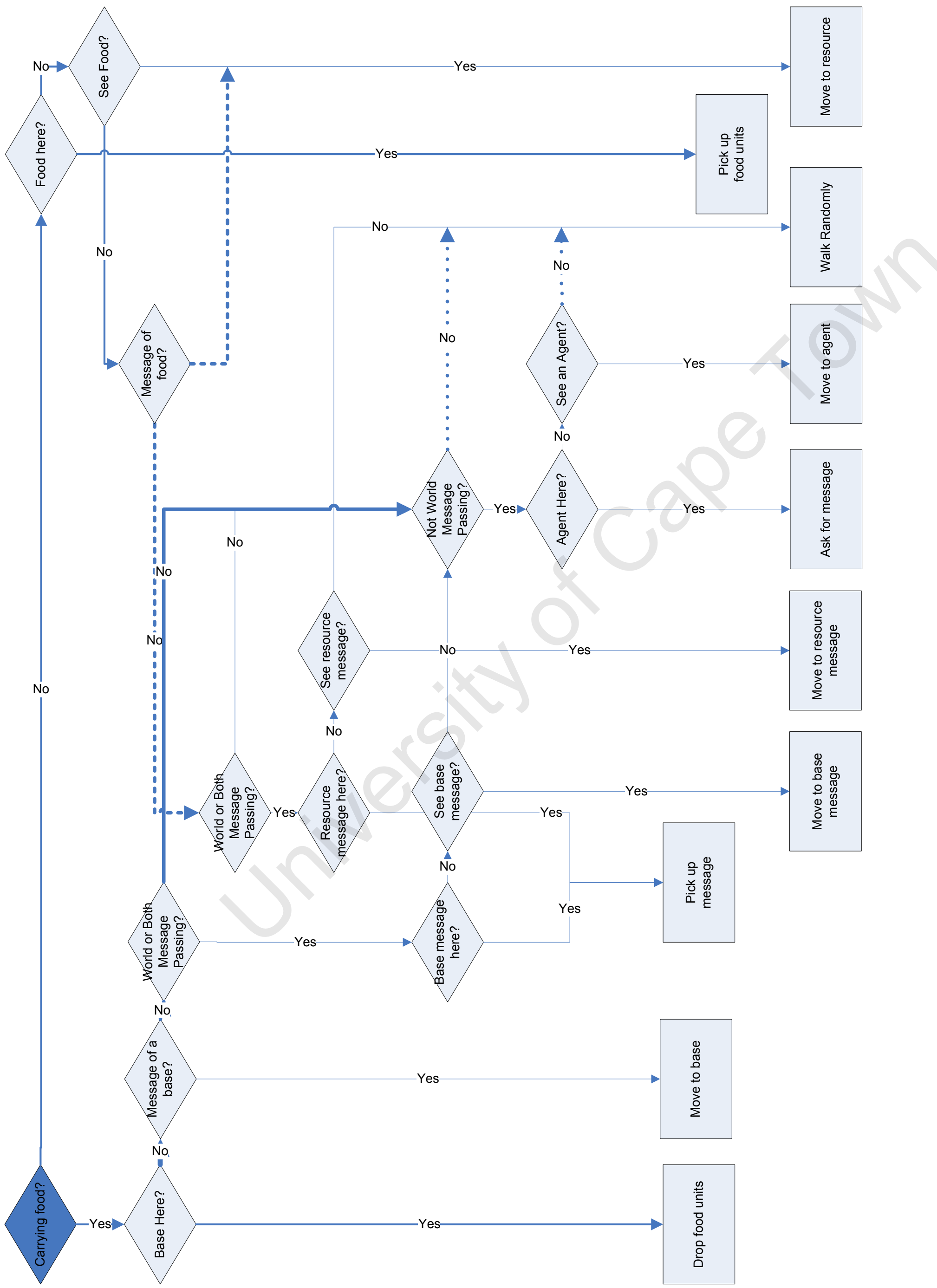

Figure 13: Decision tree for collecting food starting at the dark blue diamond

6.4 Communication

Communication is what separates the individual from the community. The differing styles in communication are the emphasis of this research. People can communicate in a vast array of different ways. In this research, we only examine two of those ways, word of mouth and stigmergic.

There are four modes of communicating that an agent may have set as a characteristic:

- None,
- Word of Mouth,
- Stigmergic and
- Both Styles.

These are discussed individually. Since communication is useless without a message to impart, we discuss this first in the next section.

6.4.1 Messages

Messages depict a location and some element in the environment (i.e. base or resource). The agents store these messages and use them to navigate in the environment. A typical message is comprised of an identifier or tag, x and y coordinates and the type of element in the environment. The following sections depict the different styles of communication that an agent employs to utilize these messages.

6.4.2 Message Passing Styles

➢ ***No Communication (NC)***

This exists in order to be able to determine the sum of the parts. Each agent that has this set cannot communicate with any other agent in the simulation. The only way for it to be able to consume food and live is by spotting a resource. This is more by chance than by any action taken on the agent's behalf. This setting is not very interesting and is here merely to check if the agents are becoming more evolved when using the other communication styles.

➢ ***Word of Mouth (WOM)***

Word of Mouth communication for this simulation is far more passive than word of mouth or advocacy in the real world. In the simulation, the agents want information from other agents and will go out and get the message. Normally for advocacy, the person with the information tells others because it is beneficial to the group. In the simulation, agents get a message by searching for other agents. This will allow them to receive messages from those other agents. The agents can see agents with a message of a resource or base. This was done in order to avoid agents randomly going after other agents that do not have messages.

- ***Stigmergic Style (SS)***

Agents who have this communication style set will drop messages in the environment every random number of time steps, the number of time steps depends on each individual agent. The agents can then collect messages from the environment. These agents can tell the difference between message types left in the environment. This means the messages are delayed between each agent. If a message exists in the environment, the agent's current message replaces this message. This is not like normal stigmergy since the messages do not become stronger if placed again or fade with time. This behaviour of messages would be interesting to implement in future work.

- ***Both Styles (BS)***

Using this style an agent may read both messages from the environment and receive messages from other agents. The agents will drop messages in the environment in the same manner as the stigmergic agents.

6.5 Summary

Agents have the following: Characteristics, which are unchanging during a simulation run, and Attributes, which do change during a simulation run.

Characteristics

ID, Strength, Fertility, Communication Style and Choices

Attributes

Location, Energy, Life Span, Food and Messages

Agents must decide between a few goals. They use actions to be able to achieve these goals. The following are a list of the goals and then a list of the actions. The actions have been divided up into different categories based on what the agent may interact with in the environment.

Goals

Consume Food Units, Collect Food Units and Random

Actions

Resources: Move to resource, Eat at resource, Pick up food units and Eat food units being carried

Bases: Move to base and Drop food units

Agents: Move to agent and Ask for message

Local Landscape: Move to resource message, Move to base message and Pick up message

The agents are bred using a generational method of breeding. The top agents are picked out of the results of the previous generation and are bred together to form a new generation using crossover and mutation. Agents may communicate with one another in a number of ways. They are listed with a brief explanation of each:

- **None**, there is no communication between agents.
- **Word of Mouth**, agents may communicate directly with other agents in the same local space.
- **Stigmergic**, agents leave messages in the world and can use these to navigate.
- **Both Styles**, agents employ both Word of Mouth and Stigmergy as the means to communicate.

Research

Chapter 7 Research Methodology

7.1 Introduction

The agents that have been described in the previous chapter now have to be implemented and evaluated. In order to evaluate them, a prototype was created. They needed to be evolved over time. This was done so that the agents could evolve in different ways. The manner in which they are grouped determined how they were evolved. The agents were grouped by communication style. In each group, we did evolution independently, in order to understand how the evolved agent's proficiency differed depending on communication style and scenario. The outline for this chapter is as follows:

Implementation

- Programming Languages used to implement the designs and generations.
- Populations, the initial populations and the selection of populations to be used for continued runs.
- Generations, this is the creation of new generations from previous generations.
- Single run of the simulation is described.
- Starting Conditions, this describes the different conditions under which scenarios can run in the simulation.

Evaluation

- Performance Criteria, these are the metrics that determine the fitness of the agents and a run.
- Scenarios, *Single Resource*, *Multiple Resources*, *Single Base and Single Resource* and *Single Base and Multiple Resources* were different environments that were set up in order to test how the agents operated under certain conditions.
- A summary of these starting conditions can be seen at the end of the chapter.

7.2 Implementation

7.2.1 Programming Languages used for implementation

The design outlined in the previous chapter was implemented in C++ using objects to describe the different entities (resources, agents, bases and messages). The breeding of agents was also carried out in C++ and the running and display of the simulation was done here as well. The agent brain was created in C++ and was put in to the simulation run.

The generations were sorted and the top hundred agents were extracted by Perl scripts.

7.2.2 Populations

In order to evolve the agents, we generated the initial population, which was then used in the simulation. Each population contained five hundred agents. Ten initial random populations were generated. Each agent had random characteristics assigned to it. The goal table, in the initial population, had the consume entries lower bound set at 0 instead of being random in order to insure that the agents will do something. Once the populations ran through the different scenarios, the best four performing populations, used for the rest of the generations, were selected. This was in order to speed up the running of the simulation. The process we followed is illustrated in Figure 14 below.

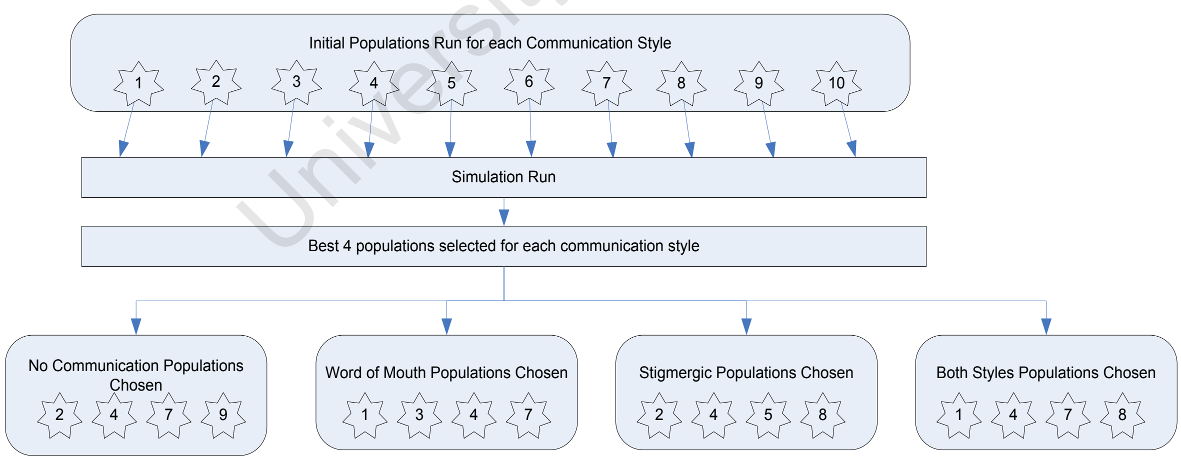

Figure 14: Initial populations to populations used for the rest of the simulation runs

These populations were then used to continue the generations from generation 1 – 9.

7.2.3 Generations

The best four populations, that were selected in the previous section, then had the fittest one hundred agents removed and used to create the next generation of agents (see the breeding in the next section for how this is done). The new generation was then placed into the simulation and was run through the testing scenarios once again. This process of selecting agents was repeated. A flow diagram illustrates this process in Figure 15. This process was repeated until the results of the populations being run through the simulation test cases start to show a marked difference to each other. Ten generations were deemed enough to find good solutions.

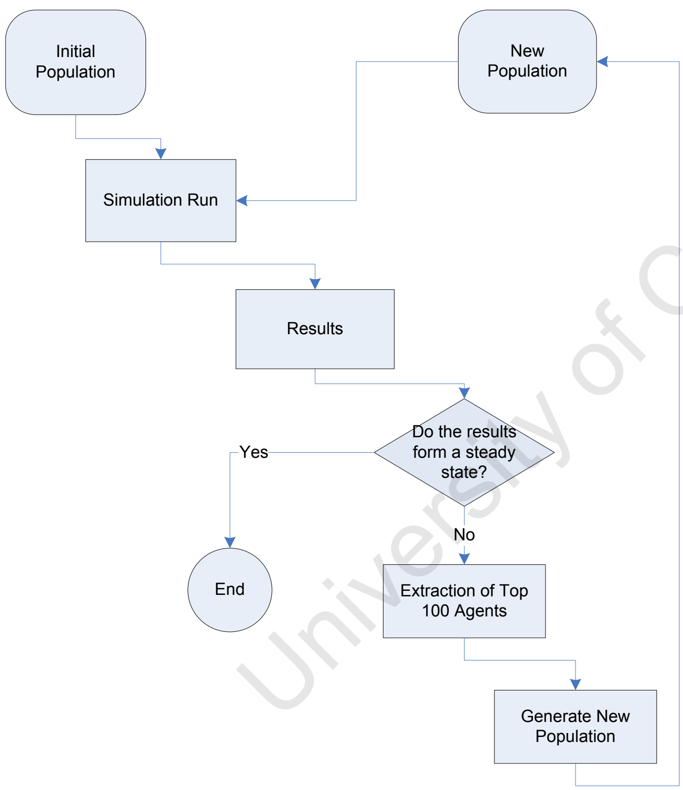

Figure 15: Flowchart of population generation for each simulation test

7.2.4 Breeding

Breeding a new creature requires there to be a change or copying of genetic material. There are several ways of going about breeding. The first few were covered in *combination* and *mutation* [Chapter 4]. There are more considerations for genetic algorithms than simply breeding two structures. There are two main sections to this chapter, Agent Breeding and Agent Selection.

➢ ***Agent Breeding***

Agents have several attributes and characteristics that allow them to function [6.2] including the decision structure [6.3.4]. These attributes help determine the agents effectiveness in the environment. An agent is selected as the dominant party and the base genetic material is taken from that agent. A second agent is selected and will be used to determine a new agent. The selection criteria is based on what Breeding Strategy is being adopted, this is discussed in *Agent Selection* below.

The Characteristics and Attributes that are used for breeding are as follows:

- Strength
- Memory
- Fertility
- Decision Upper and Lower bounds
- Decision Priorities
- Communication style

In this system, there were characteristics that could change, but some of the characteristics would have only used for alternative testing. These were Memory and Fertility; see the future work section [9.5] for their uses. There were two ways to help create new agents, Crossover and Mutation. These are discussed in the following sections.

Crossover

Each of the agents characteristics are put into a list of the same order. Characteristics in that list are chosen at random. A copy of the first agent selected is created. The characteristics chosen are then copied from the second agent into the newly created copy. Any message that the first agent has is abandoned. Uniform Crossover is used for this process over One Point or Two Point Crossover since it provides a general better result, Uniform Crossover shown to be better in almost all cases by Syswerda(38) and Single Point Crossover to be the worst by Eshelman et al. (37). Since the other two favour characteristics that are put at the beginning and at the end, this was deemed unsatisfactory for this system.

A demonstration is the easiest form of explanation in the more intricate cases:

The goal table abbreviations are Priority(Pri), Lower Bound(LBo) and Upper Bound(UBo).

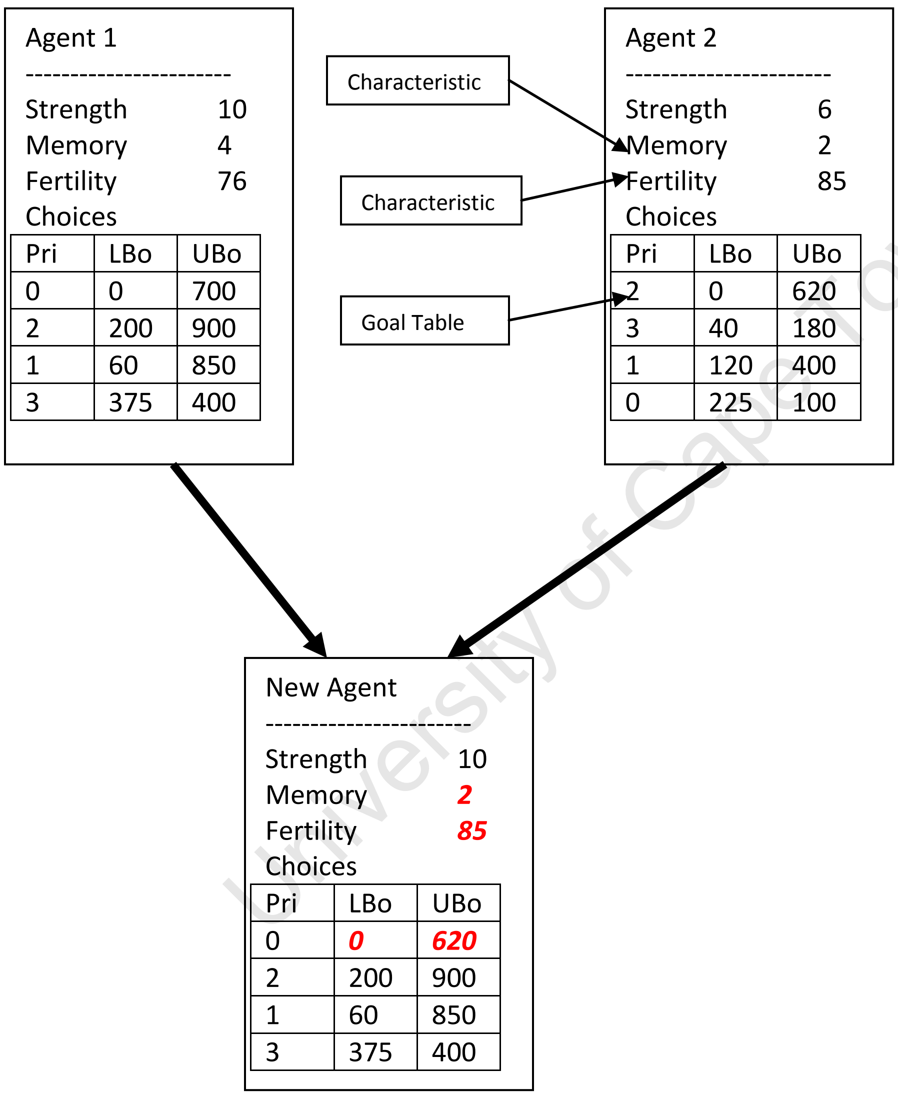

Figure 16: Crossover of the characteristics of two agents using the uniform crossover method

Priorities are not swapped since an individual priority is meaningless and only means something in relation to the other priorities; they are recompiled merging the two agents' priorities. The sequence is as follows:

Agent 1 Priorities	Agent 2 Priorities
0	2
2	3
1	1
3	0

New Agent Priorities = Agent A priority + Agent B priority

0 + 2 = 2
2 + 3 = 5
1 + 1 = 2
3 + 0 = 3

A high number means a low priority. Given the possible actions to do, the one with the lowest priority will be done over the others. The highest number is then chosen to represent the lowest priority. In this case, the second action (5) is chosen as the lowest priority. When two priorities are the same value, the first action is selected. Therefore, to demonstrate the New Agent for the above situation would be:

2 is placed in position 2
5 is placed in position 0
2 is placed in position 3
3 is placed in position 1

This would give the new agent the following:

New Agent

Strength 10
Memory 2
Fertility 85
Choices

Pri	LBo	UBo
2	0	620
0	200	900
3	60	850
1	375	400

Figure 17: The new priorities for New Agent determined by the combination of the old priorities

Mutation

In order to create diversity and not allow agents to settle on local maximum solutions mutation, is induced. This allows for new agents that can possibly be more effective in the current situation to be created. Most cases will cause no such efficiency. [For more on Mutation see section 0.0.0 ⍰].

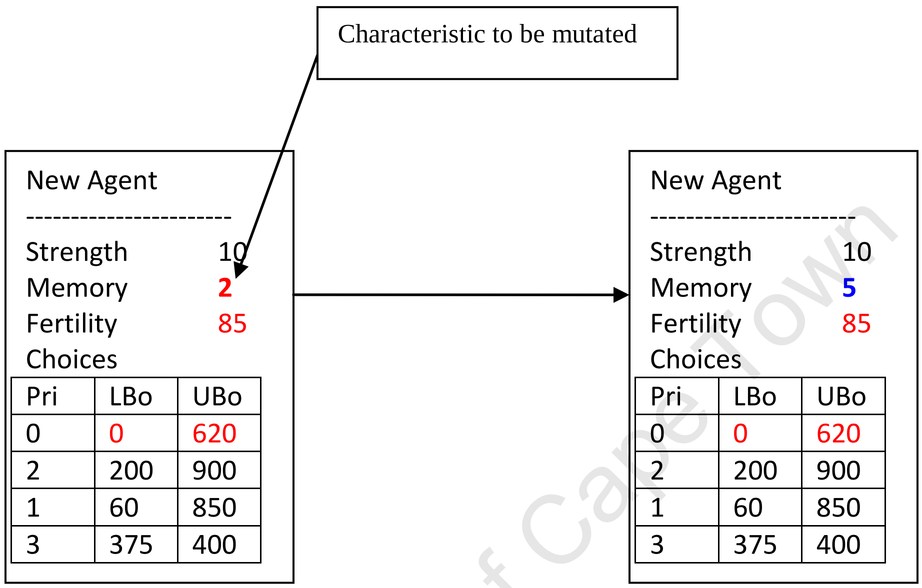

Figure 18: The mutation of an agent's characteristics

There were two ways to mutate a characteristic, small and large mutation. Small mutations have a higher chance than large ones. In this simulation, we decided that a 5% chance for a small mutation and a 1% chance for a large mutation would be sufficient. The reason for such large chances of mutation is the small number of populations that were run and the relatively small size of those populations. If steady state was used then a smaller chance of mutation should have been used.

Small mutations cause a small offset of the original value. For example, if a value is between 0 and 100 and is currently on 50, a small mutation will cause it to shift by some number from 50, so if that number is 10 then the new value will be between 40 and 60. This mutates it in small increments instead of assigning a new random number, which has the chance of being completely different. Large mutations are the same variable completely reassigned a random value inside of the range.

Since the normal bit string method was not used, this provided a nice way of creating mutation that would not jump out of bounds when it mutated. It also provided a nice way of having slight variations instead of large ones all the time. These mutation methods were based on the work by Davis (39).

- ***Agents Selection***

In the case of this simulation, consuming food units and collecting food units gave the fitness criteria. More importance is placed on the collection of food. The amount of food consumed and collected is totalled for all the different tests, and then the agents are ranked using the following formulae, where Agent(x) is a particular agent in a simulation run:

$$Fitness(Agent(x)) = amount\ consumed\ by\ Agent(x) + (20 * amount\ collected\ by\ Agent(x))$$

We use generational breeding and remove the top agents for this simulation. The top hundred agents are selected to create the next generation. These hundred agents breed until a new population of 500 is reached. The agents are selected at random and then have another random agent, out of the 100, as their breeding partner. This is how the latest population is formed. The 100 are included in the latest population. This creates 400 new agents and with the addition of the original 100 come to 500 agents for the next simulation run.

7.2.5 Single Run of a Simulation

This section describes how a single run of a simulation was performed. The simulation is a discrete time step model. This means that every agent can take a single action before the next agent takes its following action. One time step is the time it takes all the agents to perform a single action. The order of the simulation run is as follows:

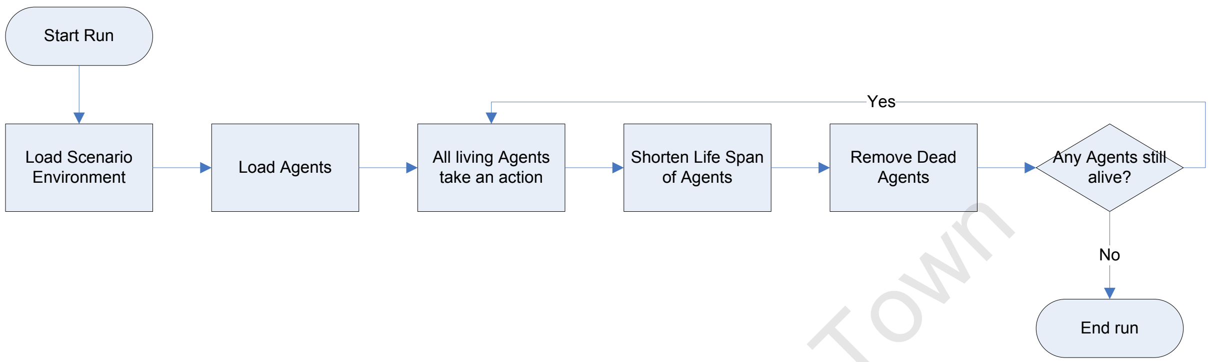

Figure 19: A single simulation run for any scenario and agent population

The different steps of a single simulation run include the following:

1. Load Scenario Environment, a Scenario's environment is created setting the location and number of resources and bases.
2. Load Agents, five hundred agents of a specific population are added to the environment at random locations. The agents have their energy set at 500.
3. All living agents take an action; each agent takes a single action that is determined by that specific agent's characteristics.
4. Shorten life span of agents, each agent has a life span with a maximum of 1500 time steps, this is so the simulation does not run forever. When an agent's life span reaches zero it dies.
5. Remove dead agents, the agents that have reached the end of their life span or run out of energy are removed and the results that the agent accomplishes are stored.

This is what constitutes a single run of the simulation. Now each scenario has a specific set of starting conditions applied to that scenario; these are discussed in the next section.

7.2.6 Message Passing Styles

In our simulation runs, we considered the different styles of message passing possible to an agent. Each of these was tested in our simulation runs. The message passing styles are *No Message Passing*, *Word of Mouth*, *Stigmergic* and *Both Styles*. Each of these styles is discussed in more detail below.

No Communication (NC)

All agents are blocked from passing messages to each other. In the Agents chapter, it outlines what this means to an individual agent. The entire group had this characteristic.

Word of Mouth (WOM)

All of the agents can only communicate using word of mouth communication. They can only pass messages by moving to an agent and acquiring a message directly in the local vicinity. This is trying to simulate a crowd that has very little means with which to communicate. In the real world, an example of this would be a stadium of people who do not know each other and where there are no signs in the stadium of where toilets are located.

Stigmergic Style (SS)

All the agents may only communicate indirectly through the environment. It mimics ant-like behaviour more than human beings do since humans use a mixture of both stigmergic and word of mouth principles to communicate. The agents are effectively interacting with only the environment. They are unaware of each other directly.

Both Styles (BS)

This is both styles of communication (stigmergic style and word of mouth) being used by all the agents. They can acquire messages from the environment and other agents. This style of communicating is the closest one to human interactions with each other.

7.2.7 Starting Condition of Simulation Runs

In order to see how the messages affect the agents the messages are given randomly to agents in a number of ways, each changes how the agents may interact with the environment and what actions need to be performed by the agent in order to achieve its goals. There exist many possible combinations. We have given five types of starting conditions as examples in order to test the system; *No Messages*, *20% Resources*, *20% Resource and Base, 20% Resource and 20% Base* and *100% Resource.* Each of these starting conditions is discussed in more detail below.

Starting Condition: No Message

Agents start with no messages of resource or base locations. This is supposed to demonstrate how effectively agents can discover a resource's location and spread the message of where it is without outside help. An example of this would be moving a number of ants from one location to another. The environment does not have any pheromones so the ants have to form a new message to pass to each other.

Starting Condition: 20% Resource

Random 20% of the agents start with a message of a random resource but no base location, even if a base exists. This demonstrates, given a bit of knowledge, the spread of the messages. This could also demonstrate the effectiveness of communication for consumption of food units by the agents.

Starting Condition: 20% Resource and Base

Random 20% of agents have both a message of a resource location and a base location. This demonstrates the effectiveness of agents to collect food and given information about the environment be able to achieve goals more easily. Depending on the communication style, this starting condition should change the consumption and collection of the agents significantly. Since some agents have a message of both a resource to collect food units from and a base to take food units to, it can immediately collect and gain an advantage.

Starting Condition: 20% Resource and 20% Base

Random 20% of agents have a message of a resource location and a different 20% have a message of a base location. Agents have to communicate with one another in order to be able to collect food. This starting condition demonstrates whether the agents are communicating with each other in order to gain additional information about the environment.

Starting Condition: 100% Resource

All agents in the simulation have a message of where a resource is located. This should have the highest consumption rates since the agents do not need to locate a message in order to find a resource.

7.3 Evaluation

7.3.1 Performance Criteria

The results are given in the form of a performance score of the run. This performance is made up of the total consumption of food units by the agents and the total collection of food units by the agents of a particular simulation run with certain starting conditions. The performance score of a simulation run is determined as follows, where Run(*y*) is a particular run with starting conditions *y* for a particular simulation run and Agent(*x*) is a particular agent inside that simulation run:

$$Fitness(Agent(x)) = amount\ consumed\ by\ Agent(x) + (20 * amount\ collected\ by\ Agent(x))$$

$$Performance(Run(y)) = \sum_{x=1}^{500} Fitness(Agent(x))$$

7.3.2 Test for Emergence applied to this research

We used the test for emergence as outlined in section 3.3 to analyse the results. We used it in the following way:

Design: L_1 was described in the Design section as the local rules for the agents, resources and bases.

Observation: L_2 were the results received about the amount of food units collected and consumed by the agents. This also demonstrated how these changed over the generations of the agents.

Surprise: The behaviour of the agents is not linked to how they evolve with the genetic algorithm and how they gain in performance or communicate with each other in order to achieve this performance. L_1

and L_2 were distinct and should give surprising behaviour; we should get unsurprising surprise since it can be worked out why the behaviour occurred.

7.3.3 Scenarios

These are specific environments, where bases and resources had specific locations. We chose to test the running of the system in a very general way by using a few test scenarios. The scenarios described below have the following format: why we chose them followed by a description of the scenario.

The scenarios are:

- *Single Resource*,
- *Multiple Resources*,
- *Single Base and Single Resource* and
- *Single Base and Multiple Resources*.

Each of these scenarios is described in more detail below.

➢ ***Scenario: Single Resource***

Aim

This scenario checked if the agents were consuming food. It also demonstrated whether the messages passed by the agents affected the ability to get to the resource from outlying areas. Agents start with a random location in the environment. This scenario caused the resource to be further from some agents and closer to others. This was to give better results for the different communication types and allowed agents to communicate in order to find the resource.

Description

A single resource existed in the centre of the environment at position (250, 250) illustrated in Figure 20. This caused it to be central in order for agents to be able to move easily towards this location. Each communication style was tested with different starting conditions. The starting conditions with bases were left out since there was no base in this particular scenario.

The starting conditions we used in this scenario were:

- No Message
- 20% Resource
- 100% Resource

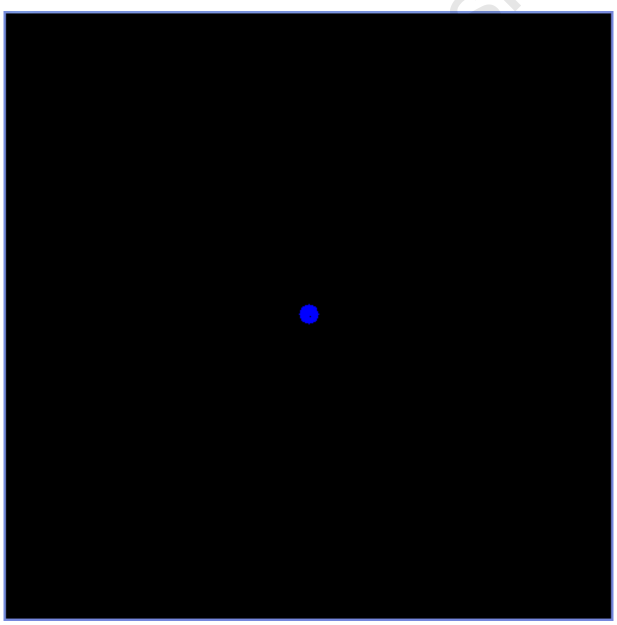

Figure 20: An environment with 1 resource (blue) at the coordinate (250, 250)

- ***Scenario: Multiple Resources***

Aim

This scenario tested how the agents responded to having more choice in the number of resources. The agents were more likely to bump into resources so more consumption could have occurred. The agents started in random locations. The difference in the agents' location to the resources would have less impact on the results. If however an agent had a message of a distant resource and it did not see a nearby resource, it could possibly have taken longer to cross the environment than simply searching the local environment.

Description

This setup had twenty resources scattered randomly over the environment as illustrated in Figure 21. The starting conditions for this scenario were the same as for the Single Resource scenario. Each communication style was tested with different starting conditions. The starting conditions with bases were left out since there was no base in this particular scenario.

The starting conditions we used for running in this environment were:

- No Message
- 20% Resource
- 100% Resource

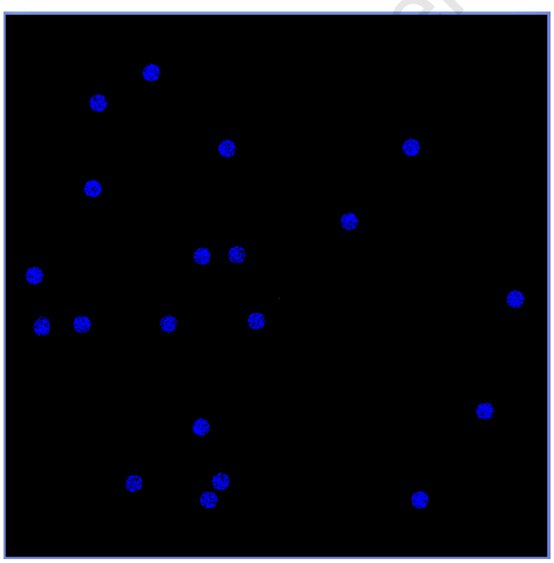

Figure 21: Twenty resources (blue) scattered in an environment

➢ ***Scenario: Single Base and Single Resource***

Aim

The aim of this test was to see how the agents responded to a base in the environment. It allowed collection to have taken place. This provided the agents with a greater advantage.

Description

This environment had a resource at (200, 200) and a base at (300, 300) illustrated in Figure 22. This environment was to test whether agents were travelling from the resource to the base in order to achieve the Collection goal. As in the previous case the distant agents might have been at a disadvantage and the nearer ones at an advantage. It was more likely that an agent would be able to walk randomly and spot the resource; however, the agents could not see the base. If an agent was carrying food units and was standing on the base then it gained a message of a base. In order to be able to collect food units the agents require knowledge of the base's location.

The starting conditions for this scenario were:

- No Message
- 20% Resource
- 20% Resource and Base
- 20% Resource and 20% Base

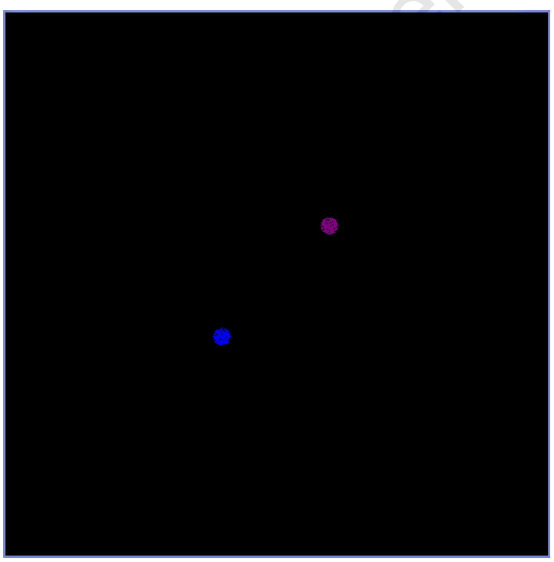

Figure 22: An environment with a base (purple) at (300, 300) and a resource (blue) at (200, 200)

➢ ***Scenario: Single Base and Multiple Resources***

Aim

The aim of this scenario was to test how the agents responded to having more options in resources and how it affected the collection rates, since some of the resources were at different distances from the base.

Description

The final environment used for testing was one with 20 resources randomly scattered in the environment with a base at coordinate (250, 250) this is illustrated in Figure 23. The agents had more opportunity to bump into a resource and the ability to collect food units. The starting conditions for this scenario were:

- No Message
- 20% Resource
- 20% Resource and Base
- 20% Resource and 20% Base

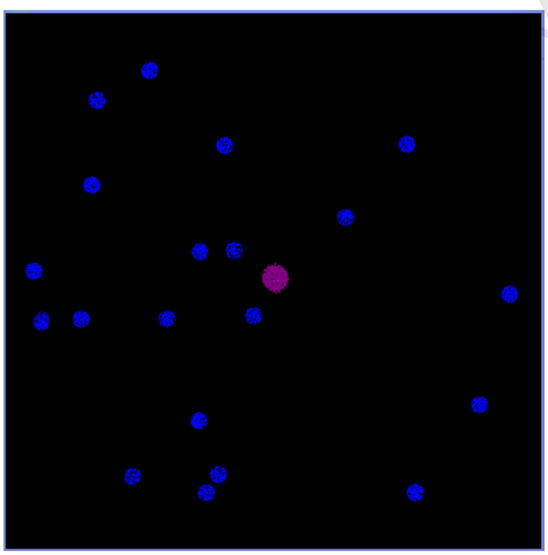

Figure 23: Twenty resources (blue) scattered in the environment with one base (purple) at coordinate (250, 250)

7.4 Conclusion

In this chapter we examined, the implementation of the system, how the system was to be tested, the starting conditions and environments that accompanied each scenario.

Summary of Starting Conditions and Scenarios

Different Message Passing Styles:

- No Message Passing, agents may not pass messages
- Word of Mouth, agents can only talk to other local agents
- Stigmergic, agents can only look at messages in the environment
- Both Styles, agents can do both styles Word of Mouth and Stigmergic

Starting Messages:

- No Message, agents without any messages
- 20% Resource, a random twenty percent of the agents have a message of a resource
- 20% Resource and Base, a random twenty percent of the agents have a message of a resource and a message of a base
- 20% Resource and 20% Base, a random twenty percent of the agents have a message of a resource and a different random twenty percent have a message of a base
- 100% Resource, all agents have a message of a resource

Scenarios:

- Resource and No Base
- Resource and Base
- Multiple Resources
- Multiple Resources and a Base

In the next Chapter, we examine whether the research accomplished what it set out to discover and whether there was surprise and emergence.

Chapter 8 Results and Analysis

8.1 Introduction

Each Scenario's starting condition has a set of results, or in the case of the emergence test the observation phase, in the form of a table and a graph, followed by an analysis of those results in terms of L_2 from the emergence test (3.3 Test for Emergence). L_2 is distinct from L_1 because you cannot determine how the results were achieved from generation to generation. This can not be determined by looking at the agent rules. The analysis, or surprise phase, describe which behaviours were emergent and what type of surprise was experienced. This demonstrates the group behaviour of the agents using different communication styles.

Each scenario has results for each of its starting conditions. They are listed as follows:

- *Single Resource*
  - No Communication
  - 20% Resource
  - 100% Resource
- *Multiple Resources*
  - No Communication
  - 20% Resource
  - 100% Resource
- *Single Base and Single Resource*
  - No Communication
  - 20% Resource
  - 20% Resource and Base
  - 20% Resource and 20% Base
- *Single Base and Multiple Resources*
  - No Communication
  - 20% Resource
  - 20% Resource and Base
  - 20% Resource and 20% Base

Each of these has results and analysis given below.

8.2 Single Resource

8.2.1 No Message

Results

Message Passing Style	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	1916	2571	2574	3180	3015	3374	2715	2647	3242	3019
Word of Mouth	9868	9434	7264	6978	8054	8236	8612	8834	9162	9192
Stigmergic	9940	10883	7823	7765	7553	7881	8228	8399	8267	8697
Both Styles	11496	10683	8701	8465	8563	9210	9098	8969	9447	9590

Table 4: Average Fitness Results for the starting conditions "No Message" in "Single Resource" Scenario

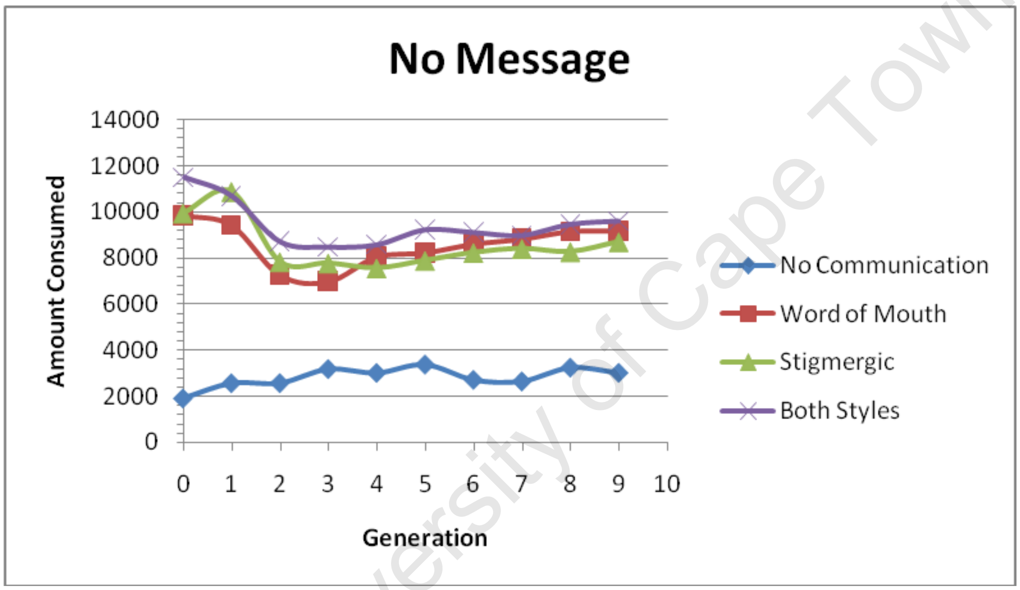

Figure 24: Graph of the different communication styles with the starting condition "No Message" in the "Single Resource" Scenario

Analysis

No Communication: Was the lowest performer and was the sum of the parts since there was no communication happening between agents. There was however, a slow increase in performance over time showing that EA's depict unsurprising surprise as the simulation continued.

Word of Mouth: This communication type experienced a large dip in performance over the first three generations but slowly started to climb in performance again after this point. This could have been because this scenario had no base in its starting conditions and the performance was based on two conditions and not one. This was emergent since it was much higher than the sum of the parts (NC), showing that the whole which was communicating was greater in performance.

Stigmergy Style: This was the same as WOM but with a slight jump up at the beginning, which showed that the evolutionary path was different to that of WOM. In later generations, it performs worse than WOM and BS, which indicates that the message spread was worse than that of direct communication.

Both Styles: This had the same sort of dip experienced by the two previous styles, and unsurprisingly was the highest performer.

Emergence was shown to happen for this test by observing the whole being greater than the sum of its parts.

8.2.2 20% Resource

Results

Message Passing Style	Generations 0	1	2	3	4	5	6	7	8	9
No Communication	4727	5922	6245	6300	6724	6622	6856	6585	6721	6564
Word of Mouth	13895	12175	8712	8491	8963	9411	9593	10153	10406	10521
Stigmergic	14080	12821	8727	8370	8434	8708	8835	9105	9334	9370
Both Styles	14851	12478	9067	8984	9233	9538	9753	9938	10133	9840

Table 5: Average Fitness Results for the starting conditions "20% Resource" in "Single Resource" Scenario

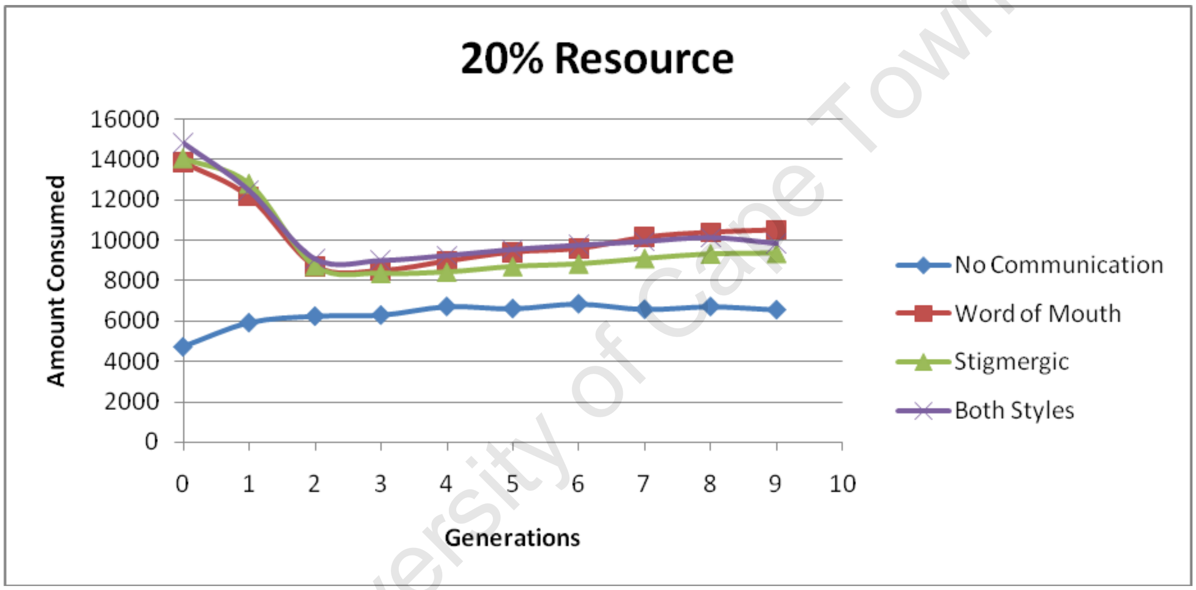

Figure 25: Graph of the different communication styles with the starting condition "20% Resource" in the "Single Resource" Scenario

Analysis

No Communication: This once again started to gain in performance but clearly performed the lowest, which is to be expected. It did however have a much higher performance than in the previous set of starting conditions and gained in performance over time in a greater manner. This could have been due to it having messages of locations. This style still experienced emergence due to the EA.

Word of Mouth: There was still a drop in performance. This was much greater than in the previous set of starting conditions. With this set of starting conditions, the performance compared to the other styles was similar in the beginning but slowly started to outperform even the expected highest performer BS. Which was surprising surprise as it could not be explained by the local rules since BS has the same communication type available to it. This could have been an aberration but was run multiple times with different populations.

Stigmergic Style: This style had the same dip in performance as WOM and BS and slowly increased after that dip. The style underperforms compared to WOM and BS. There is no explanation for this. It is expected that since, messages can be left in the world (500x500 blocks), that there are more messages available to agents than the 500x2 messages that can be gathered from agents in WOM but it is not surprising that it underperforms compared to BS, since this has the same advantage as SS combined with the advantages of WOM.

Both Styles: This had the same dip as before but sharper. It started its performance at a higher point as did WOM and SS; this could have been due to messages being available which was not that surprising.

Emergence was once again achieved due to the whole (WOM, SS and BS) being greater than the sum of its parts (NC).

8.2.3 100% Resource

Results

Message Passing Style	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	15267	19212	20296	21330	21504	21945	22222	21999	21946	21549
Word of Mouth	15279	12927	9055	8625	8915	9584	10022	10455	10701	10725
Stigmergic	15266	14222	9298	8951	8950	9235	9351	9655	9884	10136
Both Styles	15261	12910	9273	9208	9408	9829	9964	10091	10353	10161

Table 6: Average Fitness Results for the starting conditions "100% Resource" in "Single Resource" Scenario

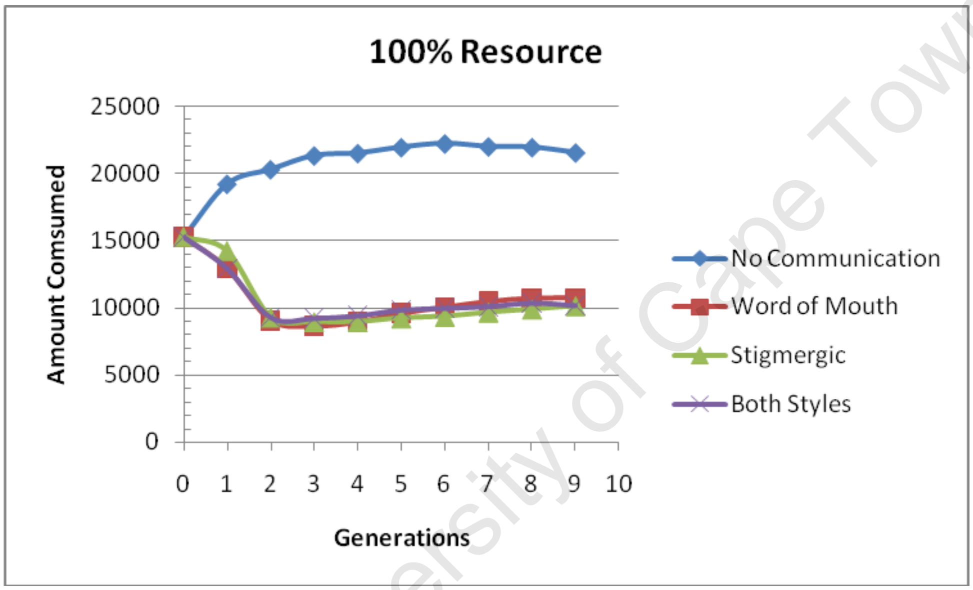

Figure 26: Graph of the different communication styles with the starting condition "100% Resource" in the "Single Resource" Scenario

Analysis

No Communication: This style has a large jump in performance and starts outperforming the other styles, this starting condition negates the advantages of the other styles as it removes communication as necessary. The agents priority list becomes more refined at merely consuming food. In this case, there is surprise because it so drastically outperforms the other styles. It is unsurprising surprise since it can be traced back as to why it performed in this way. Due to there being two conditions (resource consumption and collection) for evolution and this scenario only examines one of them this jump is not that surprising. Again the EA was shown to be emergent.

Word of Mouth: This had the same behaviour as the previous starting conditions with a slightly higher starting point due to all the agents having a message at the beginning. After three generations or so this performs in the same manner as the previous starting condition 20% Resource. This implies that the agents are spreading the message between each other rapidly from one agent to another.

Stigmergic Style: This style exhibited the same drop and then steady climb as before and is now the worst achiever.

Both Styles: This had the same drop as WOM and SS, and has the same behaviour after this point as the previous starting condition.

There was no Emergence achieved, since the whole was now merely a sum of parts because communication became unnecessary.

8.3 Multiple Resources

8.3.1 No Message

Results

Message Passing Style	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	5603	7262	7635	8288	8869	8254	8392	8418	8687	8010
Word of Mouth	13655	12000	8702	8500	8883	9473	9855	9998	10500	10563
Stigmergic	13701	12841	8579	8231	8479	8695	8862	8765	9251	9374
Both Styles	14579	12509	9229	9014	9103	9628	9739	9886	10154	9988

Table 7: Average Fitness Results for the starting conditions "No Message" in "Multiple Resource" Scenario

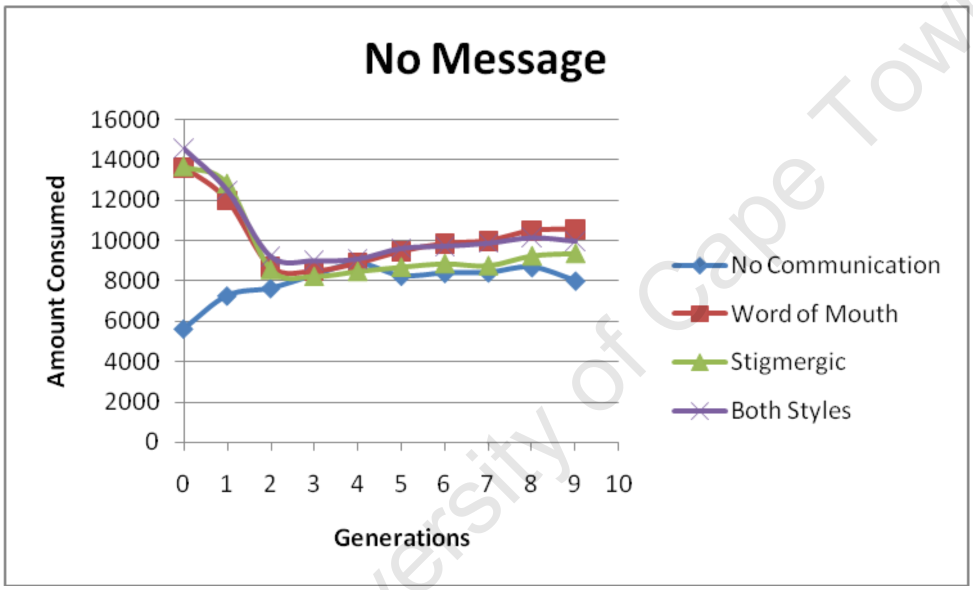

Figure 27: Graph of the different communication styles with the starting condition "No Message" in the "Multiple Resources" Scenario

Analysis

No Communication: This style increased again it had less reason for messages since it became easier to find resources because of the increase in the number of resources for this scenario. It is still the worst performer. The reason the performance improves is that the decision process becomes more refined.

Word of Mouth: WOM had the dip and climb behaviour as experienced in the previous scenario and even with the resources increased performed in the same manner. This means there is a point that the agents are no longer consuming food units and the only reason this could have been was that it was looking to collect food units rather than consume them.

Stigmergic Style: This had the same behaviour as the previous scenario and as in WOM and BS appears to have had a cut off performance point in terms of consumption.

Both Styles: This once again performs less well than WOM. It has the same cut off point that its performance had in the case with one resource.

It appears that the only communication style to have benefited from the multiple resources was NC, the others were not consuming due to not having as great an evolutionary advantage in just consuming resources.

8.3.2 20% Resource

Results

	Generations									
Message Passing Style	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	7230	9387	10442	10742	11418	10893	11369	11278	11599	10688
Word of Mouth	14477	12740	8964	8489	8945	9324	9835	10327	10552	10326
Stigmergic	13651	13051	8627	8468	8502	8670	8722	8849	9259	9266
Both Styles	14307	12320	8879	8791	9163	9466	9538	9816	10151	10354

Table 8: Average Fitness Results for the starting conditions "20% Resource" in "Multiple Resource" Scenario

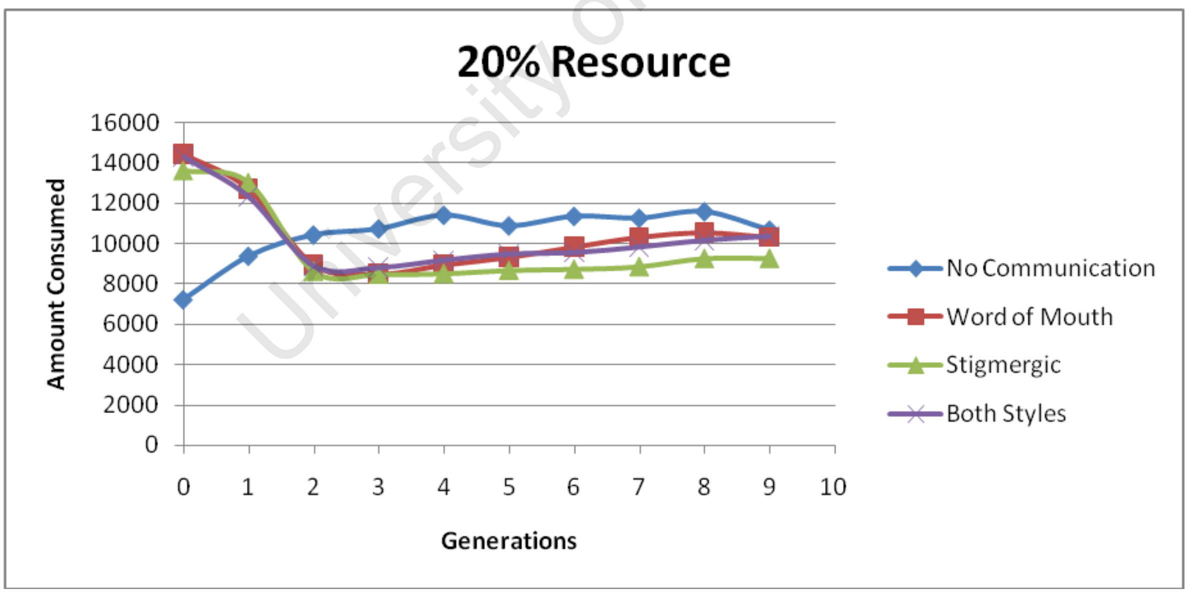

Figure 28: Graph of the different communication styles with the starting condition "20% Resource" in the "Multiple Resources" Scenario

Analysis

No Communication: This style now has the highest performance with a few messages and the ability to bump into more resources these agents simply consume. This demonstrates that performance can be greater if it evolves to a specific circumstance. NC evolves specifically to consume.

Word of Mouth: This is the same as the previous starting condition and is not surprising.

Stigmergic Style: This is the same as the previous starting condition and is not surprising.

Both Styles: This is the same as the previous starting condition and is not surprising.

The emergence with this starting condition had to do with NC as it evolves it produces fitter agents for consumption than any of the other styles.

8.3.3 100% Resource

Results

	Generations									
Message Passing Style	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	14528	18290	19265	20304	20610	20981	21379	21081	20922	20634
Word of Mouth	14504	12537	8815.3	8531	8947.5	9476	9781.8	10114	10422	10495
Stigmergic	14493	13652	9071	8835.5	8941.8	9101	9168.8	9514.8	9587.5	9828.3
Both Styles	14440	12590	8923.5	9053.3	9222.8	9567.5	9788.8	9942.8	10107	10032

Table 9: Average Fitness Results for the starting conditions "100% Resource" in "Multiple Resource" Scenario

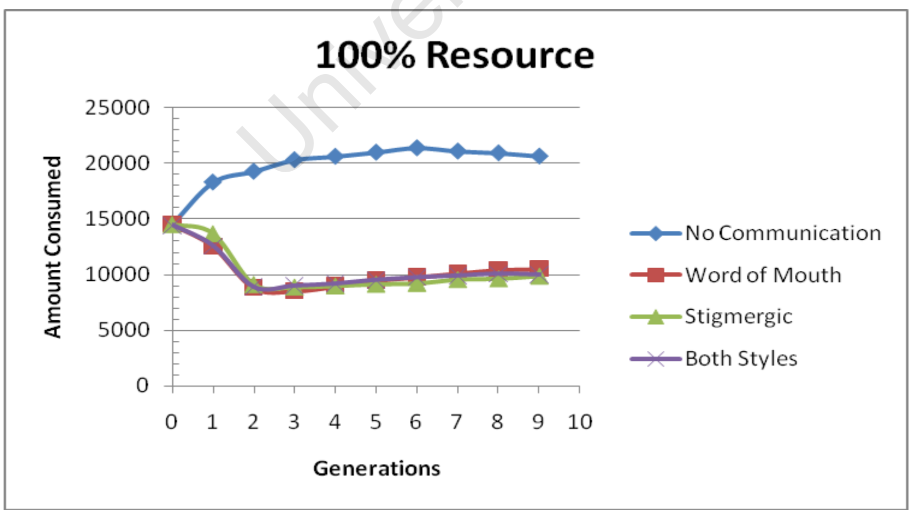

Figure 29: Graph of the different communication styles with the starting condition "100% Resource" in the "Multiple Resources" Scenario

Analysis

No Communication: This had even higher results than the previous starting condition but had lower results than the previous scenario, this could have been due to having to travel further to reach certain resources if the agents did not see a resource on the way to the resource for which they had a message.

Word of Mouth: This is the same as the previous starting condition and is not surprising.

Stigmergic Style: This is the same as the previous starting condition and is not surprising.

Both Styles: This is the same as the previous starting condition and is not surprising.

Emergence is achieved by the EA and had unsurprising surprise since it could be tied back to the EA.

8.4 Single Base and Single Resource

8.4.1 No Message

Results

	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	1241	1488	1710	1981	1582	1766	1763	1651	1748	1539
Word of Mouth	6276	7468	7880	7996	6157	9763	7726	7369	7474	8965
Stigmergic	7824	9113	7361	7199	7179	7510	7871	13331	8564	7649
Both Styles	8814	9206	7986	9316	14096	11947	8620	9711	8687	8331

Table 10: Average Fitness Results for the starting conditions "No Message" in "Single Base and Single Resource" Scenario

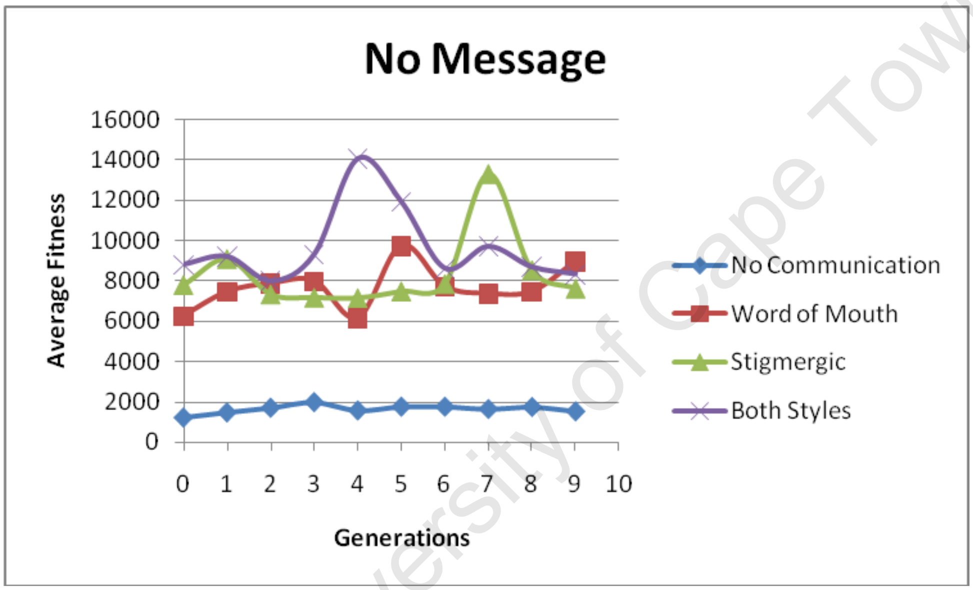

Figure 30: Graph of the different communication styles with the starting condition "No Message" in the "Single Base and Single Resources" Scenario

Analysis

No Communication: This demonstrated very little growth and was very similar to the scenario of a single resource. This was unsurprising.

Word of Mouth: There was an odd dip in the results, which showed a performance decrease before a short increase again and then returned to the same level, this could just be when agents found a base and then did not find a base. It could not be explained.

Stigmergic Style: This had a massive increase suddenly for generation 7. This was unsurprising surprise as it could be explained by the agents bumping into the base and spreading the message of its location quickly before the lifespan of the agents ran out.

Both Styles: This had more erratic behaviour than SS with higher extremes. The behaviour was put to bumping into the base and the average collection of food units can be seen in appendix A.

There was emergence since the whole (WOM, SS and BS) was greater than the sum of its parts (NC) again with higher average fitness for the communicating styles than the non-communicating one.

8.4.2 20% Resource

Results

	Generations									
Message Passing Style	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	3965	4973	5475	5667	5511	5848	5905	5949	5669	5736
Word of Mouth	13779	12425	14560	9286	21315	12966	13121	10206	25228	17016
Stigmergic	13916	14192	17659	11779	9440	15742	17478	19488	16434	12652
Both Styles	14780	13180	10049	18766	22374	27289	13055	24829	26315	26165

Table 11: Average Fitness Results for the starting conditions "20% Resource" in "Single Base and Single Resource" Scenario

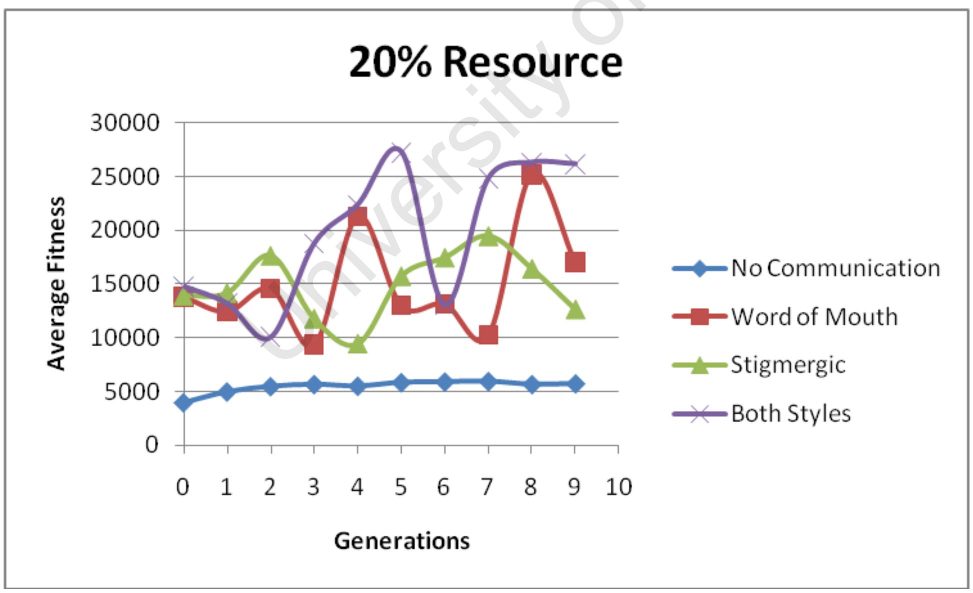

Figure 31: Graph of the different communication styles with the starting condition "20% Resource" in the "Single Base and Single Resources" Scenario

Analysis

No Communication: This style exhibited the same behaviour as a single resource for the same starting condition. Once again, this style was the lowest performer, demonstrating the sum of the parts. This style only has emergence due to the EA.

Word of Mouth: This had sporadic results. We believed it to have been because the agents having a location of a resource had more energy with which to explore and find the base. The behaviour is emergent since the agent level rules does not specify this behaviour in L_1 and had been evolved by the system. The results became increasingly higher when collection occurred.

Stigmergic Style: This had the same sporadic results as WOM but with lower fitness scores for the points where it found a base.

Both Styles: This had the highest results in its swings and its lowest swings were much higher than the lowest swings for the other communication styles.

There was emergence due to the EA but also because there was surprising surprise that the agents managed to find the base by spreading out and walking randomly. This behaviour could have been evolved on purpose to locate the base.

8.4.3 20% Resource and Base

Results

	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	6633	7611	7344	7674	8315	7747	8600	8424	8744	10384
Word of Mouth	24201	43426	76560	103424	119482	130109	127361	134579	137367	131421
Stigmergic	23813	37720	59840	79801	90746	103328	103804	106184	107067	106443
Both Styles	24967	44445	77626	100955	113207	130422	130596	136074	136337	133892

Table 12: Average Fitness Results for the starting conditions "20% Resource and Base" in "Single Base and Single Resource" Scenario

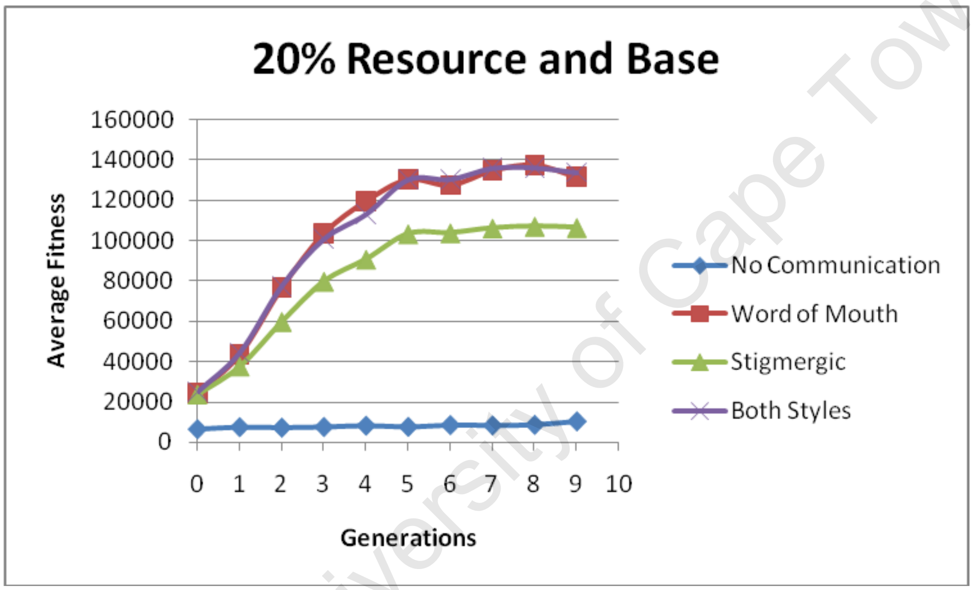

Figure 32: Graph of the different communication styles with the starting condition "20% Resource and Base" in the "Single Base and Single Resources" Scenario

Analysis

No Communication: This had higher scores than the starting conditions 20% Resource, even though there should be no real difference, which implies that there was some collection happening amongst this group of agents.

Word of Mouth: This shows the advantage of evolving to meet multiple aspects of fitness, as the scores are considerably higher than the scenarios seen so far. The growth has to do with agents being able to collect food units. The emergence is due to the EA and does not exhibit behaviour that would be considered surprising surprise but merely unsurprising surprise.

Stigmergic Style: This is the same sort of growth as was seen in WOM but with a lower fitness as the generations continue depicting that SS was not as good as WOM at passing messages of the base.

Both Styles: This had a similar evolutionary path as WOM but towards the peak of its growth, it dropped below WOM and at the height, it went above WOM.

The scores for this starting condition were much higher than previously seen. The highest before was 25 000 now it is closer to 140 000. There was emergence since the whole (WOM, SS and BS) was greater than the sum of the parts (NC). The one surprising aspect was how much lower SS was compared to WOM and BS.

8.4.4 20% Resource and 20% Base

Results

	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	3982	5139	5269	5694	5909	5942	6101	5919	6683	6173
Word of Mouth	23865	43940	75834	98495	119046	122637	131040	135750	135919	139332
Stigmergic	23504	36768	61920	78482	92836	100728	96112	105636	101830	110628
Both Styles	25185	44590	78416	98750	117708	122826	131664	126556	128860	133618

Table 13: Average Fitness Results for the starting conditions "20% Resource and 20% Base" in "Single Base and Single Resource" Scenario

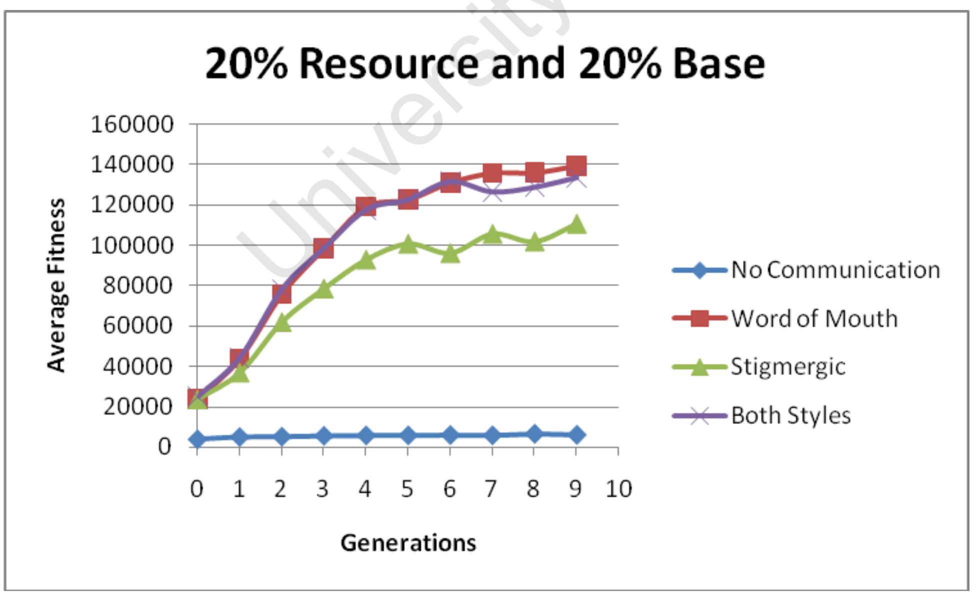

Figure 33: Graph of the different communication styles with the starting condition "20% Resource and 20% Base" in the "Single Base and Single Resources" Scenario

Analysis

No Communication: The scores for this style went down from the starting conditions 20% Resource and Base but were higher than that of just 20% Resource. This could have to do with the agents with messages of a base stumbling upon a resource and proceeding to collect food thus improving the scores.

Word of Mouth: This had similar scores as BS until generation 7 where it diverged and was even higher than BS. This was surprising as it should not have been able to find messages faster than Both Styles.

Stigmergic Style: This had a similar evolution to the previous starting conditions, with slightly more oscillating toward its higher points. It was lower than the other two communicating styles (WOM and BS).

Both Styles: This style should have been much higher than the others having advantages of both message styles. It must have been predominantly using the direct message passing that WOM used to be able to achieve the same sort of results as WOM but the fact that it used stigmergy as well may have caused it to lose efficiency towards the end of the generations.

The emergence that was achieved showed the whole to be greater than the sum of the parts for this starting condition. The communicating styles achieved higher fitness values than that of NC and are deemed to be emergent.

8.5 Single Base and Multiple Resources

8.5.1 No Message

Results

	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	5926	8199	8321	7647	8665	8843	8819	8619	9006	9063
Word of Mouth	20884	37436	61573	84313	93661	89465	96306	94276	89045	93622
Stigmergic	20978	35991	58364	69748	84159	78820	92159	89726	87746	95780
Both Styles	24451	49881	59417	98653	102024	104397	108009	106942	105523	113908

Table 14: Average Fitness Results for the starting conditions "No Message" in "Single Base and Multiple Resource" Scenario

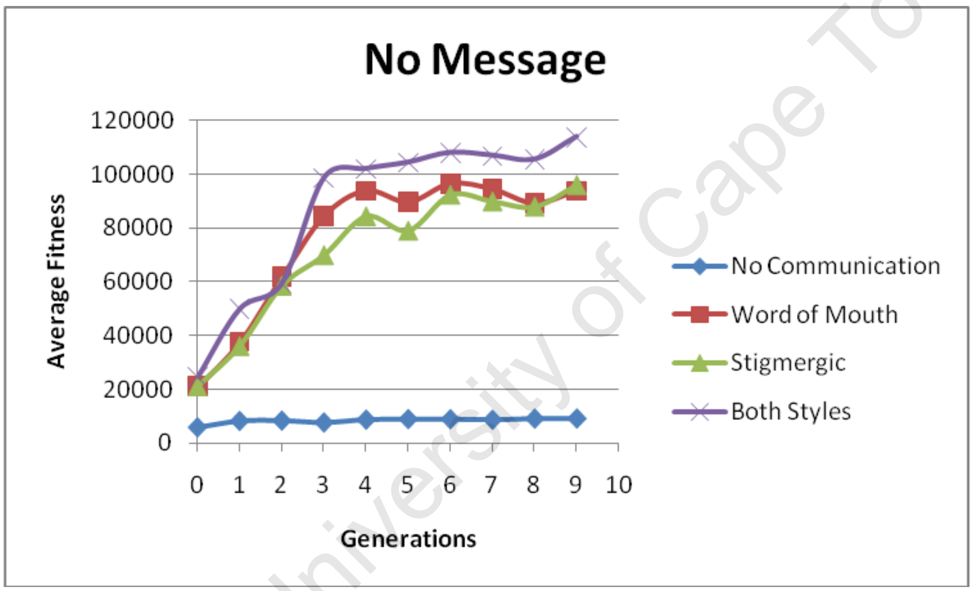

Figure 34: Graph of the different communication styles with the starting condition "No Message" in the "Single Base and Multiple Resources" Scenario

Analysis

No Communication: This had the same sort of trend as in the Multiple Resources scenario, which was unsurprising, since the agents were evolved to consume resources and would bother with very little collection.

Word of Mouth: There is considerable growth in this scenario with this starting condition compared to the Single Base and Single Resource scenario with the same starting condition. The more resources that were added to the environment allowed the agents more time to search for the base and once found allowed for collection by the agents. With this starting condition and scenario, however WOM did not score higher than BS.

Stigmergic Style: This was the same general behaviour as WOM but was the worst scoring out of the communicating styles.

Both Styles: This style had the highest performance in this scenario and showed marked improvement over the same conditions that came before.

There was emergence since the whole was greater than the sum of its parts. NC had emergence only due to an EA being emergent and becoming more streamlined in its behaviour.

8.5.2 20% Resource

Results

	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	7857	10006	10312	10737	11208	10946	11207	11440	11380	11067
Word of Mouth	17530	36082	54384	70955	68492	83667	72021	86261	89600	94547
Stigmergic	18060	28102	39534	57858	67347	74021	81472	83826	84930	79291
Both Styles	19736	26562	53489	68587	66367	78234	83822	96307	91326	97712

Table 15: Average Fitness Results for the starting conditions "20% Resource" in "Single Base and Multiple Resource" Scenario

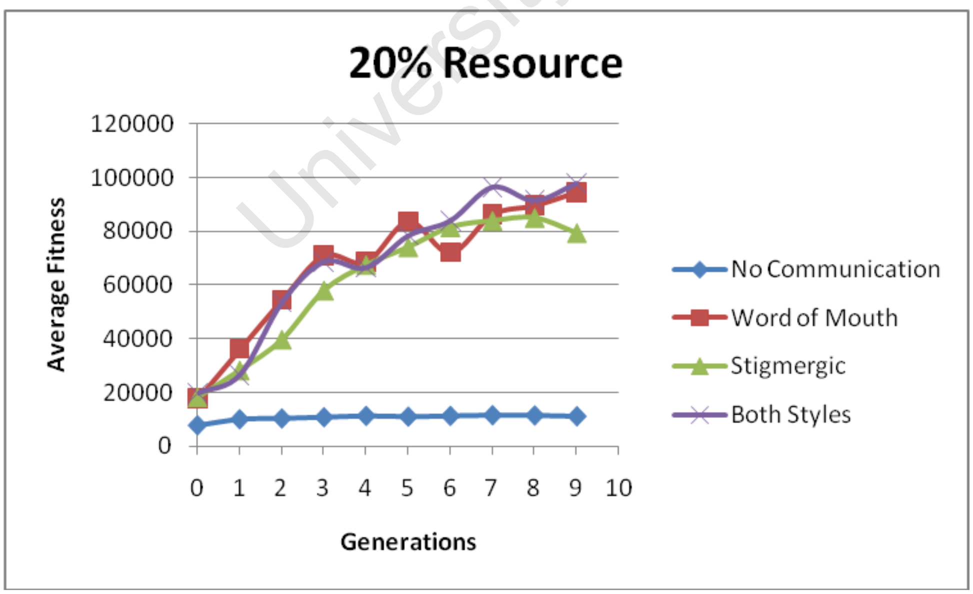

Figure 35: Graph of the different communication styles with the starting condition "20% Resource" in the "Single Base and Multiple Resources" Scenario

Analysis

No Communication: This had the similar results to the scenario Multiple Resources; this is unsurprising, as nothing had really changed for the NC agents.

Word of Mouth: This is far less chaotic than the scenario Single Base and Single Resource; this could have been because the agents have more time to find the base than they had in the previous scenario. This behaviour of looking for the base amongst the whole group was emergent since there is no correlation to the design as to why they would evolve necessarily this way and how they go about this behaviour.

Stigmergic Style: This had the least disturbance to its evolution as it had a continuous rise in efficiency, which tapered off. Compared to the previous scenario this was almost as high as the other two communicating styles.

Both Styles: This style had the highest efficiency out of the communicating styles but was subject to disturbances in its efficiency growth. This could be due to the random nature of finding a base and its ability to exploit such a find.

The emergence among the communicating styles is the whole (WOM, SS and BS) is greater than the sum of its parts (NC). The ability of WOM and BS to exploit a base whenever it was found was also emergent and was not depicted by the language L_1.

8.5.3 20% Resource and Base

Results

	Generations									
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
No Communication	10826	11936	12862	12871	13795	13417	13026	13396	14258	15166
Word of Mouth	27223	52057	79147	101456	111919	123213	126052	125749	125323	132460
Stigmergic	27405	44655	72422	84117	100539	105978	109887	111404	111826	116946
Both Styles	28521	51287	81426	96771	110635	117117	125059	117887	118251	121987

Table 16: Average Fitness Results for the starting conditions "20% Resource and Base" in "Single Base and Multiple Resource" Scenario

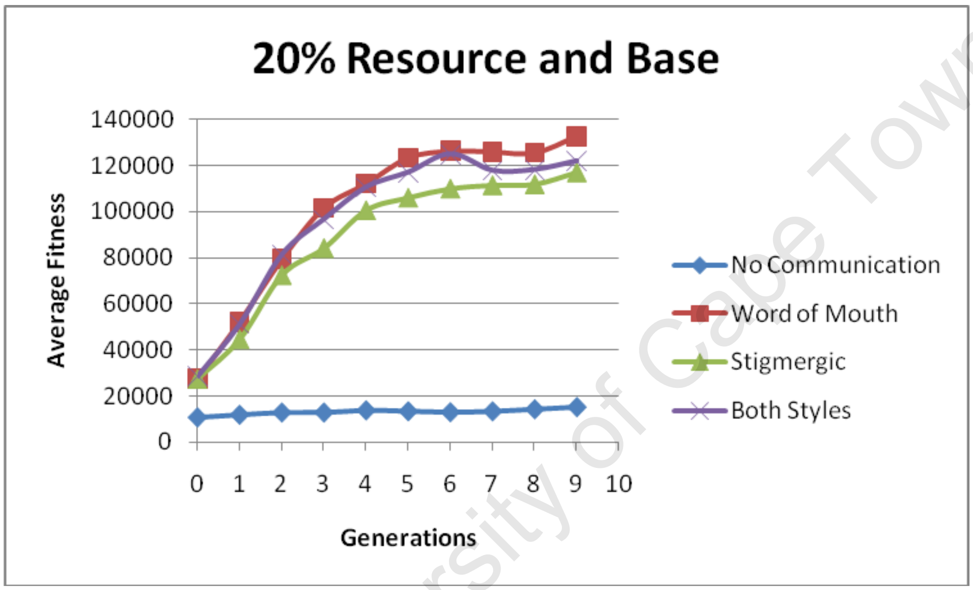

Figure 36: Graph of the different communication styles with the starting condition "20% Resource and Base" in the "Single Base and Multiple Resources" Scenario

Analysis

No Communication: This particular set of starting conditions had the highest scores for NC. This could have occurred due to the multiple resources that it can stumble upon giving the style its normal score and the agents that have both messages would collect resources thus improving the score. It however is not enough to compete with the other styles.

Word of Mouth: Since there were messages of a base, WOM outperformed the other styles allowing it to reach higher efficiency.

Stigmergic Style: This had a similar growth as WOM or BS but with lower scores showing that stigmergy did not do as well at communicating messages amongst the agents. It was however consistent in its growth compared to the swings of the other styles.

Both Styles: This style was close to WOM in its scores and behaviours but could not quite match WOM in the last few generations.

Emergence is shown by the whole being greater than the sum of its parts.

8.5.4 20% Resource and 20% Base

Results

	Generations									
	0	1	2	3	4	5	6	7	8	9
No Communication	9039	11618	11314	12473	11750	12059	12876	11751	12622	12301
Word of Mouth	27141	48214	75439	95275	110653	119486	120560	123265	119009	128110
Stigmergic	25542	43543	67564	83042	96895	95651	107261	99531	104421	106493
Both Styles	27647	50553	73592	93983	116251	113203	117065	120255	118366	123902

Table 17: Average Fitness Results for the starting conditions "20% Resource and 20% Base" in "Single Base and Multiple Resource" Scenario

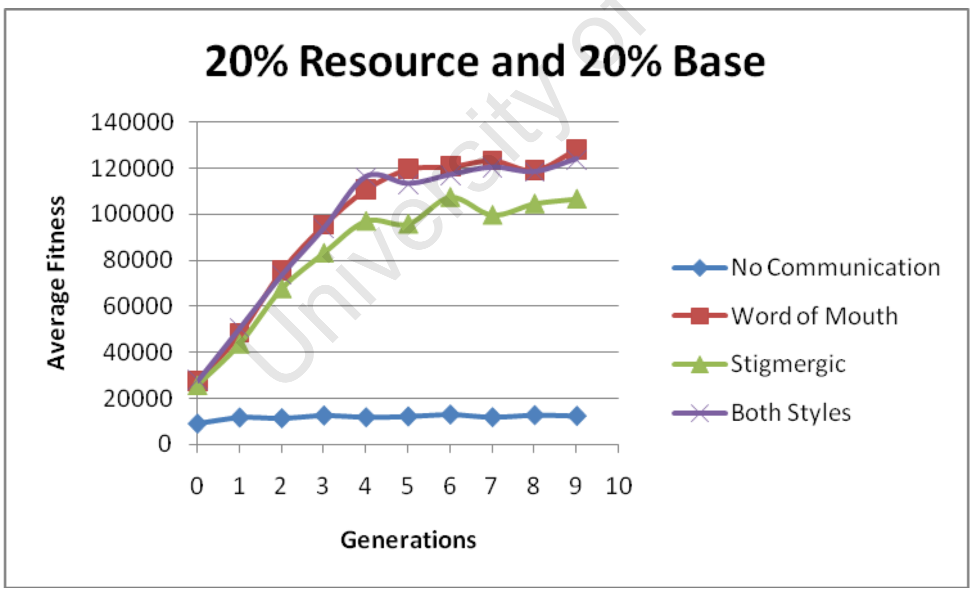

Figure 37: Graph of the different communication styles with the starting condition "20% Resource and 20% Base" in the "Single Base and Multiple Resources" Scenario

Analysis

No Communication: This was similar in behaviour to the scenario Single Base and Single Resource and the same starting conditions behaviour but with more agents finding resources. Simply because there were more of these resources to find this caused the scores to be higher than that of the previous scenario. It was lower than the starting condition run 20% Resource and Base in the same scenario as itself showing that collection influenced it far more greatly.

Word of Mouth: This showed again that it could produce the highest results and adapted quickly to being able to distribute messages of locations.

Stigmergic Style: This was the lowest performer out of the communicating styles. It dipped and climbed once it reached a plateau. This could not be explained in the behaviour of the agent using L_1.

Both Styles: This style managed to evolve as quickly as WOM but towards the end of the generation, it could not keep up with its efficiency and dropped slightly below that of WOM. This behaviour was surprising.

Emergence was achieved by WOM, SS and BS being higher in their performance at collecting from resources. This was unsurprising surprise as it can be explained as to why it would do such a thing.

8.6 Observed Emergent Behaviour

There were many behaviours exhibited by the agents in the simulation runs. Some of the more interesting ones are mentioned here in order to provide an example of emergence.

The surprise with Word of Mouth was the number of times it was higher than both Both Styles and Stigmergic. The spread of messages using this message style is impressive as illustrated in Figure 38, Figure 39, Figure 40 and Figure 41 below.

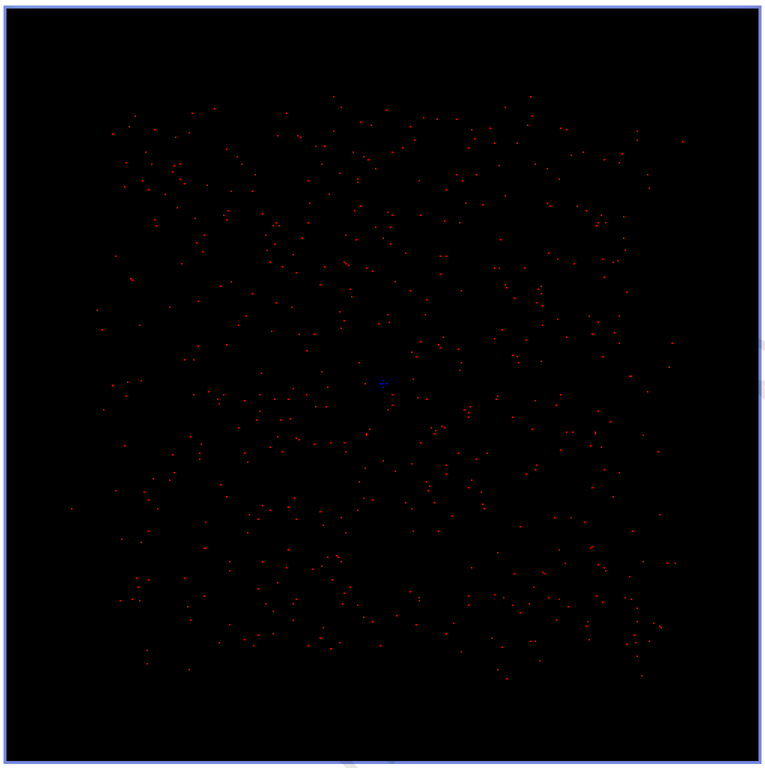

Figure 38: Scenario with one resource (Blue dot in the middle) surrounded by agents with no message (red dots) at time step 44

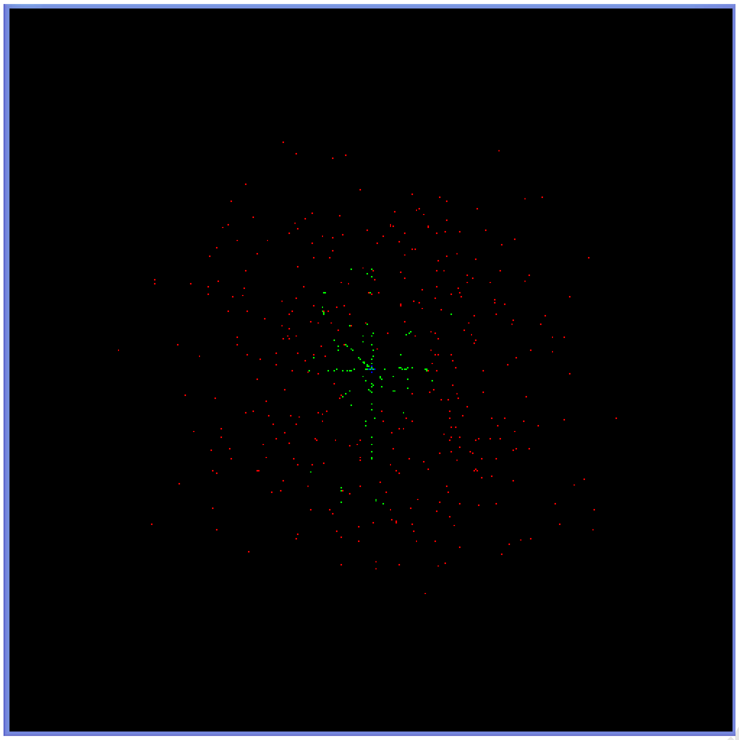

Figure 39: Scenario with one resource (Blue dot in the middle) surrounded by agents with no message (red dots) at time step 390

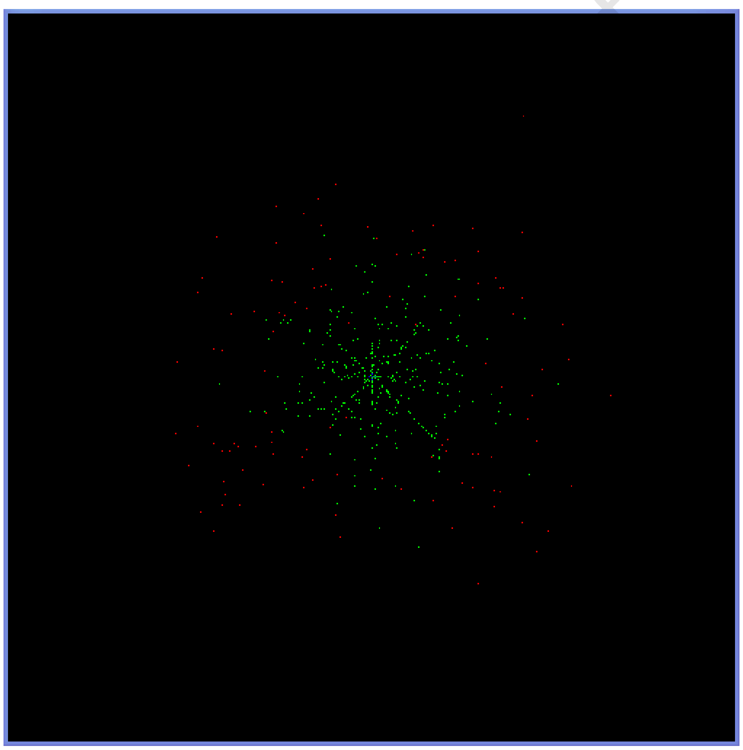

Figure 40: Scenario with one resource (Blue dot in the middle) surrounded by agents with no message (red dots) at time step 618

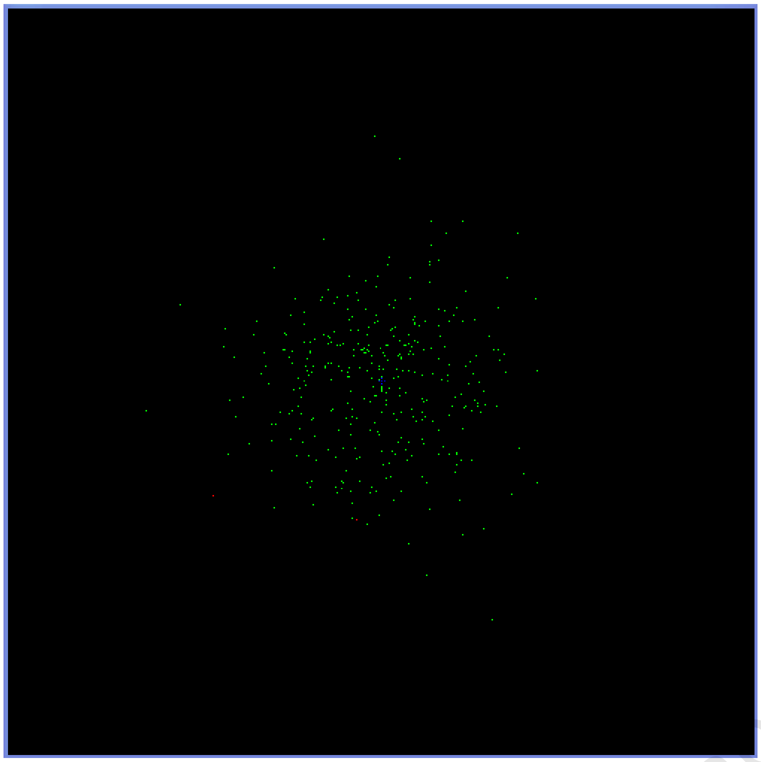

Figure 41: Scenario with one resource (Blue dot in the middle) surrounded by agents with no message (red dots) at time step 924

This is very virus like in its behaviour, infecting agents with a message but to the agent's benefit instead of its detriment.

One of the more interesting behaviours exhibited by the agents is the highway(s) that were formed between the resource(s) and the base. After a certain point the agents start to move off and spread out. This caused more spread of the message to other agents; this is illustrated in Figure 42 and Figure 43 below.

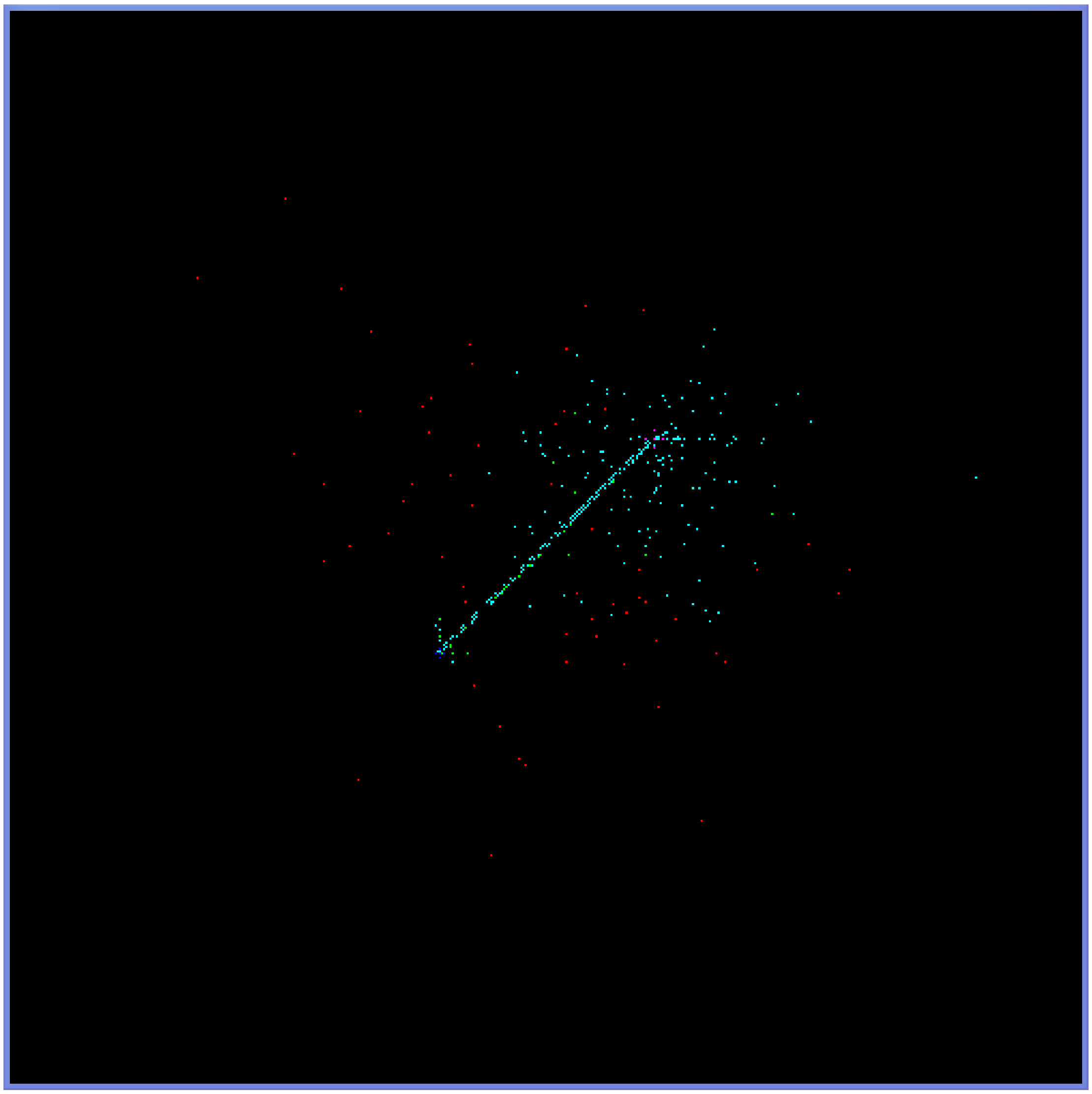

Figure 42: Scenario of Single Base (purple dot) and Single Resource (blue dot), with agents with no message (red dots), message of a resource (green dots) and message of a base (light blue dots). This has the emerging behaviour of spreading out after aquiring enough energy, and spreading the message of where the resource and the base is located

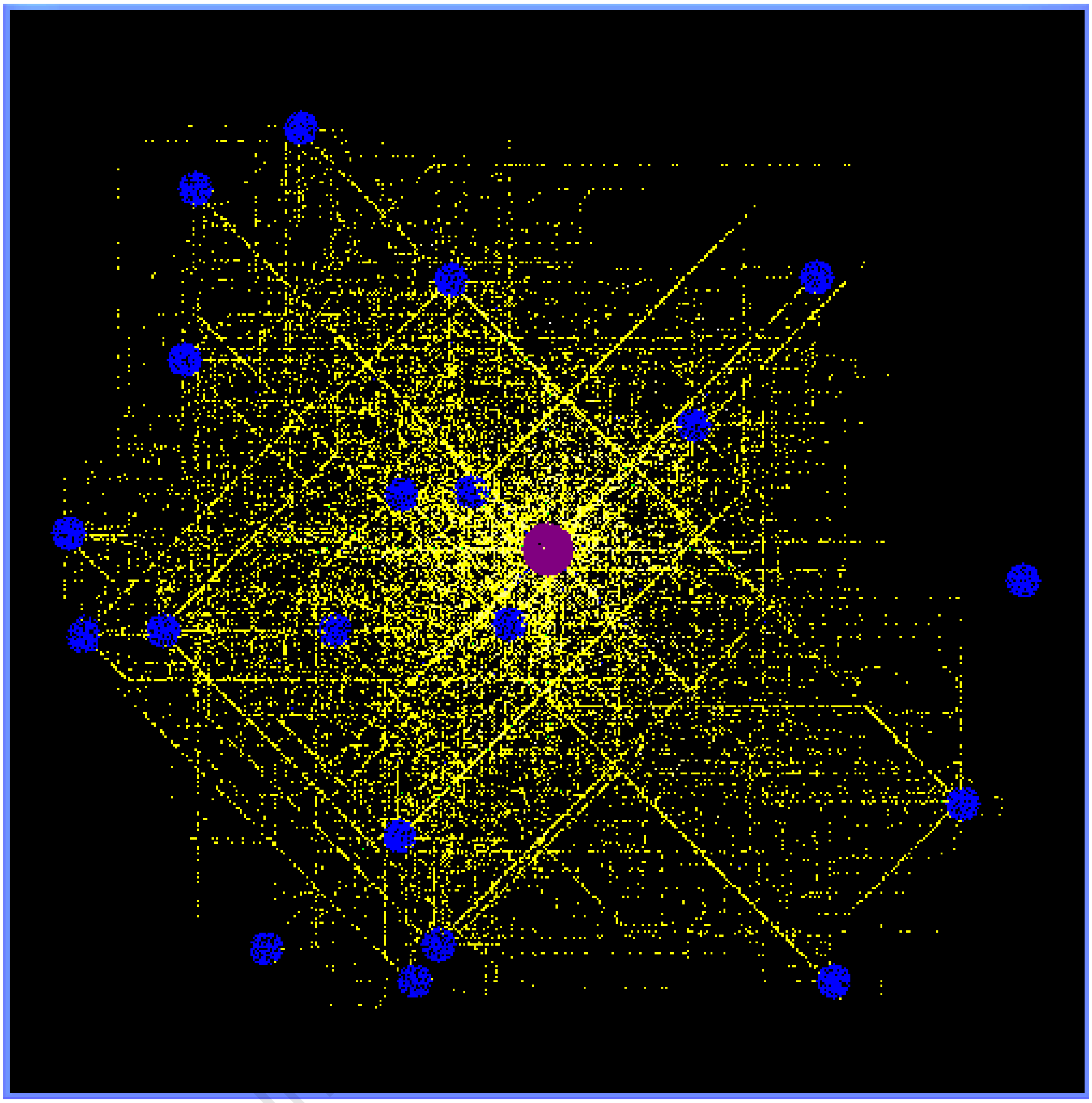

Figure 43: Scenario Single Base (purple dot) and Multiple Resources (blue dots) with landscape messages (yellow dots). This has emerging highways that are caused by the agents

This was emergent since the highways emerge just by the dropping of messages by the agents. There was a great density of messages around the base in Figure 43. This was emergent since it was not expected for the agents to achieve such clear highways.

8.7 Conclusion

	Generations				
	Gen 0	**Gen 1**	**Gen 2**	**Gen 3**	**Gen 4**
No Communication	98738	123613	129063	134885	138874
Word of Mouth	242574	352861	496888	620812	703431
Stigmergic	242173	327551	436790	522643	600002
Both Styles	259035	363192	496071	639295	717353
	Gen 5	**Gen 6**	**Gen 7**	**Gen 8**	**Gen 9**
No Communication	138635	141229	139155	143226	141893
Word of Mouth	746808	751885	777336	790705	807294
Stigmergic	634067	669208	683414	678400	692551
Both Styles	762674	775766	797200	794009	819478

Table 18: Sum of all fitness scores over the scenarios

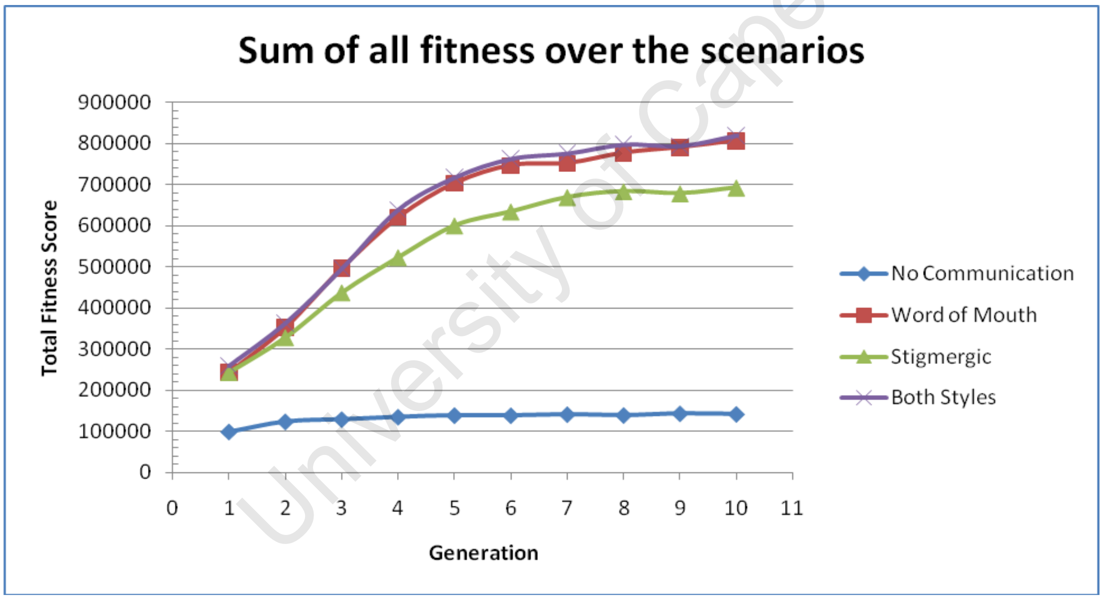

Figure 44 Graph of the sum of all fitness scores over the scenarios

This shows that overall Both Styles was the most efficient style, followed closely by Word of Mouth, then Stigmergy Style and lastly No Communication. This showed a huge discrepancy between Word of Mouth and Stigmergic Style highlighting that stigmergy might not be as profound as thought.

All communicating styles achieved emergence, by the whole being greater than the sum of all the parts, demonstrated most clearly by the graph in Figure 44, where No Communication was the worst performer of the four and the others being significantly higher in their efficiency. The different styles reacted in different ways causing an increase in efficiency of differing levels. This was based on how well the message was spread.

Conclusion

Chapter 9 Conclusion and Future Work

This chapter concludes the dissertation by giving a summary of the research done and the main results for the testing of the design. In addition, we suggest a few paths for further research.

9.1 Summary of the Research Done

The background section describes communication, emergence and the techniques of genetic algorithms. This provides a foundation for the design of agents to use the communication types and to test whether they are emergent.

In the design section, we create a model of a simple environment and agents. These agents have different styles of communication that apply. The agents attempt to achieve the goals of consumption and collection of resources. This provides them with a reward of energy, allowing them to live longer. The design of the agents is considered L_1 in terms of the emergence test.

We use a genetic algorithm to breed new generations of agents by combining agents that have performed well in achieving the goals set. This causes higher levels of performance by the groups of agents. A genetic algorithm is a subset of evolutionary algorithms. The difference between these two techniques is that evolutionary algorithms use natural selection whereas genetic algorithms find the best solutions and breed those agents.

We then record the results from running tests using different scenarios and starting conditions – we consider this to be L_2 in terms of the emergence test. We then test the results for emergence, by using the test given in section 3.3 , in order to determine that group behaviour is occurring. This is done because of the difficulty of monitoring a large number of interactions that occur in group communication. This is done instead of trying to use expensive and time-consuming testing software.

Below, we examine whether the research achieves its goals.

9.2 Achievement of Research Goals

- Can a large group of simplistic machines by communicating with each other be more efficient at collecting and finding resources than machines that do not communicate?
  The agents that communicated with each other were far more efficient at achieving goals than the agents that had no communication. This was unsurprising but was demonstrated adequately.

- Which type of communication is the most efficient in a large group at collecting and consuming resources?
  We ranked the types of communication on fitness score and found which were better overall for achieving two tasks: consumption and collection. There was an emphasis on collection since it was an indirect task and was not as easily accomplished as consumption.

- Can different types of communication cause group behaviour or emergence to happen?
  Emergence was shown to happen amongst communicating agents, since the whole was greater than the sum of its parts. The whole were the communicating agents and the sum of the parts was the non-communicating agents.

- Will a genetic algorithm cause an increase in efficiency of communicating agents?
  The genetic algorithm caused the agents to become far more efficient even with a dumb brain with a small number of characteristics being able to change. The efficiency gained was almost four hundred percent.

9.3 Summary of Results

The highest performing communication type for this simulation and scenarios was Both Styles, followed closely by Word of Mouth. The Stigmergic Style was much further down in its efficiency but still much higher than the No Communication style. The efficiencies are illustrated in a graph (Figure 44) that is at the end of Chapter 8, detailing the total fitness over all the scenarios for the different communication types.

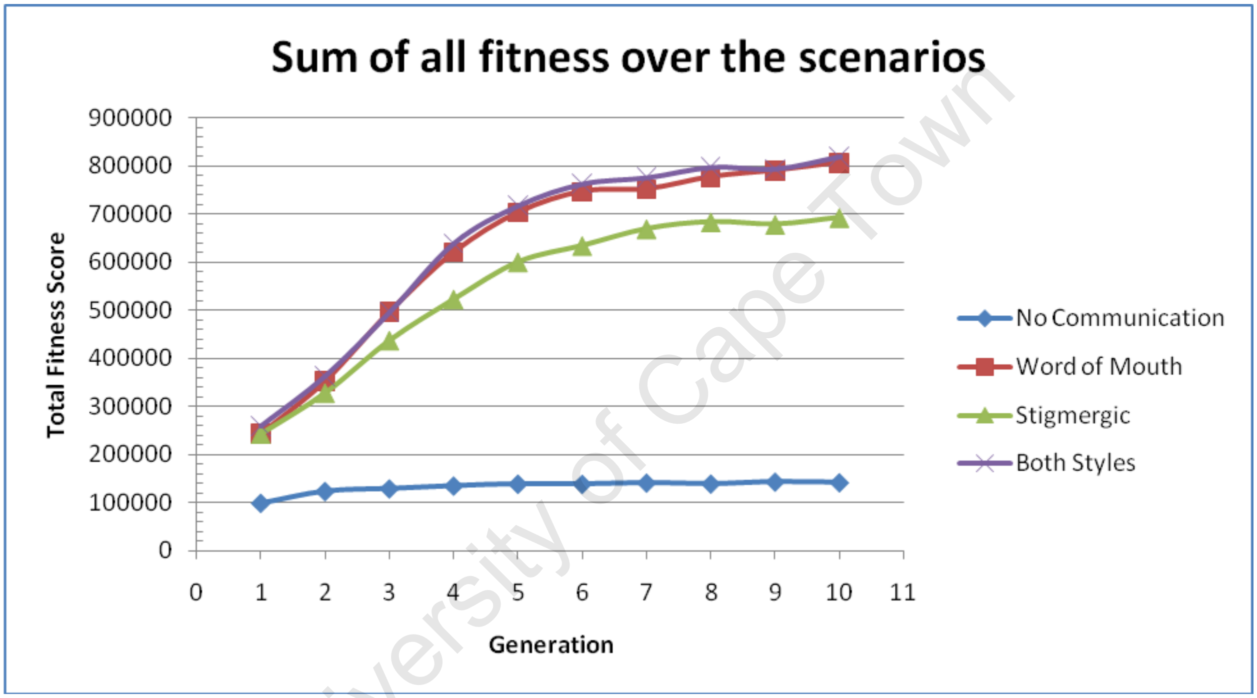

Figure 44 Graph of the sum of all fitness scores over the scenarios

9.4 Contributions of the Research

This research contributed to the communication field, artificial life and genetic algorithms. It compares these different communication types and evaluates a design regarding emergence. This can be directly applied to fields such as:

- Marketing, allowing for better understanding of group dynamics;
- Gaming, making use of these different communication styles in order to produce a more immersive world;
- Effective router communication, changing routers depending on the loads and types of communication received;

- Robotics, demonstrating effective communication amongst swarms, such as NASA's robots in space;
- Swarm intelligence, swarms can become more efficient using a genetic algorithm is demonstrated once again to work well.

9.5 Future Work

The paths that this research can be taken further are:

- Adding the ability to give false information and to be sceptical about a message;
- To allow a more in-depth stigmergy model with proper pheromone trails and to see if this makes a bigger difference;
- Testing the different communication styles when in direct competition with each other;
- Testing with larger and smaller populations;
- Allowing the agents to live longer;
- Creating more elaborate scenarios such as walls;
- Adding predators to the simulation;
- A better analysis of how the messages spread;
- Better resource model;
- Creating a more flexible brain for the agents possibly using neural networks or genetic programming;
- Allowing the agents multiple actions such as fighting and defending;
- Allowing for a heavier load to be carried through the cooperation of multiple agents.

9.6 Concluding Remarks

In this research, significant progress was made in the understanding of how stigmergy and word of mouth communication occurs in large groups. It is hoped that this research will inspire others to pursue this problem and research even more thoroughly.

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Appendix A

Single Resource

Consumed

Starting Conditions
No Message

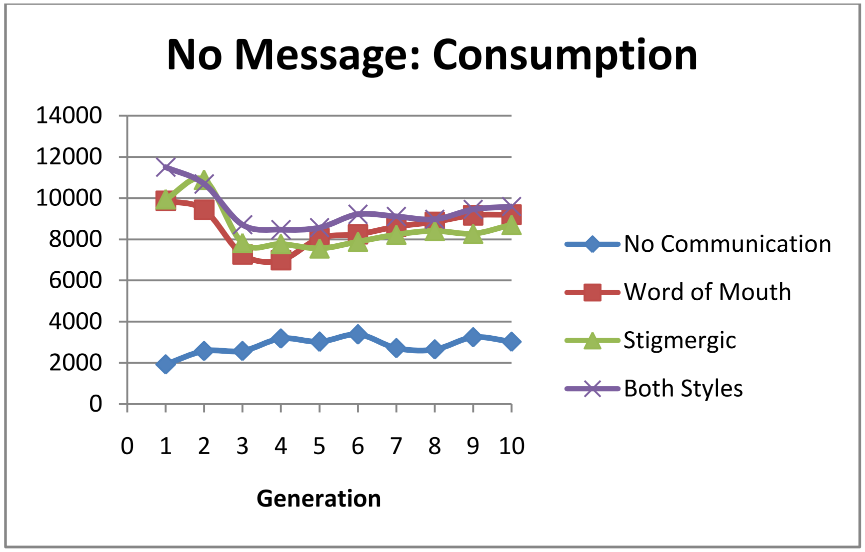
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	1916	2571	2574	3180	3015	3374	2715	2647	3242	3019
Word of Mouth	9868	9434	7264	6978	8054	8236	8612	8834	9162	9192
Stigmergic	9940	10883	7823	7765	7553	7881	8228	8399	8267	8697
Both Styles	11496	10683	8701	8465	8563	9210	9098	8969	9447	9590

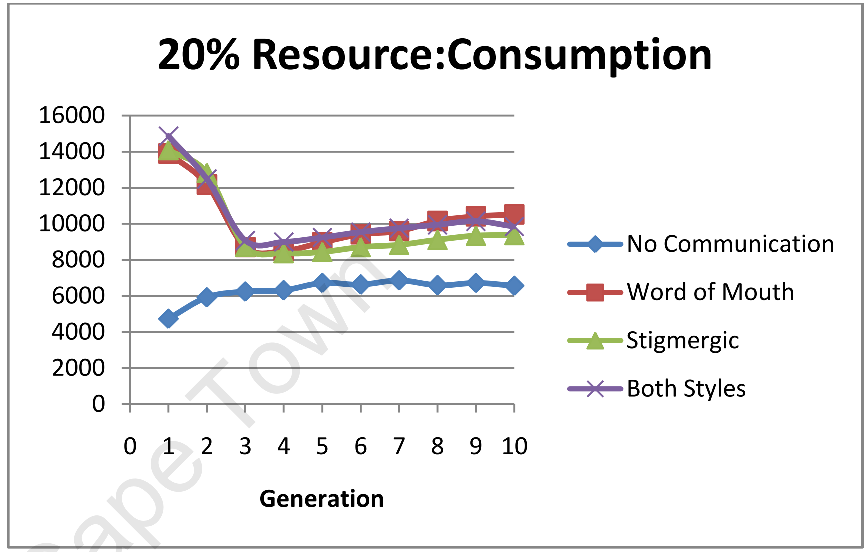
Starting Conditions
20% Resource

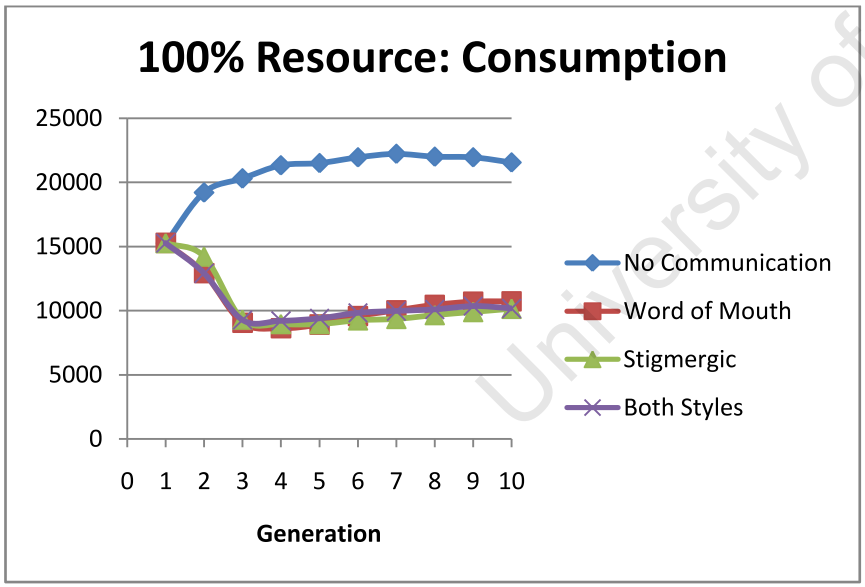
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	4727	5922	6245	6300	6724	6622	6856	6585	6721	6564
Word of Mouth	13895	12175	8712	8491	8963	9411	9593	10153	10406	10521
Stigmergic	14080	12821	8727	8370	8434	8708	8835	9105	9334	9370
Both Styles	14851	12478	9067	8984	9233	9538	9753	9938	10133	9840

Starting Conditions
100% Resource

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	15267	19212	20296	21330	21504	21945	22222	21999	21946	21549
Word of Mouth	15279	12927	9055	8625	8915	9584	10022	10455	10701	10725
Stigmergic	15266	14222	9298	8951	8950	9235	9351	9655	9884	10136
Both Styles	15261	12910	9273	9208	9408	9829	9964	10091	10353	10161


No Message: Consumption
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource:Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


100% Resource: Consumption
25000
20000
15000
10000
5000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles

Multiple Resources **Consumed**

Starting Conditions
No Message

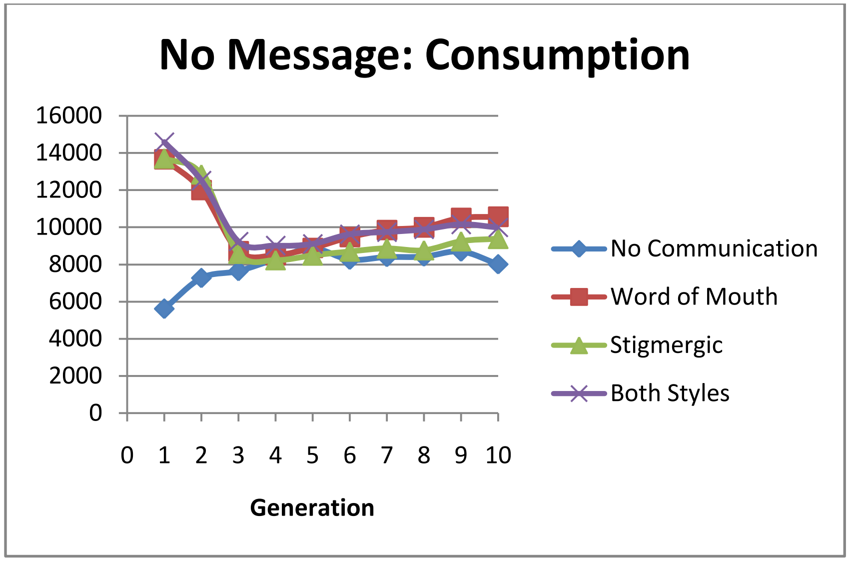
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	5603	7262	7635	8288	8869	8254	8392	8418	8687	8010
Word of Mouth	13655	12000	8702	8500	8883	9473	9855	9998	10500	10563
Stigmergic	13701	12841	8579	8231	8479	8695	8862	8765	9251	9374
Both Styles	14579	12509	9229	9014	9103	9628	9739	9886	10154	9988

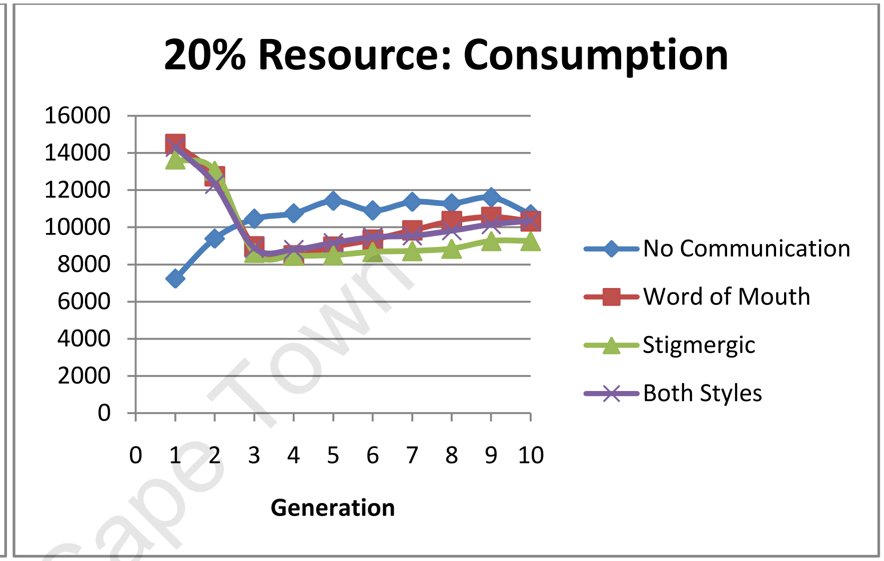
Starting Conditions
20% Resource

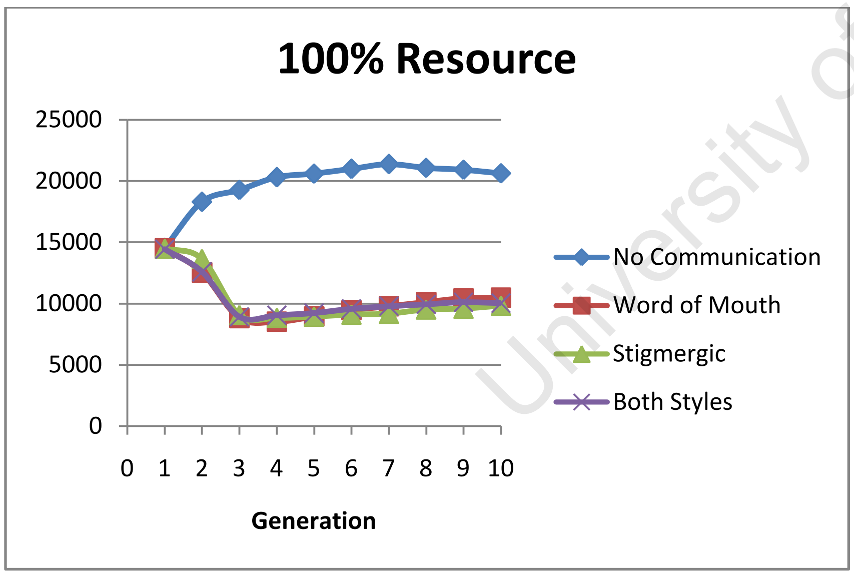
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	7230	9387	10442	10742	11418	10893	11369	11278	11599	10688
Word of Mouth	14477	12740	8964	8489	8945	9324	9835	10327	10552	10326
Stigmergic	13651	13051	8627	8468	8502	8670	8722	8849	9259	9266
Both Styles	14307	12320	8879	8791	9163	9466	9538	9816	10151	10354

Starting Conditions
100% Resource

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	14528	18290	19265	20304	20610	20981	21379	21081	20922	20634
Word of Mouth	14504	12537	8815	8531	8948	9476	9782	10114	10422	10495
Stigmergic	14493	13652	9071	8836	8942	9101	9169	9515	9588	9828
Both Styles	14440	12590	8924	9053	9223	9568	9789	9943	10107	10032


No Message: Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource: Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


100% Resource
25000
20000
15000
10000
5000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles

Single Base and Single Resource **Consumed**

Starting Conditions
No Message

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	1241	1488	1710	1981	1582	1766	1763	1651	1748	1539
Word of Mouth	6258	7418	5550	6126	6057	6843	6551	7079	6589	6890
Stigmergic	7728	8733	6596	5824	5994	6600	6251	7111	6834	7259
Both Styles	8798	8951	6831	6981	7431	7812	7625	7806	7852	7546

Starting Conditions
20% Resource

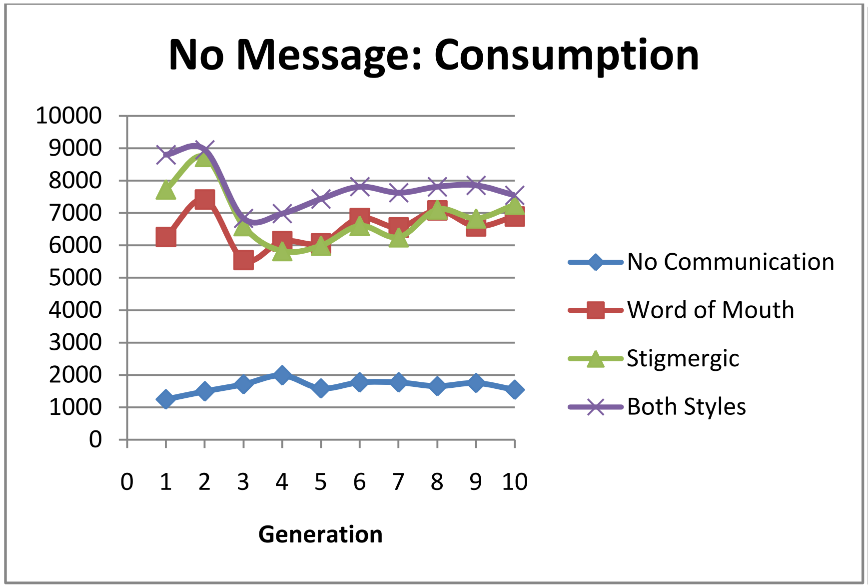
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	3963	4973	5375	5667	5511	5848	5905	5949	5669	5686
Word of Mouth	13485	11590	8415	7946	8555	8906	9266	9706	9783	9896
Stigmergic	13912	13287	9004	8479	8310	8717	8868	9288	9224	9292
Both Styles	14780	12510	9109	9146	9374	9804	9875	10084	10015	10180

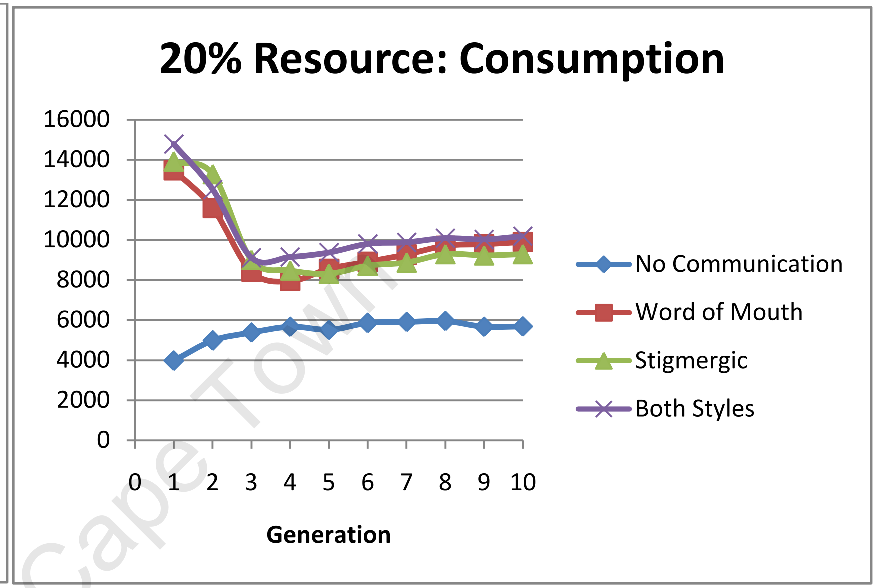
Starting Conditions
20% Resource and Base

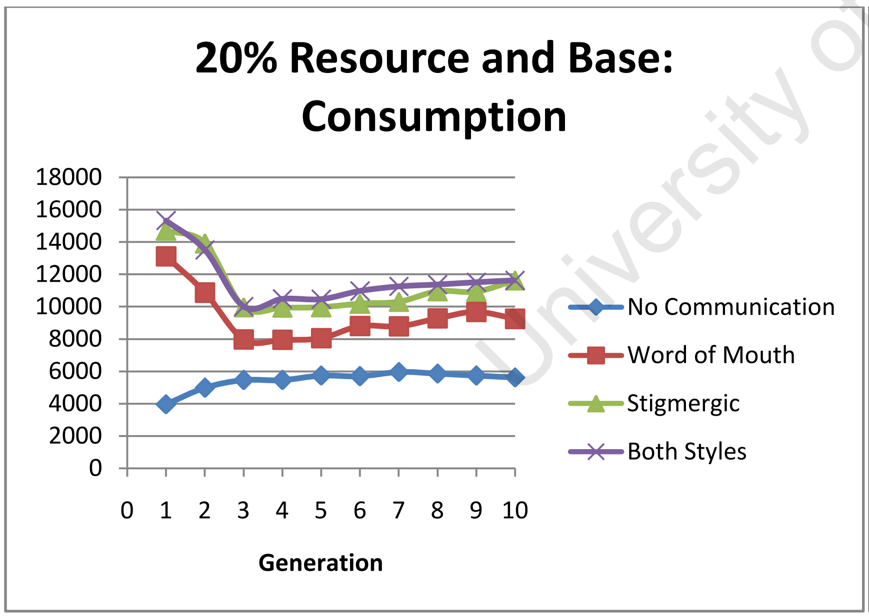
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	3947	4971	5444	5444	5735	5682	5955	5849	5724	5614
Word of Mouth	13117	10866	7965	7944	8052	8794	8781	9279	9672	9241
Stigmergic	14713	13915	9970	9946	9971	10188	10299	10949	10932	11628
Both Styles	15321	13510	10001	10475	10462	10962	11246	11364	11512	11617

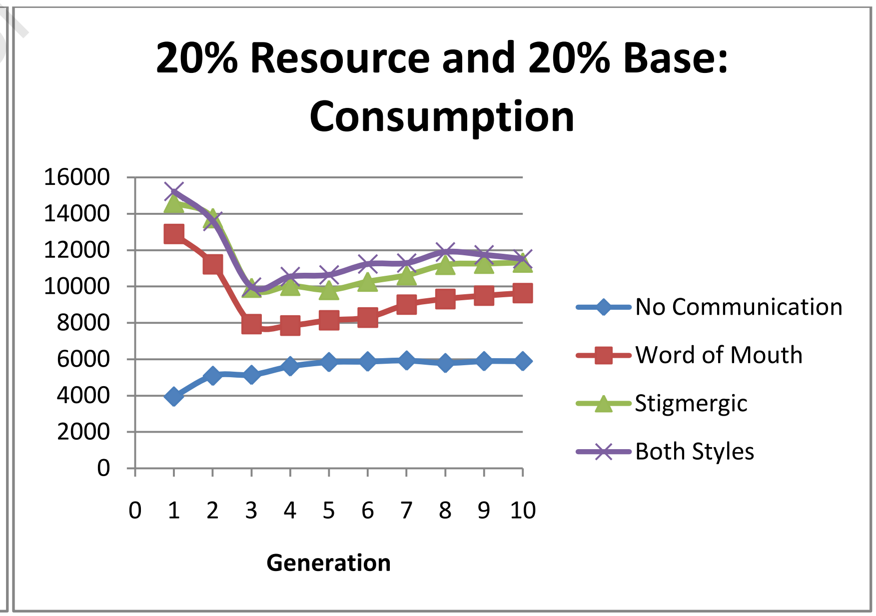
Starting Conditions
20% Resource and 20% Base

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	3926	5079	5134	5594	5839	5862	5926	5779	5888	5883
Word of Mouth	12891	11210	7924	7850	8141	8287	9005	9305	9489	9627
Stigmergic	14612	13758	9930	10037	9811	10263	10617	11191	11255	11313
Both Styles	15227	13580	9971	10540	10638	11231	11289	11891	11735	11513


No Message: Consumption
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource: Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource and Base: Consumption
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource and 20% Base: Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles

Single Base and Multiple Resources **Consumed**

Starting Conditions
No Message

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	5674	7764	8081	7617	8610	8613	8819	8369	8796	8783
Word of Mouth	13622	12201	9453	9278	9481	10065	10616	11246	11400	11147
Stigmergic	13684	13161	9124	9223	9089	9265	9474	9826	9851	10485
Both Styles	14467	12841	9867	9843	10284	10792	11074	11242	11573	11173

Starting Conditions
20% Resource

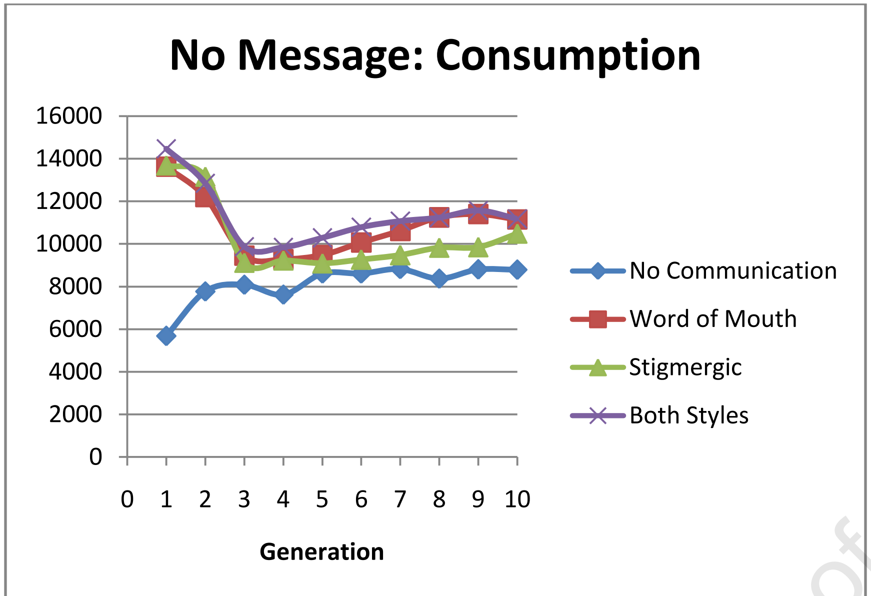
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	7497	9641	9977	10477	11023	10866	11102	11075	11170	10717
Word of Mouth	14320	12987	9079	9025	9397	9947	10296	10911	11335	11472
Stigmergic	13522	13087	8994	8793	8482	9236	9477	9366	9895	9961
Both Styles	14444	12342	9329	9717	9572	9974	10452	10692	10961	10972

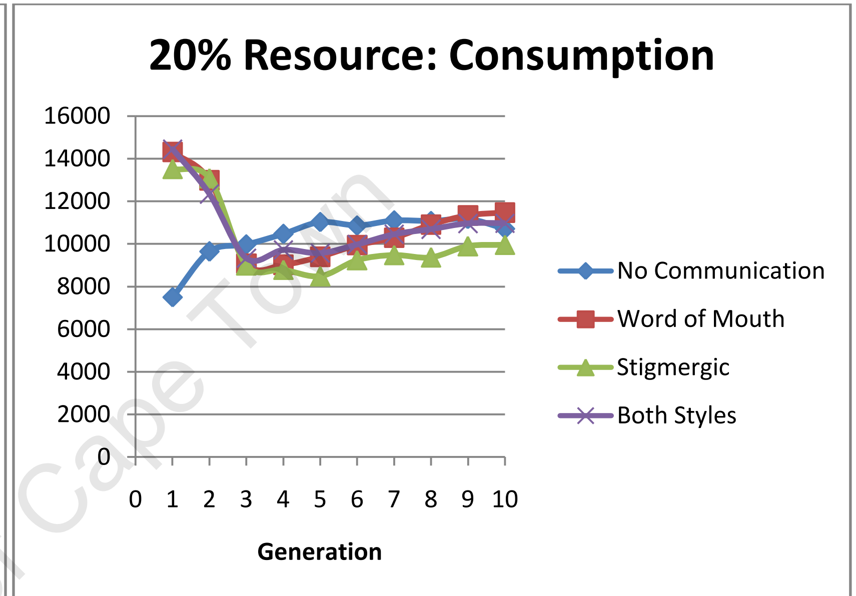
Starting Conditions
20% Resource and Base

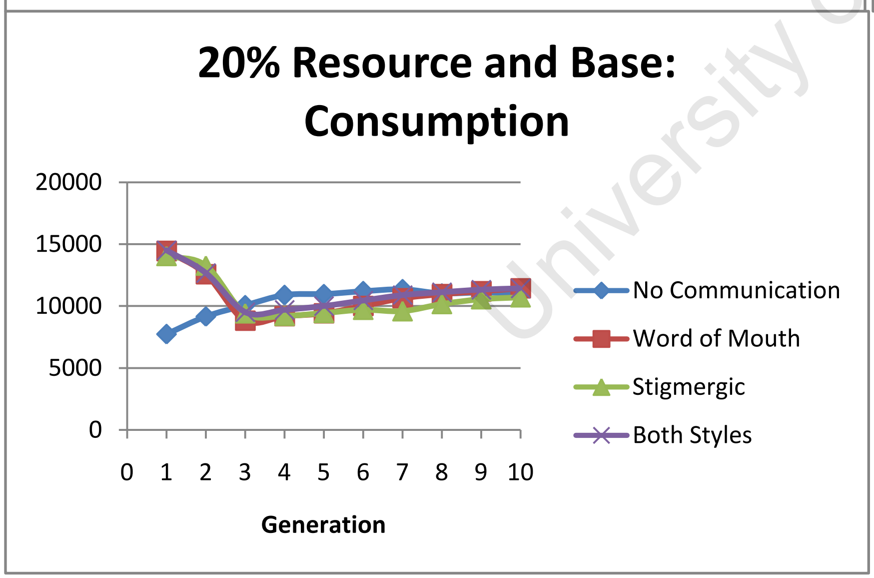
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	7724	9156	10052	10886	10980	11192	11351	11031	11103	11026
Word of Mouth	14453	12582	8832	9196	9419	10008	10642	10964	11193	11430
Stigmergic	14053	13280	9422	9222	9454	9708	9592	10179	10561	10711
Both Styles	14505	12667	9511	9696	10000	10462	10889	11117	11321	11427

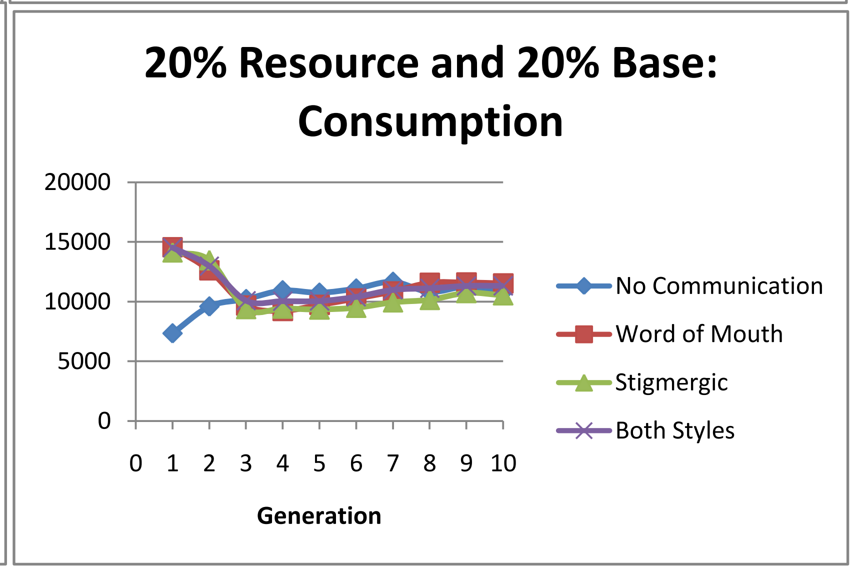
Starting Conditions
20% Resource and 20% Base

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	7345	9603	10209	10928	10755	11094	11666	10811	11257	10816
Word of Mouth	14561	12619	9674	9240	9733	10261	10850	11585	11599	11535
Stigmergic	14122	13473	9389	9422	9345	9491	9951	10146	10726	10528
Both Styles	14523	12983	10082	10043	10056	10403	10985	11125	11321	11327


No Message: Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource: Consumption
16000
14000
12000
10000
8000
6000
4000
2000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource and Base: Consumption
20000
15000
10000
5000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource and 20% Base: Consumption
20000
15000
10000
5000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles

Single Base and Single Resource

Collected

Starting Conditions
No Message

Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
0	0	0	0	0	0	0	0	0	0
1	3	117	94	5	146	59	15	44	104
5	19	38	69	59	46	81	311	87	20
1	13	58	117	333	207	50	95	42	39

Starting Conditions
20% Resource

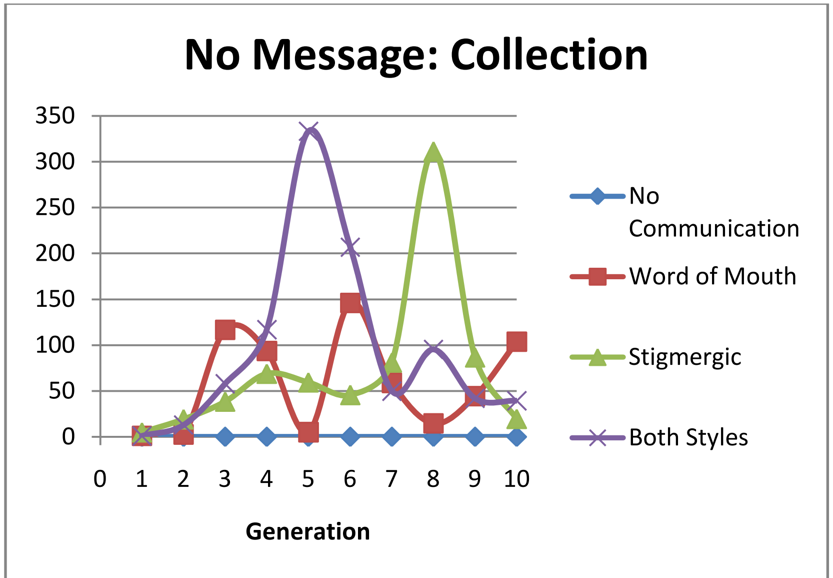
Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
0	0	5	0	0	0	0	0	0	3
15	42	307	67	638	203	193	25	772	356
0	45	433	165	57	351	431	510	361	168
0	34	47	481	650	874	159	737	815	799

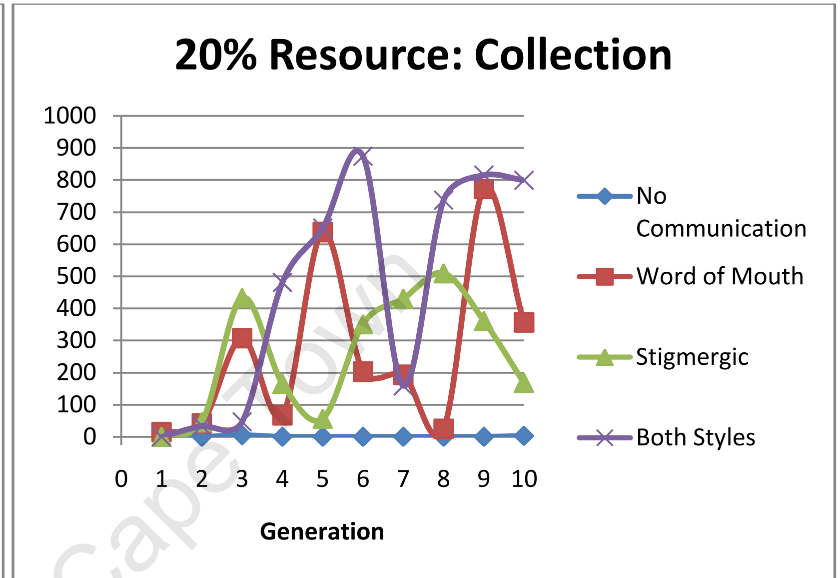
Starting Conditions
20% Resource and Base

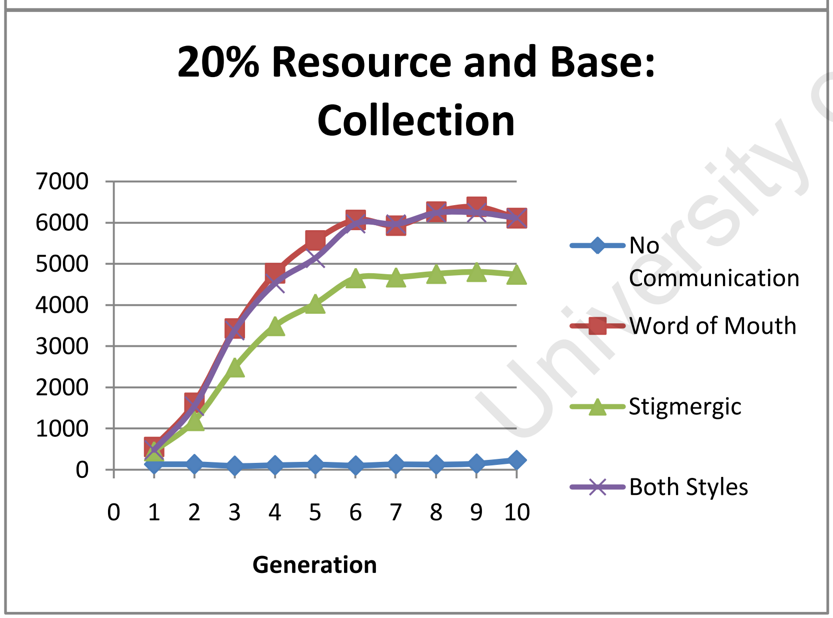
Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
134	132	95	112	129	103	132	129	151	239
554	1628	3430	4774	5572	6066	5929	6265	6385	6109
455	1190	2494	3493	4039	4657	4675	4762	4807	4741
482	1547	3381	4524	5137	5973	5968	6236	6241	6114

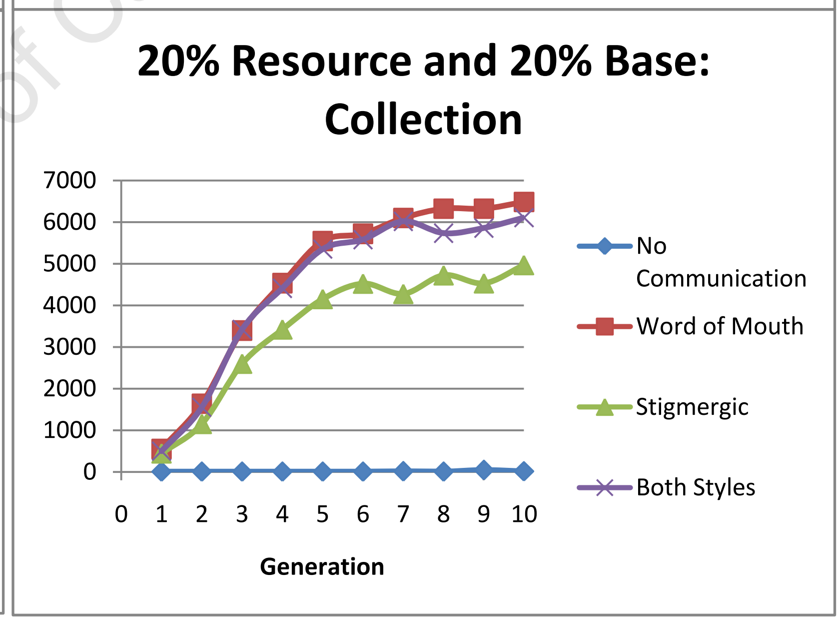
Starting Conditions
20% Resource and 20% Base

Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
3	3	7	5	4	4	9	7	40	15
549	1637	3396	4532	5545	5718	6102	6322	6322	6485
445	1151	2600	3422	4151	4523	4275	4722	4529	4966
498	1551	3422	4411	5354	5580	6019	5733	5856	6105


No Message: Collection
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource: Collection
1000
900
800
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource and Base: Collection
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource and 20% Base: Collection
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles

Single Base and Single Resource

Collected

Starting Conditions
No Message

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	0	0	0	0	0	0	0	0	0	0
Word of Mouth	1	3	117	94	5	146	59	15	44	104
Stigmergic	5	19	38	69	59	46	81	311	87	20
Both Styles	1	13	58	117	333	207	50	95	42	39

Starting Conditions
20% Resource

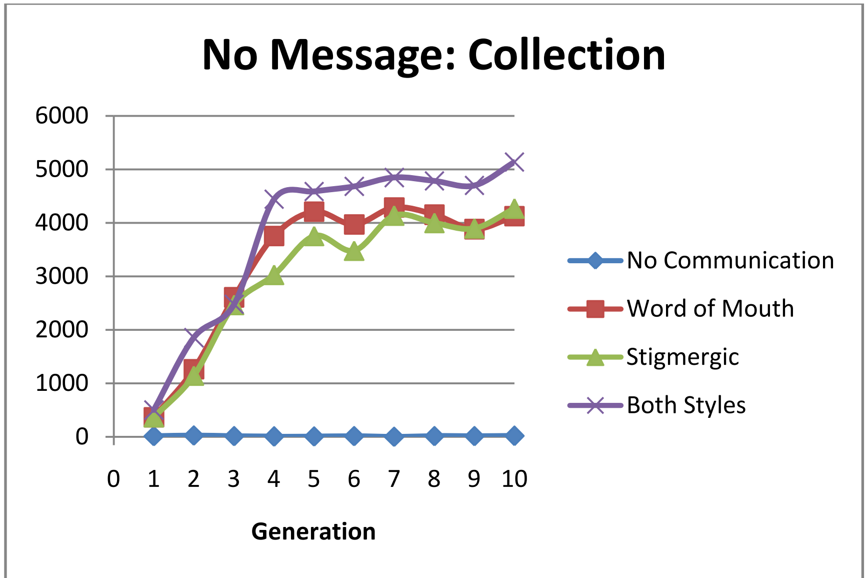
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	0	0	5	0	0	0	0	0	0	3
Word of Mouth	15	42	307	67	638	203	193	25	772	356
Stigmergic	0	45	433	165	57	351	431	510	361	168
Both Styles	0	34	47	481	650	874	159	737	815	799

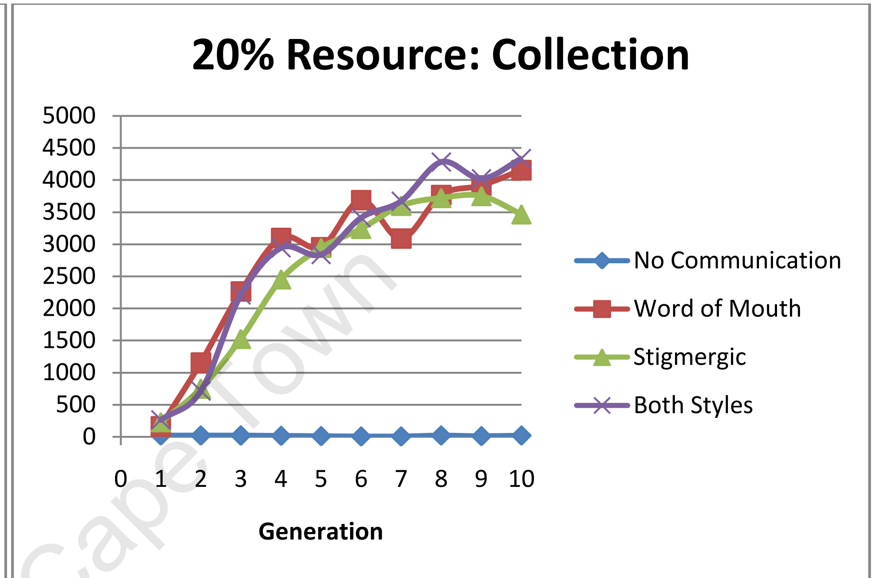
Starting Conditions
20% Resource and Base

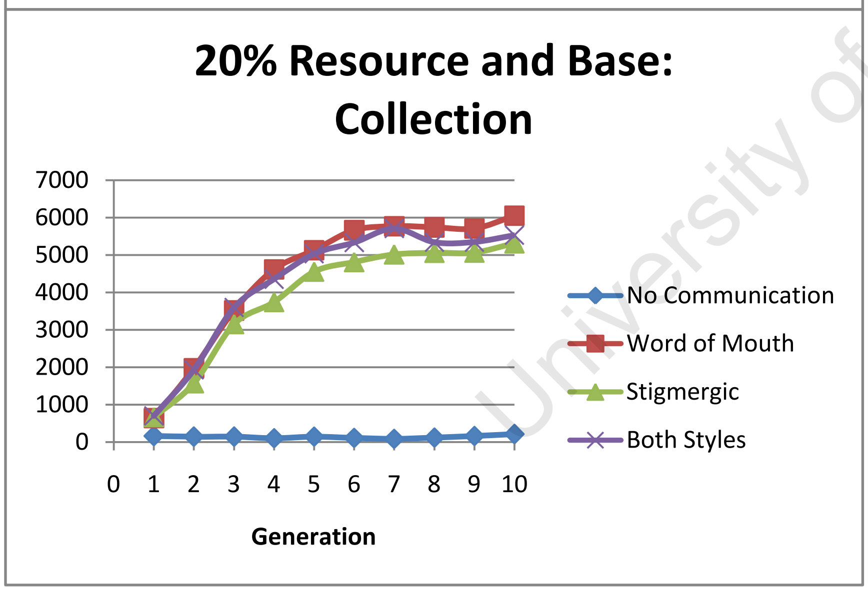
Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	134	132	95	112	129	103	132	129	151	239
Word of Mouth	554	1628	3430	4774	5572	6066	5929	6265	6385	6109
Stigmergic	455	1190	2494	3493	4039	4657	4675	4762	4807	4741
Both Styles	482	1547	3381	4524	5137	5973	5968	6236	6241	6114

Starting Conditions
20% Resource and 20% Base

Communication Style	Gen 0	Gen 1	Gen 2	Gen 3	Gen 4	Gen 5	Gen 6	Gen 7	Gen 8	Gen 9
No Communication	3	3	7	5	4	4	9	7	40	15
Word of Mouth	549	1637	3396	4532	5545	5718	6102	6322	6322	6485
Stigmergic	445	1151	2600	3422	4151	4523	4275	4722	4529	4966
Both Styles	498	1551	3422	4411	5354	5580	6019	5733	5856	6105


No Message: Collection
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles


20% Resource: Collection
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles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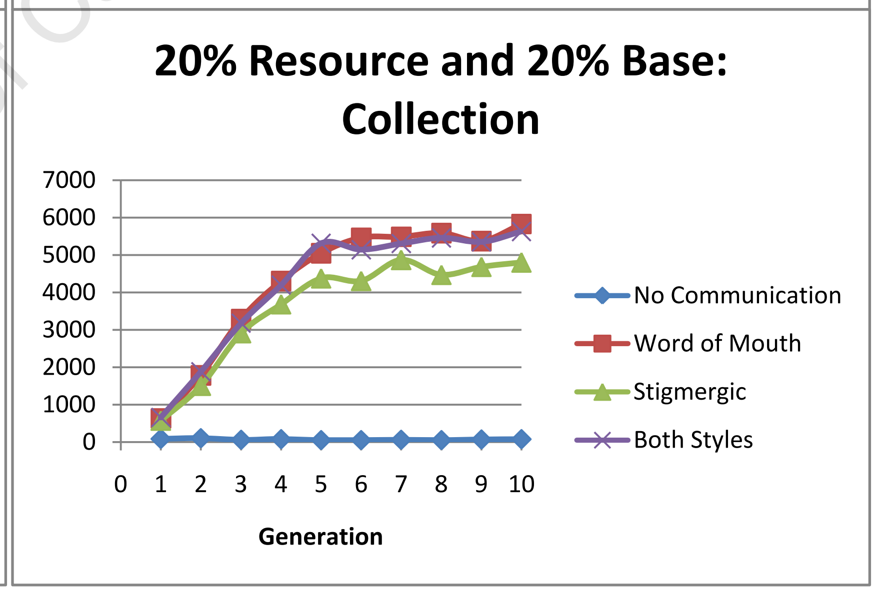
5000
4000
3000
2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
Stigmergic
Both Styles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2000
1000
0
0 1 2 3 4 5 6 7 8 9 10
Generation
No Communication
Word of Mouth
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